Reserve Constrained Economic Dispatch Incorporating Solar Farm using Particle Swarm Optimization

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Abstract- Static Economic Dispatch (SED) with combined Solar Thermal generation systems incorporating spinning reserve cost is presented in this paper. Particle Swarm Optimization (PSO) algorithm is used as the optimization tool here. Spinning reserve is an essential requirement in power system network to handle the situations arising during generation or transmission outages. Therefore, incorporation of spinning reserve cost and capacity can provide more realistic dispatch. B-coefficients method is used to determine the losses from the generators for solving the SED. Based on historical data, the output of solar farm is forecasted in this case. Beta distribution function which is the best suited probability density function for irradiance modeling is used to model the output of the solar farm. The uncertainty in solar energy with various seasonal effect is also discussed. Comparative analysis without and with the incorporation of solar farm is carried out. The proposed methodology is tested and validated in IEEE 30 bus test system and South Indian Utility 89 bus test system.

Keywords Solar; Economic Dispatch; Beta distribution function; PSO; Spinning reserve.

Nomenclature

$F_i(P_i)$	Sum of fuel cost of all the generators ($/hr).	$P_i^{\min}, P_i^{\max}$	Minimum and maximum generation limits
P_D	Total system demand	P_L	Power Loss of the system
a_i, b_i, c_i	Cost coefficients of ith generator	P_{SRi}	SR power of the i^{th} generator.
B_{ij}	Transmission loss coefficient	d_i, e_i	cost coefficients of the i^{th} generator.
P_{se}	Solar Power Scheduled (MW)	P_{sd}	Solar power dispatched (MW)

1. Introduction

With the rise of energy crisis and intemperate increment of power consumption, Penetration of wind and solar power generation has increased in existing power systems. The operation of large-scale wind and solar stations joined with grid has turned into the future pattern[1]. On the other hand, the erratic discontinuous and fluctuating characters of wind and solar causes difficulties in incorporating uncertainties into power system. The important issue correlated with incorporation of solar power into the ED model is the fact that the future solar irradiance, which is the power source for the Solar energy conversion systems, is an obscure at any given time[2]. Many methods like fuzzy logic, neural network and time series are used for irradiance forecasting, but the simplest method of probability distribution function is used in the ED model [3].

The fundamental goal of economic dispatch is to diminish the aggregate power generation cost while fulfilling different equality and inequality constraints. Generally in ED issues, the cost function for generating units has been approximated as a quadratic function[4]. Classical methods used for solving ED are lambda iteration method, gradient method, base point method and participation factor method. But these method failed in solving the ED problem due to the non linear quadratic cost function. Methods like Dynamic programming, simulated annealing, genetic algorithm and many other algorithms had been used to solve the conventional ED problem. Calculation complexity, excessive numerical iterations and premature convergence of these methods degrades the performance and leads to have a probability towards local optima[5]. So Particle swarm optimization a basic meta heuristic technique is used for solving ED due to its ability in delivering a quality solution in short time.

A review on ED methods from 1977 to 1988 are given in [6]. In [7] PSO based ED considering valve point effect is presented, which illustrates the effects of valve point loading of thermal generation in generation cost. In [8] multi objective combined economic emission dispatch is converted to single objective economic dispatch using penalty factor and ABC algorithm is used to solve the problem. From the recent literature available, it is observed that ED has been solved considering many constraints like valve point, Prohibited operating zones, emission and ramp rate.

Now the recent trend is to incorporate renewable energy sources with the existing grid. In [2] ED incorporating wind farm is presented where weibull distribution is used for estimating the wind power and then the optimization is solved considering two thermal plants and two wind plants. In [9] economic dispatch considering single solar and a wind farm is carried out on standard IEEE 30 bus system and SPEA algorithm is used for solving the problem. In these papers the output from the renewable energy sources is considered as an assumed value and the calculations are performed.

1.1 Proposed Work

In this paper modeling of solar farm is done by considering the beta distribution function. Historical data of the site is processed and is utilized for estimating output from the solar panels. The estimated output from solar panels is considered for the ED, exhibiting realistic parameters which gives accurate values.

