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# Challenges in Utilisation of Demand Side Response for Operating Reserve Provision

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**Abstract**—Utilisation of flexible demand to provide contingency reserves is generally considered beneficial to power systems, and can be a key enabler for ambitious renewable energy penetrations. Detailed techno-economic analysis of reserve provision from flexible demand is considered in this paper. A unit commitment/economic dispatch problem is set up that recognizes flexible demand side response (DSR) as a source of primary operating reserve (POR). Dispatch schedules are then verified with frequency stability and network analysis assessments to quantify any changes in system performance. It has been demonstrated that while generally beneficial, utilization of DSR does not always improve system performance. Factors such as changes in plant dispatch (largest in-feed contingency can be greater) and flexible demand resource variability have been shown to limit the benefits of DSR under certain conditions. Actual activation of DSR for POR is also shown to compromise network integrity in some cases. All results are demonstrated using the Irish power system and domestic water heaters as representative flexible load.

**Index Terms**—Primary operating reserve, contingency reserve, demand side response

## I. INTRODUCTION

Advancement in information and communication technology along with recent global drive towards renewable energy sources is changing the way power systems are operated. One of the major implications of this change has been a larger role for flexible demand. Demand side response (DSR) has been shown in literature to have the capability to provide a number of ancillary services including load shifting [1], frequency regulation [2], provision of contingency and balancing reserves [3] and a reduction in net load (system load to be met by conventional generation) variability [4]. Flexible demand is being used in a number of jurisdictions around the world such as PJM, ERCOT to provide such services [5], [6].

Power systems are operated such that the system has enough flexibility to maintain stable operation following the transient loss of a largest in-feed (leading to frequency drop) or out-feed (leading to frequency increase). The immediate power required to offset the imbalance resulting from such a contingency (up to 15s after the contingency) constitutes the primary operating reserve (POR), traditionally provided from

supply-side sources. Renewable sources can lead to displacement of conventional plants in the dispatch, while simultaneously increasing the reserve requirement [7]. Provision of POR from flexible demand is considered a potential solution. In addition, it has also been demonstrated that due to faster response time, flexible demand may at times be preferable to conventional plant [8]. The ability of flexible demand to increase consumption in a loss of load/export (over-frequency) scenario further strengthens the argument for its utilisation. Domestic thermostatically controlled appliances (TCAs) that include cooling load (AC/refrigeration), space heaters and domestic water heaters (DWHs) can be considered suitable flexible loads due to their discretionary nature, thermal inertia and significant share in total system demand. Provision of POR from TCAs by altering the thermostat setpoints has also been envisaged by ENTSO-E [9] for a potential large scale roll out.

To maximize the economic benefit of DSR reserve availability, it must be endogenously included in the market scheduling process. Research in [10] [11] evaluates including DSR in a unit commitment and economic dispatch (UC/ED) problem for not only reserve provision but also for providing energy arbitrage, but the system frequency nadir impacts (lowest value of system frequency following the loss of largest in-feed) and/or other technical implications (frequency recovery) of this DSR POR dispatch inclusion have not been fully studied. However the majority of studies that demonstrate the usefulness of flexible demand as a source of POR do so by manually replacing available POR capacity from conventional plant (mimicking a pre-scheduled POR from flexible demand), without performing an economic dispatch with DSR included as a source of POR [12] [13] [14]. Moreover only a few snapshot system conditions always yield a better system performance in the presence of flexible demand. In order to ascertain the actual benefit of using DSR as a source of reserve in the system, an integrated technical and economic assessment is warranted. Representation of flexible demand with dynamic models is also essential to capture its seasonal, weekly and intraday variation. Due to the fast response required in smaller low inertia systems and those with high wind penetration, it has been demonstrated that change in thermostat set points in proportion to local frequency measurement may be the most suitable solution

[12]. However the magnitude of this proportionality has mostly been assumed as constant in all system conditions. Provided a significant penetration of DSR enabled load, this may cause undesirable phenomena in certain circumstances. Aside from the work in [15], most studies have so far considered only the active power balance provision by DSR and neglect potential network impacts arising from it. [15]

The main contributions of the work in this paper are the identification of possible complexities in DSR POR utilization. This work bridges the gap between scheduling DSR through an economic dispatch problem only, and the important validation of its technical impacts on system performance following supply/demand-side contingencies. Instead of using a few isolated indicative cases, an extensive year-long time series study has been carried out to more broadly evaluate DSR POR impacts, allowing the identification of isolated scenarios where system performance may actually degrade without additional intervention. Further limitations arising from DSR resource variability have been shown using individual dispatch scenarios. Finally the link between DSR POR activation and system conditions from network's perspective has also been demonstrated.

