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Effects of current limit for grid forming converters on transient stability: Analysis and solution

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A R T I C L E   I N F O

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- Grid forming control
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- Current limit

A B S T R A C T

Grid forming control applied to power converters termed as grid forming converters (GFC) interfacing storage and renewable generation has been identified as a potential solution to facilitate a more significant penetration of converter-based renewable generation in the power system. The emulated electromechanical model in the GFC is also the synchronization unit which typically utilizes measured output active power from the GFC as the feedback variable. However, this feature has opened up a concern on the transient stability due to loss of synchronism under significant transient events in the power systems, which include frequency change, phase jump, and voltage dips. This paper presents a quantitative and illustrative analysis of the impact of the current limit in GFC on the transient stability of a system comprising of GFC. Furthermore, a solution based on virtual active power is proposed to improve the transient stability margin of the GFC when the GFC enters the current limit. Finally, the analysis and the proposed method to enhance the transient stability are verified by Power hardware in the loop (PHIL) experimental tests.

1. Introduction

The core of the bulk power system is evolving from conventional synchronous machine-based generation (SG) to power converter-based renewable energy (RE) generation. Currently, nonsynchronous converters, commonly termed ‘grid-following converters’, which employ a phase-locked loop (PLL) to ensure synchronization with the grid, are the dominant converter configuration for the majority of the applications, including RE generation, high voltage direct current (HVDC) and static synchronous compensator (STATCOM). However, a reduction in the share of synchronous generators and an increased share of nonsynchronous power converter-based components are altering the power systems’ fundamental nature and introducing several challenges due to reduced levels of inertia and short circuit power. The grid-following converters introduce small signal and large signal stability challenges when the system is weak with low short circuit ratios and low inertia [1–4]. The grid forming control for converters (GFC) or virtual synchronous machine control is a potential solution to mitigate the challenges caused due to reduction of SG [5,6]. GFC’s characteristics which are beneficial in ensuring system security are: Higher stability margin, Instantaneous fault current contribution, Inertial response, and instantaneous active power contribution to phase jumps and system frequency changes.

It is well known that an SG could suffer from a loss of synchronization during significant transient events in the system, as discussed in [7]. This forms the basis of transient stability in power systems. Similarly, a power electronic converter-based GFC, which emulates the voltage source behavior of an SG, has also been reported to lose synchronization during power system faults. The mechanism behind the transient stability of the GFC during system voltage dips due to short circuits in the system is analyzed and explained in [8–10]. It was also demonstrated that when no inertia is programmed into a GFC, it is possible to return to a stable operating point after the first swing in a loss of synchronization event, provided that an equilibrium point exists, as shown in [8].

Faster voltage control using an Automatic Voltage Regulator (AVR) is known to increase the transient stability margin of a Synchronous Generator (SG), particularly for the first swing loss of synchronization [7]. A Grid-Forming Converter (GFC) can have faster internal voltage control than an SG, which is constrained due to significant time constants for excitation field windings. This feature of the GFC has been exploited to enhance transient stability by incorporating measured power or internal virtual rotor speed as feedforward elements to the voltage/reactive power control of the GFC [10–12].

Additionally, the transient stability of a GFC could also be increased by dynamically changing the emulated inertia [13], damping constant [14], or the direction of power swings [15]. Fault-tolerant functionality in a grid-forming converter with modification of converter control...
forming converters utilizing virtual power. The use of virtual power approach that combines overload and current limit strategies for grid-three described events. Lastly, our paper introduces a coordinated it presents methods for enhancing synchronization stability across all change of frequency, and the critical fault clearing time. Additionally, metrics, such as the maximum allowable phase jump, maximum rate of voltage dips, occurring when GFCs employ the current limiting algo-

passes various events, including phase jumps, frequency changes, and the critical fault clearing time. This includes events such as phase jumps, frequency changes, and voltage dips when GFCs employ the current limiting algorithm.

The configuration of 3 phase grid connected GFC system. 

facilitates smooth grid connection without noticeable inrush currents. In our research, we extend this strategy to enhance the transient stability margin for all grid events. Finally the conducted analysis and the proposed solution to improve the transient stability of the GFC is validated using power hardware in the loop (PHIL) experimental tests are presented. The PHIL evaluation is conducted in a simplified equivalent circuit and a modified lower inertia IEEE 9 bus system.

