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Optimal generation scheduling of wind integrated power system using Bacteria Foraging Algorithm

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ABSTRACT

In order to reduce the stress on conventional energy sources and to obtain energy in an environmental friendly manner much attention is focused on Wind Energy Conversion Systems (WECS).But, wind is intermittent and unpredictable, posing serious threats to traditional generation scheduling methodologies and operation of power system. This leads to a situation where the actual power produced from WECS may differ from the scheduled power. So, there is always a risk of over production or under production of the wind power. This paper attempts at incorporation of the random nature of wind in the formulation of OPF. The analysis is performed on IEEE-30 bus system with wind farms located at different nodes. The OPF solution depicts the variation of the overall cost incurred due to conventional generators, wind farm and reserve requirement during the optimization process. Bacteria Foraging Algorithm has been used to optimize the objective.

Index Terms— Wind energy conversion system, Optimal power flow, Bacteria foraging algorithm.

I.INTRODUCTION

The global electrical energy consumption is rising and there is a steady increase in the demand of power generation. So, in addition to conventional power generation units a large number of renewable energy units have to be integrated into the power system. The most desirable renewable source would be one that is non-pollutant, available in abundance, capable of supplying substantial amount of power and can be harnessed at an acceptable cost. The most promising source satisfying these entire requirements is the wind. However, wind is intermittent and unpredictable, posing serious threats to power system security. Despite the changes in generation mix and the market operation of power systems, priority remains on maintaining system security and minimizing the operation costs. This poses a fundamental challenge to the traditional generation scheduling methodologies. So when wind energy conversion systems (WECS) are introduced in electrical power system it becomes necessary to solve the optimal power flow(OPF) problem[1] where the goal is to find the steady state operation point which minimizes the cost of meeting the load demand while finding optimal allocation of power among various generating units to serve the system load.

II. WIND ENERGY CONVERSION SYSTEMS

A WECS is a structure that transforms the kinetic energy of the incoming air stream into electrical energy. The major components of a typical wind energy conversion system include a wind turbine, generator, interconnection apparatus and control systems. The working principle of a wind turbine encompasses two conversion processes, which are carried out by its main components: the rotor that extracts kinetic energy from the wind and converts it into generator torque and the generator that converts this torque into electricity and feeds it into the grid. Modern WECS are equipped with systems implementing supervisory control and data acquisition concept. Generally, there are three low level control systems: aerodynamic power control (by pitch control), generator control (by variable-speed control) and grid interface control. The most important objectives of the WECS control :controlling the power captured from wind for speeds larger than the rated, maximizing the wind harvested power when this is below rated as long as constraints on speed and captured power is met, alleviating the variable loads in order to guarantee a certain level of resilience of the mechanical parts, meeting strict power quality standards (power factor, harmonics, flicker, *etc.*), transferring the electrical power to the grid at an imposed level, for wide range of wind velocities.

III. SCHEDULING OF WECS

As the primary problem associated with incorporation of wind power with conventional power system is the fact that the future wind speed which is the power source for WECS is intermittent and unpredictable, so steps should be taken for reliable, secure and satisfactory operation of wind power integrated system. In this point of view, decision regarding proper scheduling of generators plays a vital role so that optimum allocation of power output among the available generators can be taken while meeting the constraints. Due to the inconsistent and variable nature of wind, it can never be predicted that the scheduled power from wind turbine generator (WTG) and actual available power will be the same value. This difficulty can be analyzed under two scenarios. Those are (i) Under Estimation, (ii) Over Estimation [2].