## II. METHODOLOGY

In order to capture the variability of domestic water heating (DWH) load, dynamic load models have been developed in Matlab to provide an estimation of the potential demand resource magnitude available across a year incorporating seasonal and temporal variation. The DSR magnitude obtained from load models, serves as an input to a unit commitment and economic dispatch problem for the Irish power system, set up in GAMS. The resultant system dispatches obtained are used to simulate the loss of largest generators in a detailed Irish power system model (in Simulink) which includes DWH dynamic load models. A detailed network model of Irish system in PSSE is also utilized to demonstrate the potential network impacts of POR provision through DSR.

### A. Aggregate water heating load model

Domestic resistive water heating load is a suitable representative TCA due to its availability throughout the year, and its large share of the domestic electricity demand. A bottom up approach has been taken, where a number of individual water heater models with corresponding water draw patterns have been simulated and their power consumptions aggregated to produce the overall power consumption profile. As opposed to a regression approach, individual water heater simulation is necessary to provide a more detailed representation of appliance response, to the control signals (such as system frequency). Each DWH has been simulated using the classical single node model [16], based on energy balance within the water heater tank. The prime driver of DWH power consumption is hot water usage, which is represented by water draw events such as hand wash, dish wash, shower and bath. These events have been modeled with the relevant flow rates, probabilities of occurrence and seasonal variations based on [17]. To recognize appliance heterogeneity and the dependence of water tank size on the

number of occupants, the Irish domestic sector has been divided by dwelling types, each having different occupancy range with actual occupancy, probabilistically determined. The water tank characteristics such as tank volume and element rating depend on the dwelling type, while thermostat settings, appliance efficiency and thermal capacitance have been probabilistically distributed across the DWH population to account for variations in the appliance characteristics in reality, as is outlined by the modeling procedure shown in Fig. 1. The model recognizes the intra-day, seasonal and weekday/weekend variations in aggregate DWH consumption.

### B. Unit commitment and economic dispatch model

The UC/ED problem minimizes the combined energy and reserve costs of the Irish power system, with an hourly time resolution. The Irish power system is a relatively small (11.7 GW installed) synchronously isolated system with limited HVDC interconnection (1000 MW) to Great Britain (GB). The Irish system case assumed here consists of combined cycle gas turbines (CCGT), combined heat and power plant, coal plant, gas turbines, hydro plants, a pumped storage hydro plant (292 MW) and wind farms (4.9 GW installed, inclusive of fixed speed (FS) and variable speed (VS) turbines. All individual units and relevant constraints for the Irish system have been included in the model. In order to accurately predict the Irish system power import/export, the GB system has been modeled with plants lumped together based on plant type. Aggregate DWH demand can be included in the model as a source of reserve, where the maximum available POR in the case of supply-side contingency (under-frequency event) is the actual magnitude of DWH demand; while the maximum available POR to a demand side contingency (over-frequency event) is the difference between the total installed DWH capacity and its demand magnitude at that time. It has been assumed that there is no cost for utilisation of DSR and customers are remunerated at the purchase of a responsive appliance through discounts. Relevant constraints on the minimum amount of reserve, minimum number of units required online and maximum penetration of wind as specified by the Irish TSO have been included. Two instances of UC/ED model are run for an entire year, with DSR recognized as a source of POR for one case and disregarded for the other. The model has been set up as a mixed integer problem (MIP) and solved using the CPLEX solver.

