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Manipulation of Static and Dynamic Data Center Power Responses to Support Grid Operations

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ABSTRACT This research investigates three frameworks for data centers to deliver fast frequency response services from their UPS storage systems, HVAC cooling units, and the ability of off-gridding the entire data center during transient frequency events. The aim of this is to provide dynamic injection during transients in real time for grid operators and for power sellers in hour ahead markets. A static and a dynamic model was developed in DIgSILENT PowerFactory. In the static model, the data centers are off-gridded in response to emergency frequency signals from system operator in a centralized manner, whereas in the dynamic model the UPS systems and shiftable cooling units power consumption was altered continuously in the data centers in response to local frequency measurements considering different real-time scenarios. The performance of the proposed operational frameworks is validated, and calibrated to actual frequency events that occurred in the Irish power system. The sensitivity analysis demonstrates that both static and dynamic load controls can significantly improve system frequency metrics, i.e., frequency nadir and rate of change of frequency during transients. The key findings show that demand response can only make a substantial frequency improvement if a large amount of energy delivered within the timeframe of inertial response.

INDEX TERMS Battery and UPS, data centers, demand-side management, fast frequency response, inertia response, load modeling, power system dynamics, wind power generation.

NOMENCLATURE

$P_{Lo,j}$	Pre-fault active power of a load at j^{th} bus.
$Q_{Lo,j}$	Pre-fault reactive power of a load.
$P_{L,j}$	Active and reactive power of a load.
$Q_{L,j}$	Reactive power of a load at j^{th} bus.
$v_{o,j}$	Pre-fault voltage of j^{th} bus.
$v_j P$	ost-fault voltage of j^{th} bus.
u_i, u_j	Committed status.
$\underline{E}$	Operational inertia floor constraint.
H_i	Inertia floor constraint of i^{th} generators.
H_{sys}	Post-event system inertia constant.
S_i	Stated nominal power limit.
f_o	Nominal system frequency.
f_i	Regional nominal frequency.
f_{COI}	Frequency at center of inertia.
$\overline{P}i$	Nominal power.
df/dt	Rate of change of frequency.
P_{Tg}	Output power of tripped generators.
P_{rg}	Output power of responsive generators.
P_{nrg}	Output power of none responsive generators.
P_L	Total system demand.
ΔP_{r1}	Post-fault power response from any source.
Tr	Response time from the start of the event.
ΔP_{rL}	Static demand response to the disturbance.
σ	Participation factor.
$u(t$ - $Tr)$	Unit step at time $t = Tr$.
P_{DR}	Manipulated dynamic demand response.
P_{DRmax}	Maximum contracted dynamic demand response.
Δf_{db}	Frequency deadband,
Δf	Change in system frequency during the event.
Δf_{max}	The maximum frequency deviation.

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$E(t)$	Total energy delivered.
T_{nadir}	Time to nadir.
T_{FFR}	Time to full fast frequency response activation.
P_{UPS}	UPS response power.
T_{RoCoF}	RoCoF rolling window.
N_{RoCoF}	RoCoF quotient over the measured window.

I. INTRODUCTION

Data centers are power-intensive digital storage warehouses with very strict redundancy operational requirements in case of any sudden power or telecommunications interruptions. Operating data centers is not without its challenges in terms of engineering and service level requirements, energy consumption, and corporate and social responsibility considering global sustainability concerns. First, the level of redundancy depends on client needs and contractual requirements. This means that all data centers are equipped with on-site uninterruptable power supplies (UPS). As a result, they can handle very sudden grid power supply disruptions rapidly by bringing their own UPS on-line to ensure data security and or accessibility depending on customer demands. This is to ensure reliable operation of data centers during grid failures [1], because 47.6% of operational interruptions at data centers relate to power failures [2], 15.9% relate to IT faults and failures and 36.5% relate to exterior impacts (e.g. storm damage, fires, flooding, earthquakes, etc.) [2].

Second, one challenge for data intensive industries (e.g. Google, Microsoft, Facebook, Amazon, even stock exchanges) is that data storage is power hungry resulting in a significant carbon footprint. Currently, data centers use about 200 TWh each year, or 1% of global electricity demand, and contribute 0.3% to global carbondioxide emissions (CO_2) [3]. This demand in digital services was predicted to increase [4] and with the Coronavirus disease 2019 (COVID-19) pandemic it may occur faster than initially expected as more working, teaching and digital socializing occurs. There are different growth estimates, but [4], [5], and [6] estimate up to 13% of global power demand by 2030. The challenge is the emissions, and most countries plan on moving to renewable energy technologies to mitigate and eliminate emissions from their power systems. The European Union (EU) has data centers to be carbon neutral by 2030 [7]. The sectors and industries that use cloud and data centers want to be seen as corporately and socially responsible and green credential pay a large part of this. Examples of this are the 2.9 GW renewable energy Amazon portfolio [7] and the Google drive for 100% renewable electricity [8].

Third, another challenge for data centers is that the energy system is undergoing its own engineering, corporate, and social changes as governments force reductions in greenhouse gas emissions to combat global warming. Already there has been a huge growth in variable renewable generation from onshore wind farms, solar photovoltaic parks, and offshore wind arrays. There is also a move away from large centralized utility fossil generators with a transmission system feeding the distribution system driven by the decentralization of heating, transport, and increased embedded distributed generation. This is the new 21st century smart grid, and should result in the deployment of smart technologies such as heat pumps, electric vehicles, solar rooftop PV, smart home appliances, etc. This means that the transmission and distribution grid will require increased interventions to maintain service of supply levels demanded by costumers because these new technologies are not as frequency stable as the traditional fossil fuel centered system [9]. This is not bad in itself, as it is a technology shift that will spawn new technology deployment, thus new jobs and opportunities, and result in changes in energy and power system management. However, increased levels of variable renewable power and smart technologies in the grid need additional grid balancing services and storage to maintain power quality [10], [11]. Data centers are potential candidates for participation in demand response (DR) programs and provision of frequency services due to their large load demand. It is here that data centers as large energy users have a role to play to ensure their corporate and social responsibilities to society for a sustainable common future, like other large industrial and commercial loads e.g. refining and mining, food chilling and storage and manufacturing facilities.

In fact, data centers with their high availability and fault ride through characteristics due to their inherent redundancy could be considered dispatchable in instances where the wider power grid needs very fast and short frequency responses. Data centers could with the correct on-site UPS set-up, provide very useful ancillary fast frequency response (FFR) services available to grid operators and indeed electricity sellers through back to back purchase agreements to ensure operational requirements and supply. These FFR services facilitate the integration of high-levels of converter-based renewable generation and reduce transmission system operator's (TSO) requirements for energy storage and online thermal generators to protect against transients. This represents an extra revenue stream for data center operators while reducing electricity bills. This new business model is a *win-win* scenario for data centers, utilities, and service providers if implemented effectively. This could also support carbon emissions reduction targets for the data center customer, the grid operator, and power producers.

If contracted correctly, data centers can provide ancillary frequency services to grid operators and wholesale electricity markets in real time and in hour-ahead markets [12]. Simulation results have demonstrated that a data center's electricity bills could be reduced by 8% with reliable energy and frequency regulation services price forecasts without scarifying service security level agreements. Energy management system to minimize the overall energy consumption of a data center's IT loads and reduce peak power consumption is proposed in [13] when participating in DR. The results in [13] also showed that 33% of total energy savings and 50% peak demand reduction were possible in the case of data center federation.

Cooling infrastructure is another important load to consider for DR, which is about 50% of the overall energy consumption in data centers [14]. This has a great potential to participate in DR by adjusting zone supply air conditioner (HVAC) temperature setpoint while remaining within the American Society for Heating and Air Conditioning Engineers (ASHRAE) recommendation limits. To this end, ASHRAE recommends that operational temperatures for data center equipment reside between 5 °C to 40 °C [15]. By exploiting these flexibilities, it is possible to alter the operating temperature setpoint for the duration of the FFR service. Demand response based on this mechanism is highly dependent on the individual data center's operational characteristics. It could take up to five minutes to heat-up/cool-down for a typical data center which serves as an excellent candidate to participate in frequency services [13].

