Value of Demand Side Participation in Frequency Regulation

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ABSTRACT

The demand for ancillary service is expected to increases significantly in the future GB system as the high penetration of wind generation. In particular, the need for frequency regulation services, required to deal with sudden frequency drops following a loss of large generating plant, will increase due to the limited inertia capability of wind plants. This paper focuses on quantifying the requirements for primary frequency response and the value of Demand Side Response in the future Great Britain system.

INTRODUCTION

The future GB electricity system is facing significant challenges, as a consequence of targets to increase the penetration of renewable energy, wind in particular. Efficient real-time demand-supply balancing with high penetration of wind power and increased contribution from less flexible low-carbon generation will become a major challenge. This will be primarily driven by the increased need for various reserve and frequency regulation services to deal with wind output uncertainty and reduced system inertia. Traditionally, these services are supplied by part-loaded or fast-start conventional plants. Due to dynamic constraints, provision of real-time balancing services by conventional plants is inevitably accompanied with delivery of energy. This becomes a major problem during low demand periods particularly if combined with high wind output. If generation side remains the only source to provide the increased need for ancillary services; this will not only reduce the efficiency of system operation, but it may also limit the ability of the system to absorb wind.

Therefore, the increased requirements for flexibility may need to be met by other flexible options, e.g. energy storage and demand side response (DSR). The major benefits and challenges of demand side management in UK electricity system were discussed in [1]. The key benefits are identified as reducing the generation margin, improving transmission grid and distribution network investment and operation efficiency, as well as managing demand–supply balance in systems with intermittent renewables. Research in [2] and [3] investigated the value for DSR providing reserve in joint energy/reserve markets. In addition, the load recovery effect is investigated in the market clearing process in [4]. The possibility for DSR to provide frequency response was discussed, simulated and tested in [5]. The concept of decentralized control is demonstrated in [6] and [7] for a portfolio of domestic load. In additional, a decentralized stochastic approach was proposed in [8] to control refrigerator to provide frequency response.

Previous research on the DSR has shown that it can be applied to respond to sudden power plant outages, and thus reduce the cost of reserve power required to deal with such events. Reference [9] demonstrates the concept and applicability of DSR in the provision of frequency response and provides a rough estimate of potential economic values. The benefit of DSR for economic and environmental performance of the electricity system has been estimated in [10], by simulating annual system operation while taking into account response and reserve requirements. However, neither of the above works considers the increased response requirement due to reduced system inertia in the future power system with high penetration of wind generation.

In this context, this paper introduces an advanced stochastic unit comment model with inertia-dependent frequency response. The model is applied to analyse the system benefits of DSR in providing frequency regulation services in the future GB low-carbon electricity system.

METHOLOGY

The methodology for assessing the value of DSR is based on the least-cost annual generation system scheduling approach, capable of considering both the delivery of energy as well as the provision of reserve and frequency regulation services. Generation scheduling determines the commitment and dispatch decisions of generators in a power system considering the need for various types of reserve and frequency response services. The cost minimization is subject to various dynamic operating constraints, e.g. start-up times for thermal units. The value of DSR is quantified by the comparison of the system operation cost with and without contribution DSR into frequency response provision.

Stochastic Unit Commitment Model

The stochastic scheduling simulation tool is designed to provide optimized generation schedules in the light of wind, demand and generator outage uncertainties. Wind realizations, wind forecast errors and generator outages are synthesized from models and fed into a scheduling tool, which finds the optimal commitment and dispatch decisions given the uncertainties and constraints. The decisions are found using a *scenario tree*, which represents a discretisation of the range of outcomes of the stochastic variables (e.g. available wind output), with each path through the tree representing a possible scenario. A simplified scenario tree is shown in Fig.1 below.

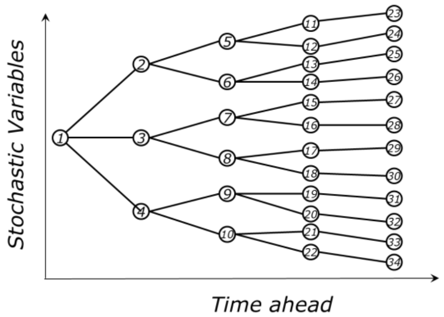

Fig.1 Scenario tree for a stochastic variable

A set of feasible control decisions is obtained for each node on the tree, such that the expected total operating cost is minimised. Because the actual realisation will differ from all the scenarios in the tree, the scheduling is performed using rolling planning, in which only the here-and-now decisions are fixed, and all subsequent decisions discarded. For this reason, the full tree, extending to 24 hours ahead, must be solved at every time step. Operating reserve requirements are endogenously optimised within the model.