### C. Power system models

A single bus model of the Irish power system has been used for frequency stability evaluations. The model assumes a uniform system frequency across the power system and contains detailed representation of each plant type. It works on frequency deviation from nominal which is determined by integrating active power imbalance, with plant performing with a 4% governor droop. It also contains representation of pumped hydro storage plants and under frequency load shedding schemes. Instantaneous static reserve provision from HVDC interconnectors (49.6 & 49.5 Hz) and on load storage plant (49.6 to 49.3 Hz) has also been represented. The model has been validated over a number of years with system contingency data obtained from the system operator. Further details on the model can be found in [18]. A flexible load block containing individual DWH dynamic models has been

incorporated, with system frequency deviation as its input and DSR POR provision magnitude as its output.

In order to carry out an estimation of network impacts of DSR provision, transmission network model of Irish power system in PSSE published by the Irish TSO has been utilized. For a chosen system condition, system bus voltages in steady state are calculated by power flow analysis. A loss of largest infeed, followed by provision of POR by flexible demand to offset the demand/generation imbalance is considered. System bus voltages corresponding to steady state reached after the POR provision from DSR are recorded. Pre and post contingency bus voltages are compared against recommended bus voltage limits (specified by TSO).

### III. RESULTS AND DISCUSSION

The water heating load model discussed in section II-A has been up scaled to 400,000 electrical DWHs (with remaining households using oil/gas fired central heating systems), assumed to represent the maximum system level flexible demand. The flexible appliances are assumed to have the capability to measure system frequency locally and alter thermostat set-point accordingly as suggested in [12]. A local frequency control is more suitable for provision of POR as it doesn't require any communication latency and ensures a quick response – a fast reserve response is essential in a low inertia power system where frequency excursions can be more extreme than larger interconnected systems. Since the flexible load is not being used here to provide system frequency regulation, erroneous triggering of DSR needs to be avoided. To that end, DSR control has been set up in such a way that there is no change in power consumption of individual appliances for a small fixed frequency deviation from the nominal, called deadband (DB). Beyond the deadband, for a specified system frequency range called operating range (OR) the aggregate flexible load POR responds linearly with respect to frequency excursion, going from 0 to 100% of available DSR. On individual DWH level, this is achieved by changing appliance thermostat setpoints akin to governor droop, as suggested in [9]. The actual DSR magnitude delivered to power system depends therefore on system frequency deviation from nominal (50 Hz) and the magnitude of available DSR. The obvious advantage of using DSR for POR when compared with conventional plant is its higher response speed. In this work, DSR has been assumed to respond with a time delay of 300 ms. The combination of DB and OR for flexible demand control can be thought of as being similar to droop of a conventional plant. In order to make the most of its faster response time, DSR should ideally have a droop setting (combination of DB and OR) smaller than a conventional plant. In all subsequent cases a deadband and operating range of 0.2 Hz has been considered for further analysis.

#### A. Aggregate water heating load profile

The aggregate water heating load profile developed for a year long duration at hourly time resolution is used to establish the UC/ED dispatch with DSR. Fig.3 shows the aggregate load profile for a typical weekday and weekend. This classical double humped profile generated from the load model demonstrates a large intra-day variation. The morning peak