Furthermore, batteries and UPS systems in data centers are primarily designed and oversized relative to the actual load requirements. They can provide quick response to possible supply failures for a minimum of 30 minutes of energy storage at full load as a backup mechanism to temporarily handle IT equipment and allow enough time for a diesel generator to pick up load operation completely off-grid [16]. From a practical viewpoint, a study filed by Swedish TSO illustrated that a 0.1 MW Fortum UPS was able to act fast enough to fulfill technical requirements for frequency containment disturbance reserve without affecting operation [1]. Interest has recently grown in more active utilization of UPS systems for peak shaving, frequency regulation, primary frequency service in power systems with high converter based renewable generation [17], [18]. However, one of the limitations of the previous literature is that data centers are not well examined for FFR service while considering their impact on system frequency metrics.

Different from existing studies, this paper developed three frameworks for data centers to participate in FFR services in the Irish power system using both static and dynamic DR frameworks. The analysis is accomplished by actively using the UPS system and shiftable HVAC systems as dynamic providers to balance the grid power during transients. The static response is presented by off-gridding and transferring the entire data center from the main grid to the local on-site generator. The operational flexibility of the on-site generators could also be leveraged to provide frequency services during a transient. However, as this is the most straightforward way for a data center to participate in frequency service provision like that of conventional generators, it is not considered in this analysis. The focus is on the UPS system and shiftable HVAC systems to provide dynamic injection during transients.

Two important questions arise from this hypothesis. First, to what extent data centers could rescue system frequency during transients? And second, what is the impact of different sources of FFR services on the power system frequency dynamics? With these objectives and to the best of our knowledge, this research is the first to investigate the FFR service based on DR from data centers. Research gaps, limitations, and future directions are also examined. The main contributions of this article are listed as follows:

i) Provides details for the calibration of real frequency events on the Irish Power System.
ii) Comprehensive frameworks for data centers to bid into the Irish FFR services and follow emergency signals in real-time operations.
iii) The effect of both static and dynamic DR on the system frequency nadir, RoCoF, and frequency rise/drop duration) are studied. The impact of the projected communication delays on the system frequency metrics (i.e. nadir and RoCoF) is also examined.
iv) The analysis shows that data centers are well suited to respond to frequency disturbances in the period between the inertial response of synchronous generators and the primary operating reserve. This has great potential to run a power system securely with high variable renewable generation. Consequently, this reduces the requirement for an online synchronous generator's spinning reserve that could eventually lower CO_2 emission footprints.

The rest of the paper is organized as follows: Section II shows the necessity of incorporating data center in the Irish power system frequency services. Section III presents the methodology and model calibration. Section IV defines the proposed FFR frameworks. Section V demonstrates results and discussions. Recommendations are given in Section VI followed by the conclusions and future directions in Section VII.

II. THE NECESSITY OF CONSIDERING DEMAND DATA CENTERS FOR FREQUENCY SERVICES IN THE ISLAND OF IRELAND

Ireland is a global leader in the ICT services sector. Nine of the top ten US ICT companies and four of the top five IT services companies have operations in Ireland [19]. The Irish government policy has matched to this it's small high educated population, and ample renewable energy resources. In Ireland, there are currently more than 1300 MVA of connected and contracted data center operational capacity [20]. There is a further 1600 MVA looking for planning permission (i.e., building consent) to connect. Each data center will have a demand equivalent to a town of approximately 25,000 residential households [14]. There are also small scales of about 1 MVA capacity. These data centers are mostly located in the Dublin metropolitan area. On the island of Ireland, the total annual electricity demand was about 28 TWh in 2019 [21]. Data center's energy usage accounted for 10% of this figure. Data centers are rapidly being developed and will become a significant segment of the Irish power system energy consumption. Analysis by Ireland's TSOs, EirGrid and SONI estimate that data centers will represent 31% of total system demand by 2027 making data centers the fastest growing power consumption subsector and are expected to continually grow [22]. Furthermore, data centers are also anticipated to represent a major share of Ireland's CO_2 emissions. A report

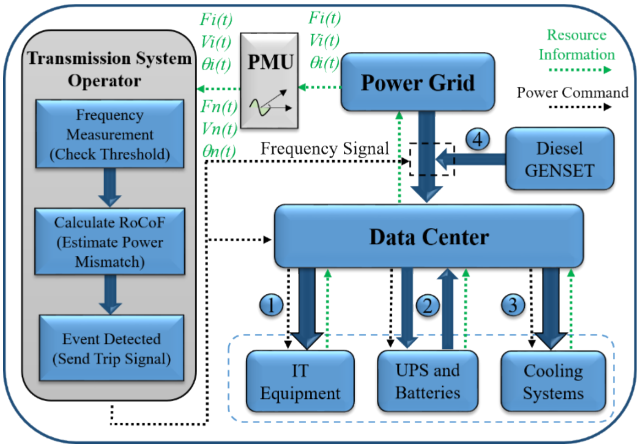

FIGURE 1. Data center demand response modeling.

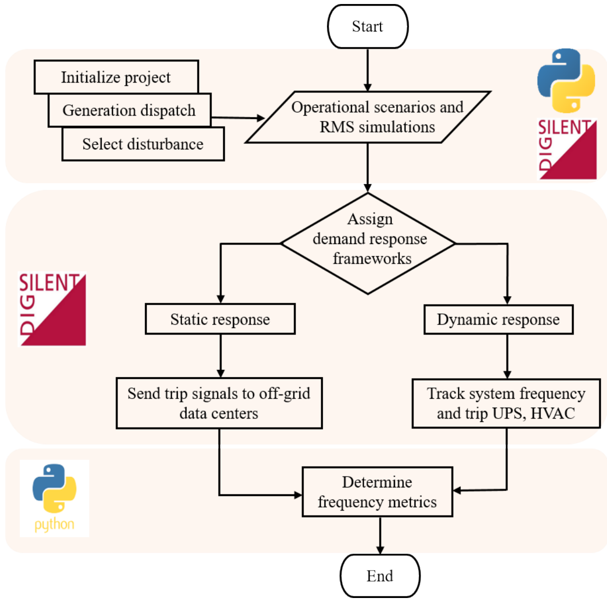

FIGURE 2. Flowchart of the proposed methodology.

by the Irish Academy of Engineering (IAE) has projected data center expansion will add at least 1.5 million tonnes of CO_2 to Ireland's emissions by 2030 [23]. This will increase Ireland's present electricity related emissions by about 13% [24]. This requires TSO and other key industry decision makers to look at things differently to tackle new anticipated challenges.

These challenges coincide with the significant transformations in the power system on the Island of Ireland. There is currently over 5.05 GW installed wind generation capacity [25]. There is further planning potential to run the power system at 70% renewable generation by 2030 [26]. Consequently, conventional synchronous generators are being replaced by intermittent non-synchronous sources (i.e., wind and solar). The key challenge is that these systems provide very limited to no rotational system inertia support to a power system [27]. Thus without fast response supplementary devices such as energy storage and DR, insufficient rotational inertia can lead to higher frequency nadir and faster rate of change of frequency (RoCoF) during disturbances [27]. These frequency metrics pose a new set of operational challenges for the TSO if they exceed the prescribed tolerances, which could result in involuntary shedding of customer loads, and distributed generation and ultimately total system blackout. Therefore, there is an increasing need for new FFR services to balance the generation/demand in real-time to boost the adoption of renewable energy and mitigate the impact of reduced system inertia. This is where grid-responsive data centers with intelligent loads and controls can help fulfill Ireland's high renewable generation objectives to meet the coming years' carbon reduction targets securely. Although a FFR service was recently introduced into the Irish electricity market and is defined as an additional MW delivered within two seconds from the start of the event and sustained for up to 10 s, the service has not yet been not well examined [28].

