A High Energy Saving Interface System Using a Matrix Converter between a Power Grid and an Engine Generator for Bio Diesel Fuel

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Abstract--**This paper discusses an interface power converter between a power grid and an engine generator. A matrix converter, which is one of the AC/AC direct converters, can achieve high efficiency without large energy storages. Therefore, the volume of the converter becomes smaller and the reliability of the interface system is improved due to no use of electrolytic capacitor.**

This paper discusses the control strategy of a matrix converter for the power grid interconnection. In addition, the performances are demonstrated by simulation and experiments with a 1.5-kW prototype. The proposed control method is confirmed in the simulation and experimental results. Furthermore, the maximum efficiency of 96.8 % is obtained in the experiment. Total loss of the power converter is approximately half of the conventional system that is using a Back-to-Back converter.

Index Terms--**matrix converter, BDF, BTB converter, interface power converter, generator**

I. Introduction

The studies and activities about a smart grid are highly conducting recently because this concept could achieves high energy saving.

Bio Diesel Fuel (BDF) is one of renewable energy resources. BDF is used for a diesel engine with a generator for electric power conversion. BDF has similarity to the wind turbines and photovoltaic cell systems in term of the carbon neutral. However, an engine generator can provide more stable power in comparison to the generation system that uses the natural energy resources such as a solar power, a wind turbine and other. Moreover, the biomass fuel which is typified as a BDF does not influence human health and environmental. Therefore, an engine generator using BDF is expected to apply in a smart grid in the future.

In the smart grid, an interface power converter is required between an engine generator and a power grid. This interface power converter adjusts the frequency and the voltage amplitude on both sides. The interface converters for the application of smart grid are expected to have high efficiency and high reliability.

Generally, a back-to-back (BTB) converter, which consists of a PWM rectifier and a PWM inverter, is applied in this system as the interface converter. However, the BTB converter uses large amount of electrolytic capacitors as the smoothing capacitors. As the results, the system size is big and regular maintenance is required. That is, the electrolytic capacitors reduce the system reliability. Moreover, the efficiency of the BTB converter is low due to the two stages power conversion within the converter. Recently, matrix converters attract a lot of attentions among the researchers because this converter achieves high efficiency and small size due to no smoothing capacitors. Therefore, the system with matrix converter is expected to achieve high reliability and long-life time. Many papers regarding to the matrix converter are being discussed in the field of adjustable speed drive applications [1-4].

On the other hand, only small portions of the papers describe using the matrix converter as a generator interface converter in a distributed power supply and a micro grid system, which discuss on the subjects of high efficiency and maintenance issue. In these papers, a matrix converter is applied to the interconnection system to adjust the frequency and voltage amplitude between the generator and the grid system. In Ref. [5-8], the control of the generator power based on the generator parameters are being discussed. The control method has to be changed regularly because it depends on the types and parameters of the generator. On the other hands, BDF generators are formed by many kinds of generators such as an induction generator, a synchronous generator and a permanent magnetic generator. These generators show a difference in terms of cost and field requirements upon to the circumstances. Due to the varieties of generators, design becomes complicated and therefore a robust interface converter is required.

This paper proposes to apply the matrix converter as an interface converter between the power grid and a diesel engine with BDF. The key feature of this proposed system is that the matrix converter can control the generator power, regardless of the generator parameters and types. In the proposed control, the generator is assumed as a simple variable amplitude and frequency power supply with the internal impedance. Then, a current regulator in the generator side controls the input filter current. As a result, the proposed system can connect voltage source at the both input and output side.

In this paper, first, the feature of the proposed interface system is introduced. Second, the control strategy of the matrix converter for the interface converter is described. Finally, the simulation results and also the experimental results which are obtained from a 1.5-kW prototype are demonstrated accordingly.

II. SYSTEM CONFIGURATION

Figure 1 shows an interconnection system using an interface converter among a BDF generator, a load and a power grid. the conventional interface converter between an engine generator and the power grid. In order to connect a generator to the power grid, the interface converter must provide a generator power in spite of the differences of the frequency, phase and voltage amplitude between the generator and the power grid. In addition, the interface converter controls the active power according to the load demands. From here, these interface converters are used to satisfy the above requirements.

An engine generator using the BDF is usually operating at a constant speed for obtaining a constant output power. Therefore, the operation condition of the generator can be set to the highest efficiency condition.

