



Interactive multi-objective active power scheduling considering uncertain renewable energies using adaptive chaos clonal evolutionary programming



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ARTICLE INFO

Article history:

Received 3 October 2012

Received in revised form

15 January 2013

Accepted 24 February 2013

Available online 3 April 2013

Keywords:

Multi-objective

Distributed generation

Renewable energy

Generation scheduling

Fuzzy set

Chaotic optimization

ABSTRACT

A stand-alone power system is an independent system that comprises micro-turbines, diesel generators, a wind park, solar photovoltaic (PV) modules and/or energy storages, etc. This paper presents a new method for dealing with the short-term active power scheduling of a stand-alone system. The fuel cost of diesel units and CO₂ emission are minimized and all operation constraints are satisfied. The maximum wind and solar PV powers with uncertainties are modeled using fuzzy sets. Adaptive chaos clonal evolutionary programming (ACCEP) is employed to solve this problem, which is formulated as an interactive multi-objective problem. Different degrees of fuzziness, preferred reference levels, and priority list for diesel generators are discussed. Simulation results show the applicability of the proposed method.

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1. Introduction

Distributed generation (DG) resources have recently received much attention as alternative means of generating electricity. DG generally consists of (i) small and modular generating systems (such as micro-turbines, diesel generators, and cogeneration heating/power systems) and (ii) renewable energy resources (such as solar, wind, geothermal, biomass, tidal, and hydropower). The advantages of DGs are that they reduce the required capacities of transmission/distribution lines, active power losses and the need to expand power using traditional thermal power plants. Moreover, renewables are able to mitigate CO₂ emissions, helping to meet the requirements that were specified in the Kyoto Protocol [1], which is an agreement under which industrialized countries must reduce their collective emissions of greenhouse gases (including CO₂) in 2012 to 5.2% below those in 1990.

Although DG has some advantages in the electric power systems, DG still has several problems. These problems include (i) the need for technologies to enhance the efficiency of DG, (ii) the need

for coordination among protective relays, and (iii) interactions among DG and existing conventional power sources. This paper focuses on the third problem, more specifically, day-ahead (24 h) active power scheduling in a stand-alone electric power system. A stand-alone electric power system is an independent system that comprises diesel generators, micro-turbines, a wind farm, photovoltaic (PV) arrays and energy storages and so on, providing active power to its internal loads. When a micro-grid is disconnected from the utility, it becomes a stand-alone power system. A stand-alone power system may exist in a remote area or off-shore island. The most essential issue in the operation of a wind farm or a solar PV array is that renewables that generate uncertain amounts of power cannot be dispatched by using the same approach as used for traditional power plants because these renewables involve climatic uncertainties, such as wind speed and solar irradiation.

Recently, stand-alone power systems have received substantial interest. Kaundinya et al. reviewed the literature on the grid-connected versus stand-alone energy systems for decentralized power [2]. Zhou et al. reviewed the simulation, optimization and control technology for stand-alone hybrid solar–wind electric power systems with battery storages [3]. Cosentino et al. presented technical and economic issues concerning smart renewable generation in stand-alone power systems [4]. Moghaddam et al. proposed a multi-objective adaptive modified Particle Swarm

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Optimization algorithm for the optimal operation of a typical stand-alone power system with renewable energy sources accompanied by a micro-turbine/fuel cell/battery hybrid power source [5]. The results and discussions of McHenry showed that the specific economic issues associated with small-scale photovoltaic arrays in both stand-alone and grid-connected systems [6]. Small renewable energy systems (≤ 6 kW) were cost-effective for both private entities and governments and had potential for use in remote locations far from the electricity network [7]. A proper control strategy may lead to optimization of the use of renewable energy and the prolongation of the battery lifespan [8]. In contrast with the grid-tied renewables [9], the emissions-related and economic issues associated with stand-alone power systems that incorporate renewables, as discussed in the above papers, are critical.

To the best of the authors' knowledge, studies of day-ahead active power generation scheduling of distributed/renewable resources are scarce in the literature. In previous studies, optimization tools such as the dynamic programming (DP) [10,11], augmented Lagrangian relaxation (ALR) [12,13], linear primal-dual algorithm (LPDA) [14], genetic algorithms (GA) [15], mixed integer linear programming (MILP) [16] and particle swarm optimization (PSO) [17] have been used. The optimizers that were employed in Refs. [10–17] have disadvantages when used to find the optimal solution based on the criteria of convergence speed, CPU time, optimality, convexity and linearity/nonlinearity:

- (1) DP needs to firstly prune infeasible values of independent variables using heuristics [10,11]. In case no heuristics are available for solving the studied problem, then the extremely large solution space will result in slow convergence and a long CPU time.
- (2) ALR excludes infeasible solution space to obtain the optimal solution by applying many linear constraints in a master-slave iterative process [12,13]. If the solution space of the formulated problem is not convex, then a duality gap exists in the relaxed solution space and the optimality is not guaranteed [12,13].
- (3) The LPDA deals with only linear/separable constraints and objective [14]. Convexity in the solution space ensures that the optimal solution in primal space is close to that in dual space, implying that iterations converge to the global optimum. Convexity cannot be guaranteed in a problem with nonlinear/non-separable constraints/objective.
- (4) The GA tends to converge to a local optimum or feasible solution only because of simple evolutionary operations that yield premature solutions. To avoid prematurity, GA needs a large population size; however, a large population size leads to slow convergence and a long CPU time [15] although the GA may obtain the global optimum.
- (5) The disadvantage of MILP is that the constraints and objective must be linear [16]. However, if the constraints and objective are non-separable and nonlinear, then only a local optimum or feasible solution can be attained due to the linearization of the problem formulation.
- (6) The traditional PSO relies on limits on the velocities of fixed particles, inertia and weighting factors, and these values remain constant throughout the iterations. In very complex problems, these constant values may reduce the diversity of the iterative solutions because swarm movements are limited [17]. Therefore, new variants of PSO have been proposed to enhance the performance of traditional PSO to solve specific problems.

With regard to the modeling of climatic factors, Contaxis employed a probability distribution model for wind speed [11] and exploited the stochastic characteristics of wind power [14].

However, the uncertain characteristics of renewable energies were not considered in many studies [10,12,13,15–17].

On the other hand, immune algorithms are population-based approaches for finding the global optimum in a nonlinear non-convex space. Immune algorithms can be regarded as enhanced genetic algorithms, which involve crossover, mutation and selection operations. Immune algorithms have diverse algorithmic steps [18]. The chaotic search-based immune algorithm requires the least CPU time. An immune quantum evolutionary algorithm that involves chaotic searching has been proposed for global optimization [19]. A chaotic immune differential evolution algorithm in which a weighted difference is added to the best individual has been proposed [20]. In that study, randomness and the space ergodicity of chaotic mapping were used to apply the chaotic immune clone operation to obtaining the best individual [20]. Chaos theory, co-evolution algorithm and immune algorithm have been integrated to improve convergence speed in finding the optimum [21].

This paper addresses short-term (24 h ahead) active power scheduling in a stand-alone power system comprising diesel generators, a wind park, solar PV modules, and batteries. Both wind and solar PV power generations are modeled by fuzzy sets because of their uncertainties that are associated with climatic factors. The problem is formulated using interactive multi-objective fuzzy programming in which the least upper bound of multi-objectives is minimized. Owing to the uncertainty associated with wind and solar power generations, DP cannot be used unless the infeasible points can be pruned heuristically [10]. ALP used in Refs. [12,13] is not considered herein because the convexity of the studied problem with fuzzy inequality constraints is unknown. The formulated problem has non-separable fuzzy constraints; therefore, LPDA in Ref. [14] and MILP in Ref. [16] cannot be used. The prematurity and slow convergence that are caused by GA [15] and PSO [17] must be improved using a more elaborate method. Therefore, adaptive chaos clonal evolutionary programming (ACCEP) is adopted to solve this problem. ACCEP does not require that the problem exhibits convexity or separability. ACCEP employs a more elaborate chaotic operation and clonal selection to converge quickly and avoid prematurity. Besides, determination of gene (independent) variables is discussed herein to eliminate the need for many gene variables.

The contributions of this paper are summarized as follows.

1. The upper bound of active power generation from renewables each hour is modeled using the fuzzy set because the forecasted 24-h power generations from wind speed and solar irradiation have errors. In this paper, the forecasted maximum and minimum provide the range of a fuzzy number. Rather than the power generation itself from a renewable resource [22,23], the fuzzy number serves the upper bound of the power generation in this paper. The advantage of this approach is that the arithmetic operations between real (non-fuzzy) numbers and fuzzy numbers can be avoided.
2. Different degrees of fuzziness can be assigned by engineers according to their confidence in forecasted results. This was not considered in Refs. [22,23]. In case the engineer has no idea about the next 24-h meteorological data at all, the degree of fuzziness is zero.
3. The proposed multi-objective method based on ACCEP can yield an optimal Pareto solution through an interactive process. Engineers can use their preferred reference levels for both the CO₂ emission (kg/h) and fuel cost (\$/h) of diesel generators until a satisfactory solution is obtained.
4. The Lagrangian multiplier of diesel generators is used to initialize antibodies such that they become feasible. This enhances the performance of the clone and the genetic chaos operations in ACCEP.

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