Impact of Fast Frequency Response on Renewable Energy Source Curtailment and Load Shedding

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Abstract

System operators in low-inertia power systems often have to curtail renewable energy sources (RES) and employ strict under-frequency load shedding (UFLS) schemes to ensure frequency security after an event leading to loss of generation. This approach limits the maximum RES penetration in a system and results to the loss of load. To tackle these problems, fast frequency response (FFR) schemes can be used to limit the frequency Nadir after a disturbance and decrease the need for RES curtailments and UFLS. This article provides insights on the interaction between the Kinetic Energy (KE), Frequency Containment Reserves (FCR), and Nadir after a disturbance, which are the driving mechanisms leading to RES curtailment. Then, it analyses the impact of FFR on the Nadir and its ability to alleviate RES curtailment problems. The low-inertia, islanded, Cyprus dynamic model is used to quantify the results and showcase the impact on a real system.

1 Introduction

System operators in low-inertia power systems are often forced to curtail power generation from RES during low loading conditions to meet minimum requirements related to the system inertia and frequency support. At the same time, after a significant disturbance, UFLS schemes are often activated to ensure system frequency stability. Both actions are undesirable in power systems and affect the distribution system's reliability. It's important to note that inertia, is currently primarily provided by conventional generators. The main parameters that affect the above situations are the system inertia and Frequency Containment Reserves (FCR), which will be explained in more detail below.

Several methods have been proposed in the literature to use converter-based units for tackling these issues. In [1], the authors give a brief explanation of how inertia and FCR affect the lowest frequency value after a disturbance (Nadir). Moreover, they showcase several frequency control methods, like virtual synchronous machines, synthetic inertia control, and fast frequency control, to improve the system's frequency response after a fault. In [2], a methodology for sizing and placing distribution energy storage systems to improve the performance of distribution networks (DNs) is proposed. In [3], the authors focus on the use of FFR to increase the frequency stability of the system, emphasizing as main challenges the placement, capacity, and operating strategy.

In this article, we adopt the FFR operation mode proposed in [3] and proceed to analyse the impact it has on the system. In contrast with [2], which tries to minimize voltage deviation, power losses, and line loading, the current work focuses on the Nadir improvement to minimise the UFLS activation and the requirements for higher KE and FCR. The paper contributions are:

- Provide insights on the interaction between Inertia, FCR, and Nadir in low-inertia systems.
- Analyse the impact of FFR units on the reduction of lost load due to UFLS activation.

This paper is structured as follows: In Section 2, a brief explanation of frequency sensitivity analysis and FFR control strategy is given. Section 3 examines how the distribution system consumers are affected by frequency disturbance events and the impact of FFR on the reduction of lost load during these situations. Finally, conclusions are drawn in Section 4.

2 Frequency Response and Control

In this section, the significance of frequency reserves and their influence on the frequency response of a low-inertia power grid following a disturbance analysed. The frequency behaviour after the loss of significant generation is shown in Fig. 1a with the most important parameters being the initial Rate of Change of Frequency (RoCoF), the minimum frequency (Nadir), and the post-fault steady state frequency. The limits of all three parameters are strictly defined in system grid codes as they can significantly impact the system security and resilience.

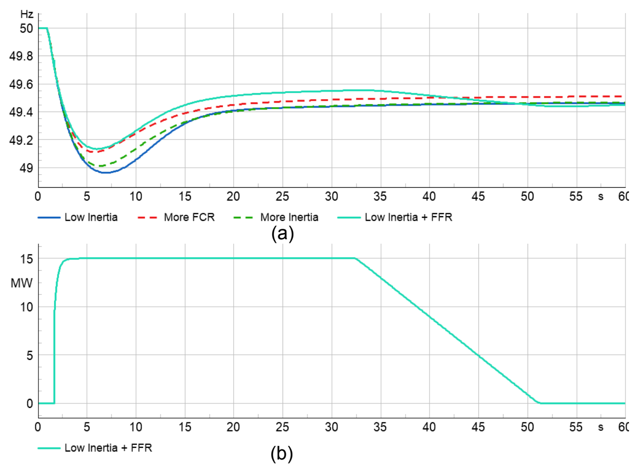

Figure 1: (a) Frequency response after loss of generation, and (b) FFR response

High RoCoF can lead to the disconnection of RESs in distribution grids and the loss of renewable generation, low

Nadir can trigger UFLS protection leading to prolonged disconnection of multiple feeders and the loss of both RES generation and customer consumption, and a low post-fault steady state frequency can lead to unwanted frequency stability events.

The frequency response is mainly impacted by the KE and the FCR available in the system immediately after the loss of generation. Their correlation and how they impact Nadir is investigated in Section 2.1 and an overview of the FFR control considered in this work in Section 2.2.