If the available wind power at a particular time is found to be more than the predicted/scheduled wind power, then there will be a surplus amount of power which is the difference between available and scheduled value. Unless it is properly utilized, it is simply going to be wasted. In that case the system operator has to pay a cost corresponding to the surplus amount of power to the wind power producer for not using the all available power. Generally the surplus amount power is not allowed to be wasted. Two possible solutions may be adopted to prevent the wastage of power. Firstly, the surplus amount of power can be sold to adjacent utilities. Secondly, by fast redispatch and automatic gain control (AGC) the output of non wind generators can be correspondingly reduced. The excess amount of power is also termed as Expected Surplus Wind Power (ESWP) and the cost corresponding to ESWP is called Penalty Cost. In over estimation, certain amount wind power which is assumed is not available at the particular time. Then a premium has to be paid to conventional generator for regulation up as a result of production fall behind the forecast and some reserve unit has to be called .That cost of calling the reserve unit is termed as reserve cost[2]. So taking into consideration of the additional cost for managing wind power intermittency along with cost of thermal power generation an optimization model can be formulated which can be represented as : Minimize F =

$$\sum_{i}^{N_g} C_i(P_{gi}) + \sum_{j}^{N_w}[C_{wj}(P_{wj}) + C_{p,wj}(P_{wj,av} - P_{wj}) + C_{r,wj}(P_{wj} - P_{wj,av})] + Pf1 \quad (1)$$

Where

N_g number of conventional generator.

N_w number of wind-powered generators.

P_{gi} power from ith conventional generator.

P_{wj} scheduled wind power from jth wind powered generator.

$P_{wj,av}$ available wind power from jth wind powered generator. This is a random variable with a value range of $0 \leq P_{wj} \leq P_{r,j}$ and probabilities varying with the given Pdf. We considered Weibull pdf for wind variation.

C_i cost function for the ith conventional generator.

C_{wj} cost function for jth wind powered generator. This factor will typically take the form of a payment to the wind farm operator for the wind generated power actually used.

$C_{p,wj}$ penalty cost function for not using all available power from the jth wind-powered generator.

$C_{r,wj}$ required reserve cost function , relating to uncertainty of wind power. This is effectively a penalty associated with over estimation of the available wind power.

Analyzing the objective function, it can be stated that the first term represents the traditional sum of the fuel costs of the conventional generator. The second term is the operating cost for the power drawn from the wind generator. This cost depends upon the ownership of the wind farm. For example, if the wind farm is owned by the system operator itself, then this term may not exist but if it is owned by independent power producer IPP then system operator has to pay for the wind farms. The third term is the cost due under estimation of wind power. Generally it comes in the form of penalty made to the wind power producer for not using all the available wind power. The last term relates to the cost that must be paid for over-estimation of the available wind power. This cost accounts the possibility of reserve need to be drawn. For the conventional generator, a quadratic cost function will be assumed, which is practical for most of the cases, and is given by

$$C_i(P_{gi}) = a_i P_{gi}^2 + b_i P_{gi} + c_i \quad (2)$$

Where a_i, b_i, c_i are the cost co-efficient for the ith conventional generator, the quadratic function will varies depending upon different fuel used. Mathematical interpretation of the direct cost can be expressed in terms of a linear cost function for the scheduled wind power and it is given by

$$C_{wj}(P_{wj}) = d_j P_{wj} \quad (3)$$

where d_j is the direct cost coefficient for the jth wind generator. As previously discussed this cost depends upon the ownership of the wind farm.

A major barrier to the integration of the wind power into the grid is its intermittency and variability. So to account this variation two cost function has been proposed. The cost obtained from the concept of under estimation of the wind power is known as penalty cost. This function helps us to determine the excess power it might produce than that of the scheduled value.

Its mathematical formulation can be done as

$$C_{p,wj}(P_{wj,av} - P_{wj}) = K_{p,j} \int_{P_{wj}}^{P_{r,j}} (p - P_{wj}) f_w(w)\, dw \quad (4)$$

Where

$K_{p,j}$ penalty cost coefficient for the jth wind generator.

$f_w(w)$ WECS wind power pdf.

The reserve cost is similar to the penalty cost but it represents the cost due to the available wind power being less than scheduled wind power. Here the cost function helps us to determine the deficit power it might produce from the distribution function. The cost function is given by

$$C_{r,wj}(P_{wj} - P_{wj,av}) = K_{r,j} \int_0^{P_{wj}} (P_{wj} - p) f_w(w)\, dw \quad (5)$$

Where

$K_{r,j}$ reserve cost coefficient for the jth wind generator. To avoid unnecessary complexity in the model, it is assumed that the difference between the available wind power and the scheduled wind power, multiplied by the wind power output probability function is linearly related to the reserve cost.

