Assessing the Impact of Primary Frequency Support from IBRs in Low Inertia Isolated Power Systems

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***Abstract*—The anticipated massive penetration of Renewable Energy Sources (RES) will significantly impact the operation of electric power systems. The effect will be more prominent on low-inertia, isolated, power systems. Modern grid code requirements can be used to ensure that RES will remain connected to the system during abnormal or transient operating conditions and provide support. In this paper, the Cyprus transmission system is used to evaluate the impact of primary frequency support (PFS) from Inverter-Based Resources (IBRs), both during low- and high-loading conditions. A sensitivity analysis of the major parameters of PFS has been performed to evaluate their impact on the frequency response in low inertia conditions. It is demonstrated that PFS provided by IBRs during low loading conditions positively affects the power system frequency stability without any additional curtailments. During high-loading conditions, PFS from RES also improves the system performance, however, significant RES curtailments from the IBGs participating in PFS are required which may raise fairness concerns.**

***Index Terms*—primary frequency control; minimum stable generation limit; frequency stability; islanded systems; low-inertia systems.**

I. Introduction

Massive amounts of Renewable Energy Sources (RES) will be installed in the following years in power systems worldwide to achieve the goals for decarbonization and the reduction of dependence on fossil fuels. Most of RES are connected to the grid via power electronics and therefore are considered as Inverter-Based Resources (IBRs). The massive RES penetration affects significantly, and in most cases adversely, the power system operation. In most cases, the system inertia and short-circuit levels are reduced as large conventional power plants, are decommissioned and replaced by IBRs. The inertia reduction has an immediate negative impact on the frequency stability, while the short-circuit levels reduction affects the performance of the grid-following inverters and the operation of protection schemes [1]. Therefore, low inertia systems will soon face unprecedented challenges during normal and emergency conditions [2].

As a result, the power system structure and principles of operation require significant reforms to ensure that the system will continue to operate within the security limits. Many solutions have been promoted over the years, including the use of Energy Storage Systems (ESS), employing flexible generation units with increased capabilities, extracting flexibility from existing resources, establishing interconnections with other power systems, and moving towards Advanced Grid Code Requirements (AGCR). Based on the European Commission's directive 944/2019, System Operators (SOs) are not allowed to own or operate ESS [3]. In addition, there is a lack of investments in conventional generator units due to their increased capital cost, and the given priority to 'green generation'. Consequently, revising the National Grid Codes and implementing AGCRs is by far the most economical and applicable solution to the SOs for the provision of support to the system during emergency conditions.

AGCRs must ensure that RES remain connected during emergency conditions and at the same time provide support to the system. The former is ensured via Fault Ride Through requirements (e.g., Low or High Voltage Right Through (L/HVRT), Frequency Ride Through, ROCOF immunity, etc.) while the latter can be provided either by active or reactive power support as a response to abnormal frequency or voltage variations. The impact of L/HVRT and reactive power support during low-voltage conditions on the system frequency has been evaluated in [4].

One of the main support functions imposed on IBRs by AGCRs is Primary Frequency Support (PFS). PFS employs active power control during under- and over-frequency events. Over-frequency active power reduction functionality helps the system frequency to remain contained within nominal limits and its impact on the stability of islanded power systems was demonstrated in [5]. Contrary, PFS during under-frequency events requires an increase in active power output. In order to achieve this, RES are required to operate below their maximum power point output to allow headroom for providing frequency containment reserves (FCR) to the system. This functionality is not widely applied yet, since it requires constant RES curtailments, which will inevitably affect RES penetration and loss of income [6].

In [7] the impact of Photovoltaic (PV) systems de-loading on the isolated power system of northern Chile was investigated. It was found that for small de-loadings up to 5%, the effect on system stability was relatively small for penetration scenarios up to 20%. Also, in [8] the provision of ancillary services from different distributed energy sources has been examined. It was demonstrated in a simplified test system that DERs can provide different ancillary services to the system. However, in low inertia isolated systems, RES

