The Impact of RES Curtailment Strategies for Congestion Avoidance on the Dynamic Frequency Performance of Low-Inertia Systems

Phivos Therapontos*† and Petros Aristidou‡
* Distribution System Operator, Electricity Authority of Cyprus, Nicosia, Cyprus.
† Dept. of Electronic and Electrical Eng, University of Cyprus, Nicosia, Cyprus.
‡ Dept. of Electrical Eng., Computer Eng., & Informatics, Cyprus University of Technology, Limassol, Cyprus
Emails: ptherapo@eac.com.cy, petros.aristidou@cut.ac.cy

***Abstract*—Network congestion due to excessive reverse power flow from distributed energy resources is one of the most pressing challenges for power system operators worldwide. There are several methods that can be used to alleviate congestion, however, most of them are either costly or currently not available to operators. RES curtailment strategies are frequently applied to reduce the reverse power flow and alleviate congestion issues. In this paper, we examine three such RES curtailment strategies and analyze their impact on RES penetration, frequency response, and available frequency containment reserves. The islanded electricity grid of Cyprus is used to showcase the results and suggestions are derived based on the operator priorities.**

***Index Terms*—RES curtailment strategies; frequency containment reserves; congestion avoidance; frequency stability; islanded systems; low-inertia systems.**

I. INTRODUCTION

Power systems worldwide are experiencing many challenges, mainly due to increased Renewable Energy Sources (RES) penetration. These challenges vary according to the grid characteristics. Low inertia and isolated systems are facing more profound challenges that can jeopardize their stability [1]. One of the most common challenges is network congestion. In many power systems, large areas of the transmission and distribution systems have already been congested due to increased penetration of RES. It has been observed that large RES systems are mostly installed in areas where the load demand is relatively low. This is due to the fact that in those areas the land availability is high, and the land cost is low. However, in these areas, both transmission and distribution systems have limited capacity, since they were built to satisfy the low load demand of the area. As a result, there is a large possibility of equipment overloading due to reverse power flows [2].

Currently, there are a few possible mitigation solutions for avoiding congestion in critical areas. For instance, employing Energy Storage Systems (ESSs) to mitigate congestion or performing network reinforcement are both solutions that are frequently used but have a high capital cost. Moreover, in most European system, ESSs cannot be installed or operated by the System Operators (SOs), which makes these options currently limiting [3]. On the other hand, new connections of RES systems can be declined when the network has reached its limitations to ensure congestion will be avoided. However, this method significantly restricts the total installed RES capacity and penetration.

As a middle option, RES curtailments can be performed at specific times of the day as mitigation measure for congestion avoidance [4]. This method is effective, but still leads to significant energy generated from RES being curtailed and to loss of income for the producers. Nevertheless, this method has some noticeable advantages compared to the other solutions. Specifically, it has a very small implementation cost, and it allows increasing the overall RES penetration without costly reinforcements.

This method is already being used in the UK by the London DSO (UKPN), known as ’flexible connections’, where new RES systems can be installed in a constrained area, without any network reinforcement. This functionality is enabled by a software that utilizes real-time data and estimates the amount of RES that has to be curtailed to avoid congestion [5]. A similar method is also applied in Northern Ireland and Ireland by the respective transmission system operators (TSOs). It has been estimated that approximately 6.2% of energy from Wind Power Plants (WPP) has been curtailed due to network constraints in 2020 in both countries, and solar curtailments have reached 4.4% in Northern Ireland [6]. In addition, setting a maximum allowable set point to RES systems connected in congested areas is under investigation by the SOs of the Power System of Cyprus.

Besides the congestion problems, isolated low-inertia systems face additional challenges related to frequency stability. In these systems, even the smallest event can jeopardize the system stability, since the system is more vulnerable [1]. Therefore, as RES penetration continues to increase drastically, more frequency support during the initial phase of each event is essential for maintaining the stability of the system. The automatic support during the initial few seconds after the event occurrence is known as Frequency Containment Reserves (FCR).

As demonstrated in [7], inverter based resources (IBRs) can provide primary frequency support to the system if they are operating below their maximum output point (curtailed). Consequently, with the appropriate actions and policies put in place, the RES curtailment strategy used to mitigate network congestion can be used to release capacity for FCR during under-frequency events.

