ARTICLE IN PRESS

Renewable Energy xxx (2015) 1–11

Contents lists available at ScienceDirect

Renewable Energy

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

Domestic fridge-freezer load aggregation to support ancillary services

M. Martin Almenta [a,*], D.J. Morrow [a], R.J. Best [a], B. Fox [a], A.M. Foley [b]

[a] School of Electronics, Electrical Engineering & Computer Science, Queen's University Belfast, Ashby Building, Stranmillis Road, Belfast BT9 5AH, United Kingdom

[b] School of Mechanical & Aerospace Engineering, Queen's University Belfast, Ashby Building, Stranmillis Road, Belfast BT9 5AH, United Kingdom

ARTICLE INFO

Article history:
Received 1 April 2015
Received in revised form
5 August 2015
Accepted 15 August 2015
Available online xxx

Keywords:
Ancillary services
Demand response
Fridge-freezer
Price control strategy
Smart grid

ABSTRACT

Grid operators and electricity retailers in Ireland manage peak demand, power system balancing and grid congestion by offering relevant incentives to consumers to reduce or shift their load. The need for active consumers in the home using smart appliances has never been greater, due to increased variable renewable generation and grid constraints. In this paper an aggregated model of a single compressor fridge-freezer population is developed. A price control strategy is examined to quantify and value demand response savings during a representative winter and summer week for Ireland in 2020. The results show an average reduction in fridge-freezer operating cost of 8.2% during winter and significantly lower during summer in Ireland. A peak reduction of at least 68% of the average winter refrigeration load is achieved consistently during the week analysed using a staggering control mode. An analysis of the current ancillary service payments confirms that these are insufficient to ensure widespread uptake by the small consumer, and new mechanisms need to be developed to make becoming an active consumer attractive. Demand response is proposed as a new ancillary service called ramping capability, as the need for this service will increase with more renewable energy penetration on the power system.

1. Introduction

The term 'smart grid' has been introduced worldwide to mean the 21st century power system and the associated modernisation of power systems, with the deployment of information and communication technology to previously unmonitored parts of the distribution system, with the aim of using real time measurement to increase its efficiency. The stochastic nature of wind and other renewable generation, which is often out of synchronization with electricity consumption, increases the flexibility and reserve requirements of power systems [1]. The single electricity market (SEM) in Ireland is currently experiencing instantaneous wind penetration of more than 60% [2]. This creates a favourable scenario for the deployment of smart grids including energy storage systems [3] and demand response [4], due to the SEM's size and scale, ambitious renewable energy targets [5], high levels of wind power and relative isolation, and the fact that it operates in two jurisdictions with different grid codes, policy targets and currencies. The SEM in Northern Ireland and the Republic of Ireland has a unique opportunity to lead the way in smart grid system introduction and development as a European test system. This has been recognised already by the European Union, and a large smart grid project has been allocated for Ireland under the Innovation and Networks Executive Agency as a project of common interest to lower wind curtailment, enhance grid control and establish a cross-border demand side management protocol [6].

Since liberalization, demand response involves the participation of loads in the commercial and industrial sectors [7]. However, residential demand response, which makes up a large proportion of electricity consumption, has not yet been developed in new liberalised markets. It is expected that within the context of a smart grid, consumers will actively participate due to the increased availability of pricing and usage data via smart meter interfaces [8]. The fast growing development in communication technologies is providing the opportunity needed for the consumer to play an important role in the smart grid. Therefore, it should more correctly be called demand side participation, as the consumer has choice in this liberalised environment. Many governments have smart meter targets. The United Kingdom (UK) has a target of installing smart meters in every home by 2020 [9]. Similarly, the Republic of Ireland

* Corresponding author.
E-mail addresses: mmartinalmenta01@qub.ac.uk (M. Martin Almenta), dj.morrow@ee.qub.ac.uk (D.J. Morrow), r.best@qub.ac.uk (R.J. Best), b.fox@qub.ac.uk (B. Fox), a.foley@qub.ac.uk (A.M. Foley).

http://dx.doi.org/10.1016/j.renene.2015.08.033
0960-1481/

is piloting a national trial of smart meters which commenced in 2009, with 6500 consumers using different smart meter technologies [10].

This paper develops an aggregated smart algorithm to control the operation of multiple fridge-freezers within permissible temperature settings of the thermostat. The smart algorithm uses a price control strategy to quantify and value the benefits of demand side participation in the SEM in order to optimise wind power integration. The smart control algorithm is developed in MATLAB© and datasets from the SEM are used to model the test system. When there is high wind penetration on the system, such as in December 2014 when the average wind penetration was 27.1% [2], the day ahead wholesale electricity price fluctuated the most, reaching values up to 500 €/MWh [11]. This study shows that demand side participation can play an important role by reducing the fridge-freezer demand during high electricity prices including those caused by inaccuracies in wind forecast and the variability of wind power.

