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Risk-averse stochastic programming approach for microgrid planning under uncertainty

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ABSTRACT

In the planning of isolated microgrids aiming for a small carbon footprint, the penetration of renewable energy resources is expected to be high. Energy supply from renewable sources are highly variable and renewable energy sources have relatively a large capital investment although with a positive impact on the environment. In planning and designing of renewable energy based microgrids, we introduce the approach of two-stage stochastic programming to incorporate the various possible scenarios for renewable energy generation and cost in the planning of microgrids to tackle uncertainty. Most planning problems are similar to portfolio optimization problems. We wish to minimize risk in the investment due to uncertain nature of the resources and also minimize the expected cost of investment. Therefore, we introduced the idea of *Markovitz* (mean-variance) objective function to minimize the effect of uncertainties in the operation of the microgrid. The model is generic and can be used for any location to suit their geographical topography and demand/supply needs. The result shows the economic advantage of using the risk-averse stochastic programming approach over the deterministic approaches while satisfying environmental objectives.

1. Introduction

Global environmental concerns and the ever increasing need for energy, combined with steady progress in renewable energy technologies have provided immense thrust in industry and academia to explore solutions for energy, which are cheap, environmentally friendly, reliable and self-sustaining. Extensive research has been carried out in the past few decades towards the design of systems which encompass the above-mentioned features. Hybrid power systems (HPS) use solar, wind, bio gas, hydro power and other renewable sources of energy with or without grid connectivity; in this paper we consider HPS without grid connectivity and using only wind and solar renewable energy technologies. These HPS are also referred to as *Microgrids.* A large spectrum of mathematical tools has been employed in an attempt to find an optimal mix of such resources to develop reliable systems. In Ref. [1] Ofry et al. developed a graphical method based on the loss of power supply probability to design a stand-alone solar electrical system. The idea adopted by Ref. [1] was to minimize a linear cost function comprising the cost of the battery and the solar arrays.

In Ref. [2], the author presented an analytical technique for the design of standalone solar and battery systems. They present an analogy between the battery storage and reservoir, queues and stocks and approached the problem by formulating the energy deficit as *Markov process*. They discretized the probability distribution for the energy deficit and solar power generated and converted them into finite states and formulated a state transition probability matrix. A similar approach was adopted by Chandy et al. [3], where they discretized the battery state and modeled it as a Markov process. They considered the state of energy deficit as an absorbing state and hence, at any instant, evaluated the probability of loss of power supply by finding the probability of the absorbing state. Similar stochastic models are already in use in hydrology for modeling a reservoir, which has a direct analogy to a battery in our case. In Ref. [4], Ponnambalam et al. presented an analysis of a multi-reservoir system based on the development of first and second moment expressions for the stochastic storage state variables. The expressions in Ref. [4] give explicit consideration to the maximum and minimum storage bounds in the reservoir system. Their formulation provided analytical results for various parameters such as the variance of storage, reliability levels and failure probabilities, which are of also of significant importance to a power

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system. The ideas of using indicator functions from Ref. [4] was extended in Ref. [5] to use the F-P (Fletcher-Ponnambalam) method for the capacity design of a battery bank in renewable energy systems with constant demand and uncertain supply.

Optimization especially with integer variables is always a challenging task, so global optimization techniques, such as Genetic Algorithms or Evolutionary Algorithms are employed extensively in the design of HPS. In Ref. [6], the authors use the genetic algorithmic framework for optimal sizing and operation of an HPS. Given the non-linearity in the system model and the system components, it becomes a very difficult and challenging optimization problem. In Ref. [6], the authors divided the algorithm into two parts: one for the optimal sizing and the other for the optimal operation of the HPS. This results in an optimal selection of a HPS configuration and an operating strategy for the given site. Genetic Algorithms have also been used in Ref. [7] for distributed energy resource selection, sizing and effective coordination. The problem was formulated as a mixed integer non-linear problem which minimizes the total capital cost, operational and maintenance cost subject to constraints as energy limits, emission limits, and loss of power supply probability. Simulated Annealing based approach for optimal sizing and siting is used in Ref. [8].

A report by the Consortium for Electric Reliability Technology Solutions (CERTS) [9], further explains the concept of Microgrids. The CERTS Microgrid concept assumes an aggregation of loads and micro sources operating as a single system providing both power and heat. The majority of the micro sources must be power electronic based to provide the required flexibility to ensure operation as a single aggregated system. This control flexibility allows the CERTS Microgrid to present itself to the bulk power system as a single controlled unit that meets local needs for reliability and security. This report is the basis for many research articles published recently in the context of microgrids and RES.

