Dynamic Studies for 100% Converter-based Irish Power System

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Abstract

Given increasing shares of wind and/or solar power in many power systems, the possibility of a 100% power converter-based system becomes more plausible. Consequently, the dynamic response of the Irish transmission system with 100% (grid-following and grid-forming) power converters under 3-phase faults is investigated. Time domain simulations show that when active or reactive current prioritisation limits are applied, grid-forming converters can introduce large high-frequency oscillations but a scaling-down current limitation approach can help to avoid such problems. Furthermore, applying scaling-down current limits, together with freezing the virtual angular speed, for a grid-forming converter, can limit the current and enhance transient stability during faults. Finally, with modified controls applied to the grid-following converters, the grid-forming requirement can be reduced from approximately 40% to less than 30%, with the future Irish grid remaining robust against bolted 3-phase faults, and oscillations quickly damped out during and post fault.

1. Introduction

Many power systems are transitioning towards converter-based wind and photovoltaic generation [1][2], such that there could be extended periods of operation with 100% power converters, when wind / PV production is sufficient to entirely meet the demand. For example, Ireland is targeting a 70% renewable energy share by 2030, implying that for >40% of the time wind and PV availability will exceed instantaneous demand [3]. At the same time, an increasing fraction of loads are themselves being interfaced to the grid through converters, e.g. electric vehicles. Furthermore, many offshore and onshore high voltage direct current (HVDC) projects are being implemented, or are planned for the near future. As a result, parts of mainland Europe, such as the Iberian Peninsula, Germany or Denmark may occasionally operate with few, if any, synchronous machines. Moreover, with high shares of converter-based generation, system splits could occur more often, possibly resulting in only converter-based generation in some parts of the system [4].

Currently power converters are controlled as current sources through using a phase-locked loop (PLL) to synchronise the converter with the grid frequency by measuring the converter terminal voltage. As they follow system frequency instead of independently creating it, such converters are termed as “grid-following” or “grid-feeding”. Under this control principle, the permissible share of converters can be limited due to two main reasons: (1), 100% share of the converter is impossible since there will not be a ‘frequency source’ to follow [5], and (2), when the converter share is higher, online voltage and frequency regulation units will be fewer, then the AC voltage can vary more dramatically [6], and finally the synchronisation process becomes more challenging [7]. Moving forward with higher converter shares, “grid-forming” converters, with the ability to regulate voltage and frequency, are envisioned to displace synchronous-based generation. However, they have a lower overload capability, and, so, studying how grid-forming converters can maintain system transient stability under stringent overcurrent limits becomes important. Moreover, it is necessary to modify the control for existing and/or future grid-following converters to enhance power systems robustness and thus reduce regulation requirements.

Our previous related work has investigated the minimum required share of grid-forming converters for a reduced Irish grid under fault conditions, with all existing (conventional) generation replaced by converters of equivalent capacity [8]. In that work, the grid-forming converters were not strictly current limited, since virtual impedance based “soft” current limit was employed, and the grid-following converters were assumed to not actively support the grid during fault conditions. In this paper, it is found that the reduced Irish grid under the above minimum grid-forming share with the grid-following converters equipped with current LVRT control is only marginally stable. Moreover, according to the projections in [3], a future Irish grid is assumed with most converters located in relatively remote locations. Stability enhancement of the future Irish grid with 100% grid-forming converters, and a mix of grid-forming and grid-following based generation, is investigated under fault conditions, with the performed studies indicating that:

- Due to distorted current references under active or reactive current prioritisation limits (especially the latter), large high-frequency oscillations can be excited in a grid-forming converter with a LC filter. In contrast, such problems are avoided under scaling-down current limits, which provides smooth current references.
- With scaling-down current limits applied, along with freezing of the virtual angular speed, grid-forming converter current limits are strictly applied, leading to faster post-fault recovery and improved dynamic response.
- When modified (transient stability enhancement) controls are applied to grid-following converters, the reduced and future Irish grid, can robustly operate with a grid-forming share of less than 30% (compared to 40% without the
controls) under 3-phase fault conditions, with oscillations quickly damped out during and post fault.

The remainder of the paper is organised as follows: Section II introduces grid-forming droop control, along with formulations of three current prioritisation limiting strategies under a conditional anti-windup integration, and the proposed freezing of virtual angular speed technique. Section III deduces the existence condition of the PLL equilibrium point, and then introduces the proposed grid-following transient stability enhancement method. Section IV presents selected simulation results, and Section V concludes the paper.

