Review of Fault Ride Through Support Schemes and a New Strategy for Low-Inertia Power Systems

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***Abstract*—A massive deployment of renewable energy sources (RESs) is required to enable the decarbonization of the energy infrastructure. The replacement of conventional generators with inverter-based RESs reduces the rotational inertia and can threaten the frequency stability of the system. This work is motivated by analyzing an actual cascading event in a low-inertia system where a voltage sag event that was cleared within few milliseconds triggers a severe frequency disturbance. During a low voltage sag event, the reactive power is prioritized for voltage support purposes according to the existing low voltage fault ride through (LVFRT) grid regulations, which lead to a significant reduction of active power by RESs that triggers the cascading phenomenon. This event indicates that the existing LVFRT regulations require re-evaluation, especially in low-inertia power systems with increased penetration of RESs. Therefore, the existing grid regulations are thoroughly analyzed with a particular emphasis on the coupling phenomena where a voltage support can threat the frequency stability. Moreover, a new LVFRT strategy is proposed where active power prioritization is introduced for enabling an intense voltage support without causing a significant reduction on active power. The existing and proposed LVFRT schemes are benchmarked considering theoretical and simulation-based analysis indicating that the proposed scheme provides improved support and is adequate for low-inertia power systems with intense RESs penetration.**

Keywords—Fault ride through strategy, grid codes, inverter-based resources, low voltage grid faults, low-inertia systems.

I. INTRODUCTION

The global effort towards the green transition and the long-term strategies set by the European Commission (EC) related to the climate neutrality, renders the decarbonization of the energy sector as a top priority to minimize the environmental footprint [1]. In this direction, a high penetration of RESs is required to replace the large traditional power plants for eliminating the energy sector dependency on fossil fuels. The increasing share of unpredictable in nature RESs, along with their grid integration through power electronics inverters, impose critical challenges related to the stability, efficiency, and cost-effective operation of power systems. As conventional synchronous machines with large rotating mass are substituted by stationary electronic-based RESs, the inertia level of the system is significantly reduced [2]. In low-inertia power grids, the frequency stability is among the highest concerns for the operators, since the system becomes more sensitive and vulnerable under grid disturbances and abnormal conditions. Therefore, it is of high importance to advance the control strategies applied in inverter based resources to provide support functions for enhancing the system stability and ensuring the system robustness under any grid conditions.

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Several grid regulations have been extensively introduced across the globe indicating that during abnormal voltage conditions, RESs should remain interconnected to the grid and provide voltage support [3]-[4]. More specifically, during low voltage short-circuit faults, RESs should maintain their synchronization and provide reactive power injection to support the grid voltage in compliance with the LVFRT regulations [5]. These regulations dictate that RESs should remain interconnected for few milliseconds even under zero voltage conditions in some cases [6]. Also, these regulations are sometimes applied even in low voltage distribution grids on small-scale power inverters [7]. Furthermore, different LVFRT support strategies have been proposed in [8], where inverter aims on maximizing the positive sequence voltage and/or suppressing the negative sequence voltage during grid faults to contribute towards the voltage stability enhancement and on voltage asymmetries elimination.

In line with the above, control strategies are also proposed in the literature or in grid codes to provide frequency support as well, when an upward flexibility is available in inverter based resources. Previous works considered several droop-based inverter control schemes that enhance the frequency stability by introducing the concepts of virtual synchronous generator and synthetic inertia in case of flexible resources [9]-[10]. Moreover, for enhancing the upward flexibility of non-flexible photovoltaic (PV) systems, a delta power constrain control mode is introduced in [11] where the inverter is operating below the maximum power availability to reserve an amount of active power to be injected to the system during an under-frequency event. Additionally, many studies have shown that the frequency stability is improved, especially on weak power grid, when the inverter control mode is switched from the grid following approach, where a phase locked loop is used to synchronize the inverter with the grid voltage, into the grid forming approach, where the frequency and voltage are directly controlled by the inverter [12]-[13]. Further, the flexible capabilities of energy storage systems have been exploited to provide coordinated voltage and frequency support in case of combined voltage and frequency disturbances considering the fault intensity and the high resistive characteristics of low voltage distribution grids [14].