Figure 2 (a) shows a conventional system using a BTB converter. The PWM inverter needs to control the interconnection current to sinusoidal waveform for the grid. On the other hand, the PWM rectifier needs to control the generator current to sinusoidal waveform. Both input and output of the BTB converter do not interfere with each other because the smoothing capacitors in the DC link could separate the controls. Therefore, the interconnection current and the generator can be controlled easily. As a result, a BTB converter is usually used as an interface converter. On the other hand, the problems of this system are as following; the smoothing capacitor in DC link is bulky; the smoothing capacitor is the shortest life-time element in the system; the system efficiency becomes lower because of two times conversion between the generator and the power grid.

Figure 2 (b) shows a conventional system with a matrix converter using nine bidirectional switches as an interface converter. The smoothing capacitor is not required because the matrix converter has no DC stage. In addition, the matrix converter can achieve the minimum loss due to only one stage conversion in term of AC to AC conversion. The power loss of the matrix converter is approximately half of that of the BTB system [9].

However, these conventional interface systems in Figure 2 have another problem in term of the generator control. In order to control the power from a generator, the generator parameters first must be designed and known. The most common generators seen in this application are such as the induction generator, the synchronous generator with external exciter, or the permanent magnetic generator. Therefore, it is complicated to change the control methods according to the generators, especially in a low cost system.

Figure 3 shows the proposed interconnection system with a matrix converter. A LC filter is added between the generator side and the input line of the matrix converter. The generator power is controlled by adjusting the input filter current instead of the generator current. The generator current is decided by the amplitude and phase angle of the input filter capacitor current. The matrix converter can control the filter reactor

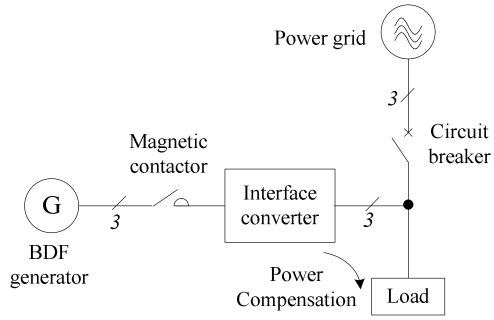

Fig. 1. Configuration diagram of an interconnection system using an interface converter for a smart grid.

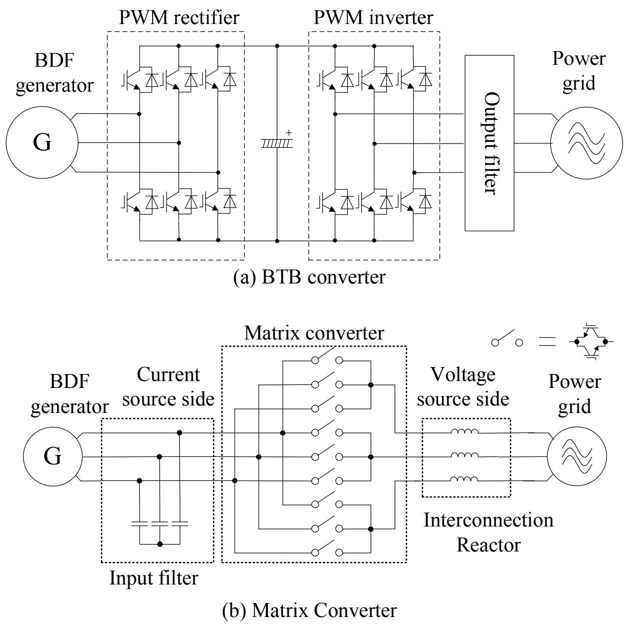

Fig. 2. Configuration diagram of the conventional power grid connected system using a power converter.

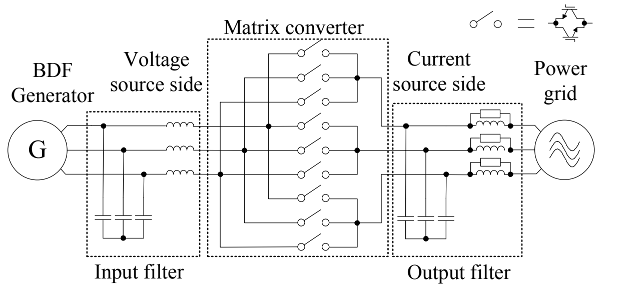

Fig. 3. Configuration diagram of the proposed power grid connected system using a matrix converter.

current with the control block diagram by not using the generator parameters, such as internal impedance and back electromotive force of the generator. Moreover, the operating speed and phase angle of the generator from its encoder are unnecessary because the active power can be controlled by the detection of the generator terminal voltage from the input filter capacitors. As a result, the generator can be assumed as a simple variable frequency power supply with internal impedance. From this, all types of generator, especially a very low cost generator, can be used in this system.

