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Generation-scheduling-coupled battery sizing of stand-alone hybrid power systems

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ABSTRACT

Properly sizing the battery energy storage system (BESS) of a stand-alone hybrid power system is an important step to guarantee its reliability and low cost. This study applies the technique of storage-integrated generation scheduling using metaheuristics to the BESS sizing, which helps to achieve the optimal scheduling scheme for each sizing plan, as its advantage over the rule-based sizing method. Such technique incorporates the storage dispatch with the scheduling of the dispatchable generators, and is formulated and solved as an optimisation with metaheuristics. Compared with existing approaches of storage-integrated generation scheduling, the metaheuristics-enabled approach proposed here relieves the modelling complexity of the optimisation, by using fewer decisions variables. Different degrees of solar and wind, as the renewable energy, are penetrated into the system, together with traditional diesel generators. The mixed-coded non-dominated sorting genetic algorithm II (NSGA-II) is employed as the main numeric tool, which shows the advantage of mixed-coded modelling over the real-coded modelling for the generation scheduling problem. The numeric evaluation of the system planning adopts the levelised cost of electricity (LCOE) as the economic indicator, to guide the real system planning and operation.

1. Introduction

Stand-alone hybrid power systems (SAHPSs) that differ from a central grid by integrating renewable generation and a battery energy storage system (BESS), have to concurrently achieve two goals, namely ensuring reliable electrification, and economic design and operation [1,2]. Both goals (usually conflicting) depend and also have influence on the appropriate sizing of each component in the systems: over-sizing the components increases reliability at the expense of cost, while under-sizing sacrifices reliability for system economics. In such isolated microgrid where the BESS incorporates with the scheduling of the dispatchable generators, the optimal sizing is correlated with the generation scheduling — a sizing plan can only be justified by a reliable and economic scheduling scheme of the system. As such, the BESS sizing must rely on the storage-integrated generation scheduling; the power system planning and operation are thus correlated. The "storage-integrated generation scheduling" refers to incorporating the BESS charge/discharge process, or the "storage dispatch", with the scheduling of the dispatchable generators.

Due to the correlation of system planning and operation, the BESS sizing is two-loop optimisation: the outer loop sets up the sizing plan of the system, while the inner loop determines the operation strategy of the components, i.e. the method of storage dispatch, given the components' sizing plan. Therefore, classified according to the operation strategies used, two BESS sizing methods have been widely discussed in the literature, both relying on the storage dispatch: one applies the rule-based storage dispatch to the BESS sizing [1–3], and the other applies the storage-integrated generation scheduling, or the optimal storage dispatch, to the sizing [4,5]. Orientated by providing a solution for the electrification of the remote regions off the grid coverage, the proposed work applies metaheuristics to formulate and solve the storage-integrated generation scheduling, which is, in turn, employed for the BESS sizing in a complete model of the stand-alone hybrid power system composed of multiple dispatchable generators.

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1.1. Storage dispatch and BESS sizing methods

The rule-based methods prefix the dispatch strategies for the BESS operation [1–3]. At each time step, the BESS charge/discharge is only decided according to the predefined rules such as the load following or cycle charge strategies [1], while the decision-making does not consider whether it will benefit the future operation or the total cost of operation.

The rule-based operation of energy storage has been widely used in works about component sizing or system operation, including the HOMER software [2]. Component sizing of a hybrid generation system without dispatchable generators in Ref. [3] has the advantages of the multi-criteria optimisation and, therefore, uses rule-based operation for calculation efficiency, wherein a mixed-integer multi-objective particle swarm optimiser searches for different sizing plans of the system instead of the scheduling schemes. Similarly, a hybrid of evolutionary algorithms is used in Ref. [6], and a biogeography -based optimisation algorithm is used [7]; both studies use rule-based strategy for the annual operation of the system. Other works include the sizing and operation of a hybrid power system emphasising environmental efficiency in Ref. [8], operation of a PV-seawater pump system in Ref. [9], the analysis of daily energy balance of a PV-battery system in Ref. [10], the energy management of a hybrid energy system that omits the constraints of diesel generators in Ref. [11], the energy management of stand-alone energy system in Ref. [12] with the HOMER software. A hybrid energy storage system that is composed of a bulk storage takes part in dispatch and a fast storage that absorbs the renewable intermittency is sized in Ref. [13], which applies the rule-based strategy for the operation of the bulk storage. EnergyPLAN simulates the rule-based annual operations of energy systems in the time step of an hour, with a fast calculation speed [14], and, as the simulator, is embedded into to the optimisation programme, GenOpt, in Ref. [15]. The annual rule-based operation is abbreviated into one in a monthly time step in Ref. [16], while the generation models are omitted in the tool developed for supporting the decision-making on the public level, whose targeted users are not specialists of the energy domain. The advantage of these methods is the coverage of a wide range of data, e.g. all 8760 h of a year, due to the low calculation intensity; but on the other hand, the scheduling scheme in most cases is sub-optimal.