The following case studies are conducted on IEEE 30 bus system[18] and South Indian Utility 89 bus test system[16] considering seasonality

- Dispatch analysis without considering Spinning Reserve
- Dispatch analysis by considering Spinning Reserve

The above said analysis are done with and without considering losses in the system. Solar farm is assumed to be operated by private sector in one case and operated by system operator in other case.

The rest of the paper is organized as follows: Section 2 describes the combined economic dispatch considering solar and thermal generating units. In Section 3 particle swarm optimization applied to ED has been discussed. In Section 4 modelling of solar farm for different seasons is discussed. Finally in section 5 the simulation results with implementation of PSO to ED problem are presented.

2. Economic Dispatch of Solar Thermal system

Economic dispatch problem cheapens the operating cost of convectional thermal generating units to meet the system demand and also satisfying generator constraints[10]. The cost curve of the thermal generators is approximated as a quadratic function in many practical cases[20]. So the objective function can be formulated as

$$F_i(P_i) = \sum_{i=1}^{n} (a_i P_i^2 + b_i P_i + c_i) \quad (1)$$

subjected to

Equality Constraints:

The Power balance equation[11] for the test system is given by

$$\sum_{i=1}^{m} P_i - P_D - P_L = 0 \quad (2)$$

Transmission losses calculated using B-coefficient method are represented by

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j \quad (3)$$

Inequality Constraints:

The generators must be operated between the defined limits

$$P_i^{\min} \le Pi \le P_i^{\max} \quad (4)$$

Spinning Reserve

The Spinning Reserve(SR) requirement for a particular load demand is represented as[17]

$$F_i(P_{SRi}) = \sum_{i=1}^{n} (d_i P_{SRi} + e_i) \quad (5)$$

So the updated objective function considering SR is given by [17]

$$\text{minimize } C_i(P_i) = F_i(P_i) + F_i(P_{SRi}) \quad (6)$$

The data related to spinning reserve is considered from [17].

2.1. Economic Dispatch incorporating Solar farm

The output power from a solar panel depends mostly on the irradiance. Along these lines, the power output for different irradiance values is to be evaluated which requires suitable functional model. The best embraced model is beta distribution function. The recorded information of solar irradiance is prepared by and after that it is used for modeling the beta distribution function. Utilizing this function the output of a solar panel is assessed and afterward the aggregate output got for the whole solar farm is computed. This power produced by the solar farm is considered as negative demand and is injected at the particular point. At that point economic dispatch is carried out utilizing this model and the outputs are analyzed. The output obtained from a solar farm is considered as negative demand and the dispatch is solved for updated demand.

The equation corresponds to new demand is given by

$$P_D^{'} = P_D - \sum_{jS=1}^{n} P_{jS} \qquad (7)$$

where $P_D^{'}$ is new power demand and $\sum_{iS=1}^{n} P_{iS}$ is the sum of solar power generators.
The cost corresponds to generated solar power[12] is given by

$$C_j(P_{jS}) = d_j(P_{jS}) \qquad (8)$$

where d_j is the direct cost of solar power of jth generator purchased from the utility

So the total cost of combined thermal + solar generation is given by

$$\text{minimize } T(P_g) = C_i(P_i) + C_j(P_{jS}) \qquad (9)$$

3. Particle Swarm Optimization for Economic Dispatch

In 1995, Kennedy and Eberhart initially presented the PSO strategy[12], propelled by social conduct of organisms, for example, fish schooling and bird flocking. PSO, as an enhancement instrument, gives a population-based search method in which organisms called particles change their positions (states) with time[13]. In a PSO framework, particles fly around in a multidimensional search space. Amid flight, every particle conforms its position as indicated by its own particular participation, and the participation of neighboring particles, making utilization of the best position experienced without anyone else and its neighbors. The swarm heading of a particle is characterized by the arrangement of particles neighboring the particle and its past experience.

