Impact of Distributed Energy Resources Capabilities and Protections on Islanded Power System Frequency Stability

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***Abstract*—The massive penetration of Distributed Energy Resources (DERs) will unavoidably change the fundamental principles of Power System operation. Modern grid codes define specific capabilities and protections of DERs, mostly focused on the behaviour of the units to abrupt voltage and frequency excursions. In this paper, we use the Cyprus power system to analyze the impact of DER protections and capabilities on the bulk power system dynamic behaviour for different RES penetration levels on a low-inertia islanded system. It is demonstrated that the DER capabilities positively affect the power system frequency stability by providing active power support. On the contrary, protection mechanisms of DERs can have a negative impact on frequency stability during severe events with high RES penetrations, but the impact is significantly affected by their settings.**

***Index Terms*—grid code requirements; protections; capabilities; frequency stability; islanded systems; low-inertia system.**

I. INTRODUCTION

Europe is aiming to become the first carbon-neutral and climate-resilient continent by 2050. To achieve this, the European Commission recently published ”Fit for 55 package” [1], which is a set of proposals to revise the EU legislation and achieve its raised 2030 target of at least 55% greenhouse gas emission reduction compared to 1990 [1]. As a result, massive penetration of Distributed Energy Resources (DERs) is expected, including Renewable Energy Sources (RES), Electric Vehicles (EVs), Battery Energy Storage (BES) units, and Flexible Loads (FLs). The aforementioned DERs will inevitably modify the traditional power system fundamental principles. At the same time, conventional synchronous-machine-based power plants are being decommissioned, leading to significantly reduced short-circuit levels and inertia. The latter affects the frequency stability of the power system, while the former has an explicit effect on the fault-ride-through performance of Converter Interfaced Generators (CIGs) [2].

Recent grid codes define specific operations from DERs during disturbances, that could affect the overall power system stability [3]. The impact of Distributed Generator (DG) under-voltage protection on bulk power system voltage stability has been evaluated in [4]. It has been shown that the disconnection of DGs after a voltage event can cause voltage instability. In addition, they examined how the under-voltage protection settings (pick-up value and time delay) can be adjusted to avoid the DG disconnection. Also, in [4] it was found that the lack of frequency ride-through capabilities of distributed photovoltaic systems (PVs) can have a noticeable impact on the frequency response of the system due to the disconnection of large number of PVs, especially in low-inertia islanded power systems.

In [5], it was presented that the Rate Of Change Of Frequency (RoCoF) protection, over-/under-frequency protections, frequency and voltage control by means of active power, RoCoF immunity, and low-/high-voltage ride-through (L/HVRT) capabilities, have to be carefully modelled for frequency deviation phenomena, but their impact on power system frequency stability has not been investigated.

In [6], the LVRT capability was included in the evaluation of the impact of PV penetration on the bulk system stability. However, the paper was mainly focusing on combined Transmission-Distribution dynamic co-simulation methods. Similarly, in [7], the impact of fault ride-through (FRT) and reactive power support strategies during faults have being examined using a generic aggregated distribution network model consisting of various voltage levels.

The impact of Loss-of-Mains (LoMs) protection mechanisms has been demonstrated during the events of 9th August 2019 in the UK [8]. During these events, approximately 500 MW of DGs tripped due to LoMs protection, causing the disconnection of more than 1 million customers [8].

The contributions of this paper are twofold: 1) to evaluate the impact of DERs Grid Code Requirements (GCR) on the frequency stability of low-inertia islanded systems, and 2) to examine the importance of accurately modelling unit protection on frequency response. For the analysis, the islanded transmission system of Cyprus was modelled in detail. Afterwards, possible disturbances have been applied to the transmission system and its frequency response was evaluated with and without the major GCR.

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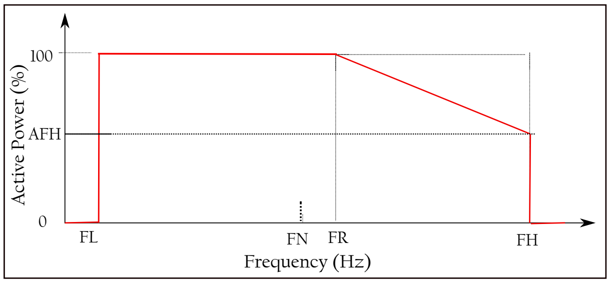


Fig. 1. Under-/Over-frequency protection and active power reduction during over-frequency conditions

The rest of the paper is organized as follows. In Section II, a comprehensive review concerning the primary grid code protection and capabilities requirements is performed. In Section III, the Case Study is described while in Section IV, the impact of DERs capabilities and protection mechanisms on frequency stability is evaluated for different scenarios. Finally, Section V summarizes the main findings and insights.