However, the proposed interface system has technical issues in term of the interconnection. The matrix converter controls both input and output waveforms at the same time. Therefore, the input side control affects the output side control due to the lack of energy buffer, which is different from a BTB converter. Therefore, if the generator terminal voltage and current are distorting, the fluctuation will affect the power grid conditions. In addition, the proposed system uses LC filters at both input and output sides, which the resonance between L and C is possible to occur at both sides. The resonance in the output side is suppressed by the damping resistor and the resonance in the input side is suppressed by voltage and current feedback control which will be described in next chapter.

On the other hand, the matrix converter must compensate the load power even if a trouble such as interruption occurs at the power grid. When the trouble occurs at the power grid, circuit breakers shown in the Figure 1 are opened. Therefore, the matrix converter must control the load power using the power provided from the generator only. Thus, the control for independent operation of the matrix converter is required in case a trouble occurs at the power grid.

III. Control Strategy

There are two types of power source in a matrix converter known as, the voltage and current source. Usually, the voltage source side is connected to reactors, and the current side is connected to capacitors. In general, the current source side is located on the voltage power source i.e. a power grid. In an adjustable speed drive system, the current source side is located on the power grid side. In the proposed system, however, the current source side of the matrix converter is connected to the power grid, which is treated as a load side. That is, this system is operated similar to the regeneration mode of an adjustable speed drive system.

The generator side becomes the voltage source side alike a voltage source inverter. The reactor current and the capacitor voltage in the input filter are controlled by the proposed method. Note that the input voltage of the matrix converter is lower than 86.6% of the power grid voltage because of the limitation in the voltage transfer ratio of a matrix converter. In other words, the proposed system boosts up the generator terminal voltage. Thus, the matrix converter of the proposed system can operate even if the generator voltage lowers due to the generator frequency fluctuation. On the other hand, the conventional interface system using a matrix converter such as Figure 2 (b) has the lower limitation of the generator terminal voltage which the matrix converter can operate at, because of the limitation of the voltage transfer ratio.

Figure 4 shows the relationship between the γδ and the dq axis to consider the active power and reactive power on the proposed control. Note that γδ axis is based on the back electromotive force of the generator and dq axis is based on the terminal voltage of the generator. In Figure 4, $\boldsymbol{e}$ is the back electromotive force vector of the generator, $\boldsymbol{i_g}$ is the generator current vector, $\boldsymbol{i_c}$ is the capacitor current vector, $\boldsymbol{v_c}$ is the

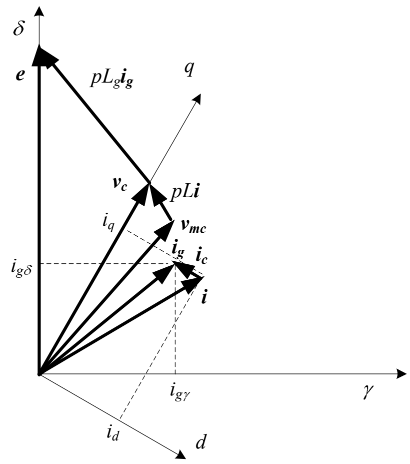

Fig. 4. Relationship among the voltages and the currents on the generator side with dq axis based on the terminal voltage and γδ axis based on the back electromotive force of the generator.

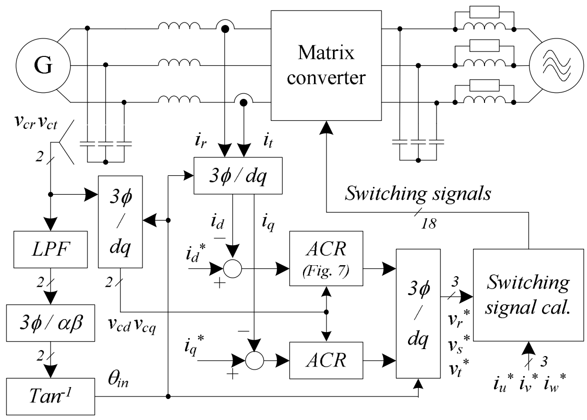

Fig. 5. Control block diagram of the proposed interface system between an engine generator and the power grid.

voltage vector of the input filter capacitor, $\boldsymbol{i}$ is the current vector of the input filter reactor, $\boldsymbol{v_{mc}}$ is the input voltage vector of the matrix converter, $pL\boldsymbol{i}$ is the voltage drop vector at the input filter reactor, and $pL_g\boldsymbol{i_g}$ is the voltage drop vector at the generator inductance. Note that p is a differential operator. Generally, the dq axis is based on the back electromotive force of the generator. In this paper; however, the terminal voltage of the generator is defined as the basis of the dq axis. These axes are obtained from the rotating frame and rotate at the same speed.