III. METHODOLOGY AND MODEL CALIBRATION

A. DATA CENTER LOAD MODELING

In this analysis, data centers are represented by the aggregated load at the bulk supply point connected to the transmission network, as shown in Fig. 2. Bus 04 was chosen due to the topological similarity to the real aggregation of Irish data centers in the Dublin area [21]. Data center controllers and breakers are simulated using generic-defined models in DIgSILENT PowerFactory while the communication delays are considered using python-DIgSILENT interfacing [29]. Shown in Fig. 1 layout of the overall data center load models that are modelled to participate in the DR program. As the response from IT loads and the diesel generator are not considered in this research, clearly, the remaining two types of loads are available to participate in DR using static and dynamic operation modes.

The overall methodology for data centers to participate in the FFR service is summarized in Fig. 2. The procedure starts with various DR operational scenarios for the same power generation dispatch. For the selected disturbance, system frequency metrics (i.e., frequency nadir and RoCoF) are calculated in response to both static and dynamic load models, which will be explained in the following sections. Here the static providers are modeled in such a way that the power grid is off-loaded from the entire data center in a super-fast way. This type of response is triggered immediately after the detection of the onset of a disturbance at a pre-defined frequency deviation or as an action of the TSO. In contrast, DR based on the UPS system and shiftable HVAC loads are considered as smart dynamic providers. The UPS system is developed using the standard generic energy storage model in PowerFactory. The controller is trained to provide frequency service using droop response characteristics. A portion of the exceeded UPS capacity can effectively be leveraged on command to provide FFR services similar to a vehicle to grid configuration. Furthermore, the HVAC units are modeled by non-linear dynamic model using DIgSILENT Simulation Language (DSL) with the assumption that the temperature set-point of the HVAC device is continuously altered to track

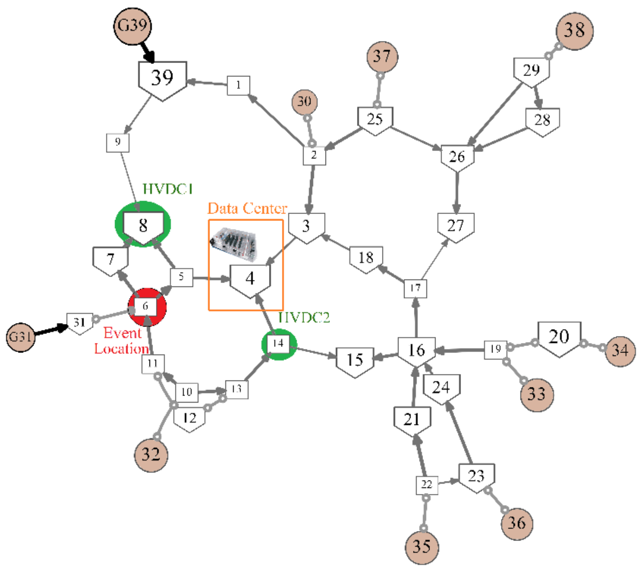

FIGURE 3. Configuration of the modified IEEE 39 bus New England system.

the system frequency signal. These committed users are continuously tracking system frequency for all frequency values outside the deadband threshold limits.

Two assumptions are made for the TSO to observe the onset of the disturbance and estimate the amount of power loss in order to trigger sufficient demand units:

i) Phasor Measurement Unit (PMU) ensures observability of the relevant major generators and controllable loads including Bus frequency, voltage, and voltage angle, etc.
ii) Distributed PMU systems can provide information about load availability involved in DR.

B. POWER SYSTEM UNDER STUDY

The standard 39 Bus New England system is used to evaluate the dynamic performance of the Irish power system under a large single infeed generator trip. The island of Ireland is synchronously isolated from any other large AC system. It is a small power system with ∼9.53 GW of dispatchable thermal generation. Peak demand of 6.53 GW and a minimum demand of 2.42 GW was recorded during the winter and summer of 2017 respectively [22].

The system contains 10 synchronous generators with a total generation and demand of 6.14 GW and 6.10 GW respectively, 34 transmission lines, 19 loads, and 12 transformers, as displayed in Fig. 3. Thus at steady state, the New England system is scalable to the peak winter demand on the Irish power system. All but two generators are responsive machines (P_{rg}) that are operating in frequency sensitive mode. Their output power change with an IEEEG1 standard governor model [30]. Generator G30 modeling is a hydro plant equipped with an IEEEG3 standard governor. Generator G39, provides inertia but no inherent droop, it is a non-responsive generator (P_{nrg}). All conventional generators are equipped with the IEEE type 1 automatic voltage regulator system and no power system stabilizers are used. The voltage dependency of loads is modeled using (1) and (2).

$$P_{L,j} = P_{Lo,j}(v_j/v_{o,j})^{\alpha j} \tag{1}$$
$$Q_{L,j} = Q_{Lo,j}(v_j/v_{o,j})^{\beta j} \tag{2}$$

where αj and βj are factors to show active and reactive power dependency of j^{th} load on the terminal voltage which are set to 1 and 2 respectively [31].

C. CALIBRATED FREQUENCY EVENT ON THE IRISH POWER SYSTEM

The New England System is calibrated in DIgSILENT PowerFactory to reflect the behavior of the Irish power system during an actual under frequency event captured by twenty PMU installed at generation sites. During the event (X), a 379 MW thermal power plant tripped resulting in a frequency nadir of 49.4 Hz after 4.32 s [32]. This accounts for 6.17% of the total system generation capacity. The system experienced a maximum RoCoF 0.42 Hz/s calculated from five points moving average using 0.1 s sampling rates. As there is no synchronous generator in the New England system with the same magnitude of the real tripped generator, the event is modeled by switching in additional load on Bus 6 in Fig. 3. This should have little difference with the generator event as the system inertia and the governor parameters are calibrated to observe frequency behavior like that captured by the PMU systems.

Validation of standard models to reflect the behavior of an actual power system is vital due to the high confidentiality reaching real power system parameters. Shown in Fig. 4, the actual frequency trace, from PMU measurements, is plotted alongside the DIgSILENT model frequency. These data are reported at 50 frames per second. As can be seen, the two graphs are highly matched for the duration up to 25 s. The uncertainty differences between both graphs are presented by mean absolute percentage error (MAPE) which is shown in the dotted black line.

The first step of the model validation was to replicate the observed RoCoF following the synchronous generation trip. The inertia of the New England system is reduced from 77 GW.s to 22.18 GW.s to fit the simulated RoCoF trace with the actually observed real power system using PMU data. This reduction is of interest as the operational inertia floor constraint ($\underline{E}$) on the Irish power system is 23 GW.s [33]. Equation (3) ensures that the operational inertia of the network remains near the constraint limits. Under the current operational scenario, inertia floor constraint of all generators (H_i) is set to 2.82 s while the inertia constant of generator G39 is adjusted to 0.30 s. It is noteworthy that the stated nominal power limit (S_i) of G39 is 10 MVA which is ten times larger than its power delivery, meaning the inertia of this unit is comparable to other units.

$$\sum_{i\notin g^{ns}} u_{i,t} \,.\, H_i .\, \overline{S_i} \geq \underline{E} \quad \forall t \tag{3}$$

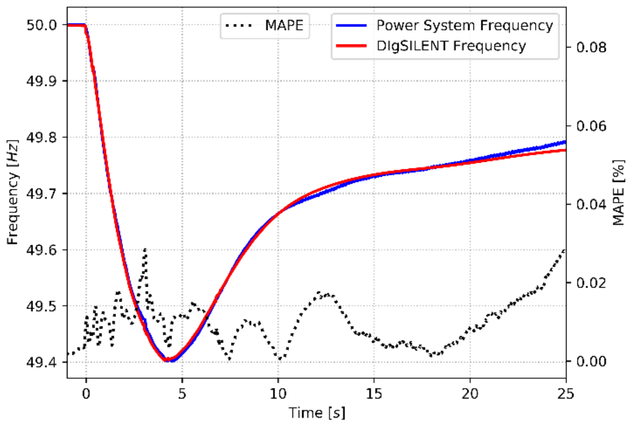

FIGURE 4. Comparison of frequency on real and modeled power systems following the loss of generation with MAPE.