In general, the majority of LVFRT regulations indicate that RESs must remain interconnected to the grid to provide voltage support during voltage sag events by prioritizing the reactive power injection. This action may suppress the inverter active power injection during a voltage event, especially if the inverter is operating near its nominal power. As a result, such a reactive power prioritization by the standard LVFRT regulations might initiate a cascading frequency event due to the sudden reduction of the active power injection by RESs. It is noted that, even though a voltage fault usually last for a short period of time (e.g., 100-200 ms), the overall active power reduction in the power system may last longer since it is subjected to the recovery rate capability of RESs (rate to return to the pre-fault conditions). Thus, if a power imbalance is imposed on the system for a longer period of time (e.g., 500-2000 ms), then a frequency event can be triggered threatening the system stability. For this reason, Irish grid codes have been recently updated to revise the LVFRT scheme for minimizing such risks [15]. It is also noted that such cascading phenomena threatening the frequency stability have been already observed in low-inertia power systems (e.g., Cyprus) even under low or medium penetration of RESs. Such an actual example captured in Cyprus power system is analyzed in Section II that motivates required changes on the existing LVFRT regulations.

This paper analyzes existing LVFRT regulations and proposes a new LVFRT support strategy adequate for low-inertia power grids to enhance the system stability. The main contributions of this paper are: (a) to analyze in depth a real cascading disturbance event that occurred in a low-inertia power system which was initiated due to the existing LVFRT regulations; (b) to evaluate the performance of existing grid regulations regarding the LVFRT operation with a particular emphasis on the voltage support intensity and on the active power reduction that may be introduced under different conditions; and (c) to propose a new LVFRT strategy with active power prioritization tailor-made for low-inertia power grids to enhance system stability.

The rest of the paper is organized as follows. Section II provides a thorough analysis on an actual cascading event that motivates the need for modification of the LVFRT regulations. Section III provides an overview of the existing regulations, while Section IV proposes a new LVFRT method appropriate for low-inertia power systems. Section V presents simulation results and a benchmarking of different fault ride through strategies, while the paper concludes in Section VI.

II. Analysis of an Actual Cascading Event

In traditional power systems, voltage and frequency disturbances are usually examined as decoupled events and it is not expected that a voltage fault can initiate a frequency disturbance. However, as already mentioned, the reactive power prioritization, imposed by the LVFRT regulations for voltage support, can cause a reduction of active power, which can potentially trigger a frequency event, especially in low-inertia systems. Such cascading phenomena are already observed in low-inertia systems with moderate RESs penetration indicating the need for further analysis of the LVFRT regulations and revision, particularly under high RESs penetration in weak grids.

An example of a real cascading event captured in Cyprus power grid (an isolated and low-inertia system) is analyzed in this section. The voltage and frequency behavior of the system was captured by a Phasor Measurement Unit (PMU) with 20 ms resolution and is demonstrated in Fig. 1. In this event, an intense asymmetric voltage sag fault occurred (at $t = 2920$ s) and was cleared within 130 ms. The specific fault occurred at a transmission line, and it was a phase-to-phase short-circuit fault (Type C [16]), which was observed by a PMU at the distribution side as a Type D fault [16], due to the asymmetric fault propagation through a transformer connected in Wye-Delta configuration. The specific voltage fault did not directly cause any severe power imbalance when the protection relays

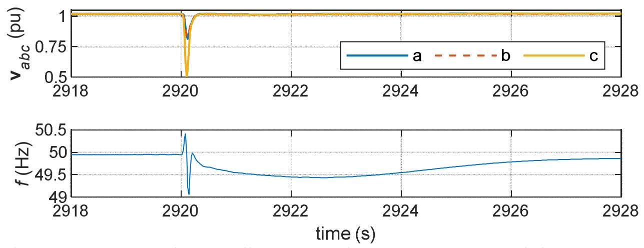

Fig. 1. An actual cascading event in Cyprus, captured by a PMU, demonstrating the phase votlage amplitudes and the frequency of the system.

cleared the fault; however, a severe cascading frequency event was triggered after the voltage event which cause a decrease of the frequency from 49.98 Hz (pre-fault conditions) to 49.4 Hz within 2.5 seconds after the voltage fault.