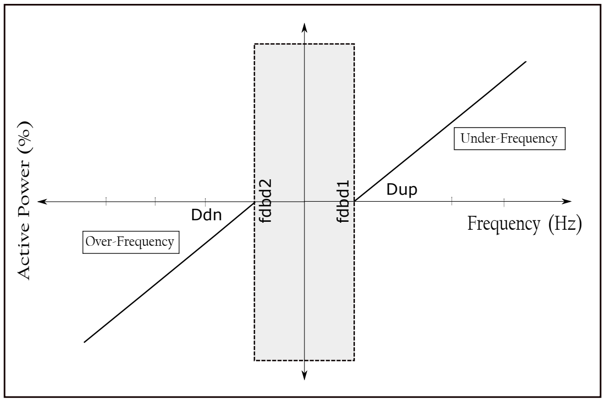

Fig. 1. Primary Frequency Support from IBGs droop characteristic

curtailments can be performed also due to excess generation from RES [9] (further discussion in Section II). Therefore, the system performance can be enhanced if PFS is applied in such systems without significant loss of RES generation.

The contributions of this paper are: 1) propose the combination of curtailment solutions due to MSGL with PFS to enhance frequency stability of low-inertia grids at a reduced overall cost; and, 2) assess the amount of IBRs participating in PFS on fairness and system performance.

The analysis has been performed on the detailed Cyprus transmission system model. More specifically, the frequency stability is assessed by applying disturbances to the transmission system while performing sensitivity analysis on the amount of RES curtailed, the upward ramp-rate capabilities of the IBRs, and the number of IBRs participating in PFS. It is shown that PFS from RES has a beneficial effect on the system frequency stability *without additional RES curtailments*.

The rest of the paper is organized as follows. In Section II, the background is presented. In Section III, the Case Study is described while in Section IV, a sensitivity analysis is performed on the RES curtailments, the IBRs capabilities, the amount of IBRs participating in PFS, and the event critically. In each analysis, the frequency stability of the power system is evaluated. Finally, Section V summarizes the main conclusions.

II. Background: Primary Frequency Support and Minimum Stable Generation Limit

AGCRs impose several capabilities and protection mechanisms on IBRs. It should be mentioned that, in this paper, only the effect of PFS is evaluated while the IBRs are considered to remain connected to the grid. Each IBR estimates its frequency from local measurements at the point of connection. A droop characteristic is be applied to the IBRs, and when the frequency is below fdbd1 (see Fig. 1) the unit has to start increasing its active power output with a constant rate of increase (Dup) as presented in Fig. 1. In this study, IBRs are de-loaded based on the percentage scheme in which IBRs reserve a constant percentage of their maximum active power output [10]. In addition, in over-frequency conditions (above

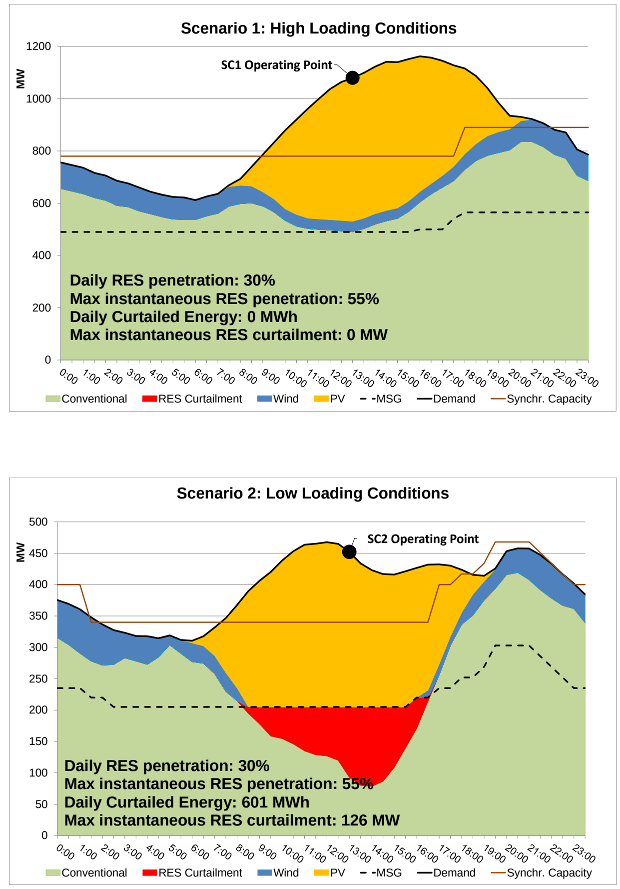

Fig. 2. Representative daily operation of the system during high- and low-loading conditions used for the scenario selection

fdbd2) IBRs must reduce their active power output with a droop (Ddn) according to the measured system frequency.