2.1 Correlation of FCR and KE with Nadir

FCR is activated in generators participating in this service to keep the frequency within predetermined levels by increasing/decreasing their power production according to a droop gain to match a sudden decrease/increase in power generation [4]. Since the majority of generators providing FCR today are conventional (synchronous-machine-based), the response time to stabilize the frequency is measured in seconds [5]. Thus, FCR significantly impacts the Nadir and the post-fault frequency steady state but has no impact on the RoCoF.

On the other hand, the KE refers to the energy stored in large rotating generators and certain industrial motors [6, 7]. It provides immediate response after the loss of generation by injecting power in response to the sudden frequency change. Due to the response speed (starting from few ms) and nature (proportional to RoCoF), it mainly affects RoCoF and Nadir but has no impact on the post-fault frequency steady state.

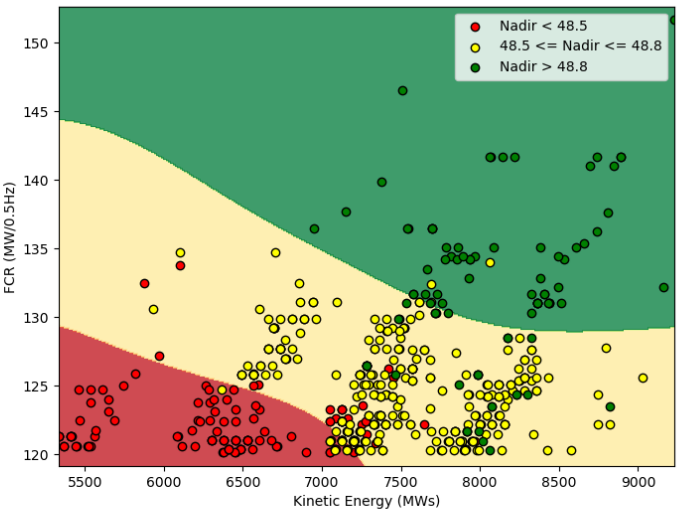

Figure 2: Overview of dynamic analysis of multiple operating points to the loss of largest infeed

Figure 2 shows the overview of a frequency analysis of an isolated power network (Cyprus system) at various operating points with different values of FCR and KE. The loss of the largest infeed is considered, and dynamic simulations are used to extract the system Nadir. The minimum FCR value is defined by the acceptable post-fault frequency steady state deviation and the largest infeed while the minimum KE is defined by the maximum acceptable RoCoF and the largest infeed [8]. The Support Vector Machine (SVM) classification technique with a radial basis function (RBF) kernel was used to separate the results based on the frequency Nadir.

From the figure, it can be seen that when a large percentage of conventional generators is operating in the system (low RES percentage), the high KE and FCR lead to high Nadir (green area) and, by extension, minimum to no activation of the UFLS protection after a disturbance. On the other hand, when a significant generation percentage is from RES (less committed conventional generators), the lower KE and FCR lead to lower Nadir values (yellow area). Thus, leading to activation of UFLS protection after a disturbance to ensure the security of the system.

Finally, during peak RES power generation periods, the power grid may need to operate with a minimum number of conventional generators, leading to low KE and FCR values and therefore unacceptable Nadir values (red area) and frequent UFLS activation. Since the red area is outside the acceptable operating limits defined by the grid code, system operators often curtail RES generation and re-dispatch conventional generators in their place to avoid this area of operation.

It should be noted that the FCR response time (speed of activation of units participating in FCR) is also a critical parameter that affects Nadir. As we can observe in Fig. 2, there are scenarios with larger KE and FCR that lead to lower Nadir (yellow dots in green area) than scenarios with lower KE and FCR (green dots in yellow area), and vice versa. Thus, a fast response time allows having higher values of Nadir with lower KE and FCR requirements. Thus, alleviated the need for RES curtailment to re-dispatch. This observation has led to the introduction of FFR schemes that try to bridge the speed of response between KE and FCR, allowing for higher values of Nadir with lower KE and FCR requirements and consequently lower RES curtailments and fewer UFLS activations.

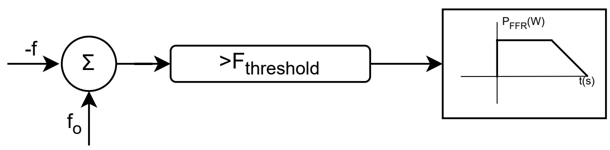

Figure 3: FFR controller used in this paper

2.2 FFR Implementation

As stated above, the FFR schemes provide a quick reserve during disturbances by injecting power into the power grid to reduce Nadir [4, 7]. The FFR response time is usually less than a second and has a support duration of several seconds (at least until the FCR is fully activated) [7]. Figure 3 shows the FFR controller that was used in this work, adapted from [6]. When the frequency decreases beyond a limit, the controller immediately activates the FFR power injection. After a period of time, the FFR controller gradually decreases the power output. The smooth deactivation is done to allow for the FCR controllers to take on the power change.

