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Chance constrained programming using non-Gaussian joint distribution function in design of standalone hybrid renewable energy systems

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ABSTRACT

Performance of a HRES (hybrid renewable energy system) is highly affected by changes in renewable resources and therefore interruptions of electricity supply may happen in such systems. In this paper, a method to determine the optimal size of HRES components is proposed, considering uncertainties in renewable resources. The method is based on CCP (chance-constrained programming) to handle the uncertainties in power produced by renewable resources. The design variables are wind turbine rotor swept area, PV (photovoltaic) panel area and number of batteries. The common approach in solving problems with CCP is based on assuming the uncertainties to follow Gaussian distribution. The analysis presented in this paper shows that this assumption may result in a conservative solution rather than an optimum. The analysis is based on comparing the results of the common approach with those obtained by using the proposed method. The performance of the proposed method in design of HRES is validated by using the Monte Carlo simulation approach. To obtain accurate results in Monte Carlo simulation, the wind speed and solar irradiance variations are modelled with known distributions as well as using time series analysis; and the best fit models are selected as the random generators in Monte Carlo simulation.

1. Introduction

Increasing energy demand and depletion of fossil fuel resources have made renewable energy resources more attractive [1] and advances in technologies had led to reduced cost, making renewable energy systems competitive with fossil fuels especially in remote places where grid connection is not available [2]. The power generated from renewable resources is completely dependent on renewable resources and therefore, largely unpredictable. There are many research works reported on the assessment of global energy potentials resources [3] and on investigating the vulnerability of renewable systems and improvement of their performance. Kalogirou [4] investigated the effect of environmental pollutants and dust that are transferred with the air on performance of PV (Photovoltaic) panels. Greening [5] performed an evaluation on the life cycle environmental sustainability of micro-wind turbines in the UK, as compared with grid electricity and solar PV panels. As the isolated operation (standalone operation) of these power units may not be effective in terms of cost and reliability [6] unless properly optimised for those qualities. In recent years there has been an increased interest in the use and optimisation of HRESs (hybrid renewable energy systems) as a viable solution to provide a reliable power supply, particularly in rural areas with standalone systems [7]. Generally, an HRES combines two or more energy sources to generate reliable power to satisfy the load demand at all times and under various weather conditions. Conventionally, the balance between demand and the system output in standalone systems is obtained by using an auxiliary power source such as a diesel generator and/or a storage such as battery bank. To ensure an effective use of available renewable energy resources (wind, sun, …), optimal design and sizing of HRES are essential. The aim is to optimise the mix of renewable energy systems available to meet the load power demand, minimise the combined intermittency in power generation, maximise their contribution to the peak load (thus minimising power generation from the auxiliary power source) and do this at a minimum cost [8]. That is, using optimal design to achieve cost effective and reliable HRES. Generally two approaches are followed in design of HRES; deterministic or stochastic.

In the deterministic approach, all design inputs and variables are considered as known variables without any randomness involved during system design and analysis. Common deterministic approaches use mean values as the systems' inputs and most of the work reported on the deterministic design approach of HRES implement the hourly average of solar radiation, wind speed and

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Nomenclature

A_{PV}	PV panel area (m^2)
A_{WT}	wind turbine rotor disk area (m^2)
α	reliability of compliance of the constraint
ARMA	autoregressive moving average model
C_0	total constant cost including the cost of installation of the wind turbine and PV panels
C_{Bat}	nominal battery bank capacity (Ah)
C_{IC}	the total cost of the system
$C_{O\&M}$	present value of maintenance cost
C_{rep}	the present value of replacement cost
$C_{Unit,Bat}$	unit cost of battery bank ($/Ah)
$C_{Unit,PV}$	unit cost of PV panel ($/$m^2$)
$C_{Unit,WT}$	unit cost of the wind turbine($/$m^2$)
C_p	wind turbine power coefficient,
Δt	the time step (1 h in this study)
$Demand_t$	deterministic load demand at each time step
DOD_{max}	maximum depth of discharge of the battery
DPS	power shortage at each hour
DPSP	deficiency of power supply probability
η_{PV}	efficiency of the PV array and corresponding converters
η_{Bat}	battery efficiency
η_C	battery bank charge efficiency factor
f	inflation rate
F	joint cumulative distribution function
F^{-1}	inverse of joint cumulative distribution function
h	the total hours under study
HRES	hybrid renewable energy system
I	horizontal solar irradiance in (W/m^2)
I_{Bat}	battery current
k_d	annual real interest rate
L_p	system life period in years
Load	maximum daily load (Wh)
MSE	mean squared error
N_{Bat}	Total number of batteries
N_{rep}	number of replacements of the battery over the system life period
P_{Bat}	battery bank available power (W)
P_{PV}	the PV array output power (W)
P_{WT}	wind turbine power (W)
$P_{PV,Nom}$	PV panel nominal power (W/m^2)
ρ	air density (1.225 kg/m^3)
S_D	number of days of autonomy (One day in this study)
$\delta(t)$	hourly self-discharge rate
SOC	state of the charge of the battery
TC	the total cost of the system
V_{Bat}	battery voltage
V_{ref}	the wind speed at the reference height
V_w	hourly average wind velocity (m/s)
Y	system life span in (years)
z_{hub}	wind turbine hub height
z_0	surface roughness length (m)
z_{ref}	reference height (m)