Overall the key contributions of the paper are,

(1) Identify the challenges and the mechanism where GFCs face in maintaining synchronization with the grid when the current limit is invoked.
(2) Provide a quantitative analysis of transient stability of GFC with current limiter case. This includes events such as phase jumps, frequency changes, and voltage dips when GFCs employ the current limiting algorithm.
(3) Provide methods to quantitatively define crucial transient stability metrics for GFC with current limiter, including the maximum allowable phase jump, rate of change of frequency, and the critical fault clearing time.
(4) Incorporate virtual power concept during transient to improve the stability of grid-forming converters, and demonstrate that the strategy significantly extends the transient stability margin for all grid events.

2. Grid forming converter configuration

The single-line diagram of the GFC considered in the paper is shown in Fig. 1. The filter circuit comprises a reactor ($X_{f}$), a capacitor with reactance ($X_{Cf}$), and a damping resistor ($R_{f}$). The point of common coupling (PCC) is located at the terminal of the filter capacitor, where measurements of $v_{fcc}$, $i_{pcc}$, and $i_{f}$ are taken. The reactance ($X_{f}$) and ($X_{Cf}$) represent the reactance of the transformer and grid impedance, respectively. The grid-forming control, with an inner current control loop control-based current limit was not in the scope of these studies and hence was not included when analyzing the transient stability limits. Nevertheless, a converter-based GFC has limited overload capability in contrast to the SG, which has an overload capacity of several times its rated value during short-term overload and grid faults. For the sake of protection, it is the fast current limiting function that acts first during large transients. Therefore, it is essential to include the current limiting functions in the analysis for systematic insights on the loss of synchronism phenomenon during large transients.

The majority of GFC types reported in the literature achieve syn-
chronization using an active power control loop with measured output power as the feedback variable [10–12,14,15,17–22]. Therefore, when overload current limit is activated in each scenario. Subsequently, the paper with preserving the synchrony of the GFC with the broader grid when changing the frequency, and the critical fault clearing time. Additionally, metrics, such as the maximum allowable phase jump, maximum rate of voltage dips, occurring when GFCs employ the current limiting algo-

The majority of GFC types reported in the literature achieve synchroniza-

Fig. 1. The configuration of 3 phase grid connected GFC system. 

Fig. 2. General control system of GFC with current control inner loop and virtual admittance.

This paper begins by illustrating the specific scenarios that can trigger the current limit in a Grid-Forming Converter (GFC) within a low-inertia power system. It also outlines the challenges associated with preserving the synchrony of the GFC with the broader grid when the current limit is activated in each scenario. Subsequently, the paper offers a detailed quantitative analysis of transient stability. It encompasses various events, including phase jumps, frequency changes, and voltage dips, occurring when GFCs employ the current limiting algorithm.

The study includes the definition of critical transient stability metrics, such as the maximum allowable phase jump, maximum rate of change of frequency, and the critical fault clearing time. Additionally, it presents methods for enhancing synchronization stability across all three described events. Lastly, our paper introduces a coordinated approach that combines overload and current limit strategies for grid-forming converters utilizing virtual power. The use of virtual power for synchronization during startup, as previously demonstrated in [30],
incorporates inertia, frequency droop, and damping emulation through active power control (APC(s)) with an active power setpoint \((P_{\text{ref}})\). The power output from the GFC, measured at the PCC \((P_{\text{GFC}})\), is typically chosen as the feedback power \((P_{\text{fb}})\) for the active power control loop.

A lead–lag (LL) compensator-based power controller \((PC(s))\) is employed to emulate the electromechanical behavior of the synchronous machine, as discussed in [32]. The compensator is represented as follows:

\[
\Delta\phi_{\text{pc}} = \frac{K_{p\phi} + K_{i\phi}}{s + K_{d\phi}} (P_{\text{ref}} - P_{\text{GFC}}) \tag{1}
\]

The compensator \(PC(s)\), similar to the swing equation-based electromechanical model can realize virtual inertia constant, \(H\), and frequency droop \(R\). In addition, LL-based electromechanical model has an additional degree of freedom to increase the power control's damping coefficient \((\zeta)\). The parameters \((K_{p\phi}, K_{i\phi}, K_{d\phi})\) can be calculated from a given virtual inertia constant \(H\) in seconds, power-frequency droop gain \(R\) in pu and damping coefficient \((\zeta)\).