II. GRID CODE PROTECTION REQUIREMENTS AND CAPABILITIES

Modern grid codes require several protection mechanisms and capabilities from DERs. In this work, only capabilities that can have an effect on power system frequency stability are considered. Generally, GCRs that can impact the system frequency stability can be divided into three main categories: i) Frequency protection and capabilities; ii) Loss of Mains protection; and iii) Voltage protection and capabilities.

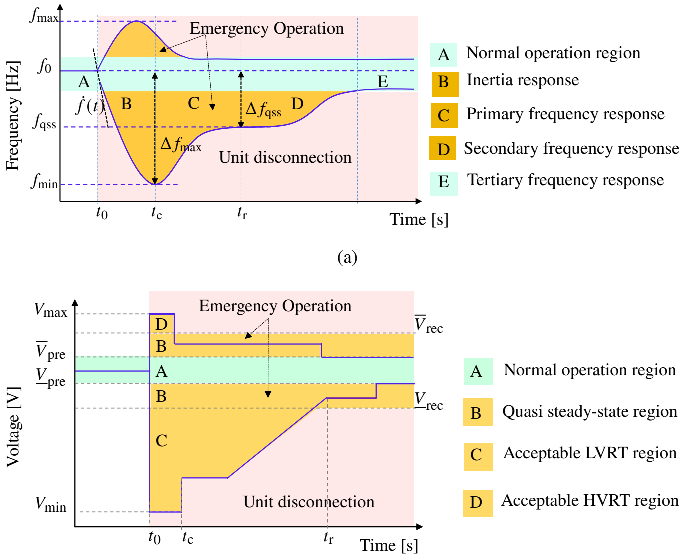
A. *Frequency Protection and Support*

Most common frequency related protections is the under-/over-frequency, that requires the disconnection of DERs when frequency is not within the predefined limit. As shown in Fig. 1, when frequency is above FH or bellow FL the DER unit disconnects.

In most modern GCRs, in over-frequency conditions (above FR) DERs must reduce the active power output according to the system frequency to provide support. Additionally, some grid codes may require active power support from DERs during under-frequency events [9]. Currently, this is not very common in practice, especially for RES, because it requires storage or to operate constantly bellow maximum active power output, thus resulting in reduced generation and loss of income.

B. *Loss of Mains Protection*

Formation of an unintentional islanding poses several dangers for personnel, users and the network. Therefore, an essential protection GCR is LoMs or anti-islanding protection. It ensures that DERs will be disconnected when an island is detected. There are several methods used to detect the islanding classified as passive, active, hybrid and remote [10]. Passive methods are relatively accurate and have short detection time and thus dominate the industry practice. Examples of passive detection methods are RoCoF (see $\dot{f}(t)$ in Fig. 2a) and Voltage Vector shift. RoCoF LoM protection is employed in many systems worldwide, including Cyprus [10], and is thus used in this work.



(a)

(b)

Fig. 2. DER frequency (a) and voltage (b) FRT profile and support regions with grid fault occurring at time t_0.

C. *Voltage Protection and Support*

Under-/over-voltage protection disconnects the DERs when voltage is not within predefined limits. At the same time, LVRT capabilities (Fig. 2b) ensure that DERs will remain connected to the grid while voltage is above the LVRT curve. Similarly, DERs must remain connected while voltage is bellow the HVRT capability curve (Fig. 2b). There are several different types of LVRT and HVRT capability curves depending on the system operator needs with different minimum and maximum values.

In most modern GCRs, DERs must provide reactive power support both in steady-state and during transients. The reactive power management is proportional to the magnitude of the voltage change. While voltage is within Low Voltage DeadBand (LVDB), and High Voltage DeadBand (HVDB), DERs should provide reactive power according to GCR during steady state conditions [4].

III. CASE STUDY

For evaluating the impact of DER capabilities and protection mechanisms on power system frequency stability, the islanded Cyprus system has been modelled. All simulations have been performed using the DIgSILENT PowerFactory simulation software [11].