In the majority of power systems, active power support by IBRs during emergencies is not used, since it requires a noticeable amount of RES curtailments to create the headroom required for upwards regulation. However, in some isolated low-inertia systems, RES curtailments are already occurring due to system limitations related to inertia requirements. In the Cyprus power system, the energy produced from RES is curtailed during low-demand periods. This occurs because of the requirement of the Transmission System Operator of Cyprus (TSOC), which requires that at all times at least 4 synchronous generators must be online to comply with the minimum stable generation limit (MSGL) [9]. RES curtailments occur when the net load of the system (a demand satisfied only by conventional generation) reaches the MSGL, as shown in Fig. 2. This situation is more prominent during the months of spring and autumn, where cooling and heating requirements are minimized. Approximately 3% of the total energy generated from RES has been curtailed in 2022, and is expected to increase to 7% in 2023 [9].

TABLE I
SCENARIOS DESCRIPTION

SCENARIO	SC1 (RES 55%)		SC2 (RES 55%)	
Demand	**1093 MW**		**438 MW**	
Generation	**UC**	**ED**	**UC**	**ED**
VPS ST	3X120	180	2x120	120
DPS ST	2X60	60	2X60	70
CCGT	2X220	263	N/A	N/A
RES	N/A	590	N/A	248
RES Curtailments	**0**		**126 MW**	
$E_{kin,sys}$ [MWs]	**7054**		**3217**	

TABLE II
WECC DER MODEL - FREQUENCY RELATED PARAMETERS AND VALUES

Functionality	Parameter	Value
Under Frequency Protection	FL	47.5 Hz
Over Frequency Protection	FH	51 Hz
PFS	fdbd1	49,8 Hz
PFS	fdbd2	50,2 Hz
PFS	Droop (Ddn)	20 %
PFS	Droop (Dup)	20 %

III. CYPRUS CASE STUDY

For assessing the impact of PFS from IBRs on the power system frequency stability of low-inertia isolated systems, the power system of Cyprus has been utilized. All simulations have been performed using the power system analysis software DIgSILENT PowerFactory (Version 2022 SP4) [11].

A. Cyprus Power System Model

The power system of Cyprus is an isolated 50 Hz low inertia system. The nominal operating voltages of the transmission system are 132kV and 66kV. Currently, there are three conventional power plants Vasilikos (VPS), Dhekelia (DPS) and Moni (MPS) in operation with a total installed capacity of 1480MW. The available generators are steam turbines (ST), combined cycle gas turbines (CCGT), gas turbines (GT) , and internal combustion engines (ICE). The installed capacity of PV Systems is 389 MW and 158 MW wind power plants (WPP) [12].

B. Operating Conditions

A high and a low operating scenarios of the Cyprus power system with both 30% daily and 55% instantaneous maximum RES penetrations have been applied for the analysis. The unit commitment (UC), the economic dispatch (ED) and the total kinetic energy of the system ($E_{kin,sys}$) for the two scenarios are shown in Table I.

- **SC1**: High-loading conditions (Fig. 2, above)
- **SC2**: Low-loading conditions with RES curtailments due to MSGL (Fig. 2, below)

C. Inverter Based Resources Modelling

The WECC DER model (available in DIgSILENT PowerFactory) was used for the modeling IBRs connected in both Transmission and Distribution systems. This model has implemented all the major grid code requirements [13]. The frequency-related parameters applied to the IBRs models are presented in Table II based on the requirements of Fig. 1.

