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Optimal allocation of energy storage systems considering wind power uncertainty

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ABSTRACT

Energy storage systems (ESSs) play a major role in power system planning and operation. As evolution of the storage technologies continues, planners will be regarded the ESSs in future power systems more than ever. Simultaneous determination of size and site of ESSs is a non-deterministic, and non-convex problem, which should take into account the uncertain nature of today's power systems. This paper, for the first time, investigates uncertain optimal allocation of ESSs considering practical constraints, including prohibited zones, and ramp rate, as well as simultaneous reduction of three different and incompatible objective functions of operation cost, voltage deviation, and air emission. Due to complexity of the problem, two multi-objective hybrid algorithms called MOGSA and MOPSO-NSGA_II were proposed. Furthermore, five-point estimation method is utilized in order to model the wind power uncertain nature. The simulation results on IEEE 30-bus test system are detailed. To increase the accuracy and ensure selection of the best solution from among the set of optimal solutions, the multi-criteria decision-making techniques (TOPSIS) are used. The simulation results clearly show the efficiency and effectiveness of the proposed method.

1. Introduction

In recent decades, the ESSs have been highly focused by power system planners and operators. The optimal ESSs allocation problem means minimizing the investment costs (or initial costs) as well as minimizing the Network's expected operation cost. By increasing the ESS capacity, the investment costs are increased, but the network operation cost reduces; therefore, selecting the inappropriate ESSs size and site will led to undesirable costs in the system [1]. Generally, the improved operation costs of power system and voltage profile are the prominent features of ESSs. In addition, increasing the renewable energy resources penetration, such as wind and solar power, due to their various advantages, has led to new challenging aspects in this regard [2,3]. Integration of ESSs is introduced as one of the best solutions to improve the power system's features by facilitating the wind power generation resources; although, its high investment costs necessitate accurate modelling and optimal adjustment of ESSs in order to economic justifiability operation [2–6].

Several researches are reported in this context. In [7], a reinforced learning-based algorithm was proposed to optimize coordination of different ESSs in a micro-grid. Reference [8] focused on the large consumers' random power supply from renewable resources such as wind and solar power; besides, it investigated the effects of demand response program and ESS in such power systems. Modification of the wind resource penetration by integrating battery storage system in an economic load dispatch model is discussed in [9], applying PSO and bacterial foraging algorithms to solve the proposed optimization problem. Reducing the costs resulted from the wind power output fluctuations, unit commitment, environmental costs, and spinning reserve are the most important objective considered in that reference. Reference [10] investigated the transient system stability using optimal ESS location, in which the development of micro-grid's energy function based on the voltage source converter and a new heuristic optimization method would lead to the better stability of the micro-grid. In [11], Van et al. used MOPSO to find the optimal size and site of EESs in order to reduce the operation costs and greenhouse gas emissions. They mentioned the uncertainty of wind energy in the network-connected multiple wind farms by Clayton-copula technique. In [12], Jean et al. proposed a multi-objective evolutionary algorithm to solve the economic- emission load dispatch (EED) problem in presence of wind power, based on minimizing the environmental emission and operational costs. Increasing the wind power penetration into the power systems facilitates emission reduction; however, it may resulted to low reliability. Therefore, especially in the geographically close sites, it is necessary to take into account interdependence of the wind speed at different places in EED [13–15]. As mentioned in [16], various

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approaches, including Monte Carlo simulation (MCS) and analytical methods, are used for modeling the relationship between different wind-dependent resources.

In [17], a new NSGA_II-based method is proposed for increasing the reliability in electrical distribution networks equipped with ESSs. The objective functions including MAIFI (Momentary Average Interruption Frequency Index) and SAIDI (System Average Interruption Frequency Index) and the equipment cost were investigated. In [18], the game theory is applied via GA and PSO algorithms to reduce the storage system's cost and wind power generation fluctuations. In [19], the authors tried to reduce the wind farm-related variations applying ESSs. They focused on assessment of the effect of a regulatory framework for the techno-economic feasibility study of ESSs. Furthermore, they discussed the relationship between wind farm dimensions, wind farm variations rate, capacity and type of storage, and ESS costs repayment time for both economic and regulatory scenarios. Reference [20] was focused on optimal allocation of storage device in an 11 kV radial distribution network to reduce the investment and operation costs. The authors proposed a gray wolf algorithm-based method and compared it with the other classical methods as well as dynamic planning and PSO algorithm. Reference [21] investigated the problem in a distribution network to support a photovoltaic system, in order to reducing the voltage fluctuations resulted from PV system. Frequency adjustment in micro-grids with ESS was studied in [22], which increased the service-requirement time of ESSs, besides controlling the frequency of micro-grid, by providing an appropriate solution. In [23], a bi-objective optimization and mixed-integer non-linear programming (MINLP) model were used for optimal allocation of ESSs, applying GAMS software. The objectives include reducing the investment and operational costs and reducing the expected power losses. Reference [24] investigated the peak shedding at peak hours in the network by ESSs. Regarding the high cost of ESS ownership, operation, and maintenance, the authors proposed a subscription-based architecture, in which the customer demand’s was modeled randomly, and power supply was adapted with a combination of network and ESSs, when the demanded load was more than the network's capacity.