In addition, the model can consider alternative technologies capable of providing frequency regulation services over short timescales from seconds to tens of minutes. These can include both conventional generators and alternative providers of frequency regulation such as DSR. Given that the model captures the loss in efficiency i.e. the increase in operating cost as the result of conventional generators providing frequency regulation, this modelling framework can be used to assess the value of alternative frequency regulation providers by reducing the need for conventional generation to supply these services. The resulting reduction in system operating cost is used to assess the value of DSR.

Requirements for Frequency Regulation Services in the Future GB Power System

Given that high penetration of wind generation will reduce output of conventional generation and also reduce the number of synchronised plants, the aggregated system inertia provided by rotating mass will decrease, requiring increased demand for frequency response to ensure adequate system performance in terms of maintaining the frequency within the statutory limits. This section presents the modelling of system frequency variations used for quantifying the requirements for frequency regulation services.

The time evolution of system frequency deviation can be described by a first order ODE:

$$2H\frac{\partial \Delta f(t)}{\partial t} + D * P^D \Delta f(t) = \sum_{g,s\in \mathcal{G},\mathcal{S}} \Delta P_{g,s}(t) - \Delta P_L \quad (1)$$

where H [MWs^2] is the system inertia, D [%/Hz] represents the load damping rate, P^D[MW] is the load level and $\Delta P_{g,s}$ [MW] describes the additional power provided by the generator g or storage s following the generation loss ΔP_L [MW].

The aim of frequency control is to contain the dynamic evolution of frequency (e.g. after a generator outage) within certain security thresholds. The GB Security and Quality of Supply Standard (GB-SQSS) [11] specifies the limits of frequency deviation for secured faults. As show in Fig.2, the differential equation (1) is mapped into the SUC model through considering three characteristic periods in the form of constraints associated:

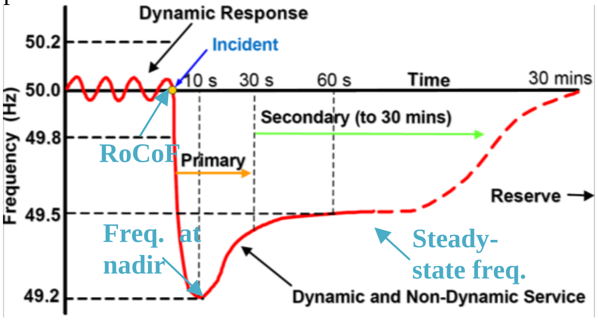

Fig. 2 System frequency evolution after a contingency (National Grid)

1. **Rate of Change of Frequency (RoCoF)**

The time scale that involves the RoCoF constraint is limited to the first few seconds after the generator failure. During this period, the governors' response is not triggered yet ($\Delta P_g \cong 0$) as the frequency deviation is still negligible ($\Delta f \cong 0$). For a given generation loss, the minimum level of inertia, required to satisfy the maximum RoCoF requirement, can be obtained as:

$$H = \frac{\sum_{g=1}^{G_{conv}} H_g P_g^{max} N_g^{up}(n)}{f_0} \geq \left| \frac{\Delta P_L}{2RoCoF_{max}} \right| \quad (2)$$

2. **Frequency at Nadir**

The frequency nadir is defined as the point when the system frequency evolution achieves its minimum value during the transient period; the time scale for this interval goes from 2s up to 10s after the generator failure. The nadir depends on system inertia and governors' response. Following the work in [12], the nadir requirements can be formulated as MIL constraints:

$$\begin{cases} \dfrac{\sum_{g\in G_{CONV}} H_g * P_g^{max} * y_g}{50} \geq k^* \\ -M(1 - N_g^{up}(n)) \leq y_g - R \leq M(1 - N_g^{up}(n)) \\ -M * N_g^{up}(n) \leq y_g \leq M * N_g^{up}(n) \end{cases} \quad (3)$$

where M is a large number and k* is the unique solution of

$$\frac{2k^*}{T_d} \cdot log\left(\frac{2k^*}{T_d * D\Delta P_L{}' + 2k^*}\right) = -D^2 \Delta f_{min} - D\Delta P_L{}' \quad (4)$$