Figure 1a shows the frequency response after the loss of the same power generation in four different operating conditions. First, the solid blue line presents a low KE situation without FFR support. To overcome this unwanted event, operators can increase FCR (dashed red line) or increase KE (green dashed line). Both solutions are not desirable, as they usually require to curtail RES generation. On the other hand, adding FFR (light blue line) can achieve the desired results without curtailing RES generation. It is important to note that RoCoF and post-fault frequency steady state are not affected by the addition of FFR, confirming the non-replacement of minimum FCR and KE requirements. In the Fig. 1b, the FFR operation response for this scenario is presented.

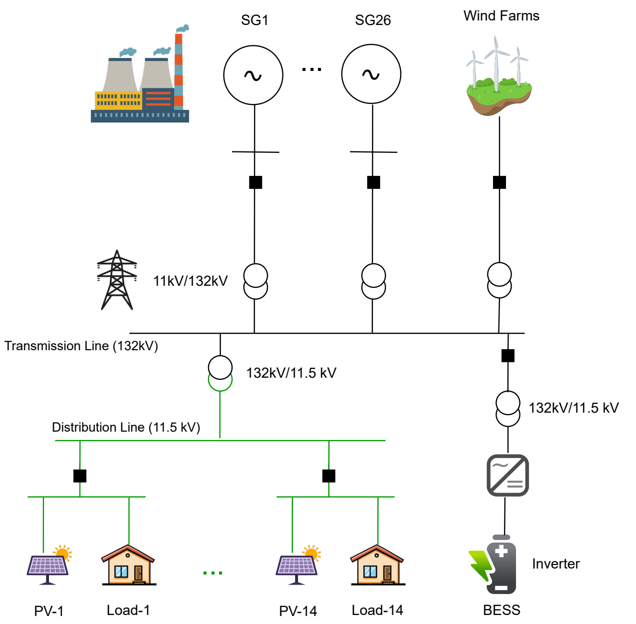

Figure 4: Simplified Cyprus system diagram

3 Impact of FFR on RES Curtailment and Lost Load

In this section, the Cyprus power system dynamic model is used to analyse the impact of FFR on frequency performance, the requirements for RES curtailments, and the UFLS leading to loss of RES generation and customer load.

Table 1: System parameters

Parameters	Value
Load power	700 MW
Power disturbance event	90 MW
Minimum FCR at 0.5 Hz	83 MW
Minimum post-fault KE	2250 MWs
Post-fault frequency steady state	49.5 Hz
FFR maximum activation time	0.8 s
FFR support duration	30 s
1^{st} UFLS stage	49 Hz
2^{nd} UFLS stage	48.9 Hz

3.1 Test System Description

The simplified Cyprus power system dynamic model is implemented in the DIgSILENT PowerFactory software and the investigation is automatised using Python. The system diagram is depicted in Fig. 4 and includes 26 generators, wind farms, 14 groups of aggregated PV generation and load consumption in the DN, and one Battery Energy Storage System (BESS) providing the FFR. The 14 PV and Load groups correspond to the 14 stages of the existing UFLS protection scheme, where, based on the frequency, protection is activated to disconnect the corresponding segment (including the load and distributed PV generation). The switch breakers are shown with a solid black square.

More information on the system generation can be found in [9] and in Table 1. The BESS dynamic model is provided by DIgSILENT PowerFactory [10] with the FFR control model shown in Fig. 3 implemented by the authors.

