International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 03, March-2021

Optimal Dispatch of Power System with Integrated System Constraints

Aditya Kumar Rawat[1]
Electrical Engineering Dept.
DSMNRU
Lucknow, India

Ashutosh Kumar Singh[2]
Electrical Engineering Dept.
DSMNRU
Lucknow, India

Dinesh Kumar Nishad[3]
Electrical Engineering Dept.
DSMNRU
Lucknow, India

Ranitesh Gupta[4]
Electrical Engineering Dept.
DSMNRU
Lucknow, India

***Abstract*—This paper presents an economic load dispatch (ELD) model, incorporating wind power with thermal generator units.ELD is a fundamental issue that simulates optimal scheduling and dispatch of available generation by minimizing overall cost subjected to physical and functional constraints. Uncertain nature of wind results in the calculation of overestimation and underestimation. Forecasting of wind power is an issue in economic load dispatch, that is why, the wind turbine output prediction, is being done by scenario analysis method. In this, a mathematical model is used which quantifies the dispatch flexibility of thermal generation by integrating the renewable energy source (wind energy). To investigate system operations, one of the modern optimizations technique named as Particle Swarm Optimization (PSO) is being used. The results are demonstrated on the basis of calculation of overestimation and underestimation cost factor separately. The optimization problem is numerically solved for a scenario involving six thermal generators units and a wind farm.**

Keywords—Economic load dispatch, Scenario analysis, Wind power, Penalty cost, Reserve cost, Particle swarm optimization.

I. INTRODUCTION

In maximum cost-effective power system services, ELD plays a pivotal role. The goal is to reduce energy costs by meeting all physical constraints together with the energy source [1]. The regular increase in fuel costs, environment concerns and the depletion of fossil fuels have prompted the inclusion of current generation in the renewable energy resources. Therefore, the integrated energy planning has become a requirement of any country for sustainable energy sector development since economic load dispatch models helps to enhance the stochastic availability of wind power. As the production of fossil fuels reached its peak in 2015 [2], it is now declining because, when consumed, fossil fuels can't be extracted and it takes a long geographical time to recover, keeping in view of our future demand of electricity and to

meet them alternative of fossil fuels are mandatory as wind. Wind energy is the fast-growing renewable energy source because of its abundance in nature and maturity of its technology. The main driver of this transformation is the advent of wind as the strong price winner against fossil fuels and nuclear energy as a clean source of energy. Therefore ,wind energy impacts are generally seen as more environmentally friendly than thermal energy source impacts.

The first important issue of wind energy is that the nature of wind, which is uncertain [3]. Because, it is highly dependent on weather and geographic situations. Because of this discontinuous nature, the power generated with wind farm is uncertain and difficult to dispatch. For this reason, renewable energy source, such as wind, is overestimated and underestimated making a mathematical model, which also quantifies the direct cost, Penalty cost and Reserve cost.

As, India rank 4th in global wind power installed capacity index [4].In present scenario, our dependency is growing towards power, and India will require 3-4 times as much energy than the total energy consumed today, in order to meet the energy requirement of such a fast-growing economy renewable energy is one and only option because approximately 63% of total power is generated through fossil fuels, which pollutes the environment, but renewable energy accounts for approximately 33% of India's primary consumption[5] and as of now reducing global CO_2 emissions is one of today's major challenges [6]. However, it seems more than uncertain in many parts of the world whether the objectives of the Paris Climate Agreement (PCA) will be achieved [7].

There are many options for power generation as Solar Energy, Super capacitors, Super-conducting magnetic energy storage, Wind energy, Wind energy storage system, Hydro pump stations, Compressed air system and many more [8]. As, available technology is allowing the renewable industry to achieve important milestones. In general, the future of renewable energy, and especially wind energy, is very promising since electricity generated by wind turbines does not pollute the water we drink or the air we breathe, so wind power means less smog, less acid rain, and less emission of greenhouse gases. Because of this reason, Wind energy is truly well to fulfill the objectives of Paris Climate Agreement (PCA) and providing a motivation to move towards renewable energy sources.

"The collective cost function of conventional thermal generators, with the consideration of renewable energy source, is considered as an economic factor. To achieve this economic factor, a day-ahead scheduling of wind is performed, for 24 hours. Moreover, an economic optimization is obtained by

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 03, March-2021

newly developed algorithm named as Particle Swarm Optimization (PSO) introduced by Kennedy and Eberhart [9]." The aim of this paper is to combine wind generators with traditional thermal generators to solve the problem of economic dispatch using a mathematical model.