For a N-dimensional problem like ED, PSO algorithm is illustrated as follows. Let *P*, *V* and *i* be the particle position, velocity and no of particles in the search space. Out of the obtained solutions of each particle the best previous solution will be saved in *Pbest*. Out of all the *Pbest* values the best solution is termed as *Gbest*. Using the current velocity and distance between *Pbest* & *Gbest* the updated velocity and position are given by following equations[14].

$$\begin{aligned} V_{ij}^{(iter+1)} &= w * V_{ij}^{(iter+1)} + c_1 * \mathrm{rand}1 * (Pbest_{ij} - P_{ij}^{iter}) \\ &+ c_2 * rand2 * (Gbest_{ij} - P_{ij}^{iter}) \end{aligned} \qquad (10)$$

$$P_{ij}^{(iter+1)} = P_{ij}^{iter} + V_{ij}^{(iter+1)} \qquad (11)$$

Suitable determination of the inertia weight gives a harmony in the middle of global and local exploration and exploitation, and results in less iterations to discover an adequately optimal solution.

The equation for setting inertia weight is given by[14]

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} * iter \qquad (12)$$

3.1 Steps for solving Economic Dispatch using PSO

1. The number of generators in the test system gives the dimension of the problem. PSO parameters considered are Population= 10, Iterations=250 Weights=[0.9, 0.4]
2. Randomly generate particles between the operating limits of the participating generators. Assume there are N units, the jth particle is represented by $P_j=[P_{j1},P_{j2},....,P_{jN}]$
3. Randomly generate particle velocities in the range $[-V_i^{\max}, V_i^{\max}], V_i^{\max} = \frac{P_{i\max} - P_{i\min}}{R}$, R- number of intervals.
4. Objective function of all the particles are solved using equation (1) and these values are considered as Pbest.
5. Identify the global best Gbest, which is among all the Pbest values.
6. calculate the new velocity of all the dimensions using equation (10).
7. Now update the position of each particle using equation (11).
8. Calculate the objective function for the updated velocity and position.
9. If the latest value obtained is better than the previous Pbest, then set Pbest to the latest. If the obtained Pbest is better than Gbest, update the Gbest by Pbest. Repeat until stopping criteria is met.
10. The particle which generates the Gbest is the optimal generation power of each unit with minimum cost.

4. Modelling of Solar farm

A stochastic model of Solar panel is developed based on Beta distribution function. Beta distribution is considered to be the most suitable model for statistical representation of the probability density function. The Solar irradiance distribution of the panel is given by[15]

$$f_b(s) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} s^{(\alpha-1)} \left(1-s\right)^{(\beta-1)} ; 0 \le s \le 1; \alpha, \beta \ge 0 \qquad (13)$$

where $\beta = (1-\mu)\left(\frac{\mu(1+\mu)}{\sigma^2} - 1\right)$, $\alpha = \frac{\mu\beta}{1-\mu}$, $f_b(s)$ is Beta distribution function, *Γ(°)* is the gamma function and *s* is the random variable of solar irradiance (kw/m^2). α and *β* are the parameters of the Beta distribution function. *μ* and *σ* are the mean and standard deviation of *s* for the corresponding time segment.

The output of a PV array is given by[15]

$$P(s) = P_o(s) * f_b(s) \tag{14}$$

The total output of the PV array corresponding to specific time segment is given by [15]

$$TP = \int_0^1 P_o(s) * f_b(s) ds \tag{15}$$

where power generation of panel at solar irradiance s is given by[15]

$$P_o(s) = N * FF * \mathrm{V}_y * I_y \tag{16}$$

where N is the total number of PV arrays.

The specifications of a 220 W PV panel are given in Table 1

Table 1: Specifications of 220W solar panel[18]

Parameter	Value
Maximum Power point Voltage, V_{MPPT}	28.36 V
Maximum Power point Current, I_{MPPT}	7.76 A
Open circuit Voltage, V_{OC}	36.96 V
Short Circuit current, I_{SC}	8.38 A
Nominal Operating Temperature, N_{OT}	43 °C
Ambient Temperature, T_A	30.76 °C
Voltage Temperature Coefficient, K_v	0.1278 V/°C
Current Temperature Coefficient, K_i	0.00545 A/°C

The solar distribution for a solar panel during 11°clock of a random day in winter is shown in Fig 1.