A. *Power System of Cyprus*

The Cypriot transmission system was modeled in detailed with data provided by Cyprus Transmission System Operator (TSOC). This is a small (60 transmission substations) and

TABLE I
PENETRATION SCENARIOS DESCRIPTION

SCENARIO	**P1 (RES 20%)**		**P2 (RES 30%)**		**P3 (RES 40%)**	
Generation [MW]	**UC**	**ED**	**UC**	**ED**	**UC**	**ED**
ST	4X60	180	3X60	124	3X60	120
GT	1x37.5	32	-	0	-	0
CCGT	2X220	334	2X220	334	2X110	234
ICE	4X16.7	64	2X16.7	32	1X16.7	16
PV	N/A	200	N/A	300	N/A	400
WPP	N/A	40	N/A	60	N/A	80
$E_{kin,sys}$ [MWs]	**9075**		**8150**		**7163**	

TABLE II
WECC DER MODEL PARAMETERS AND VALUES

Functionality	**Parameter**	**Value**
Frequency (Fig. 1)	FL	48.8 Hz
Frequency (Fig. 1)	FH	51 Hz
Frequency (Fig. 1)	FR	50.2 Hz
Frequency (Fig. 1)	Droop	5 %
Reactive Support	LVDB	0.9 p.u
Reactive Support	HVDB	1.1 p.u
Reactive Support	Droop	4 %
Q(V)	Upper Deadband	1.03 p.u
Q(V)	Lower Deadband	0.97 p.u
Q(V)	Droop	4 %

islanded system with nominal voltages 132 kV and 66 kV and frequency 50 Hz. There are currently three major conventional power plants with total installed capacity of 1478 MW, which includes 750 MW steam turbines (ST), 440 MW combined cycle gas turbines (CCGT), 188 MW gas turbines (GT) and 100 MW internal combustion engines (ICE). The total RES penetration, computed as the energy generated by RES over the total electricity demand of the island, is approximately 20%. The RES installed capacity is 260 MW PV systems and 158 MW wind power plants (WPP) [12].

B. Operating Conditions

The operating conditions from the historically highest demand has been used as reference. This refers to a total demand of 1200 MW (occurred in August 2021) with 20% RES penetration and is presented in Penetration Scenario 1 (P1). Penetration Scenarios 2 and 3 (P2 & P3) correspond to future energy scenario predictions defined by the TSOC with 30% and 40% penetration, respectively. Table I shows the Unit Commitment (UC) and Economic Dispatch (ED) solutions for each scenario, along with the total kinetic energy of the system ($E_{kin,sys}$). It can be seen that with higher penetration levels, the total available kinetic energy decreases.

C. Distributed Energy Resources Modelling

The well-known WECC generic models for PV and Type-4 WPP have been used for this study [13]. First, all the support capabilities of the models were deactivated. Then, a percentage of the installed DER units provided support according to the parameters represented in Table II. The different percentage of DERs providing support defines the five case studies of Table III.

TABLE III
MODELLING PENETRATION DESCRIPTION

Case Study	**% of DERs equiped with Table II Capabilities**
1	0
2	20
3	50
4	65
5	100

