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Reliability constrained optimization of SAHPS using markov based GA and PSO

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Renewable energy resources like wind, solar, biomass, tidal, hydropower and geothermal constitute a type of power generation and received much attention as alternatives for conventional power generation. Renewable Energy Resources (RER) will help to mitigate the emission of greenhouse gases. In this paper, a study on reliability constrained optimization of Small Autonomous Hybrid Power System (SAHPS) is carried out. It consists of the 10 kW wind unit, 5 kW solar unit, 5 kW pico-hydro unit and 20 kW diesel unit. Hourly speed of wind, solar radiation and water discharge and load profile is obtained using data synthesizer. The objective function with cost and the number of units and reliability constraint is formulated. Cost minimization and optimal sizing of SAHPS is performed using Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). Later markov models for the wind, solar, pico-hydro and load profile with transitions among all states are developed. Markov models are integrated with GA and PSO techniques to minimize the total cost and get the best combination of generation units. All the above analysis is carried out in the MATLAB™ software environment. Results for chronological method and markov method will be presented and analyzed.

Keywords: *Renewable Energy Resources (RER), optimization, data synthesizer and markov models*

1.0 INTRODUCTION

Renewable Energy Resources are considered as the future source of power generation, because of the cost free availability of natural resources. Normally the hybrid systems are reliable and economical. In general load demand of hilly and rural areas is low and to meet the load, wind and solar power are widely used energy resources. In conjunction with these resources, other resources like biomass, tidal, pico-hydro, geothermal, etc. can also be used to meet the fluctuations in load demand.

In general Small Autonomous Hybrid Power System (SAHPS) is incorporated to meet the low power demand. Renewable Energy Resources (RER) are used as an important source of energy in SAHPS and located in remote and hilly regions. Ajay kumar *et al.* [1] Has presented the economic analysis and a power management study of SAHPS using Biogeography based optimization and compared the results with other techniques. Tahri *et al.* [2] presented the optimizationof Wind, solar and diesel hybrid power system using HOMER™. Hong and Lian [3] presented the optimal sizing of Wind, solar and Diesel units using chronology based GA and Markov Genetic algorithm. Lund [4] presented the various types and capacities of the system with configurations that meet the desired system reliability by changing the size and type of the systems. The systems with the lowest levelized cost of energy gave the optimal choice. Suryoatmojo *et al.* [5] has presented the optimal design for a wind-PV-diesel-battery hybrid system. CO_2 emissions are considered in

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this paper and the optimization has been done based on genetic algorithm. There are so many optimization techniques to minimize the cost based on the implicit and explicit variables. Hakimi *et al.* [6] has presented the PSO technique to find the optimum number of units of stand-alone hybrid system. Manco and Testa [7] have presented the Markovian approach to model the power availability of wind turbine with transitions among all and contiguous states.

In this paper, the hybrid power system consists of 5 kW Solar, 5 kW pico-hydro, 10 kW Wind and 20 kW Diesel units. Hourly water discharge, wind speed, solar radiation and load profile is obtained using data synthesizer. Optimal sizing and cost minimization of SAHPS is performed using Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). Later markov models for the wind, solar and pico-hydro and load profile with transitions among all states are established. Markov models are integrated with GA and PSO techniques to minimize the total cost and get the best combination of generation units.

2.0 MODELS

In this paper,the optimum cost and the best combination of DG units of SAHPS is obtained using GA and PSO and integration of Markov models with GA and PSO.

The weather statistics (wind speed, solar radiation and water discharge) of the hybrid power system considered in this paper for reliability optimization is in [1, 2]. Weather statistics of SAHPS is shown in Table A1 and water availability is shown in Table A2.

2.1 Wind Power model

Wind Power equation [5] is given by

$$P_W = \begin{cases} 0, & V_W \leq V_C V_W \geq V_F \\ P_R \times \left\{ \frac{(V_W - V_C)}{(V_R - V_C)} \right\}, & V_R \leq V_W \leq V_F \\ P_R, & V_R \leq V_W \leq V_F \end{cases} \quad ....(1)$$

Where

$V_C \rightarrow$ cut-in speed (m/s)

$V_R \rightarrow$ Rated speed (m/s)

$V_F \rightarrow$ Cutout speed (m/s)

