# Ride Through Capability of Matrix Converter for Grid Connected System under Short Voltage Sag

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***Abstract*—This paper proposes a FRT (Fault ride through) method of a matrix converter under three-phase short voltage sag. The feature of the proposed method is to control grid reactive current and generator torque at the same time. In order to realize these capabilities, this paper describes a modulation method dividing a control period into 3 modes. The first mode is to turn off all switches and the second mode is a zero vector output. By these 2 modes and utilizing a snubber circuit, the generator torque is controlled during the voltage sag. In the third mode, a non-zero vector is selected to provide the reactive current to the grid. In contrast, this paper also proposes a feedback control of the snubber voltage to obtain the stable ride through operation. From experimental results, the grid reactive current of 0.44 p.u. and the generator torque of 0.7 p.u. are achieved by the proposed method during three-phase voltage sag.**

***Keywords—matrix converter; fault ride through; generator; reactive current; three-phase voltage sag***

## I. Introduction

Nowadays, wind turbine systems have attracted attentions and have been introduced rapidly [1]. In a wind turbine system, a grid code is regulated in many countries in order to prevent a huge power interruption and support rapid recovery of grid voltage [2]. A typical topic of the grid code is following: 1) a power converter in the wind turbine system should continue to operate during short grid voltage sag if retained voltage and its duration are within a defined area of the grid code; 2) the power converter delivers reactive current to the grid depending on the retained voltage. In addition, it is expected that these grid code will cover distributed power supplies such as an engine generator and a micro turbine system in the future.

On the other hand, in the wind turbine system, generator torque should be maintained regardless of the grid state in order to avoid unexpected acceleration and vibration of the wind turbine [3]. Moreover, in the engine generator and the micro turbine systems, the generator cannot react to a quick torque disturbance caused by the grid voltage sag [4]. Thus, a grid connected converter should also equip the following capability aside from the grid code: 3) the grid connected converter should maintain the generator torque during the grid voltage sag in the same manner as the normal operation.

In contrast, a matrix converter has attracted a lot of attentions as a high performance AC-AC converter [5-7]. A matrix converter promises to achieve higher efficiency, smaller size and longer life-time compared to a conventional rectifier-inverter system. In previous works, grid connected systems using a matrix converter for a wind turbine and a micro turbine systems have been reported [8-10]. However, generator terminal voltage of the grid connected matrix converter is forced to be lower during the grid voltage sag because the matrix converter is a step-down converter. Thus, it is difficult for the matrix converter to realize a ride through operation.

Some literatures about a FRT (Fault ride through) method of the matrix converter have been published [11-17]. The FRT methods proposed in [11-16] are able to ride through a matrix converter during the voltage sag. In particular, [11] proposes a simple FRT method against a small voltage dip by adjusting a modulation index of the matrix converter. Reference [12] verifies that the proposed FRT method continues to operate the matrix converter and transfers power from a motor to a snubber circuit in order to keep a control hardware operation. In addition, [13] shows matrix converter topologies with added switches for FRT. In other ways, [14] describes a FRT method for a matrix converter driving an industrial induction motor, which controls stator flux of the induction motor and enhances the ride through duration. Reference [15] reports a FRT scheme for an aircraft actuator by blocking gate pulses. Moreover, [16] represents a control method which retains grid filter capacitor voltage during the grid failure. However, although these methods obtain the ride through capability during the short voltage sag, the reactive grid current control and the generator torque control cannot be achieved. In contrast, [17] adds a braking chopper in the snubber circuit of the matrix converter to convert braking energy to heat which is equal to control the generator torque. However, this method also cannot realize the grid reactive current control.

This paper proposes a FRT method to achieve a stable ride through operation, the grid reactive current control and the generator torque control during three-phase voltage sag in the same time. The proposed method divides a control period into three modes to ensure compatibility between the grid reactive current control and the generator torque control. The stable ride through operation without any over-voltage and over-current is realized by using two feedback controls for the snubber voltage and the generator current amplitude. In addition, the snubber circuit is utilized to consume the generator power and to minimize additional component for FRT. Finally, it is confirmed that a fine ride through capability is obtained by the proposed FRT method in simulations and experiments.

