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Probabilistic coordination of microgrid energy resources operation considering uncertainties

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ABSTRACT

This paper presents probabilistic coordination of distributed energy resources (DERs) operation in an islanded microgrid with consideration of the associated uncertainties. In doing so, a comprehensive stochastic mathematical model is developed which incorporates a set of valid probabilistic scenarios for the uncertainties of load and intermittency in wind and solar generation sources. The uncertainty is addressed through a combination of a stochastic optimization model and additional reserve requirements. The model also includes hourly interruption costs for a variety of customer types as a means of determining the optimal probabilistic interruptible load whose reliability-based value is low enough to enable it to be shed if necessary. A case study is carried out using a benchmark microgrid; numerical results demonstrate that coordinated operation of DERs brings notable benefits in terms of expected operation costs and system security. This probabilistic coordination further reduces the consequences of the expected power dispatch of controllable generators and hourly unserved power.

1. Introduction

Driven by the need for realizing the smart grid concept and the requirement for reliable integration of sustainable and green energy in a decentralized fashion, microgrids have received significant attention from researchers over the last decade [1]. Microgrids can be defined as medium or small power systems that are either isolated and control clusters of local Distributed Generation (DG) units and loads, or connected to the main grid as a means of supplementing supply requirements [1]. Energy resource scheduling in a microgrid is different from that of a large power network due to its size, power exchange with the main grid, and charging/discharging of energy storage system (ESS) [2]. Indeed, controllable DGs in a microgrid are much smaller than power systems, reflecting an easier switching operation and hence a more flexible scheduling [2]. However, today's microgrids are subject to operational challenges such as bidirectional power flows and instantaneous power balance, mainly in the presence of excessive renewable energy generation. Thus to provide reliable service, several controllable and non-controllable distributed energy resources (DERs) must interact in a smart microgrid in the presence of uncertainty. The primary goal of this paper is to enable such interaction under uncertainty, with an emphasis on islanded microgrids.

Numerous studies and control topologies related to the microgrid energy management problem have been reported in the literature [3–12]. Basu et al. [3] proposed a differential evolution method for reducing fuel costs and emissions in a microgrid based on a heat-and-power combination. The proposed model included constraints related to real-time balance, DER capacity limits, and heat balance inequality. A single optimization objective was employed based on consideration of the cost of emissions as a penalty factor. Ahn et al. [4] described an Economic Dispatch (ED) model that accounts for active power reserve in case of isolated operations. In this model, the operation of interconnected microgrids is kept stable by sharing power among different sections or areas, with the main limitation being the capacity of the feeders connecting the areas. Ross et al. [5] presented a Knowledge-Based Expert System (KBES) that includes an hourly discrete scheduling algorithm for an isolated microgrid. The KBES optimizes schedules by minimizing the use of dump loads through incorporating an ESS, thereby reducing operation costs and emissions.

Conti et al. [6] presented an optimization procedure that enables optimal dispatch of DGs and an ESS in a medium-voltage (MV) islanded microgrid with the objective of minimizing both operation costs and emissions. In this method, the proposed multi-objective

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Nomenclature

Sets and indices

do	demand variation downward
J, j	set of indexes of the generating units
K, k	set of indexes of the time periods
S, s	set of indexes of the scenarios
up	demand variation upward

Parameters

B_{UP},B_{DOWN}	maximum upward/downward variation (%)
C^{max},C^{min}	max/min allowable energy stored in the ESS
C_{st}, C_E	initial/final energy stored in the ESS
$P_{ES}^{\max}$	maximum allowable charge/discharge limits
$P_j^{\max}$	capacity of unit j (kW)
$P_j^{\min}$	minimum power output of unit j (kW)
$P_{k,s}^{D,R\text{-}C\text{-}I}$	demand with DR for each type of customer in period k, considering scenario s (kW)
$P_{k,s}^{PV}$	power output of solar generation in period k and scenario s (kW)
$P_{k,s}^{W}$	power output of wind generation in period k and scenario s (kW)
$SR_{k,s}$	spinning reserve requirement in period k and scenario s (kW)
ηc, ηd	charge/discharge efficiency of the ESS
λ_S	probability of occurrence of scenario s