$P_R \rightarrow$ Rated wind power (kW)

and $$V_W = V_m \times \left(\frac{H_h}{H_a}\right)^z \quad ....(2)$$

$V_m \rightarrow$ Measured wind speed

$H_h \rightarrow$ Height of the hub of 10-kW WTG

$H_a \rightarrow$ Height of the anemometer

$z \rightarrow$ Friction coefficient for the ground

2.2 Solar Power Model

Solar Power output equation [2] is given by

$$P_{PV} = E \times A_S \times N_S \times \eta \quad ....(3)$$

where,

$E \rightarrow$ Mean solar irradiation (W/ m^2)

$A_S \rightarrow$ Area of single module (m^2)

$N_S \rightarrow$ Number of solar modules

$\eta \rightarrow$ Efficiency (%)

2.3 Pico-Hydro Power Model

Hydro Power output equation [1] is given by

$$P_h = \eta_h \times \rho_w \times g \times H_h \times Q_t \quad ....(4)$$

Where

$\eta_h \rightarrow$ Efficiency of pico-hydro

$\rho_w \rightarrow$ Density of water

$g \rightarrow$ Acceleration due to gravity

$H_h \rightarrow$ Effective head

$Q_t \rightarrow$ Turbine flow rate

2.4 Diesel Model

The fuel cost of the diesel generator can be modeled as a quadratic function [3] as

$$C_d^{fuel}(h) = a + b \quad P_d + c \times P_d^2, \text{(Rs./h)} \qquad ....(5)$$

Where

a (in Rupees per hour),

b (in Rs./kilowatt-hour [kWh]), and

C (Rs. /kWh) is the cost coefficients

The values of *a*, *b* and *c* for the 20 kW diesel generator used in this paper are 1.07, 0.0657, and 0.00006, respectively.

CO_2 emission can be evaluated from the heat in Eqn. (6) as follows [3]:

$$CO_2 = d + e \times P_d + f \times P_d^2 \text{ (kg/h)} \qquad ....(6)$$

The values of *d, e* and *f* for the 20 kW diesel generator used in this paper are 0.028144, 0.001728, and 0.0000017, respectively [3].

Let 't' be the index for loss of load. P_W (h), P_{pv} (h) and P_{ph} (h) are the known kilowatt generations for the wind, solar and pico-hydro models respectively. The chronological variable P_L(h) represents the known total system load at hour 'h'. Then the LOLP, fuel cost and CO_2 emission is calculated:

$$LOLP = LOLP = \frac{t}{8760};$$

Total Fuel Cost,

$$C_d^{fuel} = \sum_{h=1}^{8760} C_d^{fuel}\left(P_d(h)\right) \text{ (in Rs.)}$$

$$\text{Total } CO_2 \text{ emission} = \sum_{h=1}^{8760} CO_2\left(P_d(h)\right) \text{ (in kilograms)}$$

3.0 PROBLEM FORMULATION

The objective function formulated using the concept of chronological data including hourly load, wind speed, hourly water discharge and irradiation/temperature as follows [3]:

$$\text{Min } \{N_W \times (C_W^{unit} + C_W^{in}) + N_{pv} \times (C_{pv}^{unit}) + N_d \times (C_d^{unit} + C_d^{in} + C_d^{fuel}) + N_{ph} \times (C_{ph}^{unit})\} \qquad ....(7)$$

Subject to

$$N_W^{min} \le N_W \le N_W^{max} \qquad ....(8)$$

$$N_{pv}^{min} \le N_{pv} \le N_{pv}^{max} \qquad ....(9)$$

$$N_d^{min} \le N_d \le N_d^{max} \qquad ....(10)$$

$$N_{ph}^{min} \le N_{pv} \le N_{ph}^{max} \qquad ....(11)$$

$$LOLP \le LOLP^{max} \qquad ....(12)$$

Where

N_W, N_{pv} and N_d represent the number of Wind units, Solar units and Diesel units. C_W^{Unit}, C_{Pv}^{Unit}, C_{Ph}^{Unit} And C_D^{Unit} Denote the costs per unit (Rs./kW) for Wind, Solar and diesel units. C_W^{In} Is the installation cost (Rs./kW) for the Wind unit. C_D^{Fuel} And C_D^{In} Are the fuel and installation costs (Rs./kW) for the diesel generator.

3.1 Genetic Algorithm

Genetic algorithms are search and optimization techniques inspired by two biological principles, namely the process of natural selection and the mechanics of natural genetics. The objective function assigns search individual a corresponding number called its fitness. The chromosome's fitness is assessed and a survival of the fittest strategy is applied.

