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Comfort, peak load and energy: Centralised control of water heaters for demand-driven prioritisation

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ABSTRACT

Recent advances in smart grid technology enable new approaches to address the problem of load control for domestic water heating. Since water heaters store energy, they are well-suited to load management. However, existing approaches have focused on the electrical supply side, ignoring the obvious link between the user and the grid: individual hot water consumption patterns. This paper proposes a load spreading approach in which water heaters compete for access to the heating medium. The proposed smart grid solution takes grid load limits, real-time temperature measurements, water usage patterns, individual user comfort, and heater meta-data into consideration. The scheduler only turns on the heaters with the highest level of need, but limits the number of *on* heaters to ensure that the grid load stays below a set limit for a set time. The method is evaluated by simulation against various heater set temperature levels, and for various load limits, and compared with ripple control and actual consumption measured in a field trial of 34 water heaters. The proposed algorithm reduces the load from 62 kW to 20, 30, 40, and 50 kW (vs. 106 kW for full ripple control). The resulting number of unwanted cold events is fewer than for ripple control, and only slightly more than no control, while reducing the total energy by 14% from a user-optimised natural experiment.

Introduction

Electricity generators are responsible to supply sufficient generation capacity for the worst-case demand, and therefore strive to limit the power demand during peak times for smoother demand profiles (Beute & Delport, 2006; Howlader, Furukakoi, Matayoshi, & Senjyu, 2017a) Electricity supply is a recurrent concern, particularly in developing countries that experience capacity constraints and limited reserve margins (Naude, 1995; Gabriel, Kirkwood, Walton, & Rose, 2016; Wilken & Delport, 2000; Sebitosi, 2008). This challenge is compounded by peak demand periods of the residential load sector coinciding with the peak demand periods experienced by the supply grid (Beute & Delport, 2006; Roux, Naude, Booysen, & Barnard, 2017; Howlader, Furukakoi, Matayoshi, & Senjyu, 2017).

In South Africa, for example, constrained power has led to rolling blackouts and the implementation of large-scale demand-side management (DSM) techniques, such as ripple control on electric water heaters (EWHs), to limit the burden on the grid (Beute & Delport, 2006). In South Africa, which hosts 5.4 million electric water heaters and where instantaneous water heaters are not commonly used, electric water heating is responsible for 7% of the grid load and between 30% and 50% of the residential energy demand (Beute & Delport, 2006; Eskom Geyser Fact Sheet, 2013).

EWH-controlling DSM can be implemented in a variety of ways with financial incentives and direct control being popular choices. Direct control in its simplest form, which is employed in developing countries such as South Africa, is established by means of ripple controllers that are connected to the electric supply of each EWH and controlled centrally, using a signal superimposed on the supply lines to disable EWHs over whole neighbourhoods, towns, or districts (Beute & Delport, 2006; Wilken & Delport, 2000). Direct control is useful during critical demand periods to remove loads from the grid to reduce the demand. However, direct control fails to take the consumer into account, and could lead to users experiencing cold water, especially if the user happens to also apply a coinciding heating schedule of their own to reduce their energy costs. Moreover, since direct control does not address standing losses to the environment and only shifts the load temporally, it does not provide an energy-efficient solution.

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On the contrary, consumers want to reduce the energy they consume to limit expenses (and potentially their environmental footprint), while maintaining user comfort (water being hot when needed). In South Africa, water heating is responsible for 35% of the average households' energy consumption (Eskom Geyser Fact Sheet, 2013). Since cost-sensitive consumers in developing countries (such as South Africa) pay for energy consumed, and are not penalised for the time of use, many consumers resort to applying scheduled heating to only heat water in preparation for hot water usage (Booysen & Cloete, 2016). The energy used for water heating can be reduced by as much as 29% if intelligent scheduling is employed to only heat water as and when needed, but, the impact of this self-serving scheduling has an adverse impact on the grid (Roux et al., 2017; Roux & Booysen, 2017; Booysen & Cloete, 2016).

These apparently competing objectives for the utility provider and the consumer, depicted in Fig. 1, can be managed through the use of the emerging smart grid (SG) technology. One of the key focal points of SGs is improved energy efficiency through load management (Fang, Misra, Xue, & Yang, 2012). The SG concept enables the use of demand response (DR) techniques that have the main objective of matching the consumer consumption to the available supply capability. This objective is achieved either through direct control of specialised devices or by encouraging consumers to adjust their consumption pattern by rescheduling their power demand to off-peak periods and to use less energy overall. However, to make this informed type of direct control possible, a centralised algorithm, bidirectional communications (measure and control) between the EWH controller and the schedule controller, and knowledge of the consumption patterns are required.