This paper investigates how different RES curtailment methods applied for congestion avoidance can also provide FCRs during under-frequency events using the curtailed power. For the analysis, the isolated, low-inertia power system of Cyprus has been used.

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, the impact of the different curtailment methods on the RES penetration, the equipment loading, and the system frequency stability is evaluated. Finally, Section V summarizes the main conclusions.

II. BACKGROUND: NETWORK CONGESTION AND FREQUENCY CONTAINMENT RESERVES

A. Network Congestion

Network congestion occurs when the power flow through the equipment is higher than its nominal rating. A common area where congestions take place are transmission substations. A transmission substation normally has at least two power transformers, in order to satisfy N-1 criterion. A general planning guideline for RES connection approval is to check if the firm capacity of the substation is bigger than the total possible maximum instantaneous RES generation at the substation. The transmission substation firm capacity can be estimated by subtracting from the total nominal capacity of the substation the power rating of the biggest power transformer. In some cases, the historically minimum demand of the substation can be added to the firm capacity. In this paper, when the firm capacity of the transmission substation is not adequate for installing additional RES capacity, we consider the following options:

- **Method 1 (M1) - RES connection request declined:** If the substation firm capacity is not higher than the total RES installed capacity the SO can decline any additional RES connection requests. This method is currently used by the DSO and TSO of the Cypriot power system.
- **Method 2 (M2) - Constant maximum allowable generation:** Some or all RES systems have a constant maximum active power output limit (in percentage of their capacity). The limit is selected at a value that at any time the transmission substation firm capacity cannot be exceeded, thus during peak hours some energy from RES is always curtailed.
- **Method 3 (M3) - RES curtailment when the total power injected to the grid is higher than the N-1 capacity:** Curtailments occur only when N-1 criterion is not satisfied. Therefore, RES curtailments are initiated when the power injected to the grid is higher than the firm capacity and the local instantaneous load demand. This is the only method considered that has a dynamic (real-time) limit change.

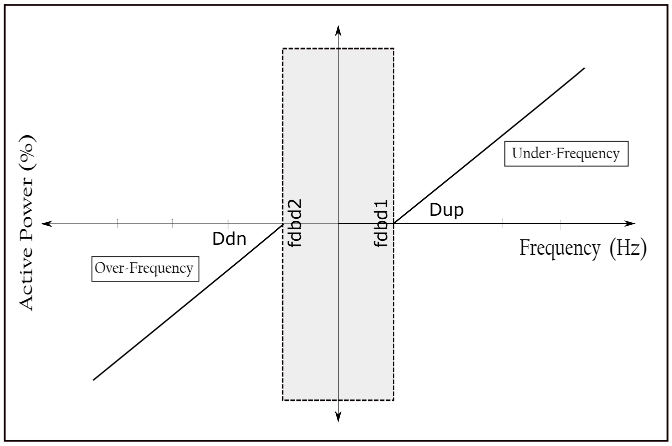

Fig. 1. Droop characteristic for active power support during frequency events [7]

B. Frequency Containment Reserves (FCRs)

FCRs are vital for containing the system frequency as close to the nominal limits as possible, and have been traditionally provided by synchronous generators. Due to the massive RES penetration, synchronous generators are being decommissioned, thus FCRs are reducing. However, FCRs can also be provided by IBRs operating below their maximum output power and modifying their active power output according to a droop characteristic, as demonstrated in Fig. 1. Basically, this droop requires the IBRs to increase (or decrease) their active power output when the system frequency is below (or above) the frequency of the low (or high) deadband. In this manner, active power from IBRs is provided during frequency events to help the system remain stable.

III. CASE STUDY

For assessing the impact of different RES curtailment methods on the RES energy lost and 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) [8].

A. Description

1) Power System of Cyprus: The Cypriot power system is an isolated and low-inertia system. It has 50 Hz frequency and nominal voltages up to 132 kV. There are three power stations with a 1480MW total installed capacity. In Vasilikos Power Station (VPS), there are steam turbines (ST) of 130 MW and combine cycle gas turbines (CCGT) of 220 MW. In Dhekelia Power Station (DPS) there are 60 MW steam turbines and small internal combustion engines. Currently, there are approximately 400 MW of Photovoltaic Systems (PV) and 158 MW of wind power plants (WPP) installed [9].