## II. CIRCUIT CONFIGURATION

Fig. 1 shows a matrix converter for an interface between a power grid and a generator. Fig 1 consists of a power grid, LC filters, bi-directional switches, a snubber circuit including a braking circuit and a generator. During the short voltage sag, active power delivered from the generator to the grid is zero because the matrix converter provides reactive current to the grid. However, the generator should be applied the same torque as before the voltage sag. Therefore, a braking IGBT is turned on and the active power provided from the generator is consumed by a braking resistor $R_{brk}$ which is designed for FRT. It should be noted that this dedicated braking circuit is used in not only a matrix converter but also a conventional rectifier-inverter system. Hence, the advantages of the matrix converter compared to the conventional system are not degraded.

## III. MODULATION METHOD DURING GRID VOLTAGE SAG

Fig. 2 shows a circuit diagram of an IMC (Indirect matrix converter) to consider the proposed FRT method. This chapter replaces the matrix converter illustrated in Fig. 1 with a CSR (Current source rectifier) and a VSI (Voltage source inverter) as shown in Fig. 2. This replacement is based on a virtual indirect control [7] and simplifies a consideration about the modulation method during the voltage sag. Note that the LC filters is eliminated and the snubber circuit is composed of a diode bridge and a DC voltage source in Fig. 2. Then, in order to yield the same waveforms between the matrix converter and the IMC at the input and output terminals except an effect of the filter in Fig. 1, (1) should be satisfied.

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

where, $s_{mn}$ is a switching function of the switch $S_{mn}$. $s_{mn}$ is 1 when $S_{mn}$ is turned on and $s_{mn}$ is 0 when $S_{mn}$ is turned off.

Modulation methods of the CSR and the VSI in Fig. 2 are based on a triangular carrier modulation presented in [7]. Thus, the CSR controls grid power factor and the VSI adjusts generator terminal voltage waveform. In order to inject the reactive current to the grid during the voltage sag, the grid power factor reference of the CSR is set to zero. Besides, the grid power factor reference is set to 1 in a normal mode and the active power is delivered from the generator to the grid.

In contrast, the VSI in the normal mode controls the generator with a field oriented control. However, during the voltage sag, the generator terminal voltage of the VSI becomes zero because dc-link voltage $e_{dc}$ is zero due to the zero power factor operation of the CSR. Hence, a modulation method to synthesize the generator terminal voltage should be developed to control the generator torque for the FRT. In addition, the VSI needs to provide a constant current at the dc-link to inject

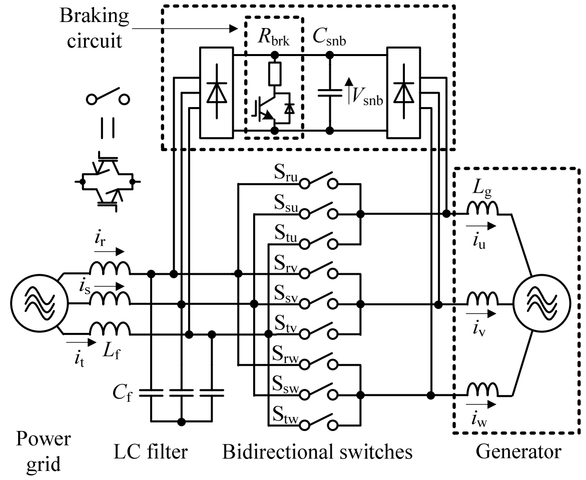


Fig. 1. Circuit diagram of the matrix converter for a grid connected system. The snubber circuit includes a braking circuit.

