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GENERATION SEARCH METHOD IN POLAR COORDINATES FOR OPTIMIZATION OF ECONOMIC EMISSION LOAD DISPATCH

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ABSTRACT

The paper investigates the performance of proposed search technique for different kinds of economic dispatch problems by searching generation pattern of committed units in polar coordinate system being projection of phasor on real axis with respect to its displacement. A slack generator is introduced to meet the demand constraint while generation pattern is searched within operating limits of generators. Economic dispatch with valve loading, economic dispatch with ramp rate and prohibited operating zones and economic-emission dispatch are explored. Economic-emission dispatch problem treats economic and emission as competing objectives and the conflict between them is resolved exploiting fuzzy satisfying method. Weight pattern assigned to participating objectives is searched as weighting technique is applied to generate the non-inferior solutions. The non-inferior solution is adjudged as the best operating point that attains maximum satisfaction level in terms of the membership function of participating objectives. Performance of the algorithm is investigated on dispatch problems of different size and complexity. The proposed optimization technique has emerged as a useful optimization tool for handling network losses, ramp rate limits and prohibited operating zone avoidance in account to determine the optimal dispatch solution as well as optimal operating point in the non-inferior domain for any number of the goals.

Keywords: ***Economic Emission Load Dispatch (EELD), Economic Load Dispatch (ELD), Prohibited Operating Zone (POZ)***

INTRODUCTION

The increasing energy demand and decreasing energy resources have necessitated the optimum use of available resources. Economic dispatch is optimization scheme intends to find the generation outputs that minimize the total operating cost while satisfying several unit and system constraints. Traditional economic dispatch methods require the generator cost curve to be continuous. Hence the operating cost function for each generator has been approximately represented by a quadratic function and the effect of valve-point loading was ignored. Due to physical limitations of power plant apparatus generating unit may have prohibited operating zones between their minimum and maximum operating power outputs. Economic-emission load dispatch problem treats economy and emission as competing objective for optimal dispatch which needs some form of conflict resolution to arrive at a final decision. Various optimization techniques have been proposed by many researchers to deal with different kind of economic dispatch problems

with varying degree of success. It is of great importance to solve this problem quickly and accurately as possible considering all kind of discontinuity in non-linear search space. Improvement in the scheduling technique of the committed units output can lead to significant cost saving. The conventional methods include the lambda-iteration method, the base point and participation factor and gradient method [1]. In these numerical methods, an essential assumption is that the incremental cost curves of the units are monotonically increasing. Unfortunately, the input-output characteristics of modern units are inherently highly non-linear. These non-linear characteristics of generating units are due to discontinuous prohibited operating zones, ramp rate limits and cost functions, which are not smooth or convex, thus gives inaccurate dispatch results. So, various mathematical programming techniques are required that do not have restrictions on the non-linear characteristics of the units. Classical calculus based techniques fail to address such type of problems satisfactorily. Furthermore, for large-scale mixed generating system, the conventional method has oscillatory problem results in large solution time. A dynamic programming (DP) method for solving the emission load dispatch problem with valve point loading become extremely large, thus requiring enormous computational efforts. Modern heuristic algorithms are considered as effective tools for non-linear optimization problems. The algorithms do not require that the objective function has to be differentiable and continuous. With the advent of stochastic search algorithms, such as genetic algorithms (GAs), evolutionary strategies (ESs), evolutionary programming (EP) [2] and simulated annealing (SA) [3] prove to be very effective in solving nonlinear economic load dispatch problems without any restrictions on the shape of the cost curves. Genetic algorithm methods have been employed successfully to solve complex optimization problems; recent research has identified some deficiencies in genetic algorithm performance. This degradation in efficiency is apparent in applications with highly epistatic objective functions (i.e. where the parameters being optimized are highly correlated), the crossover and mutation operations cannot ensure better fitness of offspring because chromosomes in the population have similar structures and their average fitness is high towards the end of the evolutionary process. Moreover, the premature convergence of genetic algorithm degrades its performance and reduces its search capability that leads to a higher probability towards obtaining a local optimum.