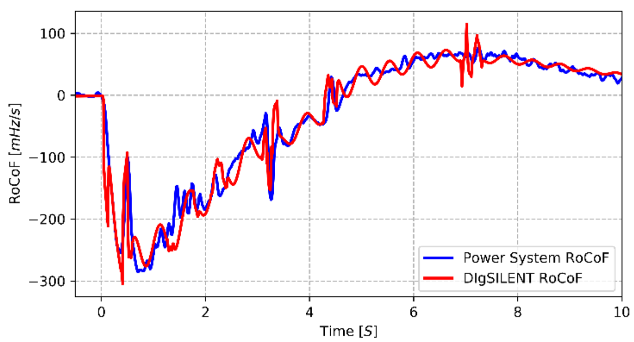

FIGURE 5. Calibrated model RoCoF versus observed power system RoCoF.

$$\sum_{j \notin g^{ns}}^{j \neq i} u_{j,t} \,.\, H_i \,.\, \overline{S_i} \geq \frac{f_o \,.\, \overline{P_i}}{2 \,.\, RoCoF} \quad \forall t, i = X \tag{4}$$

where $i \notin g^{ns}$ is set of non-synchronous interconnectors (i.e., high voltage direct current (HVDC)). After these modifications, the model RoCoF matched the actual power system RoCoF during the first 10 s post-event, as presented in Fig. 5. These observations confirm the accuracy of the validated model for the duration of the actual disturbance. In such a case the operational constraint (3) becomes (4) which ensures that inertia constant of any N-1 generators events operating at nominal frequency (f_o) and nominal power ($\overline{P}i$) does not count toward the total system inertia. These operational limits are similar to that investigated in [34].

The all Island power system import/export power from Great Britain electricity grid via two HVDC interconnectors. Both HVDC systems are modeled as negative loads placed at Bus 08 and Bus 14, respectively. Their impact comes into play during the primary response timeframe, which is considered with the addition of a term to swing (6) [35].

$$P_{rg} + P_{nrg} + P_{Tg} - \sum_{i=1}^{M} P_L = 0 \tag{5}$$

$$P_{rg} + P_{nrg} + 0 - \sum_{i=1}^{M} P_L + \Delta P_{r1} = 2 \,.\, H_{sys} \,.f_o \,.\, \frac{df}{dt} \tag{6}$$

$$P_{rg} = \sum_{i=1}^{n} P_{i,rg},\ P_{nrg} = \sum_{i=1}^{m} P_{i,nrg},\ P_{Tg} = \sum_{k=1}^{N} P_{i,Tg} \tag{7}$$

$$H_{sys} = \sum_{i=1, i \neq k}^{n} H_i \,.\, \overline{S_i} \tag{8}$$

where *df/dt* is the maximum RoCoF in (Hz/s). It is proportional to the available system inertia. P_{Tg} is aggregated output power of N tripped machines in (MW), P_{rg} is the total power of n responsive generators operating in frequency sensitive mode in (MW), P_{nrg} is a total output power of m numbers of generators none equipped governor response in (MW), P_L is the total system demand in (MW), H_{sys} is the post-event system inertia constant that no longer includes the tripped generator given in (MW.s), and ΔP_{r1} can be a response from any source of active power (i.e., HVDC, DR and storage) during the period of primary frequency response given in (MW). The response from static HVDC stations was observed when the system frequency dropped below 49.70 Hz. This represents a delay time between 1.20 s and 2.02 s from the time of the event initiated, as illustrated in Fig. 6. These observations were reported by the actual PMU measurement units that were installed at the HVDC stations.

The power imbalance equation is then used to determine the approximate operating inertia of the Irish power system during the time of the frequency event. Assuming the damping of the loads is negligible, and taking into account frequency dependency of loads in (1) operating system inertia can be calculated from (9):

$$P_{rg} + P_{nrg} - \sum_{i=1}^{M} P_L = 2 \,.\, H_{sys} \,.f_o \, \frac{df}{dt} \quad \forall\, P_L = \sum_{i=1}^{M} P_{Lo}(1 + \alpha.(f - f_o)) \tag{9}$$

The subscript (o) indicates that the quantity is evaluated at the nominal system frequency. Typically, α is 2% per Hz which denotes that for every 1 Hz drop in the system frequency, the active power of the loads drops by 2% [35]. From (9) it was roughly found that the Irish power system was operating at 22.2 GW.s during the event. This is close to the inertia of the validated DIgSILENT model with only 1% error.

IV. PROPOSED DEMAND RESPONSE FRAMEWORKS FOR DATA CENTERS

A. STATIC AND DYNAMIC FRAMEWORKS

The TSO of Ireland has defined a Service Scalar Factor (SF) for DR to be rewarded based on the response time and the trajectory to provide full active power. On the island of Ireland, DR quicker than 0.15 s following frequency excursion is within the bounds of system inertial response. The SF of 3 will be applied for this type of DR [28]. Various scalars incentivizing FFR demand provision will be applied as per (10) and (11) for a slower response within various timelines:

If 0.15 s < *Tr* < 0.5 s:

$$SF = ((0.5 - T_r)/0.35) + 2 \tag{10}$$

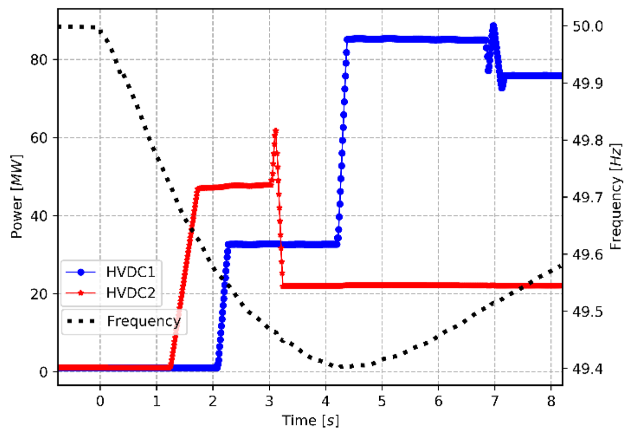

FIGURE 6. HVDC interconnectors' response to the frequency disturbance.

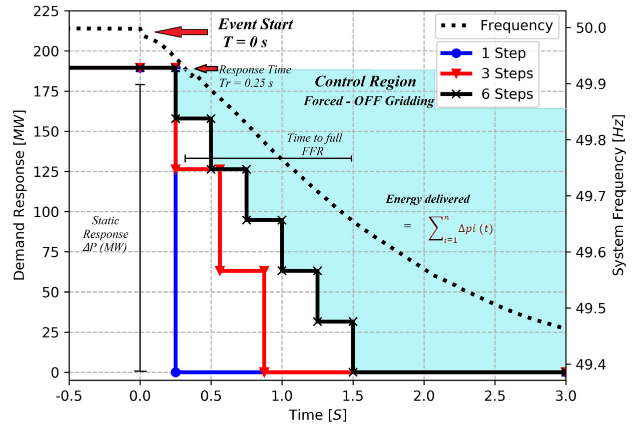

FIGURE 7. Static response frameworks deliver a different amount of energy.

If 0.5 s <= Tr < 2 s:

$$SF = ((2 - T_r)/1.5) + 1 \tag{11}$$

Considering product scalar timelines, in this study, three possible frameworks are developed for data centers to participate in FFR services in Ireland. It is assumed that 189.5 MW and 18.95 MVAR data centers are available to participate in the FFR service. This is equivalent to 50% of the magnitude of the system dimensioning generator event. The nuances of these are investigated using three control methods for data centers to respond to central and local frequency measurements. The fundamental differences in the nature of FFR configurations and their subsequent effect on the power system frequency are examined.