In order to overcome the possibility of having the infeasibility solution penalty functions are incorporated. In this paper the penalty function $Pf1$ has been added to check the voltage limit violation and is expressed as

$$Pf_1 = abs[1 - sign(V_k - V_{min})] * pf + abs[1 + sign(V_k - V_{max})] * pf \quad (6)$$

In the above expression V_k is the voltage magnitude of the bus under consideration and V_{min} is the minimum value of bus voltage.

To obtain a numerical value for the reserve and penalty costs, it is necessary to find or assume the pdf for the wind power output. Although, the wind speed is an unknown at any future time; however, in order to obtain some quantitative results, some known probability function for the wind speed will be assumed. This leads to the next section.

IV.WIND SPEED CHARACTERIZATION

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The most challenging issue for the integration of the wind power into the grid is its variability. So wind power prediction plays an important part in the system integration of the large-scale wind power. Wind power production is highly dependent on the wind resources at the site. So the wind distribution depends upon the seasonal and the geographical area. Wind prediction has been investigated by many authors in variety of ways. Each predicting method based on time series, fuzzy logic, neural network, artificial intelligence etc has some unique features and certain degree of accuracy. Unfortunately, the statistical data are not stationary and there are weak variations and changes, which may lead to very inaccurate results. Physical models usually require long computational time compare to the statistical method. Recent researches have investigated the fitting of specific distribution to wind speed. Various probability distribution models were used or proposed for the statistical analysis of recorded wind speeds. Among them the most widely used probability density function (pdf) to describe the wind speed is the Weibull functions [7] because wind speed profile at a given location most closely follow a Weibull distribution over time. The pdf for Weibull distribution is given by

$$f_v(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)}(e)^{\left(-\left(\frac{v}{c}\right)^k\right)}, 0 < v < \infty \qquad (7)$$

Where

v wind speed

c scale factor at a given location (units of wind speed);

k shape factor at a given location(dimensionless).

The Weibull distribution function with a shape factor (k) of 2 is also known as the Rayleigh distribution. In [9], the advantages of the Weibull distribution are noted as (i) it provides a good fit to observed wind speed data and (ii) if the shape factor (k) and scale factor (c) parameters are known at one height, methods exist to find the corresponding parameters at another height. Normally the shape parameter varies from 1 to 3 and the scale factor range from 5 to 25 for any wind speed characteristics.

In this paper, the weibull pdf for the wind speed is assumed and then transformed to corresponding wind power distribution for use in the optimal power flow model.

Fig.1. shows the weibull pdf with shape factor 1, 2 and 3. Within each of these plots, curves of scale factor 5 , 10 , 15 and 20 are indicated. In general, every probability function is defined by two parameters namely mean and standard deviation/variance.

From the knowledge of scale and shape parameter we can easily estimate the mean and standard deviation of the distribution curve. The mean of the weibull function is given by

$$E(V) = c * \Gamma(1 + k^{-1}) = \frac{c}{k} * \Gamma\left(\frac{1}{k}\right) \qquad (8)$$

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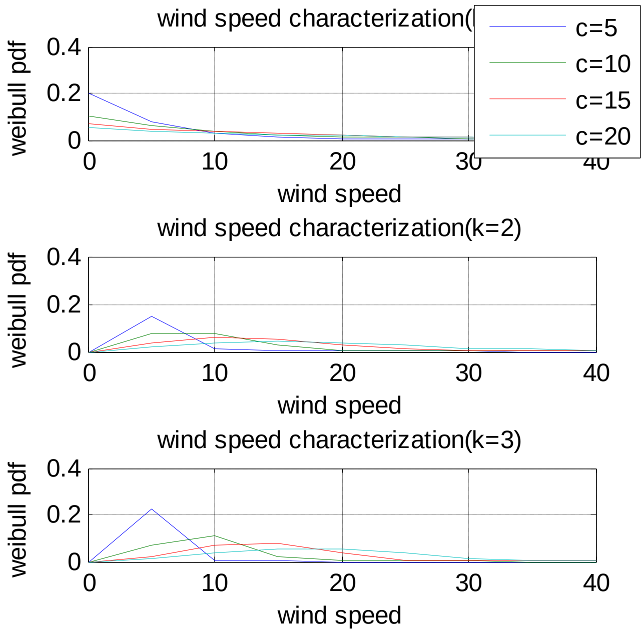

