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A Multi-Objective Economic Load Dispatch Considering Accessibility of Wind Power with Here-And-Now Approach

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ABSTRACT

The major problem of wind turbines is the great variability of wind power production. The dynamic change of the wind speed returns the quantity of the power injected to networks. Therefore, wind–thermal generation scheduling problem plays a key role to implement clean power producers in a competitive environment. In deregulated power systems, the scheduling problem has various objectives than in a traditional system which should be considered in economic scheduling. In this paper, a Multi-Objective Economic Load Dispatch (MOELD) model is developed for the system consisting of both thermal generators and wind turbines. Using two optimization methods, Sequential Quadratic Programming (SQP) and Particle Swarm Optimization (PSO), the system is optimally scheduled. The objective functions are total emission and total profit of units. The probability of stochastic wind power is included in the model as a constraint. This strategy, referred to as the Here-and-Now (HN) approach, avoids the probabilistic infeasibility appearing in conventional models. Based on the utilized model, the effect of stochastic wind speed on the objective functions can be readily assessed. Also a Total Index (TI) is presented to evaluate the simulation results. Also, the results show preference of PSO method to combine with HN approach.

KEYWORDS: Economics load dispatch, PSO and SQP algorithm, Wind turbine.

1. INTRODUCTION

In recent years, a growing interest in renewable energy resources has been observed. In particular, wind and solar energy are non-depletable, site-dependent, non-polluting, and constitute potential sources of alternative energy options. Due to the impeding demand of mitigating the greenhouse effect, the share of Wind Power Generation (WPG) in the total utility is daily on the increase [1]. Some European countries like Denmark and Germany are making very ambitious plans to increase the share of WPG up to 50% of the national electricity demand in the near future [2]. Electric power, generated by wind turbines, is highly erratic; therefore, the wind energy penetration in electrical power systems can lead to problems related to system operation and the planning of electrical power systems. Wind power intermittency, load mismatch, and negative impacts on grid voltage stability are some key problems which should be solved [3]. One of the major challenges associated with the generation scheduling is the way that it accommodates large amount of wind power generation. Hence, the Wind–Thermal Generation Scheduling (WTGS) problem plays an essential role to implement clean power producers in such competitive environment [4, 5]. In the literature, various approaches have been proposed to describe the impact of random parameters on electrical power systems. Numerous solutions have been proposed to solve the optimal programming problems [6,7], such as Priority List (PL), Dynamic Programming (DP), Lagrangian Relaxation (LR), Genetic Algorithm (GA), Mixed Integer Programming (MIP), Evolutionary Programming (EP), Immune Algorithm (IA), Artificial Immune System (AIS) and Particle Swarm Optimization

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(PSO). In [8], Muller method was introduced to solve Economic load Dispatch (ELD) problem and Information Pre-Prepared Power Demand (IPPD) table was introduced to solve combinatorial sub problem for deregulated environment. In nodal ant colony optimization [9], to maintain the good exploitation and exploration search capabilities, the movements of the ants are represented with a search space consisting of optimal combination of binary nodes for unit on/off status. In [10], Delarue achieved the difference between the obtained profits when using perfect price forecast and without using perfect price forecast. From the literature survey, it is observed that most of the existing algorithms have some limitations to provide the qualitative solution. The first work in the minimization of emission dispatch has been done by Gent and Lamont [11]. Also, ref. [12] presented a PBUC formulation using GA which considers the softer demand constraints and allocates fixed and transitional costs to the scheduled hours. A new formulation to the Unit Commitment (UC) problems suitable for an electric power producer in deregulated markets was proposed in [13]. In addition, a hybrid LR-EP method was explored in [14] that helps Generation Companies (GENCOs) to make a decision on how much power and reserve should be sold in markets, and how to schedule generators in order to receive maximum profit by incorporating both power and reserve generation at the same time. The same problem is presented in [15] in addition to the line flow constraints to minimize the emission. Reference [16] employed an auxiliary hybrid model to solve the PBUC problem with evolutionary programming used to update the Lagrangian multiplier. The application of PSO technique to maximize the GENCOs profit is illustrated in [17]. The common ELD problem can be also presented by SQP technique by assigning weighting factors for generation and emission cost functions; the above method was proposed by [18]. Conventional ELD models need to be enhanced to characterize the stochastic behavior of wind power. In this paper, MOELD model that takes the Probability Density Function (PDF) of wind as one of the constraints is presented. One of the basic approaches to estimate the PDF has been based on Monte Carlo simulation. The convolution method was another common approach to estimate the PDF of solutions [19]. All of these approaches tried to find probabilistic characteristics of solutions of the problem under investigation. This kind of approach is called the Wait-and-See (WS) strategy in the context of Stochastic Programming (SP) [20]. In contrast, the Here-and-Now (HN) strategy introduces the probabilistic characteristics to the problem model itself, which introduces the CDF of parameters to constraints. Both WS and HN strategies are representative approaches in the discipline of SP. This paper is in line with HN approach. In the context of optimal power flow with wind power generation, there are also several representative works. The model presented in [21] is an ELD model with the objective function of the total generation cost of traditional units. The planning horizon of simulations was divided into five stages, and each stage was 30 minutes. Later this model and power flow analysis were extended in [22], where the costs of expected surplus WP and expected deficit WP were added to the objective function. A recent comprehensive review can be found in [23], where the authors described the representative models of ELD with WPG and also discussed risk management strategies in the power market. For the convenience of presentation, throughout this paper, WP means the real electric power generated by WPG units rather than the input wind power. The rest of this paper is organized as follows. In Sec. 2, an ELD model with WP is introduced. In sec. 3, we use the probability distribution of WP to the constraint. Then, Sec. 4 describes the two models of HN approach. Simulation results for a ten-generator system are reported in Sec. 5. Finally, remarks and conclusions are included in Sec. 6.