1) METHOD I – STATIC RESPONSE THROUGH DATA CENTER OFF-GRIDDING

The entire data center is modeled as a static dispatchable reserve without tracking the power system frequency. The providing units are required to respond to direct frequency signals from TSO indicating a large generator loss. In this case, six different configurations are presented to trigger demand up to 189.5 MW in response to the frequency event explained in Section III-C. The TSO of Ireland commits the static units to respond with no greater than 75 MW as the maximum power delivered in a single discrete step [28]. However, to examine the insights gaining from a large single demand trip and its subsequent impact on the system frequency oscillations, the providing unit is simulated first to provide the entire FFR available volume in one single step as an emergency response. It is then extended to multiple-step responses in six different configurations as an action from the operator to arrest system frequency deviation in early stages of the event, as shown in Fig. 7.

The instantaneous response from DR blocks is represented as a unit step function (u) to provide frequency control services as in (12) [35].

$$\Delta P_{rL} = \sum\nolimits_{i=1}^{m} -\sigma \, . P_{Trip} \, . u(t - T_r) \tag{12}$$

$$P_{rg} + P_{nrg} - \sum\nolimits_{i=1}^{n} P_L + \Delta P_{r1} + \Delta P_{rL} = 2.H_{sys}.f_o \frac{df}{dt} \tag{13}$$

2) METHOD II – DYNAMIC RESPONSE THROUGH HVAC LOADS

The HVAC units are developed in DIgSILENT PowerFactory as a user-defined ramp-up function. It is assumed that 189.5 MW of the controllable HVAC loads are available to participate in the FFR service. With the help of a rather simple frequency controller, the individual HVAC units can be adjusted independently to deliver an incremental change in consumption at various Tr within a timeframe $\in [0, T_{FFR}]$. The aggregated response (P_{DRmax}) of all small-scale controllable loads is ramped down and linearly deployed within the window T_{FFR}. This process creates a stepped shaped signal similar to the static response with very little power change (ΔP) per step using (14).

$$P_{DR} = \begin{cases} 0, & \forall \Delta f > \Delta f_{db} \\ -K(\Delta f - \Delta f_{db}), & \forall \Delta f_{db} \geq \Delta f \geq \Delta f_{\max} \\ P_{DR\max} = \Delta P_{\max}, & \forall \Delta f > \Delta f_{\max} \end{cases} \tag{14}$$

where K is the demand response coefficient similar to the droop based characteristics. At Δf_{max}, the manipulated DR unit providers must provide all contracted power. These unit providers are simulated to continuously track system frequency deviations with a trajectory shown in Fig.8. It is noteworthy that the mandatory requirement for DR to ensure eligibility for the FFR service in Ireland is that the units are required to respond in at least ten discrete steps in a continuously controlled manner, with no individual step size greater than 5 MW or than the average step size plus 1 MW [36].

3) METHOD III – DYNAMIC RESPONSE THROUGH UPS SYSTEMS

In this method, the onsite UPS systems are modeled in DIgSILENT using a generic battery energy storage model. It is assumed that 189.5 MW UPS systems are in operation

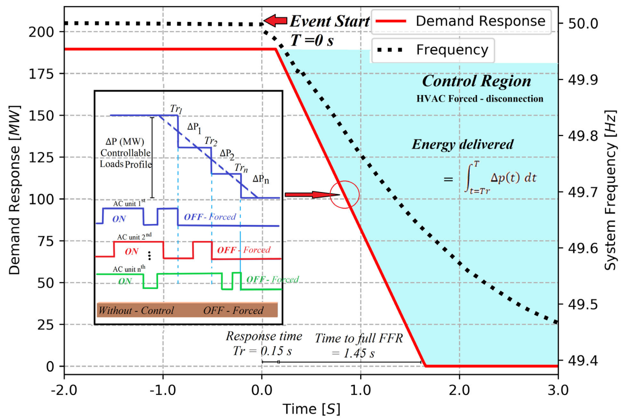

FIGURE 8. Dynamic DR trajectory framework based on the HVAC loads.

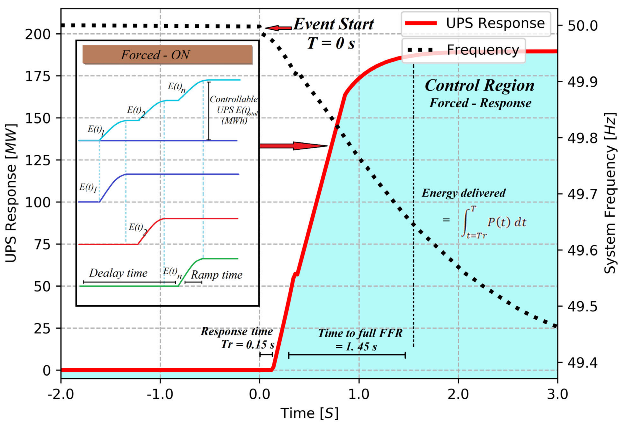

FIGURE 9. Dynamic DR trajectory framework based on the UPS systems.

which accounts for the aggregation of 158 units with about 1.2 MW each. These models are designed to continuously track system frequency deviations with a trajectory shown in Fig. 9. The local frequency controller inside the UPS monitors system frequency and instantly creates control signals in response to any frequency deviations within a deadband ± 0.05 Hz. In this particular disturbance, system frequency deviation reached the predefined threshold limits after 0.15 s following the event. The UPS systems are fully activated when the system frequency dropped below 49.5 Hz within a period 1.45 s. This ramping in the UPS power corresponds to 0.2% droop response. The total energy delivered to the grid before the frequency reaches nadir takes the form given in (15).

$$E(t) = P_{UPS} \times (T_{nadir} - \frac{T_{FFR}}{2} - T_r) \tag{15}$$

This expression indicates that the ameliorating impact on the frequency deviation is directly proportional to additional energy provided during the FFR service before the frequency nadir is reached [37]. It is important to ensure the state of charge (SoC) of the UPS to remain within the upper and lower bands to prolong the battery life time as well as to guarantee the operational safety of the system. These limits are predefined for which the $SoC_i \in [SoC_{i,min}, SoC_{i,max}]$ and they are limited to 20% and 80% of the UPS storage capacity, respectively [38].

V. RESULTS AND DISCUSSIONS

A. EFFECT OF DEMAND RESPONSE ON SYSTEM FREQUENCY NADIR

The primary objective of this subsection is to examine the impact of developed static and dynamic DR methods on the performance of the calibrated frequency event in Section III-C. Displayed in Fig. 10 is the impact of 189.5 MW static DR on the frequency nadir resulting from the trip of a thermal plant operating on the Irish power system model. The disturbance occurred at 0 s while test conditions are recorded and evaluated for 12.0 s using 0.02 s sampling rate. It is noteworthy that during the first few instants following the event, regional frequency measurement (f_i) in the power system may not reflect the so called center of inertia frequency (f_{COI}). In this section, the f_{COI} is calculated using the center of inertia constants and frequencies on individual buses as per (16).

$$f_{coi} = \sum\nolimits_{i=1}^{n} H_i \,.f_i / \sum\nolimits_{i=1}^{n} H_i \tag{16}$$

where n is the total number of buses in the model. As shown, static DR can effectively offset the impact of generator outage, and therefore the frequency nadir, T_{nadir}, and recovery time are significantly reduced. Cleary demand units were capable to arrest system frequency at 49.75 Hz within less than 2 s compared to 49.4 Hz after 5 s for the grid with no DR. Lastly, system frequency recovered to 49.9 Hz after another 6 s with very little oscillations.

One important observation is that, as the size of DR unit providers was half of the tripped generator, system frequency did not recover completely to the steady-state value. Another observation is that the degree of frequency nadir improvement is varied depending on the number of discrete stepped response. A linear improvement can be observed with a decreasing number of steps. This is primarily due to greater energy remaining in the power system as a result of the power change occurring earlier. Aggressive remedial action can clearly have a larger influence on rebalancing generation/demand resulting in a more favorable frequency nadir. This is most obvious from the single trip load response that was able to arrest system frequency at a nadir 49.82 Hz within 2 s. The frequency trace is then recovered to quasi-steady-state value after 8 s from the start of the event. Since the provision of FFR service is to arrest frequency nadir, a single step response is vital and desirable during emergencies.