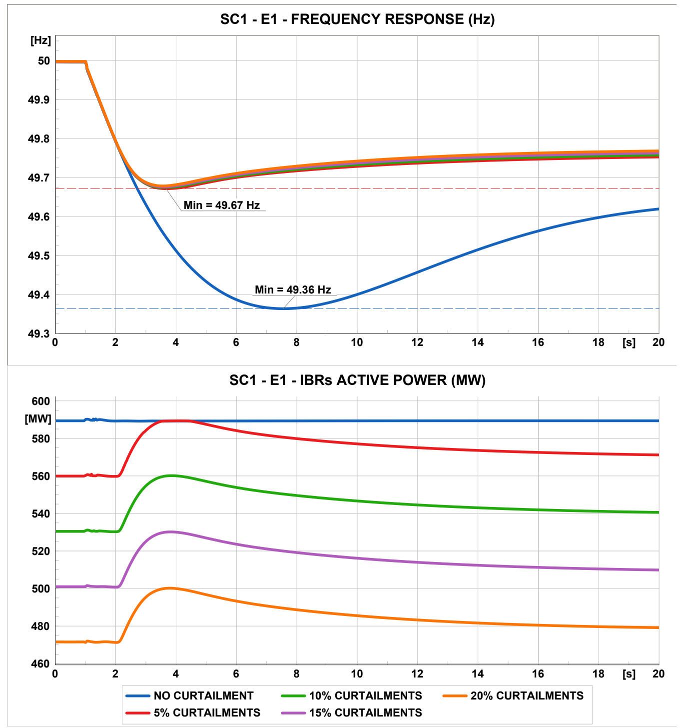

Fig. 3. SC1 - E1 - Frequency response and active power support from IBGs with constant Dup 20%

D. Event Description

In this study, the following two events have been simulated until $t = 20$s:

- **E1**: Loss of a large ST generator at VPS at $t = 1$s
- **E2**: Same as E1 with the cascading loss of an identical large ST at VPS with $\Delta T = 1.5$s after E1

IV. ANALYSIS

A. Impact of RES curtailments

Initially, a sensitivity analysis was performed on the percentage of RES curtailed, to provide PFS against the impact they have on the power system frequency stability for scenario SC1. As it can be seen in Fig. 3, there is a noticeable impact from the PFS provided by the curtailed RES on the frequency response after event E1. It can be seen that in this particular scenario, only the 5% curtailment leads to exhausting all the available PFS power during the event. In the other curtailment percentages, the system frequency restores within the nominal limits before the available power is injected into the grid. Therefore, we have concluded that RES curtailments of approximately 5% are adequate for providing the FCR to the system, under these operating conditions and events.

Nevertheless, these RES energy curtailments are significant if they are constantly applied throughout the day. The daily energy curtailed from RES based on the representative days of Fig. 2 varies from 193 MWh to 771 MWh depending on the

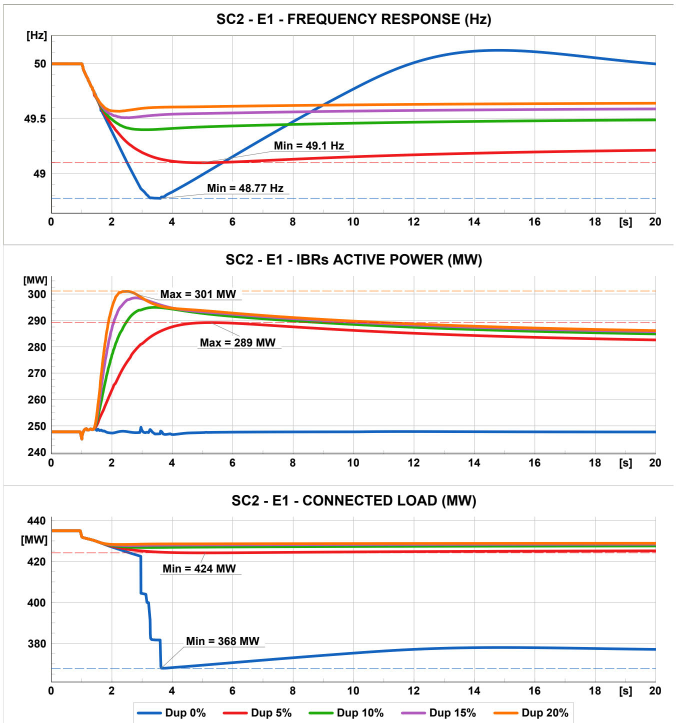

Fig. 4. SC2 - E1 - Frequency response, active power support from IBRs and connected load with varying Dup