2. ELD MODEL WITH WP

In electrical power systems, the generic ELD problem takes the following form [2]:

$$Y = \sum_{i=1}^{n} (a_i + b_i p_i + c_i p_i^2) \tag{1}$$

$$P_{min,i} \le P_i \le P_{min,i} \qquad (i = 1,2,3,\ldots,n) \tag{2}$$

$$\sum_{i=1}^{n} P_i = P_d + P_s \tag{3}$$

The unit of P_i is megawatts (MW), then the units of a, b, and c are, respectively, \$/h, \$/MWh, and \$/MW2h. Consequently, the unit of Y is \$/h. In numerical analysis, usually per unit (P.U.) system is employed, in which the base is 100 MVA. In the present work, we introduce a new MOELD model to minimize the fuel cost and emission and maximize profit, taking the stochastic WP as a constraint. The proposed model will add a set of constraints:

$$0 \le W_j \le w_{jr} \qquad (j = 1,2,3,\dots,m) \tag{4}$$

where, Wj and wjr are the real power and rated power generated by WPG unit jth, respectively.
Also, equation (3) can be replaced with (5).

$$\sum_{i=1}^{n} P_i + \Psi(W) = P_d + P_s \tag{5}$$

where, $\Psi(W)$ is a function of random variable (RV) W.

3. PROBABILITY OF WIND POWER

The wind speed V (m/s) is an RV. A comprehensive review for probability distributions of wind speed can be found in [24], where the authors cited more than two hundred publications and described more than ten well-known distributions. They indicated that the two-parameter Weibull distribution had become the most widely accepted model and had been included in regulatory works as well as several popular computer modeling packages. The CDF of Weibull distribution is:

$$F_V(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^c\right] \qquad (v \ge 0) \tag{6}$$

where, $c > 0$ and $k > 0$ are referred to as the scale factor and shape factor, respectively. Note that there are two special cases. The cases of $k = 1$ and $k = 2$ lead to the exponential distribution and the Rayleigh distribution, respectively. In the literature, most studies adopted $k = 2$. Corresponding to its CDF, the PDF of V is:

$$f_V(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{7}$$

$$W = \begin{cases} 0 & (V < v_{in} \text{ or } V \ge v_{out}) \\ w_r & (v_r \le V < v_{out}) \\ \frac{(V - v_{in})}{v_r - v_{in}} w_r & (v_{in} \le V < v_r) \end{cases} \tag{8}$$

The relation between the input wind power and the output electric power system relies on several factors, such as the efficiencies of generator, wind rotor, gearbox, and inverter, depending on what type of power generation unit is investigated. For a generic WPG unit, some researchers [25] used a simplified model to characterize the relation between the WP and wind speed (8). We will adopt the above model in our ELD model. According to the probability theory for function of RVs [26], in the interval $v_{in} < V < v_r$, the PDF of W is:

$$f_W(w) = \frac{khv_{in}}{w_r c}\left[\frac{\left(1 + \frac{hw}{w_r}\right)v_{in}}{c}\right]^{k-1} \times exp\left\{-\left[\frac{\left(1 + \frac{hw}{w_r}\right)v_{in}}{c}\right]^k\right\} \tag{9}$$

Where, $h = (v_r/v_{in}) - 1$. The CDF of W, however, must take into account the piecewise linear properties shown in (8). The probability of event W =0 and $W = w_r$ are:

$$Pr(W = 0) = Pr(V < v_{in}) + Pr(V \ge v_{out}) = 1 - exp\left[-\left(\frac{v_{in}}{c}\right)^k\right] + exp\left[-\left(\frac{v_{out}}{c}\right)^k\right] \tag{10}$$

$$Pr(W = w_r) = Pr(v_r \le V < v_{out}) = exp\left[-\left(\frac{v_r}{c}\right)^k\right] - exp\left[-\left(\frac{v_{out}}{c}\right)^k\right] \tag{11}$$

For the continuous part, the integration of (9) is:

$$\varphi_W(w) = 1 - exp\left\{-\left[\frac{\left(1 + \frac{hw}{w_r}\right)v_{in}}{c}\right]^k\right\} \tag{12}$$

Furthermore:

$$Pr(W > w_r) = 0 \tag{13}$$

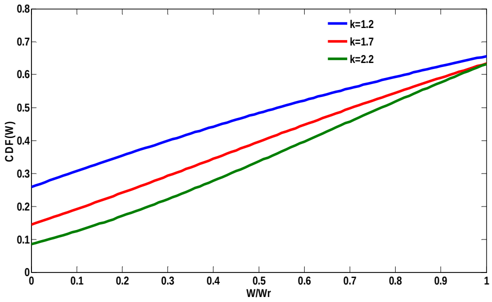

Fig. 1. Examples of cdf of WP.