A concern may be that such an aggressive step load response introduces frequency oscillations. However, none are observed in Fig. 10. Typically, engineers are very reluctant to introduce a large step response due to the fears in regard to the subsequent frequency oscillations. It is important to note that the static step responses introduced with demand units are quite different from cyclic loads, such as cement mills and aluminum processing plants, that are known to cause system

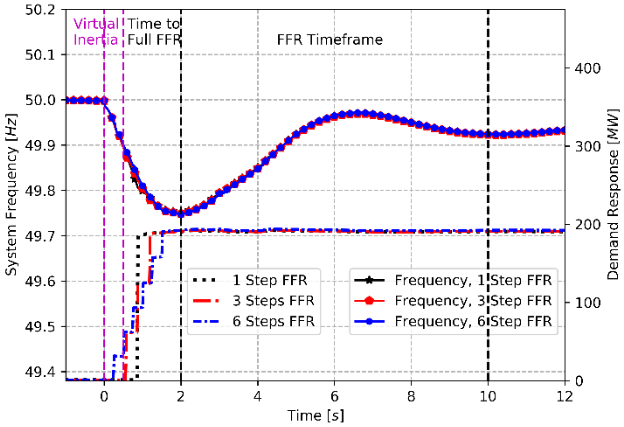

FIGURE 10. Effect of static DR configurations on the frequency nadir.

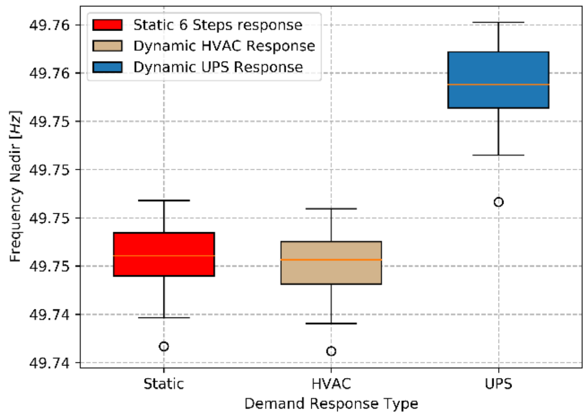

FIGURE 11. Impact of dynamic and static DR on the system frequency nadir.

oscillations [39]. Frequency oscillations tend to emerge when the power system is perturbed at frequencies similar to a natural system mode [40]. In this research, generator swing and rotor angle have not been exhaustively studied to assess rotor angle stability and interarea oscillations.

The analysis is further developed to compare the impact of both static and dynamic DR developed methods on the frequency nadir, as shown in Fig. 11. It is important to note that static six-steps demand response is the only comparable case with the dynamic providers over the same time frame Tr to T_{FFR}. Other step response can also be compared if more aggressive dynamic droop characteristics are considered. Nevertheless, these are extensively considered in the next section. Shown in Fig. 11 is the collected frequency nadirs from all the terminals inside the 39 Bus New England system. Then the maximum, minimum, and standard deviation of the frequency nadirs are illustrated as the whisker box plot. It is obvious that similar frequency deviations are observed from all the developed methods. This has resulted from the amount of energy delivered from dynamic providers over a course of the time period 1.45 s was the same as the energy provided from static six-steps unit providers throughout the first 1.25 s from the start of the event. Nevertheless, for the dynamic response to provide the same energy as the static provider, the earlier has activated after 0.15 s from the time of the event began and reached full output power after 1.6 s which is slightly later than static six-step response.

B. EFFECT OF DEMAND RESPONSE ON ROCOF

The main problem with the RoCoF calculations, both on a real and simulated system, is the measurement window used to calculate the second derivative of the phase angle. Much noise can be attributed to the RoCoF if it is calculated over a short period due to the fact the differentiation tends to amplify noise mainly during a short timeframe [37]. Another factor that affects RoCoF measurement is the place where the RoCoF is monitored in the network under transient conditions. As an example, during the first few seconds following the disturbance, the remaining synchronous generators swing against each other resulting in different RoCoF values being observed at various locations. Therefore, RoCoF can be very sensitive to both voltage vector shift and rotor angle oscillations which can imply substantial RoCoF values during a short timeframe [27]. Thus a consistent system wide RoCoF measurement can be obtained considering only mechanical transient on the system while eliminating electrical transients from the analysis. The analysis here avoided these concerns and the RoCoF is computed as the first derivative of the system frequency (*df/dt*). For a given time period of the analysis, the raw data is captured from PowerFacotry using 0.02 s sampling step size (T_{step}) and the maximum RoCoF ($RoCoF_{max}$) is calculated using (17).

$$RoCoF_{\max} = \max\{RoCoF_{x,i}\}, \quad \forall x, i \in N_{RoCoF} \tag{17}$$

$$RoCoF_{x,i} = \sum\nolimits_{i}^{N} f_{x,i}/N_{RoCoF}, \quad \forall x, i \in N_{RoCoF} \tag{18}$$

$$N_{RoCoF} = T_{RoCoF}/T_{step} \tag{19}$$

where i is the time step of the time domain simulation, T_{RoCoF} is the measurement window (0.5 s) over which the RoCoF is calculated. The timeframe of 0.5 s corresponds to that deployed for the current anti-islanding RoCoF relay settings in the Irish power system grid code [34], [41]. Other shorter rolling windows (e.g., 0.1 s and 0.25 s) are also proposed in literature [41]. However, short timeframes result in a higher RoCoF values which might be challenges for some technologies to detect the onset of a disturbance accurately. Thus the use of 0.5 s RoCoF rolling window is supported by the TSO definitions. It also reflects the issues of calculating RoCoF data from frequency waveform over short timeframes [37]. Furthermore, by extending the RoCoF measurement window, electrical transients can be excluded from the measurement waveforms resulting in a more consistent system RoCoF. This may also remove the mechanical transients leading to false RoCoF values.

The impact of various static DR patterns on the performance of system RoCoF is shown in Fig. 12. As illustrated for all scenarios the fast DR alleviated the initially high RoCoF measurement, without causing subsequent RoCoF disturbances. However, the impact of the FFR service is gradually

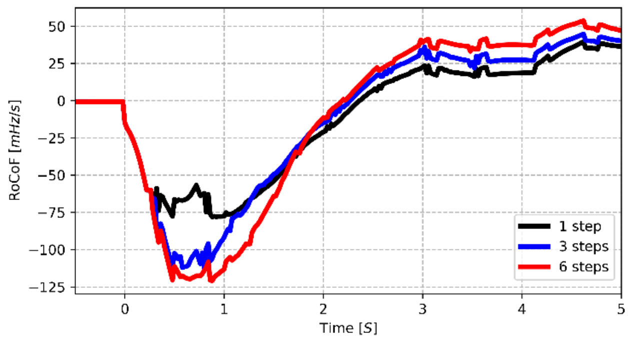

FIGURE 12. Effect of static DR discrete steps on the system RoCoF.

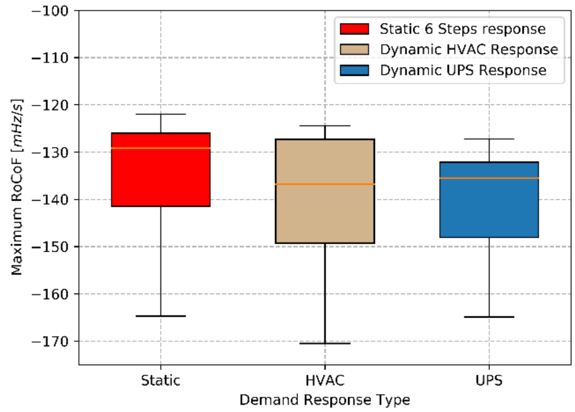

FIGURE 13. Impact of dynamic and static DR on the maximum RoCoF.