2) Area of Study: The area under investigation is a part of the transmission system of Cyprus where PV penetration is large and the load demand of this area has been traditionally very small. Consequently, the capacity of the substations is

TABLE I
CRITICAL SUBSTATIONS DESCRIPTION

Substation	Nominal Capacity	Firm Capacity	Minimum Load
SUB 1	30	20	3
SUB 2	32	16	2
SUB 3	63	31.5	5
SUB 4	63	31.5	5

TABLE II
SCENARIOS DESCRIPTION

SCENARIO	SC1	SC2
Demand	**636 MW**	**952 MW**
Generation	**Unit Commitment**	
VPS ST	3X130	3X130
DPS ST	2X60	4X60
CCGT	-	2X110
WPP	19	26
PV	287	287
$E_{kin,sys}$ [MWs]	**4338**	**7552**

not adequate to satisfy further RES system installations. The nominal capacity, the firm capacity and the minimum load of each substation involved in the analysis are shown in Table I. For simplicity, the substations of the congested area are called ”critical”.

B. Operating Conditions

Two operating scenarios with relatively high RES penetration are considered for the analysis (see Fig. 2):

- Scenario 1 (SC1): Medium load demand (636 MW) where reverse power flow is maximized;
- Scenario 2 (SC2): High load demand (952 MW) operating scenario where reverse power flow is relatively limited.

It should be noted that scenarios with low loading conditions (300 - 600 MW) have not been examined in this work. During such low load conditions, the Cyprus TSO currently performs RES curtailments to maintain the minimum stable generation limit, thus congestion due to increased RES penetration is avoided implicitly [2], [7]. Fig. 2 and Table II present the description of the two operating scenarios, while $E_{kin,sys}$ represents the total kinetic energy of the system.

C. Inverter-based Resources Modelling

The RES connected in both Transmission and Distribution systems have been modelled as aggregated IBRs, using the WECC DER model available in DIgSILENT PowerFactory. The WECC PV model implements the major grid code requirements considered in the Cypriot system [10], [11]. The most important frequency-related parameters applied to the IBRs models are presented in Table III.

The curtailment methods M2 and M3 have been modelled based on the following assumptions. In M2, a constant 50% maximum set point has been applied to all the IBRs connected to the critical substations, thus the RES installed capacity in M2 (and M3 for comparison) is doubled compared to M1. This set point can be optimally selected, if an extensive cost-benefit analysis is performed, that takes into consideration the expected income loss of RES producers (due to the curtailments) and the cost of FCR provision by the TSO. However, this analysis is out of the scope of this paper.

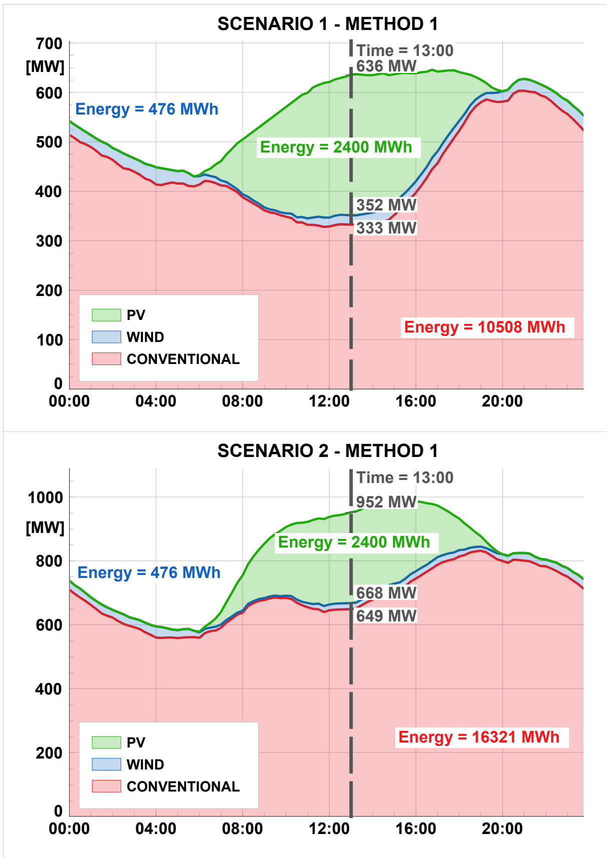

Fig. 2. Daily operation of the system during medium (SC1)- and medium-high (SC2)-loading conditions used for the scenario selection