Fig.1. Weibull probability density function for wind speed.

and variance is given by

$$var(V) = E(V^2) - E^2(V)$$

$$= \frac{c^2}{k}\left[2\Gamma\left(\frac{2}{k}\right) - \frac{1}{k}\left[\Gamma\left(\frac{1}{k}\right)^2\right]\right] \qquad (9)$$

V.RANDOM VARIABLE TRANSFORMATION

Once the wind speed is characterized as a random variable, the output power of the WECS can also be characterized as a random variable through a transformation from wind speed to wind power. Generally, the power output of the wind generator will be in three ranges. Those are

Below cut in wind speed (v_i) and above cut-out wind speed (v_o). Between cut-in wind speed (v_i) and rated wind speed (v_r) and between (v_r) and (v_o). Mathematically the power output of wind energy conversion system in the above ranges can be expressed as

$$p = 0, \quad for\ v < v_i\ and\ v > v_o \qquad (10)$$

$$p = p_r * \frac{(v-v_i)}{(v_r-v_i)}, \quad for\ v_i \le v \le v_r \qquad (11)$$

$$p = p_r, \quad for\ v_r \le v \le v_o \qquad (12)$$

Where

p WECS output power (KW or MW)

p_r WECS rated power.

From the above relations it can be summarized that: - WECS has no power output for wind speed below cut in value and beyond cut out value. A linear power output relationship exists for wind speed between cut-in value and rated value. Finally a constant rated power output appears for wind speed between rated value and cut-out value.

Due to the fact that the WECS power output has a constant zero value below the cut-in wind speed and also above the cutout wind speed, and due to the fact that the power output is constant between rated wind speed and cut-out wind speed, the power output random variable will be discrete in these ranges of wind speed. The WECS power output is a mixed random variable, which is continuous between values of zero and rated power, and is discrete at values of zero and rated power output.

If it is assumed that the wind speed has a given distribution such as weibull, then it becomes necessary to convert that distribution to a wind power distribution. The linear transformation is accomplished with V as the wind speed random variables. A linear transformation of X is the quantity aV + b for some constants a and b. Then the linear transformation in general can be described as

$$P = g(V) = aV + b \qquad (13)$$

Then $f_p(p) = f_v[g^{-1}(w)]\left[\frac{dg^{-1}(w)}{dw}\right]$

$$= f_v(v)\big|_{v=\frac{p-b}{a}} * \left[\frac{dg^{-1}}{a}\right]$$

$$= f_v\left(\frac{p-b}{a}\right) * \left|\frac{1}{a}\right| \qquad (14)$$

Where
g: a transformation function
P: wind power random variable
V: wind speed random variable.

From equation (12); it shows that there is a linear increase in the wind power output in the region between the cut-in speeds to the rated-speed. Hence it is continuous distribution so random variable transformation is accomplished from the wind speed random variable to the wind power output random variable.
According to (10) and (12), there are two discrete probabilities event occurs when there is no wind power output and rated power output.
Probability of event P=0 is

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$P_r(P = 0) =$

$$P_r(V < v_i) + P_r(V \geq v_o) \qquad (15)$$

$$= F_V(v_i) + (1 - F_V(v_o))$$

$$= 1 - exp\left(-\left(\frac{v_i}{c}\right)^k\right) + exp\left(-\left(\frac{v_o}{c}\right)^k\right) \qquad (16)$$

Probability of event $P=P_r$ is

$$P_r(P = P_r) = P_r(v_r < V < v_o)$$

$$= F_V(v_o) - F_V(v_r)$$

$$= exp\left(-\left(\frac{v_r}{c}\right)^k\right) + exp\left(-\left(\frac{v_o}{c}\right)^k\right) \qquad (17)$$

From equation (15), (16) and (17) it is clearly proves that it is mixed probability function with some discrete power output and continuous power output. The sum of the probability of discrete function and continuous function is 1.

