



Review Paper

## Economic Dispatch Incorporating Wind Power Plant Using Modified Particle Swarm Optimization

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### Abstract

*This paper presents a new approach for Economic Dispatch (ED) problems incorporating wind power plant using Modified Particle Swarm Optimization (MPSO) method. As Wind Power Plant increases in power systems, its effects to conventional units should be analyzed. Also the total cost is dependent on wind speed in specific period of time. Therefore, the mathematical techniques are not appropriate to find the global optimum ED. In this paper, MPSO is proposed to deal with wind power plants in ED. To show efficiency of wind power plant in reducing total cost, different simulation scenarios with and without wind power production are simulated*

**Keywords:** Economic dispatch, modified particle swarm optimization, nonsmooth cost function, Weibull probability density function, wind power plant.

### Introduction

Sustainable energy resources, especially wind power, are currently increasing in power systems. Advantages of this resource can be summarized as follows: i. Reducing dependence on fossil resources. ii. Reducing greenhouse gases emission. iii. Reducing the energy production cost<sup>1</sup>. Therefore, it's important to consider wind power plants in Economic Dispatch (ED) problems. Because of stochastic availability of wind power, the incorporating wind power plant to the ED problems is difficult. This problem can be solved by several investigations have looked at the prediction of wind speed for use in determining the available wind power<sup>2</sup>. In this paper, the known Weibull probability distribution function (PDF) that its parameters are estimated by the maximum likelihood method, is used as the basic numerical solution of the ED model<sup>2-3</sup>. Because of the uncertainty of the wind energy, factors for overestimation and underestimation of available wind energy must be included in the cost function of wind power plant<sup>2</sup>. The ownership of wind power plant is another factor that is considered in cost function. In this paper, Modified Particle Swarm Optimization (MPSO) method is applied to ED problem with non smooth cost functions including valve-point effects<sup>4-5</sup>.

To show the efficiency of wind power plant in total cost, MPSO method is applied to ten and forty unit systems incorporating a wind power plant with different scenarios, with and without wind power plant and with different ownership of them.

### Formulation of ED Problem

In this paper, we deal with ED problem with nonsmooth cost function and equality and inequality constraints. To understand the issue better, it is necessary to know the ED problem with

smooth cost function then we should extend this to nonsmooth cost function.

**ED Problem with Smooth Cost Function:** The ED problem with detects the optimal combination of power generators that minimizes the total generation cost while satisfying equality and inequality constraints. The most simplified cost function of each generator can be indicated as a quadratic function as given in (1) and total cost of generation given in (2)<sup>5</sup>:

$$F_j(P_j) = a_j + b_j P_j + c_j P_j^2 \quad (1)$$

$$C = \sum_{j \in J} F_j(P_j) \quad (2)$$

C: Total generation cost,  $F_j$ : Cost function of generator  $j$ ,  $a_j, b_j, c_j$ : Cost coefficients of generator  $j$ ,  $P_j$ : Electrical output of generator  $j$ ,  $J$ : Set for all generators.

While minimizing the total generation cost in power systems, the total generation should be equal to the total system demand plus the transmission network loss. But, the network loss is not considered in this paper for simplicity. This gives the equality constraint.

$$D = \sum_{j \in J} P_j \quad (3)$$

where  $D$  is the total system demand.

The generation output of each unit should be between its minimum and maximum limits. So, the following inequality constraint for each generator should be satisfied.

$$P_{j \min} \leq P_j \leq P_{j \max} \quad (4)$$

Where the  $P_j$  min,  $P_j$  max is the minimum and maximum outputs of generator  $j$ <sup>5</sup>.

**ED Problem Including Nonsmooth Cost Functions with Valve-Point Effects:** In fact, the practical function of an ED problem has no differentiable points according to valve-point effects and change of fuels; therefore, the practical function should be composed of a set of nonsmooth cost functions. In this paper, nonsmooth cost function according to valve-point effects is considered. The generator with multi-valve turbines has very different input-output curve compared with the smooth cost function. Typically, the valve point results as each steam valve begins to open, are shown in figure 1. To calculate and consider the valve-point effects, sinusoidal functions are added to the quadratic cost functions as follows<sup>5</sup>:

$$F_j(P_j) = a_j + b_j P_j + c_j P_j^2 + |e_j \times \sin(P_{jmin} - P_j)| \quad (5)$$

Where  $e_j$  and  $f_j$  are the coefficients of generator  $j$  which cause valve-point effects. In this case, the problems have multiple minima; therefore, the task of finding the global solution still remains to be tackled<sup>5-6</sup>.

