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Analysing the impact of large-scale decentralised demand side response on frequency stability

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ABSTRACT

Advances in communications technology, higher penetration rates of renewable energy and an evolution towards smarter electrical grids are enabling a greater role from demand side response (DSR) in maintaining power system security and reliability. The provision of primary operating reserve (POR) from domestic loads through a decentralised, system frequency based approach is discussed. By considering a range of system configurations (generation mix, system generation and load) and control strategies, this paper endeavours to answer critical questions concerning the large-scale roll out of decentralised DSR, including the following: what are the implications of DSR resource seasonal variability on system operation and performance following the loss of a large infeed/load? Do increased load coincidence and energy payback phenomena have the potential to significantly impact system frequency recovery? How do DSR controller hardware characteristics influence the provision and effectiveness of reserve delivery? What are the repercussions of a "fit & forget" approach to decentralised control from flexible load on frequency stability as the technology penetration increases? Can DSR be directly substituted for conventional reserve sources while recognising its post-event recovery period? Residential customer behaviour, seasonal effects and the diversity of individual device characteristics are recognised in a detailed thermodynamic flexible load model which is integrated with a detailed power system model to perform the analysis.

Introduction

Technological advancements, coupled with a global drive towards utilising natural energy resources, have encouraged the exploitation of flexibility in the demand resource. Historically, the role of demand in system operation has been limited to the provision of emergency static reserve, whereby a contracted fraction of load was disconnected as a measure to arrest system frequency decline following a generator contingency. However, with higher penetrations of renewable energy sources, particularly wind and solar, there are increased opportunities and benefits from demand playing a greater role in system balancing. An increasing number of jurisdictions around the world are utilising flexible load for system ancillary services e.g. PJM and ERCOT, with flexible load providing 50% of ERCOT's spinning reserve requirement [1].

A demand/generation imbalance resulting from a contingency (loss of generation or load) manifests itself as a variation in the system frequency. In the absence of flexible loads, part-loaded generators under droop control increase/decrease their output to counter any imbalance. Depending on the size and configuration of a power system, other resources such as storage units and interconnection may be activated. Flexible loads offer an alternative as they can quickly increase/decrease their output [2], thus acting as virtual generation. However, it is important to recognise differences between flexible load and conventional generators in terms of their available capacity and sustained response. For thermostatically controlled appliances (TCAs), variations in ambient temperature as well as user interaction affect the demand resource as a function of time of day and year [3]. Cooling TCAs (fridge/freezers, air conditioners) will tend to have a higher flexible resource during the summer and daytime hours, while heating TCAs (space heating, water heating) will tend to offer a higher resource during the winter, morning and evening hours. User activity, e.g. fridge door openings for cooling TCAs, coupled with ambient temperature variations will also affect the intra-day resource variability. It should be noted that the rated output of certain generation technologies will also be affected by variations in ambient conditions, e.g. gas turbine plant, but the variations are less dramatic [4]. Domestic electricity consumption makes up almost 30% of electricity

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consumption in the EU-27 countries [5], and is largely responsible for creating the peaks and troughs in the system load profile, further leading to increased system ramping requirements. Thermal loads from the residential sector can be considered flexible as they are mostly non-critical and discretionary. However, each individual load is small, and therefore many such loads need to be controlled in concert to yield the desired aggregate demand.

Control schemes and infrastructure requirements for deploying flexible demand generally vary with the nature of the service envisaged: flexible load has been suggested for load shifting [6], frequency regulation [7,8] and load following [9,10]. However, displacement of part-loaded conventional generation at higher wind penetration levels restricts a system's ability to cope with the loss of a major infeed [11], making provision of primary reserve a key area of concern. The concept of altering thermostat setpoints of TCAs in proportion to the system frequency deviation, thus utilising the least energy deficient appliances first was presented in [12], to provide primary operating reserve (POR) from a homogenous fleet of cooling appliances. Switching multiple load types (refrigerators, space and water heating) based on the magnitude and duration of a disturbance was demonstrated in [13]. For the Great Britain system [14], simulates the impact of switching flexible appliances using frequency measurements from smart meters to determine the amount of flexible load required to maintain the system frequency within required levels (for a single large infeed loss). In [15], all appliances have been assumed to be switched at a uniform frequency threshold for providing system frequency control. However the above studies [14–17] ignore the flexible load daily/seasonal variability which impacts the magnitude of the available DSR based reserve, while considering only loss of generation scenarios and therefore not catering for the asymmetric nature of DSR reserve for an upward/downward response. These studies also assume fixed decentralised control settings, ignoring the impact of a change in parameters on the improvement/deterioration of the frequency nadir. As opposed to previous studies [16,17], propose a semi-decentralised mechanism involving two-way communication, whereby an aggregator pre-configures the DSR based POR for local frequency based triggering, maximising the aggregator's profit [17] and customer welfare through load utility functions [16]. All of the mentioned studies [14–19] however, adopt a simplified lumped representation of conventional generation, thus ignoring the impact of static reserves on the frequency nadir, while considering only a single set of system operating conditions (generation mix, system demand, flexible load level). These studies consider only the short-term (several seconds after a contingency) impact of DSR on the system frequency, but not considering phenomenon such as the energy payback, and its impact on system frequency as the load resumes normal operation after providing the requested response.

