Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Performance of industrial melting pots in the provision of dynamic frequency response in the Great Britain power system

Meng Cheng [a], Jianzhong Wu [a,*], Stephen J. Galsworthy [b], Nikola Gargov [c], William H. Hung [d], Yue Zhou [a]

[a] Institute of Energy, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
[b] Open Energi, London EC4A 3BG, UK
[c] National Grid, Warwick CV34 6DA, UK
[d] WH Power System Consultant Ltd, Leamington Spa CV32 6PJ, UK

HIGHLIGHTS

- Thermodynamics of Melting Pot (MP) loads is modeled based on field measurements.
- Power consumption of MPs is controlled to keep varying with grid frequency changes.
- Frequency response (FR) of MPs is similar but faster than that of generators.
- FR provided by loads can mitigate the impact of reduced system inertia.
- Firm FR in the GB power system is most beneficial for load aggregators to tender.

ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form 19 November 2016
Accepted 3 December 2016
Available online xxxx

Keywords:
Demand response
Distributed control
Dynamic demand
Frequency response
Smart grids

ABSTRACT

As a result of the increasing integration of Renewable Energy Source (RES), maintenance of the balance between supply and demand in the power system is more challenging because of RES's intermittency and uncontrollability. The smart control of demand is able to contribute to the balance by providing the grid frequency response. This paper uses the industrial Melting Pot (MP) loads as an example. A thermodynamic model depicting the physical characteristics of MPs was firstly developed based on field measurements carried out by Open Energi. A distributed control was applied to each MP which dynamically changes the aggregated power consumption of MPs in proportion to changes in grid frequency while maintaining the primary heating function of each MP. An aggregation of individual MP models equipped with the control was integrated with the Great Britain (GB) power system models. Case studies verified that the aggregated MPs are able to provide frequency response to the power system. The response from MPs is similar but faster than the conventional generators and therefore contributes to the reduction of carbon emissions by replacing the spinning reserve capacity of fossil-fuel generators. Through the reviews of the present balancing services in the GB power system, with the proposed frequency control strategy, the Firm Frequency Response service is most beneficial at present for demand aggregators to tender for. All studies have been conducted in partnership between Cardiff University, Open Energi London – Demand Aggregator, and National Grid – System Operator in GB to ensure the quality and compliance of results.

1. Introduction

The increasing integration of Renewable Energy Source (RES) will reduce the capacity of fossil-fuel generators and therefore reduce the Green House Gas (GHG) emissions. However, the intermittency of RES causes power quality issues [1] including voltage and frequency fluctuations and harmonics that will affect power system planning, operation and evaluation [2]. The uncertainties in the power supply challenge the real-time power balance between generation and demand of the entire system and consequently lead to the stability issue of grid frequency. Furthermore, the integration of RES through power electronics reduces the system inertia. This will cause even greater and faster frequency variations in case of any imbalances between supply and demand.

* Corresponding author.
E-mail addresses: Chengm2@cardiff.ac.uk (M. Cheng), WuJ5@cardiff.ac.uk (J. Wu), stephen.galsworthy@openenergi.com (S.J. Galsworthy), Nikola.Gargov@nationalgrid.com (N. Gargov), ukwilliamhung@gmail.com (W.H. Hung), ZhouY52@cardiff.ac.uk (Y. Zhou).

http://dx.doi.org/10.1016/j.apenergy.2016.12.014
0306-2619/© 2016 Published by Elsevier Ltd.

The conventional solution of regulating grid frequency mainly relies on the spinning reserve of frequency-sensitive generators. In order to increase or decrease the power output in response to frequency deviations, the generators are required to be partly-loaded which results in considerable opportunity costs [3]. Also, running at reduced power output means running at reduced fuel efficiency for most generation technologies [3]. There are also the costs of wear-and-tear of generators caused by the continually changing outputs [3]. As reported by the Great Britain (GB) System Operator – National Grid, the cost of the procurement of frequency response only in July 2014 was £14.27 million [4]. The cost will be increased further because the uncertain supply from RES requires more capacity of frequency response. In addition, the frequency-sensitive generators are mainly large fossil-fuel generators and therefore aggravate the GHG emissions. One alternative low carbon solution is the use of Energy Storage System (ESS), such as the flywheel energy storage system and the battery energy storage system, when a large amount of variability exists in the system. Ref. [5] reports that several projects have been carried out which validated the control of BESS charging/discharging and the power converters can support grid frequency regulation and to enhance the power quality. However, most grid-scale ESS is still considered as a high cost technology [6].