An extensive investigation was performed to analyze this event, concluding that the cascading disturbance was initiated due to the response of RESs according to the LVFRT regulations. During the voltage sag fault, the LVFRT mode of wind power plants was activated and the reactive power injection was prioritized to support the voltage stability, as defined by the grid codes [17]. According to these regulations, the LVFRT mode indicates that the intensity of reactive power injection should be provided according to the real-time voltage sag conditions, while due to the reactive power prioritization, a reduction of the active power may be imposed to avoid thermal violations on the inverter current limits. During the specific short-circuit event, three wind farms in Cyprus with a combined installed power of 42 MW were operating near to their nominal power (above 75% of their maximum power). Therefore, during the specific voltage event, the provision of reactive power injection in combination with the low voltage conditions caused a reduction of the active power which created an instant power imbalance of 13.5 MW for the duration of the voltage fault. After the fault was cleared (after 130 ms), the wind turbines initiated the return to the pre-fault active power conditions and the power imbalance was recovered within approximately 1-2 seconds. The active power recovery rate was fast and according to the grid code requirements (considering a recovery rate between 10 and 20%/s). However, the power imbalance of 13.5 MW that had been introduced to a low-inertia power system due to the LVFRT control mode and gradually recovered within 1-2 seconds, triggered a severe frequency event with a frequency nadir of 49.4 Hz.

The analysis of this event highlights that in case of high penetration of RESs in low-inertia power systems, the existing LVFRT regulations applied during voltage sag conditions to support the voltage stability can initiate a cascading frequency event that may threaten the system stability. Hence, it is important to investigate the existing LVFRT regulations and modify them whenever is necessary (e.g., weak grids) to ensure the stability of power systems.

III. Overview of the Existing Grid Regulations

In this section, the LVFRT requirements of existing grid regulations are presented and analyzed to identify how the voltage support is provided and to investigate how the frequency stability can be affected. The voltage support intensity is quantified by the injection of reactive current while the impact on the frequency stability is related to the reduction of the active power. First, the conventional LVFRT regulations that are valid in most of the countries are presented and then, a new version of LVFRT regulations applied in the Irish low-inertia power system are described.

A. Conventional LVFRT grid regulations

Common grid codes have been applied in most countries for at least a decade now, requiring that the RESs should remain interconnected during low voltage grid faults. In particular, the voltage drop intensity and duration of the fault is considered and RESs must remain interconnected when the voltage is above the characteristic line presented in Fig. 2. In contrast, when the voltage is below the characteristic line, then the RESs can be disconnected. It is noted that, the characteristic line may be slightly different in each country.

During LVFRT mode, an adequate reactive power support is required for enhancing the voltage stability of the system. The reactive power injection during a low voltage event is determined according to reactive current (I_Q) that should be injected by the inverter, as presented in Fig. 3(a). The reactive current injection is calculated according to the voltage drop (ΔV) and the parameter k that defines the intensity of the support, as given by (1).

$$I_Q = k \cdot \Delta V = k \cdot (V_N - V_{PCC}) \tag{1}$$

V_N is the nominal voltage and V_{PCC} is the measured voltage at the Point of Common Coupling (PCC). It is noted that, k must be equal or greater than 2 according to the grid codes and thus, a full reactive support is always provided under a voltage sag event with 50% or higher voltage drop. Further, the reactive current corresponds to the current element, which is responsible of the reactive power injection, while the active current is related to the active power injection, as given by,

$$I_P = I \cdot \cos\varphi \,, I_Q = I \cdot \sin\varphi \;\text{ and } I = \sqrt{I_P^2 + I_Q^2} \tag{2}$$

where I is the current injection and φ is the phase difference between the voltage and current vector. Moreover, reactive current provision must be achieved within 20 ms after the fault occurs, while the LVFRT operation should remain activated for additional 500 ms after the fault is cleared and the voltage return to normal conditions (nominal voltage ±10%).