The provision of reserve from frequency dependent flexible load (specifically thermostatically controlled appliances) in a completely decentralised manner is being considered by a number of TSOs, including ENTSO-E (European Network of Transmission System Operators for Electricity) for large-scale implementation [18]. Analysing the performance of such a resource over a range of future system scenarios (particularly if the volume of appliances increases in magnitude), while considering the effects of seasonal resource variability, the lack of real-time controllability and observability, and a subsequent loss of load diversity is essential to identify potential operational issues and to evaluate possible mitigating measures. Moreover, the underlying controllers for such appliances are likely to be low cost [12], and since the resolution and response time of the hardware is likely to be affected, the impact of both attributes on DSR performance must be analysed. In this work, domestic fridge/freezers are considered as a representative TCA, as unlike other flexible loads, e.g. air conditioning and space heating, the cold load resource sees a smaller daily and seasonal variation, making it a dependable source of primary reserve. Considering the recent industry developments mentioned above and previously carried out research, the main contributions of this work are the following:

Using detailed models for the responsive load and the underlying power system (Section 'Modelling Approach'), for various system operating points (generation mix, system demand and responsive demand magnitudes) this study highlights the system impacts of utilising large-scale decentralised DSR based POR, on short and longer-term frequency stability. The impact of DSR resource seasonal and diurnal variability on the system frequency profile is demonstrated, and the unsymmetrical nature of an under & over-frequency demand resource, and the implications of decentralised "fit & forget" control are shown (Section 'Variation of system reserve'). The analysis is extended to post-DSR event frequency stability by evaluating the impact of loss of aggregated load diversity and the associated energy payback (Section 'Loss of load diversity'). Large-scale implementation issues are highlighted by quantifying the impact of the DSR response time and input resolution (controller hardware) on the system frequency response following a contingency (Section 'Required controller hardware characteristics'). Various response triggering and restoration strategies are considered to highlight phenomena such as the relationship between the frequency nadir improvement and resource over-responsiveness, with control mechanisms proposed to address the identified trade-off (Section 'System implications of DSR triggering'). Potential issues regarding post-contingency DSR resource recovery, such as a second frequency nadir, and flexible load profile uncertainty due to sustained response provision, are demonstrated (Section 'System implications of DSR energy recovery') and changes to system operation policy for wide-scale implementation of decentralised DSR are proposed.

Modelling approach

Individual fridge/freezer appliances have been stochastically modelled and aggregated to represent system-level power consumption. Fridge/freezer load has been chosen as being representative of TCAs owing to their high penetration levels and availability throughout the year. The aggregate flexible load model (fridge/freezers) has been integrated into a detailed power system model [19] for further analysis.

Aggregate load model

Many different refrigerator models have been developed from a thermal performance point of view, which tend to be very detailed and computationally intensive [20,21]. Here, however, analysis is focused on a load resource for system services: a model is required that can accurately predict the energy consumption of individual appliances while providing reasonably fast computation, so that a sufficiently large and diverse fleet of such devices can be simulated individually and aggregated to system level. Modelling individual appliances has the advantage of greater transparency into the load states, which is particularly relevant for the deployment of a demand resource scheme, as respect for individual appliance (thermal) limits can be ensured, as part of any governing control strategy. An individual appliance model has been adopted from [12], with the additional modelling of fridge openings to represent consumer behaviour. Individual appliance components, such as the freezer box, freezer contents, fridge air space, fridge contents and the room in which the appliance is placed are modelled as separate components that exchange heat with all the adjacent components. The heat exchange $dE_{l,i}$ in an appliance i through a heat link l