Energy 117 (2016) 166–175

Contents lists available at ScienceDirect

Energy

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

A framework for sensitivity analysis of data errors on home energy management system

Dae-Hyun Choi [a,*], Le Xie [b]

[a] School of Electrical and Electronics Engineering, Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul 156-756, Republic of Korea
[b] Department of Electrical and Computer Engineering, Texas A&M University, College Station TX, USA

ARTICLE INFO

Article history:
Received 22 February 2016
Received in revised form
30 July 2016
Accepted 19 October 2016

Keywords:
Home energy management system (HEMS)
Energy consumption scheduling
Demand side management
Sensitivity analysis

ABSTRACT

This paper investigates the impact of data errors on home energy management systems (HEMSs) that reduce energy cost and maintain comfort for residential consumers. In particular, we conduct a sensitivity analysis of HEMS subject to various types of input data such as the predicted energy consumption, the forecasted outdoor temperature, the consumers' comfort settings, static and dynamic operation constraints for home appliances, and the demand response (DR) signal. Using the perturbed Karush-Kuhn-Tucker (KKT) condition equations from the HEMS optimization formulation, we develop a linear sensitivity matrix to assess the impact of data on optimal solutions for: (1) electricity cost; (2) consumer's dissatisfaction cost; (3) the energy consumption for home appliances; and (4) the indoor temperature. The results of a simulation study using the developed sensitivity matrix provide HEMS operators with unique insight into factors that account for the relationships of HEMS operations to the change in the various data. Furthermore, these results can be used to provide insights for residential consumers and to evaluate the security risks of HEMS to cyber attacks through data manipulation.

1. Introduction

There has been significant increase in smart energy appliances such as air conditioners, washers, and refrigerators. Furthermore, smart meters and distributed energy resources (DERs) (e.g., solar and energy storage systems) are deployed in a smart grid based on an advanced metering infrastructure (AMI). It is therefore necessary to develop systems with which a utility is provided for consumers to manage their residential energy consumption for a reduction in household CO2 emission, energy savings, and efficiency of home appliances.

Home energy management systems (HEMSs) are the core technology for residential energy management in smart grids. The main functions of HEMS include: monitoring the real-time energy usage of consumers using smart meters and smart plugs, optimizing and scheduling the energy consumption of home appliances, and reducing consumers' electricity bills while satisfying consumers' comforts and preferences. It should be noted that the operation of HEMS strongly relies on various types of sensor data associated with energy consumption— from smart meters, weather information (e.g., outdoor temperature), operational parameters for appliances such as power ratings, comfort settings by consumers such as preferred indoor temperature range, and demand response (DR) signals from a utility such as a demand reduction request (KW) and duration (hours). Obviously, the change in these data caused by inherent and/or human attack could result in the serious malfunction of HEMS.

Maintaining the quality of data in a smart grid is becoming a crucial issue, which was well expressed by Gib Sorebo, chief cybersecurity technologist at Science Applications International Corporation, *"Even small changes in the data could affect the stability of the grid and even jeopardize human safety"* [1]. This message is primarily relevant for operators of transmission and distribution systems whose primary role is to ensure reliable and secure grid functioning, although it is also relevant for HEMS operators of the last-mile distribution network. For example, the cyber security concern about HEMS has recently been addressed, where an adversary can stealthily manipulate data related to appliance energy consumption, a DR event, and priority/preference settings, consequently providing incorrect energy consumption scheduling for appliances to consumers or incorrect household consumption data to a utility [2].

The main objective of this paper is to study the sensitivity of HEMS to small changes in various input data caused by inherent

* Corresponding author.
E-mail address: dhchoi@cau.ac.kr (D.-H. Choi).

http://dx.doi.org/10.1016/j.energy.2016.10.062

and/or human disruptions (e.g., low accuracy sensors, adversary attacks, etc.). Fig. 1 illustrates the conceptual system model for HEMS, along with the data-dependent HEMS optimization process and the proposed sensitivity framework. Based on input data **a**, HEMS computes the optimal energy consumption of each home appliance $\mathbf{x}^*$ and controls its operation according to $\mathbf{x}^*$. The novelty of this paper is that it proposes an analytical framework with which to evaluate the sensitivity of the optimal solution from HEMS in response to changes in five different types of data: (1) predicted energy demand; (2) operational constraints of appliances; (3) DR signals; (4) consumer's comfort setting; and (5) outdoor temperature.