Variables

ETC	expected total cost of the microgrid ($)
$\Delta P_{k,s}^{UP,R\text{-}C\text{-}I}$	demand increase in period k and scenario s, for three types of customer (kW)
$\Delta P_{k,s}^{Do,R\text{-}C\text{-}I}$	demand decrease in period k and scenario s, for three types of customer (kW)
$C_{k,s}$	energy stored in ESS until period k, considering scenario s (kWh)
$C_k^{DR,R\text{-}C\text{-}I}$	hourly price responsive demand for three types of customer ($/kWh)
$C_k^{Int,R\text{-}C\text{-}I}$	time-varying interruption cost for three types of customer ($/kWh)
$P_{j,k,s}$	output power of committed unit j in period k, considering scenario s (kW)
$P_{k,s}^{CH}$	charging power of the ESS in period k, considering scenario s (kW)
$P_{k,s}^{Int}$	power interruption in the load in period k and scenario s (kW)
$P_{k,s}^{DCH}$	discharging power of the ESS in period k, considering scenario s (kW)
$P_{k,s}^{DEM}$	variable demand with DR in period k and scenario s (kW)
$V_{j,k}$	binary variable: =1 if unit j is online in period k; = 0 otherwise
$V_{k,s}^{CH}$	binary variable: =1 if the ESS is charging in period k and scenario s; =0 otherwise
$V_k^{Int,R\text{-}C\text{-}I}$	binary variable: =1 if power is interrupted in period k and scenario s; =0 otherwise
$V_{k,s}^{DCH}$	binary variable: =1 if the ESS is discharging in period k and scenario s; =0 otherwise

Optimal Power Flow (OPF) problem is solved using a niching evolutionary algorithm capable of finding multiple optima and the objective function's variations in their neighborhood. Jiang et al. [7] proposed a novel double-layer coordinated approach that offers microgrid energy management under different modes of operation. The approach consists of two layers: the schedule layer which provides an economical operating scheme; and the dispatch layer which builds on the first layer and considers the other constraints of the system, such as power flow and voltage limits. A smart grid strategy has been proposed by Arabali et al. [8] for matching renewable energy sources (RESs) with the controllable heating, ventilation, and air conditioning loads using a hybrid system that combines RESs and ESS. A generic algorithm based optimization approach and a two-point estimation method were used to minimize the cost and increase the efficiency of the hybrid system. Using a stochastic framework, the authors further studied [9] the optimal sizing and reliability of the hybrid system. A pattern search optimization method and a sequential Monte Carlo simulation were employed to minimize the system cost and stratify the reliability requirements. In a number of other models proposed for optimizing the operation of microgrids [10–14], DERs and loads are fully controlled by the microgrid aggregator which is treated as a non-profit agent. In these studies, the objective was either to minimize the operating costs of the entire microgrid or to maintain a balance between the demand and local generation.

To the best of our knowledge, the variability and uncertainty impacts of excessive renewable energy generation on the unit commitment decisions and real-time dispatch of a microgrid with controllable DGs in the presence of ESS, demand response (DR) and interruption loads have not been investigated before. Thus, this paper examines probabilistic coordination of DERs on microgrid operation considering the associated uncertainties and hourly interruptible loads for a variety of customers. The work presented in this paper can be summarized as follows:

(1) A comprehensive stochastic mathematical model has been developed to enable operation interactions of DERs under uncertainty in an islanded microgrid in order to mitigate the variability and intermittency associated with large-scale integration of renewable energy generation.
(2) The coordinated influence of DERs on microgrids' operation has been examined with respect to their independent presence and with consideration of the stochastic operational framework.
(3) The hourly interruption cost for a variety of customers has been incorporated as a means to determine the optimal probabilistic load interruption, if required. The effects of probabilistic coordination of DERs on load interruptions have also been investigated.

The structure of the paper is as follows. Section 2 discusses the main approaches proposed in the literature for handling uncertainties in energy management problem, followed by a description of the uncertainty sets created for representing the load, wind, and solar power forecasting errors addressed in this work. A comprehensive mathematical model of the energy management problem for isolated microgrids is introduced in Section 3. The developed model was applied to a benchmark microgrid; the numerical results are presented and discussed in Section 4. The paper is concluded in Section 5.

2. Managing uncertainty in the operational planning problem

Two main types of uncertainty affect power system operations: outage of the generation units and departures from the forecasts. The outage of generation units can lead to a supply shortage in a system, which is usually met from both spinning and non-spinning operating reserves. Departures from the forecasts resulting from uncertain loads and the integration of RESs add additional