A crucial aspect of these LVFRT regulations is that the reactive current injection is prioritized, over active current injection, during abnormal voltage conditions. Thus, the reactive current injection should be first satisfied and then the remaining capacity should be allocated for the active power injection. This aspect is particularly important to be considered when ensuring the thermal limits of the inverter, where the current injection (I) must never exceed the nominal current (I_N). Therefore, the grid code requirements for additional reactive current injection (I_Q) in combination with the reactive power prioritization in LVFRT mode can limit the active current injection (I_P) by the inverter, according to (3).

$$I_P \leq \sqrt{I_N^2 - I_Q^2} \tag{3}$$

It is obvious that, during intense voltage sag events where a significant reactive current injection is required, the active power injection can be significantly limited or eliminated for voltage drops higher than 50%.

Since the active power injection (P) is directly related to the active current (I_P) and the voltage at the PCC (V_{PCC}) as given by (4), a significant decrease of the active power may be introduced during a voltage sag event.

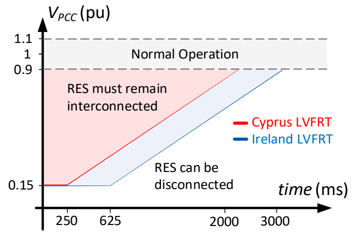

Fig. 2. Grid regulations for the region where RES must remain interconnected during a voltage sag event.

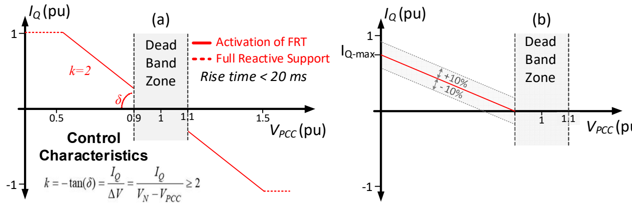

Fig. 3. Reactive current support, as required (a) by the conventional grid

$$P = V_{PCC} \cdot I_P \text{ and } Q = V_{PCC} \cdot I_Q \tag{4}$$

Therefore, an active power reduction according to (3) can directly decrease the active power injection. It should also be noted that during a voltage sag event (V_{PCC} < 0.9 pu), the reduction of the voltage can also affect the active power injection. The inverter can maintain the pre-fault active power injection by increasing the active power injection, but this can only be achieved if (3) is satisfied.

From the above analysis, the active power can be reduced during the provision of LVFRT support. An intense power reduction is expected when pre-fault active power or current injection is close to the inverter limits, since the active current will be reduced even under a mild voltage sag where a small reactive current injection is required. The power reduction is of course higher when more intense voltage sag event occurs since a high reactive current injection will significantly limit active current, according to (3), and in combination with the low V_{PCC} will both affect the active power injection according to (4). Hence, from the analysis of the existing LVFRT regulations is indicated that the voltage stability is supported by the reactive current injection, however, the active power is reduced due to the reactive current prioritization introducing a power imbalance that can trigger a frequency event.

B. Recent LVFRT strategy according to Irish Grid Codes

Since the conventional LVFRT regulations impose an extra active power reduction during the fault due to the reactive current prioritization, the frequency stability can be threatened, especially in low-inertia power systems. This aspect has been recently recognized by some operators of low-inertia power systems and as a result, an effort to revise these regulations is observed. An example of regulations that have been recently updated to consider this aspect is the new Irish grid codes, that are analyzed in this section.

The power system of Ireland is a low-inertia systems and consequently the frequency stability is a crucial aspect. Therefore, to enhance the system frequency stability during low voltage faults, the reactive current prioritization is excluded in the revised grid codes and a new LVFRT support strategy is introduced. In the new support scheme, the active current is prioritized and then the remaining capacity of the inverter can be allocated to reactive current injection for voltage support. The new scheme requires that the active current injection during the fault (I_P) must remain constant and equal to the pre-fault conditions ($I_{P\text{-}pf}$), as given by (5).

$$I_P = I_{P-pf} \tag{5}$$

As a result, during the low voltage fault, the active power must be proportional to the grid voltage (V_{PCC}), according to (6), with a tolerance of ±5%.