Recent research shows the potential of managing the existing network assets – flexible loads in the power system, to mitigate the risks caused by the integration of RES and to reduce the overall operational costs of the power system [7]. Through measurements, quantifications and estimations on the flexibility of flexible loads, the loads can be scheduled to provide peak shaving and load shifting [8–10]. This reduces the congestions in the electric network during the peak demand period, facilitates the integration of RES and also reduces the requirements of the costly peak power plants. Demand is also able to be controlled to change the power consumption in response to regulation signals for different applications. For example, as illustrated in [11], demand response was coordinated with the battery energy storage to provide tie-line smoothing of a Microgrid. Furthermore, as compared in [12], demand response is able to provide a greater reduction in the electricity bill in the residential sector compared with the battery energy storage, in the context of the installation of self-consumed photovoltaic systems. Ref. [13] developed an event-driven smart home controller on the smart appliances to respond to the Time of Use tariff which reduces the customer bills.

As demand can provide response to the aforementioned regulation signals, demand is also considered to be controlled to change the power consumption in order to provide balancing services and to gain benefits from the System Operator.

The GB System Operator at present procures balancing services including the frequency response services and the reserve services [14] in order to balance the supply and demand and to maintain the grid frequency at 50 Hz. Among the services, demand mainly participates through the Frequency Control by Demand Management (**FCDM**) and the Short Term Operating Reserve (**STOR**) services.

FCDM [15] is a static response to severe frequency drops and mainly procured from industrial loads such as steelworks and smelting aluminum. Demand needs to be switched off in 2 s when frequency falls below pre-set set-points, e.g. at 49.7 Hz, and remain off for 30 min. **STOR** [16] is a service for the provision of additional active power from generation and/or demand reduction. It is needed, at certain times of the day, to deal with actual demand being greater than forecast demand and/or plant unavailability. Demand is required to deliver the power reduction in 240 min from receiving instructions from National Grid, and to sustain the demand reduction for at least 2 h when instructed.

However, both services aim at switching off loads for the lack of generation in the power system. The services are considered as the static or non-dynamic frequency response which usually is a discrete service triggered at a defined frequency deviation [17]. In the future, with the uncertainty from RES generation, there will possibly be redundant generation in the system. Therefore, it is expected that demand can be regulated to increase the power consumption when the system needs, for instance, in response to the increase in grid frequency. A dynamic frequency response is therefore expected which is a continuously provided service to manage the normal second by second power changes on the system [17]. At present, such dynamic frequency response is mainly provided by conventional generators through the droop control.

Time-flexible loads, e.g. thermostatically controlled loads such as domestic water heaters and domestic refrigerators, were considered to be suitable for the provision of grid frequency response [18,19]. The power consumption of the loads can be shifted in time as long as their temperature stays within the pre-set set-points. However, these domestic loads usually have small power consumption (e.g. 4.5 kW for water heaters and 0.1 kW for refrigerators) and hence require an aggregation of great numbers of loads in order to provide a notable response in the context of the GB power system with a minimum demand of approx. 20 GW. This makes the investment process rather long and costly. In addition, the temperature set-points of water heaters and refrigerators (e.g. 5.6 °C and 1 °C) are narrow which will cause unexpected synchronization in their operating status especially during a severe frequency drop [20] which switches all available loads off. After the frequency incident, these loads will then be switched on simultaneously which leads to a second disturbance in grid frequency. Furthermore, as illustrated in [19], variations of temperature set-points of thermal loads in order to provide frequency control sometimes cause the internal temperature of a load to be outside the normal operating range.

To minimize the adverse impacts of using demand for grid frequency response, this paper utilizes the industrial heating loads – Melting Pots (MPs) as an example, to dynamically provide grid frequency response both upwards and downwards without undermining the primary heating function of the loads. The loss of diversity amongst loads is reduced which alleviates the impact of synchronization of loads after the provision of frequency response. A thermodynamic model of individual MPs was developed and validated based on the field measurements carried out by Open Energi. The model can be a generic model and be applied to the modelling of different types of thermal loads. The only required parameters for the model are the temperature variations and power consumption of the loads which can be easily measured, and there is no need for the physical thermal parameters such as the specific heat capacity of the materials or the area of thermal contacts. Case studies were undertaken to show the performance of the controlled MPs on the GB power system models that are used by National Grid at present. The potential benefits of demand to participate in the balancing services based on the present operational practice of the GB power system were also discussed and compared.

2. Model of melting pot loads and validation

The industrial Melting Pots (MPs) are electrically heated loads which are used for storing molten metal in readiness for casting. Inherently, a hysteresis temperature control is used in each MP to control the On/Off state and maintains the molten metal at the specified temperature. The specified temperature is usually high, for example, the molten aluminum is required to be maintained at around 730 ± 25 °C. The power consumption of a MP is