Contributions and content

This paper presents a novel algorithm that reduces peak demand on the grid through intelligent management of EWHs that have an inherent thermal storage capacity. However, the algorithm bases heating priority on individual users' demand for heated water, and by doing so, also reduces energy by not heating when warm water is not needed. The proposed algorithm uses measured water consumption patterns and set peak load limits and periods for the grid to apply dynamically-calculated priorities for heating scheduling, using real-time measured temperature, observed consumption patterns, and individual EWH metadata as input. For this paper, the water consumed by each EWH over four weeks was used as a representative set of hot water demand for each individual EWH, and that was considered the consumption pattern to which the controller must schedule. The algorithm is simulated with a validated EWH model (Nel, Booysen, & Van Der Merwe, 2014; Cloete, 2017), and data from a field trial of 34 electric water heaters, measured per minute over 28 days.

This paper is organised as follows. Related work section presents the baseline EWH model and investigates SG scheduling techniques for grid optimisation and maintaining user comfort with EWHs. The proposed scheduling algorithm is developed in Proposed Peak Demand Manager section. The results of simulations utilising the proposed algorithm is presented and compared in Results and discussion section, and Conclusion section concludes the paper.

Related work

This section contains an overview of the existing literature on direct control of water heaters. The objectives, methods, results, and shortcomings are highlighted. The properties of the related work are summarised in Table 1, at the end of this section.

It is well-established that water heaters are suited to direct control due to their capacity for storing thermal energy vs. their relatively high power ratings and high energy consumption (Xu, Diao, Lu, Lian, & Zhang, 2014). Various studies have explored the potential of using EWHs for that purpose (Xu et al., 2014; Gholizadeh & Aravinthan, 2016; Zeng, Sun, Ye, Qi, & Li, 2017; Binini, Munda, & Dintchev, 2017; Song, Park, & Yoon, 2015; Kondoh, Lu, & Hammerstrom, 2011; Cui, Wang, Wang, & Zhang, 2016; Belov, Vasenev, Havinga, Meratnia, & van der Zwaag, 2015).

The objectives of these studies all fall in the broad categories of

- Thermal modelling of EWHs, which allows assessment of control strategies,
- Utility's peak load shaving by shifting water heaters' load through direct control,
- Users' cost reduction through load shifting under Time of Use (ToU) tariffs,
- Users' cost reduction through intelligent heating schedules, which reduces energy usage,
- Managing users' comfort despite load shifting.

Gholizadeh and Aravinthan (2016) presents a simple "event-driven" demand response solution to manage EWHs in a smart grid with distributed control. The objective is to shift the load from peak times by heating during off-peak periods. The proposed algorithm fundamentally controls to high target set temperatures for EWHs out of peak grid load periods, leveraging the energy storing capacity of EWHs. The method is to control the temperature inside water

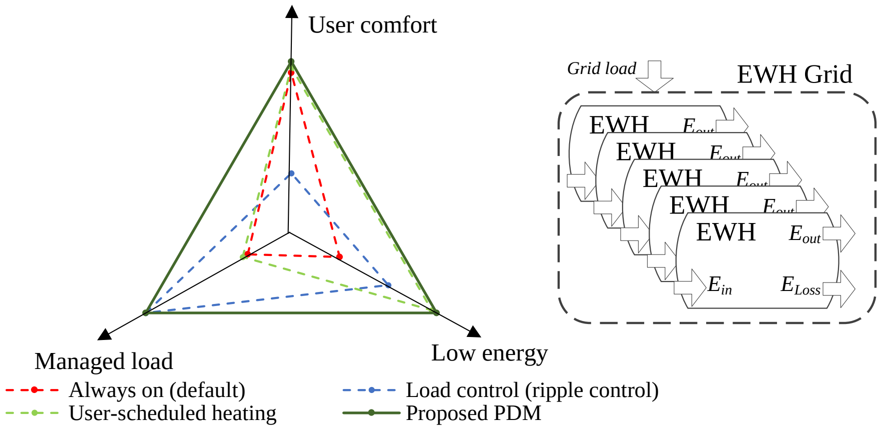

Fig. 1. The balancing act with electric water heaters between the impact of high grid loads on the supplier or reseller (*Grid load*), the cost to the individual user (and the environment) of energy consumption (E_{in}), and the impact on the individual user's comfort (E_{out}).