Figure 5 shows the proposed control block diagram. The active and reactive current controls are implemented on the rotating frame. The direction of the q-axis is defined as the same direction of the input filter capacitor voltage. The active and reactive power on the dq axis is indicated by

$$\begin{cases} p_{dq} = \mathbf{v_c} \cdot \mathbf{i} = v_{cd} i_d + v_{cq} i_q \\ q_{dq} = \mathbf{v_c} \times \mathbf{i} = v_{cd} i_q - v_{cq} i_d \end{cases} \tag{1}$$

where p_{dq} is the active power, q_{dq} is the reactive power of the input of the matrix converter. The direction of the voltage vector of the input filter capacitor conforms to the q-axis. Then, (1) is calculated by

$$\begin{cases} p_{dq} = v_{cq} i_q \\ q_{dq} = -v_{cq} i_d \end{cases} \tag{2}$$

Therefore, it is shown that i_d is the reactive current and i_q is the active current on the dq axis. That is, the d-axis current command i_d^* controls the reactive power; the q-axis current command i_q^* controls the active power on the dq axis. This current control is implemented with an automatic current regulator (ACR). The output and input phase angles are calculated by the arctangent function respectively. The dq axis is obtained by the detected voltage of the input filter capacitor. However, the γδ axis cannot be obtained without the information from the generator encoder. Therefore, the proposed system adopts the dq axis to control the generator power. A low-pass filter (LPF) is necessary after thegenerator voltage detection because the filter capacitor voltage v_{cr}, v_{ct} may contain distortions due to the LC resonant. Note that the resonant suppression control is applied with an ACR. The voltage control of the capacitor is not necessary because the capacitor voltage is clumped by the generator voltage.

The control of the matrix converter is applied with a virtual AC/DC/AC PWM carrier comparison method [10]. The control of the power grid current and the control of the input voltage are separated by using a virtual rectifier command and a virtual inverter command in this method. As a result, the control becomes simple. The power grid side can obtain a unity power factor.

Figure 6 shows the vector diagram on the generator side when the generator current vector and the back electromotive force vector of the generator are in the same phase. Note that the current of the input filter capacitor is assumed to be zero for simplicity because the capacitor current is small sufficiently. Therefore, the generator current vector conforms to the input current vector of the matrix converter. The active power $P_{\gamma\delta}$ on the γδ axis is obtained by

$$p_{\gamma\delta} = \mathbf{e} \cdot \mathbf{i_g} = v_{cq} \cos\phi \cdot \frac{i_q}{\cos\phi} = p_{dq} \tag{3}$$

where ϕ is the phase angle between the dq axis and the γδ axis because of the internal impedance of the generator. The active power on the γδ axis is equal to the active power on the dq axis. Therefore, the active current command i_d^* is calculated by

$$i_q^* = \frac{p_{dq}^*}{v_{cq}} \tag{4}$$

When the generator current vector and the voltage vector of the back electromotive force are in the same phase, the cupper loss of the generator becomes the least because the generator provides no reactive current on the γδ axis. The minimum cupper loss is achieved when the reactive current of the generator $i_{g\gamma}$ becomes zero. The matrix converter controls $i_{g\gamma}$ to zero by adjusting the reactive current command i_d^* on the dq axis. i_d^* is calculated by

$$i_d^* = -\frac{X_L i_q^{*2} v_{cq}}{e_\delta^2} \tag{5}$$

where X_L is the reactance of the generator. Thus, derivation of

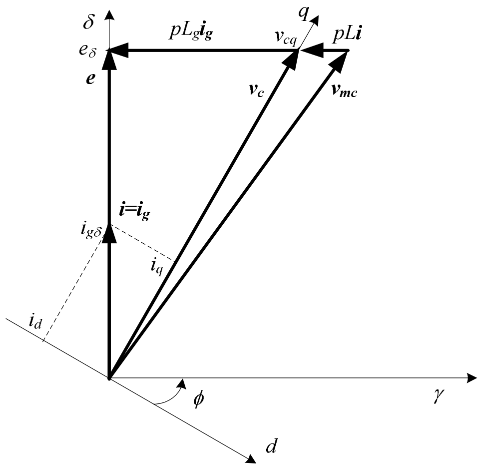

Fig. 6 The vector diagram on the generator side when the generator current vector and the voltage vector of the back electromotive force of the generator are in the same phase.