$$P = V_{PCC} \cdot I_P \tag{6}$$

Considering that the active current is prioritized over the reactive current, the inverter must satisfy the active power injection according to (3) and then utilize the remaining capacity for the voltage support purposes. As a result, the maximum reactive current injection ($I_{Q\text{-}max}$) is determined according to (7) by considering the inverter limit (I_N) and the active current injection (I_P).

$$I_{Q-max} = \sqrt{I_N^2 - I_P^2} \tag{7}$$

The reactive current support is provided by considering a proportionality between the voltage deviation from the normal voltage conditions and the maximum current injection, according to (8), with a tolerance of ±10%, while the reactive power injection can be calculated according to (9).

$$I_Q = -I_{Q-max} \cdot V_{PCC} + I_{Q-max} \tag{8}$$

$$\mathrm{Q}{=}V_{PCC} \cdot I_Q \tag{9}$$

The reactive current injection is demonstrated in Fig. 3(b) and it shall continue until the normal operation voltage levels met or for at least 500ms, whichever is the sooner.

The new regulations of the Irish system can potentially restrict the decrease of active power injection, which is beneficial for the frequency stability; however, the intensity of the voltage support is significantly reduced. It should be highlighted that by considering a constant active current injection according to (5), an unnecessary active power reduction is introduced according to (6) during voltage sag which can be potentially avoided if an increase of active current was allowed.

IV. Proposed LVFRT with Active Power Prioritization

The review of existing LVFRT in Section III indicates some limitation in both the conventional LVFRT and in the recent Irish LVFRT regulations. The conventional LVFRT may introduce a significant active power reduction in case of voltage sag events that can threaten the frequency stability of low-inertia power system. The attempt of the recent Irish codes to deal with this issue may decrease the power reduction only in certain condition while the intensity of voltage support has been significantly reduced. In light of the above issues, this section proposes a new LVFRT scheme adequate for low-inertia systems that can maintain the intensity of the voltage support while restricting the active power reduction to benefit in this way both frequency and voltage stability.

An obvious way to limit the active power reduction during a voltage sag event is to reduce the support intensity which is correlated with the parameter k in the conventional LVFRT; however, this deteriorates the voltage stability. The proposed LVFRT scheme aims on maintaining the voltage support intensity (k=2), whenever is possible, while a reduction of the voltage support is allowed when the reactive current injection starts affecting the active power injection. Also, this scheme considers active current prioritization over reactive current to limit the power imbalance introduced by the voltage support.

Since the active current is prioritized in the new LVFRT, the active current injection must be determined first. The active current during the fault is defined according to the grid voltage (V_{PCC}) and the pre-fault active current injection ($I_{P\text{-}pf}$), as according to (10). The active power then, is given by (11).

$$I_P = \min\left(\frac{1}{V_{PCC}} \cdot I_{P-pf}, I_N - \Delta I_{P-max}\right) \tag{10}$$

$$P = V_{PCC} \cdot I_P \tag{11}$$

The active current is determined by considering the minimum value of the two elements in (10). The first element aims on maintaining a constant active power injection under voltage sag events. Thus, the active current is increased until it reaches the value of the second element of (10). In the second element, an allowable active current reduction limit (ΔI_{P-max}) is introduced as a percentage of the inverter nominal current (I_N).

This allowable reduction is introduced to secure a margin in the inverter capacity that should be allocated for reactive support. If $\Delta I_{P-max} = 0$, then during a voltage sag, the active current will increase (according to (10)) to maintain a constant active power according to (11) until reaching the nominal current of the inverter. When the nominal current is reached, then the active current will remain constant to the nominal value and the active power will be proportionally reduced according to the PCC voltage, according to (11). In this case, when the active current reaches the inverter nominal current, then there will not be any margin for voltage support. By introducing a small, but non-zero, allowable active current reduction limit (e.g., $\Delta I_{P-max} = 10\%$), then the active power remain unchanged until the active current reaches the slightly reduced limit $I_N - \Delta I_{P-max}$. In this case, the remaining inverter capacity can be allocated for reactive support.