Many recent papers have been presented on the subject of home energy management in smart grids. In Refs. [3,4], the authors characterized the detailed load models of controllable major home appliances associated with demand response. They then developed an algorithm to schedule operations for maintaining the desired total power consumption using the consumers' preset priorities and preferences. A large amount of research has recently been conducted on optimization algorithms for HEMS: with a distributed energy resource (DER) [5–12], based on particle swarm optimization [5], using mixed integer linear programming [6–8], using convex optimization [9,10], using mixed integer nonlinear programming based on a relaxed convex optimization with an L_1 regularization term [11], and considering a balance between the energy saving and a comfortable lifestyle [12]. Distributed HEMS algorithms for both the utility company and consumers have been proposed in Refs. [13,14]. A literature survey on the recent HEMS optimization problem was summarized well in Ref. [15]. More recently, the impact of an optimization interval on HEMS was investigated [16] and a novel HEMS algorithm with voltage control was proposed, which led to the minimization of the load shifting operation [17]. It is noted that the aforementioned optimization-based HEMS algorithms involve various sets of data for the optimal energy consumption scheduling of appliances. Therefore, maintaining high-quality data improves the performance of HEMS, and a data quality assessment tool is required for HEMS operators to ensure efficient and secure HEMS operation.

To the best of our knowledge, no study has been presented concerning the degree to which changes in data influence HEMS operations. This paper is therefore a first attempt that we know of to conduct an impact analysis of HEMS subject to data errors. Many existing works have proposed a perturbation approach to data sensitivity analysis in the economic dispatch problem at the transmission level of an electric power system: with Lagrangian relaxation-based analysis with storage, network, and inter-temporal ramp constraints [18] and with the DC and AC optimal power flow models [19,20] for a study of locational marginal price (LMP) sensitivity. Our proposed sensitivity framework is based on a perturbation approach using Karush-Kuhn-Tucker (KKT) conditions for general nonlinear optimization problems [21], which has been verified and illustrated in Ref. [20]. In this paper, we apply this perturbation approach at the transmission level to the HEMS model at the distribution level. We derive the desired sensitivity matrix, validate its feasibility, present meaningful observations through simulation studies, and suggest potential applications of the proposed approach. The main contributions of this paper are two-fold:

- We propose an analytical framework to assess the sensitivity of HEMS to changes in various types of data. We derive the linear sensitivity matrix based on the perturbed KKT equations from the HEMS optimization formulation. This matrix explains the relationship between the optimal solution and the input data in HEMS. The proposed framework is a closed-form online analysis tool with a linear sensitivity matrix, offering HEMS operators a quick and accurate method to predict and analyze the performance of HEMS with varying data. From an implementation perspective, the advantage of the proposed approach is that the developed framework can be applicable to any HEMS optimization problem and readily integrated into the existing HEMS without the need to modify the HEMS.
- We perform rigorous simulation studies on the proposed sensitivity approach applied in a house with five controllable home appliances (air conditioner, cloth dryer, washing machine, dish washer and oven). For a household joining a residential DR program with a Time-of-Use (TOU) pricing scheme, we first validate the feasibility of the proposed sensitivity framework, and then quantify and compare the sensitivity of HEMS to different types of data. The calculated sensitivities can potentially be used by an energy consulting service to maximize electricity bill savings and comfort for residential consumers, and as a cybersecurity tool for HEMS operators to assess the risks of cyber data attack on HEMS.

The remainder of this paper is organized as follows. Section 2 introduces a system model and mathematical optimization problem for HEMS. In Section 3, we formulate a mathematical framework to assess the sensitivity of HEMS to corrupted data. The simulation results for the proposed sensitivity framework are provided in Section 4, and the concluding remarks and discussion on future work are given in Section 5.

2. System model for home energy management

2.1. Preliminary

In this paper, we consider the scenario where the HEMS schedules the operation of two types of controllable loads: (1) reducible loads such as air conditioners, known as thermostatically controllable loads (TCLs), and shiftable loads such as washing machines and dishwashers. The HEMS performs optimal day-ahead scheduling of these controllable appliances under Time-of-Use (TOU) pricing. We assume that HEMS is equipped with all input data prior to the optimal energy consumption scheduling. For example, the energy consumption data are collected, processed, and delivered by sensors (e.g., smart meter and smart plug) to HEMS and a prediction module [22] in HEMS uses these data to forecast appliance energy consumption and the consumer's consumption pattern. The main notations used throughout this paper are summarized in Table 1. Bold symbols represent vectors or matrices. Hat symbols represent predictions of true parameter values.

2.2. HEMS formulation

In general, an algorithm for HEMS is formulated as an optimization problem with equality and inequality constraints as follows:

$$\min_{\mathbf{x}} J(\mathbf{x}, \mathbf{a}) \tag{1}$$

s.t.

$$\mathbf{f}(\mathbf{x}, \mathbf{a}) = 0 \tag{2}$$

$$\mathbf{g}(\mathbf{x}, \mathbf{a}) \leq 0 \tag{3}$$

where $J(\mathbf{x},\mathbf{a})$ is a scalar objective function, consisting of electricity cost $J_1(\mathbf{x},\mathbf{a})$ and the consumer's dissatisfaction cost $J_2(\mathbf{x},\mathbf{a})$, $\mathbf{f}(\mathbf{x},\mathbf{a})$ are equality constraints for the balance equations of the predicted appliance energy consumption and operational dynamics of the