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Information gap decision theory-based risk-constrained scheduling of smart home energy consumption in the presence of solar thermal storage system

Afshin Najafi-Ghalelou, Sayyad Nojavan*, Kazem Zare

Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz 51666-15813, Iran

A R T I C L E I N F O

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A B S T R A C T

In domestic sector, robust scheduling of energy usage under various uncertainties is an important factor for any smart home energy management systems (EMS). In this paper, information gap decision theory (IGDT) is proposed for robust scheduling of apartment smart building (ASB) in the presence of price uncertainty and solar thermal storage system (STS). The proposed sample ASB contains combined heat and power (CHP) generator, boiler, battery storage system (BSS), STS system and smart appliances. IGDT approach doesn't depend on the size of the model. So, the EMS of ASB which is known as small scale loads can use IGDT to make more informed decisions against the price uncertainty. IGDT contains two functions namely robustness and opportunity functions. Risk-averse perspective of optimal scheduling of ASB is modeled by robustness function and opportunity function is used to model risk-taker perspective of optimal scheduling of ASB. Also, to assess the effect of STS system on proposed problem, two case studies are studied, and significant results were obtained, which indicate the validity of proposed model.

1. Introduction

Smart home EMS is one of the important issues in the smart grid that makes consumers able to adjust their power consumption (Alsharif, 2017). With the emergence and popularity of intelligent appliances, renewable energy sources (Camilo et al., 2017; Ghalelou et al., 2016; Kabalci and Kabalci, 2017) and uncertainty of power market price (Nojavan et al., 2017a), consumers may find it difficult to schedule/manage home appliances/renewable energy sources manually (Borujeni et al., 2017; Majidi et al., 2017; Zhang et al., 2015). Considering this reality, EMS becomes essential for reducing operation cost of ASB and increasing comfort life in ASB automatically with respect to fluctuations of market price.

1.1. Literature review

Optimal energy management of IGDT-based models have been investigated as follows: IGDT based determination of selling price problem by the retailer under a dynamic market price environment is presented in (Nojavan et al., 2017d). A new risk-based model for incorporating price-responsive customers in day-ahead scheduling of smart distribution networks is provided in (Mazidi et al., 2016). In order to minimize operation cost of hybrid system under electrical load uncertainty, a sample model is studied in (Nojavan et al., 2017b). In order to make bidding strategy in the day-ahead market for a large consumer, IGDT-based model is proposed in (Zare et al., 2010a). An IGDT-based optimal self-scheduling method is presented in (Moradi-Dalvand et al., 2015) for a wind power generation model under market price and wind generation uncertainties. A robust solution algorithm is presented in (Nikoobakht et al., 2016) to manage the risk of uncertain wind power generation in flexible power systems. A new IGDT-based strategic multiyear model is presented in (Shivaie and Ameli, 2016) for transmission expansion planning. A hybrid approach based on the modified particle swarm optimization and IGDT has been used in (Nojavan et al., 2015) to maximize the profit of generation station in the presence of market price uncertainty. An IGDT based model has been provided in (Nojavan et al., 2013) to maximize profit of thermal unit producers considering the market price uncertainty. In this regard, the IGDT is employed to model the uncertainty of market price in this paper, which is one of the important factors in robust scheduling of smart homes. A risk-constrained IGDT-based problem of daily hydro-thermal generation scheduling has been provided in (Charwand et al., 2016) to minimize the operation cost under load uncertainty. A novel method based on information gap decision theory has been provided in (Aghaei et al., 2017) to evaluate a profitable operation strategy for combined heat and power units in a liberalized electricity market.

Literature review about STS system can be expressed as follows: The effect of combining metal fins to absorb heat and release heat

* Corresponding author.
E-mail addresses: afshin.najafi95@ms.tabrizu.ac.ir (A. Najafi-Ghalelou), sayyad.nojavan@tabrizu.ac.ir (S. Nojavan), kazem.zare@tabrizu.ac.ir (K. Zare).

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Nomenclature

Sets

t index of time
j index of smart homes
i index of smart appliances
θ operation time index of each smart appliance

Parameters

λ^{Gas} natural gas price (£/kWh)
η^{CHP}, η^{Boiler}, $\eta^{Battery}$, $\eta^{Ch.Solar}$, $\eta^{Dch.Solar}$, κ^{Solar} CHP, boiler, charge/discharge power of BSS, charge/discharge rate of STS system and solar thermal panel efficiency (%)
$\lambda^{Battery}$, λ^{Solar} maintenance cost of BSS and STS system (£/kWh)
$\hat{\lambda}_t^{Buy}$, λ^{Sell} forecasted market price and cost of selling power to the upstream grid (£/kWh)
L^{CHP}, L^{Boiler}, $L^{Battery}$, L^{Solar} CHP generator, boiler, BSS and STS system capacities (kWh)
δ time interval of simulation (hour)
$CL^{Battery}$, $DL^{Battery}$ charge/discharge limits of BSS (kW)
$C^{Max.Ch.Solar}$, $C^{Max.Dch.Solar}$ maximum charge/discharge rates of STS system (kW)
θ^{Solar}, θ^{Static} coefficient of solar/static STS losses (scalar number)
Tem^{Min}, Tem^{Max} minimum/maximum operation temperature (°C)
$Tem_t^{Ambient}$ ambient temperature (°C)
φ_t solar irradiation (W/m^2)
A^{Solar} surface of solar thermal panel (m^2)
$M^{Battery}$, M^{Grid} maximum capacity of BSS, purchased power from upstream grid (kW)
$T_{j,t}^{Start}$, $T_{j,t}^{Finish}$ earliest starting/latest finishing time of ith smart appliance at jth smart home (hour)
P_i processing time of ith smart appliance (hour)
$P_{i,\theta}^{App}$ consumption power of ith appliance at the operation period θ (kW)
γ^{CHP} heat to power ratio of CHP
C_R, C_W critical cost for the robustness/opportunity functions (£)