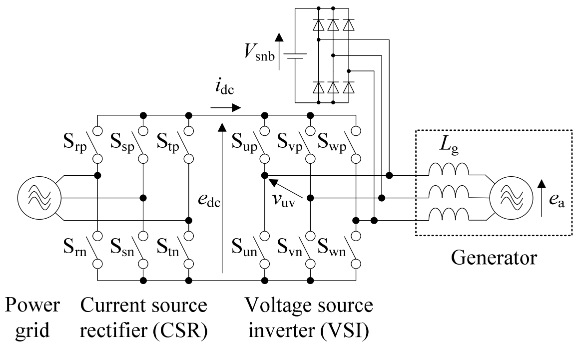


Fig. 2. Circuit diagram of an indirect matrix converter (IMC). The filter is omitted and the snubber circuit uses an ideal voltage source.

the reactive current to the grid. Thus, this paper proposes a modulation method of the VSI to overcome these two problems.

Fig. 3 shows operation of the VSI in the voltage sag. The proposed modulation method divides a carrier period of the VSI into three modes.

### *1) Mode 1: Snubber conduction mode*

In this mode, all of the VSI switches are turned off and the generator current flows to the snubber circuit. The snubber conduction mode is controlled by snubber conduction duty $d_{snb}$. In addition, the dc-link current is zero and the generator terminal voltage is equivalent to snubber voltage $V_{snb}$. It is noted that the generator terminal voltage between the same current direction phases becomes zero due to the diode bridge.

### *2) Mode 2: DC-link conduction mode*

Fig. 4 shows a space vector diagram of the VSI. This mode select a vector (V1-V6) except two zero vectors. The dc-link conduction mode is controlled by dc-link conduction duty $d_{link}$. By using this mode, a constant dc-link current is obtained and the generator terminal voltage equals the dc-link voltage because all phases of the generator side are connected to the dc-link. Then it should be noted that the average voltage of the dc-link is zero per 1/6 of the grid period.

### *3) Mode 3: Freewheeling mode*

In this mode, a zero vector V0 or V7 is chosen to obtain a circulating path of the generator current. Then, the dc-link voltage and the generator terminal voltage become zero. Additionally, duty of freewheeling mode is 1-$d_{snb}$-$d_{link}$.

Fig. 5 shows an equivalent circuit of the IMC in the snubber conduction and the freewheeling modes. The equivalent circuit consists of the VSI, the snubber circuit and the generator because the dc-link current in these modes is zero. Switches $S_1$ and $S_2$ in Fig. 5 are turned off in the snubber conduction mode and turned on in the freewheeling mode. It is obvious that the VSI is equivalent to an uni-directional boost converter in these modes. Hence, the VSI modulates the generator terminal voltage by switching of $S_1$ and $S_2$ in the grid voltage sag. Then, the generator terminal voltage becomes a waveform such as 120 deg. conduction mode and its average voltage $V_{gene\_line}$ during a positive period is expressed by (2).

$$V_{gene\_line} = d_{snb} V_{snb} \tag{2}$$

Then, $d_{link}$ seems to be a disturbance in the generator terminal voltage modulation apparently because the freewheeling mode duty is defined as 1-$d_{snb}$-$d_{link}$ although the snubber conduction mode duty is $d_{snb}$. However, the generator terminal average voltage becomes zero in the dc-link conduction mode similar to the freewheeling mode because the dc-link average voltage is zero due to the CSR operation. Thus, $d_{link}$ does not act as a disturbance of the generator terminal voltage modulation. As a result, the generator torque control is achieved by combination of modulating the generator terminal voltage, which uses the snubber conduction and the freewheeling modes, and a feedback control as described in the following chapter.

