Electrical Power and Energy Systems 73 (2015) 448–455

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Demand response for home energy management system

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ARTICLE INFO

Article history:
Received 17 September 2014
Received in revised form 8 May 2015
Accepted 9 May 2015
Available online 28 May 2015

Keywords:
Smart scheduling
Demand response
Heuristic algorithm
CPLEX

ABSTRACT

The optimization of energy consumption, with consequent cost reduction, is one of the main challenges for the present and future smart grid. Demand response (DR) program is expected to be vital in home energy management system (HEMS) which aims to schedule the operation of appliances to save energy costs by considering customer convenience as well as characteristics of electric appliances. The DR program is a challenging optimization problem especially when the formulations are non-convex or NP-hard problems. In order to solve this challenging optimization problem efficiently, an effective heuristic approach is proposed to achieve a near optimal solution with low computational costs. Different from previously proposed methods in literatures which are not suitable to be run in embedded devices such as a smart meter. The proposed algorithm can be implemented in an embedded device which has severe limitations on memory size and computational power, and can get an optimal value in real-time. Numerical studies were carried out with the data simulating practical scenarios are provided to demonstrate the effectiveness of the proposed method.

Introduction

Over the past decades, energy crisis and environmental pollution have attracted great attention to energy utilization efficiency and energy saving. Therefore, new technology, such as demand response (DR) program, is incorporated into smart grid to improve the efficiency. The DR program could motivate changes in electricity usage by end-user customers, in response to incentives regarding the electricity prices, energy saving, cost reduction, and optimization of the grid operation (e.g., by reducing the contribution of the consumer to the peak load) [1].

Recently, two surveys on DR programs were present in [1,2], where authors presented comprehensive reviews of various DR schemes, programs, and models that have been proposed so far. There has been an extensive research effort on the optimization models on the DR programs over the past several years.

The DR programs are mainly applied to three sectors: residential, commercial and industrial consumers [1,3]. In industrial sector, due to the high energy demand, it is vital to increase power and voltage efficiency [4,5]. The DR programs were used to increase the reliability and economic efficiency of the electricity infrastructure [6,7]. DR methods can help to reduce power consumption for the commercial consumers whose main power consumption comes from heating, ventilation and air-conditioning (HVAC) and electronic equipment. Developing efficient DR programs in the residential sector have received considerable attention recently [18–23]. In general, the main objective of the DR program is to minimize the electricity bill or maximize their satisfaction by allocating available resources and actively managing the load of the appliances. It is much more complicated to design an efficient DR program for residential consumers compared to the to other two sectors. That mainly due to complex appliance loads and random consumption patterns. These appliances include heating, ventilation, battery, washing and air conditioning systems, etc., whose physical models depend on environmental factors such as the building structure, weather, and thermal dynamics.

The review of the optimization methods of the DR programs have been presented in [1], the main target of the optimization approach is to find an optimal solution under a set of constraints. The optimization approaches can be classified base on the nature of both the objectives and constraints. The traditional algorithms can provide efficient solutions when the optimization problems are linear or convex. Both an Integer Linear Programming method [8] and a Mixed Integer Programming method [9] were used to minimize electricity usage when it was formulated as a linear programming problem. Lagrangian algorithms [12,13], Lagrange–Newton [10], interior point method [11] and Lyapunov techniques

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http://dx.doi.org/10.1016/j.ijepes.2015.05.032
0142-0615/

Nomenclature

H	time step $h \in \{1, 2, \ldots, 24\}$
TOU(h)	time-of-use price
$P_{grid}(h)$	power exchange between main grid and smart home
$P_{batt}(h)$	battery's output power at hour h
$P_{ms}(h)$	power consumption of must-run load
$P_{shif}(h)$	power consumption of deferrable load
$P_{tm}(h)$	power consumption of air conditioner
$P^{ch}_{batt}(h)$, $P^{dch}_{batt}(h)$	battery's charging and discharging power
P^{max}_{dch}, P^{max}_{ch}	battery's maximum discharging and charging power
η_{ch}, η_{dch}	battery's charge and discharge efficiency
SOC^{max}, SOC^{min}	battery's maximum and minimum state of charge
$T_{in}(h)$	temperature of indoor
$T_{out}(h)$	temperature of outsider
α_a β_b	appliance work range
δ	appliance status: 0 off; 1 on
H_i	number of time slots required by appliance to finish task i
NK	number of tasks of appliance
$\delta_{i,t}$	binary variable indication the operation status of task i at time t
PSO	particle swarm optimization
BPSO	binary particle swarm optimization
HPSO	hybrid particle swarm optimization
COPSO	cooperative particle swarm optimization
PV	photovoltaic generation

