Electrical Power and Energy Systems 64 (2015) 1007–1016

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A cloud computing framework on demand side management game in smart energy hubs

Aras Sheikhi *, Mohammad Rayati, Shahab Bahrami, Ali Mohammad Ranjbar, Sourena Sattari

Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 6 December 2013
Received in revised form 16 July 2014
Accepted 19 August 2014
Available online 20 September 2014

Keywords:
Cloud computing (CC)
Demand side management (DSM)
Game theory
Smart Energy Hub (S.E. Hub)
Smart grid (SG)

ABSTRACT

The presence of energy hubs in the future vision of energy networks creates an opportunity for electrical engineers to move toward more efficient energy systems. At the same time, it is envisioned that smart grid can cover the natural gas network in the near future. This paper modifies the classic Energy Hub model to present an upgraded model in the smart environment entitling "Smart Energy Hub". Supporting real time, two-way communication between utility companies and smart energy hubs, and allowing intelligent infrastructures at both ends to manage power consumption necessitates large-scale real-time computing capabilities to handle the communication and the storage of huge transferable data. To manage communications to large numbers of endpoints in a secure, scalable and highly-available environment, in this paper we provide a cloud computing framework for a group of smart energy hubs. Then, we use game theory to model the demand side management among the smart energy hubs. Simulation results confirm that at the Nash equilibrium, peak to average ratio of the total electricity demand reduces significantly and at the same time the hubs will pay less considerably for their energy bill.

Introduction

Recently, energy consumptions growth has led researchers to suggest integrated view of energy systems with multiple energy carriers, instead of focusing on a single one. By coupling different energy infrastructures, such as natural gas and electricity networks, the integrated system aims at attaining an optimal solution instead of two sub-optimal ones [1].

The Energy Hub (EH) model and concept was proposed by Geidl for the first time [1]. In the simple definition, an EH is a multi-generation system, where various forms of energy carriers are converted, stored and distributed using a converter system such as *combined heating and power* (CHP) to meet the energy demands [1]. The studies related to the applications of EH can be categorized in two different groups. The first group dealt with financial aspects of deploying EH in residential, commercial and industrial sectors [2–11]. In [2], authors calculated required financial parameters to analyze feasibility of an energy hub plant. Determining the optimal size of elements in an energy hub consisting of CHP, auxiliary boiler, absorption chiller, battery, and heating storage have been investigated in [3]. In [4], Kienzle et al. proposed a financial valuation method for the energy hubs with conversion, storage, and demand side management (DSM) capabilities.

The second category comprises different methods of controlling and optimizing operation of an energy hub [5–10]. In [5], the optimal operation of an energy hub is investigated by applying non-linear programming. In [6], the optimization model of a residential energy hub has been presented to incorporate into automated decision making technologies. Arnold in [7] applies a model of predictive system control approach for an energy hub with respect to the loads which are completely probabilistic. Additionally, Parisio et al [8] propose a control mechanism for an energy hub based on robust optimization (RO) technique which is less sensitive to converter efficiencies. In [9], a distributed control method has been applied to a system consisting of several interconnected hubs to shape the demands by incentivizing customers. Finally, in [10], the storage level controlling of an energy hub has been developed based on responding to the energy prices. In comparison with the existing studies, we modify EH in the smart environment, and we name it a Smart Energy Hub (S.E. Hub). We also consider interaction between the S.E. Hubs in the DSM programs.

By increasing the penetration level of CHP and micro-CHP in several countries [11], and also realizing the smart grid (SG) in electrical networks, it is not farfetched to have a smart natural gas infrastructure in the near future. Therefore, the development of new methods for *demand side management* (DSM) in natural gas and electricity networks simultaneously seems imperative. Techniques used for DSM can be categorized in two different

* Corresponding author. Tel.: +98 912 6613840.
E-mail address: sheikhi@ee.sharif.edu (A. Sheikhi).

http://dx.doi.org/10.1016/j.ijepes.2014.08.020
0142-0615/

groups: voluntary load management programs [12–14], and direct load control [15]. Among these methods smart pricing is one of the efficient tools that can encourage users to consume electricity more wisely [16]. Recent increases in energy price make consumers to be more active in DSM programs, and to shift the energy consumption to off-peak hours for reducing their energy bills [17]. Although most of the existing studies were successful to achieve optimal solutions for the DSM, they neglect the fact that considerable portion of the consumers, especially in the industrial sectors, do not have shiftable loads in reality. This paper deals with this issue by introducing S.E. Hubs which enables consumers with must-run loads, i.e. with strict energy consumption scheduling constraints, to be active in DSM programs.

So far, most of the proposed demand response systems have been based on master-slave architecture [12–17]. Utility's energy management system (EMS) interacts with customers' EMS individually. Basically, master-slave architecture is host-address centric communication (the senders and the receivers need to know their addresses (e.g., IP address) for communication) and is good for a small scale network due to its simplicity. However, from system protection perspective, master-slave architecture for demand response has several potential drawbacks [18–20]. It is possible that home's smart meters and EMS can be compromised by cyber attackers. From scalability perspective, the maximum numbers of clients are limited by the server's capacity. Additionally, when demand response operates as an iterative process the communication latency between a master and slaves can be high. Hence, if the utility wants to deploy a large-scale demand response program, the utility's EMS server must be able to resolve the potential problems listed so far.