Here, the objective of economic load dispatch (ELD) is to minimize the operating cost of generation from integration of classic thermal generators and wind farm including the underestimation and overestimation, having certain physical constraints. The mathematical equation [10] which specifies the model considered and taken as objective function is as follows:

$$\sum_{i=1}^{M} C_i(p_i) + \sum_{i=1}^{N} C_{w,i} + \sum_{i=1}^{N} C_{p,w,i}\left(W_{i,av} - w_i\right) + \sum_{i=1}^{N} C_{r,w,i}\left(w_i - W_{i,av}\right) \quad (1)$$

II. PROPOSED MODEL

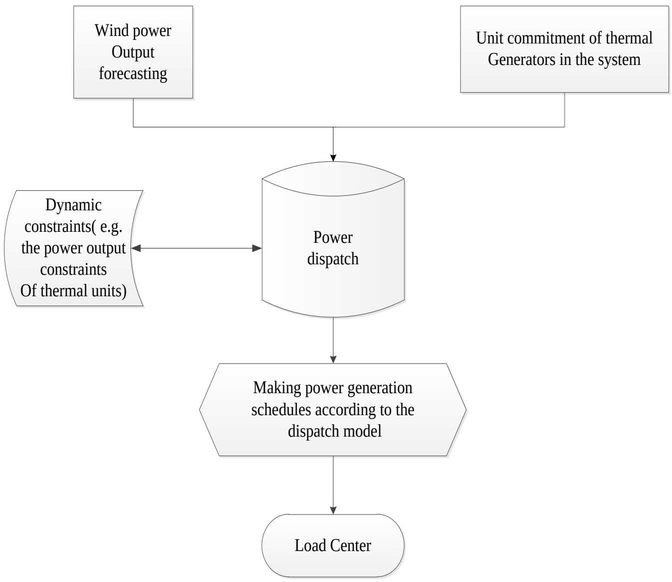

Fig.1. Proposed model

The entire model is based on the summation of generated power through conventional thermal generators and wind farm, should be equal to losses as follows:

$$\sum_{i=1}^{M} p_i + \sum_{i=1}^{N} w_i = D \quad (2)$$

And $D = P_{load} + P_{losses}$ (3)

Subjected to $p_{i,min} \leq p_i \leq p_{i,max}$ (4)

$0 \leq w_i \leq w_{r,i}$ (5)

Where,

M number of conventional thermal generators;
N number of wind generators;
p_i power form the conventional generators;
w_i scheduled wind power from wind generator;
$W_{i,av}$ available wind power from the ith wind generator;
$w_{r,i}$ rated wind power from the ith wind generator;
C_i cost function for the ith thermal generator;
$C_{w,i}$ cost function for the ith wind generator;
$C_{p,w,i}$ penalty cost function;
$C_{r,w,i}$ reserve cost function;
D total demand.

Taking a clear view of objective function which specifies each term as the 1st the term $\sum_{i=1}^{M} C_i(p_i)$ is the traditional sum of fuel costs of the thermal generator units. 2nd term $\sum_{i=1}^{N} C_{w,i}(w_i)$ is the direct cost of wind generator. The 3rd term $\sum_{i=1}^{N} C_{p,w,i}(W_{i,av} - w_i)$ accounts for penalty cost of available wind power (underestimation) and the last term $\sum_{i=1}^{N} C_{r,w,i}(w_i - W_{i,av})$ signifies reserve cost because of overestimation of available wind power.

For classic thermal generators, a quadratic function is taken into account [11] and this function is applied for most of cases and defined as:

$$C_i\,(p_i) = a_i(p_i)^2 + b_i p_i + c_i; \quad (6)$$

Where p_i is the generated (input) power from i^{th} conventional generators, and $a_i, b_i, and\, c_i$ are the operating cost coefficient of i^{th} conventional thermal units, which are obtained from input−output of generators and relies on type of fuel used as per objective function equation.

For wind generators, a linear cost function is taken into account in which the wind power generation cost $C_{w,i}\,(w_i)$ may not exist if the operator owns the wind Powered generators, because the output of the wind powered generators is restricted by an upper and lower limit, decided by the system operator based on the annexure for optimal operation of system, but it could be assumed as a payback cost or maintenance cost and defined as:

$$C_{w,i}\,(w_i) = d_i w_i \quad (7)$$

Where,

w_i scheduled wind power from the ith wind generator;
d_i direct cost coefficient for the ith wind generator.

