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Multi-objective design optimisation of standalone hybrid wind-PV-diesel systems under uncertainties

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ABSTRACT

Optimal design of a standalone wind-PV-diesel hybrid system is a multi-objective optimisation problem with conflicting objectives of cost and reliability. Uncertainties in renewable resources, demand load and power modelling make deterministic methods of multi-objective optimisation fall short in optimal design of standalone hybrid renewable energy systems (HRES). Firstly, deterministic methods of analysis, even in the absence of uncertainties in cost modelling, do not predict the levelised cost of energy accurately. Secondly, since these methods ignore the random variations in parameters, they cannot be used to quantify the second objective, reliability of the system in supplying power. It is shown that for a given site and uncertainties profile, there exist an optimum margin of safety, applicable to the peak load, which can be used to size the diesel generator towards designing a cost-effective and reliable system. However, this optimum value is problem dependent and cannot be obtained deterministically. For two design scenarios, namely, finding the most reliable system subject to a constraint on the cost and finding the most cost-effective system subject to constraints on reliability measures, two algorithms are proposed to find the optimum margin of safety. The robustness of the proposed design methodology is shown through carrying out two design case studies.

1. Introduction

In optimal design of standalone hybrid renewable energy systems (HRES), reliability of the system in supplying power for a demand load is as important as the levelised cost of energy (LCE) produced by the system. the system. Reliability of a standalone HRES in supplying power depends on various parameters, including, system configuration (e.g. wind-PV-battery, wind-diesel, etc), size of its components, reliability of each component in terms of operation and the availability of renewable resources. The availability of resources has the major influence on the reliability of a standalone HRES as stochastic nature of renewable resources imposes a great deal of uncertainty to the system operation and the power produced. Stochastic nature of renewable resource makes the reliability analysis of a standalone HRES impossible without employing probabilistic methods of analysis. In other words, multi-objective optimisation of standalone HRES (with cost and reliability as two objectives) cannot be performed deterministically.

Results of probabilistic analyses have random errors that can be reduced by increasing the size of sampling space. In order to achieve a desired level of accuracy in the results of probabilistic methods of analysis high computational time is required. This becomes a major concern within a design process, as evaluation of design candidates with respect to their cost and reliability becomes highly time-consuming. In practice, to circumvent this problem, adopting a deterministic approach, design of standalone HRES is carried out for a worst-case-scenario, while applying a load factor on the demand load. All calculations are based on the averaged values and the stochastic nature of demand load and renewable resources as well as the possible errors in the results due to employing low fidelity models are ignored. No reliability measure is calculated as part of the design candidate assessment. It is assumed that a suitable selection of the worst-case-scenario and safety factors will lead to reliable solutions. In fact, the multi-objective optimisation problem with two objectives of reliability and cost is reduced to a single-objective optimisation problem with the objective of cost only. In practice, normally, the size of the storage or backup/auxiliary components are determined based on a suitable worst-case-scenario to achieve a level of confidence in the expected power supply, while the remaining components are optimised for minimising the cost. After sizing the storage or

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backup/auxiliary components a single-objective optimisation search can be carried out to find the optimum size of the renewable components. Most of the literature on design of standalone HRES adopt this approach; for instance see Refs. [1–10].

In deterministic optimal sizing of a standalone wind-PV-diesel hybrid system, the margin of safety applied on the demand load affects the nominal size of the diesel generator and consequently the reliability of the power supply and the levelised cost of produced energy. Adopting high-enough margins of safety leads to reliable systems. However, as mentioned above since in deterministic design methods no actual reliability measure is calculated as part of the design candidate assessment, these methods cannot be used for quantifying the optimum value for margin of safety. A procedure including both deterministic and probabilistic analyses is required to find the margin of safety which corresponds to a desired reliability with minimal cost.

More recently, recognising the shortfall of deterministic methods in design of reliable and cost-effective standalone HRES, development of robust nondeterministic design methods has received increasing attention from the research community [11,12]. The aim of the present study is to develop a robust method of design under uncertainties for wind-PV-diesel configuration with minimal number of probabilistic analysis. Section 2 begins with definition of reliability measures used in this study, and then elaborates on power and cost modelling. Section 3 explains the fundamentals of the proposed design methodology and its development steps. Section 4 details two algorithms proposed for performing two design scenarios and the results of case studies delivered using the proposed design methodology.