![Fig. 1. Proposed control structure of grid-forming converter with LCL filter, and (optional) virtual impedance control.](image)

![Fig. 2. (a) Windup integration PI, (b) conditional anti-windup integration PI.](image)

2. Grid-Forming Converter Current Limiting Strategy for Transient Stability Enhancement

Acting in a similar role to synchronous generators towards independently regulating voltage frequency and amplitude, grid-forming converters, however, possess a much smaller over-current capability. Therefore, in this section, current reference limiting, together with anti-windup integration, is proposed to strictly limit the converter current, with the capability also added to freeze the virtual angular speed input when the converter loses regulation capability under current limits, to improve grid-forming transient stability under faults.

The proposed grid-forming converter control strategy is shown in Fig. 1. In addition to the existing P-f-Q-V droop control, threshold virtual impedance control ($\Delta V_{f1d}, \Delta V_{f1q}$), damping enhancement control ($\Delta e_d, \Delta e_q$), and cascaded voltage and current vector control, two further elements are introduced: scaling-down current limits with conditional anti-windup integration for outer voltage control, and freezing of the angular speed input under fault conditions. The reasons for and implications of these changes are now introduced.

Although for a grid-following converter, the current references can be directly limited, cascaded PI control anti-windup integration for the outer PI loop must be employed in the grid-forming case, as shown in Fig. 2(b), which follows IEEE Standard 421.5-2016 [9]. For comparison, windup integration is shown in Fig. 2(a).

Although threshold virtual impedance control can reduce the converter current by decreasing the voltage references, it provides a soft, rather than hard, limit. Combined with conditional anti-windup integration, three types of current priority limiting strategies are considered (assuming active or reactive power prioritisation regulation under existing low voltage grid-code requirements), where $u_q$ and $x_d$, and $u_q$ and $x_q$, are the inputs and outputs of the d-axis and q-axis integrators, while $\gamma = \frac{l_{max}}{\gamma} I_{cd, dq}$ $l_{max}$ is the maximum converter current, and variables with/without, superscript 0 represent values before, and after, the limiter in Fig. 2(b).

- **Active (d-axis) current prioritisation limit:**

  $$\begin{align*}
  i^*_c &= \left\{ \begin{array}{ll}
  i_{cd}^{0} & x_d = k_i u_d \\
  l_{max} & x_d = 0
  \end{array} \right. \text{if } |i_{cd}^{-0}| \leq l_{max} \\
  i^*_c & = \left\{ \begin{array}{ll}
  l_{max} & x_d = 0 \\
  \sqrt{l_{max}^2 - i_{cd}^{0}} & x_d = 0
  \end{array} \right. \text{if } |i_{cd}^{0}| > l_{max}.
  \end{align*}$$

- **Reactive (q-axis) current prioritisation limit:** the same as (5), but with d and q subscripts exchanged.

- **Scaling-down limitation:**

  $$\begin{align*}
  i^*_{cd, dq} & = \left\{ \begin{array}{ll}
  i_{cd}^{0} & x_{dq} = k_i u_{dq} \\
  l_{max} & x_{dq} = 0
  \end{array} \right. \text{if } |i_{cd}^{0}| \leq l_{max} \\
  i^*_{cd, dq} & = \left\{ \begin{array}{ll}
  l_{max} & x_{dq} = 0 \\
  \sqrt{l_{max}^2 - i_{cd}^{0}^2} & x_{dq} = 0
  \end{array} \right. \text{if } |i_{cd}^{0}| > l_{max}.
  \end{align*}$$

Due to the use of an LC filter, high-frequency oscillations are easily excited under d- and q-axis current prioritisation limits, since distorted currents are generated. Hence, scaling-down current limits can avoid such difficulties and it is proposed here as it can generate smooth current references, which also aligns with the requirement to regulate both active and reactive power.

Note that a grid-forming converter loses its regulation capability when $I_c \geq I_{max}$. However, the virtual angle $\theta_{vsm}$ will keep increasing. Due to the fast response of voltage source converters, the virtual speed $\omega_{vsm}$ in a grid-forming converter is proposed to be frozen when the current hits its limit, as shown below, where $\omega_{vsm}$ is the pre-fault virtual angular speed.

$$\omega_{vsm} = \left\{ \begin{array}{ll}
\omega_0 + m_p (P_{ref} - p^*) & l_{cd}^{0} < l_{max} \\
\omega_0 & l_{cd}^{0} \geq l_{max}
\end{array} \right. \text{if } 0 < l_{cd}^{0} \leq l_{max}.$$

where $l_{cd}^{0} = \sqrt{l_{cd}^{02} + i_{cd}^{02}}$. It should be noted that under the proposed scaling-down current limits, supported by freezing the virtual angular speed input, then virtual impedance control can assist with other functions, e.g. improving damping, mitigating the impact of unequal or resistive line impedances [10][11].