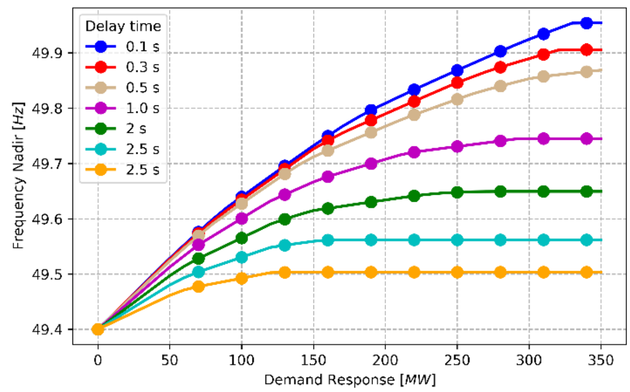

FIGURE 14. Impact of static single-step DR times and sizes on the frequency nadir.

degraded with increasing number of the step response. As an example, the most aggressive single-step static response has resulted in significantly better RoCoF −75 mHz/s in comparison to the static six-steps response that reduced RoCoF to −125 mHz/s. Furthermore, in a single-step DR, the severity of RoCoF diminished after 3 s and approached zero earlier compared to other scenarios. This is caused by the large volume of energy dispatched from single-step DR over a timeframe of 0.5 s from the time of the event began compared to other scenarios. Although this approach does not replace synchronous inertia response from conventional generators, it can considerably alleviate the high RoCoF in low inertia power systems.

The analysis is extended to compare the effect of dynamic and static DR on the maximum system RoCoF. The extreme RoCoF values experienced on all the buses are recorded during the same frequency event. Then the maximum, minimum, and standard deviation for all the maximum RoCoF values are shown in Fig. 13 using box plots. As can be seen, the RoCoF differences among all the terminals in the power system are nearly similar. This is evidence that delivering equal energy during the first 0.5 s from the moment of the event initiated results in the same RoCoF improvement regardless of the source of the DR.

Clearly, there is a big difference between static single-step DR shown in Fig. 12 with the dynamic and static six-steps DR in Fig. 13. The problem with the dynamic response based on frequency controller and static multiple-step response is that there is always the possibility of activating a part of the loads when the system frequency falls below 49.70 Hz. On the Irish power system, this frequency is typically reached after ∼1.0 s and that is too late to reduce the risk on activating RoCoF relay which response within the first 0.5 s from the start of the event to protect distributed generators [37]. Thus these results demonstrate that dynamic response, as well as static based multiple discrete step response, may not significantly improve the system frequency RoCoF unless the delay time between the subsequent triggers is shortened. However, the shorter delay time translates directly into aggressive droop response which eventually provides a trajectory similar to a large single-step static response.

C. IMPACT OF RESPONSE TIME AND DEMAND POWER ON FREQUENCY NADIR

This section investigates the effect of the projected communications delays and the DR capacity in MW on the frequency nadir resulting from the frequency event in Section III-C. Since the provision of FFR is considered to be the fastest form of energy reserve following the timeframe of inertial response, the quickest activation of FFR service is significantly important. The effect of static step response time (*Tr*) on the frequency nadir is shown in Fig. 14. The consistency of the results is evaluated assuming that the unit providers deliver 100% of their available volume within a single-step response. Then the response time is changed from 0.1 s up to 2.5 s beyond which DR procedure may fail to have significant effect on the nadir. Then for each delay time, the participant capacity is increased from 50 MW up to 379 MW and that is equivalent to the power lost during the generator event.

As would be expected DR with minimum delay time and maximum dispatched power has the greatest impact on the frequency nadir. This type of response is vital to rapidly arrest system frequency deviation in low inertia systems. However, to avoid the likelihood of false triggering and frequency overshoot, robust control systems are required to accurately estimate power mismatch within a short time following generator

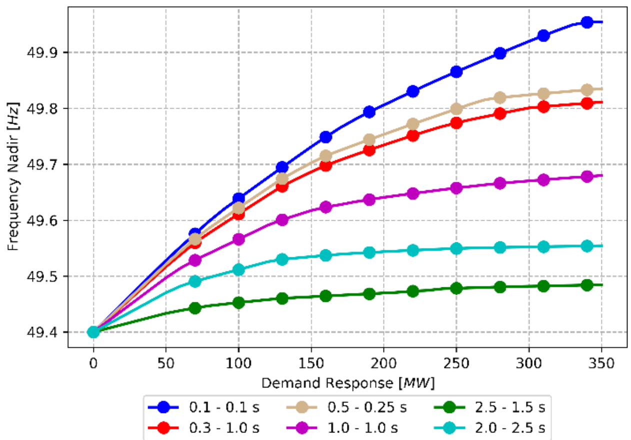

FIGURE 15. Impact of dynamic DR time, ramp time and sizes on the frequency nadir.

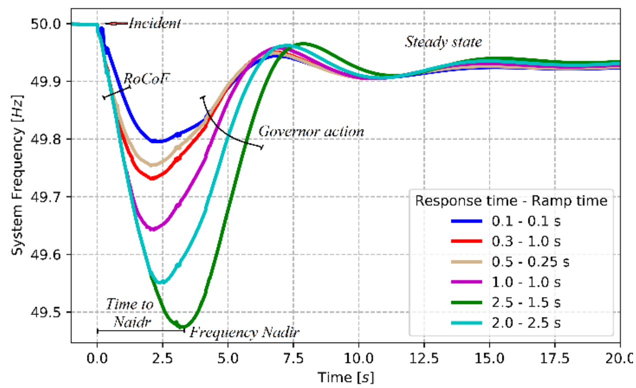

FIGURE 16. Effect of 189.5 MW dynamic DR times and ramp times on the time to reach frequency nadir.

outages. As shown in Fig. 15, for the fast activation of FFR service below 1.0 s, frequency nadir changes almost linearly. The prompt activation of DR was capable of handling system frequency with a relatively lower capacity compared to the slower response. As an example, 150 MW DR with a delay time of 0.5 s resulted in a frequency nadir of 49.67 Hz. Nevertheless, for the same nadir at a delay time of 1.0 s, 200 MW DR will be required. In addition, there is a significant positive correlation between frequency nadir and the power delivered up to 1.5 s delay time. However, no difference of more than 0.1 Hz can be observed for trigger time slower than 1.5 s at various power ratings. These figures show how the FFR service diminished for a response time later than 2.5 s with the frequency nadir becoming closer to the originally observed frequency disturbance.

A similar analysis is performed to examine the impact of various parameters associated with dynamic DR equipped with droop characteristics on the frequency nadir, as shown in Fig. 15. This kind of response could be provided from either the UPS or the HVAC units. A range of response times varied from 0.1 s up to 2.5 s with different ramp times 0.1 s up to 2.5 s are examined. These parameters are chosen to comprise many scalar factors that are designed for FFR service providers' capabilities in Ireland. It is obvious from these graphs, the quickest response time with extreme frequency trajectory (droop response) reduces frequency nadir significantly. This is most obvious from 0.1 s response time with 0.1 s trajectory ramp time that enhances the usefulness of the service. These features are more prevalent in island networks such as Ireland and the UK with high wind power generation. Typically, linear frequency nadir improvement can be seen for DR up to 0.5 s with extreme droop response up to 1.0 s and that is similar to the static DR in Fig. 14. Lastly, for a response time within a course of 0.5 s up to 2.0 s, demand size greater than 150 MW does not affect frequency nadir significantly.

Another important frequency metric that diminishes with the FFR service is the time to reach frequency nadir and the time required to recover to a steady state. As shown in Fig. 16, the prompt DR with aggressive ramping reduces the time required to arrest the system frequency drop. Therefore, the frequency recovered and reached a steady state earlier without causing subsequent frequency oscillations. This feature is important as it reduces droop response requirement from synchronous generators and eventually the requirement for additional dispatchable spinning reserve falls during contingencies. It is apparent from the graph that with a successive increase in response time and ramp time, the nadir and the RoCoF moved closer to the originally occurred frequency disturbance.