In order to know the relationship between the critical wind speed values related to WECS generator power output and the critical values (c and k) that define wind speed probability profile a plot is drawn in figure.2.

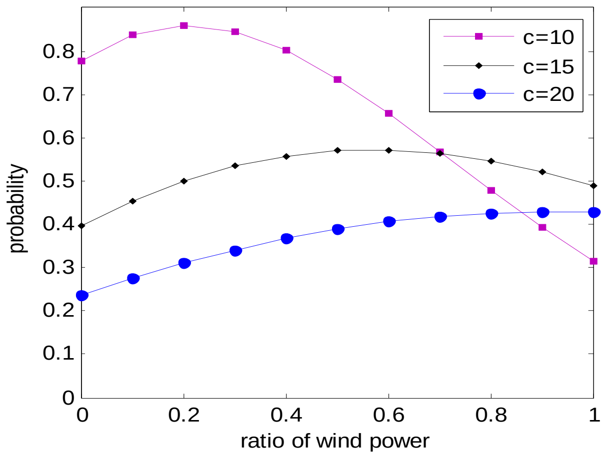

Fig. 2. wind power o/p mixed probability function for weibull distribution

Fig.2, shows the discrete and continuous portion portions of the wind power output probability function based on the Weibull wind speed pdf with k = 2 and c factors of 10 , 15 , and 20. As the c factor in the Weibull distribution function is increased, a greater proportion of the wind speed profile will be located at higher values of wind speed. This translates to a lower discrete probability of zero power, a higher discrete probability of rated power, and less power in the continuous portion of the plot. As with any other mixed discrete and continuous probability function, the sum of the discrete probabilities at zero and rated power, plus the integral from 0 to 1 of the continuous function will sum to 1.

Here certain assumption is made such as cut-in speed is 5 m/s, rated wind speed as 15 m/s and cut-out speed to be 45 m/s.

VI.OPF INCORPORATING WECS

The OPF can be considered as a constraint optimization. The objective aims at minimizing the cost associated with operation of the conventional generator, purchase of wind power from the private owner, and reduce the risk involved in the wind power uncertainty when WECS is integrated with existing power system. So the system operator (SO) ensures security of supply from a technical point of view and scheduled the wind power with certain fixed tariff paid to the wind farm owner. The OPF model is developed in the most general case, so that it is adaptable to all situations, no matter of who owns the generation facilities.

The optimal power flow dispatching with a wind generator is subjected to a variety of constrain which include equality constrain (power balance) and inequality constrain as reactive power constrain, voltage constrain, line flow constrain, etc. The equality constraints of the OPF contemplate the law of physics in the power system. The physics of the power system are enforced through the power flow equations which require that the net injection of real and reactive power at each bus sum to zero. Alternately, the sum of power generated by the conventional and wind farms is equal to the sum of the total demand in the network and losses in the system.

$$\sum_{i}^{N_g} P_{gi} + \sum_{j}^{N_w} P_{wj} = P_{loss} + P_{load} \qquad (18)$$

$$\sum_{i}^{N_g} Q_{gi} + \sum_{j}^{N_w} Q_{wj} = Q_{loss} + Q_{load} \qquad (19)$$

The inequality constraints of the OPF reflect the limits on generators in the power system as well as the limits created to ensure system security. This section will lay out all the necessary inequality constraints needed for the OPF implementation. Each generator has maximum and minimum power outputs, but in wind generators the minimum output will be zero and maximum output is equal to the rated capacity of the wind generators.