**ED Problem Incorporating Wind Power Plant:** Due to lack of using fuel to generate energy, the cost function of the wind power plant must be described in another model. Also, because of the uncertain nature of wind and output of the wind power plant, the factors must be considered for underestimation and overestimation of the available wind energy in this model. In other hand, it is necessary to consider the ownership of the wind power plant. Thereby, the cost function of wind power plant can be calculated as follows (6)<sup>2</sup>.

$$C = \sum_{i=1}^N C_{w,i}(w_i) + \sum_{i=1}^N C_{p,wi}(W_{i,av} - w_i) + \sum_{i=1}^N C_{r,wi}(w_i - W_{i,av}) \quad (6)$$

Where,  $N$ : number of wind-powered generators;  $w_i$ : scheduled wind power from the  $i^{\text{th}}$  wind-powered generator;  $W_{i,av}$ : available wind power from the  $i^{\text{th}}$  wind-powered generator. This is a random variable, with a value range of  $0 \leq W_{i,av} \leq w_r$  and probabilities varying with the given pdf. We considered Weibull pdf for wind variation;  $w_{r,i}$ : rated wind power from the  $i^{\text{th}}$  wind-powered generator;  $C_{w,i}$ : cost function for the  $i^{\text{th}}$  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;  $C_{p,wi}$ : penalty cost function for not using all available power from the  $i^{\text{th}}$  wind-powered generator;  $C_{r,wi}$ : required reserve cost function, relating to uncertainty of wind power. This is effectively a penalty associated with the overestimation of the available wind power.

In equation (6), the first term is the cost that system operator must pay to producer of wind power. A linear cost function will be assumed for the wind-generated power actually used as<sup>2</sup>:

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

Where  $d_i$  is the direct cost coefficient for the  $i^{\text{th}}$  wind generator.

The second term is the penalty cost for not using all the available wind power which will be assumed that it will be linearly related to the difference between the available wind power and the actual wind power used. The penalty cost function will then take the following form<sup>2</sup>:

$$C_{p,wi}(W_{i,av} - w_i) = k_{p,i}(W_{i,av} - w_i) = k_{p,i} \int_{w_i}^{W_{i,av}} (w - w_i) f_W(w) dw \quad (8)$$

Where,  $k_{p,i}$ : penalty cost (underestimation) coefficient for the  $i^{\text{th}}$  wind generator;  $f_W(w)$ : wind energy conversion system (WECS) wind power PDF.

The third part is the reserve requirement cost that will be similar to penalty cost, except that, in this case, it is a cost due to the available wind power being less than the scheduled wind power. It is indicated in (9)<sup>2</sup>:

$$C_{r,wi}(w_i - W_{i,av}) = k_{r,i}(w_i - W_{i,av}) = k_{r,i} \int_0^{w_i} (w_i - w) f_W(w) dw \quad (9)$$

Where  $k_{r,i}$  is the reserve cost (overestimation) coefficient for the  $i^{\text{th}}$  wind-powered generator. If the wind power plant is not owned by the system operator, the direct cost coefficient and penalty cost may be zero. The wind speed is a random variable. A comprehensive review for probability distributions of wind speed has been presented by Carta et al.<sup>7</sup>. They 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. The pdf of Weibull distribution is as follows<sup>7</sup>:

$$f_V(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{(k-1)} e^{-(v/c)^k}, \quad 0 < v < \infty \quad (10)$$

Where  $V$  is the wind speed random variable;  $v$ : wind speed;  $c$ : scale factor at a given location (units of wind speed);  $k$ : shape factor at a given location (dimensionless).

Methods of estimating the Weibull shape and scale factors using the available wind speed data have been presented by Seguro and Lambert<sup>3</sup>.