According to (10-13), the CDF of W is shown in (14.1-14.3). The reader is reminded that the derivation of (14.1-14.3) has followed several axioms in the probability theory [26], including the continuity from the right. Three examples of the CDF of W are illustrated in Fig. 1, where the values of factor k are specified. Since the CDF notion includes both continuous and discrete probabilities, the overall height of CDF is affected by the probability of (14.1-14.3):

$$F_W(w) = Pr(W \le w) = 0 \qquad (w < 0) \tag{14.1}$$

$$F_W(w) = Pr(W \le w) = 1 - exp\left\{-\left[\frac{\left(1+\frac{hw}{w_r}\right)}{c}v_{in}\right]^k\right\} + exp\left[-\left(\frac{v_{out}}{c}\right)^k\right] \qquad (0 \le w < w_r) \tag{14.2}$$

$$F_W(w) = Pr(W \le w) = 1 \qquad (w \ge w_r) \tag{14.3}$$

4. TWO MODELS OF HN APPROACH

In this section, we describe and solve two ELD models constrained by the probabilistic metric. The first model, ELD-EQ, has a closed-form solution, which is helpful to gain some fundamental insights. The second model, ELD-INEQ, includes more constraints and has no closed-form solution [2].

4.1. ELD model with equality constraints

In this subsection, we consider the model, referred to as ELD-EQ, which consists of (1) and the following constraint:

$$Pr\left(W + \sum_{i=1}^{n} P_i \le P_d + P_s\right) = Pa \tag{15}$$

where, W represents all WP to be dispatched, and P_a is a specified threshold representing the tolerance that the total demand P_d plus power losses cannot be satisfied. For example, if P_a=0.15, then up to 15% of the chance of insufficient supply could be tolerated. Therefore, a larger P_a implies more tolerance toward insufficient supply, and vice versa. To avoid degenerated results, Pa is chosen such that $\Pr(W=0) \le P_a < 1$. Since the total WP is characterized by a single RV here, it implies that all wind turbines are located in a coherent geographic area, represented by a small wind farm or a cluster of turbines in a large wind farm. Accordingly, constraint (15) can be rewritten as follows.

$$F_W\left(P_d + P_S - \sum_{i=1}^{n} P_i\right) = = Pr\left(W \le P_d + P_S - \sum_{i=1}^{n} P_i\right) = P_a \tag{16}$$

Substituting (14) into (16), for $0 \le w < w_r$ equations 17 and 18 are obtained. The above inequality can be easily converted into expression (18), where h_p, is the penetration factor of WP and defined by (19).

$$Pr\left(W \le P_d + P_S - \sum_{i=1}^{n} P_i\right) = 1 + exp\left[-\left(\frac{v_{out}}{c}\right)^k\right] - exp\left\{-\frac{1}{w_r^k c^k}\left[v_{in}w_r + (v_r - v_{in})\left(P_d + p_S - \sum_{i=1}^{n} P_i\right)\right]^k\right\} = p_a \tag{17}$$

$$\sum_{i=1}^{n} P_i = P_d + P_s + \frac{v_{in}w_r}{v_r - v_{in}} - \frac{w_r c}{v_r - v_{in}}\left\{-ln\left[1 + exp\left(-\frac{v_{out}^k}{c^k}\right) - p_a\right]\right\}^{1/k} = P_d + P_s + \frac{v_{in}w_r}{v_r - v_{in}} - \frac{w_r c}{v_r - v_{in}}\left|ln\left[1 + exp\left(-\frac{v_{out}^k}{c^k}\right) - p_a\right]\right|^{1/k} = P_d + P_s - w_r h_p \tag{18}$$

$$h_P = \frac{c}{v_r - v_{in}}\left|ln\left[1 + exp\left(-\frac{v_{out}^k}{c^k}\right) - p_a\right]\right|^{1/k} - \frac{v_{in}}{v_r - v_{in}} \tag{19}$$

In (19), note that

$$1+exp\left(-\frac{v_{out}^{k}}{c^{k}}\right)-p_{a}<1 \qquad (20)$$

$$p_{a}\geq Pr\left(W=0\right)=1-exp\left(-\frac{v_{in}^{k}}{c^{k}}\right)+exp\left(-\frac{v_{out}^{k}}{c^{k}}\right) \qquad (21)$$

As a result, constraint (15) in model ELD-EQ becomes:

$$\sum_{i=1}^{n}P_{i}=P_{d}+P_{s}-w_{r}h_{P} \qquad (22)$$

Finally, the solution of ELD_EQ is as follows [2]:

$$P_{optm,\,j}=\frac{2\left(P_{d}+P_{s}-w_{r}h_{P}\right)+\sum_{i=1}^{n}\left(\frac{b_{i}}{c_{i}}\right)}{2c_{j}\sum_{i=1}^{n}\left(\frac{1}{c_{i}}\right)}-\frac{b_{j}}{2c_{j}},\qquad \left(j=1,2,3,\ldots,n\right) \qquad (23)$$

For a system consisting of ten thermal generators and one wind farm, C=15, V_{in} =5, V_{out} =45, V_r=15, w_r = 1(p.u), P_s = 0.5 (P.u) are chosen.

