



Domestic EWH and HVAC management in smart grids: Potential benefits and realization



Amir Safdarian^{a,*}, Mubbashir Ali^b, Mahmud Fotuhi-Firuzabad^a, Matti Lehtonen^b

^a Center of Excellence in Power System Control and Management, Electrical Engineering Department, Sharif University of Technology, Tehran, Iran

^b Department of Electrical Engineering and Automation, Aalto University, Espoo, Finland

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ABSTRACT

Demand response is envisioned as a key solution to increase network efficiency as well as to alleviate challenges such as growing demand. In this paper, domestic electric water heater (EWH) and heating, ventilation, and air-conditioning (HVAC) are considered for potential demand response applications. An interaction between the system operator and consumers is considered to facilitate managing cyclic operation of consumers' heating loads. A centralized control model is first developed and formulated to achieve potential benefits of demand response of EWH and HVAC loads. Then, a distributed control algorithm is designed for practical implementation. In the proposed algorithm, house-wide modules (HwMs) submit their load modification proposals to system-wide module (SwM). SwM judges the received proposals and accepts those which are in line with the objective. This process iterates until no further proposals are received. Finally, the distributed control algorithm is applied to a group of consumers and the obtained results are thoroughly discussed. The objective is to attain a desirable load profile while the consumers' thermal comfort is not sacrificed. The analyses affirm significant benefits of demand response from domestic EWH and HVAC loads which are effectively realized by the distributed algorithm.

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1. Introduction

Demand response enables power system operators to enhance power systems operation from several aspects [1]. Demand response flattens load profiles thereby reduces network losses [2], prevents operation of high-cost/emission generating units [3,4], and defers capital intensive reinforcements [5]. Moreover, it is a promising complement to renewable energy resources with inherently variable generation [6,7]. These benefits have motivated electric companies around the world to make plans for activating demand response potential. Although majority of the implemented demand response programs have focused on large industrial consumers [8], substantial research has been devoted to activate demand response potential of domestic consumers. A research reported in [2] revealed that majority of residential demand response potentials can be unleashed by just managing the EWH and HVAC loads. This unique capability of EWH and HVAC loads is due to their significant contribution in total electricity usage

as well as their great flexibility thanks to thermal inertia of building structures and heat storage capability. In Finland alone, thermal demand of a typical household accounts for about 70% of the total energy usage [9]. To this end, the aim of this paper is to study demand response potential of residential EWH and HVAC loads. Also, the paper presents a distributed management approach to bridge the gap between demand response potential and realization.

In order to clarify unique contribution of this paper, a survey on reported researches on demand response from domestic EWH and HVAC loads and the relevant management approaches is given here. The research reported in [10] has presented an algorithm for managing operation of domestic EWH load to minimize energy expenses while consumer's comfort preferences remain intact. The model presented in [11] jointly optimizes the energy scheduling of electric vehicle and HVAC load in a house to minimize energy payments. In [12], operation of HVAC load and partial thermal storages has been optimized in the hope of reducing energy costs without sacrificing user's comfort. While most of the works focused on benefits to a single consumer, the system-wide benefits are envisioned to be significant as well. The work presented in [13] has estimated demand response potential of EWHs as a balancing reserve. The potential of HVAC loads in providing load balancing services was evaluated in [14]. The study demonstrated that demand response capability of HVAC loads varies significantly with

* Corresponding author. Tel.: +98 21 66165907.

E-mail addresses: safdarian@sharif.edu (A. Safdarian), mubbashir.ali@aalto.fi (M. Ali), fotuhi@sharif.edu (M. Fotuhi-Firuzabad), matti.lehtonen@aalto.fi (M. Lehtonen).

temperature settings and outdoor temperatures. A centralized control mechanism of HVAC loads was proposed in [15] to provide load balancing services. A comparison between centralized and decentralized demand response frameworks has been conducted in [16] demonstrating the importance of developing decentralized management models. In [17,18], decentralized management approaches were developed to coordinate demand response from different customers. However, optimal operation cycling of EWH and HVAC loads was not considered in the reported researches. In [19], a control strategy was developed to dispatch HVAC loads such that variation of nonrenewable power demand is minimized. The research reported in the reviewed papers is valuable, as they focused on the capability of demand response in load balancing. This is why demand response from domestic EWH and HVAC loads can be used as a feasible tool to modify system load profile thereby enhancing power system operation from several aspects.