TABLE III
WECC DER MODEL - FCR PARAMETERS AND VALUES

Functionality	Parameter	Value
Frequency Low Deadband	fdbd1	49.8 Hz
Frequency High Deadband	fdbd2	50.2 Hz
Droop Upwards	Ddn	20 %

In Fig. 3 the simplified flowchart for implementing the curtailment method M3, is demonstrated. It can be seen that curtailments are initiated only when the equipment under investigation is about to be overloaded. The latest capacity factor (CF) before overloading is applied as a constant setpoint to all IBRs affecting the equipment loading. CF is the ratio of the active power generated to the installed capacity of the equipment.

IV. ANALYSIS

In this section, we analyze the impact of the different curtailment methods on the RES penetration, the equipment loading, and the system frequency stability.

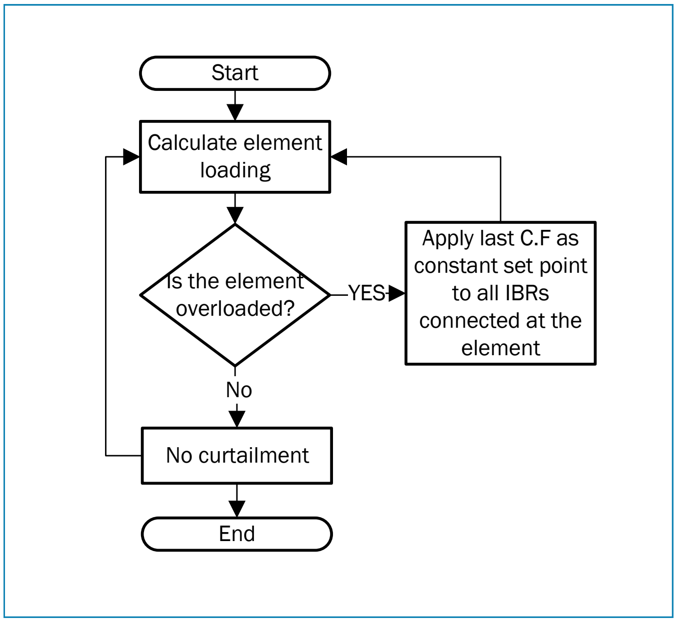

Fig. 3. Flowchart for modelling method M3 curtailment strategy

A. Impact on RES penetration

Initially, the impact of each curtailment method on the daily and instantaneous RES penetration has been evaluated, and the results are presented in Table IV. It should be noted that curtailments have only been applied to RES installed in the critical substations. It can be easily concluded that M2 and M3 provide increased daily RES penetration compared to M1, despite the required curtailments. This is because in M2 and M3, more RES systems are allowed to be installed in each substation, which results in increased energy generation in periods without congestion.

At the same time, it can be observed that method M3 is more efficient than M2 (less curtailed energy) because it takes advantage of the real demand of each substation, which is always higher than the minimum demand presented in Table I. This is more evident in SC2, where the system demand is higher. As a result, even more energy from RES can be injected into the substation, resulting in lower RES curtailments. It should be noted that the curtailed energy in M2 is the same for both scenarios as it doesn't depend on the loading conditions but only the RES generation.

In Fig. 4, it is demonstrated how energy from RES is affected by the curtailment method at each critical substation. The labels show the additional energy that can be injected to the grid depending on the congestion avoidance method. It can be seen that for the identical substations 3 and 4 (same nominal capacity and minimum load), there is a noticeable impact of M3 on the total energy injected into the grid. Also, depending on the operation scenario the injected energy in M3 varies, while in M2 is constant. The "Energy Curtailed" refers to the minimum energy that has to be curtailed based on M3 in Scenario SC2 to avoid congestion.