3. Grid-Following Converter Control for Transient Stability Enhancement

The PLL is recognised as the key component for a grid-following converter to maintain stability, especially in a weak grid and low voltage situations. In this section, the existence
condition of PLL equilibrium point is first deduced, based on which a readily implementable grid-following transient stability enhancement method is then proposed.

3.1. PLL Stability Condition

Fig. 3 shows a grid-following converter with filter resistance and inductance \( R_f \) and \( L_f \), which is connected to an AC grid with equivalent grid resistance and inductance \( R_g \) and \( L_g \). A PLL (in the standard synchronous reference frame) is used for the converter to follow the terminal voltage phase to achieve synchronisation with the AC grid.

The active and reactive output power in the synchronous dq-frame are expressed as \( P = v_{td}i_d + v_{tq}i_q \), \( Q = v_{tq}i_d - v_{td}i_q \). When the converter is synchronized with the grid, the q-axis and d-axis terminal voltages, \( v_{tq} \) and \( v_{td} \), become 0 and \( V_t \), and thus, \( P = v_{td}i_d, \ Q = -v_{td}i_q \). Hence, the active and reactive output power are decoupled, and can be independent controlled by the d- \((i_d)\) and q-axis \((i_q)\) currents. Therefore, the grid-following converter for normal operation outputs active and reactive power setpoints \((P^*, Q^*)\) by using the current references as

\[
\begin{align*}
    i_d^* &= \frac{P^*}{V_t} \quad (4) \\
    i_q^* &= -\frac{Q^*}{V_t} \quad (5)
\end{align*}
\]

Under normal operation, active current is prioritised, hence \( |i_q^*| \leq I_{max} \) and \( |i_d^*| \leq \sqrt{I_{max}^2 - |i_q^*|^2} \), where \( I_{max} \) is the maximum converter current. Assessing the PLL model and stability prerequisites, from Fig. 3 it has that

\[
v_i^* = v_i^* + R_i i^* + L_g \frac{di^*}{dt} \quad (6)
\]

where the superscript \( s \) indicates the voltage and current vectors in the stationary reference frame, and \( \omega_o \) is the base angle frequency. In (6), the voltage, \( v_i^* \), and current \( i^* \) phasors are represented in the static coordinate, and need to be transformed to \( v_t \) and \( i \) in the PLL output synchronous reference frame. Since \( v_i = v_i e^{-j\theta_{pit}} \) and \( i^* = i^* e^{-j\theta_{pit}} \), (6) can be equivalently rewritten as

\[
\begin{align*}
    v_{td} &= V_0 \cos \delta + R_g i_d + (\omega_o + \Delta \omega_{pit})L_g i_q \\
    v_{tq} &= -V_0 \sin \delta + R_g i_q + (\omega_o + \Delta \omega_{pit})L_g i_d
\end{align*}
\]

where \( \delta = \theta_{pit} - \theta_g \), and \( \omega_o = 1.0 \) is the nominal angular frequency. If PLL is stable, there are \( v_{td} = 0 \), and \( i_d = i_d^\star \) and \( i_q = i_q^\star \). So, from (8), the necessary condition for PLL stability (existence condition for equilibrium point [12], or within transmission line transfer limit [13]) follows as

\[
|L_g i_d^\star + R_g i_q^\star| \leq V_g, \quad (9)
\]

3.2. Control based on LVRT Grid-Code Requirement

Condition (9) is not the final form, since under normal conditions \( i_d^\star \) and \( i_q^\star \) are given by (4)(5), while during faults they are given by (10)(11) based on LVRT grid code of [14].

\[
\begin{align*}
    i_d^\star &= \min(1, 2(0.9 - V_t)), \quad V_t < 0.9, \quad (10) \\
    i_q^\star &= \min\left(\sqrt{I_{max}^2 - |i_d^\star|_V^2}, \frac{P^*}{V_t}\right), \quad V_t < 0.9. \quad (11)
\end{align*}
\]

Design of the current references for (10) and (11) during faults may not fulfill the PLL stability necessary condition (9), especially for weak grids. Moreover, the 1 pu current limit should change to \( I_{max} \) (usually larger than 1 pu in practice) to limit \( i_d^\star \) and thus improve PLL stability.