\[
K_{p\phi} = \frac{\omega_B}{2H} \quad K_{i\phi} = \frac{K_{d\phi}}{2H}, \quad \text{where} \quad K_{d\phi} = \frac{1}{R} \tag{2}
\]

\[
K_{p\phi} = \zeta \frac{2\omega_B}{P_{\text{max}} H} - \frac{K_{d\phi}}{2H P_{\text{max}}} \tag{3}
\]

where \(\omega_B\) is the base frequency of the system, \(P_{\text{max}}\) is the maximum static power transfer possible between the GFC and an infinite voltage source. If the power-frequency droop is not required, the parameter \(K_{d\phi}\) is to be set to zero in (2)-(3). For the GFC electromagnetic model, a quasi-stationary model has been superior to a dynamic electromagnetic model for GFC [33]. Variable superscripted with \(d\) and \(q\) are variable vectors of the direct and quadrature frame original parameters represented in the synchronously rotating reference frame defined by the virtual rotor of the GFC \((\theta_{\text{vsc}})\). The electromagnetic model consists of the internal voltage source \((E)\) in series with an algebraic representation of an impedance. It is realized by multiplying the difference between the internal voltage source \((E')\) of the GFC and PCC voltage \((\sqrt{3} E_{V_p})\) virtual phasor admittance resulting in reference unsaturated stator current \((I_{\text{pc}}^{\text{q}})\)

\[
I_{\text{pc}}^{dq} = \frac{E - \sqrt{3} E_{V_p}}{R_e + jX_e} \tag{4}
\]

where \(R_e, X_e\) are the virtual internal virtual resistance and reactance of the GFC. The virtual impedance is chosen such that the output impedance is predominantly inductive with an \(X/R\) ratio of 10. The electromagnetic model of the GFC also includes the current limiting algorithm. Fast acting current limiters for GFC is critical as the GFC responds to grid events is nearly instantaneous. A circular current limit on \(I_{\text{pc}}^{dq}\) as shown in (5) is an ideal choice as it precisely limits current and preserves the angle of the injected current and thus limiting the interaction with the active power-based synchronization [29,34].

The limited current vector \(I_{\text{pc}}^{dq\text{Lim}}\) is given by

\[
I_{\text{pc}}^{dq\text{Lim}} = \frac{1}{K_{\text{Clim}}} I_{\text{pc}}^{dq}, \quad \text{where} \quad K_{\text{Clim}} = \frac{I_{\text{pc}}^{dq\text{Lim}}}{I_{\text{lim}}} \tag{5}
\]

\(I_{\text{pc}}^{dq\text{Lim}}\) is the magnitude of the unsaturated reference current vector and is equal to \(\sqrt{I_{\text{pc}}^{dq}\text{Lim}}^2 + I_{\text{pc}}^{dq\text{Lim}}^2\) and \(I_{\text{lim}}\) is the nominal maximum peak current, and thus the vector \(I_{\text{pc}}^{dq\text{Lim}}\) is of the magnitude \(I_{\text{lim}}\) during current limited operation.

The paper's focus is on the interaction between the current limit and active power control and its consequences on the transient stability of GFC. Therefore, to preserve the paper's brevity, the outer reactive power control or voltage control is assumed to be slow. Thus, the voltage control and reactive power control dynamics are not accounted for in this work. Also, the DC link dynamics and other supervisory controls are not considered in this paper for the sake of easier understanding.

3. GFC analysis under current limit

The analysis presented in this paper assumes that the dynamics of the employed current limit are faster than other control and thus time scale separated from the stability study considered in the paper. Additionally, the paper’s focus is applying the GFC on large power systems with a low \(X/R\) ratio; therefore, only the reactances of the virtual impedances and grid impedances are considered in the quasistatic analysis.

