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Optimal sizing of distributed generation considering uncertainties in a hybrid power system

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ABSTRACT

The scope of this study is the optimal sizing of distributed generation in a hybrid power system with wind and energy storage units considering uncertainties. The load demand and wind speed uncertainties are modelled using the autoregressive moving average technique, and the system states are chronologically sampled using the sequential Monte Carlo simulation. The contribution of the paper can be stated as follows: (1) an objective function based on self-adapted evolutionary strategy in combination with Fischer–Burmeister algorithm is proposed to minimize the one-time investment and annual operational costs of the wind/energy storage sources; and (2) the effect of the cycle efficiency and charging/discharging rate of different energy storage units on the system cost is investigated under different reliability and load shifting levels. The computational performance of the proposed optimization solver is proven in order to obtain the minimum possible investment cost. The presented case studies in this paper provide remarkable insights for the suitable capacity installation at different values of reliability and load shifting levels.

Introduction

Deploying distributed generators (DGs) in power networks is considered as one of the solutions to reduce reliance on fossil fuels through exploitation of renewable energy sources. It also deferring the investment for network upgrading as the load demand grows. In rural areas, it is very difficult and uneconomical to deliver power over long distances through transmission lines to supply such areas. The lack of an electrical network to supply remote areas, high connection cost of grid extension and rough topography often leads to other options to supply energy. Stand-alone hybrid systems which are dependent on renewable sources are found to be a promising way to satisfy the energy supply requirements for these areas [1]. The need for efficient electric power sources in remote locations is a driving force for the research in hybrid energy systems [2].

The wind power is considered as one of the possible energy sources in rural areas. In general, wind energy avoids the full fuel cost and a considerable portion of annual operation and maintenance costs of the displaced conventional units. However, the level of avoided capital costs depends on the extent to which wind power capacity can displace the conventional units, and so that level is directly related to the capacity factor of the wind plants, while the main drawback of the wind power is its uncertainty nature [3]. With the market liberalization and the occurrence of competitive markets, vital questions have arisen regarding the optimal sizing of wind generators to contribute to supplying the network with the constraints of power quality. In the new power market model, the investors tend to favor dispatchable energy sources characterized by low capital costs, such as gas turbines, despite their high operating costs. Consequently, the wind energy, which is characterized by high capital cost, is hurt by the shift to low capital cost technologies. Usually, batteries are used to back intermittent energy sources, especially in the small and medium-sized energy systems [4]. However, the problem of keeping the power balance is still more difficult for stand-alone networks supplied by intermittent generators. The characteristics of such grids require scheduling more reserve for ensuring adequate security and reliability levels, but the higher reserve requirements may substantially increase the investment and operational costs of those systems.

In [5,6], Vrettos and Arabali performed optimal sizing of stand-alone hybrid power systems; nevertheless, the reliability analyses were not considered. In [7,8], Wang and Yang proposed analytical methods to model the hybrid power systems and evaluate the reliability indices; but, these methods cannot properly represent the random nature of the hybrid power systems [9]. In [10,11], the

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Nomenclature

S_t, μ_t, σ_t	hourly simulated, mean and standard deviation of load/wind speed
APE	absolute percentage error
w_i, w_r, w_f	wind turbine cut-in speed, rated speed and furling speed
P_r	wind turbine rated power
η_{wt}	wind generator converter efficiency
$\lambda_{bat}, \lambda_{wt}$	annual discount rate of the battery and wind turbine units
m_{bat}, m_{wt}	annual maintenance cost of the battery and wind turbine units
Q_{bat}, P_{bat}	battery unit capacity and power rating
p_{bat}, p_{inv}	unit price of the battery and inverter units
IC	wind turbine unit and installation cost
$P_{bat}^{\max}$	battery maximum power rating
$P_L^t, P_{L_i}^t, P_{sh}^t$	hourly load demand, interrupted and shifted load
η_d, η_c	battery discharge/charge efficiency
$P_{E_d}^t, P_{E_c}^t$	hourly discharged/charged power
C	battery stored energy
$EENS$	expected energy not served
Δt	time interval
IC	wind turbine unit and installation cost

