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Fault-Ride-Through Capability of VSG-Based Grid-Forming Converters

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Keywords

«Converter control», «virtual synchronous generator», «inertia support», «frequency dynamics», «fault ride-through».

Abstract

Grid-forming virtual synchronous generator (VSG)-based converter has a promising potential to be used as an interfaced converter for high penetration of renewable energy resources. Although emulating inertia and oscillation damping features in the control scheme of converters is possible, the short-circuit behavior of synchronous machines during fault conditions or other large-signal disturbances is not replicable in these converters, as their semiconductor devices are current-sensitive. This paper proposes a modified control technique for grid-forming VSG-based converters, enabling their fault-ride-through capability during fault situations. The proposed control technique limits converter current to its allowable amount while prevents windup in the outer control loops. To validate the performance of the proposed control technique, simulation results in Matlab/Simulink are provided and discussed in detail.

I. Introduction

Integration of renewable energy sources (RES)-based generators are on the rise because of their eco-friendly features. Nevertheless, high penetration level of such generators has emerged as a challenge for the modern power systems and made them subjected to instability issue under dynamic events, as these generators do not inherently provide inertia and damping characteristics unlike conventional synchronous generators (SGs) [1, 2]. To address this issue, numerous control techniques have been proposed for grid-following and grid-forming converters, which modify the control scheme of the interfaced converters by emulating these characteristics of SGs [1-9].

Providing inertia through grid-following converters is limited and requesting more inertia may cause instability, as their operation is dependent on the strength of the power grid. So, relying on such converters for a fully converter-based system is not appropriate and, grid-forming converters have received increasing attention in this concept [3]. Different control techniques for grid-forming converters such as synchronverter [4], VSG [5, 6], synchronous power controller (SPC) [7], and power synchronization control (PSC) [8, 9] are presented to imitate important characteristics of SGs.

Although emulating inertia and damping, as the most important features of SGs, in converters is possible, short-circuit characteristic of SGs is not replicable, because the semiconductor components of the converters cannot tolerate a larger current than their rated current. It is important to modify the control scheme of the grid-forming converters by adding fault-ride-through capability, i.e. the capability of generators to stay connected to the grid at lower voltages during faults, making them more compatible with grid codes.

Numerous control techniques have been proposed to provide fault-ride-through capability for converters. A control technique is presented in [9] to improve the transient stability of a PSC during grid faults. In this control technique, by modifying active power reference, transient angle stability of PSC is improved to prevent the risk of loss of synchronization. Directly limiting the reference current for overcurrent protection of converters is proposed in [10]. However, this control technique may cause instability because of the windup in the outer control loop when the reference current is saturated. To solve this problem, anti-windup in the PI controller of the outer control loop is proposed in [11]. This technique cannot address the issue when a large fault current is requested. Using virtual impedance as a way to decrease the converter current reference through reducing voltage reference is proposed in [12] to protect converters from overcurrent while prevents the outer control loop windup. However, the issue is that this method depends on the fault current and choosing the appropriate virtual impedance, which makes this method inapplicable. To avoid windup in the outer controller, indirectly limiting the converter current is proposed in [13]. In this control technique, the active and reactive power references are changed during fault situations or other large-signal disturbances. However, this method takes time to limit the current and it is not helpful in practice. Applying this indirect method of limiting overcurrent along with the direct reference current limiter is proposed in [7] to provide overcurrent protection for an SPC in fault situations. Although many efforts have been put into addressing the issue, the fault-ride-through capability of the converter still needs further investigation, as the converter-based renewable generation is expected to contribute more and more to the future power grid [14, 15].

Herein, a control method is proposed to provide the fault-ride-through capability for a VSG-based grid-forming converter. The proposed control technique limits the converter current to its allowable amount to protect the converter from overcurrents. An anti-windup for the PI controller is employed, and active and reactive power references in the outer control loop of the VSG are updated during the fault situation based on the size of the fault. The remaining of the paper is organized as follows. The control structure of the grid-forming VSG-based converter is explained in Section II. The proposed fault-ride-through capability is described and the simulation results are discussed in detail in Section III. Finally, Section IV concludes this study.

II. Control Method of the Grid-Forming VSG-Based Converter

The schematic diagram of the VSG-based grid-forming converter connected to the grid and its control scheme is shown in Fig. 1. An LC filter with the inductance of L_f and the capacitance of C_f is employed to filter out the power injected by the converter. Parameters of the model and the controller are listed in Table 1.