4.2. ELD model with inequality constrains

In this subsection, we consider the model, referred to as ELD_INEQ, which consists of (1), (2), and the following constraints [2]:

$$Pr\left(W+\sum_{i=1}^{n}P_{i}\leq P_{d}+P_{s}\right)\leq p_{a} \qquad (24)$$

Similar to Model ELD_EQ, constraint (24) can be converted into the following expression:

$$\sum_{i=1}^{n}P_{i}\geq P_{d}+P_{s}-w_{r}h_{P} \qquad (25)$$

Where h_P was defined in (19). Note that model ELD_INEQ involves two sets of inequality constraints. Therefore, the classic lagrange multiplier method cannot be directly applied [2]. Therefore, a numerical optimization procedure is needed. Thus, we have developed a computer program to solve Model ELD_INEQ and implemented it in MATLAB. The minimum and maximum value of produced active power for units are 0.03 p.u. and 1.5 p.u., respectively.

4.2.1. Minimization of total emission (stage 1)

Minimization of emission is one important issue with regard to economic and optimal operation of electrical power system. Consequently, using the probability of wind turbine output, the cost function of stage 1 is considered as minimization of emission. It is expressed in the following formula.

$$Min\ EC_{i}=\alpha_{i}+\beta_{i}(P_{it})+\gamma_{i}(P_{it})^{2} \qquad (26)$$

Where α_i , β_i and γ_i are the emission co-efficient of ith unit. The objective function is subjected to the following constraints. Where P_{it} is the output power of i^{th} unit at hour *t*.

4.2.2. Maximization of total profit (stage 2)

Maximization of profit is very important issue with regard to ELD and optimal operation of electrical power systems. As ELD model plays key role in electrical power systems in terms of cost and revenue, its effects should be considered in many electrical power system scheduling. Therefore, the cost function of stage 2 is considered as the maximization of total profit. It is expressed in the following formula with equations (27) to (30) [3].

$$Max\ PF=(RV-TC) \qquad (27)$$

$$RV=\sum_{i=1}^{T}\sum_{i=1}^{N}P_{it}.SP_{i} \qquad (28)$$

$$TC=\sum_{i=1}^{T}\sum_{i=1}^{N}FC_{i}(P_{it}) \qquad (29)$$

$$FC_{i}(P_{it})=a_{i}+b_{i}(P_{it})+c_{i}(P_{it})^{2} \qquad (30)$$

4.2.3.Multi-objective optimization problem (stage 3)

In the third stage, the optimization algorithm minimizes multi-objective cost function (MCF) using the results of two previous stages. In [27, 28] presented a multi-objective mathematical programming to find the best reactive power control strategy in a microgrid with uncertainty of wind farms. Based on the concept of this algorithm, in this paper an MCF is proposed to minimize total emission and maximize the total profit, which can be written by (31).

$$Min.MCF=\sqrt{\alpha\left(\frac{\text{Emission}}{\text{Emission}^{*}}\right)^{2}+\beta\left(\frac{Pr\text{ofit}^{*}}{Pr\text{ofit}}\right)^{2}} \qquad (31)$$

In stage 1, the total emission is minimized with setting $\alpha=1,\beta=0$; and in the stage 2, the total profit is maximized when $\alpha = 0, \beta = 1$; Then, a compromise programming is employed in the third stage with $\alpha = 1, \beta = 1$; which is designed to minimize emission and maximize profit. Emission* and profit* are the minimum and maximum amount of emission and profit respectively. Fig. 2 shows the flowchart of SQP based optimization algorithm.

PSO is an evolutionary computational algorithm derived from a natural system. On a given iteration, a set of particles or solutions move around the search space in consecutive iterations. The movement rules of particles are expressed in [29]. Because of abilities of PSO algorithm, in this method, the three stages are combined and solved simultaneously which may result in a better global optimum.

To apply the PSO algorithm in ELD, the following steps should be taken:

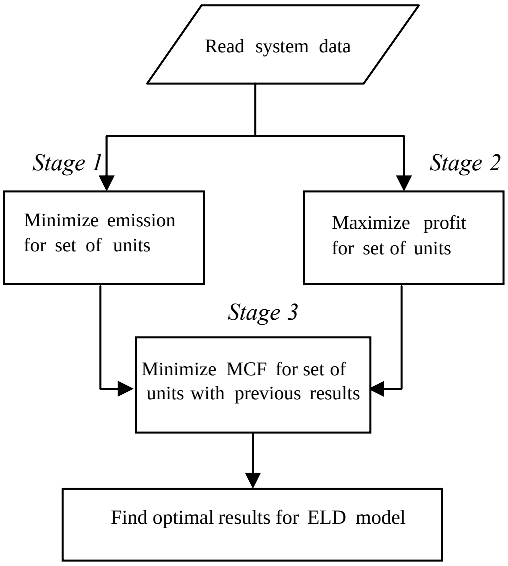

Fig. 2. The flowchart of the proposed SQP based optimization algorithm.

Step 1: The input data should be specified.

Step 2: The initial population and initial velocity for each particle should randomly be produced.

Step 3: The objective functions should be calculated for each individual.

Step 4: The value of objective functions should be normalized in accordance with related fuzzy membership function.

Step 5: The Minimum value of normalized Objective Functions (MOF) should be chosen for each individual as ith row of MOF matrix.

Step 6: The individual that has the maximum value of MOF should be selected as global position (Gbest).

Step 7: The ith individual is selected.

Step 8: The best local position (Pbest) for the ith individual is the individual with the minimum value for the ith row of MOF matrix.

Step 9: The modified velocity and position for each individual should be calculated based on expressed movement rules in [29].

Step 10: If all individuals are chosen, go to next step, otherwise i =i+1 and go to the ***Step 7***.

Step 11: If the current iteration is the maximum iteration number, PSO is stopped, otherwise go to ***Step 3***.

The last Gbest is selected as optimal solution. The proposed PSO algorithm optimizes the generated active power of units. Finally, a Total Index (TI) is computed in accordance with (32) to find the better solution. This index is defined to distinguish between two methods of ELD. As there should be low emission and high profit (low cost) in a power system, the smallest value for TI expresses that optimal situation is dominated in the grid.

$$TI = \sqrt{\left(\frac{\text{Emission}}{\text{Emission}_{\min}}\right)^2 + \left(\frac{\text{Cost}}{\text{Cost}_{\min}}\right)^2} \tag{32}$$

5. SIMULATION RESULTS

In order to demonstrate the accuracy and effectiveness of the used algorithm, it is applied to IEEE 39-bus test system [3].

The PSO and SQP formulation and solution methodology has been implemented using MATLAB 7.10 and executed on a corei5 (2.53 GHz) personal computer with 4 GB RAM, and average computing time is around 4 minutes. The control parameters of PSO algorithm are simply adjusted as following:

$c_1=c_2=2,\ w=0.9-((0.5)/iter_{max})*iter$

This work analyzed the impact of wind power on generation scheduling problem with the test system consists of ten thermal units and one wind farm to solve a multi objective problem. If there is *N* number of units in the system, some of them have high fuel cost and other generating units have low fuel cost. Therefore, the GENCOs decide to save production cost by starting up the units with low fuel cost over a period of scheduling.

Before economic load dispatch, the GENCOs want to get an accurate hourly demand and price forecast for the period of scheduling horizon.

Developing the forecasted data is an important matter, but it is beyond the scope of this paper. For the results existing in this section, the forecasted load and price are taken as shown in Figs. 3 and 4, respectively. The amount of base load and peak load of the system is 700MW at 01:00 am and 1300MW at 11:00 am, respectively. In addition to the forecasted hourly price and demand, which are shown in table 1 and the generator parameters listed in table 2, ELD program needs the parameters of each generating unit.

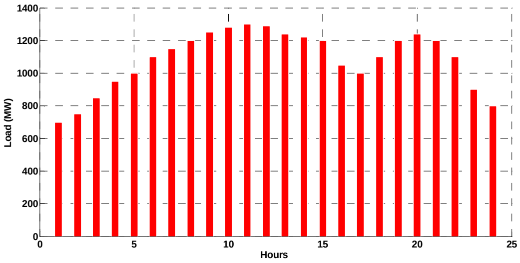

Fig. 3. Base load and peak load unit operating cycles [3].

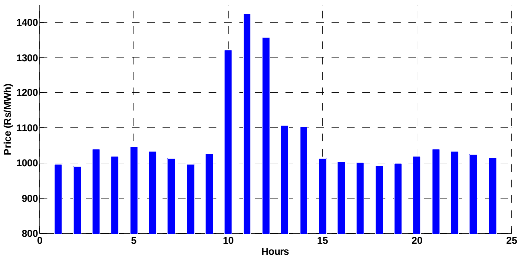

Fig. 4. Forecasted prices for 10 generator units [3].

Table 1. Forecasted demand and prices (10 units) [3].