D. IMPACT OF RESPONSE TIME AND DEMAND POWER ON ROCOF

This section turns now to highlight the effect of response time and demand size in MW on the maximum RoCoF averaged over 0.5 s. These parameters are examined using both static single-step DR as well as dynamic DR. The impact of single-step DR time and size on the plot of maximum RoCoFis shown in Fig. 17. As can be seen, there are many similarities between these graphs with the plot of frequency nadir for response times up to 0.5 s. Literally, the maximum RoCoF reduces linearly within the timeframe of inertial response 0.15 s. Outside these boundaries and up to 0.5 s, the effectiveness of DR is gradually moderated. This is a rather remarkable outcome, as the RoCoF remains unchanged for static response later than 0.5 s regardless of the dispatched demand size. As an example, a 150 MW DR within 0.15 s reduces the maximum RoCoF to roughly 135 mHz/s. Nevertheless, the same demand capacity with a response time slower than 0.5 s does not affect the maximum RoCoF.

A similar analysis is primarily presented to examine the effect of dynamic DR parameters on the RoCoF, as illustrated in Fig. 18. These results are comparable with the static step response as there is very little improvement in the maximum RoCoF for a dynamic response beyond the inertial response timeframe.

In summary, for the FFR service to make significant contributions toward the maximum RoCoF, a rapid

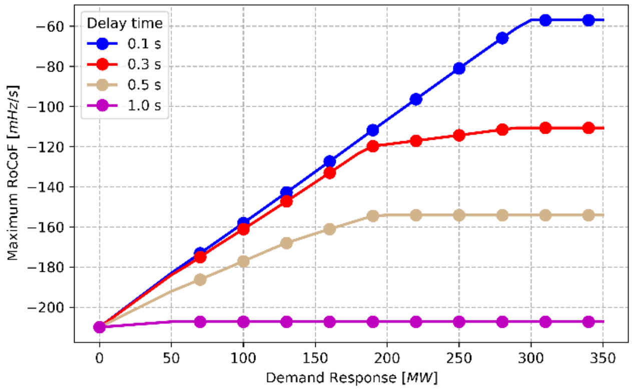

FIGURE 17. Impact of single-step static DR time and size on the maximum RoCoF.

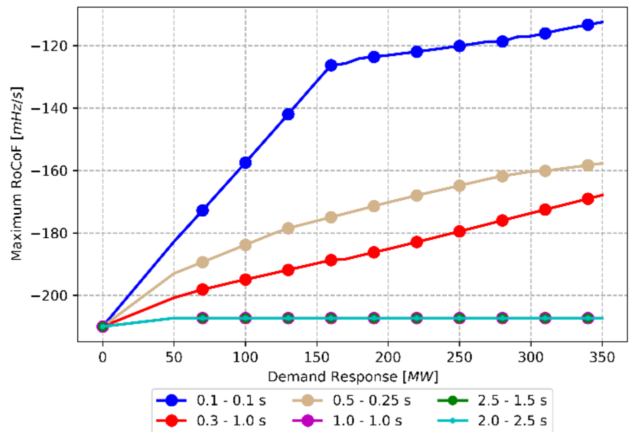

FIGURE 18. Impact of dynamic DR times and ramp times on the maximum RoCoF.

emergency response signal is required within less than 0.3 s with extreme droop response. However, there is an inherent trade-off between RoCoF measurement period, detection, and measurement accuracy. The longer measurement time (e.g., 0.5 s) translates directly into latency in the final control signal whereas low inertia systems require a shorter response time to arrest frequency deviation as quickly as possible. Overall, these results indicate that the whole control system should take prompt action under contingencies that may require high-speed communication signals to coordinate multiple responsive data centers. However, under certain conditions, communication congestion results in a large delay time that degrades the performance of the system frequency as presented.

VI. IMPORTANT FINDINGS AND RECOMMENDATIONS

Maintaining grid operating parameters closer to the nominal level is more difficult on islanded networks (e.g., Ireland, Australia, New Zealand, and the UK) [27]. These grids typically have lower inertia and the loss of large infeed, i.e., synchronous generator, and HVDC causes significant frequency deviation [42]. Such frequency excursions are more likely to result in cascade failures and in extreme cases, complete system blackouts, similar to that occurred in South Australia in 2016 [43]. Thus fast active power response and new FFR services are required to offset the active power deficit as soon as the power imbalance occurs. Nevertheless, there is still limited technical information related to the application of DR for FFR services in these power systems. In some circumstances, there is inadequate data available to perform DR analysis for the FFR service. Though FFR service can pose significant barriers to the deployment of grid-scale DR, the superior interaction of the electricity consumers with the power system also presents its own concerns. This is mainly caused by the need for greater data collection and an escalation in information flow between both the demand side and the TSO from the supply side of the power system. Thus comprehensive data recording and analysis regimes are recommended in place for the DR demonstration projects to ensure that there is abundant high quality data for long term analysis.

This investigation is intended to facilitate analysis of the technical characteristics and capabilities of data centers as an opportunity for the FFR services. Typically, a large number of domestic or light industrial loads are considered for such services, but these present challenges in terms of monitoring and control. However, DR based on data center makes the status of controllable loads fully known for the TSO at any time, which assists in managing power system security efficiently. In this piece of work, data centers are modeled using both static and dynamic sources of FFR providers that could respond to emergency signals in both centralized and decentralized manners. This could boost the adoption of renewable energy, increases the green contribution of data center, and generate revenue.

Data centers are seen as having great potential to provide fast-acting reserve enabling aggregation of a large number of UPS systems as well as HVAC cooling systems. Modern UPS systems with the supporting features can deliver a fast response to meet TSOs need to deliver FFR services against disturbances. This investigation showed that the DR type whether it is static or dynamic does not make a notable difference in system frequency performance as long as dispatched energy over the timeframe of the FFR service remains the same. Furthermore, the analysis results suggests that the DR strategy should not solely aim at maximizing frequency nadir as this can potentially lead to high system RoCoF in case of FFR service responded later than 0.5 s. It was also shown that the precise relationship between the required DR capacity for the FFR service depends on the nature and specific response characteristics of the service (e.g. response time and ramp time).

Furthermore, the static DR is modeled using six different configurations in which the unit providers were able to respond to emergency trip signals from the TSO. The unit providers were able to deliver different amounts of energy within the timeframe of FFR service. It was shown that it is important for the demand to dispatch as much energy as possible within a very short time in response to transient frequency events. This was possible to gain from static single-steps DR that effectively rebalanced the power system without introducing subsequent frequency oscillations. However, the ability to respond faster requires the capability of being able to measure what to respond to more quickly and accurately to avoid frequency overshoot. It is noteworthy that the fast event detection based on the current PMU technologies might not technically viable due to the communication delays, and attributed noise to the RoCoF measurement if it is calculated over short periods. This limitation on the PMU data measurement capabilities and the lack of previous experience pervades most of the challenges and barriers associated with deployment of FFR service. Thus, robust monitoring systems will be fundamental future needs for FFR services.

VII. CONCLUSION

The operational flexibility of data centers can be leveraged to provide FFR services in the Irish power system. In this analysis, three frameworks are developed for data centers to deliver FFR services from their UPS storage systems, HVAC cooling units, and the ability of off-gridding the entire data center during transient frequency events. The proposed methods are implemented and extensively analyzed on the standard 39 Bus New England system calibrated to an actual frequency event that occurred on the Irish power system using real-time DIgSILENT PowerFactory. The impact of both static and dynamic DR models on the system frequency metrics i.e. frequency nadir, RoCoF, and frequency recovery times are presented and compared. It was possible to conclude that all models can significantly improve system frequency metrics and able to arrest system frequency nadir in the early stage of the disturbance. However, compared to the dynamic response, a linear improvement was found in the system frequency when the number of static step response is decreased. Another important observation is that for DR to make a significant contribution to system frequency nadir and RoCoF, response time within the inertial response interval will be required in less than 0.3 s following the event. This kind of response was possible to gain from the deployment of static single-step load trips in a super-fast way as well as from dynamic loads equipped with aggressive droop parameters.

Future analysis will investigate the proposed approaches on the projected low inertia Irish power system, operating at high and super high wind generation. The coordination capability between different sources of static FFR services will be examined to avoid undesirable implications.

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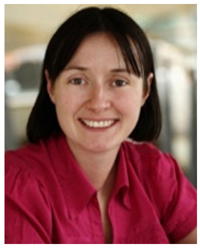

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