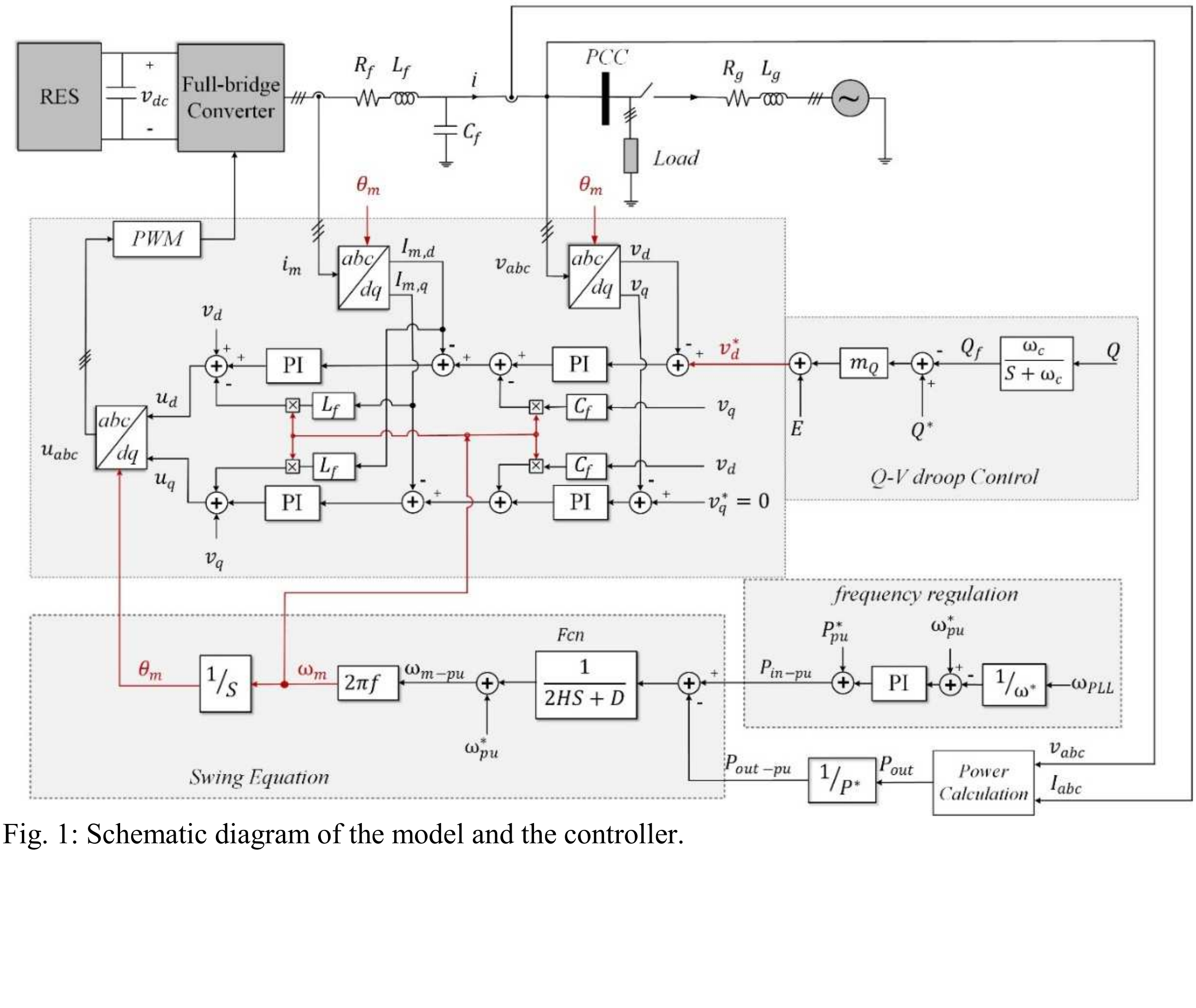

Fig. 1: Schematic diagram of the model and the controller.

Table I: Parameters of the System Under Study.