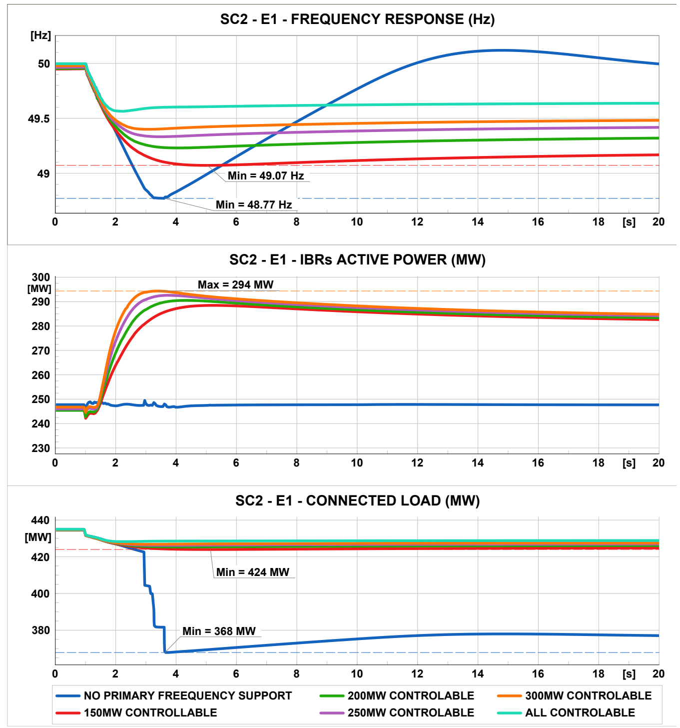

Fig. 5. SC2 - E1 - Impact of the number of IBGs participating in PFS on power system frequency stability

curtailment percentage (5%-20%). It should be noted, that the performance of the system even without the support from IBRs is adequate. Therefore during high-loading conditions, such as in SC1, a compromise between RES energy curtailed and system dynamic performance has to be made by the TSOC.

B. Impact of IBRs Ramp Rate Capabilities

For this analysis, the RES curtailment is kept to 30% (which is the amount of RES already curtailed due to MSGL requirement), while a sensitivity analysis on the IBRs' upward ramp rate capabilities (Dup) for scenario SC2 has been performed. Since in this scenario RES are already curtailed due to MSGL requirements (see Fig. 2), additional curtailment has not been applied. As shown in Fig. 4, when Dup is 0% (that is, no PFS) the system needs to resort to load-shedding, as dictated by the Under-Frequency Load Shedding (UFLS) scheme employed by TSOC to maintain the frequency to the acceptable range. For Dup>0%, the PFS from IBGs is beneficial for the system operation. The frequency response of the system has a noticeable improvement in both nadir and rate of change of frequency (RoCoF), especially for higher Dup values. As a result, load shedding is avoided for all scenarios with PFS.

C. Impact of the Amount of IBRs Participating in PFS

The results of the previous analysis have assumed that all IBRs participate in PFS. However, this is not true, especially for small-size IBRs. Therefore, the analysis of Subsection IV-B has been repeated with a constant Dup of 20%, 30% RES curtailments, and with varying the amount of IBRs participating in PFS.

As it can be observed, in Fig. 5, the amount of the IBRs participating in PFS through curtailment has a noticeable effect on the system's response. The active power support from IBRs is reducing while the percentage of IBRs participating in PFS (Participation Factor (PF)) reduces, despite the fact that the same amount of active power is curtailed and thus is available for PFS. This is due to the fact that the total ramp rate capabilities of the IBRs are lower when the number of participating IBRs is reduced. However, in any case, the performance of the frequency stability of the system has been enhanced and load shedding is avoided. It should be mentioned that the amount of RES curtailments cannot descend below a certain limit (126MW in SC2) in order to satisfy the MSGL requirement.

The amount of IBRs that participate in PFS affects significantly how curtailments are distributed among the RES producers. As the amount of IBRs participating in PFS increases, the curtailment factor (CF) is reduced, since the total required curtailments are distributed by more IBRs. This is demonstrated in Table III.