Table I shows selected VSI vectors in the dc-link conduction mode (mode 2) and the freewheeling modes (mode 3) during the voltage sag. It should be noted that generator current vector angle $\theta_{ig}$ is defined as zero when the generator current vector corresponds to β-axis in the space vector diagram. In addition, Fig. 6 shows a current path if vector V1 is selected in the dc-link conduction mode. From Fig. 6, the dc-link current $i_{dc}$ conforms to the u-phase current $i_u$ in this pattern. Therefore, the constant $i_{dc}$ is obtained by changing the VSI vector with reference to Table I. In contrast, either V0 or V7 in the freewheeling mode is selected to turn only one switch at a transition between the modes. Furthermore, VSI duty references should be given with reference to Table I because of a relationship between the VSI vectors in the dc-link conduction and the freewheeling modes. Then, $d_{link}^*$ and $d_{snb}^*$ are references of $d_{link}$ and $d_{snb}$. In consequence, the grid reactive current control is realized by combination of VSI modulation using the dc-link conduction mode and the zero power factor modulation of the CSR. In addition, the grid reactive current and the generator torque controls are achieved at the same time because the $d_{snb}^*$ and $d_{link}^*$ are independent of each other.

Fig. 7 shows a modulation block diagram of the IMC. The CSR employs a single-leg modulation proposed in [7] and the modulation scheme of the CSR is not changed because the CSR modifies the grid power factor reference only in the voltage sag. However, the VSI has to change the modulation strategy in response to the grid state. Therefore, the VSI

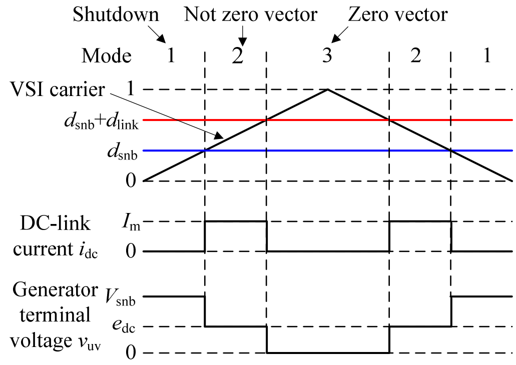


Fig. 3. VSI operation in short voltage sag. The control period is divided into three modes.

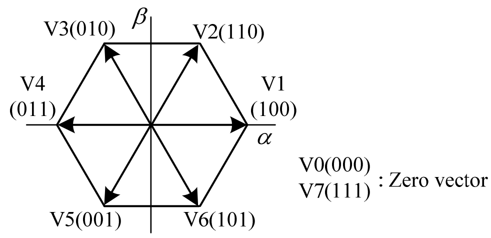


Fig. 4. Space vector diagram of the VSI.

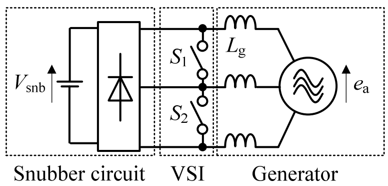


Fig. 5. Equivalent circuit diagram of the IMC in mode 1 and 3. $S_1$ and $S_2$ turn off in mode 1 and turn on in mode 3.

TABLE I. SELECTED VSI VECTOR IN MODE2 AND MODE 3, AND VSI DUTY REFERENCES.

| Generator current vector angle | Mode 2 | Mode 3 | VSI duty reference | | |
|---|---|---|---|---|---|
| | | | $d_u^*$ | $d_v^*$ | $d_w^*$ |
| 0 deg. ≤ $\theta_{ig}$ < 60 deg. | V6 | V7 | 1 | 1-$d_{link}^*$ | 1 |
| 60deg. ≤ $\theta_{ig}$ < 120deg. | V1 | V0 | $d_{snb}^*+d_{link}^*$ | 0 | 0 |
| 120deg. ≤ $\theta_{ig}$ < 180deg. | V2 | V7 | 1 | 1 | 1-$d_{link}^*$ |
| 180deg. ≤ $\theta_{ig}$ < 240deg. | V3 | V0 | 0 | $d_{snb}^*+d_{link}^*$ | 0 |
| 240deg. ≤ $\theta_{ig}$ < 300deg. | V4 | V7 | 1-$d_{link}^*$ | 1 | 1 |
| 300deg. ≤ $\theta_{ig}$ < 360deg. | V5 | V0 | 0 | 0 | $d_{snb}^*+d_{link}^*$ |