TABLE IV
IMPACT OF RES CURTAILMENT METHODS ON RES PENETRATION

Curtailment Method	**M1**	**M2**	**M3**
SCENARIO 1			
Instantaneous RES Penetration (%)	47.6	47.6	48.7
Daily RES Penetration (%)	21.5	23.8	24.8
Daily Energy Curtailed (MWh)	0	651	598
SCENARIO 2			
Instantaneous RES Penetration (%)	31.8	31.8	33.5
Daily RES Penetration (%)	14.9	16.5	17.2
Daily Energy Curtailed (MWh)	0	651	523

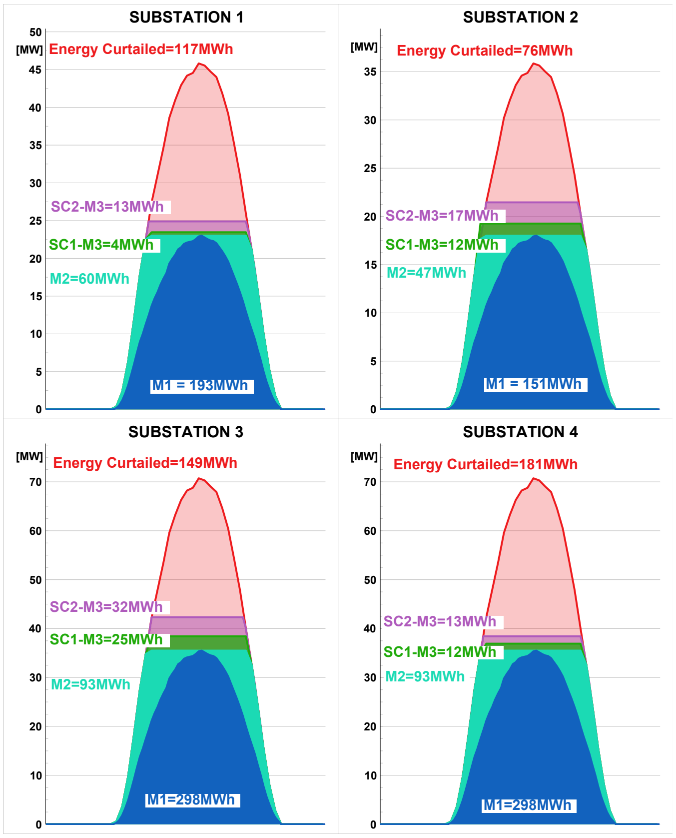

Fig. 4. SC1 - Energy injected to the grid from RES in each substation based on the RES curtailment method applied for congestion avoidance

B. Impact on Substation Loading

In this section, an N-1 contingency analysis was performed on the critical substations to evaluate the impact of each strategy on the substation loading. For the contingency analysis, the power transformer with the higher nominal power rating in each substation, is set out of service. As shown in Fig. 5, congestion is always avoided in both operating scenarios. The substation loading is always higher when M3 is used and lower with M1. This is because M1 is a much more conservative approach that has a higher security margin.

C. Impact on Frequency Stability

The impact of the different curtailment methods on the frequency stability of the system has been evaluated assuming

