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Optimal Sizing of Hybrid Energy System using Ant Colony Optimization

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Abstract: A Hybrid Energy System (HES) consisting wind/solar/Battery has been analyzed for a particular load profile. This analysis is done with the aim of obtaining optimal sizing of HES. Optimal sizing results are obtained with considering important factors such as reliability, cost and other unexpected uncertainties. Dependency of Sources on atmospheric factors introduces nonlinearity in the system and on the demand side also load is fluctuating. For highly non-linear problem it is not preferable to do analysis with conventional optimization technique. Further this paper proposed an Ant Colony Optimization (ACO) based approach to get optimal sizing of HES. The outcome is compared with the previously applied technique to confirm the efficacy and compatibility of proposed technique for considered HES.

Keywords Hybrid Energy System, Ant Colony Optimization, Optimal Sizing

1. Introduction

Depletion of fossil fuels and environmental issues are a major area of concern worldwide in power sector. In developing countries many remote areas are not electrified till now and in future also there is less scope of electrification in remote areas owing to technical and economic problems in grid extension. Currently remote areas population is dependent on kerosene and diesel for their daily needs [1], which are not affordable and neither are clean sources. Renewable energy sources like solar, wind, biomass based isolated HES can be considered as effective, economic, reliable and environment friendly [2]. Equivalent HES system analysis has been done in literature and various techniques have been suggested for improving the overall performance of system. A simulink model for hybrid energy system considering economic and environmental affects has been analyzed considering diesel only, battery-diesel and PV-battery diesel for remote villages and found that integration of PV array with diesel-battery standalone reduces operation cost, greenhouse gas emissions [3] [4]. In depth analysis of various HES is must to make competitive with conventional energy cost. Optimal generation of energy requires economical sizing of sources and it is achieved by applying various optimization techniques. Numbers of deterministic and stochastic optimization techniques are discussed in literature. Both types of techniques have their own dominancy based on objective of problem, variable nature of the problem and constraints.

Various objectives of HES are:

a) Optimal sizing or capacity planning of sources

b) High power supply reliability

c) Optimization of battery charge and discharge rates

c) Full capacity utilization of sources,

d) Minimization of total cost of the system

A deterministic method Lagrangian and stochastic method Genetic Algorithm (GA)has been compared for the optimal capacity planning of stand-alone photovoltaic - battery storage system and results conclude that GA has the breadth to solve capacity planning of the system [5].

A methodology for sizing and simulation of an autonomous photovoltaic-wind hybrid energy system with battery storage, using simulation tools and linear programming has been presented for a small rural property located in the south of Brazil [6]. A HES consisting wind, solar and battery for storage, has been modeled for village Sukhalai in Hoshangabad district of Madhya Pradesh (India)[7]. Simulation of wind-photovoltaic HES with battery storage and optimization with genetic algorithm show the expected energy benefit in terms penetration and the impact on the economics of the island system previously covered only through diesel [8]. To consider the reliability as a main criteria to fulfill, an objective of minimization loss of power supply probability (LPSP) is taken into consideration and finally optimal configuration is achieved by single and multi-objective optimization [9]. An improved sizing method for wind-solar-battery HES considering almost all the objectives has been presented for China [10]. An optimal hybrid wind/PV/Diesel/battery model for an area of Jaipur, Rajasthan, using biogeography based optimization technique has been proposed and results are validated through Homer, PSO, GA [11]. An Algorithm based on PSO and MATLAB platform is developed for the prediction of the optimal sizing of PV/Diesel/Battery hybrid energy system for remote area railway station[12].

Static and dynamic characteristic variation of sources and inclusion of other electrical component makes the problem as NP-hard which is solved effectively through metaheuristic optimization techniques such as [13] biogeography algorithm and mainly evolutionary algorithm like genetic algorithm (GA) , memetic algorithm, Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) [14] [15][16]. Literature overview and technology advancement develop a faith on solar and wind as main sources of HES. Wind and solar sources are significant energy sources for HES due to their high potential and topological advantages as well as they are having complementary nature also. This paper proposes an ACO based approach for optimal wind-solar-battery based hybrid system and results provide the better optimal value as compare to present earlier for almost samdddddde load profile and same parameter value of the system[10]. This paper is organized as follows. Section 2 describes the hybrid energy system and energy management strategy to be followed further for analysis. Section 3 discuss in detail about modeling of various parameters of HES. Further section 4 about the objective formulation and constraint and section 5 about the optimal sizing strategy needs to be applied during objective analysis. Section 6 presents the results of optimization and finally section 7 conclude the paper.

2. Hybrid Energy System and Energy Management Strategy

HES which is considered in proposed approach, is shown in Fig. 1. It integrates Wind Turbine Generators (WTGs) and PV panels (PV), supplement power source as battery, and others equipment such as converters etc.

The PV panels are attached to DC bus via DC/DC converters and wind turbine via AC/DC converters, batteries are connected to DC bus directly. DC bus is connected to AC bus via DC/AC converters.

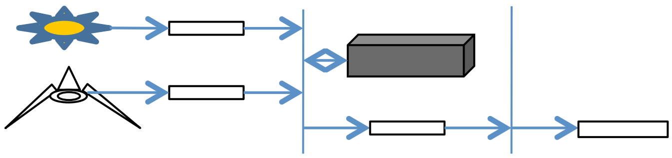

Fig. 1. Hybrid energy system

Complementary characteristics sources solar and wind considered as primary sources and batteries comes into picture on non-availability of primary sources or lower energy received from primary sources. Here the HES has been designed to satisfy energy required by the load shown in fig 1, with average power of 100 kW, peak power of 315 kW, and the daily variation of 10 %. So a defined energy management strategy for HES system is as follows:

First the load is met by wind and solar based on availability if at any point of time PV panel and wind turbine power is greater than or equal to power required by load.

$$P_{pv}(t) + P_{wr}(t) \geq PL(t) \quad (1)$$

If total output power at any time is greater than load requirement than battery will be charged based on constraints of maximum state of charge (SOCmax) applicable for battery.

$$P_{BC}(t)=(P_{pv}(t) + P_{wr}(t) - PL(t)) \quad (2)$$

If vjtotal output power is less than required by load at particular time, than difference in power will be met by battery with constraint fulfilment that battery will discharged up to depth of discharged (DOD) defined by manufacturer.

$$P_{BDC}(t)=(PL(t) - P_{pv}(t) - P_{wr}(t)) \quad (3)$$

3. Hybrid Energy System Modelling

3.1. Modelling of wind turbine

In the wind power generation system, wind turbine is used to extract the power from the blowing wind. The power can be calculated by (1) [17].

$$P_m = ½ \rho A C_p V\omega^3 \quad (4)$$

Where the variables in (1) are defined as follows:

C_p: Power coefficient

A: Area swept by turbine

ρ: Air density

V_ω: Speed of the wind

Based on the rated power wind power calculation can be done

$$P_{wt}(t) = \begin{cases} 0 & V_w(t) < V_{ci} \\ P_{wr} * \frac{V_w(t)-V_{ci}}{V_r-V_{ci}} & V_{ci} \le V_w(t) < V_r \\ P_{wr} & V_r \le V_w(t) < V_{co} \\ 0 & V_w(t) \ge Vco \end{cases} \quad (5)$$

P_{wr} : Rated power of wind turbine

$V_w(t)$: Wind velocity with respect to time

V_{ci} : Cut-in velocity of wind turbine

V_r : Rated velocity of wind turbine

V_{co} : Cut-off velocity of wind turbine

3.2. *Modelling of Solar Photovoltaic*

The electrical output power of solar panel can be calculated by following eq[10] .

$$P_{pv}(t)= f_{pv} * (P_{pv\_r}/1000)*(G(t)/G_{STC})*(1+\alpha_T(T-T_{STC}) \quad (6)$$

Where f_{pv} is derating factor considering shading, wiring losses and snow cover, P_{pv_r} is rated power output of solar panel, G_{STC} (1000 W/m^2) and T_{STC} (25^{0}C)are the solar radiation and temperature on PV cell under Standard Test Condition (STC), α_T is the temperature coefficient. G(t) is solar radiation in kW/m^2 and T is the temperature in degree celsius in current time respectively.

3.3. *Modelling of battery*

Battery capacity is defined in terms of state of charge (SOC), which is constantly changing with time as per the other sources output and load requirement. Battery SOC is defined as:

$$SOC(t)=SOC(t-1)*(1-SDR)*effRTE+Pbs(t-1) \quad (8)$$

SRD is self-discharge rate, effRTE is round tip efficiency of battery, Pbs(t) is power available at time t either for charging of battery or required by load from battery depending upon the condition. In charging case it will be positive and in discharging case it will be negative.

Battery charging and discharging power rate is determined by considering various standard specification given and current status of battery state. Charging rate is decided by comparing three parameters, available power for charging, maximum charging rate specified by manufacturer and current state of charge of battery. The minimum among three is chosen as charging rate.

Pb_ch(t)=((Pwt(i,t)+Ppv(i,t)-Pl(t))(PBcap_rT/Tmin)
(PBcap_rT -Pbs(i,(t-1))) (9)

For discharging comparison is done to obtain maximum discharging rate. This is decided by based on required power for load, maximum discharging rate and current state of charge of:

Pb_ch(t)=((Pl(t)-Pwt(i,t)-Ppv(i,t))(PBcap_rT/Tmin)
(Pbs(i,(t-1))-(1-DODmax)*PBcap_rT)) (10)

4. Problem Formulation

Different power sources have different impact on overall cost, performance and reliability of HES system.As a result optimal sizing and economic power dispatch strategy is needs to be considered. Decision variables for the problem is taken as number of wind turbines, number of PV panel and number of battery.

4.1. *Objective function*

The objective is defined as economical design of hybrid energy system considering 100 % supply of power to load for any point of time. Investment cost, Operational and maintenance cost, and replacement cost have been considered in total cost calculation of HES.

$$\min f= Min (C_i+C_{om}+C_r) \quad (11)$$

The total initial investment cost is defined as follows:

$$C_i = (N_{pv} * C_{pv} + N_{wt} * C_{wt} + N_{bs} * C_{bs} + N_{inv} * C_{inv})(12)$$

N_{pv} ,N_{wt} and N_{bs} are the number of pv array, wind turbine and battery respectivel, C_{pv} , $C_{wt}$and C_{bs} are investment cost of pv array, wind turbine and battery respective.

a) The total operational and maintenance cost is given as follows:

$$C_{om} = (C_{pv\_om} + C_{wt\_om} + C_{bs\_om} + C_{inv\_om})(13)$$

b) Replacement cost of components depends upon the project life and corresponding component life specified by the manufacture

$$C_r = (N_{pv}C_{pv\_r} + N_{wt}C_{wt\_r} + N_{bs}C_{bs\_r} + N_{inv}C_{inv\_r}) \quad (14)$$

4.2. *Constraints*

Constrained applied for objective function are following:

a) *PV array installation constraint*:minimum sizing is decided by average load required and

$$N_{pvmin}>avgLoad/ \eta_{pv} \quad (15)$$

η_{pv}: overall efficiency for PV array

maximum size is decided by maximum load requirement

$$N_{pvmax}< (MaxLoad/ \eta_{pv}) \quad (16)$$

b) Wind turbine minimum sizing is decided by average load required and maximum sizing is decided by maximum load required

$$avgLoad<N_{wt}< (MaxLoad / \eta_{wt}) \quad (17)$$

η_{wt}: overall efficiency for wind turbine

c) *Battery installation constraints:*Minimum sizing is decided to provide at least back power to load for λ number of days

$$N_{wt}> \lambda * avgLoad \quad (18)$$

λ: number of days

Battery state of charge should be under the defined maximum SOC and minimum SOC

$$SOC_{min}<SOC <SOC_{max} \quad (19)$$

Battery charging, discharging current and charging, discharging rate should be limited by maximum defined value

$$I_{ch} < I_{ch\_max} \quad (20)$$

$$I_{dch} < I_{dch\_max} \quad (21)$$

$$r_{ch} < r_{ch\_max} \quad (22)$$

$$d_{ch} < d_{ch\_max} \quad (23)$$

5. Optimal Sizing Strategy for HES

For sizing of various components of HES, day-wise annual load requirement, wind speed, solar radiation and temperature, are shown in Fig. 2, Fig. 3, Fig. 4 and Fig. 5 respectively.

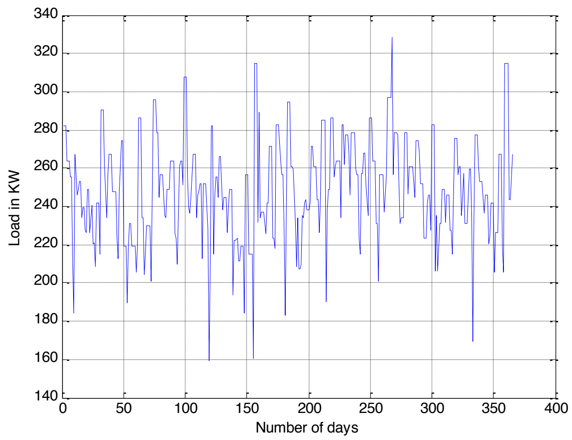

Fig. 2. Load profile

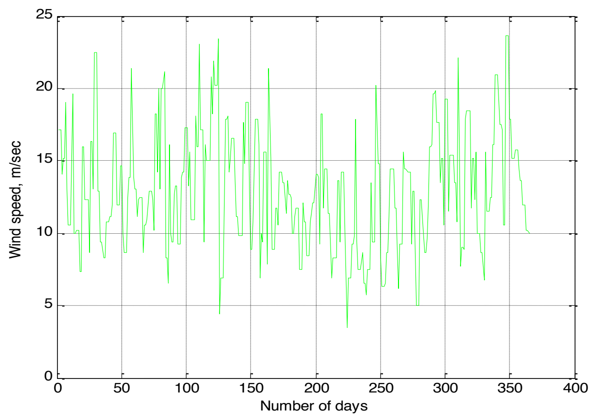

Fig. 3. Wind speed in mt/sec

Obtained power from sources is supplied to load by applying energy management criteria discussed in section 2. At any point of time, maximum loss of required power by load is assumed 0.05 %. Optimal sizing variables are taken as number of wind turbine, solar PV cell and number of battery. Single unit specification and cost parameters of wind turbine, solar PV cell and battery are given in Table 1, Table 2 and Table 3 respectively [10]. Wind turbine, solar PV panel and batteries of same size unit have been considered in optimal desining. HES optimal sizing strategy is obtained using ACO based approach.

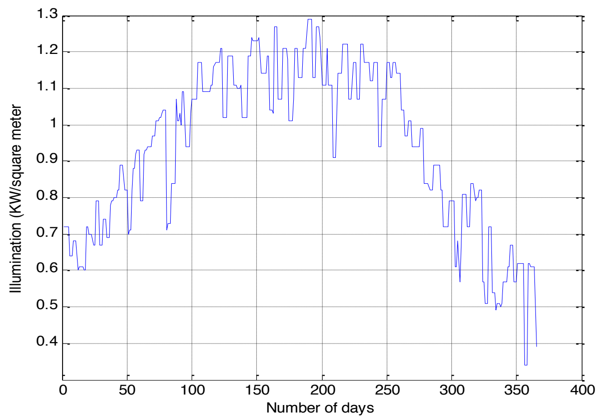

Fig. 4. Solar Illumination

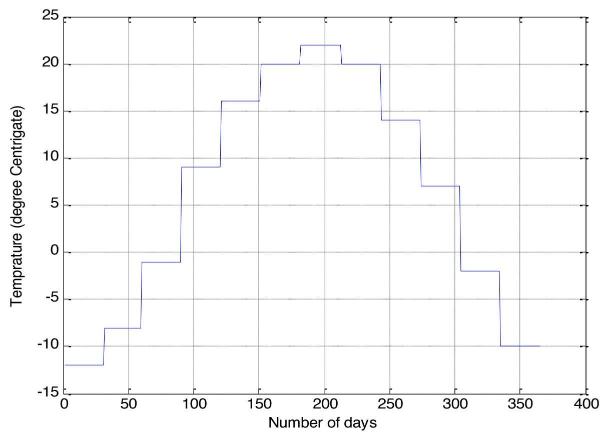

Fig. 5. Temperature in ^{0}C

Table 1. PV specification

Rated power	200 W
Open circuit voltage	30.8 V
Short circuit current	8.7 A
Optimum voltage	24.5 V
Optimum current	8.16 A
Investment cost	420 $
Operational and maintenance cost	15
Replacement cost	420$
PV efficiency at std. test condition	13 %

Table 2. Wind turbine specification

Rated power	35 KW
Cut-in speed	3 m/s
Cut-out speed	25 m/s
Rated power wind speed	11 m/s
Rotor diameter	19.2m
Investment cost($/per)	25000 $
Operational and maintenance cost ($/KW)	30
Replacement cost($/per)	25000
Survival wind speed	52.5 m/s

Table 3. Battery specification

Rated capacity	600 Ah
Rated voltage	2 V
Minimum state of charge	35 %
Round tip efficiency	85 %
Self-discharge rate	1 %
Investment cost($/per)	150
Operational and maintenance cost ($/kWh)	20
Replacement cost($/per)	150
Maximum charge /discharge current	100 A/75 A

5.1 Ant Colony Optimization (ACO)

Ant colony optimization is a metaheuristic optimization technique inspired from biological behavior of ant, approaching shortest path for food finding, using chemical substance-pheromone laid by ant on her path. Basic Ant System was developed by Marco Dorigo (Italy) in his PhD thesis in 1992. Ant Colony Optimization (ACO) algorithm is as follows:

Step 1. Initialization - Initialize pheromone trail

The n variable values are generated randomly for m ants and a constant pheromone value τ0 is assigned to each variable for each ant

$$\begin{cases} x_1^1, x_2^1, x_3^1 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots x_n^1 \\ x_1^2, x_2^2, x_3^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots x_n^2 \\ x_1^3, x_2^3, x_3^3 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots x_n^3 \\ \vdots \\ x_1^m, x_2^m, x_3^m \dots\dots\dots\dots\dots\dots\dots\dots\dots x_n^m \end{cases} \quad (24)$$

Step 2. Solution construction - For each ant Repeat Solution construction using the pheromone trail

The index $l_i^{(k)}$ of the variable value selected by ant k for the ith variable is

$$l_i^{(k)} = \begin{cases} \arg\max\{\tau_i^{(1)}, \tau_i^{(2)}, \dots\dots\dots\dots\dots \tau_i^{(m)}\}, & if q < q0 \\ L_i^{(k)}, & \text{otherwise} \end{cases} \quad (25)$$

Where q is a uniform random value in [0 1), i=1, 2, 3….n and k =1, 2, 3….m. The parameter q0 decides the variable to be chosen from the previous iteration based on highest pheromone criteria or randomly choose the value as $L_i^{(k)}$ according to the probability distribution given by

$$P_{ij} = ([\tau_j][\rho_{ij}]) / \textstyle\sum_k [\tau_k]^\alpha [\rho_{ik}]^\beta \quad (26)$$

Step 3. Sort solution from best to worst ranking

Step 4. Update the pheromone trail

Local pheromone updating is applied on every ant solution completion according to the ant solution ranking or defined criteria for updating

$$\tau_i^{m+1} = \begin{Bmatrix} \rho^{local} . \tau_i^m if\, s_i \epsilon s_k \\ \tau_i^m \end{Bmatrix} \quad (27)$$

Where τ_i^m pheromone amount s_i and $\rho^{local}$is the local pheromone reduction rate.

The global pheromone update is applied to best so far solution after all ants have completed their tour

$$\tau_i^{e+1} = \begin{Bmatrix} \rho^{global} \tau_i^e + \Delta\tau_i^e) & if\, s_i \epsilon s_{best} \\ \rho^{gloal} \tau_i^m \end{Bmatrix} \quad (28)$$

whereρ^{global} is the global pheromone evaporation rate and $\Delta\tau_i^e$is the amount of pheromone received in iteration *e*

Step 5: Apply exploitation to best so far solution s_{best}

Step 6: Apply exploration to last ϑ worst solutions

Step 7: Update the pheromone according to step 4

Step 8: Repeat the process until the stopping criteria meat

6. Results and Discussion

Figure 6 shows the ACO convergence speed for minimization cost function and obtained minimum Per Unit Cost (PUC) is coming as 0.2025 $/kWh. Sizing value of all sources and other components corresponding to minium cost function are given in table 4. Total PV panels 2840 are connected in 110 parallel paths consisting series connected 24 panels in each path.

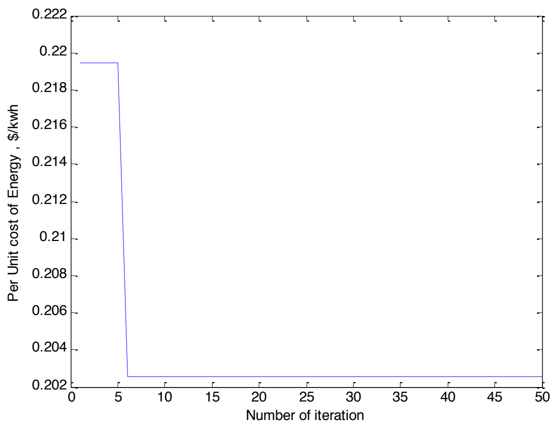

Fig. 6. Optimal Value convergence of PUCE

Table 4. Optimal results comparison

Method	Wind turbine	No of PVpanel	No of battery	Per unit cost of energy $/kWh	LPSP
Proposed ACO	10	2840	1320	0.2025	0.05
Previous	13	2250	1530	0.2080	0.05

Same way batteries are connected in 8 parallel paths. Each path consist 40 batteries in series connection. Similar type of configuration result, analyzed earlier, is also presented in table 7. The per unit cost obtained through this configuration is 0.2025 $ which is comparative better.

7. Conclusion

This paper discusses the metaheuristic ACO technique to acquire optimal sizing of wind-solar HES. Proposed ACO for HES optimization gives Rs 0.2080 for per unit cost of energy, better value as compare to earlier discussed technique. Optimal sizing measures results confirm pre-eminence of proposed ACO for considered HES.

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