$$V_i^{min} \le V_i \le V_i^{max} \qquad i \in N_g$$

$$P_{wj} \le P_{wj}^{max}$$

$$0 \le P_{wj} \le P_{r,j} \qquad j \in N_w$$

VII.OPTIMIZATION USING BFA

BF algorithm is an efficient population based stochastic search technique recently developed by Passino[18] . BF has found an increasing interest in the recent years as an optimization technique due to its high ability to search the promising areas of the solution space. The idea of BF algorithm is based on the foraging mechanism of *E. coli* bacteria that are present in human intestines. During foraging of the real bacteria, locomotion is achieved by a set of tensile flagella. Flagella help an E.coli bacterium to tumble or swim, which are two basic operations performed by a bacterium at the time of foraging. When they rotate the flagella in the clockwise direction, each flagellum pulls on the cell. That results in the moving of flagella independently and finally the bacterium tumbles with lesser number of tumbling whereas in a harmful place it tumbles frequently to find a nutrient gradient. The various steps of this approach are (a) chemo tactics (b) Reproduction and (c) Elimination and dispersion.

VIII.SIMULATION AND RESULTS

When WECS is incorporated with conventional system the difficulty arises in that the derivatives with respect to the generator outputs for the objective cost components (4) and (5) are not easily found because the solutions to the integrals cannot be derived in the closed form. Keeping this in view the optimization problem has been solved in an OPF environment for the case of five conventional and one wind farm consisting of five wind turbine generators. The use of the Weibull probability distribution to model the wind speed has been explained in section (III) and the wind speed distribution has been transformed into wind power distribution using the linear wind power equations. A MATLAB program based on the OPF model with four conventional and five WECS generators has been developed to provide a numerical tool to investigate how variations in the wind speed profiles and variations in the different cost coefficients in the model will affect the optimum solution of the OPF problem. The power flow calculations are carried out on IEEE30- bus test system.

The system under consideration consists of six generators which includes a slack bus at node1. Node 2, 5, 8 and 11 represents four thermal generators. Node 13 represents a wind farm. In other words generator 6 (G6) represents a wind farm of 20MW installed capacity. The wind farm includes five wind generators with the same type, each of which is having a rated capacity of 4MW.

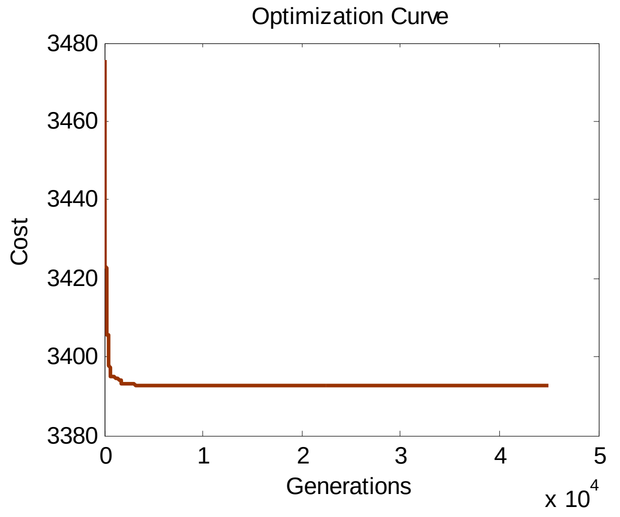

Fig.4. Variation of wind-thermal operating cost

Fig.4. shows the variation of total cost with generations. It can be seen that BFA has almost converged by end of generation. So it can be concluded that increased number of generations provides an average improvement in the total cost and solution quality is improved in terms of accuracy of optimal solution. From this it is found that minimum value of total cost is achieved and its value is 3393.6 $/h.

