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Performance improvement of a battery/PV/fuel cell/grid hybrid energy system considering load uncertainty modeling using IGDT

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ABSTRACT

Nowadays with the speed that electrical loads are growing, system operators are challenged to manage the sources they use to supply loads which means that that besides upstream grid as the main sources of electric power, they can utilize renewable and non-renewable energy sources to meet the energy demand. In the proposed paper, a photovoltaic (PV)/fuel cell/battery hybrid system along with upstream grid has been utilized to supply two different types of loads: electrical load and thermal load. Operators should have to consider load uncertainty to manage the strategies they employ to supply load. In other words, operators have to evaluate how load variation would affect their energy procurement strategies. Therefore, information gap decision theory (IGDT) technique has been proposed to model the uncertainty of electrical load. Utilizing IGDT approach, robustness and opportunity functions are achieved which can be used by system operator to take the appropriate strategy. The uncertainty modeling of load enables operator to make appropriate decisions to optimize the system's operation against possible changes in load. A case study has been simulated to validate the effects of proposed technique.

1. Introduction

Increasing penetration of renewable and non-renewable energy resources in power systems is a deniable fact that operators are faced. Different types of these resources like fuel cell [1], battery [2] and photovoltaic systems [3] and other ones ensure a reliable energy to the load by their grid-connected operation in an integrated system like hybrid energy system [4]. It should be noted that load is an uncertain parameter and therefore, the operators of power system should take appropriate decisions to handle such issues.

1.1. Literature review

Hybrid energy systems have been widely studied by many researchers and these researches are summarized in this section. For more clarification, the works done before are classified into operation and sizing problems. The Refs. [5–24] have discussed about operation problems. In order to minimize total cost, optimal operation of a PV/wind/diesel hybrid energy system has been obtained through genetic algorithm in [5]. Optimal operation of an on-grid wind/fuel cell/PV hybrid system has been achieved through an energy management strategy in [6]. The economic and optimal operation of an on-grid PV-wind hybrid system combined with battery storage has been completely investigated in [7]. Energy management strategy and control has been presented in [8] for a hybrid micro-grid system to analyze and improve performance of mentioned hybrid system. A nanofluid-based photovoltaic/thermal hybrid system has been developed in [9] to efficiently use solar energy and it is compared with a standard PV system to show the effects of proposed system. The effect of a rule-based control strategy on optimal performance of a hybrid system including photovoltaic system, battery and fuel cell has been studied in [10]. Performance of a combined PV/thermal-fuel cell system has been analyzed in different operational conditions to improve the efficiency of system in [11]. A multi-objective optimization model has been proposed in [12] to improve the environmental and economic operation of a PV/battery/diesel hybrid system. In order to improve and coordinate performance of energy resources inside a hybrid PV/fuel cell system, a controlling strategy has been utilized in [13]. In order to improve the operation of a PV/fuel cell/battery hybrid system, an optimization model has been proposed to minimize the system's total cost and CO_2 emission in [14]. Utilizing genetic algorithm, operation of a wind-diesel-battery hybrid system has been optimized in [15]. Several hybrid energy systems with different characteristics have been

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analyzed in [16] to decrease energy consumption and improve the economic and environmental operation of a building. Optimum operation of an off-grid PV-H_2-battery hybrid system has been achieved through an effective energy management strategy in [17]. Performance of a PV/Wind/Battery hybrid system has been optimized through an optimization technique called hybrid FPA/SA algorithm in [18]. A new energy management system has been presented in [19] for optimum operation of a battery-hydrogen hybrid system in which total cost of system is minimized and efficiency of hybrid system as well as the system's life-span is increased. A control strategy has been utilized in [20] to ensure optimal operation of a PV-FC–battery hybrid system. Performance of an on-grid PV-fuel cell hybrid system has been analyzed for various climate conditions in [21]. A control strategy optimization has been employed in [22] to improve the efficiency and environmental performance of fuel cell/battery/photovoltaic hybrid system to be used in off-grid telecom stations. A power management strategy has been employed in [23] to improve the output energy of a fuel cell-battery hybrid system supplying an electrical vehicle.