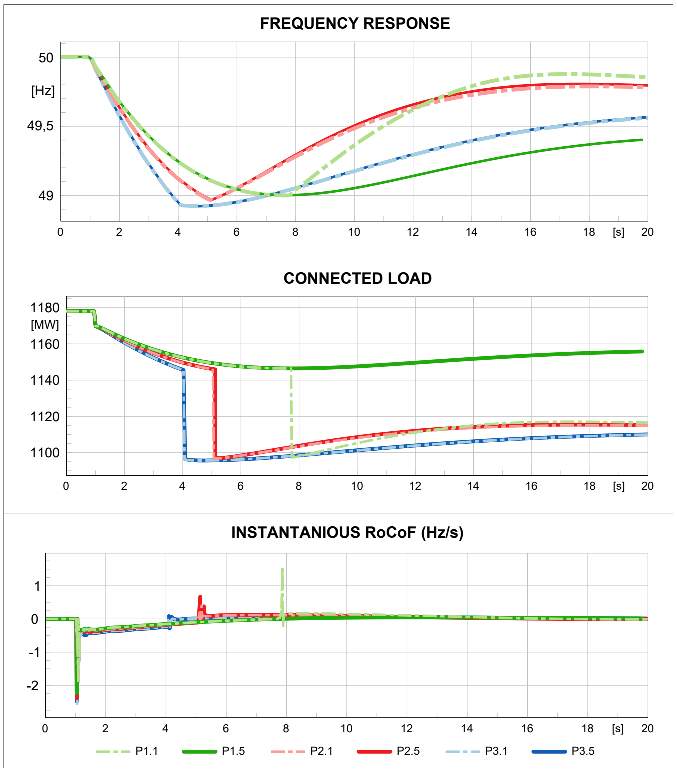


Fig. 3. P1,P2,P3 - Event 1 - Frequency response

D. Events Analyzed

Two different frequency-related events have been used in this study, as described bellow.

1) Event 1 (E1): In this event, the loss of a large generator is simulated by disconnecting a ST with 120MW active power output at t=1s. The system is then simulated until t=20s.

2) Event 2 (E2): In this event, a cascaded loss is simulated after E1. That is, a ST with 120MW active power output is disconnected at t=1s followed by a second identical ST disconnecting at t=1.5s at the same location. The system is then simulated until t=20s.

IV. RESULTS

In the following section, the case studies are referred to with the convention *Px.y*, where $x \in [1, 3]$ defines the penetration level according to Table I, while $y \in [1, 5]$ defines the DER modelling assumptions according to Table III.

A. Impact of DER Capabilities

Initially, the effect of DERs capabilities on the power system frequency stability has been evaluated without taking into