D. Impact of Event Criticality

Furthermore, the performance of the power system has been evaluated during the cascading event E2. The applied settings for the IBRs were 10% RES curtailments and 20% Dup for SC1. For SC2 additional RES curtailments were unnecessary

TABLE III
RES CURTAILMENTS DISTRIBUTION

IBGs Participating in PFS	PF	CF
150MW	40,1%	84%
200MW	53,4%	63%
250MW	66,8%	50,4%
300MW	80,2%	42%

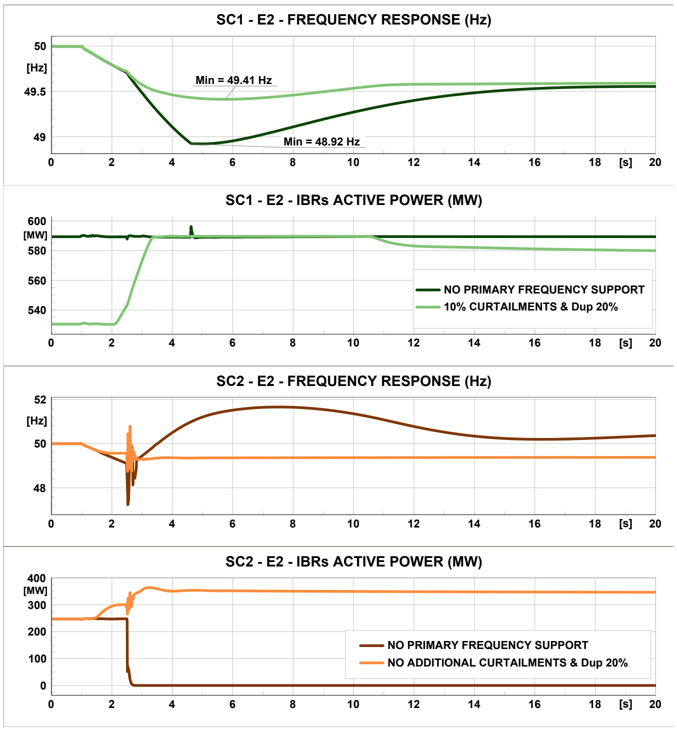

Fig. 6. E2 - Impact of event criticality (SC1 and SC2)

since, already 30% of RES is being curtailed due to the MSGL requirement. From the results shown in Fig. 6, it can be concluded that PFS from IBRs provides vital support to the system. In SC1, all the available 60MW PFS from IBRs are injected into the grid during the event.

In SC2, it can be observed that without the active power response, the frequency deviation leads to the disconnection of all IBRs due to under-frequency protection, and as a result, the system's UFLS is triggered to restore the frequency. This leads to an undesirable situation where all IBRs had been tripped and the majority of the load had been disconnected. The significant amount of load disconnected, in combination with the increased ramp rate capabilities of the two synchronised ST generators in DPS, forced the system frequency above 50 Hz. On the contrary, when the IBR PFS is activated, the frequency excursion is constrained and all IBRs remain connected to the grid, thus providing an additional 126MW. The UFLS scheme is not triggered and all the load is served. It should be noted that the analysis has been performed with all IBRs providing PFS. In the scenarios with equal or less than 300MW of IBRs providing PFS, the system behaviour follows that of no PFS.

V. CONCLUSIONS

In this paper, the impact of PFS from IBRs on low-inertia, isolated power systems has been assessed. It has been demonstrated that PFS from IBRs can improve the dynamic performance of the frequency response at the cost of large amounts of RES curtailments during high-loading conditions. Thus, during high inertia conditions, PFS provided through the curtailment of RES can be avoided if the system stability is maintained.

At the same time, during low-loading conditions, where RES curtailments are already occurring due to the MSGL, PFS is extremely beneficial, as no additional RES curtailments are required. It is important to state that in both scenarios the maximum instantaneous RES penetration is the same, thus, the system inertia should be taken into consideration for PFS provision from IBRs.

Moreover, the percentage of IBRs participating in PFS has a noticeable impact on the distribution of RES curtailments among the producers. Consequently, system operators in low-inertia, isolated, power systems should try to introduce a notion of fairness either through appropriate compensation, or widespread use of this technique. In this manner, the distribution of the RES curtailments will be fairer and the frequency response of the system will be improved.

VI. ACKNOWLEDGMENT

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