Given the forecast of wind speed distribution and speed-to-power conversion function, the wind power output distribution can be obtained. In this paper, a linear speed-to-power conversion function is used<sup>2</sup>.

$$\begin{aligned} w &= 0 & \text{for } v < v_i \text{ and } v > v_o \\ w &= w_r \frac{v - v_i}{v_r - v_i} & \text{for } v_i < v < v_r \\ w &= w_r & \text{for } v_r < v < v_o \end{aligned} \quad (11)$$

Where,  $w$ : WECS output power (typical units of kilowatt or megawatt);  $w_r$ : WECS rated power;  $v_i$ : cut-in wind speed (typical units of miles/hour or miles/second);  $v_r$ : rated wind speed;  $v_o$ : cut-out wind speed.

According to the probability theory for function of random variables<sup>8</sup>, in the interval  $v_i < V < v_r$ , the PDF of W is:

$$f_W(w) = \frac{klv_i}{c} \left( \frac{(1+\rho l)v_i}{c} \right)^{(k-1)} \times \exp \left( - \left( \frac{(1+\rho l)v_i}{c} \right)^k \right) \quad (12)$$

Where,  $\rho = \frac{w}{w_i}$  is the ratio of wind power output to rated wind power;  $l = \frac{(v_r - v_i)}{v_i}$  is the ratio of linear range of wind speed to cut-in wind speed.

**Implementation of Particle Swarm Optimization:** Kennedy and Eberhart developed a PSO algorithm based on the behavior of individuals (i.e. particles or agents) of a swarm<sup>4</sup>. It has been perceived that members within a group seem to share information among them, a fact that causes to increase efficiency of the group. An individual in a swarm approaches to the optimum condition by its present velocity, previous experience, and the experience of its neighbors.

In a physical n-dimensional search space, parameters of PSO technique are defined as follows<sup>4</sup>:

$X_i = (x_{i1}, \dots, x_{in})$  : Position of individual i.  
 $V_i = (v_{i1}, \dots, v_{in})$  : Velocity of individual i.  
 $Pbest_i = (X_{i1}^{pbest}, \dots, X_{in}^{pbest})$  : best position of individual i.  
 $Gbest_i = (X_{i1}^{gbest}, \dots, X_{in}^{gbest})$  : Global best position.

Using the information, the updated velocity of individual i is modified by the following equation in the PSO algorithm<sup>4</sup>:

$$V_i^{k+1} = wV_i^k + c_1 rand_1 \times (Pbest_i^k - X_i^k) + c_2 rand_2 \times (Gbest_i^k - X_i^k) \quad (13)$$

Where,  $V_i^k$ : velocity of individual i at iteration k,  $w$ : weight parameter,  $c_1, c_2$ : weight factors,  $rand_1, rand_2$ : random numbers between 0 and 1,  $X_i^k$ : position of individual i at iteration k,  $Pbest_i^k$ : best position of individual i until iteration k,  $Gbest_i^k$ : best position of the group until iteration k.

The individual moves from the current position to the next position by equation (14)<sup>4</sup>:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (14)$$

The search mechanism of the PSO using the modified velocity and position of individual i based on equations (13) and (14) is illustrated in figure 2<sup>5</sup>.

## Implementation of Modified Particle Swarm Optimization

In this section, a new approach to implement the PSO algorithm will be described in solving the ED problems. Especially, a suggestion will be given on how to deal with the equality and inequality constraints of the ED problems when modifying each individual's search point in the PSO algorithm. Additionally, to accelerate the convergence speed, the dynamic search-space reduction strategy is devised. The process of the modified PSO

algorithm can be summarized as follows<sup>5</sup>: i. Step 1) Initialization of a group at random while satisfying constraints. ii. Step 2) Velocity and position updates while satisfying constraints. iii. Step 3) Update of Pbest and Gbest. iv. Step 4) Activation of space reduction strategy. v. Step 5) Go to Step 2 until satisfying stopping criteria.