power demand as the design inputs [9–11]. To ensure the system reliability, the system is designed based on worst case scenarios (for example the system is designed based on the month with least available renewable resources) [12] or a margin of safety is usually considered. It is also shown in Ref. [13] that in the context of multi-objective optimisation with conflicting objectives of cost and reliability, for each design problem, there exists an optimum margin of safety that can be used to produce a Pareto solution. Following the deterministic design approach, different methods in optimal sizing of HRES have been considered based on different design objectives. Belfkira, Zhang and Barakat [14] used a deterministic algorithm to design the optimum hybrid system among commercially available system devices with minimum total cost. Kaabeche, Belhamel and Ibtiouen [15] recommended an optimisation model based on iterative technique to optimise the size of a hybrid wind/photovoltaic system combined with a battery bank and minimise LCOE (levelized cost of energy). Balamurugan et al. [16] proposed a hybrid energy system consisting of biomass, wind, photovoltaic and battery to deliver maximum renewable energy by considering appropriate energy storage to meet peak demand during periods of low (or no) solar radiation or wind. Diaf et al. [17] analysed the optimum configuration of a standalone hybrid photovoltaic–wind system that guarantees the energy autonomy of a typical remote consumer with the lowest LCOE. Yang et al. [18] proposed an optimal sizing method based on GA (Generic Algorithm) technique using a typical meteorological year data. The proposed optimisation model calculates the system optimum configuration which is capable of achieving the desired LPSP (loss of power supply probability) with minimum Annualised Cost of System. Deterministic approaches are widely used in design of HRES, though they rely on many uncertain parameters which have direct effects on the performance of the designed HRES. Improper estimation of the uncertainties may lead to violation of system design constraints such as lower reliability. On the other hand overestimation in the effect of uncertainties in the output of the HRES may yield in high maintenance costs. Consequently, to obtain an optimum design that is robust in operation and control, consideration of uncertainties and their stochastic properties is necessary [19].

Stochastic approaches attempt to solve the optimisation problem involving uncertainties. They deal with uncertainties by using resource functions and chance constraints to transform the stochastic optimisation to an equivalent deterministic optimisation problem [20]. Different methods to integrate the uncertainties in renewable resources in the design of HRES have been reported. Giannakoudis et al. [21] considered adding a known disturbance to the design inputs to maintain optimum mix of renewable resources. Refs. [22,23] fitted wind speed variation with Weibull distribution. Lujano-Rojas et al. [24] used time series theory to simulate the uncertainties in wind speed in the design of small wind/battery systems. Usually, the Monte Carlo simulation approach is used in solving probabilistic problems. Given a significantly large sample size, this method can provide highly accurate results. However, the main drawback is the computational burden associated with the large number of repeated calculations [25]. In addition to the common 'under uncertainties' design methods, the chance constrained programming approach is also a popular method in solving the problems dealing with random parameters. This method was first introduced by Charnes and Cooper [26] in 1959. Its main feature is that the resulting decision ensures the probability of complying with constraints [27]. The chance constrained method has been widely applied in different disciplines for optimisation under uncertainty [28], but a very few studies are reported using this method in the design of HRES. Arun et al. [29] used the chance constrained programming approach in the design of photovoltaic battery system to deal with the uncertainties in the solar radiation. Sreeraj et al. [30] used this method to find the battery bank size when renewable