Motivated by mentioned drawbacks, in this paper we propose a model for utilizing the cloud computing technology, a next-generation computing paradigm, in the smart grid domain. Cloud Computing refers to manipulating, configuring, and accessing the applications online [21]. It offers online data storage, infrastructure and application [22]. Computing, software and data services can be used by end users without knowledge of the users' IP address or configuration of the systems. Cloud computing is probably the simplest and best fitted way for smart grids due to its scalable and flexible characteristics, and its capability to manage large amounts of data [23]. The utility company and customers interact through the cloud, and the functions for realizing demand response are performed in a cloud rather than in the utility's EMS. From utility's perspective, cloud appears to be an information system that takes an input from utility (e.g., the amount of power deficit), processes the information, and gives an output to utility (e.g., how much to reduce loads per customers and at which incentive price) [24–27].

In this paper we present a cloud-base architecture that embeds SG in to a cloud environment and we explore how CC can play an effective role in DSM game among a group of S.E. Hubs.

The rest of this paper is organized as follows. The S.E. Hub model is introduced and in Section 'Smart Energy Hub; definition and modeling'. In Section 'DSM in a group of S.E. Hub', DSM in a group of S.E. Hubs is modeled with three configurations and information management methods. In Section 'DSM game optimization problem', DSM game among S.E. Hubs based on CC configuration is formulated and solved by using distributed projected gradient algorithm. Simulation results and discussions are given in Section 'Simulation and discussion', the paper is concluded in Section 'Conclusion'.

Smart Energy Hub; definition and modeling

A general model of an energy hub is presented in Fig. 1 [1]. Power conversion through the hub is modeled as follows.

$$\begin{bmatrix} P^{out}_{\alpha,i} \\ P^{out}_{\beta,i} \\ \vdots \\ P^{out}_{\omega,i} \end{bmatrix} = \begin{bmatrix} C_{\alpha\alpha} & C_{\beta\alpha} & \dots & C_{\omega\alpha} \\ C_{\alpha\beta} & C_{\beta\beta} & \dots & C_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ C_{\alpha\omega} & C_{\beta\omega} & \dots & C_{\omega\omega} \end{bmatrix} \begin{bmatrix} P^{in}_{\alpha,i} \\ P^{in}_{\beta,i} \\ \vdots \\ P^{in}_{\omega,i} \end{bmatrix} \quad (1)$$

where $P^{in}_{\alpha,i}, P^{in}_{\beta,i}, \dots, P^{in}_{\omega,i}$ are the input energy carriers' power of ith S.E. Hub and $P^{out}_{\alpha,i}, P^{out}_{\beta,i}, \dots, P^{out}_{\omega,i}$ are the output energy carriers' powers, and $C_{\alpha\beta}$ denotes the coupling factor between input energy carrier α and output energy carrier β energy flow.

A simple energy hub with two inputs (electricity and natural gas) and two outputs (electrical and heating loads) is shown in Fig. 2.

The matrix equation for the above-mentioned energy hub is

$$\begin{bmatrix} P^{out}_{e,i} \\ P^{out}_{h,i} \end{bmatrix} = \begin{bmatrix} \eta_{trans.,i} & \lambda_i \eta^{e}_{chp,i} \\ 0 & \lambda_i \eta^{h}_{chp,i} + (1-\lambda_i)\eta_{boiler,i} \end{bmatrix} \begin{bmatrix} P^{in}_{e,i} \\ P^{in}_{g,i} \end{bmatrix} \quad (2)$$

where λ_i is the dispatch factor that determines the amount of natural gas dividing between the auxiliary boiler and the CHP in ith S.E. Hub. Parameters $\eta_{trans.,i}$, $\eta_{boiler,i}$ denote the efficiencies of the transformer and the auxiliary boiler, respectively. $\eta^{h}_{chp,i}, \eta^{e}_{chp,i}$ are the heating and the electrical efficiency of the CHP.

Eqs. (3) and (4) introduce new variables $P^{in}_{chp,i}$ and $P^{in}_{Boiler,i}$ to simplify (2), where $P^{in}_{CHP,i}$ and $P^{in}_{Boiler,i}$ are amount of natural gas that inputs CHP and boiler.

$$P^{in}_{chp,i} = \lambda_i P^{in}_{g,i} \quad (3)$$

$$P^{in}_{Boiler,i} = (1-\lambda_i) P^{in}_{g,i} \quad (4)$$

By using (3) and (4), Eq. (2) can be rewritten as follows.

$$\begin{bmatrix} P^{out}_{e,i} \\ P^{out}_{h,i} \end{bmatrix} = \begin{bmatrix} \eta_{trans.,i} P^{in}_{e,i} + \eta^{e}_{CHP,i} P^{in}_{CHP,i} \\ \eta^{h}_{CHP,i} P^{in}_{CHP,i} + \eta_{boiler,i} P^{in}_{Boiler,i} \end{bmatrix} \quad (5)$$

We call an energy hub a S.E. Hub, if the EH locates in the SG and equipped with smart meters for both electricity and natural gas networks with appropriate communication infrastructures (wire or wireless network).

The overall view of a simple S.E. Hub has been illustrated in Fig. 3. All exchanged messages between the smart meters and utilities are communicated through the LAN by using appropriate communication protocols such as ZigBee, Z-Wave and KNX [28].

DSM in a group of S.E. Hub

By increasing the coverage of SG in the real world, DSM programs and their implementation turn into the hot topic for electrical engineers. Researchers deal with this issue by integrating the implementation of different components such as Home Energy Management System (HEMS) [29], Building Energy Management System (BEMS) [30] and Energy consumption scheduler (ECS)

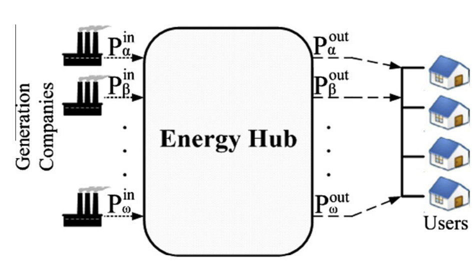

Fig. 1. The general model of an Energy Hub.