Overestimation represents the deficit of wind power because, if a certain amount of wind power is a considered and that power is not found at the considered time, power must be purchased from an alternate source and it is defined as:

$$C_{r,w,i}\left(w_i - W_{i,av}\right) = k_{r,i}\left(w_i - W_{i,av}\right); \quad = k_{r,i} \int_0^{w_i} (w_i - w) f_w\,(w) dw\,; \quad (8)$$

Where,

$K_{r,i}$ reserve cost(overestimation)coefficient for the ith wind powered generator;
f_W(w) wind power pdf.

And underestimation represents the surplus of wind power because, if available wind power is actually more than what was considered, that power will be wasted, and it is reasonable for the system operator to pay money to the wind power producer for the waste of available wind power and it is defined as:

$$C_{p,w,i}\left(W_{i,av} - w_i\right) = k_{p,i}\left(W_{i,av} - w_i\right); \quad = k_{p,i} \int_{wi}^{wr,i} (w - w_i) f_W(w) dw; \quad (9)$$

Where,

$K_{p,i}$ penalty cost (underestimation) coefficient for the i^{th} wind generator.

International Journal of Engineering Research & Technology (IJERT)
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III. SCENARIO ANALYSIS METHOD FOR WIND FORECASTING

The generation of wind power varies from traditional thermal generation due to the stochastic nature of wind [12]. Wind power forecasting therefore plays a key role in resolving the problems of supply balancing and demand. Precise wind power projections minimize the need for additional energy balance and reserve wind power integration capability. Tools for wind power prediction allow better transmission, planning and thermal generators device involvement [13]. There are three steps in the forecasting of wind power:

I. Wind speed of a model
II. Wind power measurement
III. Prediction of outputs.

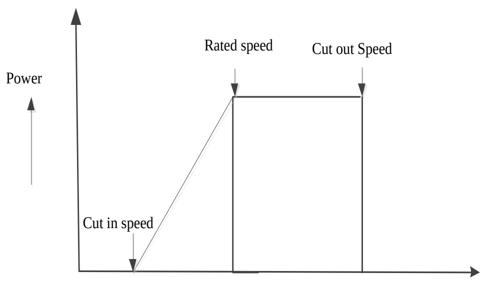

Fig.2. Variation of output wind power with wind speed

Power equation of wind turbine is described as below:

$$P_w(t) = \begin{cases} o & v(t) \leq V_{ci} ar v(t) \geq V_{co} \\ P_r \frac{v^3(t) - V_{ci}^3}{V_r^3 - V_{ci}^3}; & V_{ci} < v(t) < V_r \\ P_r & V_r < v(t) < V_{co} \end{cases}; \qquad (10)$$

Where,

v wind speed;
V_r rated wind speed;
V_{ci} cut-in wind speed;
P_r rated wind power.

Rated wind power can be defined as:

$$P_r = \frac{1}{2} C_p \, \rho_a \, n_g \, A_w V_r^3 \, ; \qquad (11)$$

Where,

P_r rated wind power;
C_p power co-efficient;
ρ_a air density;
n_g efficiency of turbine generator;
A_w area swept by turbine blade;
V_r rated speed of wind.

One of the ultimate objectives of a model of prediction of wind power is to estimate the output of the wind as early and as accurately as possible. Because overall detailed prediction of wind power reduces wind insecurity's financial and technological danger power generation.

There are various methods for forecasting the production of wind power. These approaches are categorized as centered on time scales and according to numerous methodologies available in the literature [14]. They are exactly divided in four categories:

I. Ultra-short-term forecast: Form a few minutes to 1hr ahead.
II. Short-term Forecast: From 1hr to several hrs ahead.
III. Medium term Forecast: From several hrs to 1 week ahead.
IV. Long-term Forecast: From 1 week to 1 year ahead.

In this paper wind power forecasting done by using scenario analysis method.

I. Short-term Forecast [15], which focuses on wind hourly data. So, the wind power data of one year is picked from NREL.
II. Since, nature of wind is uncertain, Due to which the curve of forecasted wind would be non-linear.

Normal Distribution

The normal distribution is an extraordinary symmetrical distribution approach used to make comparisons among different kinds of statistical decisions having bell curve [16]. This curve says that mainly results lie close to centre as we move away from centre its frequency decreases. Sometimes is also known as natural distribution.

$$px = e - x - \mu^2/2\sigma^2 \, \pi \, ; \qquad (12)$$

Where,

e exponential constant;
μ mean or location parameter;
σ standard deviation ;
σ^2 variance or scale parameter.

Bell curve relies on two parameters μ and σ which controls the x-axis and y-axis respectively. In this, the curve is completely symmetrical about μ. This expresses that μ is equal to expectation. It can also be used to determine the percentage of data present above or below of assumed data.

TABLE 1. Probability of wind power.

S. No.	Forecast error	Rate of wind power	Probability
1.	-3σ	70%	0.0063
2.	-2σ	80%	0.0607
3.	$-\sigma$	90%	0.2416
4.	0	0	0.3834
5.	$+\sigma$	110%	0.2416
6.	$+2\sigma$	120%	0.0607
7.	$+3\sigma$	130%	0.0063

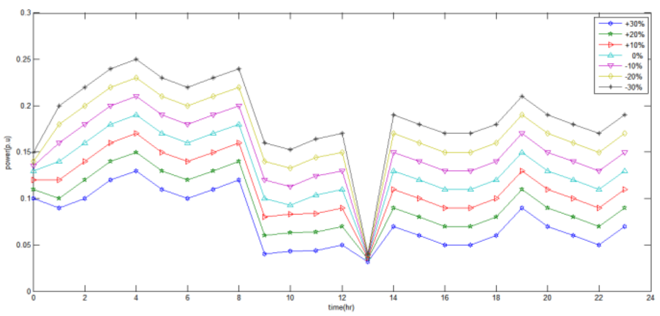

Fig.3. Wind power curves under different scenarios.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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III. METHODOLOGY

In this objective function, an optimization tool, which determines location and velocity of particles in multi-dimensional search space, and whose each particle adjust itself making best use of its own experience and that of its neighbor named as PSO, and is being used [17]. In PSO conventional terminology parameters are defined as:
Let x and v denotes particle location and velocity in multi-dimensional search space respectively. Therefore, i^{th}particle location is defined as:

$$x_i = (x_i1, x_i2, x_i3, \ldots, x_im); \quad (13)$$
$$d = 1,2,3,4, \ldots, m; \quad (14)$$

Where,

m no of units in multi- dimensional space.

Previous portion of particle is taken into account and represented as:

$$p_{besti} = (p_{besti}1, p_{besti}2, p_{besti}3, \ldots, p_{besti}m); \quad (15)$$

Here the best position of particle is taken as (p_{best}) and in particular dimension (d) the index of best particle among all the particles is denoted by (g_{bestd}), and it is also termed as global best. The velocity of i^{th} particle is denoted as:

$$v_i = (v_i1, v_i2, v_i3, \ldots, v_im); \quad (16)$$

Now, modified velocity and location of each particle can be demonstrated by using following formulas:

$$v_id^{t+1} = w * v_id^t + c1 * U1 * (p_{besti}d - x_id^t) + c2 * U2 * (g_{besti}d - x_id^t); \quad (17)$$
$$x_id^{t+1} = x_id^t + v_id^{t+1}; \quad (18)$$
$$d = 1,2,3, \ldots, m; i = 1,2,3 \ldots, n; \quad (19)$$

Where,

n population size;
m number of units;
t pointer of iterations;
w inertia weight factor;
c1, c2 acceleration constant;
U1, U2 uniform random values in the range [0, 1];
x_i^t location of particle i at iteration t;
v_i^t velocity of particle i at iteration t.

The acceleration constants $c1$ and $c2$ on basis of past experience were often set to be 2.0 which (w) denotes the weighting of the stochastic acceleration terms that pull each particle toward p_{best} and g_{best} positions.
Proper selection of inertia weight factor (w) is helpful to increase the rate of convergence of the standard PSO algorithm and suitable to find the optimal solution. As originally developed inertia weight factor(w), very often decrease from 0.9 to 0.4 linearly during a run. In general, the inertia weight (w) proposed in velocity equation is represented by following equation:

$$w = w_{max} - \frac{(w_{max} - w_{min})}{iter_{max}} * iter; \quad (20)$$

Where,

$iter_{max}$ maximum number of iterations;
iter current number of iterations.

Computational parameters used in PSO are given below –

- No. of particles = 25
- No. of iteration / $(iter_{max})$ = 1000
- Acceleration constant, c1 =2 & c2 = 2
- Weighting factor, w_{min} = 0.4 &w_{max} = 0.9
- Change in velocity for each individual,

$$Vpd^{max} = 0.5Pd^{max}; \quad (21)$$
$$\mathrm{Vpd}^{\min} = -0.5\mathrm{Pd}^{\min}; \quad (22)$$