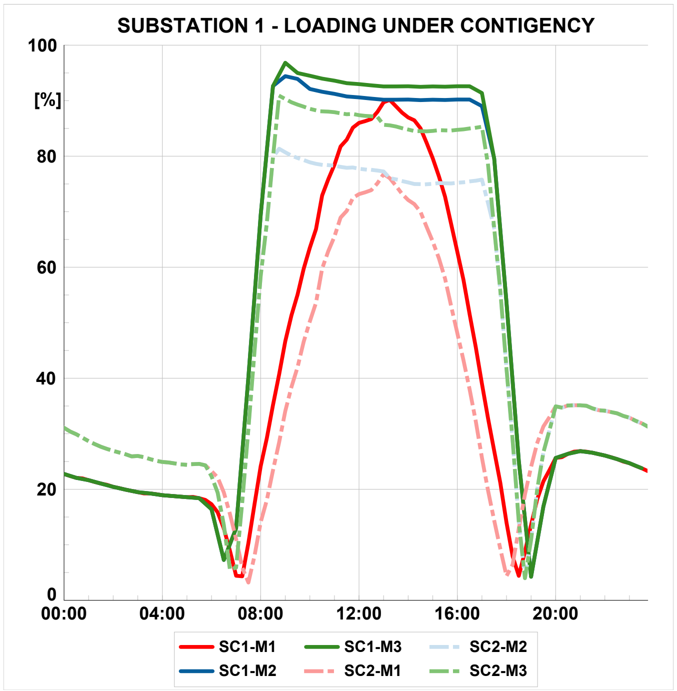

Fig. 5. Substation loading under contingency for scenarios SC1 and SC2

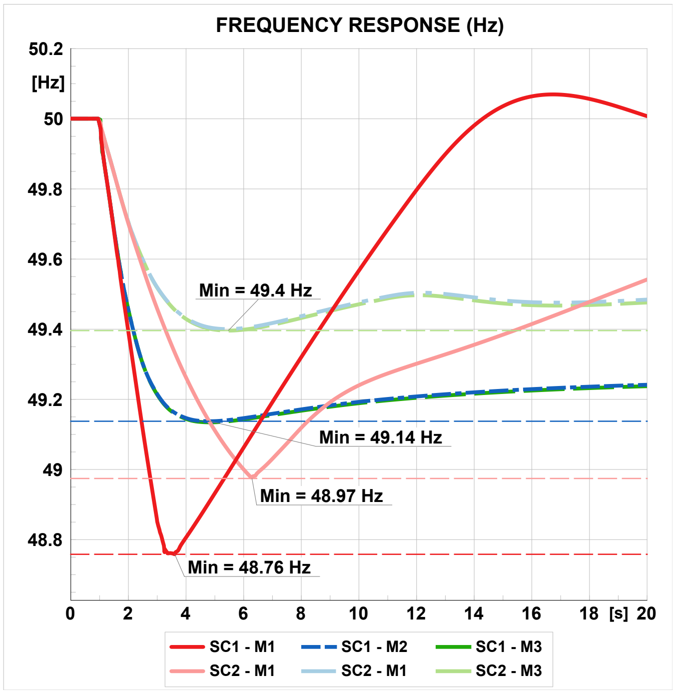

Fig. 6. Frequency response of the power system during the outage of a steam turbine at t=1 s

that all the curtailed power is offered for FCR. For this analysis, the loss of a 130 MW (operating at 90 MW) ST generator at VPS at $t = 1$ s has been simulated until $t = 20$ s. The event considers the operating time of 13:00 where PV generation is maximized (Fig. 2). Also, in this analysis, the primary frequency support functionality from IBRs is enabled with the settings presented in Table III.

It can be seen in Fig. 6, that for methods M2 and M3 the frequency response of the system has been significantly improved. The frequency nadir in SC1 has been increased from 48.76 Hz to 49.14 Hz and as a result load shedding is avoided (Fig. 7). This is attributed to the fact that when the frequency drops below 49.8 Hz (fdbd1), IBRs start to inject active power to the grid with a rate of Dup, thus providing FCR to the system. This is demonstrated in Fig. 8, where the active power from IBRs during the event is presented. It can also be observed that the initial active power injection in M3 is higher than M2. Also, the active power support from IBRs is higher in SC1 compared to SC2. This is due to the fact that the system inertia in SC2 is higher than the inertia of SC1, therefore for the same event, the frequency response is more contained.

In Fig. 9, the active power that can be used for FCR depending on the RES curtailment method is demonstrated. It should be noted that method M2 is independent of the loading conditions. During the hours when PV generation is zero, the available active power is always zero since there is no energy generated from the PV systems and therefore curtailments are not required. When the generation from PV systems exists 50% of their nominal installed capacity (at 08:45), RES curtailments are initiated. The available active power from M3, is always lower than M2, since the required curtailments with M3 are lower. Similarly, in SC2 the available active power from M3 is lower compared to scenario SC1. It is worth mentioning that the available active power for FCR during the peak hours in all scenarios is above 80 MW. This is definitely adequate since the larger single event contingency (for the power system of Cyprus) is currently 130 MW.