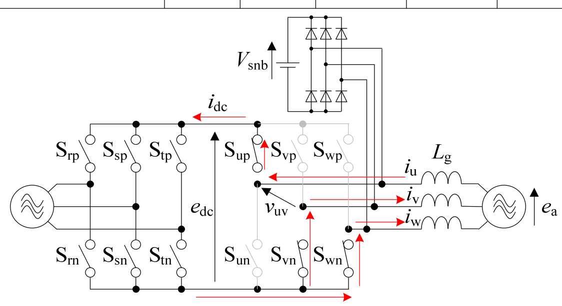


Fig. 6. Current path of the VSI in the dc-link conduction mode when V1 is selected. In this pattern, $i_{dc}$ corresponds to $i_u$.

modulation block is separated into the normal mode which is based on [7] and the FRT mode which is used during the voltage sag only, by using a multiplexer MUX2. On the other hand, in order to divide the dc-link conduction mode from the snubber conduction mode, MUX1 is inserted before MUX2. In addition, $d_{link}^{**}$ is calculated to compensate a dc-link current ripple caused by changing the VSI vector in the dc-link conduction mode per 60 deg. according to Table I. Moreover, $d_{link}^{***}$ is also computed to obtain a sinusoidal grid current with a compensation of the single-leg modulation of the CSR. Thus, the grid current amplitude $I_{grid}$ is presented by using the generator current amplitude $I_{gene}$ and (3).

$$I_{grid} = \frac{\sqrt{3}}{2} d_{link}^{*} I_{gene} \quad (3)$$

It should be noted that (3) is satisfied in the ideal condition using an ideal current source instead of the generator. The grid current amplitude in real system has an error compared to (3) due to the snubber diode and the generator inductance. However, by referring Table I and using the obtained dc-link conduction duty $d_{link}^{***}$ and $d_{snb}^{*}$, gate pulses of the VSI during the voltage sag are generated.

## IV. Feedback Controls during Grid Failure

Fig. 8 shows a feedback control block diagram for the FRT duration. From Fig. 1, it is required to control the snubber voltage and the generator current stably during the voltage sag in order to obtain a stable ride through operation and a desired generator torque. Hence, this paper uses two feedback controls for the snubber voltage and the generator current. The snubber voltage control is defined as an outer loop and the generator control is set as an inner loop from Fig. 5. Snubber voltage reference $V_{snb}^{*}$ is determined according to the active power consumed by the braking resistor $R_{brk}$, which is equivalent to control the generator torque, because the braking IGBT is turned on during the voltage sag. The snubber voltage and the generator current controls use PI controllers respectively. However, the generator current control does not have a sufficient degree of freedom to control the generator current phase because $S_1$ and $S_2$ in Fig. 5 are driven synchronously. Therefore, only the generator current amplitude is controlled in Fig. 8. In contrast, a subtraction using a feedforward term $E_a$, which is amplitude of the generator induced voltage, and division after the PI controller for the generator current amplitude are to calculate $d_{snb}^{*}$. By introducing these feedback controls, the stable ride through operation and the generator torque control are achieved during the voltage sag.

## V. Simulation Result

Fig. 9 shows a simulation result of the IMC under the ideal condition (No LC filters, ideal AC current source load, DC voltage source snubber, ideal commutation and no delay of the voltage dip detection). Table II shows a simulation condition. The feedback controls in Fig. 8 are not introduced in this chapter in order to verify the proposed modulation method. In addition, red waveforms in Fig. 9 shows averaged waveform by using a low pass filter with a cut-off frequency of 1 kHz. In

