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Maiden application of Cuckoo Search algorithm for optimal sizing of a remote hybrid renewable energy System

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ABSTRACT

Solar and wind power based hybrid energy system with energy storage unit provides a reliable and cost effective energy alternative above the conventional diesel generator based system commonly used by remote consumers. In this context, this paper explores the application of a new meta-heuristic algorithm called Cuckoo Search (CS) in the area of a hybrid energy system design problem. Cuckoo Search (CS) is applied for optimal sizing of three different system schemes viz. Photovoltaic-Battery, Wind-Battery and Photovoltaic-Wind-Battery system applicable to a remote area located in Almora district of Uttarakhand, India while minimizing total system cost and considering seasonal variation of load. The effectiveness of Cuckoo Search algorithm in solving hybrid energy system design problem is investigated and its performance is compared with other well known optimization algorithms like Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm. Optimization results further, shows that hybrid integration of photovoltaic, wind and battery storage gives most reliable and economical system scheme for the study area. In addition, this paper assesses the effect of wind turbine generator (WTG) force outage rate (FOR) on the optimal system reliability and economics.

1. Introduction

In case of remote area applications, supplying power through a hybrid renewable energy system has become a promising and reliable option. A hybrid energy system combines different renewable energy sources to form a single system and is usually more cost effective and reliable than single energy source based system. Implementation of hybrid renewable energy units has showed a remarkable increase recently and consequently determination of optimal hybrid system design in terms of operation and component size is much crucial in order to have reliable and economical power supply. However, the choice of sizing techniques is a key issue with respect to achieving global optimum and computational simplicity as well as effective utilization of the available resources.

Generally, there is a vast spectrum of reported literature available dealing with hybrid system design and optimization. Quasi Newton algorithm is applied in Ref. [1] to get the optimal components size based on minimum total life cycle cost. A trade off/risk method is utilized in Ref. [2] to get the optimal solar photovoltaic array and battery size while minimizing capital investment and for a minimum Loss of Load Probability requirement. Various sizing tools such as Hybrid Optimization Model for Electric Renewables (HOMER), Hybrid Power System Simulation model (HYBRID2) etc. are available and widely used in many applications. Besides, many optimization techniques like genetic algorithm (GA), simulated annealing (SA) and particle swarm optimization (PSO) have been reported in literature for hybrid system sizing. In Refs. [3], HOMER is adopted to analyze the technical and economic potential of autonomous hybrid wind/PV/diesel power system for a typical remote village in Saudi Arabia. Size optimization of a hybrid energy system combining solar photovoltaic and wind turbine using HOMER is carried out in Ref. [4] considering diesel generator as the back-up source and the battery as the storage device. Further applications of HOMER simulation software are reported in the literature [5,6]. GA is utilized in Refs. [7,8] for sizing of a stand-alone hybrid PV-wind system. An optimum hybrid PV, wind and fuel cell system is designed [9] using GA, based on economic criteria. Methodology based on PSO for unit sizing of PV-wind-fuel cell micro-grids is reported in literature [10,11]. The optimization of a hybrid energy system is carried out in Ref. [12] using Homer software, PSO and CPSO and their comparison is made applicable for a

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Nomenclature

A_i	unit cost of *i*th component, Rs/kWh
α	power law exponent
C_{Total}	total system cost, Rs
C_{ENS}	cost for energy not supplied, Rs/kWh
C_{pv}	probability distribution for capacity states of PV array
E_{batt}	energy rating of battery storage, kWh
$EENS$	expected energy not supplied, kWh/year
η_{inv}	inverter efficiency
η_{batt}	battery charging/discharging efficiency
FOR	force outage rate
$F_{pv}(i)$	probability associated with $P_{pv}(i)$
h_{hub}	wind turbine hub height, m
h_{anem}	height of the anemometer, m
HES	hybrid energy system
I_T	global solar radiation incident on the PV array
$Load^t$	load during t^{th} time unit, kW
$LOLE$	loss of load expected, hours/year
m	component life time, years
om	percentage operation and maintenance cost
P_{pv}^t	output power of PV at *t*th time unit
$P_{pv-actual}^t$	actual output power of PV at *t*th time unit
$P_{pv}(i)$	capacity level of PV array when *i* out of N_{pv} modules are operating
P_{WTG}^t	output power of WTG at t^{th} time unit, kW
$P_{WTG-actual}^t$	actual output power of WTG at t^{th} time unit, kW
P_{batt}^t	charged/discharge battery power, kW
q_{pv}	unavailability of PV
R_i	capacity of i^{th} component
r_0	annual interest rate
SOC	battery state of charge
SOC_{min}	minimum value of battery SOC
SOC_{max}	maximum value of battery SOC
σ	self discharge rate of battery
$V(h_{hub})$	wind speed at hub height, m/s
$V(h_{anem})$	wind speed at anemometer height, m/s
Y_{pv}	PV array capacity, kW