V. CONCLUSIONS

The massive RES penetration has already made a significant impact on power systems worldwide. Rural areas, where the transmission system capacity is usually low, are experiencing increasing reverse power flows from RES that can potentially cause network congestion. There are several methods of RES curtailments that can be applied for congestion avoidance. At the same time, since RES are operating below their maximum output power, this can be used for FCR provision during under-frequency events.

In this paper, the impact of the different curtailment methods on the frequency stability of low inertia systems has been evaluated during medium and high-loading conditions. It has been concluded that combining RES curtailment for congestion avoidance with active power support from IBRs is extremely beneficial for the power system operation. The benefits for the frequency stability of the system are more profound during lower loading conditions, where the system inertia is lower and the available active power that can be provided by IBRs is higher. From the authors' point of view, Method M3 is more efficient compared to M2 and M1 since it allows RES penetration to be maximized, while maintaining

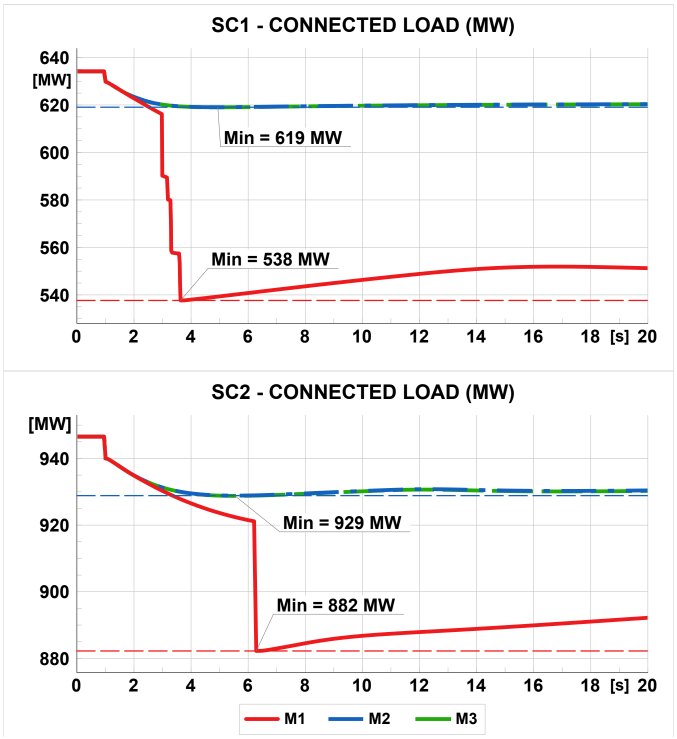

Fig. 7. Load remained connected during the outage of a steam turbine at t=1s

adequate FCR from IBRs when the system needs them the most.

VI. Acknowledgment

This work was partially supported by the European Union's Horizon 2020 OneNet project under grant agreement No. 957739.

References

[1] F. Milano, F. Dorfler, G. Hug, G. Verbic, "Foundations and Challenges of Low-Inertia Systems", PSCC 2018., July, 2018.

[2] P. Therapontos, R. Tapakis, A. Nikolaidis, P. Aristidou, "Current and Future Challenges of the Cyprus Power System", MEDPOWER22, November, 2022.

[3] "Directive (EU) 2019/944 on Common Rules for the Internal Market for Electricity", Official Journal of the European Union, 2019.

[4] T. Bongers, J. Kellermann, M. Franz, A. Moser, "Impact of curtailment of renewable energy sources on high voltage network expansion planning", 19th Power Systems Computation Conference, PSCC 2016, 2016.

[5] "Flexible Connections Customer Guide", UK Power Networks, December 2021.

[6] "Annual Renewable Energy Constraint and Curtailment Report 2020", EIRGRID and SONI, May 2021.

[7] P.Therapontos, R. Tapakis, P. Aristidou, "Assesing the Impact of Primary Frequency Support from IBRs in Low Inertia Isolated Power Systems", IEEE General Meeting 2022, 2022.