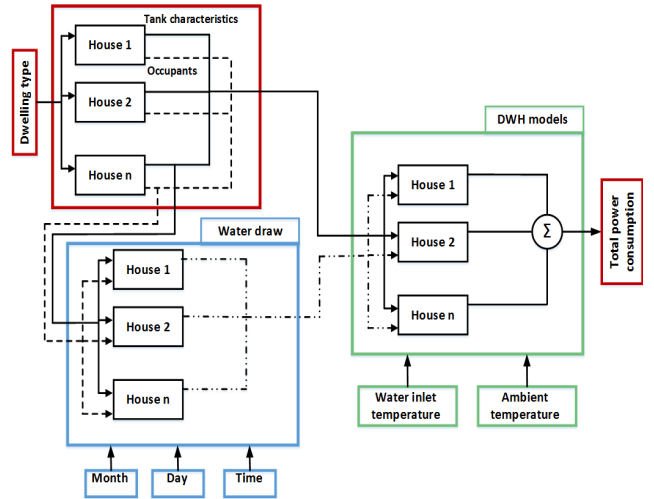


Figure 1. Aggregate load modeling

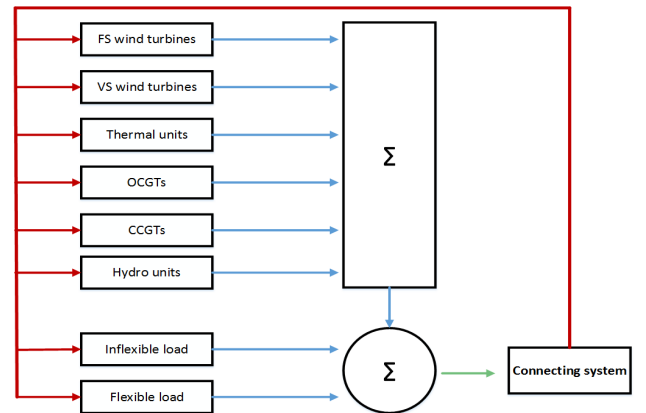


Figure 2. Power system model

represents showering, breakfast dish wash activity and occurs later on a weekend than a weekday. The evening peak during the weekend tends to be higher due to a more frequent bathing activity over the weekend. As suggested previously, the system support provided from DSR depends on the amount of flexible load available suggesting greater potential for system support during DWH consumption peaks. The high variability of flexible load implies that it is essential to have a reasonable estimate of its magnitude to properly include it as a source of POR in UC/ED model.

#### B. Impact of DSR on system performance

To perform a detailed analysis of the impact of DSR provision on system performance (measured in terms of system frequency nadir), an annual distribution of cases needs to be considered comparing the base case (no DSR) with the case in which DSR has been dispatched for POR provision (with DSR). Two instances of year long unit commitment with hourly resolution (8760 instances) have been run, for aforementioned cases. A sample of dispatches (with varying wind, demand and generation levels) for base case and the same number of corresponding DSR included dispatches have been compared using detailed power system model and dynamic DWH models. In each case loss of a largest infeed is simulated and system frequency nadir is recorded. Fig.4 shows a histogram of frequency nadirs obtained with and without DSR providing POR. Frequency nadir is dependent