3.3. Grid-Following Converter Transient Stability Control

Under existing LVRT grid-code requirements, in relation to (10) and (11), it can be observed that:

- Only the terminal voltage magnitude is fed back to the reference order, but, voltage phase angle information, e.g. PLL output (frequency or angle), can be used to enhance grid-following converter stability
- Only reactive current is controlled, while the other control variable, i.e. active current, is not utilised
- Under this type of control, the active current reference becomes easier to oscillate if the reactive current reference hits against \( I_{max} \). Oscillating active and reactive current references are seen in the terminal voltage variations, which in turn feed through to the current references.

Against the above considerations, a strategy for enhancing grid-following transient stability is proposed:

- Active current is controlled based upon voltage phase angle information. Here, a PLL frequency based PI term is added to the active current reference. Both proportional and integral terms are beneficial in a weak or local grid with a high share of grid-following converters.
- Reactive current support gain is suggested as above 2 based on LVRT grid code of [14].
- For a transmission network with low \( R_g/L_g \), reactive current is prioritised, while for a distribution network with high \( R_g/L_g \), scaling-down current limits are suggested.

Fig. 4 summarises the proposed transient stability control for grid-following converters in a transmission network. The current references are given as

\[
\begin{align*}
    i_q^\star &= \begin{cases} 
      \frac{-Q^*}{V_t}, & V_t \geq V_{th1} \\
      -Kv(V_{th1} - V_t) - \frac{Q^*}{V_{th1}}, & V_t < V_{th1}
    \end{cases}
\end{align*}
\]

\( V_t \geq V_{th1} \quad (12) \)
\[ l_d = \left( \frac{P^*}{V_t} \right) - \left( \frac{P^*}{V_{th3}} \right) - \left( K_v f + K_{if} s \right) \Delta \omega_{p1ll}, \quad V_t \geq V_{th2} \]

\[ V_t < V_{th3} \] (13)

where $\Delta \omega_{p1ll} = \Delta \omega_{p1ll} + \Delta \omega_{db}$, and $K_v, K_{pf}, K_{if}$ and $k$ are positive constants.

Only symmetrical faults are studied in this paper, but under unbalanced conditions, separate control of positive- and negative-sequence current components, proposed in [15], is suggested, with the positive current references in [15] and negative-sequence current components, proposed in [15], modified to those proposed in (12)/(13).

Fig. 5. Single line diagram of Urban (left) and Remote (right) Irish grids with $\approx 38\%$ and $\approx 28\%$ share of grid-forming converters (by rated capacity). Bus nodes roughly correspond to geographical locations.

Table 1 Grid-following converter parameters

| Parameters | Values (pu) |
|------------|-------------|
| $R_f, L_f, \omega_0, \omega_0$ | 0.005, 0.15, 1, 314 rad/s |
| $k_{pp1ll}, k_{ip1ll}, k_{p1ll}, k_{i1ll}$ | 6, 10, 0.961, 171 |
| $K_{pf}, K_{if}, K_e, k, \Delta \omega_{db}$ | 20, 10, 5, 0.1, 0.02/50 |
| $V_{th1}, V_{th2}, V_{th3}, I_{max}$ | $V_0-0.05, V_0-0.05, V_0-0.1, 1$ |

Table 2 Grid-forming converter parameters

| Parameter | Values (pu) | Parameter | Values (pu) |
|-----------|-------------|-----------|-------------|
| $R_f, L_f$ | 0.005, 0.15, 0.066, $k_{pp1}, k_{ip1}$ | 0.52, 1.161022 |
| $C_f, R_g$ | 0.005, 0.15 | $k_{pp1}, k_{ip1}$ | 0.7388, 1.19 |
| $m, q$ | 0.02, 0.0001 | $\omega_e, \omega_0$ | 31.4 rad/s, 1 |
| $K_{ff}, K_{ff}$ | 1, 1 | $\omega_{ff}, K_{ff}$ | 16.66, 0.01 |
| $K_{V1}, K_{V/R}$ | 0.67, 5 | $I_{limit}, I_{max}$ | 1, 1.1 |

4. Case Study Results

4.1 Future Irish Grid with 100% Power Converters

Fig. 5 shows the simulated Urban and Remote Irish grids. In the Urban system, i.e. the “base case” Irish grid in [8], the locations and rated capacities of the converters are the same as exiting generation plant on the current Irish grid. In the Urban system only the transmission network with voltages $\geq 220$ kV are modelled, with lower voltage connections represented by equivalent loads, leading to 14 generators, 47 loads, 85 lines, many shunt capacitors and transformers. In the Remote system, many converters are now located in the west based on 2040 planning for the Irish grid [3], and extra 110 kV lines are then added in the west to connect the new converters to the transmission network. In comparison, both grids possess the same converter capacity and load demand. For the Remote system, extra capacitors are added, as necessary at converter buses in the east and west, to maintain system voltage levels within acceptable levels. Constant impedance loads and equivalent $\pi$ electrical lines are used.