Parameters	values	parameters	Values
Reference frequency	50 Hz	Cut-off frequency (w_c)	10 rad/sec
Reference voltage	400 V	Inertia constant (H)	3 s
Switching frequency (f_{sw})	10 kHz	Damping factor (D)	250
DC-link voltage	750 V	Active power reference (P^*)	40 kW
Rated power	40 kW	Reactive power reference (Q^*)	0
Filter (L_f, C_f)	1.7 mH, 10 µF	Active power droop coefficient (m_p)	0.05 (PU)
Grid impedance (R_g,L_g)	0.16 Ω, 5 mH	Reactive power droop coefficient (m_Q)	0.002 (SI)

As depicted in Fig. 1, the controller includes two control loops, i.e., the inner voltage and current control loop and the outer frequency-power control loop. The inner control loop provides overcurrent protection and its implementation is based on the AC-side dynamics of the converter, which are presented using the complex-valued vectors ($x = x_d + jx_q$) as:

$$L_f \frac{di_m}{dt} + \left(R_f + jL_f\omega\right)i_m + v = u \tag{1}$$

$$C_f \frac{dv}{dt} + i + jC_f v\omega = i_m \tag{2}$$

where v is the output voltage of the converter, u is the command voltage to the converter, and i_{mc} and i represents the converter output current before and after the LC filter, respectively. In the current control loop, the PI controllers are employed to track the reference current (i_{mc}^*) defined by voltage controller. Hence, the current controller in dq reference frame is defined by:

$$u = v + j\omega L_f i_m + \left(K_{p1} + \frac{K_{i1}}{s}\right)(i_m^* - i_m) \tag{3}$$

The PI controllers are also employed for the voltage control loop, which can be extracted from (4). The q-axis voltage reference is set to zero and the well-known Q-V droop defined by (5) is applied to generate the d-axis reference voltage (v^*). In this equation, m_Q represents the reactive power droop coefficient, Q^* and Q_f are the reference and the filtered reactive power of the converter, respectively.

$$i_{mc}^* = jC_f\omega v + \left(K_{p2} + \frac{K_{i2}}{s}\right)(v^* - v) \tag{4}$$

$$v^* = E + m_Q\left(Q^* - Q_f\right) \tag{5}$$

In the outer control loop, the inertia and damping characteristics are employed to extract phase angle and angular frequency reference for the inner control loop. These features are implemented through swing equation defined in per unit system as follows:

$$2H\frac{d\omega_m}{dt} = P_{in\_pu} - P_{out\_pu} - D\left(\omega_m - \omega_{pll}\right), \qquad \frac{d\theta_m}{dt} = \omega_m \tag{6}$$

where P_{in_pu} and P_{out_pu} are the input and output active power of the converter, D is the damping factor, H is the inertia constant, w_m represents the angular frequency, and w_{pll} is the angular frequency of the voltage at the point of common coupling (PCC) measured by the phase-locked loop (PLL), respectively.

The well-known P-f droop control, shown in (7), is used in the outer control loop of the VSG to realize the frequency control, as in the conventional SGs. Thus, the VSG can operate in parallel with other VSGs and SGs. In this equation, m_p, w^* and $P^*$are the active power droop coefficient, the angular frequency reference, and the active power reference, respectively. The output of the P-f droop control (i.e. P) is used as the input active power of the converter (P_{in_pu}).

$$P = P^* + \frac{1}{m_p}\left(\omega^* - \omega_{pll}\right) \tag{7}$$

In the outer control loop, the swing equation is added to the primary and secondary frequency control and together provide the reference phase angle and angular frequency for the inner control loop. Also, angular frequency is used to implement the coupling term between the d- and q- axis in the current and voltage control loops. The dq reference frame and the park transformation are based on the phase angle provided by the outer control loop. The PLL is employed to measure the real grid frequency to implement frequency regulation.

III. Description of the Proposed Fault-Ride-Through Capability

In this section, the fault-ride-through capability of the VSG-based grid-forming converter is discussed in detail. To illustrate the importance of such capabilities, a three-phase fault is considered in the line connecting the converter to the grid at 1.5 s, which lasts 150 ms. Fig. 2 shows the performance of the VSG-based grid-forming converter without any modification in its control during the fault. As can be seen from this figure, the converter significantly supports the voltage level at the PCC by injecting a large reactive current (5 pu). In fact, the inner current control loop gets its reference from the outer voltage control loop which inherently requests more current during fault. Although it can be considered as a great support for the grid, it is not normally possible to request such a big overcurrent, as the power-electronic devices are very sensitive and cannot tolerate it. Thus, it is important to protect them from overcurrent. Considering an oversized grid-forming converter to provide more current during fault is not a reasonable solution, as it is highly costly and, it is better to limit the current of the normal size converter.