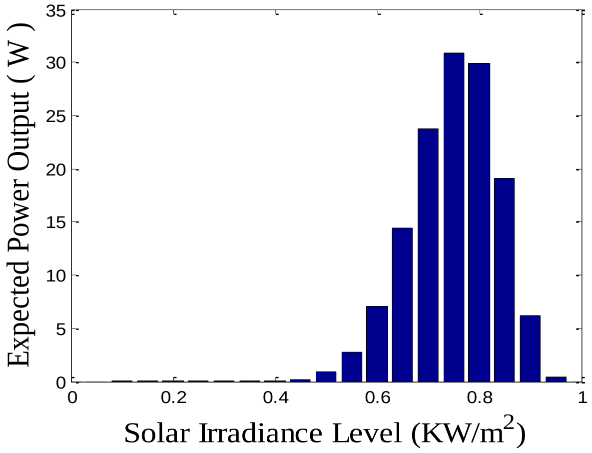

Fig. 1 Discrete Power distribution of a solar panel in winter

5. Results and Discussion

Economic dispatch problem incorporating solar farm is solved using PSO technique. Aspects like seasonality, losses and direct cost of generating solar power are included as constraints for the problem. The proposed methodology is implemented on IEEE 30 bus test system and South Indian Utility 89 bus test system.

Table. 2 Mean and Standard Deviation for various seasons

Season	Mean	Std dev
Summer	0.886	0.151
Winter	0.739	0.225

Due to noticeable seasonal changes, historical data of solar irradiance for a location named Vellore (79.15°E, 12.95°N), Tamilnadu, India is considered. It is also assumed that the climatic conditions of the test systems are similar to considered location. The mean and standard deviation obtained from the historical data[19] are given in Table 2.

5.1 Scenario 1: Solar farm run by the private sector

In this case it is assumed that solar farm is run by private sector and a fixed tariff has been set by the system operator for purchasing power from the utility. Here cases without and with spinning reserve are considered for the study. A uniform load is assumed in all the seasons for the analysis.

5.1.1 Case 1: Economic dispatch without Spinning Reserve

ED is carried out without and with considering the losses on IEEE 30 bus system. For the study solar farm with 350000 panels which gives an maximum capacity of 77 MW (350000*220W) is considered. The tariff considered for purchasing Solar power is 2$/MW.This corresponds to 25% of the overall demand. A comparison between the cases without solar and with solar in different seasons is carried out. From this analysis, the contribution of generators, fuel cost and cpu time are obtained. The results are given Tables 3 and 4. It is observed that with more penetration of solar energy significant reduction in costs are observed. The PSO method took 0.381 sec to converge for the best solution which shows its ability in solving the multi-dimensional problem.

Table 3. Simulation results of ED without considering losses

Generating Units	Without solar	Summer	Winter
P_1 (MW)	185.40	141.63	148.12
P_2 (MW)	46.87	37.50	38.91
P_3 (MW)	19.13	16.45	16.87
P_4 (MW)	10	10	10
P_5 (MW)	10	10	10
P_6 (MW)	12	12	12
P_S (MW)	0	55.81	47.48
Cost ($/hr)	767.60	699.16	708.21
Iterations	250	250	250
CPU time (sec)	0.366	0.358	0.359

Table 4. Simulation results of ED considering losses

Generating Units	Without solar	Summer	Winter
P_T(MW)	289.05	231.1	239.74
P_S (MW)	0	55.81	47.48
P_L (MW)	5.67	3.52	3.82
Cost ($/hr)	787.56	710.12	720.34
Iterations	250	250	250
CPU time (sec)	0.381	0.376	0.378

The convergence characteristics of the optimal cost solved using PSO for the case considering losses in IEEE 30 bus system are given in Fig's 2 and 3. In Fig 2 the convergence curve without solar power is shown. Here the algorithm converged in 0.381 sec. Fig 3 shows the curve with the integration of solar power at a convergence rate of 0.376 sec. This signifies that the proposed algorithm converges at a faster rate for various cases considered.