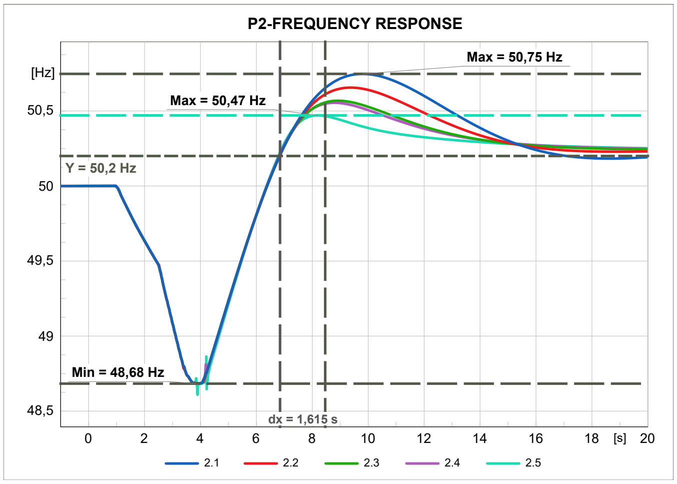


Fig. 4. P2 - Event 2 - Frequency and total DERs active power response

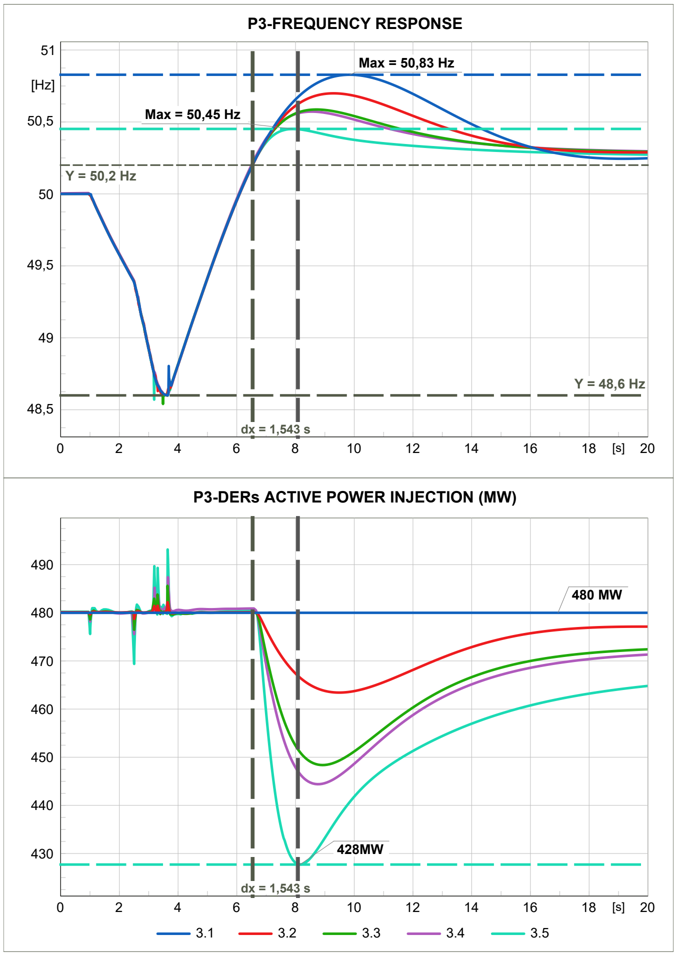


Fig. 5. P3 - Event 2 - Frequency and total DERs active power response

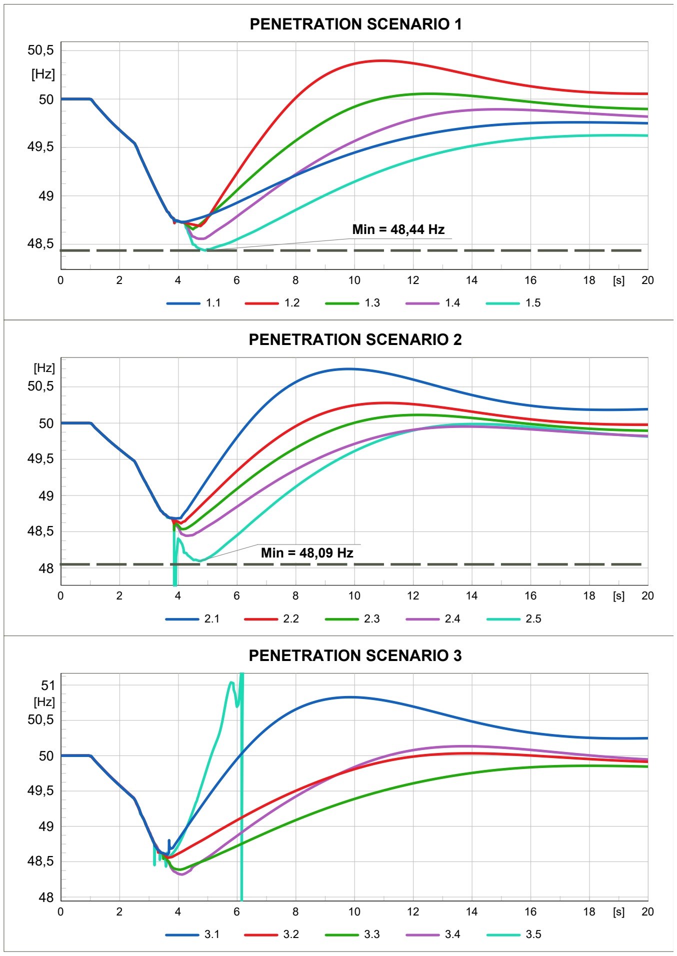


Fig. 6. P1,P2,P3 - Event 2 - Frequency response with DERs equipped with Under-/Over-Frequency Protection

consideration LOMs and Under-/Over-frequency protection mechanisms. Figure 3 shows the system response when E1 is analyzed. For P2 and P3, the results with and without DERs capabilities are almost identical. However, for P1, the lack of support (P1.1) leads to an activation of the UFLS while with all DERs providing support (P1.5) the same is not true. Also, as expected it can be seen that while RES penetration increases, frequency nadir reduces, RoCoF increases, and the activation of UFLS activation is certain.

Concerning E2, Figs. 4 and 5 show that the impact of DERs capabilities is significant for the penetration scenarios P2 (30%) and P3 (40%), respectively. In Fig. 4, it can be observed that the frequency response when DERs provide support is different compared to the initial case (P2.1) after t=6.4s. As the percentage of the DERs providing support increases, the frequency overshoot reduces due to the frequency support provided by the DERs (see Fig. 1). This effect is more evident in Fig. 5, showing also the corresponding DER power reduction during the over-frequency. It should be noted that the UFLS activations lead the frequency to stabilize above the nominal value.

B. *Impact of DER Protection Mechanisms*

In this subsection, the impact of the DER unit protection mechanisms on the power system frequency stability has been assessed.