[14] can obtain good results when the optimization problems are formulated as convex optimization problems. However, the aforementioned optimization methods may not find a feasible solution or the computational times are too high when the problems belong to non-convex programming, Mixed Integer Nonlinear Programming or NP-hard problems. For such cases, heuristic-based evolutionary algorithm can provide a fast and near optimal solution. A greedy algorithm was applied in [15] to maximize social welfare by determining the optimal load schedule. Particle swarm optimization (PSO) was extensively applied to get fast and near optimal solution for complicated problems [16,21,24]. For instance, PSO in [16] was applied to intelligently control the vehicles, as well as the thermal units; the decision-support energy service model was solved by the hybrid particle swarm optimization (HPSO) [21]; and the binary particle swarm optimization (BPSO) algorithm was used to determine on/off status of the appliances, where the Canonical PSO (CPSO) is used to determine the hourly continuous energy value of battery and heating power. Also, several commercial solvers such as CPLEX and MOSEK were applied to the complex optimization problems in [18,19,25].

In this paper, we are committed to propose a DR program which controls various electric appliances. This program can be run in resource-limited embedded devices such as a smart meter. Firstly, a mixed discrete–continuous optimization nonlinear problem is formulated. As previously, commercial software CPLEX or heuristic algorithms can be applied to solve this complex problem. However, these commercial solvers such as CPLEX are specialized optimization packages whose computational requirements are not suitable to be run in embedded devices such as the smart meter. While heuristic algorithms, such as the PSO and the greedy algorithm, are notorious for their slow convergence rate and high computational cost when the problem is highly constrained. They cannot guarantee near real-time execution and is not suitable to run in an embedded device. Therefore, in this paper, a gradient-based repair PSO optimization technique is proposed to solve the mixed discrete–continuous nonlinear problem. The gradient repair method is applied to deal with constraints which can speed up the PSO and guarantee near real-time execution.

The major distinctive features of this paper can be summarized as follows.

1. A complex mixed discrete–continuous nonlinear model is proposed and applied to a household scenario. Different from most studies that consider one or two types of controllable electric loads, we assume in this paper that the DR program controls almost all electric appliances. For a systematic illustration, it is equipped with the following types of appliances: interruptible appliance, deferrable appliances, multiple operation appliances thermal loads, PV generation and Battery-assisted appliances. It is more close to practical applications.
2. Instead of solving the complex DR problem with the commercial optimization software. In this paper, we devised a gradient based PSO that can be implemented on resource constrained embedded devices with low computation power, and can obtain near optimal values with near real-time execution. Its performance is comparable to the commercial software CPLEX and superior to the other two proposed heuristic algorithms.

The rest of the paper is organized as follows: Section 'Mathematical model' provides a brief description of the optimization mathematical model; the detailed solution procedure and the methodology are proposed in Section 'Gradient-based PSO for smart scheduling procedures'; Illustrative case studies are presented in Section 'Simulation results'; and the paper is concluded in Section 'Conclusions'.

Mathematical model

In this section, the DR program for home energy management system is briefly described.

Overview of demand response program

Fig. 1 shows the overview of the DR program in a home energy management system (HEMS).

It is assumed that most electric appliances are networked together and controlled by the home energy management system.

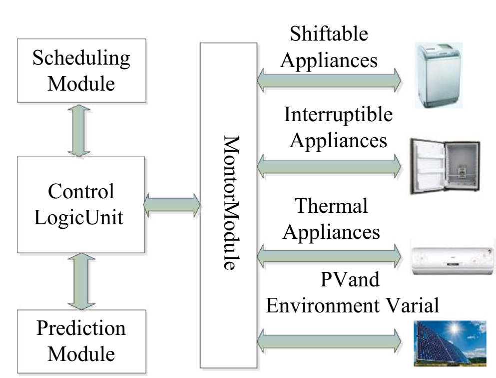

Fig. 1. Architecture of HEMS.