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Synergetic frequency response from multiple flexible loads

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ABSTRACT

Flexible load is likely to be a key component of future systems with the potential to enhance overall system efficiency. Multiple flexible end uses can be utilised to provide system frequency sensitive reserves. However, consideration of inter/intra day end use variability is required when tuning the flexible load response to achieve acceptable frequency behaviour. To that end, a generic synergetic mechanism is presented for frequency based primary reserve provision using representative thermostatic and charging loads. Based on differing dynamic response and load availability patterns of flexible end uses, it aims to enhance the frequency response while avoiding frequency overshoots, and minimising communication requirements. Scheme validation involves a year-long contingency analysis with varying generation mix, system demand and flexible load scenarios. The results show a marked improvement in frequency nadirs, while avoiding frequency overshoots and avoiding contracted load shedding.

1. Introduction

Recent trends in power system evolution towards a smarter grid have enabled a greater role from the demand side. Mitigating demand-generation imbalances by altering consumption patterns has received significant attention from industry and academia alike, with a number of jurisdictions utilising demand response (DR) for system ancillary service provision [1]. The imbalance following the loss of a large generator or transmission asset is traditionally resolved by conventional generation, using (frequency-based) governor droop characteristics. The same concept can be extended to flexible loads, although the latter can often respond faster to changes in frequency [2], as compared to the former, leading potentially to improved frequency nadirs. In addition, utilising flexible load instead of (or combined with) conventional units to provide primary frequency reserve (PFR) can reduce part-loading of generation, leading to improved operational cost efficiency [3]. Discretionary loads are ideal candidates for PFR provision due to negligible implications for short-term energy deferral. Such loads are abundant in the residential sector, which makes up a significant (≈30% in EU-27 countries) portion of total electricity consumption.

Various individual end uses, such as fridge/freezers [4], domestic water heating [5] and plug-in electric vehicles [6], among others, have been studied in the literature for PFR provision. In the future, however, the responsive demand portfolio will likely consist of multiple flexible loads, as proposed by ENTSO-E (European Network of Transmission System Operators for Electricity) [7]. A portfolio of flexible end uses (as opposed to one end use) with varying seasonal, daily and weekly demand deployed in concert can result in a more uniformly available source of DR reserves. It, however, also presents challenges regarding management of the combined demand response, resulting from an autonomous "fit and forget" philosophy [8]. PFR provision from multiple end uses has recently received some attention in literature. For example, the authors in Moline-Garcia et al. [9] suggest triggering multiple flexible end uses sequentially, based on time-frequency characteristic. However, individual end use variability and its impact on control settings is not considered. A multi-step adaptive frequency restoration process, using step-wise activation of responsive demand, is highlighted in Chang-Chien et al. [10]. The required DR volume is based on real-time estimation of event severity using rate of change of frequency measurements, but the study does not consider the varying dynamic frequency response characteristics of different load types. In Vedady Moghadam et al. [11], the consequences of triggering large (varying) flexible load volumes with fixed frequency controls settings, in terms of frequency overshoots are highlighted. Staggering individual load responses into discrete time intervals is proposed as a solution, but it compromises the frequency nadir improvement. Managing the variability of flexible load resource volume by its pre-restriction in advance of an event, has also been proposed. In Weckx et al. [12] a market-based approach, with a price-based droop characteristic for flexible loads is proposed, requiring regular adjustment and updated broadcast, with multiple entity (customer, aggregator and system operator), two way communication. Study in Zhao et al. [13] proposes eval-

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uation of contingency volume at load level, using a simplified power system model and regular local area communication to determine the aggregate PFR requirement. This approach however, requires sophisticated load controllers, a significant communication overhead and high computation time (up to 3.5 s) before a response, resulting in compromised nadir improvement. A completely centralised approach is presented in Biegel et al. [14] where a portfolio of flexible loads transmits state information and receiving the activation commands from the aggregator. Apart from the longer response times resulting from such a control philosophy, the flexible loads are represented as energy storage with a constant drain rate, ignoring the stochastic load behaviour based on user impacts and weather conditions, etc. All the aforementioned approaches [9–14] treat the available portfolio of flexible loads as binary (on/off) devices. The capability of charging loads, such as electric vehicles and storage space heaters, to dynamically modulate their charging rates [15] has not been utilised. Additionally, these studies are idealised, validated only on a single operating condition using reduced power system models and without the recognition of DR based PFR provision on generation dispatch.