In this paper, GA is employed to solve Eqns. (7) to (12). The variables N_W, N_{pv} , N_d and N_{ph} are considered as the gene strings (binary bits)in the chromosome (control variables) while LOLP and CO_2 emission are the state variables. N_W^{max}, N_{pv}^{max}, N_d^{max} and N_{ph}^{max}correspond to the values of 31, 63, 7 and 11 respectively [3, 5] .

The fitness function is given by Eqn. (7). To deal with inequality constraints for the state variables (LOLP and CO_2 emission) in GA more efficiently, the penalty functions are employed.

A penalty term is augmented to Eqn. (7) for further genetic selection. Specifically, the penalty function is defined as follows:

$$P_f = PF^{(It/Ns)}\{LOLP - LOLP^{max}\}^2 \qquad ....(13)$$

Where, PF is called the penalty factor.

The flowcycle of GA is shown in Figure 1.

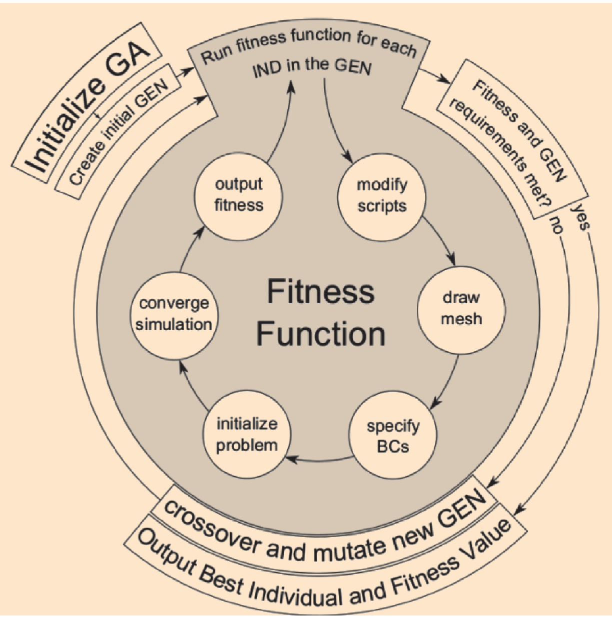

FIG. 1 FLOWCYCLE OF GENETIC ALGORITHM

Initial GA Variables

Population Size = 16

Mutation Rate = 0.15

Selection Rate = 0.5

Maximum Iterations = 100

Number of Parameters = 5

3.2 Particle Swarm Optimization

PSO is inspired by the behavior of animals like, fish schooling and bird flocking. It doesn't involve crossover and mutation operators,as in GA. The rows of the matrix are called particles (like chromosomes in GA). They contain the variable values and are not binary encoded. All the particles move around the cost with some velocity. Velocities and positions are updated based on the global and local solutions as follows [6]:

$$v^{new}_{m,n} = C \times [v^{old}_{m,n} + \Gamma_1 \times r1 \times (p^{localbest}_{m,n} - p^{old}_{m,n}) + \Gamma_2 \times r2 \times (p^{globalbest}_{m,n} - p^{old}_{m,n})] \qquad ....(14)$$