The filter and control parameters for the grid-following and grid-forming converters are shown in Tables 1 and 2. Fast PLLs are used in the grid-following converters so that angle tracking is fast and accurate under different conditions. The grid-forming converter PI parameters follow those in [16], chosen through pole placement to achieve maximum damping across a range of conditions. Converter switching dynamics are not modelled, i.e. converter voltage reference $v_c^*$ is assumed equal to the output $v_c$. Both grid-forming and grid-following converters assume a constant DC voltage source, so transient stability issues relate only to the AC-side controls, with DC-side dynamics ignored. Simulations are performed in the Dymola environment, whereby details of system component models and control algorithms are fully transparent, which is especially beneficial when assessing stability issues for converter-based systems.

Case 1: The Remote Irish grid, Fig. 5, consists only of grid-forming converters, with current limits based on active and reactive current prioritisation. A 250 ms 3-phase bolted fault is applied at bus Inchicore (near Dublin) at 2 s for both situations. Fig. 6 presents two converters close to the fault location, assuming active current priority. Large post-fault oscillations of the output voltage are seen in Fig. 6(a), while Fig. 6(b) indicates that the current remains saturated after fault clearance. With reactive current priority (not shown), larger oscillations result for the output voltage.

Fig. 6. 250 ms 3-phase fault at Inchicore (Case 1), with grid-forming converters applying active current priority current limits. (a) Voltage output of grid-forming converter at Dublin Bay. (b) Current of grid-forming converter at Huntstown.

Case 2: As for Case 1 with only grid-forming converters, but now with alternative controls considered: (1) only virtual impedance ($VI$) control (activated when $I_v \geq I_{limit}$, as seen in Fig. 1); (2) scaling-down current limits ($Scaling$); (3) $VI$ together with freezing of the virtual angular speed input of Eqn. 3 ($Frozen + VI$); (4) $Scaling + Frozen$; and (5) $Scaling + Frozen + VI$.

A 250 ms 3-phase bolted fault is applied at Aghada (near Cork) at 2 s under the above 5 scenarios, with Fig. 7 showing results for grid-forming converters at Aghada and Huntstown. Fig. 7(a) shows that with a scaling-down approach, current is strictly limited within 1.1 pu, while under virtual impedance control the current can be transiently higher (shortening converter lifetime). Fig. 7(a) also shows that without freezing...
the virtual angular speed, under both VI and Scaling the current takes \(\approx 1\) s to return to normal, much slower than the Scaling+Frozen approach, which verifies the effectiveness of the proposed speed freezing control. In contrast, for Scaling, the converter takes a long time to return to normal from the current saturated state, during which the active power output is negative. Fig. 7(f). In general, the VI strategy improves upon Scaling, as the equivalent impedance seen from a grid-forming converter is changed. However, including virtual angular speed freezing along with scaling-current limits, causes the current, voltage and active power to quickly return to steady-state after the fault is cleared, Fig. 7(a)(d)(f), which indicates that the combination of both controls presents an attractive option for limiting the current and enhancing the transient stability of grid-forming converters.

Examining the response at Huntstown (distant from fault location) in Fig. 7(b), Frozen+VI option reduces oscillations relative to Scaling+Frozen, which indicates the damping benefits that virtual impedance control provides. Fig. 7(c) shows that in both cases, \(\omega_{\text{em}}\) is frozen during the fault since \(\omega_{\text{em}}^0 > 1.1\) pu, while under VI and Scaling \(\omega_{\text{em}}\) increases during and after the fault, leading to the extended recovery period, i.e. from Fig. 7(d)(e) the voltages under VI and Scaling remain low for \(\approx 0.8\) s after fault clearance, while if the Frozen option is included they immediately recover close to nominal. Finally, Scaling+Frozen+VI presents similar dynamics to Frozen+VI, with the virtual impedance activated before Scaling, since \(\lim_{\text{it}} < \lim_{\text{max}}\). Thus, VI control should be retained under the fully combined approach, given that VI+Frozen displays inferior performance to Scaling+Frozen.