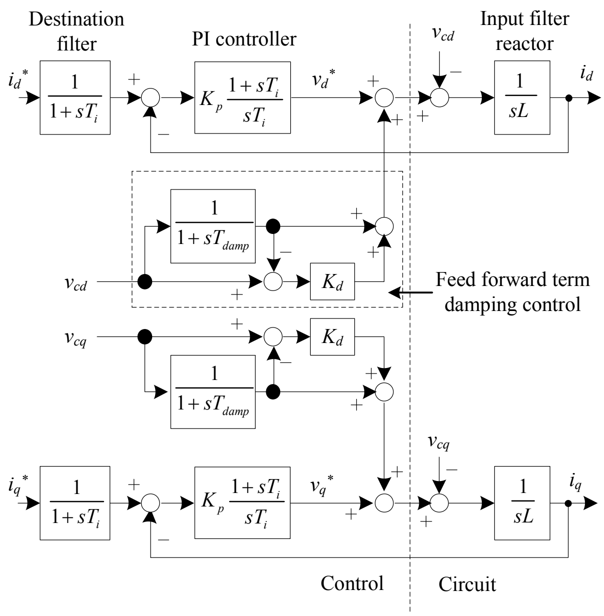

Fig. 7. Transfer function block diagram in ACR to control the input current of the matrix converter.

i_d^* using (5) must use the generator parameters. Equation (5) cannot be used in the control of the matrix converter because the key feature of the proposed system is that the matrix converter controls power from the generator without the generator parameters. However, it is useful for the generator efficiency to control i_d^*. Therefore, the maximum power point tracking (MPPT) method which is applied to the generation system with the natural energy resources must be considered.

Figure 7 shows a control block diagram which is used for the control of the input current. The control strategy in Figure 7 does not use the generator parameters. The destination filter is used to prevent overshoot in the input current. The gain values of the PI controller are decided from natural angler frequency ω_n and the damping factor ζ.

In addition, a feed forward term is applied into the damping control to suppress the LC resonant at the PI output. The feed forward term means the voltage of the input filter capacitor. It is effective for stable operation on the generator side to suppress the voltage ripple of the input filter capacitor. In Figure 5, the fundamental frequency component of the input filter capacitor is converted to a constant value alike a DC component by the rotating frame. On the other hand, the resonant component of the input filter capacitor is converted to ripple component. In the damping control for the feed forward term in Figure 7, first, low pass filters, which have the time constant T_{damp}, separate the DC and ripple components of the voltage of the input filter capacitor. Then only the ripple component is multiplied by a damping gain K_d. As a result, the compensated value for the ripple due to LC resonant is obtained.

IV. Simulation and Experimental Results

At first, the proposed system is evaluated in simulations in probable situations for the interconnection between an engine generator and the power grid. Table 1 shows the generator parameters. Note that the generator is assumed as a voltage source and a large reactor (50%) to evaluate the validity of the proposed system in principle. Table 2 shows the simulation conditions.

Figure 8 shows the operation waveforms of the proposed system with only active current command (i_q^*=1 p.u.) at steady state. The input current of the matrix converter is controlled to rated current 14 A (RMS) by the ACR. The unity power factor is obtained on the power grid and the generator side. The unity power factor on the power grid side is obtained easily by the open loop control from the virtual current source rectifier. On the other hand, the unity power factor on the generator side is obtained by the ACR with no reactive current command (i_d^*=0 p.u.). In addition, both the grid current and input current obtain sinusoidal waveforms. Thus, the feature of the proposed method, that is the simultaneous control on the input and output side without a DC link is confirmed.

Figure 9 shows the relationship between a zero point of the γ-axis current $i_{g\gamma}$ and the input current commands of the matrix converter. Note that back electromotive force of the generator is set to 100 V_{rms} (line to line), the generator frequency is set to 60 Hz in Figure 9. The dq axis current i_d and i_q are through a LPF for observation. The matrix converter controls the input power factor with the reactive current command i_d^*. Note that the active current command i_q^* is a constant value and provides constant active power to the power grid. When the reactive current $i_{g\gamma}$ on the γδ axis is zero, the reactive current i_d on dq axis is -0.143 p.u.. Note that the theoretical value of i_d using (5) is -0.155 p.u. when $i_{g\gamma}$ is zero. The generator current is preferred to be a small value because the amplitude of the generator current affects copper loss of the generator. In other words, it is required to control $i_{g\gamma}$ to zero by adjusting i_d^*.