In the Refs. [24–33], the sizing problems of hybrid energy systems have been discussed. Genetic Algorithm has been employed in [24] to find the optimal size of a PV-wind-diesel-battery hybrid system. Utilizing Hybrid Big Bang–Big Crunch (HBB–BC) algorithm, the best possible size of a PV-wind-battery hybrid system has been found in [25]. Harmony search algorithm has been implemented in [26] to ideally size a photovoltaic-wind-diesel hybrid system combined with energy storages. A developed energy management strategy has been employed to optimally size a PV-wind-diesel hybrid system in [27]. Different sizing approaches used for sizing off-grid PV–wind hybrid systems have been presented in [28]. Interval optimization approach has been utilized in [29] to ideally size the energy storage system used in a hybrid PV-diesel-ESS ship power system. Utilizing particle swarm optimization algorithm, optimum size of a PV-wind-battery hybrid energy system has been found in [30]. With the aim of minimizing investment cost and operation cost as well as improving the environmental operation, optimal size of a PV-diesel-battery hybrid system has been determined in ship power system in [31]. Besides three management strategies, three different sizing approaches including the genetic algorithm, HOMER software approach and manual calculations have been utilized to design a PV-FC-battery hybrid energy system in [32]. A hybrid PV/battery/H_2 energy system has been optimally sized utilizing particle swarm optimization algorithm (PSO) in [33].

1.2. Novelty and contributions of proposed paper

In this paper, optimum performance of a PV/battery/fuel cell hybrid energy system is studied with considering uncertainty of electrical load. To model the uncertainty of electrical load, information gap decision theory (IGDT) approach is proposed. Utilizing the IGDT approach, robustness and opportunity functions are obtained. The obtained results from robustness and opportunity functions based on IGDT approach enable the operator to take appropriate decisions at the times load shows uncertain behaviors. Summarizing the explanation above, the contributions and novelty of proposed paper can be presented as follows:

1. Optimum performance of on-grid PV/battery/fuel cell hybrid system with considering electrical load uncertainty.
2. Employing risk-based information gap decision theory (IGDT) approach to model the uncertainty of electrical load.
3. Robust strategy of hybrid system's operation obtained from robustness function of IGDT approach.
4. Opportunistic strategy of hybrid system's operation obtained from opportunity function of IGDT approach.

1.3. Organization of paper

The other parts of proposed paper are organized as follows: IGDT background is explained in Section 2. Section 3 has formulated the IGDT-based risk-constrained PV/battery/fuel cell hybrid system's economic operation problem with considering electrical load uncertainty. In Section 4, a case study is simulated and the results are presented in risk-averse, risk-neutral and risk-taker strategies. Finally, the conclusions of proposed paper are presented in Section 5.

2. IGDT background

In an energy system, due to variable feature of some parameters such as load, uncertainty modeling of such parameters is necessary. IGDT models the system's robustness and opportunity functions against the variations that mentioned parameters may have [34,35]. An IGDT model includes three main components namely system model, operation requirements and uncertainty model.

2.1. System model

The input/output structure of the system to which the information gap decision theory (IGDT) is applied, is indicated by the system model $C(q,l)$. In the proposed paper the uncertainty parameter is the electrical load shown by l and q is the decision variable.

2.2. Operation requirements

The operation requirement explains the targets expected from the system and it can be in the form of cost function or other functions. Based on the robustness and opportunity functions described by Eqs. (1) and (2), the mentioned requirements are evaluated.

$$\hat{\alpha} = \max_{\alpha}\{\alpha : \textit{maximum total cost which is is not higher than a specified cost}\} \tag{1}$$

$$\hat{\beta} = \min_{\beta}\{\alpha : \textit{ minimum total cost which is less than a specified cost}\} \tag{2}$$

The robustness function evaluates how robust the system is against the possible increase of load and also how immune the system is against the total cost. Furthermore, the maximum amount of uncertainty that the uncertain parameter can have is determined by robustness function. In other words, this function describes the risk-aversion ability of purchased strategy. As expressed by Eq. (3), robustness function can be described as an optimization problem in a mathematical form as follows [33,34]:

$$\hat{\alpha}(C_r) = \max_{\alpha}\{\alpha : \max(C(q,l)) \leqslant C_r\} \tag{3}$$

$\hat{\alpha}(C_r)$ shows the resistance degree of the decisions against the uncertain parameter. In other words, it determines how robust the taken decisions are. For a $\hat{\alpha}(C_r)$ with greater value, the resistance of the taken decisions against the uncertain parameter is high.

The amount of benefit that can be achieved from uncertainty is measured by the opportunity function. This function expresses the opportunity of getting benefit from the low amount of uncertain parameter.

$\hat{\beta}$ is the least value of α which enables the minimum amount of total cost as a result of decisions. In other words, for the opportunity function which is the minimum amount of α, the total cost is as small as a given value C_o. It should be noted that a small $\hat{\beta}$ is desired. A small value of $\hat{\beta}$ expresses the condition in which minimum cost is achieved in the presence of limited uncertainty. The mathematical formulation of mentioned explanation is expressed by (4) as follows: