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Optimization of an isolated photo-voltaic generating unit with battery energy storage system using electric system cascade analysis

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ABSTRACT

This paper presents an improvement to the iterative method of electric system cascade analysis (ESCA) for the optimisation of an isolated PV system with battery energy storage system (BESS) for a residential load. The ESCA algorithm is implemented on MATLAB software environment with Final Excess Energy (FEE), Loss of Power Supply Probability (LPSP) and system cost as optimization constraints. The load, temperature and solar radiation profiles are considered for a year, based on historical data. Practical losses in solar radiation reaching the PV collector surface are considered for analysis. Change in PV efficiency due to variation in temperature and change in charge/discharge efficiency of the battery based on current state of charge (SOC) of BESS are taken into consideration which further bolsters the credibility of the ESCA methodology. The ESCA methodology is used to optimize a PV-BESS system for a residential load with average daily consumption of 26.1 kWh. The optimized result obtained from improved ESCA are compared and verified with benchmark HOMER software.

1. Introduction

Attention towards renewable energy generation has increased in the past two decades because of the high increase in energy demand and harmful impacts of the conventional energy generation [1]. Among the renewable sources like solar, wind, bio-power, geothermal, etc., the most popular resources are wind and solar [2]. For small load areas, solar energy presents the best solution because of ease of installation and low maintenance. In 2017, China with 131 GW of installed capacity is the world leader in solar PV generation followed by Japan at 49 GW and USA at 43 GW [3]. The total installed capacity of solar PV of the world in 2017 is 397 GW, which is expected to increase to 489 GW by 2020 and 1760 GW by 2030 [3]. Stress on the conventional energy sources can be greatly reduced by penetration of renewable energy sources into the current grid, but the popularity of standalone system with high renewable energy penetration has gained recently, for example, Liu et al. [4] have performed comparative study of various configuration of isolated renewable energy systems. Yilmaz and Dincer [5] have performed optimization of isolated hybrid renewable energy system for city in Turkey. Fara and Craciunescu [6] have designed and modelled an isolated PV system for a mountain village in Romania. Researchers [7–9] have shown in their literature review that hybrid renewable energy system has a rising trend in isolated system studies. For isolated systems, it is prudent to use energy storage unit(s) to overcome the uncertainty in power generation from renewable sources like solar and wind [10]. Even though addition of storage provides higher reliability of power, but the cost of the system and control complexity of the system increases [11]. Therefore, optimal sizing of the renewable energy system becomes important. There are several studies which have been conducted using optimization techniques like particle swarm optimization (PSO), genetic algorithm (GA), etc. and software like RETscreen, HOMER, HYBRID2, etc. For example, Upadhyay and Sharma [12] have compared different combinations of HRES with diesel generator to find the most economic configuration using particle swarm optimization (PSO), Maleki and Askarzadeh [13] have compared artificial intelligence techniques for optimization of hybrid energy system (HES) consisting of fuel cell and battery as storage units and found PSO to be the most effective. Katsigiannis et al. [14] have found the optimum generator scheduling to reduce the cost of energy of the HES using tabu search (TA) and simulated annealing (SA) methods. Paliwal et al. [15] have performed the reliability analysis of isolated HRES for a rural area using PSO. Koutroulis and Kolokotsa [16] have analysed the optimization of a desalination system fed by PV, WECS and diesel generator using genetic algorithm (GA) technique. Bahramara et al. [17] have performed the optimal planning of an isolated HRES using HOMER. Hove and Tazvinga [18] have presented economic analysis of a PV and diesel system with the variation in renewable fraction using RETScreen. Singh et al. [19] have compared HRES in grid

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Nomenclature

Symbols

A	Extra-terrestrial flux (W/m^2)
H	Hour angle
k	Optical depth
L	Life time of the system
L	Latitude
m	Air mass ratio
n	Day number of the year
T	Time period of analysis
A_{PV}	Area of each PV panel (m^2)
C_0	Total fixed cost ($)
C_{Bat} (t)	Charging energy of BESS (Wh)
C_{ICC}	Initial capital cost ($)
C_{TSC}	Total cost of the system ($)
C_{TASC}	Total annualized system cost ($)
CRF	Capital recovery factor
$D_{Bat}(t)$	Discharging energy of BESS (Wh)
$E_{C,new}(t)$	Hourly net cumulative energy (Wh)
E_c (t)	Net accumulated charge in BESS (Wh)
E_l (t)	Hourly primary load demand (Wh)
E_{PV}	Hourly energy generated (Wh)
I(t)	Hourly solar radiation (Wh/m^2)
I_{NOCT}	Solar radiation at NOCT (W/m^2)
I_{BN}	Normal component of solar radiation (Wh/m^2)
I_D	Diffused component of solar radiation (Wh/m^2)
I_R	Reflected component of solar radiation (Wh/m^2)
I_{bat}	Nominal capacity of BESS (Ah)
LCE	Levelized cost of energy ($/kWh)
LPS (t)	Hourly loss in power supply (Wh)
N_{bat}	N_{bat}
N_{PV}	Number of PV panels
NOCT	PV normal operating cell temperature (°C)
N(t)	Hourly net surplus energy (Wh)
P_{inv}	Inverter rating (W)
P_L (max)	Max load (W)
T_a	Ambient temperature (°C)
T_r	Temperature at rated PV efficiency (°C)
T_c	Computed ambient temperature (°C)
V_{bat}	BESS voltage (V)
α	Cost of each PV unit ($)
β	Altitude angle of the sun
β_b	Cost of each battery ($)
β_N	Altitude angle at noon
β_T	PV temperature coefficient of efficiency
δ	Solar declination angle
η_{pv}	Calculated PV panel efficiency (%)
η_r	Rated PV panel efficiency (%)
η_{inv}	Inverter efficiency (%)
η_{char}	Charging efficiency of BESS (%)
$\eta_{dischar}$	Discharging efficiency of BESS (%)
ρ	Ground reflectance coefficient (%)
Ø	Azimuth angle (°)
∈	Tilt angle of the collector (°)

Abbreviation

BESS	Battery energy storage system
DOD	Depth of discharge
ESCA	Electric system cascade analysis
FEE	Final excess energy
GA	Genetic algorithm
HES	Hybrid energy system
LPSP	Loss of power supply probability
PoPA	Power pinch analysis
PSO	Particle swarm optimization
PSO	Particle swarm optimization
SA	Simulated annealing
SOC	State of charge of BESS
TA	Tabu search

and islanding mode of operation for a residential load in Mumbai using HOMER. The major drawbacks of these studies are limited time period of 24 h, simple system modelling, and complex system optimization technique, especially in case of GA, PSO, etc. There are several limitations to the optimization techniques, e.g., for GA approach there is no guarantee of finding the best solution, for fuzzy logic approach estimation of membership function is difficult and time consuming process and software provides results based on the only input range of the user. Therefore, this paper presents a simple and goal oriented ESCA methodology which overcomes some of the flaws in other optimization techniques.

ESCA is a technique which is based on power pinch analysis used during optimization of raw material like heat, mass, carbon and gasses [20]. Wan Alwi et al. [21] implemented this method to minimise the outsourced electricity for a grid connected load. Bandyopadhya [22] implemented power pinch analysis for the design and optimization of isolated energy system. Ho et al. [23] further improved upon this technique and introduced a new iterative method of ESCA for optimisation of non-intermittent source of biomass and energy storage system for distributed energy generation system. Ho et al. [24] further extended his work to optimize an isolated system with intermittent source of PV, where the cascade table analysis helped in PV system size optimization and power pinch analysis was performed to obtain the size of the storage unit. All these works provide a deep insight into the successful implementation of ESCA in optimization of the renewable energy system, but there is scope of improvement.

The common approach in all these studies is having load and geometric climate data for 24 h only, which has its limitations on practical implementation. Therefore, this paper considers the historical data for a year of load, temperature and solar radiation for optimal system design of an isolated PV generating system using ESCA methodology with constraints of FEE, LPSP and system cost. Unlike other techniques which optimize the system first and then find the most economical solution, in this paper reliability and economic constraints are analysed simultaneously to arrive at the optimized results. Also included in the analysis, is the practical variation of the PV efficiency with temperature and the battery efficiency with state of charge. The solar radiation profile is considered by incorporating the attenuation, diffusion and reflection of the solar beam radiation reaching the PV collector surface. The FEE constraint is used to optimize the BESS. FEE > 0, may lead to accretion in the initial charge of BESS on recursive use thereby over estimating the BESS capacity and FEE < 0, may lead to depletion in the initial charge of BESS over recursive use which can lead to failure of the system. LPSP constraint is a good indicator of the reliability of the system, which is the main optimization constraint for the PV system planning. The LPSP constraint can be achieved by reducing BESS capacity and/or reducing PV system rating, therefore system cost constraint is also incorporated in the analysis to obtain an optimized system configuration with minimum cost. In this work, the load profile considered is for a residential load with latitude and longitude as 40° N and 70° W respectively. The ESCA algorithm is implemented firstly, with a time period of 288 h with the constraint of reducing FEE below 100 Wh. The load, solar and temperature profile for this analysis are formed by combining 24 h profile of each month,