Variables

$P_{j,t}^{CHP}$, $Q_{j,t}^{Boiler}$ output power of CHP generator/boiler (kW)
$P_{j,t}^{Import}$, $P_{j,t}^{Export}$ imported/exported power from/to the upstream grid (kW)
$S_{j,t}^{Battery}$, S_t^{Solar} stored energy in BSS/STS system (kWh)
$C_{j,t}^{Battery}$, $D_{j,t}^{Battery}$, P_t^{Loss} charge/discharge/heat loss rates of STS (kW)
$F^{Battery}$ stored energy at the beginning/end of each sample day (kWh)
C_t^{Solar}, $D_{j,t}^{Solar}$ charge/discharge rates of BSS (kW)
P_t^{Unuse} unused energy of STS system
Q_t^{Solar} converted solar irradiation to heat (kW)
λ_t^{Buy} real market price (£/kWh)

Binary variables

$\omega_{j,i,t}^{App}$ binary variable; equal to 1 if smart appliances active within the specific time period; otherwise 0
$B_{j,t}^{Grid}$ binary variable; equal to 1 if electricity is bought from upstream grid by the jth smart home at time t; otherwise 0
$B_{j,t}^{Dch.Solar}$ binary variable; equal to 1 if STS system is discharged at time t; otherwise 0
$B_t^{Ch.Solar}$ binary variable; equal to 1 if STS system is charged at time t; otherwise 0
$B_{j,t}^{Battery}$ binary variable; equal to 1 if BSS is charged at time t; equal to 0 if BSS is discharged at time t

Functions

$\hat{\alpha}(C_R)$, $\hat{\beta}(C_W)$ robustness and opportunity functions

effectively is investigated on the performance of a STS system in (Augspurger and Udaykumar, 2017). A new type of solar air collection-storage thermal system is designed and introduced in (Wang et al., 2017b) which absorbs solar energy and stores it to extend utilization hours. The dynamic efficiencies of a solar thermal energy storage unit and open-loop air receiver is investigated in (Li et al., 2016). A lunar based solar thermal power system including thermal storage is analyzed in (Lu et al., 2016). In order to improve tracking of losses based on storage and ambient temperatures, a new distributed energy resource model of STS system is presented in (Steen et al., 2015). In this regard, the effect of solar thermal storage system on total operation cost of ASB is evaluated in this paper.

Optimal energy management of smart homes have been investigated and presented in detail in Table 1.

1.2. Differences of IGDT and robust optimization approach

Deterministic modeling does not provide a real image of the dynamic behavior of the real world. In this regard, the importance of stochastic modeling has been revealed. IGDT approach and robust optimization approach are powerful tools to model the uncertain parameters. The procedure of this two approaches are completely different with other each. In this regard the procedure of this two approaches has been described in the following:

One of the similarities of both methods is that the worst case of uncertainty parameter can be modeled by both methods. But, the best case of uncertainty parameters can be modeled by IGDT approach which is impossible in robust optimization approach. Also, the big differences between two mentioned methods is related to their inputs parameters.

IGDT method can be useful when there are not sufficient data about the uncertain parameters. The purpose of this procedure is to reveal the results of the difference between actual and predicted values of uncertainty. In decision-making based on IGDT, two cases occur; risk-averse or risk-seeker. In risk-averse case, the decision-maker is looking for a robust decision against possible errors of uncertain parameters prediction. This decision is created when the objective function be protected against the maximum variations of uncertainty. Another case is risk-seeker case which tries to find the minimum variations of uncertain parameters. This means that for a degree of freedom for the objective function, it find the minimum variation of uncertain parameters.

Robust optimization approach are used when the statistical information of input parameters is insufficient (Nojavan et al., 2017c). In this method the interval values are used for displaying uncertainty and the problem is solved for the worst case at any interval. Thus, this method is very conservative. In the case of a parameter that is characterized by uncertainty, robust optimization ensures the decision maker that even if there are errors in the prediction of uncertain parameters, the objective function value will remain optimized.

1.3. Aims, scopes and contributions of this research

In this paper, the information gap decision theory (IGDT) is proposed for robust scheduling of ASB in the presence of price uncertainty. IGDT method is a non-possibilitic and nonprobabilistic method that