Figure 10 shows the matrix converter waveforms which is operates under a starting sequence. The starting sequence is

Table 1. Generator parameters.

Rated terminal voltage (line to line)	176 V_{rms}
Rated back e.m.f. (line to line)	151 V_{rms}
Rated current	14 A_{rms} (=1 p.u.)
Rated power	3.7 kW
Rated speed	1800 rpm
Rated frequency	90 Hz
pole	6
Synchronous inductance	6.56 mH (50 %)

Table 2. Simulation conditions.

Grid voltage (line to line)	200 V_{rms}
Grid frequency	50 Hz
Generator back e.m.f. (line to line)	150 V_{rms}
Generator frequency	90 Hz
MC rated input power	5.5 kVA
MC rated input voltage (line to line)	173 V_{rms}
Carrier frequency	10 kHz
Grid side LC filter	2 mH (2.35 %)
	13.2 μF
Grid side damping resistor	47 Ω (ζ=0.131)
Generator side LC filter	2 mH (15.2 %)
	6.6 μF
ACR damping factor ζ	0.7
ACR natural angular frequency ω_n	4000 rad/s

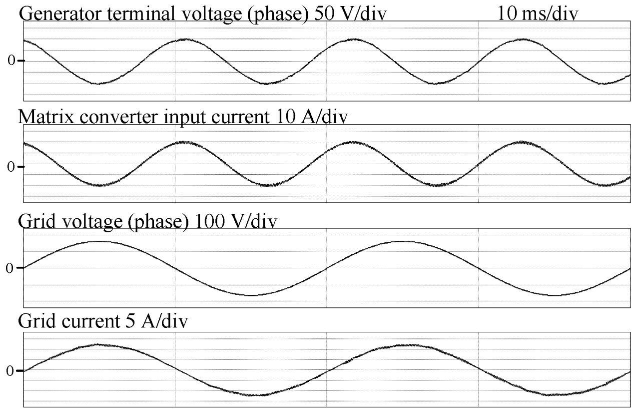

Fig. 8. Operation waveforms of the matrix converter in the proposed system at steady state in simulation.

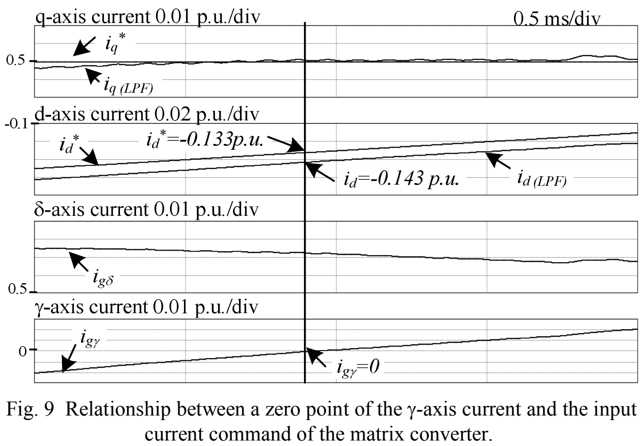

Fig. 9 Relationship between a zero point of the γ-axis current and the input current command of the matrix converter.

like following; contactors on the generator side in Figure 1 are closed. Then, the matrix converter starts to operate with zero current commands. After that, the current commands are fed into the ACR. From 0 to 10 ms, the generator is not connected to the matrix converter. The generator is already operating at this period. However, the matrix converter does not operate. At 10 ms, contactors on the generator side in Figure 1 are closed to connect the generator and the matrix converter. After this, the resonant current due to the internal impedance of the generator and input filter capacitor occurs. Note that the matrix converter blocks off all the gates of IGBTs from 10 to 30 ms. At 30 ms, the matrix converter starts to control the input current to zero by the ACR. The LC resonant is suppressed by the damping control in the ACR. Then, at 50 ms, a ramp current command is inputted to suppress the surge voltage on the input filter capacitor. As a result, the generator connection is enabled by the above sequences. The generator terminal voltage angle θ_{in} calculation for ACR is important for stable control in the transient state. However, there is no surge current except LC resonant current in the transient period. Therefore, if the LPF for θ_{in} calculation eliminates the frequency band over the rated generator frequency, the ACR can start to operate stably right after the generator connection.