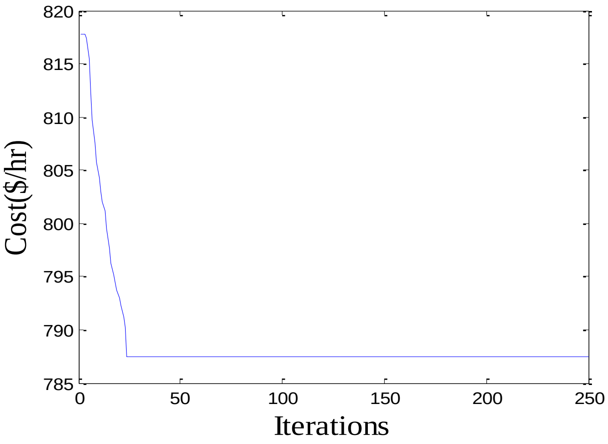

Fig 2. Convergence characteristics of PSO algorithm for solving ED problem without Solar

Table 5. ED with losses in South Indian 89 bus system

Generating Units	With out Solar (MW)	Summer (MW)	Winter (MW)
P_1	209.9631	209.7533	209.9645
P_2	209.9524	178.1274	210
P_3	38.34671	85.12217	37.28651
P_4	140.0574	207.6168	209.197
P_5	68.14655	82.41155	71.48633
P_6	101.1717	116.2393	78.46172
P_7	64.60217	59.11574	78.55032
P_8	47.45182	16.93417	31.61467
P_9	40.76732	11	17.97512
P_{10}	10.18391	10.88693	11.13507
P_{11}	10.04662	48.91798	10
P_{12}	10	10.05717	10
P_{13}	112.483	160.6434	36.89976
P_{14}	131.4764	21.9017	84.56578
P_{15}	90.70228	20	107.3136
P_{16}	122.0651	36.52658	86.68134
P_{17}	115.3469	132.2934	132.2834
P_S	0	111.62	94.96
P_L	38.4635	34.8676	34.0752
Cost ($/hr)	67675	62435.24	62765.92

Now ED is carried out by considering the losses in South Indian Utility 89 bus test system. Here a capacity of 145 MW Solar farm is considered and the output of the solar farm is calculated based on the mean and standard deviation given in Table 2. The results obtained for ED considering solar farm are furnished in Table 5. From the Table it is observed that losses decreases with the increased penetration of solar energy in the system. There is a significant reduction of cost in summer season due to high contribution of solar energy.

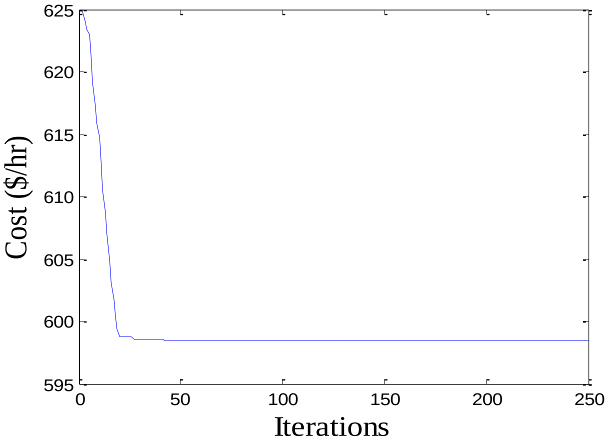

Fig 3. Convergence characteristics of PSO algorithm for solving ED problem with Solar farm

5.1.2 Case 2: Economic dispatch considering Spinning Reserve

Spinning Reserve is generally considered to improve the system reliability by satisfying the system demand in case of unforeseen emergencies. Here a SR of 10% of the total demand is considered and ED is carried out considering the losses. Initially it is assumed that there are no uncertainties in solar power. The results obtained for this case are given in Table 6. The values of spinning reserve for cases without and with solar power are presented.

Now ED is carried out by considering the uncertainty of solar farm. Due to the variable nature of solar irradiance, there is a possibility of decrease or increase in solar power than expected. If the solar power output is less than the expected value, the thermal generators must be utilized to meet the demand. Here an uncertainty of 10 percent is considered and the above case is repeated. The spinning reserve must be considered such that solar uncertainty is met in addition to the usual. The results are furnished in Table 7.