The active power \((P_{\text{GFC}})\) and the reactive power \((Q_{\text{GFC}})\) at the internal voltage source \((E)\) is given by

\[
P_{\text{GFC}} = \frac{E V_g \sin \delta}{X_T}, \quad Q_{\text{GFC}} = \frac{E^2 - \frac{V_g^2 \cos \delta}{X_T}}{X_T} \tag{6}
\]

where \(X_T\) is the total reactance of the system from between the internal voltage \((E)\) and is equal to sum of \(X_{T}'\), \(X_T\) and \(X_{\text{in}}\). The infinite voltage source and \(\delta\) is the angle difference between the internal voltage source and infinite voltage source and is equal to difference between \(\theta_{\text{vsc}}\) and \(\theta_e\). The active and reactive power at the internal virtual source \((E)\) in the rotating \(dq\) frame defined by GFC virtual angle \((\theta_{\text{vsc}})\) can also be written as

\[
P_{\text{GFC}} = E I_{\text{pc}}^{dq\text{Lim}} Q_{\text{GFC}} = -E I_{\text{pc}}^{dq\text{Lim}} \tag{7}
\]

The magnitude of the current vector \(I_{\text{pc}}^{dq\text{Lim}}\) can then also be written as

\[
|I_{\text{pc}}^{dq\text{Lim}}| = \sqrt{P_{\text{GFC}}^2 + Q_{\text{GFC}}^2} = \frac{M_e}{E_T} \tag{8}
\]

where \(M_e\) is equal to \(\sqrt{V_g^2 + E^2 - 2E V_g \cos \delta}\). The general power transfer equation for the GFC can then be calculated from (5), (6), (8)

\[
P_{\text{GFC}} = \sqrt{\frac{E V_g \sin \delta}{X_T}} \frac{E V_g \sin \delta}{X_T} \frac{\sqrt{P_{\text{GFC}}^2 + Q_{\text{GFC}}^2}}{I_{\text{pc}}^{dq\text{Lim}}} \geq I_{\text{lim}} \tag{9}
\]

It can be observed that the power transfer under current limited case is independent of the network reactance. When the drop across the virtual resistance \((R_e)\) is neglected the active power at the internal voltage terminal is same as \(P_{\text{pc}}\). The power angle curves for the GFC with and without limiter activation at different grid voltage conditions are shown in Fig. 3. It could be seen that the unstable operating points occurs at much lower phase angle \((\delta)\) and maximum power transfer possible is greatly reduced when under current limit.

3.1. Internal impedance of GFC during current limit

Recalling from (4) and (5) under current limit case is equivalent to the internal impedance \(Z_{\text{in}}^{\text{lim}}\) as shown below

\[
Z_{\text{in}}^{\text{lim}} = K_{\text{Clim}}(R_e + jX_e) \tag{10}
\]
4. Transient stability evaluation of GFC

In this section, the transient performance of GFC with and without the current limit implemented is analyzed during system events such as voltage dips, phase shift, and a RoCoF event, and conditions for GFC to maintain synchronism for each event is qualitatively described. All events typically co-occur but are studied separately here for an intuitive understanding. The quasi-static model shown in Fig. 4 is solved numerically. The total reactance \(X_{\text{in}}\), including the internal reactance of 0.3 pu, is chosen at 0.5 pu, both the internal GFC voltage and infinite bus voltage are assumed to be 1 pu for the analysis, and the current limit is set to be 1.1 pu. The damping coefficient \(\zeta\) has been set to 0.4 to study underdamped control.

4.1. GFC response against RoCoF

The infinite voltage source frequency \(\omega_s\) is varied from 50 Hz to 48 Hz at a rate of change of frequency (RoCoF)-1 Hz/s. The response of the GFC against the specified RoCoF with inertia constant \(H\) of 10 s is shown in Fig. 5.

When the infinite voltage source is decelerating, a similar deceleration is required from the virtual rotor of the GFC to stay in synchronism. The necessary deceleration power in pu \(P_{\text{dec}}\) for the virtual GFC rotor is given by

\[
P_{\text{dec}} = -\frac{2H}{f_{\text{exc}}} \cdot \text{RoCoF} = 0.4 \text{ pu}
\]

(12)

Where the \(f_{\text{exc}}\) is the nominal frequency of the GFC. When the GFC with no current limits and operating at a power setpoint of 0.8 pu with an operating point at point 1 (Fig. 5) is presented with a RoCoF event, the rotor angle moves in the trajectory 1-2-3 and settles at point 3 such that a deceleration power of 0.4 pu is impressed on the virtual rotor according to (12). However, point 3 is not reachable for the current limited case as shown in Fig. 5. Therefore the trajectory on the power angle curve with current limit follows 1-4-5, and beyond point 5, an unstable operating point is reached, and synchronism is lost, which is reflected in all the curves in Fig. 5. When the GFC is also programmed to provide frequency droop \(Rd\) the condition in (12) is modified to

\[
P_{\text{dec}} = -\frac{2H}{f_{\text{exc}}} \cdot \text{RoCoF} + \frac{\Delta \omega_{\text{exc}}}{Rd \cdot \omega_{\text{exc}}^2}
\]

(13)

From (13) one can also conclude that dynamically reducing \(P_{\text{set}}\), \(H\), \(Rd\) are some of the options to ensure \(P_{\text{dec}}\) on the virtual rotor and maintain synchronism.