2. Reliability assessment and system modelling

2.1. Reliability assessment measures

Performance of a standalone HRES in supplying power can be evaluated against different assessment criteria, amongst them total unmet load, blackout duration distribution and the mean-time between failures. For a standalone HRES the total unmet load is defined as:

$$U_{\mathrm{t}} = \int_0^T (L(t) - P_{\mathrm{a}}(t))dt \tag{1}$$

where, P_{a} and L are, respectively, the usable available power and the demand load ($0 \le P_{\mathrm{a}} \le L$). Usable available power is defined as:

$$P_{\mathrm{a}} = \min\{P_{\mathrm{t,a}}, L\} \tag{2}$$

in which, $P_{\mathrm{t,a}}$ stands for the total renewable and non-renewable available power. Using hourly-averaged load ($\overline{L}_h$) and hourly-averaged useable available power ($\overline{P}_{\mathrm{h,a}}$), and a period of analysis of $T = 1$ *year*=8760 *h*, Equation (1) can be rewritten as

$$U = \sum_{i=1}^{8760} \left(\overline{L}_{\mathrm{h}} - \overline{P}_{\mathrm{h,a}}\right)_i \tag{3}$$

Total, maximum and average blackout durations are three parameters which indicate the system downtime periods due to power deficiency irrespective of the amount of power deficiency. In contrast to the unmet load, assessment of design candidates based on blackout duration allows performing customer-need driven designs. Using hourly-averaged data, total blackout duration is defined as:

$$BO_{\mathrm{t}} = \sum_{i=1}^{8760} \left[\left(1 - \overline{P}_{\mathrm{h,a}}/\overline{L}_{\mathrm{h}}\right)_i\right] \tag{4}$$

where, pair of square brackets [ ] stands for the integer value function. The information that can be extracted from the blackout distribution, such as the maximum blackout duration (the longest continuous blackout) $BO_{\max}$ and the average blackout duration BO_{av} (the average duration of each blackout), also can play an important role in evaluation of the system performance.

Mean time between failures (MTBF) is defined as the duration of the successful system operation over a period of time divided by the number of failures during that period. If the successful system operation is defined as the case when available usable power is greater than or equal to the load ($P_{\mathrm{a}} \ge L$), using hourly-averaged quantities, the MTBF can be defined as:

$$\mathrm{MTBF} = \frac{8760 - \sum_{i=1}^{8760}\left[\left(1 - \overline{P}_{\mathrm{h,a}}/\overline{L}_{\mathrm{h}}\right)_i\right]}{n_{\mathrm{fail}}} \tag{5}$$

where n_{fail} is the number of blackout occurrences during period $T = 8760$ *h*.

2.2. Power modelling and dispatch strategies

The power produced by a wind turbine is given by:

$$P_{\mathrm{WT}} = \frac{1}{2}\rho V_{\mathrm{hub}}^3 A_{\mathrm{WT}} C_{\mathrm{P}} \eta_{\mathrm{EG}} \tag{6}$$

in which ρ is the air density, V_{hub} is the wind speed at hub elevation, A_{WT} is the rotor area, η_{EG} is the overall efficiency of the electrical components and the gearbox, and C_{P} is the rotor power coefficient given by:

$$\begin{aligned} C_{\mathrm{P}} = {} & -2.025 \times 10^{-7} V_{\mathrm{hub}}^6 + 1.926 \times 10^{-5} V_{\mathrm{hub}}^5 \\ & -7.421 \times 10^{-4} V_{\mathrm{hub}}^4 + 1.483 \times 10^{-2} V_{\mathrm{hub}}^3 - 0.162 V_{\mathrm{hub}}^2 \\ & +0.887 V_{\mathrm{hub}} - 1.508 \end{aligned} \tag{7}$$

This model is extracted via curve fitting and using the power coefficient data of about 60 wind turbines within the range of 10–500 kW. The wind turbines used for developing this model are of both types of constant and variable speeds and also both types of pitch controlled and stall regulated. This model has a maximum relative error of 7% for the range of $3 \le V_{\mathrm{hub}} \le 25$ m/s.

Given wind speed V_{ref} at elevation h_{ref}, the wind speed at the hub elevation can be calculated by the logarithmic law:

$$V_{\mathrm{hub}} = V_{\mathrm{ref}} \ln\left(\frac{h_{\mathrm{hub}}}{z_0}\right) \Big/ \ln\left(\frac{h_{\mathrm{ref}}}{z_0}\right) \tag{8}$$

in which, z_0 stands for the site surface roughness length. The hub height h_{hub} depends on the size of the wind turbine, which is unknown prior to the design. For small to medium size wind turbines the hub height can be estimated via the rule of thumb:

$$h_{\mathrm{hub}} = \max\{h_{\mathrm{c}} + R,\ 2R\} \tag{9}$$

where h_{c} is the minimum blade tip-ground clearance and R is the rotor radius.

Power produced by PV panels is given by

$$P_{\mathrm{PV}} = I A_{\mathrm{PV}} \eta_{\mathrm{PV}} \tag{10}$$

in which, I stands for the solar irradiance, A_{PV} is the PV panel area and η_{PV} is the overall PV unit efficiency.