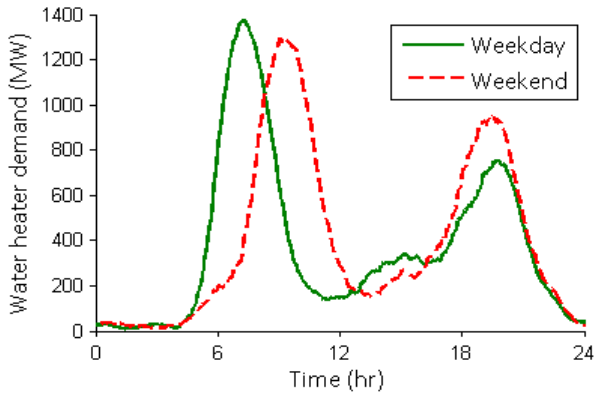


Figure 3. Aggregate DWH load on a weekday/weekend

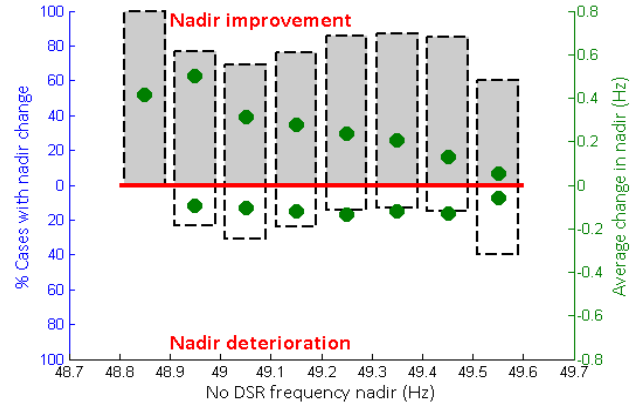


Figure 5. Changes in no DSR frequency nadir

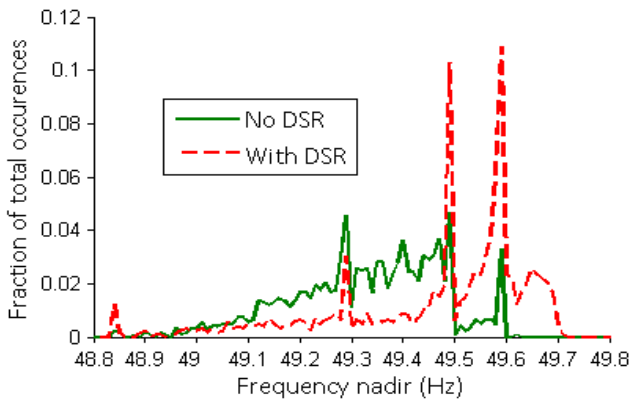


Figure 4. System frequency nadirs

on a number of factors including governor droops, size of generation trip, system inertia (also related to wind level) and magnitude of fast acting resources (such as HVDC interconnectors, pumped storage on load, DSR) dispatched. Irish power system has two interconnectors to GB, capable of providing 75 and 50 MW of fast static reserves, at trigger frequencies of 49.6 and 49.5 respectively. There are 4 pumped hydro storage units, which if dispatched at load, have the capability to provide almost instantaneous static POR. For no DSR case, a large number of cases in the vicinity of 49.6, 49.5 and 49.3 Hz demonstrate the triggering of interconnector and contracted load shedding schemes to arrest the frequency decline.

Inclusion of DSR as a source of POR generally results in a progression towards improvement in frequency nadirs, with an increase in nadir clustering around 49.6 and 49.5 Hz and a decrease in the number of nadirs around 49.3 as compared to a no DSR case. The improvement in nadirs can be attributed pre-dominantly to faster response speed of DSR. There is however a cluster of nadirs appearing in 48.8 to 48.85 Hz range which is absent for no DSR case, suggesting that for some cases, system frequency nadir has deteriorated. Fig. 5 shows in detail, how the nadirs have changed with the introduction of DSR. Frequency nadirs obtained from no DSR case have been divided into bins, starting from 48.8 to 49.6 Hz with a bin width of 0.1 Hz and represented on x-axis plotted against the % of cases for which frequency nadir has decreased and increased (corresponding

to a certain bin on the x-axis); with the average improvement/deterioration. It can be observed that the DSR is most effective for the cases which had lower nadirs in the without DSR case since the average improvement in nadirs is larger for such cases. It must however be noted that the amount of DSR available in each case is not constant. However, despite a general trend of improvement in frequency nadirs, there are a certain smaller number of cases where frequency nadirs have deteriorated with the addition of DSR.

Generally, in order to meet the system's POR requirement, the UC/ED solution traditionally tends to keep units in part loaded condition, such that sufficient headroom is available to displace a demand/generation imbalance resulting from loss of a largest infeed. If however, a significant portion of POR requirement is scheduled to be provided from DSR (and assuming that DSR has a lower cost than reserve from conventional plant), the UC/ED solution will tend to increase the conventional generator loadings from partial towards full, since their POR response headroom is no longer required. This may have two subsequent effects:

- Largest infeed in the system may increase
- More units dispatched at their maximum output

An increase in largest in-feed contingency size generally tends to deteriorate a frequency nadir, since the transient imbalance between demand and generation is greater following the loss of the largest unit. If the plants dispatched at maximum outputs are CCGTs (combined cycle gas turbine), they exacerbate a transient imbalance between supply and demand, since in the event of a fall in system frequency following the loss of largest infeed, a CCGT owing to its compressor being located at generation shaft may reduce its power output if it is operating at rated capacity [19]. One way to mitigate these effects can be ensuring a better distribution of reserve across different sources.

