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Design of isolated renewable hybrid power systems

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Abstract

Isolated electrical power generating units can be used as an economically viable alternative to electrify remote villages where grid extension is not feasible. One of the options for building isolated power systems is by hybridizing renewable power sources like wind, solar, micro-hydro, etc. along with appropriate energy storage. A method to optimally size and to evaluate the cost of energy produced by a renewable hybrid system is proposed in this paper. The proposed method, which is based on the design space approach, can be used to determine the conditions for which hybridization of the system is cost effective. The simple and novel methodology, proposed in this paper, is based on the principles of process integration. It finds the minimum battery capacity when the availability and ratings of various renewable resources as well as load demand are known. The battery sizing methodology is used to determine the sizing curve and thereby the feasible design space for the entire system. Chance constrained programming approach is used to account for the stochastic nature of the renewable energy resources and to arrive at the design space. The optimal system configuration in the entire design space is selected based on the lowest cost of energy, subject to a specified reliability criterion. The effects of variation of the specified system reliability and the coefficient of correlation between renewable sources on the design space, as well as the optimum configuration are also studied in this paper. The proposed method is demonstrated by designing an isolated power system for an Indian village utilizing wind–solar photovoltaic-battery system.

Keywords: Design space; Renewable hybrid system; Chance constrained method; Process integration; Battery sizing

1. Introduction

Isolated power systems using renewable energy sources like wind, solar, biomass, micro-hydro, etc. can be utilized to provide electricity for remote locations where grid extension is not feasible and/or economical. It was estimated that more than 1500 million people around the world had no access to electricity in 2005 (International Energy Agency, 2006). A vast majority of them are from Sub-Saharan Africa and South Asia, where electrification rates are only 25.8% and 51.8%, respectively (International Energy Agency, 2006). In 2001, about 44% of the households in India do not have access to electricity (Govt. of India, 2001). As electricity is important for rapid economic growth and poverty alleviation, Indian government has decided to provide electricity access to all households. Along with rapid expansion in conventional power generation, Indian government has also decided to go for power generation from new and renewable sources. For many remote non-electrified rural areas, power generation from stand-alone systems is cheaper than grid extension.

The National Electricity policy of India states that wherever it is neither cost effective nor optimal to provide grid connectivity, decentralized distributed generation facilities together with local distribution network would be provided so that every household gets access to electricity (Govt. of India, 2005). Non-conventional sources of energy could be

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Nomenclature

A_P	total array area (m^2)
ACC	annualised capital cost (Rs)
AOM	annualised operation and maintenance cost (Rs)
B	battery capacity (kW h)
α	confidence level
C_0	capital cost of the component (Rs)
COE	cost of energy (Rs/kW h)
CRF	capital recovery factor
D	load demand (W)
d	discount rate
D_{actual}	the deterministic demand to be met taken in the chance constrain (W)
Δt	time step for the simulation (h)
f	factor representing net charging/discharging efficiency
f_i	factor that represents inverter efficiency
H	wind turbine height (m)
H_i	specified meteorological mast height (m)
I_T	total radiation incident on the array (W/m^2)
$\mu_{P_j(t)}$	mean of power available from ith power source (W)
n	life of the component (years)
η_c	battery charging efficiency
η_d	battery discharging efficiency
η_i	inverter efficiency
η_P	photovoltaic system efficiency
P_{net}	net power available at the dc bus (W)
P_{du}	dumped excess power (W)
P_{pv}	power generated by the photovoltaic array (W)
P_r	rated electrical power of the wind power generating unit (W)
P_w	power generated by the wind turbine (W)
P_j	power generated by the jth power source (W)
Q_B	energy stored in the battery (kW h)
Q_{max1}	maximum stored energy of the battery energy before t_{ref} (W h)
Q_{max2}	maximum stored energy of the battery energy after t_{ref} (W h)
Q_{min}	minimum stored energy by the battery (W h)
$q_j(t)$	multiplication factor for finding out power produced
ρ_{ij}	coefficient of correlation between the power available from ith and jth sources
$\sigma_{P_j(t)}$	standard deviation of power available from ith power source (W)
T	time horizon for the simulation (h)
t	time (h)
t_{max1}	time at which battery reaches maximum energy before t_{ref} (h)
t_{max2}	time at which battery reaches maximum energy after t_{ref} (h)
t_{ref}	time at which battery reaches minimum energy (h)
v_c	cut-in wind speed (m/s)
v_f	cut-off wind speed (m/s)
v_i	wind speed at reference height H_i (m/s)
v_r	rated wind speed (m/s)
X	depth of discharge of battery
z	power law exponent

utilized even where grid connectivity exists, provided it is found to be cost effective (Govt. of India, 2003).

Isolated systems using renewables can be powered by a single or a combination of renewable power sources. The power available from the renewable sources is stochastic in nature. However, some of the renewable resources like solar and wind are complementary in nature. This means that during seasons of low insolation, the wind speed is typically higher and the wind speed is generally low for seasons of high insolation. In Fig. 1, monthly average value of wind speed, monthly average total rainfall, and monthly average daily global insolation for an Indian town, Ratnagiri during each month is plotted (Mani and Rangarajan, 1982). From Fig. 1, it can be observed that the amount of rainfall and wind speed is negatively correlated to solar insolation. During monsoon months, when the rainfall is high, the wind speed is also high and solar insolation is low. The wind speed and rainfall are low for summer months when the insolation is high. Thus, it is apparent from Fig. 1 that it may be advantageous to make a wind solar or a micro-hydro-solar hybrid power system. Due to complimentary nature of wind and solar power and the cost effectiveness of hybridizing these two systems, a vast literature deals with wind–solar hybrid systems and is recently reviewed by Deshmukh and Deshmukh (2008).

The performance of a hybrid system depends upon proper sizing of the system. Design and simulation followed by optimization are main steps involved in sizing an isolated hybrid system. The size of a system, that can supply the required power demand, can be determined by simulating the entire system using the resource and the demand data. Optimization of the entire system may be performed to arrive at a sizing which satisfies certain cost and reliability criteria. This is typically achieved by minimizing the net present cost of the system or the levelized cost of generated energy. The reliability of the power produced by the hybrid system is also generally included in the optimization process either in the form of constrains or as another variable to be maximized. In the latter case, a multi-objective optimization routine has to be revoked and the solution set generally consists of a set of Pareto-optimal configurations, out of which a suitable one has