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# An improved particle swarm optimisation algorithm applied to battery sizing for stand-alone hybrid power systems

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ABSTRACT

Stand-alone hybrid power systems with renewable energies are an economic alternative to the main electricity grid where the extension of the grid is too costly or the small local consumption would not justify it. Properly sizing the battery of the systems is an important step to guarantee their reliability and low cost. This paper accepts the dispatch-coupled sizing method by integrating the battery into the operation of the generation units in the system, and formulates this application problem using optimal control. Two major renewable energy sources – solar photovoltaic panels and wind turbines – are considered, together with traditional diesel generators. Penetration level is used as the lever to indicate the different integration degrees of renewables in the system. A particle swarm optimisation (PSO) algorithm is adapted and improved for this specific application. The numeric results of the system planning are benchmarked using an economic indicator, the levelised cost of electricity, to address the real-world system.



## 1. Introduction

With bursting energy demand and the depletion of fossil fuels, remote regions that have no access to an electrical network look forward to the development of stand-alone hybrid power systems (SAHPS) [1] based on renewable energies such as wind and solar [2]. Applications of the SAHPS have seen a wide spread of sizes, from domestic electricity supply for an area [3] to remote installations of mobile telecommunication stations [1]. A main structural difference in most cases of the SAHPS with the central grid is that there is an energy storage system (ESS) required that has impact on the energy management of the system. Two goals, usually conflicting, which the SAHPS needs to achieve simultaneously are ensuring reliable electrification and reducing the cost of design and operation. Both goals have influence on the appropriate sizing of each device in the systems [4–6]. At any given resource and load condition, over-sizing of the system increases reliability at the expense of cost, while under-sizing sacrifices reliability for system economics. Therefore, optimal sizing of the hybrid system not only improves its reliability, but also reduces its cost.

The renewable generating sources reduce the supply burden from the traditional generation units, but at the same time also introduce variability due to the fluctuating availability of solar and wind. Incorporation of the renewable resources into the system is evaluated by the so-called penetration level, which in this study agrees with [7] by defining it as the installed capacity of the renewable generator over the peak load demand. Existing literature covers two major methods of sizing a stand-alone hybrid power system according to the ways of the system modelling: (1) the heuristic method and (2) the dispatch-based method. Method 1 includes the load-following strategy in which the generator provides sufficient power for the loads at any given point of time and the cycle-charging strategy where the generator either supplies as much power as possible to charge the battery and meet the load, or stays offline. Method 2 incorporates optimal dispatch into the sizing determination as in [8]. It is apparent that the optimal sizing is correlated with the optimal dispatch: only if a dispatch strategy can be found for the specific configuration of the system, then the sizing proposal can be regarded as valid; optimal dispatch alone does not guarantee the lowest system cost solution, as the system tends to be over-sized. Therefore, this research work adopts the dispatch-coupled sizing method of the SAHPS, while considering the most relevant characteristics and constraints of the system, such as the minimum on/off time and permissive ramping rates of the diesel generators (DG), which are critical when optimising the system efficiency in method 1.

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In traditional power systems optimisation, electrical power dispatch optimally distributes the forecasted load among the committed generators [9] to guarantee a reliable load coverage, and to achieve the most economic operation. The stand-alone systems usually do not have as many generation units as in the main grid. Instead, the ESS makes a significant difference between two kinds of electric system. The ESS (most widely used are batteries) enables energy shifting (storing excess generation and backing up for the deficient generation) possible for the stand-alone system [10], which increases the complexity of the economic dispatch between different sources. Actually, the optimal dispatch is extended around the charging/discharging process of the battery. Besides the battery, the renewable generation due to its natural variability adds another challenge to traditional power system operation; its limited predictability has to be considered in the system spinning reserve (SSR). Therefore, when higher levels of renewable resources are to be penetrated in the system [11,12], the system is on one hand benefiting from a lower cost of electricity, but on the other hand faces higher levels of variability of the resources than the diesel-powered system. This paper analyses the impact of different renewable penetration levels, from low to high, in the form of case studies.