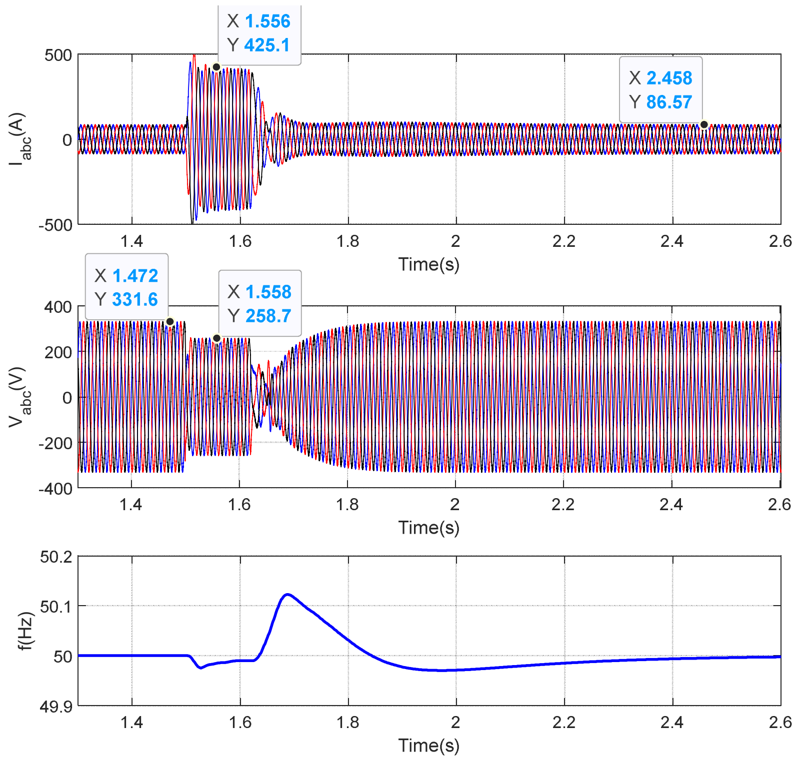

Fig. 2: Current injected by the converter, voltage, and frequency at the PCC, without modification in the control.

Limiting the current reference of the current controller to protect the devices from overcurrent may cause instability during the fault. The grid-forming converter as a voltage-controlled unit tries to maintain the voltage level at the PCC by providing a very large reference current for the inner current control loop through the outer voltage controller. So, current saturation realized by the current limiter is an undeniable fact during fault situations and, results in integrator windup in the outer control loop. This is because when the output of the PI regulator of the voltage controller which provides the reference current for the inner current controller reaches its limit and is saturated, the PI controller does not work well and an anti-windup modification needs to be implemented [5]. Fig. 3 shows the results when the current limiter is considered to limit the current to 1.2 pu. Although this action protects power electronic devices from overcurrent during the fault, the performance of the grid-forming converter after the fault is not good enough as it takes around 2 sec to return to its normal operation.