The paper is divided into six sections. The future smart grid and demand response measurements are introduced in Section 1. In Section 2, a review of smart load in the context of smart grid is outlined. Section 3 explains the methodology developed to perform the research, describing the model of a single refrigeration unit followed by the aggregate model, the price control strategy implemented is then explained and the ancillary services in the SEM. Section 4 presents the results and analysis of the implementation of the control strategy on the Irish system demand, current ancillary services in the SEM are analysed to evaluate the ancillary service payments when demand side participation provides this service, and the concept of ramping capability is explored as a new ancillary service needed in high wind penetration systems. Sections 5 and 6 present the discussion and conclusions.

2. Smart load in the context of smart grids

Today's grids are facing many challenges [1] associated with increased renewable power penetration (e.g. system balance, ramping and curtailment). Demand side participation is a scheme that can help to tackle these challenges and provide significant economic and environmental benefits. The participation of domestic loads of individual households can possibly reduce the stress on the local grid [12], creating value for the distribution network operator [4]. It has also been suggested that demand side participation could provide spinning reserve [13]. Schedulable-interruptible loads [14] using an external on/off signal would not significantly affect the consumer experience and performance of a domestic appliance. For example, the system would ensure food safety at all times and it would not apply demand side participation when the door was open. The objective of demand side participation in the smart grid is to use these schedulable-interruptible loads to reduce peak demand, mitigate system disturbances, delay or avoid additional capital investment in new power plants and prevent excessive use of more expensive or less efficient power plants. Some domestic appliances (e.g. fridge-freezers, tumble dryers and washing machines), electric heating and heat pumps [15] are considered schedulable-interruptible appliances, making them prime candidates to implement demand side participation.

InterTradeIreland is a regional trade and business development agency which gives support to small businesses, with the aim of building networks and partnerships between Northern Ireland and the Republic of Ireland. Its study [16] mentions that small electrical appliances account for a maximum of 20% of the total Irish electrical market and this is currently a growing market. A forecast study has been carried out to assess the predicted consumption by schedulable-interruptible loads in Northern Ireland between 2012 and 2025 [14]. The study showed that the energy consumption of cold appliances is anticipated to be approximately 10% of total domestic consumption by 2025, considering the low total demand forecast case projected by the System Operator for Northern Ireland (SONI) [5].

Electric heating has previously been studied and proposed as a candidate for demand side participation. Fitzgerald et al. [17] showed the power system benefits from implementing direct load control in electric water heating in Ireland. Domestic appliances such as fridge-freezers, chest-freezers and refrigerators are potential candidates because there is at least one of these appliances in every household and they possess thermal storage capabilities. Most researchers to date have focused on refrigerator loads [18–20] and domestic freezers [21], analysing the potential load-shifting effect and time of use tariffs to reduce power peaks. Short et al. [22] presented a study to provide frequency response to the power system using refrigerators. Specifically for fridge-freezers, many studies have focused on different operating factors such as the effect of ambient temperature, door opening and thermostat opening position [23], the use of different types of refrigerants [24] or the effect of different types in components of the refrigeration cycle [25]. The potential response from relevant responsive loads such as refrigeration and space heating has been analysed in a statistical manner [1]. The results indicate that the residential sector deserves attention as a potentially valuable demand side participation resource.

3. Methodology

In this research a fridge-freezer with only one compressor is modelled because it is the most widely sold domestic appliance in the UK [26] and in countries with similar climates to Ireland. The thermodynamic cycle in the cooling circuit is a vapour compression cycle [27]. In this appliance the circulation of the refrigerant is driven by a compressor, which requires a motor and thus electrical energy.

3.1. Model of a single fridge-freezer

The model of a single fridge-freezer developed in Ref. [28] predicts the temperature in each compartment of the fridge-freezer based on heat transfer equations [27]. The model used in this study is a simplified model in which it is not necessary to know the detailed technical specifications of each component of the refrigeration cycle to obtain an accurate prediction of the temperature in each compartment and therefore an accurate prediction of the electrical power consumption. The model inputs are the dimensions of the fridge and freezer compartments, the compressor power consumption, coefficient of performance (COP) tested in extreme working conditions, thermal masses and thermal time constants of the fridge and freezer.

The heat transfer equation for each compartment of the fridge-freezer is (1), which states that the heat transmitted to the thermal mass of the fridge-freezer compartment is equal to the convection heat losses, resulting from the temperature difference between the room and the compartment, minus the heat transfer from the refrigerant to the compartment. The conduction heat losses between the fridge and freezer are assumed to be negligible due to the insulation.

$$-\left(m_w c_{p_w} + m_a c_{p_a}\right)\frac{dT(t)}{dt} = \frac{(T_{room}(t) - T(t))}{R_{eq}} - Q \tag{1}$$

where m_w (kg) and m_a (kg) are the mass of the water and air stored in each compartment, c_{p_w} (J/kg °C) and c_{p_a} (J/kg °C) are the specific

Please cite this article in press as: M. Martin Almenta, et al., Domestic fridge-freezer load aggregation to support ancillary services, Renewable Energy (2015), http://dx.doi.org/10.1016/j.renene.2015.08.033