Hour	Load	Price	Hour	Load	Price
h	MW	Rs/MWh	h	MW	Rs/MWh
1	700	996.75	13	1240	1107.00
2	750	990.00	14	1220	1102.50
3	850	1039.50	15	1200	1012.50
4	950	1019.25	16	1050	100.35
5	1000	1046.25	17	1000	1001.25
6	1100	1032.75	18	1100	992.25
7	1150	1012.50	19	1200	999.00
8	1200	996.75	20	1240	1019.25
9	1250	1026.00	21	1200	1039.50
10	1280	1320.75	22	1100	1032.75
11	1300	1424.25	23	900	1023.75
12	1290	1356.75	24	800	1014.75

Emissions co-efficient of coal-fired, petroleum and natural gas power plants are quite different. It is assumed that conventional thermal units are coal-fired because of low operating cost. The operating data for 10- unit case is shown in Tables 2 and 3.

Table 2. Operating parameters of units [3].

Units	P_i(Max)	P_i(Min)	a_i	b_i	c_i
U-1	455	150	1000	16.19	0.00048
U-2	455	150	970	17.26	0.00031
U-3	130	20	700	16.60	0.00200
U-4	130	20	680	16.50	0.00211
U-5	162	25	450	19.70	0.00398
U-6	80	20	370	22.26	0.00712
U-7	85	25	480	27.74	0.00079
U-8	55	10	660	25.92	0.00413
U-9	55	10	665	27.27	0.00222
U-10	55	10	670	27.79	0.00173

Table 3. Generator emission coefficients [3].

Units	$\alpha_i(ton/h)$	$\beta_i(ton/MWh)$	$\gamma_i(ton/MW^2h)$
U-1	10.33908	-0.024444	0.00312
U-2	10.33908	-0.024444	0.00312
U-3	30.03910	-0.406950	0.00509
U-4	30.03910	-0.406950	0.00509
U-5	32.00006	-0.381320	0.00344
U-6	32.00006	-0.381320	0.00344
U-7	33.00056	-0.390230	0.00465
U-8	33.00056	-0.390230	0.00465
U-9	33.00056	-0.395240	0.00465
U-10	36.00012	-0.398640	0.00470

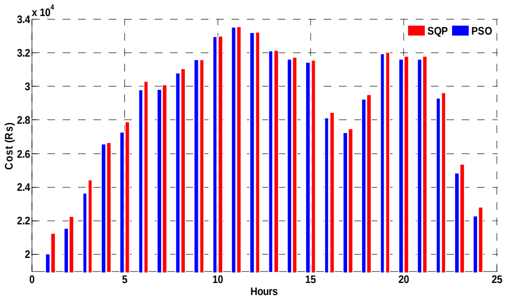

Fig. 5. Comparison of fuel cost by PSO and SQP algorithms over 24 h for 10 units with wind turbine.

Having calculation of the cost of such a scheduling, the algorithm ensures that the profit is based on a valid scheduling by considering reserved units. Figures 5 and 6 show the total cost and emission of 10-unit system, for each hour of optimization. Although the value of emission in PSO algorithm is a little, more than SQP one, TI shows that profit will outweigh the emission.

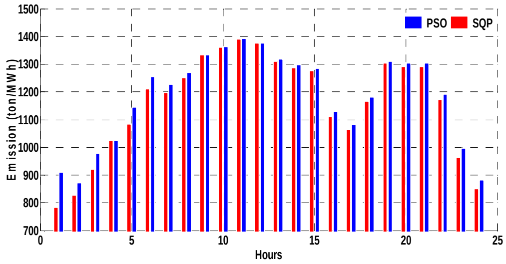

Fig. 6. Comparison of Emission by PSO and SQP algorithms over 24 h for 10 units with wind turbine.

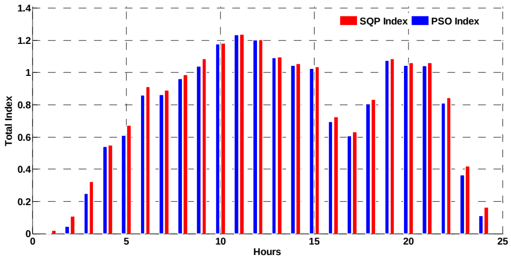

Fig. 7. Comparison of Total Index (TI) over 24 h for 10 units with wind turbine.

Figure 7 shows TI that is computed in accordance with (32). It is obvious that there has to be a trade-off between maximization of total profit and minimization of total emission over 24-hour for 10 units.

TI is improved by 3.68 % when PSO algorithm is used. According to (27), the produced total active power is constant for all units therefore for increasing total profit the fuel cost should be decreased. Therefore, the total index is defined based on emission and cost. Tables 4 and 5 indicate the optimal generated active power of units based on per-unit system and the value of objective functions over 24-houre period of time. Fig.8 shows the convergence process of PSO algorithm for the best solution. The value of the objective functions settles at the minimum value after 500 iterations, and would be constant after that.

The two-dimensional Pareto front with its surface which contains optimal and non-optimal solutions for the objective functions is shown in Fig. 9. The best solution for objectives Emission and Cost are 6920969 (ton) and 28442 (Rs) over 24-hour period of time which is shown in Fig. 9 with cursor.