An optimal approach to determine the site and size of ESSs considering the reliability improvement in radial electrical distribution network has been detailed in [25]. Minimizing the cost of energy not supplied (ENS) and ESSs investment costs, satisfying the security constraints such as voltage and line flows limits applying the PSO algorithm were addressed in this regard. The effect of ESSs on multistage distribution network expansion planning (DNEP) is proposed in [26]. The problem is formulated as a constrained, mixed-integer, and nonlinear programming and the PSO algorithm is adopted to solve it. As it was claimed the ESSs integration in DNEP will be resulted in reducing the planning cost and improving some operational parameters such as bus voltages and line loading. Ref [27]. presents a general structure for expansion planning studies applied to distributed energy storage systems (DESSs) in presence of high wind penetrated power systems. Minimizing the wind curtailment cost combined with transmission congestion cost are considered to model the issues associated with the curtailment of wind energy and constraints of transmission network. Also, the minimum normalized profit for all DESSs' owners are considered.

Ref [28], insisting on optimal ESS planning and scheduling as one of the most effective ways to reduce the ESSs costs, addresses the optimal ESS planning consisting optimal bus location, power rating, and energy capacity determination especially in distribution networks. Also a comprehensive literature survey and classification of the related studies incorporating with research gaps and future opportunities in this field are reported.

The literature review reveals that the optimal allocation of ESSs is one of the most important issues in power system optimization researches. Most of the references, proposed only one [16,20,21,25,26,29] or two [8,11,12,15,23,27,32] objective functions which used in optimization, applying mathematical and traditional computing approaches [8,15,16,23,24,29]. Also, in most of the researches [9,18,19,24,29], the location of the ESSs is already fixed and constant, and only ESSs capacity is optimized. Furthermore, some of the real-world operational conditions of the power system, such as prohibited zones, and ramp-rates are not concluded in the problem formulation [9–13,15–18,20,23,29,32]. There are some researches in optimal allocation of ESSs field which have not considered the renewable energies effects [10,17,20,22–26].

Table 1
Five-Points Discrete Estimation of produced wind power [32].

Wind (MW)	0	14.54	55.79	98.12	113
Probability (%)	6.89	20.44	40.48	19.92	12.27

The aim of this paper is to provide a method for solving the optimal allocation problem in the presence of uncertain generated wind power as an important issue in probabilistic optimization problem of operating costs in finding the optimal allocation of ESSs. The proposed model is solved applying the MOGSA or MOPSO-NSGA_II combined with the Probabilistic Power Flow (PPF). The presented algorithm tries to find the optimal site as well as the optimal size of the ESSs in the presence of operational conditions governing the power system. In this way, not only the investment and operation costs are minimized, but also the voltage deviation due to the wind power intermittent nature, as well as the emission of thermal power plants is also optimized.

The most important novelties of this paper are summarized as follows:

1 Minimizing simultaneously three different and incompatible objective functions concluding operation costs, voltage deviation and emission,
2 Considering the uncertainty of wind power generation in order to modeling the intermittent nature of these resources to increase the reliability of the power system,
3 Analyzing the effects of real-world power system such as prohibited zones and ramp-rate limits which led to nonlinear, non-convex, and complex optimization problem regarding to ESSs optimal allocation,
4 Proposing a multi-objective gravity search algorithm (GSA) framework and a multi-objective hybrid PSO-genetic algorithm for solving the studied problem.
5 Applying multi-criteria decision-making techniques (TOPSIS) in order to search the optimal solution of the problem considering three simultaneous objective functions.

The rest of the paper is organized as follows: in the second section, modelling the wind farm uncertainty’ is presented, and then the five-point estimation technique is described. In the third section, formulation of the problem among the constraints governing the system are described. Section 4 explains the applied meta-heuristic algorithms. Finally, section 5 details the simulation results for the test Case system.

2. Modelling the uncertainty of wind farms

Variability and unpredictability are two major challenges regarding the application of the wind energy resources, which increases the uncertainty in the system to the generation side. To overcome the first challenge, using the equipment such as ESSs, which balance the output power, and managing the demand side or flexible DGs can be highly effective. On the other hand, overcoming the second challenge requires some revisions on deterministic decisions and applying the new scenario-based techniques [29].

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