### C. Flexible load variability and control

Large variability of available DSR has implications for the system frequency profile following the loss of largest infeed. In reality; demand resource is likely to be composed of a number of electricity end uses, which will tend to mitigate the variability of available resource. Three specific cases are demonstrated in Fig.6, with different available DSR

magnitudes at different times of day/year. Loss of largest infeed has been simulated in these cases with the aforementioned 0.2 Hz dead-band and operating-range values. In Fig.8, a system contingency occurring at 3pm on a weekday, has a total available DSR magnitude of 236 MW which is activated completely following the loss of largest contingency and a nadir of 49.6 Hz is obtained, with subsequent restoration of the system frequency back to within the deadband ( $\pm 0.2$  Hz from 50 Hz). On a weekday at 7 PM the DSR POR magnitude available is 364 MW. Following the loss of largest infeed contingency a maximum DSR POR response of 310MW is provided, which along with interconnector static response pushes the system frequency slightly above 50 Hz. Although the system frequency has been pushed above its nominal value, indicating over responsiveness of reserves, the over-frequency magnitude is not significant in this case. If a loss of largest infeed occurs at a time of peak DHW electricity demand (10 AM on a weekend), the DSR magnitude provided is greater than the loss of generation causing a more significant over-frequency (frequency beyond 50.2 Hz). Such a scenario on a real power system can lead to thermal stress on conventional plant, and should be avoided.

It can be seen in Fig. 8, that the response provided is generally sustained beyond 15s after the contingency implying that reserve from flexible load once dispatched will not only provide primary but also secondary and tertiary reserve which should be recognised in UC/ED as mentioned. The sustained DSR from TCAs can be explained by the manner in which TCA thermostat control operates. TCAs operate in such a manner that they have no memory of their state (on/off) prior to a change in thermostat setpoints. An appliance heating up once turned off by a reduction in its thermostat setpoints, doesn't turn back on immediately if the setpoints are restored to their original value. It turns on, only when water cools down again to hit the lower thermostat setpoint. This response characteristic dictates that aggregate demand from TCAs in general (DWHs in this case) does not have the ability to continuously adjust the magnitude of resource provided in proportion to system frequency deviation immediately after an event. It must however be noted that, the DSR provided (at weekend, 10AM) is adjusted to counter for an overfrequency event (beyond deadband) by virtue of a subsequent increase in thermostat setpoints. The plateau in the DSR curve around 3 seconds indicates that the system frequency is within the deadband range. The control mechanisms to trigger DSR through local frequency measurement usually don't account for this demand variability [13] [12]. It can be observed from Fig. 6 that, if the variation on the daily magnitude of DSR available is not recognized while setting up its triggering mechanism, it may improve frequency nadir in many cases, to then cause a system frequency overshoot in some cases. A possible solution to this can be the use of controllable settings for the dead-band and the operating range of TCA POR response which can be changed through a remote server based on DSR availability magnitude, or possibly the use of alternative settings that are hard-coded for different times of the day etc.