3. **Frequency at quasi-steady-state**

The quasi-steady-state condition depends essentially on the total amount of frequency response delivered by generators and storage units. Therefore, for any given amplitude of generation loss ΔP_L, quasi-steady-state frequency deviation can be found, by assuming that RoCoF is effectively zero i.e. that the frequency has reached a constant level:

$$\Delta f^{ss} = \frac{R - \Delta P_L}{D} \geq \Delta f_{min}^{ss} \quad (5)$$

This allows quantifying the required response to satisfy the quasi-steady-state frequency criterion as follows:

$$R \geq \Delta P_L + D\Delta f_{min}^{ss} \quad (6)$$

CASE STUDIES

By implementing the proposed model, the value of DSR is assessed for the GB system in years 2020 and 2030, when a significant volume of wind generation is expected to be connected to the grid.

Simulated Scenarios for the GB System

Two different approaches are considered with respect to scheduling frequency regulation:

1. Constant response requirement
2. Inertia-dependent response requirement

With constant response requirement, it is assumed that the volume of frequency response required in the system is determined in the same manner as in the today's system dominated by conventional generators, and therefore does not vary much from hour to hour. This is similar to assuming that wind generation provides the similar level of inertia as synchronous conventional generation. Inertia-dependent response requirement on the other hand is quantified for each time interval in our study based on the level of synchronised conventional capacity in that hour, while assuming that no inertia is provided by wind generation. This approach therefore results in significant variations in response requirements across the day and between seasons of the year.

In addition to the above, several scenarios are considered with respect to the volume of primary frequency regulation provided by DSR:

1. Primary response at the level of 1% of total demand at any given time
2. Primary response at the level of 5% of total demand at any given time
3. Primary response at the constant level of 1% of average demand (385 MW in 2020, 435 MW in 2030)
4. Primary response at the constant level of 5% of average demand (1,923 MW in 2020, 2,180 MW in 2030)

Constant frequency response provision in scenarios 3 and 4 has been constructed so as to reflect the levels of 1% and 5% of average hourly demand on an annual basis. In contrast, in scenarios 1 and 2 the capability of DSR to provide frequency regulation varies from hour to hour according to the instantaneous system demand.

The value is assessed by comparing the annual system operating cost with and without the contribution of DSR to frequency regulation. The resulting operating cost savings are then expressed as the annual value per kW of flexible demand capacity, and then capitalised assuming the discount rate of 7%.

Assumptions on generation and demand background for future GB system have been based on the balanced EMR scenario analysed by the Department of Energy and Climate Change (DECC) [13]. Generation capacity in 2020 is about 92 GW, of which some 20 GW is wind generation. Total installed capacity in 2030 is around 109 GW, a quarter of which is contributed by wind capacity. The penetration of wind with respect to meeting annual electricity demand is 21% and 26% in 2020 and 2030, respectively. Annual electricity demand in 2020 is assumed at the level of 337 TWh, while in 2030 this assumption is 381 TWh. Representative UK hourly profiles are used for wind and demand fluctuations. By analysing the value provided by the responsive demand in years 2020 and 2030, it is possible to broadly establish the evolution of the potential benefits of deploying DSR for frequency regulation across time.

Value of DSR in the GB System

The results of this assessment are presented in Fig.3. The value of DSR is several times higher in the case of inertia-dependent response requirement. This is valid across all four responsive demand scenarios. We further note that the value of responsive demand per kW of flexible capacity reduces as the volume of responsive demand increases. In other words, there is a saturation effect, where the first megawatts of DSR generate the highest value for the system, while adding subsequent capacity results in lower benefits. Nevertheless, the value per kW in the inertia-dependent case is high for all scenarios, varying between £2,500/kW and £4,500/kW in 2030, with the volume of the frequency response market exceeding 5GW. The value with constant response requirement is lower (up to £1,000/kW), although still significant. In both 1% and 5% cases the values in 2020 are considerably lower than in the 2030 system (roughly half of the 2030 value). It should be noted however that the value in absolute terms is still quite significant, especially in the inertia-dependent case.