The sizing method with storage-integrated generation scheduling, in contrast, justifies the sizing plan with an optimal scheduling scheme of the generators and the BESS [4,5]. The storage-integrated generation scheduling is formulated as an optimisation, as an upgrade of the traditional generation scheduling, which has two tasks in parallel: the unit commitment (UC) and the dispatch. It inherits the decision variables of the traditional generation scheduling, i.e. the power output of all generators, as well as the constraints of dispatchable generators, namely the min/max generation constraint, the minimum on/off time constraint and the ramp rate constraint. Omitting the constraint(s) would make the model of the system incomplete, and simplify the optimisation.

Works that apply storage-integrated generation scheduling have limitations. The joint sizing of energy storage and generation in Ref. [4] uses a simplified model of dispatchable generators and omits the minimum on/off time constraint. Battery sizing of a SAHPS in Ref. [5] bounds only one of the three dispatchable generators by all constraints, while the other two are scheduled without considering the minimum on/off time constraint. The same limitation of the dispatchable generators happens in Ref. [17], wherein the modelling of the storage dispatch is not provided, though CPLEX, as an advanced solver, has to be employed. Sizing and annual operation of a microgrid is jointly optimised with a two-step evolutionary algorithm in Ref. [18], which has an advantage of optimising the system operation for 8760 h. However, the rule-based operation has to be run to generate a preliminary operation scheme ahead of the evolutionary algorithm, which fine-tunes the rule-based result. Also, the microgrid only exchanges power with the grid, instead of the having its own dispatchable generator to schedule, which reduces the constraints of the optimisation, and simplifies the optimisation. In comparison, the sizing and daily operation of a PV-pump hydro system in Ref. [19] offers optimal operation for 24 h by purely using a particle swarm optimiser. The system contains one diesel internal combustion engine as the dispatchable generator, which omits the constraints of ramp rate and minimum on/off time constraints. Day-ahead scheduling of a grid-connected battery on a 15 min base (96 time steps) is formed as a nonlinear optimisation programme in Ref. [20], with the power flow between the grid and the battery being the decision variables. The study has the value of applying the behavioural circuit model to the optimal battery dispatch, while the solution to the nonlinear programme is lent to the software, GAMS. The concept of "energy hub" and the scheduling of it are applied in the building energy system design in Ref. [21], the emphasis of which is the building system, and hence the constraints of the dispatchable generators are omitted in their operation in the form of energy hubs. The differential evolutionary algorithm is applied to the hydro scheduling in Ref. [22]. Although the hydro energy storage plants contain the functions of both generation and storage, their operation is not subject to all physical constraints of the dispatchable generator, like the minimum on/off time constraint.

The estimate of the size of energy storage relying on the total energy demand and supply as in Ref. [23] avoids building up the dispatch model; the energy storage that smooths the real-time power fluctuations as in Ref. [24] is not considered responding at the same rate with the dispatchable generators. Both cases fall beyond the scope of storage dispatch discussed here.

1.2. Metaheuristics-enabled storage-integrated generation scheduling

The charge and discharge processes of the BESS have opposite directions of power flows associated with different efficiencies due to losses. The different conversion loss in the charge/discharge modes causes the model non-differentiable (more details in Section 3), so that the BESS power flow cannot be described with one variable. The two existing models developed for the storage-integrated generation scheduling, namely the mixed logical dynamical (MLD) system model [25], and the separate charge/discharge model [4], have to introduce more decision variables into the optimisation, and hence make the models complex. To relief the modelling complexity, the proposed work applies metaheuristics to model the optimal storage dispatch, which helps to formulate and solve the storage-integrated generation scheduling with only the original decision variables and introducing no more. Furthermore, the advantage of applying metaheuristics can be enhanced by using the algorithms that enable parallel binary and real-number variable representation. This matches the variable types of the storage-integrated generation scheduling, i.e. both the binary type (the hourly DG on/off-state) and the real-number type (power output). The non-dominated sorting genetic algorithm II (NSGA-II) is selected as the main numeric tool for its two merits: (i) it offers concurrent binary and real-number coding, and (ii) it establishes an elaborate balance in computational complexity and result optimality [26,27]. The proposed study also demonstrates the advantage of formulating and solving the storage-integrated generation scheduling problem with the mixed real and binary coding of NSGA-II, in comparison with the pure real coding like in Ref. [5]. The priority list (PL) [28] that carries the domain knowledge [29] of