1) Impact of Under-/Over-Frequency Protection: The analysis of Section IV-A were repeated with the DER sup-

TABLE IV
P3 - EVENT 2 - LOMS PROTECTION

Case Study & LoMs Settings	Frequency Nadir (Hz)	Time Nadir (s)	Frequency Zenith (Hz)	DER Disc. (MW)
P3.1-N/A	48.61	3.52	50.83	0
P3.5-1Hz/s	N/A	N/A	N/A	480
P3.5-1Hz/s + 0.1s	48.53	3.7	50.38	45
P3.5-1.5Hz/s	48.61	3.52	50.45	0

port capabilities (presented in Table II) and the under-/over-frequency protection modelled (without the LoMs protection). The results are presented in Fig. 6. It can be clearly seen that under-frequency (U/F) protection has significant impact in all penetration scenarios. All DERs modelled with the capabilities and the U/F protection have been disconnected which had caused further deterioration of frequency response. Emphasis should be given to the results for P3.5 where the stability of the system is lost. This is of paramount importance since, in the scenarios where U/F protection is not modelled the stability of the system is always maintained.

2) Impact of LoMs DER Protection: The analysis of Section IV-A were repeated with the DER support capabilities and the LoMs protection modelled (without the under-/over-frequency protection). The RoCoF detection method has been chosen according to Cyprus GCRs with settings of 1Hz/s and 1.5Hz/s for pick up times 0s and 0.1s. Table IV summarises the results for scenario P3 in combination with event E2 is shown for different RoCoF settings. It can be observed that when RoCoF protection setting is instantaneous at 1Hz/s, all DERs are disconnected which causes a system blackout. On the contrary, when the setting is set at 1.5Hz/s, the frequency response is almost identical to the initial response without any GCR modeled since (P3.1), none of the DERs are being disconnected due to LOM protection, with the only difference manifested in the frequency overshoot.

C. Impact of DERs Capabilities and Protections

Finally, in this subsection, the DER support capabilities and both protection mechanisms have been modelled. U/F setting was set to 48.5Hz in order to evaluate how different U/F settings affect the system frequency response (since the default 48.8Hz caused a loss of system stability for P3.5). LoMs was modelled with RoCoF settings to 1Hz/s for 0.1s. Figure 7 shows a comparison of all variants.

CONCLUSIONS

In this paper, the impact of DER Capabilities and Protections on the frequency stability of an islanded system has been evaluated. It has been demonstrated that DER capabilities have a more noticeable impact on the power system frequency response when RES penetration is relatively high. Their effect is beneficial as they support frequency to be contained within nominal limits. On the contrary, protection mechanisms have a significant impact on system's frequency since, after a severe event DERs can be disconnected due to U/F or LoMs which will cause further reduction of the frequency. Consequently, DER capabilities and protection requirements should be modelled for evaluating power system stability under severe events with high RES penetration scenarios.

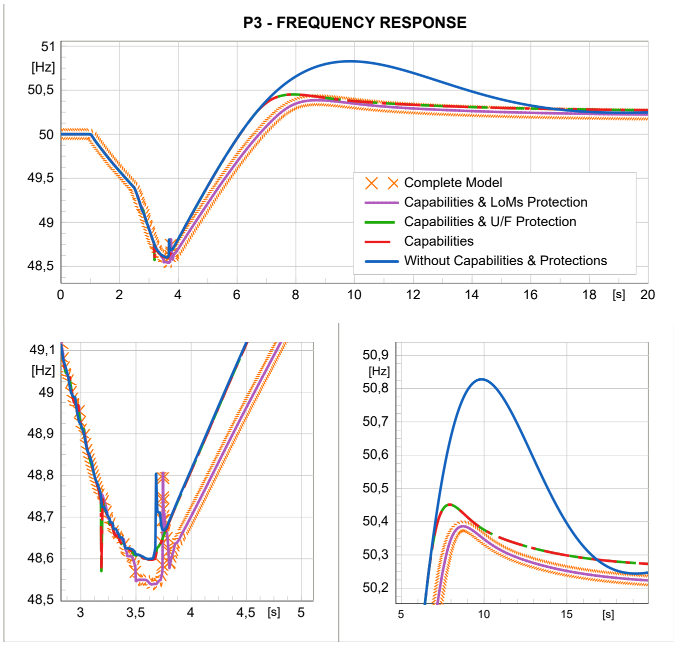


Fig. 7. P3 - Event 2 - Frequency response with DERs equipped with Protections and Capabilities

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