4.2. GFC response against phase jump

The GFC is expected to respond instantly to phase jumps in line with a voltage source behavior expected of GFC. The GFC response to simulated infinite voltage phase jump of 40° is shown in Fig. 6 with power set point at 0.9 pu \(P_{\text{set}}\). The grid phase jump is simulated by changing \(\delta_d\) in Fig. 4. From the power angle curve \((P-\delta)\) of current limited and no limit cases, it is seen that the maximum phase shift between the infinite voltage source and GFC internal voltage is significantly reduced from \(\delta_{\text{max}}\) to \(\delta_{\text{lim}}\). For the simulated phase shift, the trajectory without limiter shifts from point 3 to 1 instantly and then falls back to 3. Whereas for GFC with the current limit, the trajectory instantly moves from 3-4 and thus marginally beyond the stable operating point 4 and loses synchronism. For a given \(P_{\text{set}}\), the maximum phase shift margin possible \(\delta_{\text{lim}}\) can be solved from (9).

The inertia and damping parameters do not impact the stability margin as the instability expected is the instantaneous response.

4.3. GFC response voltage dip

The event simulates a power system fault case. The infinite bus voltage is reduced to 0.5 pu for 0.3 s with a \(P_{\text{set}}\) at 0.8 pu. The power angle curve reduces in magnitude with the reduction in infinite bus voltage, causing the virtual rotor to accelerate. For the unlimited case,
the power angle trajectory is 1-2-5-7 and back to 1. The conventional equal area criterion for transient stability is applicable in this case, and the acceleration area 1-2-5-7 is well less than the decelerating area 5-7-9. However, the accelerating area 1-2-3-5 is higher for the current limited case than the available decelerating area 5-6-8 and the momentum gained during acceleration results in rotor angle crossing the unstable equilibrium point 8 and instability (see Fig. 7).

Most of the existing studies have only evaluated the transient stability of the GFC for fault cases. In practice, GFC is not a rotational rigid body as SG, wherein it is difficult to achieve the mechanical power input reduction during fault cases through fast valving or by dynamic braking resistors, thereby limiting the acceleration torque. Both fast valving and dynamic braking can be easily implemented in a GFC by dynamically changing the power reference or simply freezing the power-based synchronization for a short duration [35,36], provided there are sufficient capacity for energy dissipation. Another possibility is to increase P-F droop $R_d$, increase programmed inertia $H$, the stability margin improves as the rotor acceleration is reduced with higher inertia and damping, unlike the RoCoF case.

5. Proposed virtual power based GFC

The challenge with saturating current is that the active power output becomes insensitive to change of phase, thereby rendering the synchronization control ineffective. In addition methods such as dynamically changing $H$ and $R_d$ is complicated and contradictory for different transient events as explained in the previous section. To counter such limitation, this paper proposes utilizing the unsaturated current references ($I^{dq}_{pcc}$) for power measurements for the synchronization loop instead of active power measurements at the PCC, i.e. the active power feedback to $APC(s)$ is chosen as

$$P_{fb} = P_{vfb} = \frac{3}{2}(V^d_{pcc}I^{dc}_{pcc} + V^q_{pcc}I^{dc}_{pcc})$$

(14)

One could also measure the virtual unsaturated power at the GFC virtual internal voltage terminals. Utilizing the virtual unsaturated power as the feedback or controlled parameters for the power synchronization is analyzed in this section.