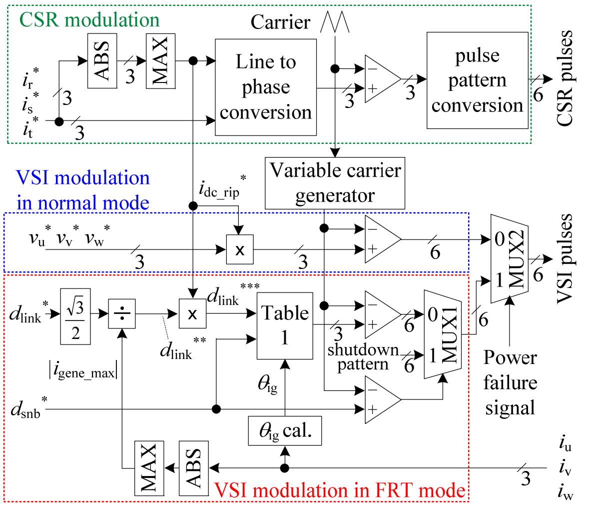


Fig. 7. Modulation block diagram of the IMC. The VSI modulation block is selected depending on the grid state.

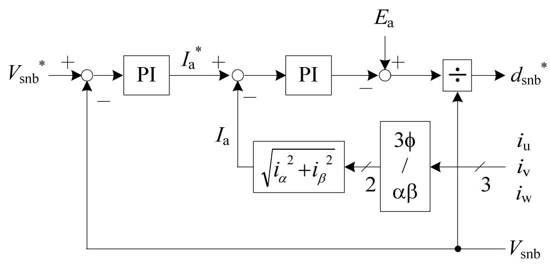


Fig. 8. Control block diagram for the snubber voltage control and the generator current amplitude control in FRT mode.

TABLE II. Simulation Parameters under Ideal Condition.

| | | |
|---|---|---|
| Circuit parameter | Grid line voltage | 200 V |
| | AC current source | 10 A |
| | Snubber voltage | 283 V |
| | Carrier frequency | 10 kHz |
| Normal mode modulation parameter | CSR power factor reference | 1 |
| | VSI modulation index | 1 |
| FRT mode modulation parameter | CSR power factor reference | 0 |
| | DC-link conduction duty $d_{link}^{*}$ | 0.3 |
| | Snubber conduction duty $d_{snb}^{*}$ | 0.5 |

Fig. 9, three-phase voltage sag of 90% (retained voltage of 10%) occurs and the matrix converter operates with the proposed FRT modulation method shown in Fig. 7 during this period. In other period, the matrix converter delivers the active power from the AC current source to the grid. From Fig. 9, the snubber conduction mode provides current to the snubber. Additionally, the generator terminal voltage becomes a square waveform such as 120 deg. conduction mode. Then, the generator terminal average voltage of 142 V is obtained and this voltage is equal to a calculated result with (2). In contrast, the dc-link current is negative value with a ripple. The dc-link current ripple is generated by the single-leg modulation of the

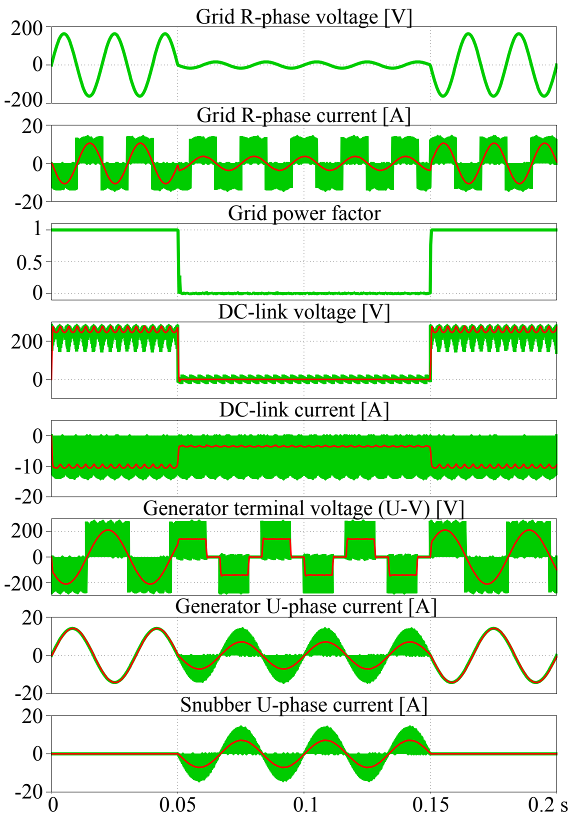


Fig. 9. Simulation result under the ideal condition. The proposed modulation method obtains zero grid power factor, a negative dc-link current and the rectangular generator terminal voltage.