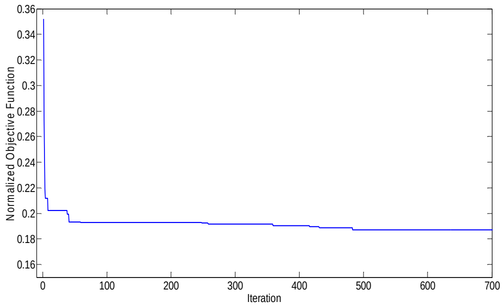

Fig. 8. Convergence process of the best solution obtained by PSO algorithm.

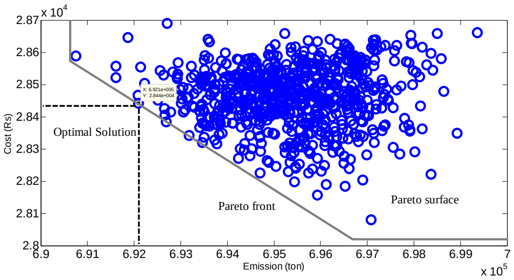

Fig. 9. Two-dimensional Pareto surface with specified Pareto front for Emission and Cost.

5. CONCLUSIONS

In this paper, Here-and-Now approach is used for solving the generation scheduling problem by considering thermal and wind energy systems. In this paper, the probability of stochastic wind power is included in the constraints set. This approach avoids the probabilistic infeasibility caused by using the average of RVs. In particular, we used a threshold parameter Pa into the constraints to characterize the tolerance that the total load demand cannot be satisfied. In addition, it has proposed a multi objective problem for optimizing profit and Emission over 24-hour period of time based on the algorithms for ten units in the presence of WPG units.

PSO algorithm with HN approach decreases TI about 3.68% than SQP algorithm. Furthermore, it provides better solution particularly for systems containing larger number of generating units. PSO algorithm with HN approach can provide a fast solution and the GENCOs can maximize their profit and minimize their emission.

Table 4. The objective functions values for PSO based algorithm.

Hour	U-1	U-2	U-3	U-4	U-5	U-6	U-7	U-8	U-9	U-10	Emission	Cost	Profit
1	1.50	1.50	1.50	1.50	1.50	0.75	0.75	0.75	0.75	0.75	911.388	20050.54	717584.3
2	1.48	1.48	1.05	1.10	1.06	0.80	0.21	0.21	0.21	0.21	872.730	21554.55	755585.6
3	1.48	1.48	1.19	1.29	1.30	0.82	0.30	0.30	0.30	0.30	977.778	23656.55	891103.5
4	1.76	1.64	0.94	0.82	1.06	1.09	0.63	0.67	0.59	0.53	1023.864	26582.11	967176.5
5	1.46	1.46	1.46	1.46	1.46	0.59	0.60	0.60	0.59	0.59	1146.266	27265.70	1047756
6	1.50	1.50	1.50	1.50	1.50	0.75	0.75	0.75	0.75	0.75	1255.853	29789.12	1135669
7	1.41	1.41	1.41	1.41	1.41	1.16	0.74	0.74	0.74	0.74	1227.064	29820.29	1104159
8	1.50	1.50	1.50	1.25	1.44	1.11	0.81	0.81	0.81	0.83	1269.930	30797.60	1125412
9	1.50	1.50	1.49	1.50	1.45	1.34	0.80	0.80	0.80	0.80	1333.193	31571.42	1199618
10	1.50	1.50	1.38	1.29	1.50	1.41	0.95	0.98	0.94	0.91	1363.286	32948.75	1604768
11	1.50	1.50	1.34	1.37	1.47	1.44	0.97	1.02	0.97	1.00	1393.817	33520.45	1763897
12	1.50	1.50	1.34	1.36	1.50	1.38	1.00	1.00	0.95	0.95	1377.215	33208.42	1662716
13	1.50	1.50	1.24	1.45	1.37	1.26	0.92	0.92	0.92	0.92	1318.940	32101.86	1301833
14	1.50	1.50	1.21	1.44	1.50	1.20	0.87	0.91	0.87	0.85	1297.559	31614.34	1278211
15	1.50	1.50	1.36	1.27	1.46	1.23	0.86	0.86	0.86	0.86	1285.412	31423.05	1163327
16	1.50	1.50	1.27	1.26	1.30	1.06	0.65	0.65	0.65	0.65	1130.608	28128.68	1025556
17	1.50	1.50	1.33	1.07	1.12	1.13	0.65	0.60	0.60	0.59	1081.431	27259.37	984013.1
18	1.49	1.49	1.30	1.21	1.49	1.09	0.70	0.71	0.70	0.70	1182.468	29238.83	1057275
19	1.50	1.50	1.24	1.35	1.50	1.42	0.84	0.87	0.84	0.90	1310.222	31923.13	1166877
20	1.49	1.49	1.25	1.49	1.44	1.23	0.87	0.87	0.87	0.87	1304.520	31617.58	1181331
21	1.46	1.46	1.34	1.40	1.46	1.32	0.84	0.85	0.87	0.84	1304.601	31612.45	1205372
22	1.50	1.50	1.33	1.30	1.38	1.20	0.68	0.71	0.68	0.70	1192.861	29292.81	1106763
23	1.50	1.50	1.17	1.18	1.31	0.79	0.43	0.43	0.43	0.43	997.792	24837.51	917022.7
24	1.49	1.49	1.04	0.96	1.18	0.77	0.27	0.30	0.29	0.26	883.275	22281.82	799655.5

Table 5. The objective functions values for SQP based algorithm.