5.2. Scenario 2: Solar farm owned by the system operator

In this case the cost for generating solar power is zero as the system operator owns the farm. Losses incurred in the system are considered and the analysis is performed. ED is performed on both IEEE 30 bus system and South Indian 89 bus test system for different seasons. The results are given in Tables 8 and 9 respectively. In both the cases it is observed that losses decreases with increase in solar share. Results clearly indicate that profits can be achieved with increase in contribution of solar energy.

Table 6. ED considering spinning reserve in IEEE 30 bus system

Generating Units	Without Solar		Summer		Winter	
	Generation	SR	Generation	SR	Generation	SR
P_1 (MW)	181.35	15.6	141.44	15.6	147.99	15.6
P_2 (MW)	50.06	8	40.31	8	41.93	8
P_3 (MW)	20.1	1.5	17.35	1.5	17.82	1.5
P_4 (MW)	15.54	1	10	1	10	1
P_5 (MW)	10	1	10	1	10	1
P_6 (MW)	12	1.2	12	1.2	12	1.2
P_S (MW)	0	-	55.81	-	47.48	-
P_L (MW)	5.67	-	3.52	-	3.82	-
Cost ($/hr)	787.56	175.848	710.12	175.848	720.34	175.848
Tcost	963.4082		885.962		896.188	

Table 7. ED considering spinning reserve and Solar uncertainty

Generating Units	Without Solar		Summer		Winter	
	Generation	SR	Generation	SR	Generation	SR
P_1 (MW)	181.35	15.6	141.44	20	147.99	20
P_2 (MW)	50.06	8	40.31	8	41.93	8
P_3 (MW)	20.1	1.5	17.35	1.5	17.82	1.5
P_4 (MW)	15.54	1	10	1.60517	10	1.17927
P_5 (MW)	10	1	10	1	10	1
P_6 (MW)	12	1.2	12	1.77583	12	1.36873
P_{se} (MW)	0	-	55.81	-	47.48	-
P_{sd} (MW)	0	-	50.229	-	42.732	-
P_L (MW)	5.67	-	3.52	-	3.82	-
Cost ($/hr)	787.56	175.848	710.12	176.017	720.34	175.991
Tcost	963.4082		886.1368		896.331	

Table 8. Simulation results of ED when solar farm is owned by system operator

Generating Units	Without solar	Summer	Winter
P_T (MW)	289.05	221.20	239.74
P_S (MW)	0	55.81	47.48
P_L (MW)	5.67	3.52	3.82
Cost ($/hr)	787.56	598.50	625.38
Profit ($/hr)	-	189.06	162.18
Iterations	250	250	250
CPU time (sec)	0.381	0.376	0.378

Table 9. Simulation results of ED when solar farm is owned by system operator

Generating Units	Without solar	Summer	Winter
P_D (MW)	1484.3	1484.3	1484.3
P_T (MW)	1522.763	1519.168	1518.375
P_S (MW)	-	111.62	94.96
P_L (MW)	38.4635	34.8676	34.0752
Cost ($/hr)	67675	62435.24	62765.92
Profit ($/hr)	-	5239.76	4909.08
Iterations	250	250	250

6. Conclusion

In this paper economic dispatch problem for a system having thermal and solar generations are solved using PSO algorithm. Cases without and with Spinning reserve are discussed on IEEE 30 bus test system and South Indian 86 bus test system. It is evident that, the incorporation of spinning reserve increases the generation cost. The percentage of spinning reserve shared by the generator seems to get increased with the incorporation of solar energy. This is because of uncertainness of the output from the solar farm. The uncertainty of solar irradiance is solved using beta distribution function and seasonal effects are also included. With the incorporation of solar farm along with the thermal generators, the generation cost and transmission losses are minimised. For a constant load demand, the power generated by the thermal generators are reduced because of the solar power which leads to the reduction in emission also. It is observed that higher profits are achieved with maximum solar share in any season. Separate analysis is made when the renewable generation is owned by private sector and also by system operator. It is clear that PSO algorithm helps in achieving quick convergence in all the cases for obtaining optimal cost.

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