CSR and the compensation with $|i_{gene\_max}|$. As a result, the grid current of 2.6 A and the grid power factor of zero are yielded. The grid current amplitude corresponds to a calculated result with (3). Therefore, the proposed modulation method obtains desired generator terminal voltage and desired grid reactive current during the three-phase voltage sag.

## VI. Experimental Result

Table III and IV show experimental conditions and control parameters. This chapter presents experimental results using a prototype drawn in Fig. 1 to confirm the ride through capability, the grid reactive current and the generator torque controls with the proposed FRT method. Note that inductors and an AC voltage source are used instead of the generator and q-axis current of the inductors is evaluated as the generator torque in experiments. The voltage sag amplitude is set to 70% (retained voltage of 30%) due to a commutation sequence of the matrix converter. $d_{link}^*$ is calculated by $d_{link}^* = 1 - d_{snb}^*$ in order to earn the maximum grid reactive current.

Fig. 10 shows grid side waveforms of the matrix converter. The grid current during the voltage sag is sinusoidal waveform with distortion. This distortion is caused by the generator inductance and the diode bridge in the snubber circuit. However, the grid active current is reduced to almost zero and the grid reactive current of 0.44 p.u. is obtained by the zero power factor modulation of the virtual CSR and the dc-link conduction mode of the virtual VSI.

TABLE III. Experimental conditions.

| | | | |
|---|---|---|---|
| Grid voltage | 200 V | LVRT duration | 100 ms |
| Rated power | 1.5 kW | LVRT voltage | 30 % |
| Grid side filter L ($L_f$) | 2.15 mH (2.53%) | Generator back e.m.f. | 140V |
| Grid side filter C ($C_f$) | 7.92 μF (6.64%) | Generator inductance ($L_g$) | 3.86 mH (9.28%) |
| Snubber capacitor | 300 μF | Carrier frequency | 10 kHz |
| Brake resistor | 141 Ω | | |

TABLE IV. Feedback control parameters.

| | | | |
|---|---|---|---|
| Normal mode (Field oriented control) | | d-axis current reference | 0 p.u. |
| | | q-axis current reference | -0.7 p.u. |
| | | Proportional gain | 1.2 p.u. |
| | | Integral time | 26.6 ms |
| FRT mode | Snubber voltage control | Voltage reference | 350 V |
| | | Proportional gain | 1.0 p.u. |
| | | Integral time | 42.3 ms |
| | Generator current control | Proportional gain | 1.0 p.u. |
| | | Integral time | 4.23 ms |

Fig. 11 shows control responses of the snubber voltage and the generator current amplitude controls. The snubber voltage reference is set to 350 V in order to obtain the same generator torque as before the voltage sag at the braking resistor. From the result, the snubber voltage and the generator current amplitude follow their references. As a result, a stable ride through operation is confirmed by the proposed control.

Fig. 12 shows dq-axis current responses of the generator. Note that the current references during the voltage sag are kept to ones in the normal mode. From Fig. 12, the dq-axis currents in the normal mode follows their references by the field oriented control. Then, ripple component in the dq-axis currents is caused by a zero-phase voltage fluctuation due to a two-phase modulation. In terms of the q-axis current during the voltage sag, the average current corresponds to the reference of 0.7 p.u.. As mentioned above, this is because the same active power as before the voltage sag is transferred from the generator to the braking circuit by setting the snubber voltage reference to 350 V. On the other hand, the d-axis current during the voltage sag does not follow the reference and the average current is -0.15 p.u.. This is because the feedback control of the generator current in Fig. 8 controls the amplitude only. In addition, ripple component during the voltage sag is caused by the generator inductance and the diode bridge in the snubber circuit in the same manner as the grid current. However, it is confirmed that the proposed FRT method obtains the same generator torque as before the voltage sag.