Figure 11 shows the generator frequency fluctuation with constant input current commands. The generator terminal voltage becomes lower as the generator frequency fluctuates because the back electromotive force of a generator is proportional to the operating speed. During the fluctuation periods, the voltage and current on the grid side have no distortion. The distortion due to the generator frequency fluctuation does not occur because the fundamental frequency current of the input filter reactor is controlled as a DC component based on the conversion from the rotating frame. Furthermore, the operation also confirms no fluctuation on the grid power factor. Note that the grid current is reduced because of the input power change due to the constant input current commands and voltage fluctuation. Moreover, the constant power control is available if the input current commands are generated with the power commands.

Figure 12 shows the operation waveforms where the power grid voltage is fluctuating. Note that the electromotive force of the generator is set to 100 V_{rms} (line to line), the frequency of the generator is set to 60 Hz. The input current is controlled to a constant value because of the ACR against the fluctuation of the grid voltage. On the other hand, the grid current increases against the fluctuation of the grid voltage. Therefore, the matrix converter can control the generator power constantly when the grid voltage fluctuates. As mentioned previously, however, when a trouble occurs at the power grid such as interruption, the circuit breakers in Figure 1 are opened. Therefore, the control method of the matrix converter is needed to study in the situation where an independent operation condition in the proposed system is required.

A 1.5-kW prototype circuit was constructed and tested with the proposed system to evaluate the efficiency. The experimental conditions are almost the same as Table 2. Note

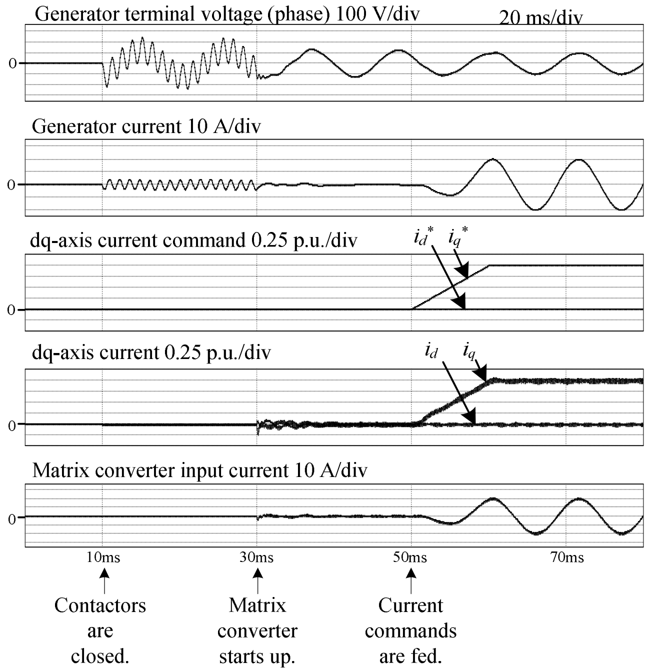

Fig. 10. Voltage and current waveforms on the generator side in the starting sequence of the proposed interface system.

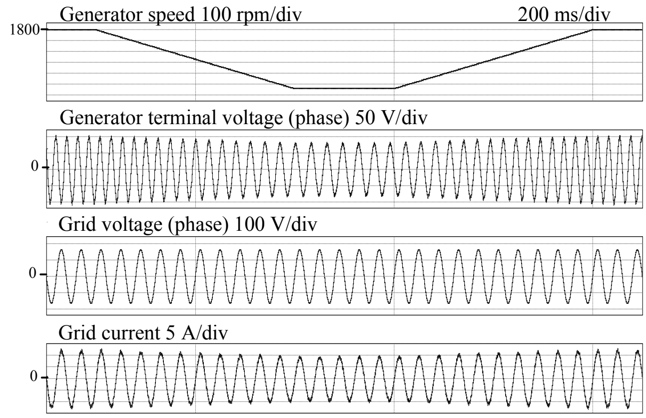

Fig. 11. Operation waveforms of the proposed system including no distortion in the period of the generator frequency fluctuation.