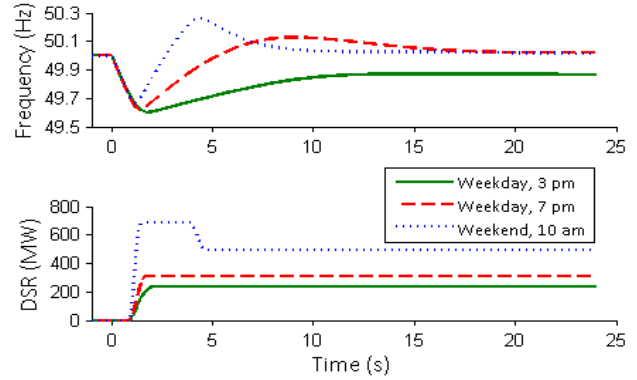


Figure 6. Impact of DSR magnitude variation

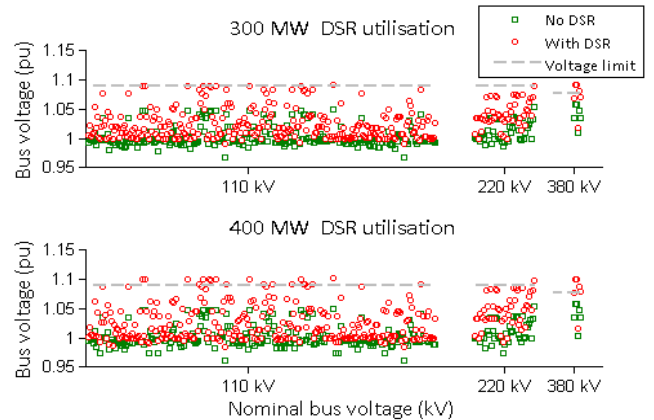


Figure 7. Impact DSR provision on the network

#### IV. NETWORK IMPACTS

Utilisation of DSR is generally considered only from the perspective of active power balance, with little consideration given to the implications of DSR on voltage profile at various points in the system. The implications of using DSR, on reactive power balance may limit the extent to which it can be utilised while maintaining a stable and secure system operation. To demonstrate the link between the active power reduction provided by flexible demand and its impact on reactive power, it has been assumed that the responsive load consists of reactive as well as inductive elements and is distributed uniformly throughout the system for the following cases. Consider a lightly loaded power system. In this work, a summer valley scenario on Irish power system has been considered as a representative of lightly loaded system conditions. Fig. 7(a) shows steady state system bus voltages before and after a loss of 300 MW largest infeed. Nominal voltage of 3 categories to which individual busses belong, are shown on the x-axis. The generation loss is offset by an equivalent amount of DSR provision, uniformly across all buses on the system, thus returning the system to steady state. It can be observed that for post contingency steady state, 4%, 2% and 50% buses for 110,220 and 380 kV respectively either hit or go beyond bus voltage limits (specified by TSO). As the demand has been reduced to provide DSR, along with the active power, the reactive power consumption has reduced therefore causing over voltages. It must be noted that the in this case the system dispatch doesn't recognise DSR as

a source of POR. As established in Section III-B, utilising DSR can result in displacement of some conventional units along with a general shift of dispatched units towards maximum loading. Following the above argument the system has been re-dispatched for the summer night valley recognising DSR as a source of POR. As according to the new dispatch, the largest infeed has increased (from 300 to 400 MW), therefore the amount of DSR provided to offset the loss of largest infeed will also tend to increase. Simulating a pre-contingency (no DSR activated) and post-contingency (with DSR activated) system state with modified dispatch results in a more pronounced demonstration of voltage profile impacts. As seen in Fig 7 (b), 8%, 2% and 83% buses for 110, 220 and 380 kV respectively approach or go breach the bus voltage limits (specified by TSO). A smaller volume of DSR utilisation in this case might have resulted in safe system operating conditions. It therefore follows that the magnitude of DSR that can be safely utilised has a link to network conditions. Of course the breached bus voltages can be restored by actions from TSO (such as changing generator setpoints or using shunt devices), but this simple example serves as an indicative case for the link between DSR utilisation and system voltages. Other manifestations of this link may include a DSR POR increase in power consumption (in an overfrequency event) which has the potential to result in system bus voltages falling below safe operating limits if the pre-contingent network is in a heavily loaded situation.

## V. CONCLUSIONS

This work co-optimises the provision of POR through DSR with a UC/ED problem. The results obtained were used to perform a year-long time series comparative analysis of the techno-economic system performance, both in the absence and presence of DSR using detailed system and dynamic load models. The results identify possible challenges in the provision of POR through DSR. Though generally beneficial, DSR utilisation for reserve provision may lead to deterioration in system frequency nadir obtained due to changes in conventional system dispatches from part load to maximum load – i.e. an increase in size of the largest in-feed contingency. A large variation in reserve provided through DSR may result in over-correction of demand generation imbalance at times of high flexible demand (assuming the TCA control mechanism to be the same under all conditions). For a power system this translates to over correction of an underfrequency event, converting it into a transient overfrequency event. This variability of DSR providing system reserves need to be fully understood and may encourage actively managed DSR control settings instead of a passive fit and forget implementation. Furthermore, although provision of reserve from DSR can serve to replace active power imbalance; however, due consideration needs to be given to the link between active and reactive power imbalance resulting from flexible demand utilisation. Since reserve provision from DSR has the potential to create over/under voltage conditions in some cases without operator intervention. Flexible demand is generally a useful resource; however the aforementioned factors need to be considered prior to a its large scale implementation.

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