## VII. Conclusion

This paper proposes a FRT method of a matrix converter for a grid connected system such as a wind turbine system and a distributed power supply. The proposed method achieves the ride through capability, the grid reactive current control and the generator torque control. From the experimental results, the proposed feedback control realizes a stable ride through operation with fine responses of the snubber voltage and the generator current. In addition, the proposed modulation scheme ensures the virtual dc-link current of the matrix converter and the reactive current of 0.44 p.u. is injected to the grid. Finally, the same generator torque of 0.7 p.u. as before the voltage sag is earned by keeping the snubber voltage and consuming the active power at the braking resistor.


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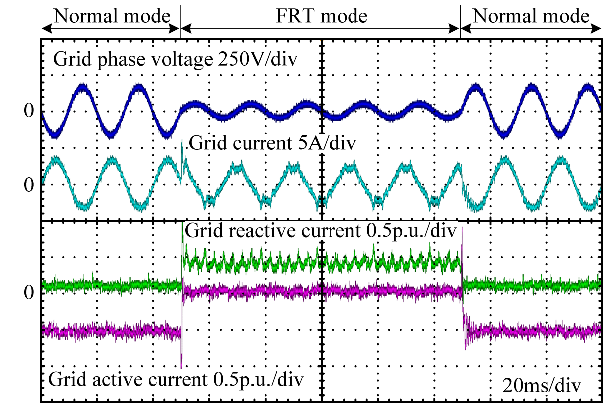


Fig. 10. Voltage and current waveforms of the grid. During the voltage sag, the grid current includes the reactive component of 0.44 p.u. only.

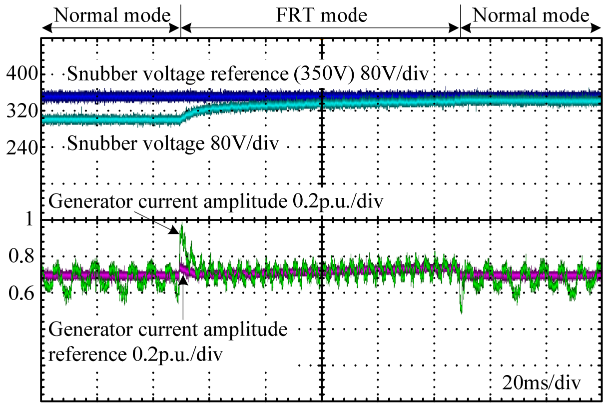


Fig. 11. Transient response of the snubber voltage and the generator current amplitude controls. The snubber voltage and the generator current amplitude follow the references.

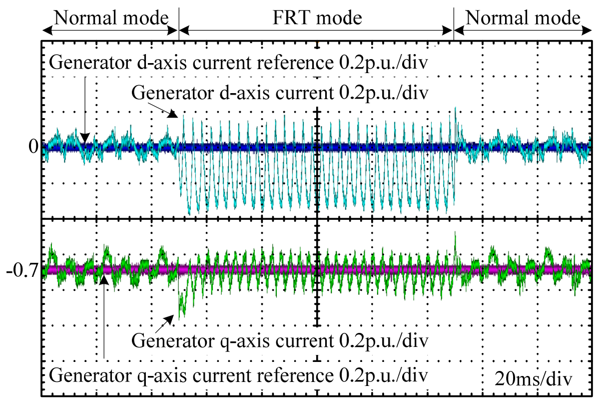


Fig. 12. Generator dq-current response. The average q-axis current is kept to 0.7 p.u. during the short voltage sag.