capacity optimization model for hybrid power systems was discussed using different heuristic optimization techniques. In both references, a constraint was imposed to ensure that the hybrid generation capacity always satisfies the load level; however, such a constraint leads to overestimation of the investment cost, especially with the possibility of adopting load management strategies. In [12,13], optimal sizing techniques of power systems were applied based on the genetic algorithm (GA) to minimize the investment cost of the generation system. Usually, the search capability of the GA is dependent on the population size which could increase the computational burden and lead to non-optimal solution. The central idea of heuristic optimization techniques is to find the optimum solution for a given problem, without the need for an exhaustive search. These algorithms may fail in complex problems where the search space is very large [14]. The computational performance of the proposed optimization solver in this study, and its superiority over GA in terms of accuracy and computational time will be clarified in section 'Computational performance'.

In [15], Arabali presented a stochastic framework for optimal sizing and reliability analysis of a hybrid power system. The uncertainties of generation/load demand were modelled using the autoregressive moving average (ARMA), and a hybrid optimization method based on GA and pattern search (PS) was used in conjunction with sequential Monte Carlo simulation (SMCS) to provide the optimum system cost with respect to different reliability constraints and at specific load shifting levels. Furthermore, in [16,17], Different methodologies for allocating energy storage systems in power networks were presented.

However in [15–17], the impact of the energy storage units' parameters on the system investment cost and reliability were not investigated.

In order to overcome the shortcomings of the previous researches mentioned in the literature, this paper performs optimal sizing of wind/energy storage sources based on stochastic modelling of historical wind speed and load demand. The ARMA modelling is used to represent the uncertainty of load demand/wind speed, and the SMCS is preformed to chronologically sample the system states. Thereafter, an objective function is presented to minimize the one-time investment and annual operational costs of the wind/energy storage sources and, the reliability index, the expected energy not served (EENS) is included as a constraint. Several case studies are considered to illustrate the results under different values of EENS/load shifting levels. Furthermore, the effect of the cycle efficiency and charging/discharging rate of different energy storage units on the system reliability will be clarified. Two battery units (Nickel–cadmium and Lithium-ion) will be separately simulated with the wind generation unit to clarify the effect of batteries characteristics on the total hybrid system cost and reliability. From the numerical simulations, it will be shown that with increasing the reliability level at 0% load shifting, the battery unit parameters are the dominant factors for determining the total hybrid system cost. On the other hand, with increasing the load shifting level at a constant reliability level, the battery unit cost ($/kW h) is the dominant factor for determining the hybrid system cost. The problem is solved using self-adapted evolutionary strategy (SAES) in combination with Fischer–Burmeister algorithm based on nonlinear complementarity problem (NCP) [18]. The competency of the proposed optimization solver will be proven in order to obtain the minimum investment cost with respect to the problem constraints. The contribution of the study can be summarized as follows:

(1) Proposing an optimization solver based on self-adapted evolutionary strategy in combination with Fischer–Burmeister algorithm, which depends on *intelligent* mutation of the offspring candidates without the need for exhaustive iterations within a complex search space;
(2) Investigating the impact of the energy storage units' parameters on the system investment cost under different values of reliability/load shifting levels, so as to provide the decision makers with the flexibility to choose the suitable capacity installation without overestimation of the investment cost.

Three years historical data of load demand/wind speed are used to process the ARMA models and provide the hourly samples of 1 year scheduling period. The historical wind speed data is based on the Warwickshire area, UK. Moreover, the historical load data of one of the main feeders of Warwick University are obtained from the energy tracker data base.

Uncertainties modelling and probabilistic reliability evaluation

The historical load demand/wind speed record form a time sequence, and therefore the ARMA technique can be used to predict a future load demand/wind speed models [19].

ARMA models

The ARMA(p, q) model is the combination of the autoregressive (AR(p)) and the moving average (MA(q)):

$$y_t = \sum_{i=1}^{p} \Phi_i y_{t-i} + \sum_{j=0}^{q} \theta_j \varepsilon_{t-j} \tag{1}$$