Since the proposed scheme considers active power prioritization, the maximum reactive current injection is determined in (12) by considering the inverter limit and the active current injection initially calculated by (10).

$$I_{Q-max} = \sqrt{I_N^2 - I_P^2} \tag{12}$$

Then, the reactive current injection is determined similarly to the conventional LVFRT considering the voltage drop and the parameter k that defines the support intensity as described in (13). However, in the proposed scheme, the reactive current should be limited according to the maximum reactive current limit calculated in (12). Then the reactive power injection can also be calculated according to (14).

$$I_Q = \min\left(I_{Q-dfmax}, k\Delta V\right) \tag{13}$$

$$\mathrm{Q}{=}V_{PCC} \cdot I_Q \tag{14}$$

Consequently, the new LVFRT scheme prioritizes the active current injection to avoid the reduction of active power, whenever is possible, limiting in this way the introduced power imbalanced during a voltage sag. Then, the remaining capacity of the inverter is allocated into the voltage support by providing a reactive current injection with the same intensity provided by the conventional grid regulations. The allowable active current reduction limit ΔI_{P-max} is intentionally introduced to secure a margin of the inverter capacity to be used for voltage support. A suggestion to use a small, but non-zero limit for ΔI_{P-max}, for example $\Delta I_{P-max} = 10\%$, ensures that under any case (e.g., intense voltage sag, high pre-fault active power injection), a minimum 43.6% of the nominal inverter capacity will be allocated for reactive current support according to (10) and (12). This feature indicates that even though the active power is prioritized, the voltage support is not significantly deteriorated. As a result, the proposed LVFRT scheme is expected to show an outstanding performance compared to the existing schemes by limiting the reduction of active power and by ensuring an adequate voltage support intensity. Hence, the new LVFRT scheme is adequate for low-inertia and inverter-dominated power systems.

V. Performance Benchmarking

This section deals with the performance benchmarking using theoretical and simulation-based validation. In the performance evaluation, different voltage sag events and different pre-fault active power conditions have been considered, while five different support scenarios were examined: (a) the conventional LVFRT scheme when k=2, named as Q_{FRT}(k=2); (b) the conventional LVFRT with $k=0$ (no LVFRT support), named as Q_{FRT}(k=0); (c) the Irish LVFRT scheme, named as IR_{FRT}; (d) the proposed LVFRT with active power priority when $k=2$ and allowable active current reduction limit $\Delta I_{P-max} = 0\%$, named as P_{FRT}(k=2, $\Delta I_{P\text{-}max}$=0); and (e) the proposed LVFRT with active power priority when $k=2$ and allowable active current reduction limit $\Delta I_{P-max} = 10\%$, named as P_{FRT}(k=2, $\Delta I_{P\text{-}max}$=10).

A. Theoretical benchmarking of LVFRT support schemes

The benchmarking starts with a theoretical based performance evaluation where the active and reactive current and the active and reactive power is presented for each support scheme. It is noted that the reactive current I_Q is the dominant factor for the voltage support while the active power P is the most important factor for the frequency support.

Fig. 4 demonstrates the provision of active and reactive current and power under all possible voltage sag levels, when the pre-fault active power injection was equal to 50% (Fig. 4(a)) and equal to 90% (Fig. 4(b)). The conventional scheme Q_{FRT}(k=2) provides the best voltage support but introduces an intense active power reduction, while by deactivating the support Q_{FRT}(k=0), the active power reduction is minimum,

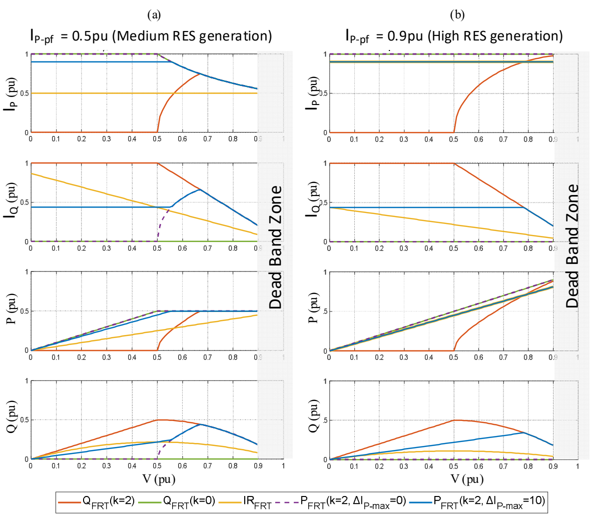

Fig. 4. Theoretical performance benchmarking of the active and reactive current and power injection by RESs for five different scenarios, when the pre-fault active power is equal (a) to $P_{pf} = 0.5\ pu$ and (b) to $P_{pf} = 0.9\ pu$.