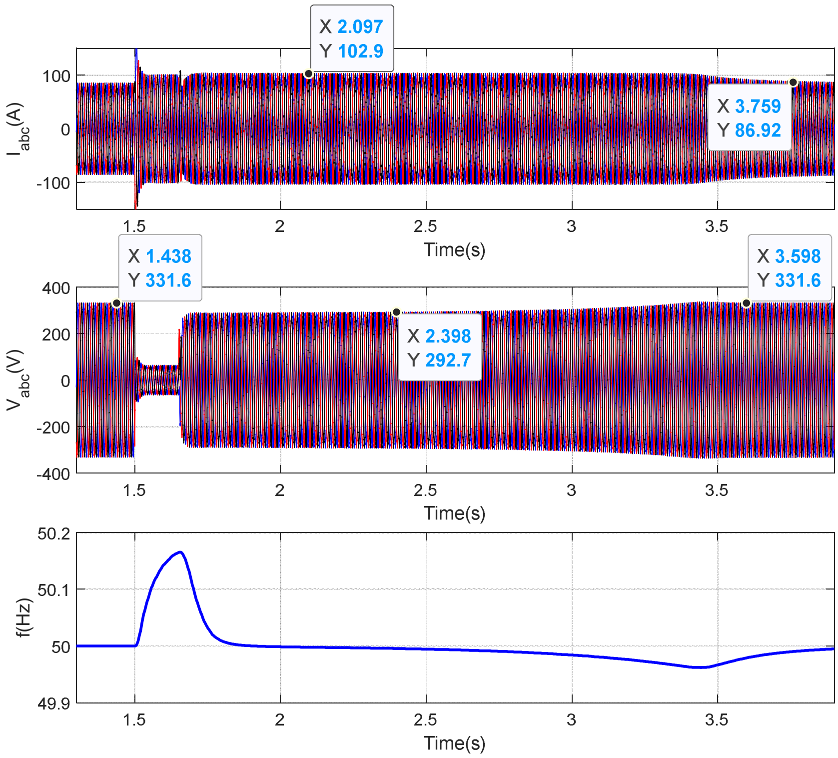

Fig. 3: Current injected by the converter, voltage, and frequency at the PCC, when current limiter limits the current to 1.2 pu.

To avoid the integrator windup in the outer control loop of a grid-forming converter as a result of large power reference in the outer loop and current saturation in the inner loop, it is proposed in [7] to change the active and reactive power reference as a way to limit the current reference instead of immediately limit the current reference. In this method, the new apparent power for the converter can be expressed as:

$$S_f = v_{pu}.S_n \tag{8}$$

The fault-mode apparent power defines the new reactive power for different fault situations as:

$$Q_f = \begin{cases} Q - V\ droop & if\ v_{pu} > 0.9\ pu \\ 2S_f(1 - v_{pu}) & if\ 0.5 < v_{pu} < 0.9\ pu \\ S_f & otherwise \end{cases} \tag{9}$$

Also, the active power reference of the converter is realized from the relationship between active power, reactive power, and apparent power of the converter as follow:

$$S_f^2 = P_f^2 + Q_f^2 \tag{10}$$

This method is added to the current limiter to improve the performance of the VSG-based grid-forming converter, especially during postfault operation. As illustrated in Fig.4, applying the aforementioned method results in the fault-ride-through capability of the converter without a large overcurrent in power-electronics devices, and improves the postfault performance of the converter.

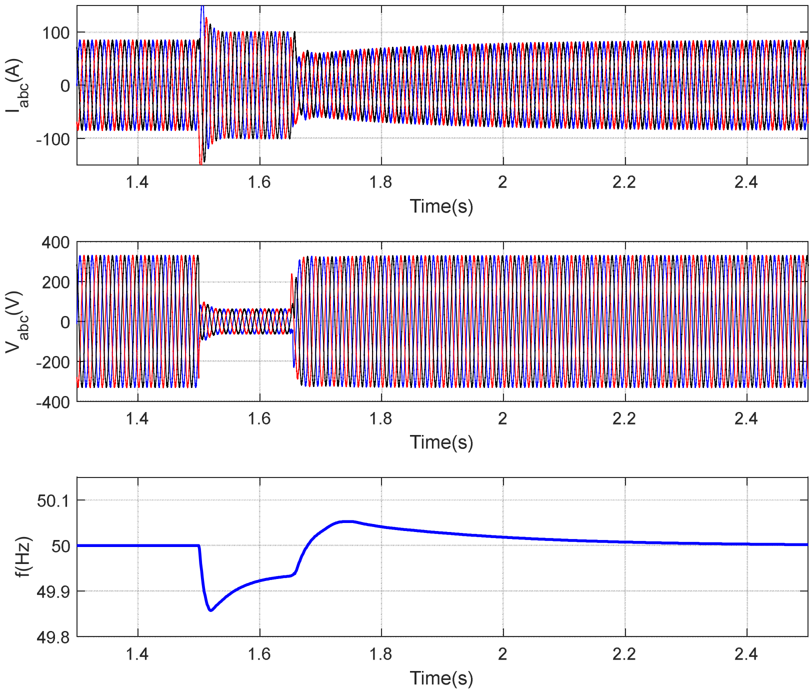

Fig. 4: Current injected by the converter, voltage, and frequency at the PCC, in the proposed control method.

IV. Conclusion

By increasing the contribution of converter-based renewable energy generators, VSG-based grid forming converter as a solution toward providing supportive functionalities (i.e. inertia and oscillation damping features) for the power grid, are becoming more and more of interest. In this paper, a control technique has been proposed for a VSG-based grid forming converter, which guarantees the connection of these converters to the grid in the presence of grid faults, while the current of the converter remains in its permissible range. The effectiveness of the proposed control technique with the fault-ride-through capability and overcurrent protection has been shown through simulation results in Matlab/Simulink.

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