The main difference between PSO and MPSO is space reduction strategy and this is necessary to explain. In this case, the search space is dynamically reduced based on the distance between the Gbest and the minimum and maximum output generator j. To understand the adjusted minimum/maximum output generator j at iteration k, the distance is changed by the optional step-size  $\Delta$  to change the minimum and maximum output at iteration k to optimize performance as described in (15):

$$P_{jmax}^{k+1} = P_{jmax}^k - (P_{jmax}^k - Gbest_j^k) \times \Delta \quad (15)$$

$$P_{jmin}^{k+1} = P_{jmin}^k - (P_{jmin}^k - Gbest_j^k) \times \Delta$$

**Case Studies:** To assess the efficiency of the wind power plant, it has been applied to ED problems where objective function can be nonsmooth. The simulated systems are ten and forty conventional unit systems<sup>6,9</sup> and the demand of systems is divided into 24 hours (intervals) for a whole day that are listed as table 1 and table 4 respectively. For each system three scenarios are considered: i. without wind power plant ii. with wind power plant owned by private sector and iii. when system operator is owner of wind power plant that in this case the direct cost coefficient and penalty cost will be zero.

The wind speed data to use in cost function of wind power plant is shown in figure 3<sup>10</sup>.

## Test System with 10 Conventional Units And One Wind Power Plant:

The MPSO is applied to ED problem with 10 units (i.e. generators) where valve-point effects are considered for this problem. The input data for 10-generator system has been presented by Victoire and Jeyakumar<sup>9</sup>. The load demand of the system over 24 hours is shown in table 1. The parameters of wind power plant are given in table 2. Having simulations using MPSO in the above system, the obtained results are shown in table 3.

By comparing results, one can find out that if wind power plant owned by system operator, total cost could be decreased more than when private sector was owner of wind power plant.

## Test System with 40 Conventional Units and four Wind Power Plants:

In this section, MPSO is applied to 40-generator system where valve-point effects are considered for this ED problem. The input data of 40-generator systems has been presented by Sinha et al<sup>6</sup>. Also, there are 4 wind power plants which have been assumed similar to wind power plant in table 2. The load demand of the 40-conventional unit system over 24 hours is shown in table 4. By applying MPSO, the obtained cost results are presented in table 5.

**Table-1**  
**Load Demand for 24H in 10-conventional unit system**

| Hour | Load(MW) | Hour | Load(MW) | Hour | Load(MW) |
|------|----------|------|----------|------|----------|
| 1    | 1036     | 9    | 1924     | 17   | 1480     |
| 2    | 1110     | 10   | 2072     | 18   | 1628     |
| 3    | 1258     | 11   | 2146     | 19   | 1776     |
| 4    | 1406     | 12   | 2220     | 20   | 2072     |
| 5    | 1480     | 13   | 2072     | 21   | 1924     |
| 6    | 1628     | 14   | 1924     | 22   | 1628     |
| 7    | 1702     | 15   | 1776     | 23   | 1332     |
| 8    | 1776     | 16   | 1554     | 24   | 1184     |

**Table-2**  
**Parameters of wind power plant**

| $P_{min}(MW)$ | $P_{max}(MW)$ | $V_i(m/s)$ | $V_r(m/s)$ | $V_o(m/s)$ | $K_d$ | $K_p$ | $K_r$ |
|---------------|---------------|------------|------------|------------|-------|-------|-------|
| 0             | 35            | 5          | 15         | 45         | 1.12  | 1     | 1     |

**Table-3**  
**Cost results of 11-unit system**

| 11 units(100 Iteration) |                    |                          |                 |
|-------------------------|--------------------|--------------------------|-----------------|
| Compared item           | Without wind power | With wind power owned by |                 |
|                         |                    | private sector           | system operator |
| Best                    | 994262.1299        | 853225.5137              | 848590.3597     |
| Worst                   | 1011829.852        | 991011.8302              | 990852.6883     |
| Average                 | 1001936.981        | 943409.8603              | 935829.0981     |

**Table-4**  
**Load demand for 24H in 40-conventional unit system**

| Hour | Load(MW) | Hour | Load(MW) | Hour | Load(MW) |
|------|----------|------|----------|------|----------|
| 1    | 7036     | 9    | 9924     | 17   | 8480     |
| 2    | 7110     | 10   | 10072    | 18   | 8628     |
| 3    | 8258     | 11   | 10146    | 19   | 9776     |
| 4    | 8406     | 12   | 10220    | 20   | 10072    |
| 5    | 9480     | 13   | 10072    | 21   | 9924     |
| 6    | 9628     | 14   | 9924     | 22   | 9628     |
| 7    | 9702     | 15   | 9776     | 23   | 7332     |
| 8    | 9776     | 16   | 8554     | 24   | 7184     |