$$p^{new}_{m,n} = p^{old}_{m,n} + v^{new}_{m,n} \qquad ....(15)$$

Where

$V_{m,n}$ → Particle velocity

$P_{m,n}$ → article variables

r1, r2 → uniform random numbers

Γ_1, Γ_2 → learning factors

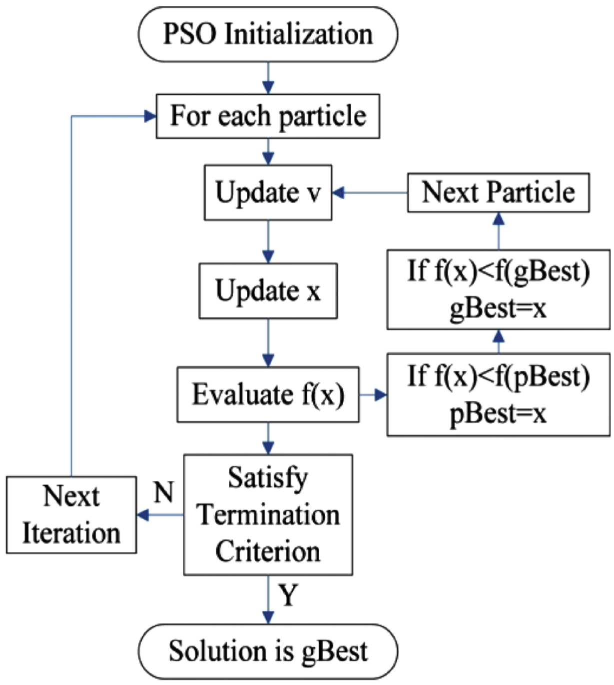

FIG. 2 FLOWCHART FOR PSO OPTIMIZATION

Figure 2 shows the flow chart for PSO algorithm. The PSO algorithm updates the velocity vector for each particle and adds that velocity to the particle positions. Velocity is influenced by both the best global solution associated with the lowest cost ever found by a particle.

Initial PSO variables:

Population Size = 10

Number of Parameters = 5

Maximum Iterations = 100

Cognitive parameter, ┌1 = 1

Social parameter, ┌2 = 4- ┌1

Constriction factor, C = 1

4.0 MARKOV MODEL

Markov model is a state variable approach [7] applied to describe the process of the system through the states.

The probability of any state is given by

$$p(.) = \frac{N(.)}{N_T} \quad ....(16)$$

Figure 3 shows the 4-state Markov model. Transition rates can be calculated as:

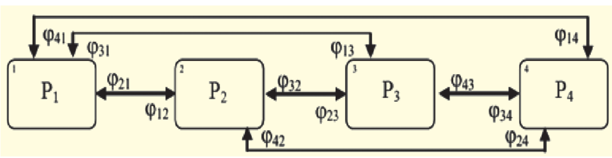

FIG. 3 FOUR STATE MARKOV MODEL

$$\varphi_{ij_{\,i\neq j}} = \frac{n_{ij}/N_T}{N_i/N_T}\cdot\frac{1}{\Delta t} = \frac{n_{ij}}{N_i} \quad ....(17)$$

$$\varphi_{ii} = 1 - \sum \varphi_{ij_{\,i\neq j}} \quad ....(18)$$

The mathematical equation of the linear system model is given by.

$$\alpha_N . \sum_{j=1, j\neq N}^{N}\{\varphi_{1j}\} = \sum_{j=1, j\neq N}^{N}\{\alpha_j . \varphi_{j1}\} \quad ....(19)$$

$$\sum_{i=1}^{N} \alpha_i = 1 \quad ....(20)$$

The probabilities of all the states are obtained by solving (N-1) equations from equation. (19) and Eqn. (20).

The frequency index of all the states is given by

$$f_i = \alpha_i . \sum_{j=1, j\neq i}^{N}\{\varphi_{ij}\},\ i = 1, 2...\ N \quad ....(21)$$

The duration index of all the states is given by:

$$d_i = 1 / [\sum_{j=1, j\neq i}^{N}\{\varphi_{ij}\}],\ i = 1, 2 \ldots N \quad ....(22)$$

Table 1, shows the power range, samples and the probability of all the states of wind, solar, pico-hydro and load models.

Reliability optimization algorithm

Step 1: Generation of Hourly Wind speed, Solar irradiation, Water availability and Load data from monthly data using Data Synthesizer software.

Step 2: Calculation of Power outputs of all renewable energy resources.

Step 3: Markov models of wind, solar, pico-hydro and load are developed which results in probability, frequency and duration of all the states.

Step 4: Computation of Loss of Load Probability (LOLP), Fuel cost and CO2 emission of Diesel generator from combined generation and load model.

Step 5: Formulation of the objective function, including costs of all DGs and number of DG units including the reliability constraint.

Step 6: Integration of Aggregate Markov model with GA and PSO techniques to find the optimum number of DG units with optimum cost.

Step 7: Comparison of the results of between Markov GA and PSO techniques

Combined Generation model is obtained from probability index, frequency index and duration of wind, solar and pico-hydro models. From the 4 state wind, 4 state solar and 4 state Pico-hydro Markov models at 64 state aggregate generation model is established.