The research scope of this article is the thorough quantification of potential benefits of responsive domestic EWH and HVAC loads to operation of distribution networks as well as the development of a system-wide management approach to achieve them. The major contributions of this paper are twofold. It firstly develops a mathematical model to optimally manage operating cycles of domestic EWH and HVAC loads such that a desirable system load profile is attained while consumers' comfort remains intact. The developed optimization problem accounts existing thermal models to consider the dynamic thermal behavior of consumers' space heating/cooling as well as their domestic hot water consumption. The thermal comfort of consumers is taken into account through imposing lower and upper bounds on the hot water and indoor temperatures. The developed model considers the stochastic nature of uncertain parameters such as hot water consumption via a scenario-based stochastic programming approach. In the approach, the constraints are written for all likely scenarios and the expected value of the objective over the scenarios is optimized. The second major contribution is to develop a distributed framework to solve the formulated problem for real world applications. In the developed framework, SwM and HwMs are independent agents whose interaction leads to the solution of the provided mathematical formulation. In the framework, the role of SwM is to coordinate the operation of HwMs such that the desirable system load profile is achieved. Whereas, HwMs are in charge of providing SwM with load modification proposals as well as ensuring consumers' thermal comfort. SwM iteratively receives HwMs' proposals and apply only the beneficial ones until no new proposal is received. The distributed algorithm respects consumers' privacy since they are not forced to broadcast their technical data as well as desirable indoor and hot water temperatures. In addition, congestion in communication infrastructure does not occur since data exchange between consumers and the program administrator is limited to consumers' and system load profiles. The capability of the distributed framework is demonstrated via applying to a system with a group of domestic customers.

2. Domestic EWH and HVAC management model

This paper considers a smart grid with a system operator serving multiple domestic consumers. It is assumed that the operator and consumers signed a contract allowing the operator to control operating cycle of EWH and HVAC loads without over riding the users' thermal preferences. The system operator needs a tool to effectively manage operating cycle of the loads. This section intends to present mathematical formulation of the problem of managing operating cycle of domestic EWH and HVAC loads to modify the system load profile. In the management model, the objective is to modify system load profile. This objective is considered since it is

general enough to cover almost all load shaping situations such as peak clipping, valley filling, and load profile flattening. This is done through considering the desired load profile as input and minimizing the expected deviation of system load profile from the desired profile. It is clear that the desired profile is defined by the system operators according to their system, experiences, and preferences. For instance, if an operator encounters capacity shortage, it makes sense to focus on peak clipping strategies. In this case, the desired profile might be one whose peak can be met without violating capacity limits. As another example, in case the network losses minimization is the target, the desired profile can be a more even profile. The general objective considered in this model can be mathematically formulated as follows:

$$\text{Minimize AD} = \sqrt{\sum_{s \in S} \sum_{t \in T} \pi_s (P_{t,s} - P_t^{\text{des}})^2} \quad (1)$$

where t and T are index and set of time intervals, respectively. s and S are index and set of likely scenarios, respectively. AD stands for expected deviation of system load profile from the desired profile. π_s is occurrence probability of scenario s . $P_{t,s}$ and P_t^{des} represent actual value of system load at time t and scenario s and desired value of system load at time t , respectively. The system load is calculated by summing up individual consumers' loads as follows:

$$P_{t,s} = \sum_{n \in N} P_{n,t,s}^{\text{firm}} + P_{n,t,s}^{\text{HVAC}} + P_{n,t,s}^{\text{EWH}}, \quad \forall t \in T, \quad \forall s \in S \quad (2)$$

where n and N are index and set of consumers, respectively. $P_{n,t,s}^{\text{firm}}$ is power absorbed by firm loads of consumer n at time t and scenario s . In this paper, since the focus is on EWH and HVAC systems, all other appliances either flexible like dishwashers or inflexible like televisions are considered firm. $P_{n,t,s}^{\text{HVAC}}$ and $P_{n,t,s}^{\text{EWH}}$ represent power absorptions of HVAC and EWH loads of consumer n at time t and scenario s .

The load management problem is subjected to a number of constraints preserving consumers' thermal comfort. The following constraints ensure that indoor and hot water temperatures are within their acceptable limits.

$$\underline{T}_n^{\text{ia}} \leq T_{n,t,s}^{\text{ia}} \leq \overline{T}_n^{\text{ia}}, \quad \forall n \in N, \quad \forall t \in T, \quad \forall s \in S \quad (3)$$

$$\underline{T}_n^{\text{hw}} \leq T_{n,t,s}^{\text{hw}} \leq \overline{T}_n^{\text{hw}}, \quad \forall n \in N, \quad \forall t \in T, \quad \forall s \in S \quad (4)$$

In the above expressions, $T_{n,t,s}^{\text{ia}}$ and $T_{n,t,s}^{\text{hw}}$ are indoor and hot water temperatures, respectively, associated with consumer n at time t and scenario s . $\underline{T}_n^{\text{ia}}$ and $\overline{T}_n^{\text{ia}}$ are upper and lower bounds of acceptable range for indoor temperature, respectively, for consumer n . $\underline{T}_n^{\text{hw}}$ and $\overline{T}_n^{\text{hw}}$ are also upper and lower bounds of acceptable range for hot water temperature for consumer n , respectively. The acceptable ranges are defined by consumers according to their thermal preferences. It is clear that wider ranges provide the system operator with higher flexibilities while tighter ranges are favorable for those consumers whose thermal comfort is their first and foremost priority.

In order to model the HVAC load, there exist several thermodynamic models having some pros and cons. The complex theoretical models are more close to the real-world however cumbersome to implement in practice. Also, simplistic models do not yield realistic results. In order to achieve a fair trade-off between complexity and accuracy, the paper uses the 1-capacity model where the dynamics of indoor ambient temperature are captured using a lumped capacity representing building fabric heat capacity as well as air heat capacity. This selection is justified as the model has been frequently employed in academic research [20,21]. Interested readers are referred to [12] where the model subtleties are well elaborated.

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