5.1. Analysis of virtual power based GFC

For calculation of the virtual power, the unsaturated current references are used, whereas the GFC actual output current when GFC enters the current limit is the saturated current defined by Eq. (5). When the GFC is not in the current limit operation, there is no difference between the $P_{vfb}$ and $P_{pcc}$ as long as the current control dynamics are neglected. In practice, the current controller is much faster than the power control loop, and thus the impact of current control dynamics on the choice of power feedback is minimal. Hence an equivalent electrical circuit as shown in Fig. 8 can be drawn to represent the GFC employed with
Table 1
PHIL scaling for the VSC hardware.

| Symbol | Description                  | Physical value | Scaled to simulation |
|--------|------------------------------|----------------|----------------------|
| \(V_{vsc}\) | Amplifier voltage         | 123 V          | 12.3 kV              |
| \(P_{vsc}\) | VSC power                  | 1.5 kVA        | 70 MVA               |

virtual power feedback. During the current limit operation with virtual power feedback, dividing the current reference by \(KC_{lim}\) is equivalent to dividing the net grid side reactance by \(KC_{lim}\) as shown in Fig. 8.

From the equivalent circuit shown in Fig. 8 the unsaturated active and reactive power when \(|ipc| > I_{lim}\) can be calculated

\[
P_{unsat} = \frac{E.Vg.\sin\delta}{Xv + X_T/KC_{lim}} - Q_{unsat} = \frac{E^2 - E.Vg.\cos\delta}{Xv + X_T/KC_{lim}}
\]

(15)

The \(KC_{lim}\) can be calculated similar to (8)

\[
KC_{lim} = \frac{\sqrt{Vg^2 + E^2 - 2.Vg.E.\cos(\delta)}}{Xv + X_T/KC_{lim}} \cdot 1/I_{lim}
\]

(16)

simplifying one can write

\[
KC_{lim} = \frac{M_v}{I_{lim} - X_T}/Xv
\]

(17)

Thus virtual unsaturated power when \(|ipc| > I_{lim}\) for can be simplified and written as independent of \(KC_{lim}\) as

\[
P_{virt} = P_{unsat} = \frac{E.Vg.\sin\delta}{Xv + X_T*X_T/(M_v/I_{lim} - X_T)}
\]

(18)

From (15) and (18) one can easily observe that the current limit activation inherently extend the peak of the power angle characteristics when virtual power \(P_{virt}\) is utilized as the feedback variable even beyond the power transfer limit for unlimited case. This can be verified by plotting the power angle curve for GFC with virtual power feedback as shown in Fig. 9. This feature greatly increases the synchronization stability margin of all the cases discussed in the previous section.

The cases studies conducted in the previous section are repeated with virtual power feedback and the results are as depicted Figs. 10–12. As shown in the figures the GFC with virtual power feedback when in current limited operation can sustain all the large transient events discussed in this paper.

6. Experimental results

The analysis presented in the previous section is validated through power hardware in the loop (PHIL) simulation. The configuration of the power hardware in the loop study is as shown in Fig. 13. Firstly, the PHIL study is conducted for GFC connected to an infinite voltage source to validate the analysis presented in Section 4. The 230 kV infinite voltage source with Thevenin grid impedance and 230/12.3 kV transformer is simulated in Realtime Digital Simulator (RTDS). The per unit values of the grid impedances and transformer impedances remain the same as in Section 4 with a base power of 100 MVA. A SEMIKRON SkiiP Voltage Source Converter (VSC) stack with an inductive filter and current and...
Two of the synchronous generators of the at bus IEEE-9 bus system (at
tative of future low inertia system with limited SG as shown in Fig. 17.
dip case.

\[ I_q \]
events are in good agreement with the analysis presented in Section 4.
Figs. 14–16. The PHIL results shown for RoCoF, phase jump, and fault
enhanced clarity. The PHIL results for the infinite bus case are shown in
interface. Both sets of data are exported to MATLAB and replotted for
event. The waveforms at the PCC are captured in the RTDS run time
out (FIFO) buffers and then saved to a file upon a configurable trigger
the real-time controller via direct memory access (DMA) first-in-first-
mH
conditioned with a first-order low pass filter with a time constant of
250 \( \mu s \) to eliminate noise and ensure the stability of the PHIL.

The VSC switching frequency is set to 10 kHz, and the inductive
filter for the VSC stack is 8 mH. The GFC control with a proportional
inner current control and the current limit discussed in the paper is
implemented on an FPGA-based digital controller from National Instruments (NI). The control is discretized using a trapezoidal integration
method with a sampling time of 40 \( \mu s \). The internal control variables
such as \( P_{int}, Q_{int} \) are captured in the NI controller and transferred to
the real-time controller via direct memory access (DMA) first-in-first-out (FIFO) buffers and then saved to a file upon a configurable trigger
event. The waveforms at the PCC are captured in the RTDS run time
interface. Both sets of data are exported to MATLAB and replotted for
enhanced clarity. The PHIL results for the infinite bus case are shown in
Figs. 14–16. The PHIL results shown for RoCoF, phase jump, and fault
events are in good agreement with the analysis presented in Section 4.