To get the numeric solutions to the optimal dispatch and the sequential sizing plan, some research works use linear programming to get numeric results, as in [8]. However, the following section will show that normal numeric tools like the basic linear programming alone cannot entirely solve this control problem, because the system model involves the non-differentiable property caused by the charging process of the battery. Hence, some works take advantage of the well-developed field of evolutionary computation algorithms, which has been applied to power system problems for decades [13]. Numeric solutions to the dispatch of the stand-alone system is achieved by an improved particle swarm optimisation (PSO) algorithm. Despite a relatively new evolutionary computation technique initialised in [14], PSO has been widely applied to the optimisation problems in the field of power systems [15]. Different from genetic algorithm (GA) which was initiated with the binary representation for combinational optimisation problems, PSO was originally aimed at treating nonlinear optimisation problems with continuous variables, though it has been gradually expanded to combinational optimisation problems with both discrete and continuous variables [14,16–19]. However, besides its easy implementation to real-numbered problems and some other merits, PSO is empirically exposed to easy falling into local optima because the particles can quickly get closer to the best particle [20]. Besides getting trapped around a local optimum, solutions in PSO are also more likely to cluster together in similar groups [21]. To overcome such issues and better fit the real-world application, an improved PSO was developed in this work, addressing the needs of the problem. It also outperforms the standard PSO in the benchmarking with the test function suite. The improved PSO arose from tries to integrate different techniques of evolutionary algorithms, so as to lessen the impact of its innate weakness: premature convergence. Three major modifications imposed on the standard PSO, include two mutation tools, mutation (a) and mutation (b), and one distribution tool. Mutation typically uses stochastic methods to perturb the solution around its neighbourhood to better avoid premature convergence [22], and has to trade off two contradictory requirements: the mutation should be powerful enough to avoid premature convergence, and at the same time, tender enough to protect optimal solution from being destroyed. Distribution assists the whole candidate solutions to assure that the global optimum is covered with them [23].

This paper addresses the growing demand for stand-alone hybrid power systems and focuses on developing the application-driven methodology. It will be able to cover some research gaps in several aspects. First, the sizing of the SAHPS is optimised via optimal dispatch of the system; the power dispatch is modelled around the ESS, the physical property of which causes that the solution to the optimal dispatch cannot be solved using primary mathematical tools. Second, the renewable energy system includes different types of energy devices, such as the two dominating renewable generators, solar photovoltaic (PV) panels and wind turbines, the battery and the traditional generation units with practical parameters. Third, this research also attempts to overcome PSO's innate weakness of premature convergence, and applies the improved PSO to solving the optimal dispatch. Finally, the methodology is validated using a real system planning which covers different penetration levels, from zero to 100%, and uses a widely accepted economic metric, the levelised cost of electricity (LCOE), to provide reference for future system installations.

The rest of the paper is organised as follows: the problem is described and modelled in Section 'Problem modelling', while the improved PSO algorithm is detailed and benchmarked with the standard PSO towards peer-defined test functions in Section 'Algo rithm development'. Section 'Results and discussion' validates the dispatch-coupled sizing methodology using a group of case studies. Section 'Conclusion' concludes the paper.

## 2. Problem modelling

The optimal dispatch of the stand-alone system optimises the hourly output of each operating generation unit, towards the objective that the operation cost of the system is minimised. Hence, optimal control is used to model and solve the problem, where the control variable is the hourly generation of all participating DGs. With multiple DGs whose hourly supply need to be optimised, the control variable, or the solution to the problem, takes the form of an $n_{DG} * T$ matrix ($n_{DG}$ is the total number of DGs, $T$ is the total number of time intervals in the horizon of interest). Moreover, rather than directly using the exact values in kW unit to express generation, the programme prefers the load ratio of the DG, $r_{DG}$, which uses the per unit (p.u.), i.e. percentage value of power generation of the DG. By doing so the generation of each DG is normalised into the range of [0, 1], which makes the algorithm more convenient to implement. The dash box in Fig. 1 encloses the concept of the solution, with each row representing the load ratio of the corresponding DG through the entire horizon, and each column representing the power output of all DGs during a certain interval.

### 2.1. System composition

The system is composed of renewable generation, traditional generation, ESS (the battery here) and AC loads (Fig. 2). The renewable generation contains solar PV systems and wind turbines (WT); the traditional generation uses diesel generators (DG). The DG and

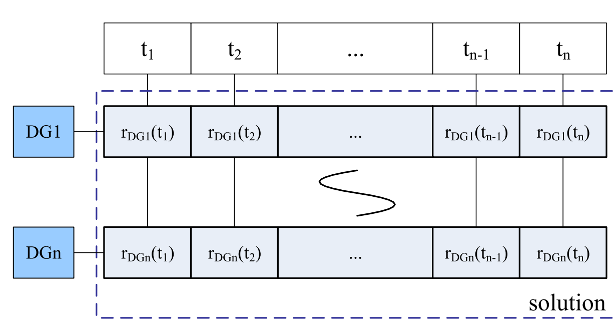


**Fig. 1.** Format of solution, control variable of the optimal control.