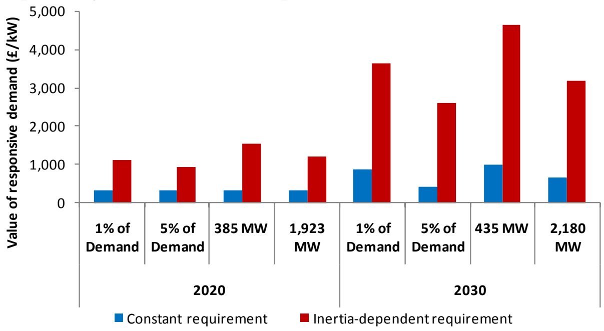

Fig.3 Value of DSR in the future GB system

In order to illustrate how the volumes of frequency regulation services change with the introduction of frequency response provision from DSR, Fig.4 presents the breakdown of the frequency regulation service provided by various generation, storage or DSR technologies. The breakdown is presented in relative (percentage) terms; we note that the average constant response requirement is 1.8 GW, while for inertia-dependent requirement this is around 2.7 GW.

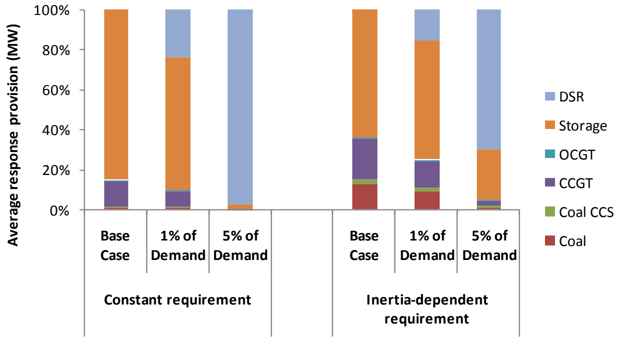

Fig.4 Composition of providers of frequency regulation for different responsive demand scenarios

In the constant response requirement case (Fig.4 left) storage and CCGT units provide the frequency response in the base case (i.e. without DSR), with the major part being contributed by storage (around 1.5 GW on average). Upon introducing DSR at the level of 1% of system demand, the provision of response by storage and CCGT drops. Increasing the DSR penetration to 5% almost completely eliminates the need to use other providers of frequency regulation.

In the inertia-dependent case (Fig.4 right), the system needs to deploy coal generation (both conventional and CCS) in order to provide sufficient levels of frequency response in the base case. Part-loaded generation will operate at reduced efficiency and will hence incur additional fuel and carbon cost. This leads to the conclusion that the provision of frequency response will be significantly more expensive in the case of inertia-dependent response requirement. The addition of DSR in that context therefore yields considerably higher benefits than with the fixed response requirement, as presented in Fig.4, We note that with 1% DSR penetration, the system still needs to rely on coal units to provide some frequency response, while it is only at 5% of DSR that the conventional generators can be almost completely released from providing frequency response.

Diurnal and Seasonal Value of DSR

Fig.5 further disaggregates the value of responsive demand presented in Fig.3 into its components according to the season of the year where this value is generated.

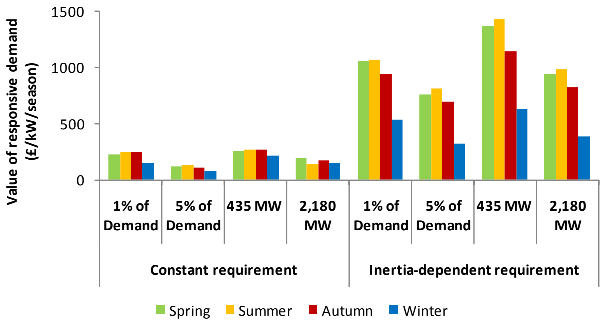

Fig.5 Value of responsive demand across seasons

We note that for the constant response requirement the value of DSR tends to be the highest in autumn, which is driven by higher wind output in that season. On the other hand, if the response requirement is inertia-dependent, the value of DSR is the highest in summer when low demand requires high volumes of frequency regulation services. The value of DSR in both cases is the lowest in winter due to high demand.

Similarly to seasonal values of DSR, it is also interesting to break down the value across different time of day. The relevant results for day and night periods are presented in Fig.6. We note that with constant response requirement the value of responsive demand is slightly higher during daytime. The reason is that during night, the storage is normally pumping, which is sufficient to provides the bulk of the required response. With inertia-dependent response requirement on the other hand, the value of responsive demand is much higher during night-time, when the synchronised capacity is low, thus requiring more frequency response.