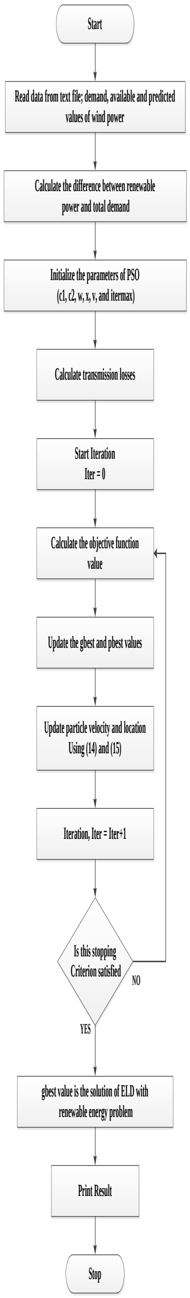

Fig.4. Flow chart of PSO

TABLE 2. Generating unit power and coefficients

$$B_{ij}=\begin{bmatrix} 0.000140 & 0.000017 & 0.000015 & 0.000019 & 0.000026 & 0.000022 \\ 0.000017 & 0.000060 & 0.000013 & 0.000016 & 0.000015 & 0.000020 \\ 0.000015 & 0.000013 & 0.000065 & 0.000017 & 0.000024 & 0.000019 \\ 0.000019 & 0.000016 & 0.000017 & 0.000071 & 0.000030 & 0.000025 \\ 0.000026 & 0.000015 & 0.000024 & 0.000030 & 0.000069 & 0.000032 \\ 0.000022 & 0.000020 & 0.000019 & 0.000025 & 0.000032 & 0.000085 \end{bmatrix}$$

Unit	P_i^{min}(MW)	P_i^{max} (MW)	a_i($/$MW^2$)	b_i($/MW)	c_i($)
1	10	125	0.15240	38.53973	756.79886
2	10	150	0.10587	46.15916	451.32513
3	35	225	0.02803	40.39655	1049.9977
4	35	210	0.03546	38.30553	1243.5311
5	130	235	0.02111	36.32782	1658.5596
6	125	315	0.01799	38.27041	1356.6592

TABLE 3: Best power output for 6- thermal generators and single integrated wind farm

Unit Output	Conventional	PSO
P1(MW)	23.90	23.84
P2(MW)	10.00	10.00
P3(MW)	95.63	95.57
P4(MW)	100.70	100.52
P5(MW)	202.82	202.78
P6(MW)	182.02	181.52
$P_{w1}(MW)$	46	45.7
Total power output(MW)	34013.07	34011.1
Total generation cost(MW)	32096.58	32094.69
Power losses(MW)	15.07	14.23

IV. RESULT

In this proposed work, an economic load dispatch model is developed with the help of integration of wind farm. To investigate system operations, one of the modern optimization technique named as Particle Swarm Optimization (PSO) has been used. The results are demonstrated on the basis of calculation of overestimation and underestimation cost factor separately. The optimization problem is numerically solved for a scenario involving six thermal generators units and wind farm.

Cost Estimation Curve

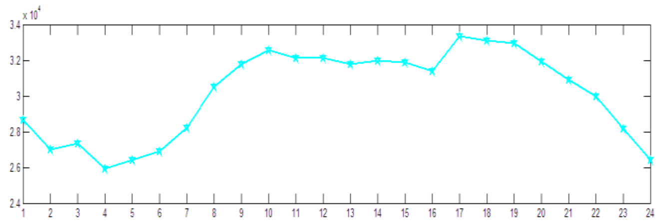

Fig.5. Curve between Cost ($) and Time (hr)

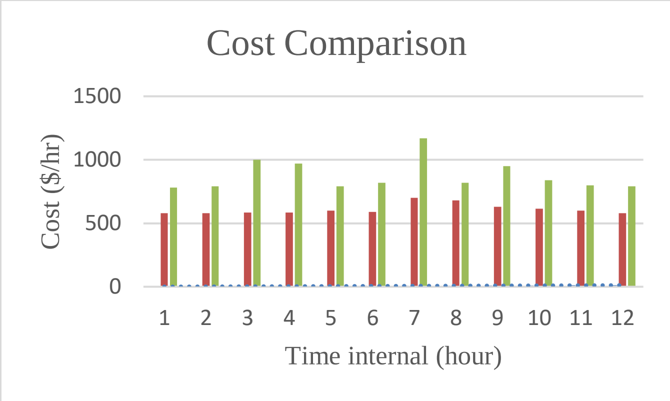

Fig.6. Cost comparison without penalty factor and with penalty factor respectively

V. CONCLUSION

In this paper, an economic load dispatch model is developed with the help of integration of wind farm. Forecasting of wind power has been done by Scenario Analysis method and uncertain nature of wind is responsible for the calculation of overestimation and underestimation factors and model results are also demonstrated on the basis of calculation of overestimation and underestimation cost factor separately. The problem is numerically solved by using one of modern optimization algorithm (PSO), for a scenario involving six thermal generators units and wind farm. The results are also found to be most reliable and environmental friendlier.

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