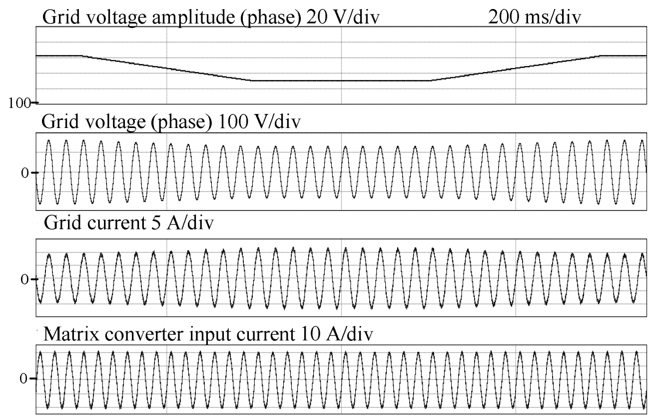

Fig. 12. Operation waveforms of the proposed system in period of the fluctuation of the power grid voltage.

that the generator was replaced with a voltage source and a transformer because of the experimental limitation. The voltage source is 130 V_{rms} (line to line) and the frequency is 50Hz. Then, the damping control in Figure 7 was not used in the experiment. Instead, the damping resistor 5.1 Ω was inserted in series to the filter capacitors on the generator side to confirm the basic characteristic of the PI controller in the ACR. The ACR gain and damping factor is adjusted according to experimental parameters.

Figure 13 shows the steady state operation waveforms of the prototype. Note that only active current command i_q^* is fed into the ACR. Sinusoidal waveforms are confirmed to obtain in the input current and grid current. The unity power factor on the input side of the matrix converter is obtained and the grid power factor is 98.6 %.

The remaining distortion in the current waveform is generated from the voltage error due to the commutation. Therefore, the quality of the current waveform will be improved by applying a voltage error compensation method [11-12].

Figure 14 shows the measurement results of the efficiency. Note that the efficiency is measured in a way opposite to the power flow because of the experimental limitation. The efficiency of over 96 % is obtained from over a 30% load; the maximum efficiency is 96.8% at a 1400 W load. In general, the efficiency of the BTB is approximately 92% - 94%. The total loss in the power converter is reduced to 1/2 of that of a BTB in the proposed system.

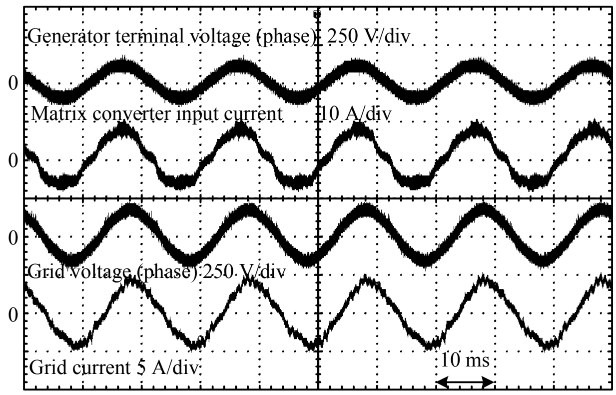

Fig. 13. Operation waveforms of the proposed system at steady state with an experiment.

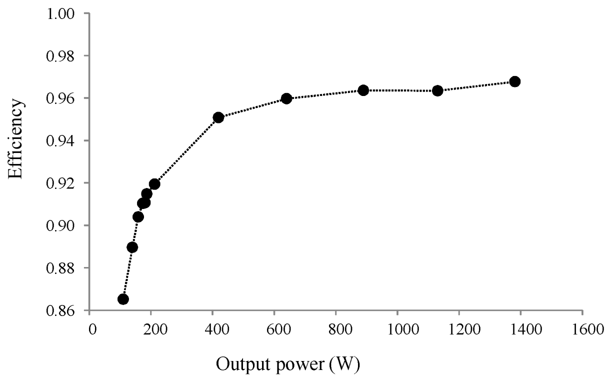

Fig. 14. Efficiency characteristics with experiment.

V. Conclusions

This paper discusses an interface converter between an engine generator and a power grid. The matrix converter is used as the interface converter in order to obtain high efficiency, reliability and size reduction in comparison to a BTB converter. The proposed interface system is characterized by the generator side control. The simulation results and experimental results confirmed the validity of the proposed system. In the simulations, the control of the input current of the matrix converter is confirmed for an interconnection system. The maximum efficiency 96.8% is demonstrated in the paper. Total power converter loss becomes approximately half of the conventional converter loss.

In future work, the current waveforms will be improved and other type of experimental results including transient response and revaluation of the system efficiency will be considered. In addition, the control of the matrix converter in case of the interruption will be investigated.

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