[8] "DIgSILENT PowerFactory User Manual 2022", DIgSLENT GmbH.

[9] "Cyprus Energy Regulatory Authority Annual Report 2022", Cyprus Energy Regulatory Authority, 2022.

[10] "Power Generating Plants in the Low Voltage Network (VDE-AR-N 4105)", VDE, 2019.

[11] G. Lammert, L. D. P. Ospina, P. Pourbeik, D. Fetzer, and M. Braun, "Implementation and validation of WECC generic photovoltaic system models in DIgSILENT PowerFactory," IEEE PES General Meeting, 2016.

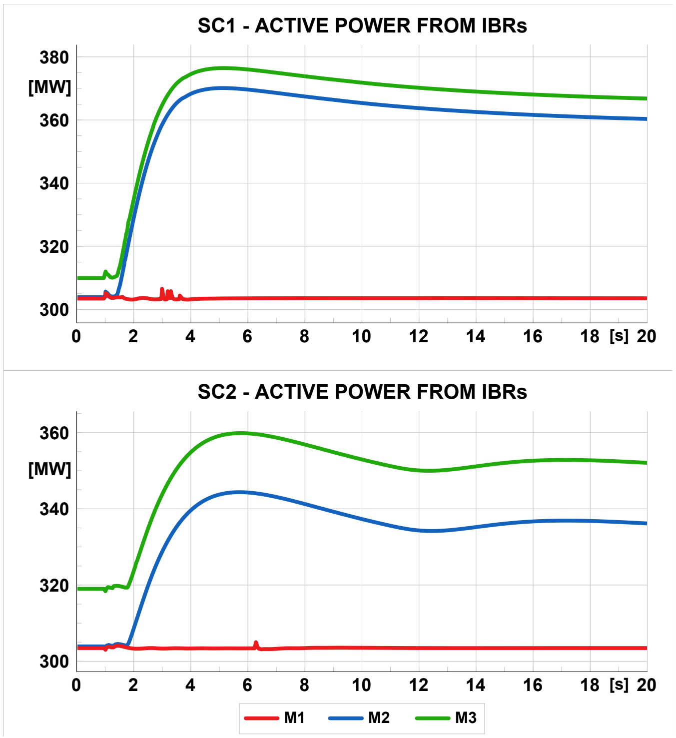

Fig. 8. Active power support from IBRs for the different RES curtailment strategy

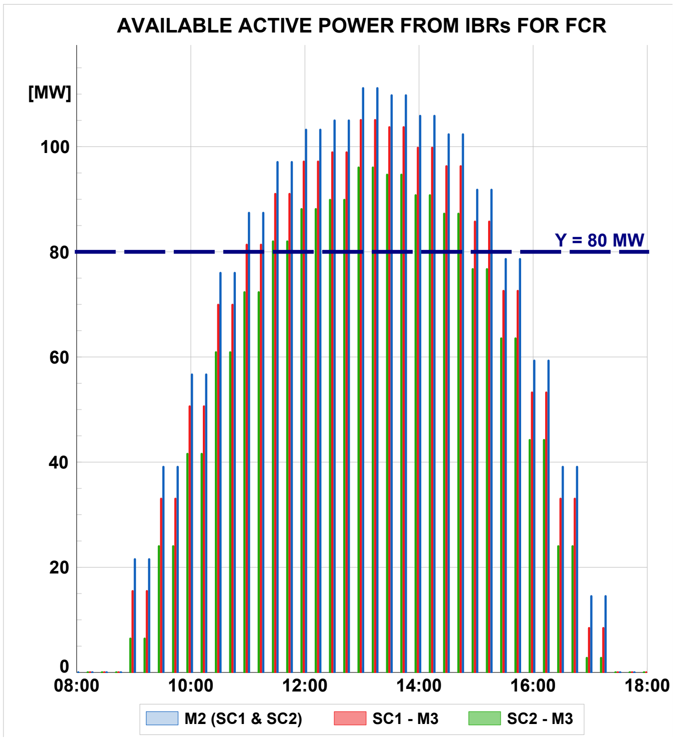

Fig. 9. Available active power for FCR for the different RES curtailment methods