but no voltage support is provided. The Irish code provide a moderate voltage support, but the reduction of active power is minimized only when the pre-fault active power generation was high (P_{pf}=0.9 pu). In case of low or medium pre-fault active power generation, an unnecessary reduction of active power is observed that can deteriorate the frequency stability. The proposed scheme P_{FRT}(k=2, $\Delta I_{P\text{-}max}$=0) presents minimum active power reduction while it can provide maximum voltage support under low or medium pre-fault active power generation or under mild low voltage sag. When a small value is set on the allowable active current reduction limit $\Delta I_{P-max} = 10\%$ in the proposed scheme P_{FRT}(k=2, $\Delta I_{P\text{-}max}$=10), then the reduction of active power is almost minimum, while the voltage support is intense during mild voltage sag and is moderate during severe voltage sag. As a result, the proposed scheme P_{FRT}(k=2, $\Delta I_{P\text{-}max}$=10), present the best combination of voltage support considering a minimum impact on the reduction of active power, which seems to be an ideal support scheme for low-inertia power systems.

B. Simulation-based validation

The different LVFRT schemes were evaluated using the two-area dynamic power system shown in Fig. 5, which was simulated in MATLAB/Simulink. The model consists of two 100 MVA synchronous machines interconnected through two delta-wye transformers and a 200 km transmission line at the 132 kV. Two loads representing the total demand at each area are connected at Bus 2 and 3, while a grid-tied inverter is used to connect a 40MW RESs to the grid. At $t = 35\ s$, a three-phase fault applied at Bus 3 and the RESs provides LVFRT support to the grid, according to the 5 different schemes.

Fig. 6 demonstrates the response of the five scenarios analyzed in Section IV, for two voltage drop faults at 0.35 pu and 0.5 pu, when the pre-fault RESs active power injection is equal to 50%, while Fig. 7 presents the same results by considering pre-fault RESs active power injection at 90%. It is noted that in each grid fault event, the frequency response is determined by the combined dynamics of the synchronous generators, loads and RES. This investigation mainly focuses on how the RES LVFRT support functionalities can affect the system stability. In the first case (Fig. 6), the proposed scheme P_{FRT}(k=2, $\Delta I_{P\text{-}max}$=10) outperforms the Irish support scheme, since a higher frequency nadir and a higher voltage is observed leading to improved frequency and voltage stability. This is expected since the proposed scheme provides more intense voltage support with a minimum reduction on active power, especially under low or medium pre-fault active power injection. On the other hand, in Fig. 7 where the pre-fault active power is high, the proposed and the Irish scheme present almost identical frequency response however, the proposed scheme achieves an improved voltage response.

In general, the conventional scheme Q_{FRT}(k=2) presents the best voltage support but this is causing the worst frequency response, so it is not adequate for low-inertia system. On the other hand, by deactivating the support Q_{FRT}(k=0), the

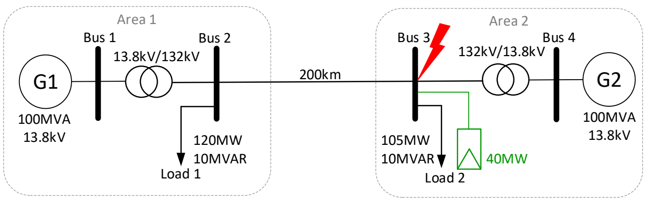

Fig. 5. Single line diagram of the two-area validation model.