Hour	U-1	U-2	U-3	U-4	U-5	U-6	U-7	U-8	U-9	U-10	Emission	Cost	Profit
1	1.47	1.41	0.71	0.72	0.91	0.74	0.33	0.40	0.34	0.32	784.190	21263.75	716331.2
2	1.50	1.47	0.76	0.76	0.96	0.79	0.37	0.44	0.39	0.36	827.356	22253.75	754906.2
3	1.50	1.50	0.88	0.88	1.10	0.93	0.48	0.54	0.49	0.46	921.751	24433.12	890316.5
4	1.50	1.50	0.98	0.99	1.24	1.07	0.60	0.66	0.60	0.57	1023.943	26670.96	967097.8
5	1.50	1.50	1.50	1.50	1.50	1.50	0.03	1.18	0.03	0.03	1084.926	27904.56	1047117
6	1.50	1.50	1.15	1.16	1.47	1.30	0.78	0.84	0.79	0.75	1210.193	30296.02	1135162
7	1.50	1.50	1.14	1.15	1.46	1.28	0.77	0.83	0.78	0.74	1199.198	30095.47	1103915
8	1.50	1.50	1.19	1.20	1.50	1.33	0.83	0.88	0.83	0.80	1251.051	31057.95	1125172
9	1.50	1.50	1.24	1.25	1.50	1.41	0.88	0.94	0.89	0.85	1333.193	31571.42	1199618
10	1.50	1.50	1.30	1.30	1.50	1.47	0.94	0.99	0.94	0.91	1360.756	32993.73	1604736
11	1.50	1.50	1.32	1.33	1.50	1.50	0.98	1.03	0.98	0.95	1391.688	33545.34	1763872
12	1.50	1.50	1.31	1.32	1.50	1.49	0.96	1.01	0.96	0.92	1375.150	33233.86	1662704
13	1.50	1.50	1.25	1.25	1.50	1.42	0.89	0.94	0.89	0.86	1311.638	32148.57	1301797
14	1.50	1.50	1.23	1.23	1.50	1.39	0.87	0.92	0.87	0.84	1288.337	31738.13	1278032
15	1.50	1.50	1.21	1.22	1.50	1.38	0.86	0.91	0.86	0.83	1277.512	31545.67	1163214
16	1.50	1.50	1.07	1.07	1.35	1.18	0.69	0.75	0.69	0.66	1111.947	28434.78	1025240
17	1.50	1.50	1.02	1.03	1.29	1.12	0.64	0.70	0.64	0.61	1064.253	27493.81	983779
18	1.50	1.50	1.12	1.12	1.42	1.25	0.74	0.80	0.75	0.71	1167.590	29497.89	1057016
19	1.50	1.50	1.24	1.25	1.50	1.41	0.88	0.94	0.89	0.85	1304.747	32027.97	1166782
20	1.50	1.50	1.23	1.23	1.50	1.40	0.87	0.92	0.87	0.84	1291.056	31786.40	1181121
21	1.50	1.50	1.23	1.23	1.50	1.40	0.87	0.92	0.87	0.84	1291.069	31786.67	1205229
22	1.50	1.50	1.13	1.13	1.43	1.25	0.75	0.80	0.75	0.72	1173.920	29615.88	1106409
23	1.50	1.50	0.92	0.92	1.17	0.99	0.53	0.59	0.54	0.51	963.175	25383.96	916466
24	1.50	1.50	0.78	0.79	1.00	0.82	0.40	0.47	0.41	0.38	851.272	22825.38	799122.1

NOMENCLATUER

c	Scale factor of the Weibull distribution
$F_W(w)$	Cumulative distribution function (CDF) of random variable W
$f_W(w)$	Probability density function (PDF) of random Variable W
k	Shape factor of the Weibull distribution
m	Number of wind power generation (WPG) units
N	Number of generators
P_d	Total load demand
$Pr\ (E)$	Probability of event E
P_s	Total transmission losses
P_a	Upper bound of probability that the sum of real power not greater than $P_d + P_s$
$a_i,\ b_i, c_i$	Cost coefficients of generator i
W_j	Real power generated by WPG unit j
w_{jr}	Rated power of WPG unit j
w_r	Rated power of WPG units if all the same
p_i	Real power generated by generator j
$P_{optm,i}$	Optimal value of P_i
Y	Cost index in the economic load dispatch (ELD) model
RV	Revenue
TC	Total Cost
PF	Profit
EC_i	Emission cost function of unit i
$GENCO$	Generation Company
WPG	Wind Power Generation
v_r, v_{in}, v_{out}	Rated, cut-in, and cut-out wind speeds

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