police control room in Central India. Simulated annealing is used and performs the size optimization of a PV/wind hybrid energy conversion system with battery storage in Ref. [13]. A hybrid renewable energy system (PV/WT/battery) optimization model is developed in Ref. [14] based on particle swarm optimization for a small load area in Kerman, Iran. Different variants of PSO are used to find the optimal values of design variables minimizing the life cycle cost, out of which adaptive inertia weight based PSO proves to be more promising. Design of multi-objective hybrid renewable energy system is carried out in Ref. [15] using preference-inspired co-evolutionary algorithm and is applied to a case study system consisting of PV panels, wind turbines, batteries and diesel generators. The algorithm is improved by proposing an enhanced fitness assignment method using goal vectors. In Refs. [16], a simulation optimization model based on meta-model based algorithm called A-STRONG is developed to find the optimal size of PV, wind and diesel power generator as well as the optimal size of energy storage system. The study also considers the power generation allocation and transmission within the hybrid renewable energy system for finding minimum expected total cost under uncertain environments. A smart hybrid renewable for communities (SHREC) is proposed in Ref. [17] considering both thermal and electricity market in a large community level. The developed SHREC system is optimized using linear programming algorithm in a weekly period. Results show the effectiveness and flexibility of developed methodology for the smart hybrid renewable energy system. A hybrid renewable system comprising of biomass gasification and photovoltaic panels with battery is designed in Ref. [18] and experimentally tested for supplying the electrical needs of ISTA-DRC laboratory complex in Republic of Congo. A simulation based optimization approach is used in Ref. [19] for optimal sizing of a hybrid renewable energy system while minimizing total net present cost, CO_2 emission and simultaneously maximizing renewable energy ratio. In Refs. [20], a techno-economic feasibility study of an off-grid hybrid renewable energy based power systems is carried out for satisfying the electrical needs of a rural community in Sri Lanka.

Although there are abundant research works concerning optimization of hybrid energy system, but limited works has been carried out using evolutionary algorithms like GA and PSO. GA and PSO can effectively explore different region of search space at a time. Hence, GA and PSO are less susceptible to being trapped in local minimum as compared to conventional approach. GA performs only two operations crossover and mutation to overcome the possibility of being trapped into local minima. Ref. [21] has identified some of the deficiencies in GA performance. Very recently, a new meta-heuristic algorithm called as Cuckoo Search (CS) has been developed by Yang and Deb [22]. In CS, the number of parameters to be fine tuned during optimization is less compared to those of GA and PSO, and thus it is more potential and generic one to adapt to wider class of optimization problems. Its effectiveness and superiority over other well-known optimization techniques like GA, PSO, ant colony algorithm etc. has been reported in the literature [23]. CS based optimal allocation of distributed generation in distribution network is found in Ref. [24] where its better performance over GA and PSO is being highlighted. However, it has not been applied to HES design problem yet.

In view of this, the current work attempts to investigate the effectiveness of Cuckoo Search in solving hybrid energy system optimization problem. A hybrid system design optimization problem is formulated considering seasonal variation in load profile with measured solar and wind energy resources, cost of the components and cost of operation and maintenance. The objective is to use Cuckoo Search in finding the optimal system that satisfies the demand reliably and has lowest total system cost. The developed methodology is applied for finding the optimal solution of three different system schemes viz. photovoltaic-battery, wind-battery and photovoltaic-wind-battery applicable to a remote case study area in India. The study is carried out taking into account the variable behavior of solar and wind resources, outages due to hardware failure of photovoltaic panel and wind turbine generator force outage rate (FOR). In addition, the current work highlights the effect of wind turbine generator force outage rate on the optimal system cost and optimal system reliability. The optimal system reliability is assessed by quantifying annual power not supplied through Loss of Load Expectation (LOLE) index. The concept of Monte Carlo Simulation is adopted to evaluate the LOLE index.