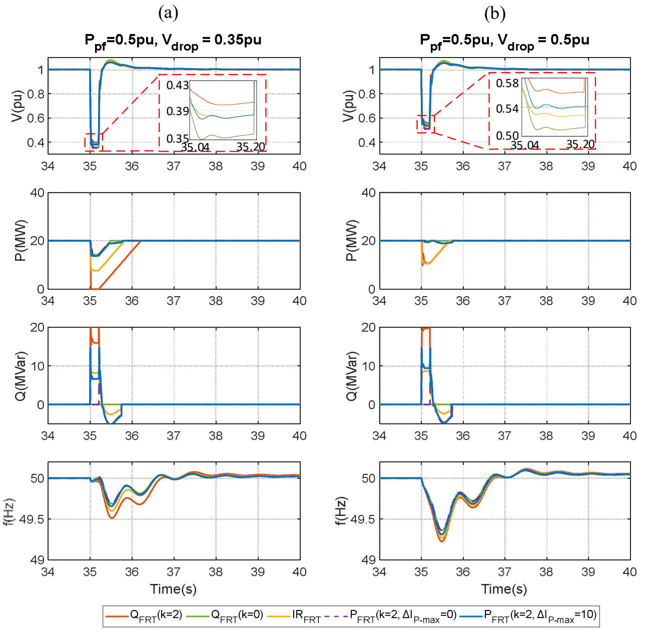

Fig. 6. Response of the LVRT schemes under two different voltage sag events at $t = 35\ s$ for five different scenarios when $P_{pf} = 0.5\ pu$.

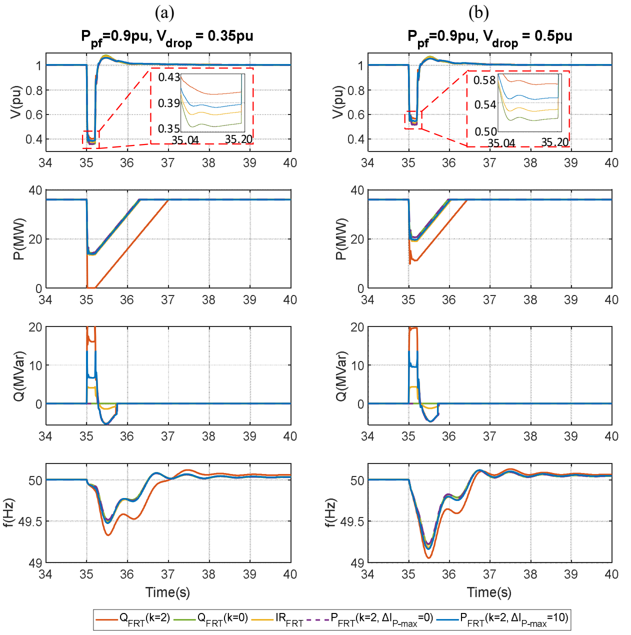

Fig. 7. Response of the LVRT schemes under two different voltage sag events at $t = 35\ s$ for five different scenarios when $P_{pf} = 0.9\ pu$.

frequency stability is improved but the voltage response is the worst one. The recent Irish scheme tries to reduce the impact on the frequency through a moderate voltage support but still under certain cases the frequency is critically affected. Finally, the proposed scheme P_{FRT}(k=2, $\Delta I_{P\text{-}max}$=10) achieves a better frequency stability, with up to 14.7% improvement on frequency nadir compared to Irish grid code and with up to 30% improvement compared to the conventional LVFRT. It also provides better voltage support comparatively to Irish grid code (up to 3.5% improvement), though not as good as the conventional LVFRT. This benchmarking concludes that the proposed LVFRT scheme with active power prioritization offers an attractive trade-off for low-inertia systems.

VI. Conclusions

This paper indicates through an actual grid fault investigation that the existing LVFRT schemes for supporting the voltage can trigger a frequency event that deteriorate the frequency stability in low-inertia systems. The existing LVFRT regulations have been analyzed and new LVFRT scheme has been proposed for maintaining the intensity of the voltage support while restricting the active power imbalance introduced by the LVFRT support that can trigger a frequency disturbance. A benchmarking analysis is performed demonstrating that the proposed scheme presents an outstanding performance since it can provide an intense voltage support with minimum reduction on active power which is beneficial for the frequency stability. Hence the proposed support scheme is adequate for low-inertia and inverter-dominated power systems, and it can be considered for updating the grid regulations in such systems.

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