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Original article

Life cycle cost, embodied energy and loss of power supply probability for the optimal design of hybrid power systems

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Abstract

Stand-alone hybrid renewable energy systems are more reliable than one-energy source systems. However, their design is crucial. For this reason, a new methodology with the aim to design an autonomous hybrid PV-wind-battery system is proposed here. Based on a triple multi-objective optimization (MOP), this methodology combines life cycle cost (*LCC*), embodied energy (*EE*) and loss of power supply probability (*LPSP*). For a location, meteorological and load data have been collected and assessed. Then, components of the system and optimization objectives have been modelled. Finally, an optimal configuration has been carried out using a dynamic model and applying a controlled elitist genetic algorithm for multi-objective optimization. This methodology has been applied successfully for the sizing of a PV-wind-battery system to supply at least 95% of yearly total electric demand of a residential house. Results indicate that such a method, through its multitude Pareto front solutions, will help designers to take into consideration both economic and environmental aspects.

Keywords: Hybrid power system; Dynamic simulation; Multi-objective design optimization; Genetic algorithm

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1. Introduction

Energy from renewable sources is being considered as a viable alternative to fossil fuels depletion. Among them, wind and solar energies have made a fast and significant breakthrough in the past 10 years. Additionally, they can be consumed locally; hence reducing both impacts from high voltage transmission lines through rural and urban landscapes, and power losses. However, neither a solar nor a wind energy standalone system can fully satisfy the load consumption due to seasonal and periodical climatic variations. Therefore, it is more reliable and efficient to install a hybrid energy system with storage due to renewable energy sources intermittent character [12]. Photovoltaic panels are often combined with wind turbines or diesel generators and batteries. To achieve such a system, finding an optimal

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Abbreviations: AC, alternative current; DC, direct current; *DE*, deposition efficiency; *DOD*, depth of discharge; *EE*, embodied energy; GA, genetic algorithm; *LCC*, life cycle cost; LCE, levelized cost of energy; *LPSP*, loss of power supply probability; MOP, multi-objective optimization; PV, photovoltaic.

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Nomenclature

Apv (m^2)	surface area of PV panels
Apv_{max} (m^2)	maximum surface area of PV panels
Apv_{min} (m^2)	minimum surface area of PV panels
Awt (m^2)	wind turbine swept area
Awt_{max} (m^2)	maximum wind turbine swept area
Awt_{min} (m^2)	minimum wind turbine swept area
Cn (Ah)	nominal capacity of the battery bank
$Cbat$ (Ah)	nominal capacity of each battery
Cn_{max} (Ah)	maximum nominal capacity of the battery bank
Cn_{min} (Ah)	minimum nominal capacity of the battery bank
Cp	wind turbine efficiency
Ir (W/m^2)	solar radiance
$LPSP_{max}$ (%)	maximum allowable $LPSP$
$Nbat$	total number of installed batteries
$Nbatp$	number of batteries strings connected in parallel
$Nbats$	number of batteries connected in series in every string
$NOCT$ (°C)	normal operating photovoltaic cell temperature
Ppv (W)	output electric power from the PV generator
Pwg (W)	electrical power output of a wind generator
$SOCmax$ (%)	maximum allowable battery storage capacity
$SOCmin$ (%)	minimum allowable battery storage capacity
Ta (°C)	ambient temperature
Tc (°C)	photovoltaic cell temperature
$Ubus$ (V)	nominal DC bus voltage
V (m/s)	wind speed
$\eta acdc$	AC/DC converter efficiency
$\eta dcdc$	DC/DC converter efficiency
ηg	wind turbine generator efficiency
ηgb	wind turbine gearbox efficiency
ηinv	DC/AC inverter efficiency
ηpc	PV module power conditioning efficiency
ηpv	power conversion efficiency of a PV module
ηr	reference PV module efficiency
ηt	wind turbine overall efficiency factor
ηwr	wires losses' factor
ρ (kg/m^3)	air density

configuration of the different sources considering consumer energy demand and available resources at a site proves to be essential. For this purpose, sizing and optimizing stand-alone hybrid renewable energy systems has been carried out by a number of researchers and studies [8].

Borowy and Salameh [10] for example, explicit a method to optimize the size of a PV-wind-batteries system: the desired unmet load is achieved by modifying the number of photovoltaic panels and batteries. Wind turbine, panels' type and battery technology are fixed. As there is more than one technically feasible solution, they select the less expensive one.

A procedure has been developed by Chedid and Rahman [11] that determines the optimal design of a hybrid wind-solar power system for either autonomous or grid-linked applications. The proposed analysis employs simple linear programming techniques to minimize the average production cost of electricity while meeting load requirements in a reliable way, and takes environmental factors into consideration both in the design and operation phases. Nevertheless,