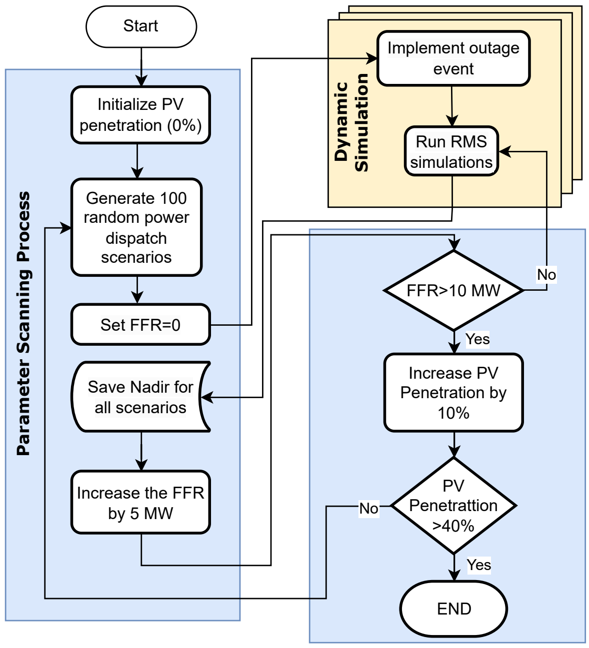

Figure 5: Flowchart of proposed investigation algorithm

3.2 Investigation algorithm

To evaluate the impact of RES penetration and FFR on the system frequency response and UFLS, the algorithm of Fig. 5 is used. First, PV penetration percentages of 0%, 10%, 20%, 30%, and 40% are considered and, for each penetration level, 100 different operating scenarios are generated with a load consumption of 700MW (the average load of system). For each scenario, the existence of a 0 MW, 5 MW, or 10 MW, BESS providing FFR is considered. Overall, 1500 scenarios are simulated with a disturbance event leading to the loss of 90MW generation. The selected power dispatch scenarios obey the minimum FCR and KE requirements of the system according to the grid code.

3.3 Results and Discussion

The results are summarised in Table 2, while a visualization in bar chart format is given in Figs. 6 and 7.

When FFR is not operating, as the RES penetration increases, the load shedding and PV curtailment increases as well. At 40% RES penetration with 0 MW FFR, an average of 5% of total load and PV (32.4 MW and 13.4 MW respectively) is disconnected after a disturbance. When 10 MW FFR operates in the system for the same scenarios, the disconnections are reduced to approximately an average of 1% of the total PV and load. Similar results are seen within each PV penetration level and across multiple levels.

Table 2: Summary of results over the 1500 scenarios

PV Penetration (%)	FFR (MW)	$Load_{\mathbf{shedding}}$ (MW)	$PV_{\mathbf{curtail}}$ (MW)
0	0	1.1	0
	5	0.5	0
	10	0.3	0
10	0	6.8	0.7
	5	3.6	0.4
	10	0.5	0.1
20	0	17.2	3.5
	5	8.6	1.7
	10	1.9	0.4
30	0	26.2	7.9
	5	12.5	3.8
	10	5.9	1.8
40	0	32.4	13.4
	5	20.9	8.4
	10	9.5	3.8

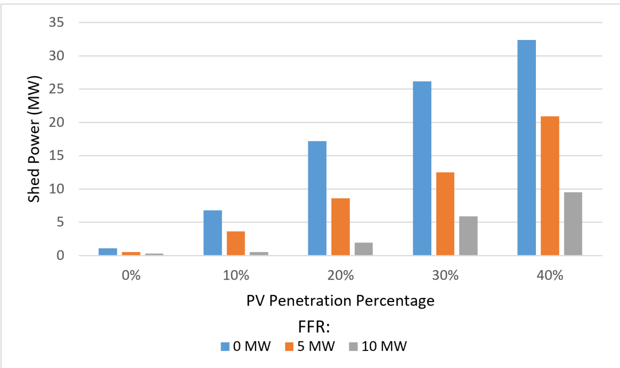

Figure 6: Load shedding results

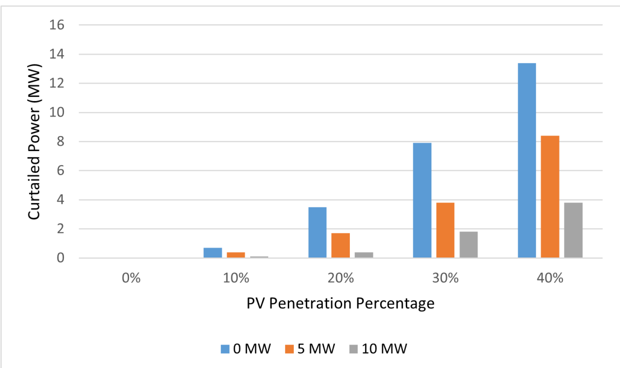

Figure 7: PV curtailment results

In the same way, the results confirm that instead of increasing FCR and KE (leading to PV generation curtailment and conventional generation re-dispatching), it is possible to use FFR for reducing UFLS activation during high PV production periods. Alternatively, the same insights can be used to further increase the acceptable RES generation limits by employing FFR, where the minimum requirements of KE for RoCoF and FCR for post-fault frequency steady-state are met and Nadir is the limiting factor.

4 Conclusion

This paper provides insights on the correlation between FCR, KE, and Nadir in low-inertia power systems and how they affect the loss of PV generation (through curtailments or UFLS) and load (through UFLS). The use of FFR to mitigate these problems and allow for higher RES penetration levels is investigated and the results are showcased using the simplified dynamic model of the Cyprus islanded system.

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