TABLE 1			
MARKOV STATES			
DG type	**Power range (kW)**	**Samples in the class N (.)**	**Class probability p (.)**
Wind	P_{W1}=2.5	4225	0.4823
	P_{W2}=5	1977	02256
	P_{W3}=7.5	1162	0.1326
	P_{W4}=10	1396	0.1594
Solar	P_{PV1}=1.3	6317	0.7211
	P_{PV2}=2.6	1009	0.1151
	P_{PV3}=3.9	844	0.0963
	P_{PV4}=5.3	578	0.0659
Pico-Hydro	P_{h1}=1.3	4175	0.4765
	P_{h2}=2.6	3460	0.3949
	P_{h3}=3.9	961	0.1097
	P_{h4}=5.3	164	0.0187
Load	P_{L1}=5.5	1549	0.1768
	P_{L2}=11	3694	0.4217
	P_{L3}=16.5	2635	0.3008
	P_{L4}=22	882	0.1007

Table 2, shows the probability, frequency and duration of all the states of all the DG units.

TABLE 2			
SOLUTION FOR MARKOV MODELS			
State	**Probability**	**Frequency (oc/h)**	**Duration (h)**
Wind	0.4819	0.0634	7.5989
	0.2259	0.0891	2.5346
	0.1327	0.0592	2.2432
	0.1594	0.0335	4.7645
Solar	0.7221	0.0421	17.1658
	0.1153	0.0709	1.6274
	0.0965	0.0545	1.7694
	0.0661	0.0231	2.8614
Pico-Hydro	0.4766	0.0597	7.9828
	0.3950	0.0816	4.8392
	0.1097	0.0276	3.9711
	0.0187	0.0056	3.3469
Load	0.1764	0.0504	3.4966
	0.4216	0.1089	3.8721
	0.3012	0.0881	3.4176
	0.1008	0.0281	3.5854

Then the aggregate generative model is combined with 4 state load model and aggregate Markov model are generated and implemented in MATLAB™. Once the aggregate frequency and duration are known, total CO_2 emission and total fuel cost can be further evaluated.

The total fuel cost is given by

$$\text{Fuel cost} = C_d^{fuel}(P_d(c')) \times F(c') \times D(c') \times 8760 \quad ....(23)$$

5.0 RESULTS

Table 3, shows the results of markov GA and PSO techniques. Chronology based optimization techniques requires more time and complex where as Markov based techniques require less computation time. Markov based PSO method resulted in the best combination of all the DG units and optimum cost for that combination. Finally, in this paper, the integration of the Markov models with optimization techniques has achieved the optimal sizing and cost minimization in an efficient manner.

TABLE 3						
RESULTS AND COMPARISON						
	N_W	N_{PV}	N_D	N_{PH}	**LOLP**	**COST(Rs.) In lakhs**
GA	14	06	02	05	0.0643	111.62
PSO	14	05	03	04	0.0643	101.92
Markov-GA	14	02	02	04	0.0643	85.73
Markov-PSO	13	03	02	03	0.0643	83.62

6.0 CONCLUSIONS

- Generation of hourly wind speed, solar irradiation, water availability and Load data from monthly data using Data Synthesizer software.
- Calculation of power outputs of all renewable energy resources.
- Markov models of wind, solar, pico-hydro and load are developed which results in probability, frequency and duration of all the states.

- Computation of Loss of Load Probability (LOLP), Fuel cost and CO_2 emission of Diesel generator from combined generation and load model.
- Formulation of the objective function, including costs of all DGs and number of DG units including the reliability constraint.
- Integration of aggregate markov model with GA and PSO techniques to find the optimum number of DG units with optimum cost.
- Comparison of the results of between Markov GA and PSO techniques is presented.

APPENDIX

TABLE A1

WEATHER STATISTICS

Month	Solar Irradiation (kWh/m²/d)	Clearness Index (k_T)	Wind Speed (m/s)
January	2.6	0.54	3.8
February	3.4	0.55	5.0
March	5.3	0.69	5.6
April	5.8	0.58	5.9
May	6.1	0.55	6.2
June	7.4	0.64	7.2
July	7.2	0.66	5.4
August	7.1	0.70	5.6
September	6.5	0.77	6.6
October	6.0	0.88	6.2
November	4.6	0.90	4.8
December	2.1	0.44	3.3

TABLE A2

WATER AVAILABILITY

Month	Water Availability (L/s)
January	18.1
February	17.0
March	22.1
April	24.2
May	24.2
June	28.8
July	30.0
August	29.1
September	26.0
October	24.2
November	24.2
December	20.0

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