The reactive current at the PCC (\( I_{qGFC} \)) is also plotted for the voltage
dip case.

The PHIL study is expanded to a modified IEEE-9 system representa-
tive of future low inertia system with limited SG as shown in Fig. 17.
Two of the synchronous generators of the at bus IEEE-9 bus system (at
bus 3 and bus 1) are replaced with a commonly used 100 MVA grid
following VSC’s with active and reactive power control. The hardware
GFC is connected to the IEEE 9 bus system at bus 9, the scaling and
method of the PHIL interface remain the same as discussed before. The
transmission line parameters are the same as the original IEEE 9 bus
system [38]. The dispatch power of the SG in the system is adjusted
to set the system frequency to 50 Hz. Also, the P-f droop of the SG
 governor is by default 5%. A generation disconnection event of the
grid following VSC1 generating 100 MW is considered in this study.
Two cases with different droop parameters and dispatch power from
grid forming converter are considered in this study. The rotor of the
synchronous generator has under damped oscillatory behavior for a
load or generation disconnection event. The response from GFC for
the VSC1 disconnection event when the programmed inertia constant
is 10 s and power setpoint of 0.5 pu is shown in Fig. The active power
response of GFC, as well as the rotor speed of the SG(\( \omega_{sg} \)), is shown in
Fig. 18. And the response from GFC for the VSC1 disconnection event
when the programmed inertia constant is 10 s and power setpoint of
0.0 pu, and P-f frequency droop \( R_d \) of 5% is shown in Fig. 19. In both
cases, GFC, when utilizing measured active power, loses synchronism.
In contrast, a seamless entry to the current limiting and a seamless exit
from the current limit is achieved when virtual active power is used for
synchronization

7. Conclusion

The analysis presented in this paper has revealed the potential
transient stability problem for a GFC is greatly accentuated when the
GFC enters a current limited operation under different system events.
This paper emphasizes the necessity to evaluate the transient stability
problem with transients such as large frequency events, phase jumps,
and voltage dips instead of limiting the transient stability analysis just
to a fault conditions.

In this context, we have introduced a quantitative and illustrative
study focusing on GFCs with current control, operating amidst chal-
 lenging large transient events. This research has not only opened new
avenues but also provided methods to quantitatively define transient
stability metrics specifically tailored to GFCs operating under current
limits.

Furthermore, our study proposes a novel approach – leveraging
internal virtual power derived from unsaturated current references –
as a means to ensure synchronization during substantial transients
when the output GFC current is constrained. This virtual power-based
synchronization strategy enhances the transient stability margin, and
thus increasing the resilience of GFCs in dynamic grid environments.

The results from the Power hardware in the loop (PHIL) experimen-
tal tests on a single GFC connected to an infinite bus as well as
on a modified IEEE-9 bus system demonstrates the transient stability
challenges for a GFC and the validates of enhanced transient stability
of using a virtual power for GFC synchronization.

The studies in this paper are based on simplified models of GFCs to
understand and analyze the mechanism of instability during transients,
where specific grid codes requirements, such as current prioritization of
active and reactive current, are not considered. The grid codes require-
ment will entail different control loops for the current limiting logic
leading to different trajectories of the converter operating points during
transients, potentially leading to variations of implementing the virtual
power effect. The exact impact of these factors needs to be further
investigated in a separate study due to the complexity involved. A
promising avenue for future research could involve studies that include
multiple grid-forming converters in proximity to study the challenges
and dynamics of their interactions.

Declaration of competing interest

The authors declare that they have no known competing financial
interests or personal relationships that could have appeared to influence
the work reported in this paper.

Fig. 18. The response from GFC for the VSC1 disconnection event, \( H \) is 10 s, \( P_{int} \) of
0.0 pu, and P-f frequency droop \( R_d \) of 5%.

Fig. 19. The response from GFC for the VSC1 disconnection event, \( H \) is 10 s, \( P_{int} \) of
0.5 pu, and no P-f frequency droop.
Data availability

Data will be made available on request.

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