This work presents a generic synergetic control mechanism for a diverse demand resource consisting of various load groups, for primary frequency reserve provision. Detailed physical based models of charging loads (CL) and thermostatically controlled loads (TCL) are presented to highlight diurnal, weekly and seasonal variability of a flexible portfolio (Section 3). Differences in their dynamic response under autonomous control are analysed (Section 4). The variability of individual loads and their respective dynamic response characteristics, are considered while designing the synergetic control mechanism for improving frequency nadirs, while minimising communication overheads and addressing frequency overshoot problems (Section 5). Instead of a completely centralised or decentralised control philosophy, a hybrid approach is adopted, with centralised commands issued prior to an event to configure flexible load for a real-time autonomous response. The effect of static reserve (pumped hydro & interconnectors) and individual generator dynamics are considered using a detailed power system model, enabling multiple operating conditions and flexible load magnitudes to be considered. Dynamic contingency analysis is performed for a wide range of scenarios spanning a year long duration (Section 6).

2. Synergetic load response problem

Flexible residential load consists of various end uses, which can be categorised as charging and thermostatically controlled loads. For the latter, electricity consumption and appliance function (i.e. temperature regulation) have a tight temporal coupling. In contrast, energy storage (charging) and later utilisation (subject to user requirements) are decoupled for charging loads. Multiple load groups (LGs), such as fridge/freezer load (FRL) and domestic water heating (DWH) represent TCLs, while CLs include electric vehicles (EVs) and storage space heating (SSH). Individual load groups exhibit varying levels of daily, weekly and seasonal variability. A potential shortage of DR-based reserve from a single group owing to its variability can be mitigated by combining other load groups, providing PFR in concert. Moreover, the urgent nature of PFR provision implies that a real time external (centralised) control is undesirable.

PFR provision from various flexible loads in a real-time autonomous manner can ensure sufficient volume and speed of reserve provision. The aggregated DR load will show diurnal, weekly and seasonal variation, however a complete autonomy of response without pre-real time configuration implies minimal control over reserve variation. Hence passive settings for decentralised reserve responsiveness can result in a sub-optimal nadir improvement when DR volume is relatively small. Conversely, aggressive settings, coupled with a large DR volume can cause frequency overshoots. A synergetic load control strategy, catering for varying system conditions, flexible load group variability patterns and their frequency response characteristics is therefore required. To that end, periodic centralised control may be required, but centralised communication must be minimal and inactive during a contingency. To achieve such an over-arching framework, quantitative assessment of individual end use variability is required. Also, the frequency response characteristics of CLs and TCLs need to be evaluated and exploited. Mechanism evaluation for multiple DR levels and system conditions is required to ensure generality.

3. Power system and flexible load modelling

Physical based modelling of multiple load groups is required to establish diurnal, weekly and seasonal variability patterns and quantify the aggregate DR resource. The developed load group models are then integrated with a detailed system model (Irish power system in 2020) to inspect the dynamic response characteristics of individual load groups, and subsequently to develop and validate the synergetic control scheme.

3.1. Power system model

The future (2020) Irish system is a relatively small system with limited DC connection (1000 MW) to Great Britain through two interconnectors, and consists of combined cycle gas turbines (4292 MW capacity), coal-fired plant (1323 MW), open cycle gas turbines (1192 MW), pumped storage hydro (292 MW), combined heat and power (161 MW), and wind farms (5 GW installed). The system model is based on a feedback loop, whereby the system frequency is calculated from the power imbalance between demand and generation, and stored energy of the rotating masses in the system [16]. All generators are assumed grid code compliant with a 4% droop setting, and individual plant characteristics, such as plant inertia, are based on data provided by the manufacturers. Wind production is assumed invariant during the POR (primary operating reserve) time frame. Frequency traces from various contingencies provided by the system operator have been used to validate the model [16]. Flexible and inflexible loads are both included. The former incorporate inherent frequency sensitivity, but do not alter their operating cycles during a disturbance. Physical-based models are adopted to better represent stochastic user behaviour and underlying load dynamics, leading to a more realistic analysis of DR actions [17]. Individual appliances for each load type are modelled, as detailed below, before being aggregated to system level using a bottom up approach.

3.2. Fridge/freezer load (FRL)

Domestic cold load is modelled as the energy balance within individual appliances for better insight into their load states. The appliance model is adopted from Short et al. [4], with the addition of appliance diversity and stochastic user behaviour [18]. Different appliance components, such as freezer box, fridge air space, fridge and freezer contents are interconnected, exchanging heat with each other. A hysteresis-based thermostat maintains the cavity temperature within a defined range. For appliance i, the temperature $T_{n,i}$ of the n^{th} component is calculated as:

$$\frac{dT_{n,i}}{dt} = \sum_{c=1}^{N_c} U_{nc,i}A_{nc,i}\left(T_{n,i} - T_{c,i}\right)/S_{n,i}m_{n,i} \tag{1}$$

where N_c is the number of appliance components adjacent to component n, and $U_{nc,i}$ and $A_{nc,i}$ are the thermal conductivity and heat