**Table-5**  
**Cost results of 44 units system**

| 44 unit(100 Iteration) |                    |                          |                 |
|------------------------|--------------------|--------------------------|-----------------|
| Compared item          | Without wind power | With wind power owned by |                 |
|                        |                    | private sector           | system operator |
| Best                   | 2567309.456        | 2516381.755              | 2501953.289     |
| Worst                  | 2691338.766        | 2683219.613              | 2683072.302     |
| Average                | 2624480.442        | 2616870.126              | 2611350.720     |

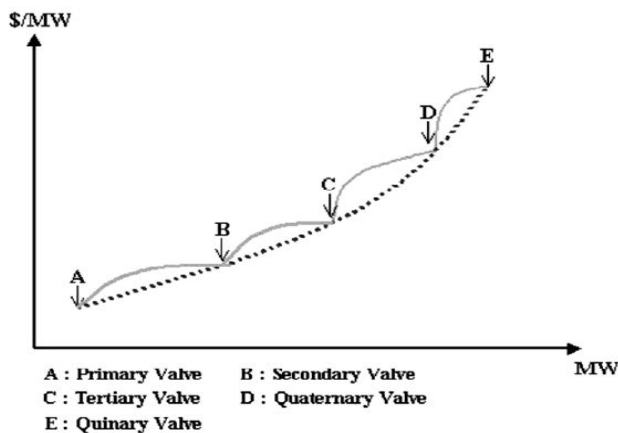


Figure-1  
Valve point effect

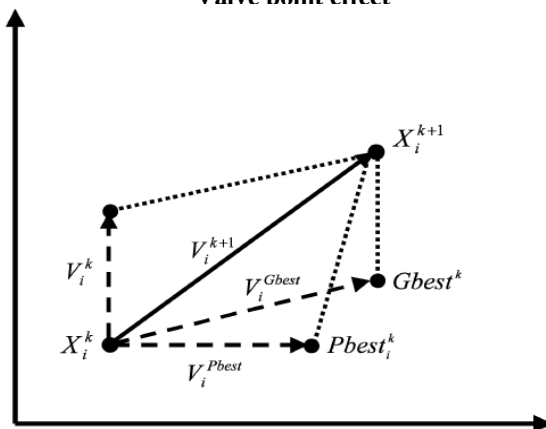


Figure-2  
Mechanism of PSO

Finally, in two power systems, one can see that using wind power plants have realistic and powerful performance in total cost of production.

## Conclusion

This paper develops a model to include wind power plants in the Economic Dispatch (ED) problems. The uncertain nature of the wind speed is represented by the Weibull pdf. We have successfully employed Modified Particle Swarm Optimization (MPSO) method to solve ED problem incorporating wind power plants. In this paper, the MPSO has been applied to 10-generator system with and without one wind power plant and 40-generator system with and without four wind power plants. The results of simulations with and without wind power plants, illustrate that wind power plants have powerful performance in total cost of production and can reduce total cost in power systems. Also, if wind power plant is owned by system operator, total cost can be decreased more than when private sector is owner of wind power plant.

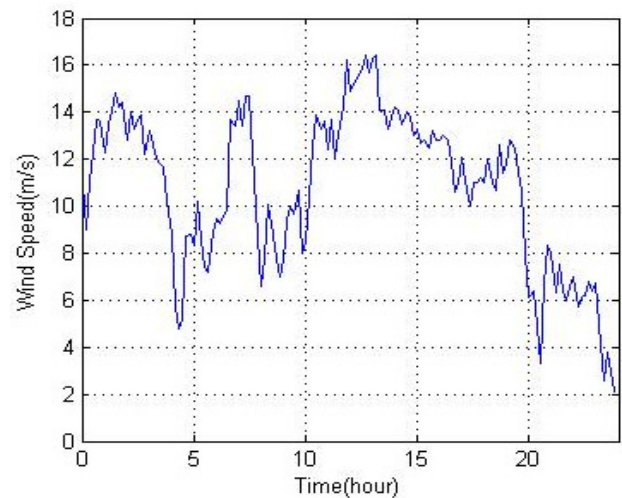


Figure-3  
Wind Speed Variation Diagram

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