In Ref. [10], a more recent algorithm, DIRECT (Dividing Rectangles), was used to solve the horizon planning optimization problem for sizing of a wind/PV system. DIRECT was developed by Ref. [11] as a global optimization method. It is an effective deterministic algorithm [10]. It finds the minimum of a Lipschitz continuous function without knowing the Lipschitz constant. In DIRECT an assumption is made that the rate-of-change of the objective function and constraints are bounded. In brief, the entire search space is divided into a set of rectangles, and optimal direction is determined by evaluating the objective function at the center points of the subdivided boxes. In this case, they used a few varieties of renewable energy sources types and capacities to choose from, but it made the search space high dimensional.

In another approach to handling uncertainty in renewable sources [12], applied stochastic optimization to identify the size of the storage in isolated grids with a wind-diesel HPS. Energy storage is important in such systems as it is a means for optimizing the energy use and for reducing the consumption of the diesel fuel. An important inference of the work is that the storage size and cost of delivered energy is dependent on wind penetration levels, storage efficiency and diesel operating strategy. They considered various scenarios of wind and demand profiles. They also employed the two-stage stochastic programming technique where the first stage variables being power rating and energy rating of the energy storage along with the initial energy storage, whereas the second stage variables constituted the diesel generator power, dump load, binary variables associated with the diesel generator dispatch and the energy discharged from the storage at any given instant of time.

An integrated approach to solve the problem of PV-Wind-Diesel-Battery HPS planning has been presented in Ref. [13]. They address the problem as a multi-objective optimization problem with two objectives: minimizing the total cost and minimizing the total CO_2 emissions, while capping the expected unserved energy. Direct and indirect assessments of emissions of all the components are obtained using life cycle assessment (LCA) techniques. They apply the approach to a city with 50,000 thousand residents. The results obtained from the linear programming model were used to construct the Pareto front, which represented the best trade-off between cost and emissions under different reliability conditions.

There have been numerous attempts for the design of micropower systems using various open source applications; HOMER [13] developed by National Renewable Energy Laboratory is commonly used. It performs techno-economic analysis and prioritizes solutions based on cost. One of the successful attempts towards microgrid design using HOMER is [14]. Unfortunately, the software has many approximations and assumptions which need to be addressed using a detailed mathematical formulation to handle the uncertainty in the renewable energy sources and demand.

Microgrids are not much different from distribution systems [15]; the planning problem including the renewable energy sources (RES) in the distribution system is modeled as a mixed integer nonlinear programming problem with an objective of minimizing the systems' annual energy loss. The constraints in the optimization model include the voltage limits, the feeders' capacity, the maximum penetration limit and the discrete size of the available DG units. The technique has been employed in various rural scenarios and results have shown a considerable reduction in costs.

The approach developed by Ref. [16] claimed to have a two-stage stochastic programming model for planning and operation of the distributed energy systems, which is proposed here in this paper. Their title however, is misleading as they do not use stochastic programming to solve their model, but utilized a two-stage decomposition and a genetic algorithm to solve the planning problem. They employed the standard approach of Monte Carlo simulations to deal with the uncertainty in the second stage. A detailed comparison of the results was done to compare the benefits of the model as compared to the deterministic one. In Ref. [17], they developed a comprehensive microgrid planning model considering uncertainties. They used a robust optimization approach by decomposing the problem into two parts: the investor problem and the operations problem. Their results were promising, but risk was not considered explicitly in their formulation. Lastly, in Ref. [18], a comprehensive review of computational techniques used in the planning of microgrids is discussed. Our research fills in the gap in this area by considering the uncertainty and risk in the planning of microgrids with renewable energy technologies.

In section 2 we describe the mathematical model for planning of microgrid, present our computational results in Section 3 and conclude with directions for future research in Section 4.

2. Mathematical system model

2.1. Stochastic two-stage model for the optimal design of microgrid

Deterministic models lack the ability to handle uncertainty in demand and supply of renewable energy in the planning of microgrids. Therefore, we use a two-stage stochastic programming with recourse for the planning of microgrid under uncertainty. The stochastic nature is captured in the model in the form of scenarios of the random variables. Our first stage design variables are for determining the capacity of solar power, wind power, diesel generation and storage. The recourse or the second stage decisions are the operating variables to decide the amount of power that needs to be generated from the diesel generators and/or supplied from the batteries. It is important to note that there is an optimal solution for each uncertain energy scenario and this is captured using these second stage variables. Therefore, minimizing the capital