Case 3: The Urban and Remote Irish grids shown in Fig. 5 are simulated (the latter is much “weaker” than the former, due to the large number of grid-following converters in the west, with the main load centres in the east). In both grids, grid-following converters incorporate the LVRT control of (10) and (11), but based upon a voltage threshold 5% below the initial converter terminal voltages, in order to provide improved voltage regulation capability. In Case 3 and later Case 4, grid-forming converters only utilise virtual impedance control, i.e. without scaling-down current limits and freezing the virtual speed input (which enhance performance), in order to more easily compare the results against previous work [8].

A 250 ms 3-phase bolted fault is applied at bus Inchicore (near major load centre) for both the Urban and Remote systems. It is seen from the Urban results of Fig. 8(a)(b) that the PLLs remain stable, but large oscillations are clear for the grid-following converter at Moneypoint. Hence, the system is only marginally stable, and the grid-following converters, with LVRT control, present weak controllability. Equivalent results for the Remote system of Fig. 5 are not shown here, since, for the given fault conditions, the PLLs lose equilibrium and become unstable with over-frequency outputs and large oscillations, similar to that shown in [8].

Case 4: The proposed transient enhancement control for grid-following converters is implemented for the future (Remote) Irish grid, for 2 scenarios with \(\approx 38\%\) and \(\approx 28\%\) share of grid-forming converters (by capacity) considered. In the latter scenario, half of the grid-forming capacity at Dublin Bay and Huntstown (both in Dublin urban region), in Fig. 5, are switched to be grid-following converters. A 250 ms 3-phase bolted fault is applied at Inchicore for both grid-forming shares, with results shown in Fig. 9 (38%) and Fig. 10 (28%) for converters of the same type and in roughly similar geographical locations. Fig. 9 shows that for the Remote system with the proposed transient enhancement control for the grid-following converters (12)(13), the voltages remain smooth and the PLL outputs are highly damped during and post-fault. Note that the Remote system is much weaker than the Urban system, although both have the same grid-forming share, since the large number of grid-following converters in the west (with the main load centres in the east) gives rise to higher equivalent impedances, as seen by the grid-following converters located behind the new 110 kV connections. With a lower grid-forming share (28%) in the Remote system, Fig. 10(a) also shows stable and smooth PLL outputs, similar to those in Fig. 9(b). Meanwhile, the grid-forming converter currents under both shares (38% and 28%) in Fig. 9(d) and Fig. 10(b) are similar, demonstrating the strong contribution provided by the grid-following converters towards supporting system stability under the proposed transient enhancement control. It should be noted that the delayed voltage recovery in Fig. 9(a) originates from the slow recovery of grid-forming converters,
as seen in Fig. 9(c)(d), similar to the results under VI in Case 2. The delayed voltage recovery can be eliminated if the grid-forming converters implement the proposed Scaling+Frozen controls (not shown).

Fig. 9. 250 ms 3-phase fault at bus Inchicore for Remote system with ≈ 38% grid-forming share (Case 4), with proposed transient grid-following stability enhancement. (a)(b) Outputs of grid-following converters. (c)(d) Outputs of grid-forming converters.

Fig. 10. 250 ms 3-phase fault at bus Inchicore for Remote system with ≈ 28% grid-forming share (Case 4), with proposed transient grid-following stability enhancement. (a) Grid-following converter PLL outputs, (b) Grid-forming converter currents.

5. Conclusions

The stability of a 100% converter-based system, based on the Irish grid, has been investigated. With converters placed in traditional generator locations, the Irish grid with ≈40% grid-forming share was seen to be only marginally stable if the grid-following converters operated under existing LVRT controls.

Placing the converters at more remote buses, for both a 100% grid-forming converter case and a mix of grid-following and grid-forming converters, was also investigated. In the former case, after fault clearance, the grid-forming converters required ≈1 s to recover to a pre-fault state under virtual impedance current limits, or they became unstable with scaling-down current reference limiting combined with anti-windup integration. However, by freezing the virtual angular speed input, the grid-forming converters were then able to quickly recover to their pre-fault state.

An enhanced control strategy for grid-following converters was also proposed, which enabled smooth PLL and voltage outputs and the minimum share of grid-forming converters to be reduced to ≈30%. Future work will translate the above simulation studies to an Opal-RT test bench.

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