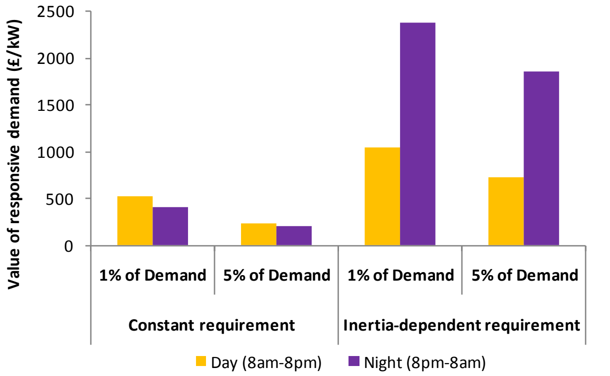

Fig.6 Value of responsive demand across times of day

Value of Simultaneous Provision of Response and Synthetic Inertia by DSR

In the case studies presented so far it is assumed that DSR is capable of providing primary frequency response, i.e. gradually reducing demand as the frequency drops following a generator outage, but could not contribute to system inertia in a manner similar to synchronised rotating machines of conventional generators. In other words, the only source of inertia i.e. resistance to rapid frequency changes was available in the form of synchronised conventional generators.

Additional inertia provided by DSR would reduce the requirements for fast frequency regulation services, which would be reflected in further added value per kW of responsive demand capacity. This is quantified in Fig.7, where the value of the combined provision of response and inertia is compared to previous results from cases where only response was provided by DSR. The result presented is based on the case of inertia-dependent response requirement.

We note that the provision of synthetic inertia creates significant additional benefits for the system. For instance, in the 2030 GB system and for the case where

1% of demand participate in DSR, the value increases the most, from £3,600/kW to £8,100/kW. Considerable increases are observed in other cases as well. These results suggest that the provision of synthetic inertia by DSR could be an important source of value for the system and that the development of the necessary functionality of the technology to provide inertia may be of great interest for future research.

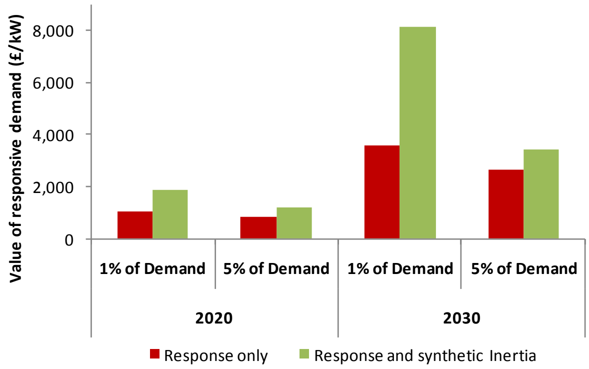

Fig.7 Value of simultaneous provision of frequency response and synthetic inertia by DSR

CONCLUSION

This paper presents the case studies aimed at quantifying the value of DSR in supporting frequency regulation in the GB low-carbon electricity system in 2020 and 2030. The results suggest that the contribution of DSR in the provision of frequency regulation could provide significant benefits to the system.

The value of DSR for frequency response is much higher in the case where the impact of reduced system inertia on the demand for frequency response is recognized. The value of DSR is the highest in summer when low demand requires high volumes of frequency regulation services, while the lowest in winter due to high demand. Similarly, the value of DSR is much higher during night-time, when the synchronised capacity is low. The analysis presented in this paper also suggests that significant additional value could be provided to the future GB system if the DSR is capable of delivering not only frequency response, but also synthetic inertia by instantly reducing the demand in reaction to a fast decline in system frequency.

The projected rapid increase in wind generation capacity seems to be a critical factor driving the high values of responsive demand in the 2020-2030 horizon. In that context, the choice of scenario is very important for determining the value of DSR in provision of frequency response. Given the relatively modest increase in wind capacity until 2030 assumed in the balanced EMR scenario considered in this analysis, the values identified in this paper could be regarded as conservative estimates. The value of DSR could be much higher if the wind penetration grows more rapidly in the future (as many other scenarios envisage). Similarly, during times of energy imports through interconnection, the capacity of which could grow substantially in the future, the value of DSR would additionally increase.

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