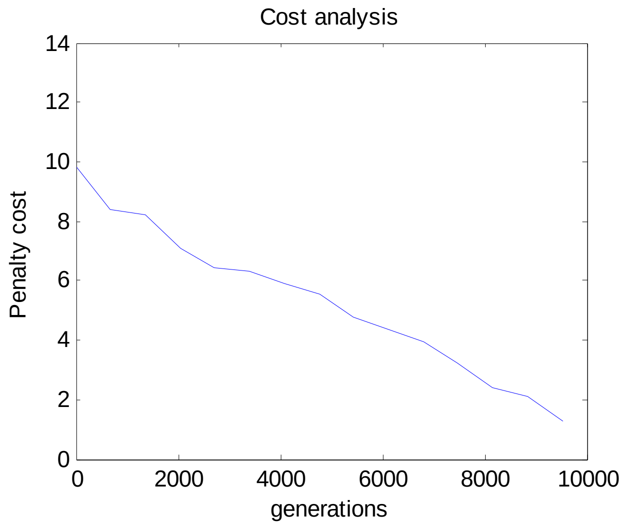

Fig.5. Variation of penalty cost

Fig.5. shows the variation of penalty cost. The value of penalty cost has been reduced from a higher value i.e. 9.7947 to 1.2747 during optimization process.

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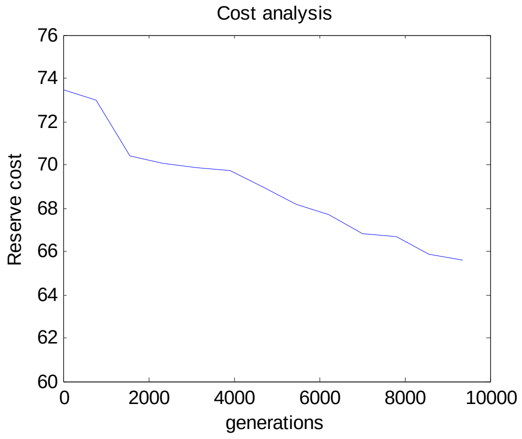

Fig.6. Variation of reserve cost

Fig.6. shows variation of system's reserve cost with number of generations. It can be concluded from the figure that at the start of optimization process the value of reserve cost was 73.4836 Rs/Mwh but with advancement of optimization it is gradually reduced and when optimal solution is reached the value of reserve cost is found as 65.6290Rs/Mwh.

Table.1. Optimized values of different cost function associated with objective function when Cpc=2.2500 and Crc=2.5000.

	Cost of thermal power	Direct cost	Penalty cost	Reserve cost	Total cost
Optimized values	3311.1	16.7594	0.00	65.6290	3393.6

Table.2. Optimized values of different cost function associated with objective function when Cpc=2.2500 and Crc=2.2500.

	Cost of thermal power	Direct cost	Penalty cost	Reserve cost	Total cost
Optimized values	3311.3	17.251	0.00	55.824	3384.4

IX.ANALYSIS

From the results it can be summarized that the optimized value of total operating cost of the wind power integrated system has been found to be 3393.6Rs/Mwh. During optimization process the penalty cost is significantly reduced and finally attains a least value which can be approximated to be zero. It suggests that optimized solution represents an over estimation scenario. Analyzing the over estimation case it can be found that although the reserve cost is reduced during optimization process from73.4836, it finally becomes 65.6290. So it can be interpreted that over estimation may be better for the analysis of OPF problem and the system performance. Also it is observed that a minor variation in the reserve cost coefficient can bring appreciable improvement in the minimization of total cost and the reserve cost can also be considerably reduced.

X.CONCLUSION

This work develops a model to include WECS in the optimal power flow problem along with thermal systems. The stochastic nature of the wind speed and wind power is represented by weibull probability distribution function. In addition to the classical economic dispatch formulation, factors to account for both overestimation and underestimation of available wind power have been included apart from the direct cost of wind energy. Further the optimal power flow problem is then numerically solved for IEEE-30 bus test system where in the bus no 13 the conventional system is replaced with a wind farm. The OPF problem has been solved and for the optimization work BFA is applied. The solution of the OPF problem presented is dependent on the various factor involved, such as weibull scale factor, reserve cost for overestimating the wind power, and the penalty cost for under estimation of the wind energy.From the optimized solution of the problem following few points are observed from which few inferences can be derived

- The penalty cost has been found to be zero in the solution where as the reserve cost remains at some non zero value, which means that an over estimation of wind power may be beneficial compared to under estimation as this encourages the wind energy to be utilized to its maximum level.
- The penalty/reserve cost coefficients play an important role in the overall optimized results.

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