These heuristics methods provide a fast and reasonable solution but don’t always discover the globally optimal solution (Suboptimal near globally optimal) in finite time.

One of the inherent characteristic associated with complex real-world decision making problems is their inescapably multifarious nature. One of the multifarious features of such problems is their multiple objectives that are usually non-commensurable and are often in conflict. Real-world decision making problems, thus, often lead to a multi-objective optimization problem formulation. The ultimate goal in multi-objective optimization is to seek a most preferred solution from the set of non-inferior solutions. The increasing public awareness of environmental protection, U.S. Clean Air Act amendments of 1990 have forced utilities to modify their design and operational strategies to reduce pollution and atmospheric emissions of thermal plants. The multi-objective optimization technique for the economic environmental dispatch problem was proposed and different techniques have been reported in the literature pertaining to economic environmental problem as well as multi-objective optimization problems [4, 5, 6, 7, 8].

The intent of this paper is to solve different kind of economic dispatch problems by performing power generation search of committed units in polar coordinate system, where by position of phasor is searched through 0 to 180 degrees in first and second quadrant which further gives power generation as projection of phasor on real axis. A slack generator is introduced to adjust the un-met demand. Operating limits of generators are taken care during the search of generation pattern. The search method performs search in angle in two moves; one, exploratory move and two, pattern move. The exploratory move is used to obtain the information concerning the behavior of the function. This information is inferred entirely from the success or failure of the exploratory move without regard to any quantitative appraisal of the functional values. This move is performed in the vicinity of the current position of phasor systematically by perturbing it suitably. The exploratory move is a success if position of phasor is different from starting position otherwise the exploratory move is a failure. In case exploratory move fails, the perturbation factor is reduced to achieve the success in successive exploratory move. On successful exploratory move, pattern move is applied to move towards optimal point quickly. Economic dispatch with valve loading effect, economic dispatch with ramp rate limits and prohibited operating zones and economic-emission dispatch are investigated. In case of economic-emission load dispatch problem, the multi-objective optimization problem is converted into single objective optimization problem using a weighted method to find the non-inferior solutions. Weight pattern search is also performed in polar coordinates with reference to angle representing the corresponding weight assigned to the participating goal. The fuzzy goals are quantified by defining their corresponding membership functions. The non-inferior solution is said to be optimal if it attains maximum satisfaction level from the membership functions of the participating objectives. The feasibility of the proposed method has been demonstrated for various power systems consisting of 3-generators [2], 6-generator [9], 13-generators [2], 15-generators [9] and 40-generators [2, 10]. The proposed method has provided the improved results as compared to other methods undertaken for comparison like various variants of evolutionary programming [2] and particle swarm optimization [9] etc.

[II] ECONOMIC LOAD DISPATCH

The economic load dispatch problem is defined as to minimize the total operating cost of a power system simultaneously meeting the total load and transmission loss within generator limits [2, 11]. Mathematically, the economic load dispatch problem is defined as:

Minimize operating cost

$$F_1\left(P_i\right)=\sum_{i=1}^{Ng} f_{1i}\left(P_i\right) \qquad (1)$$

Subject to (i) The energy balance equation

$$\sum_{i=1}^{Ng} P_{g_i} = P_D + P_L \qquad (2)$$

(ii) The inequality constraints

$$P_i^{\min} \le P \le P_i^{\max} \quad (i = 1,2, \ldots .Ng) \qquad (3)$$

Generation search in polar coordinate system is employed to achieve the optimal solution. The generating units with multi-valve steam turbines exhibit a greater variation in the fuel cost functions. The fuel cost function without and with effect of valve point loading of the generating units is given by:

Without valve point loading

$$f_{1i}\left(P_i\right)= a_i P_i^2 + b_i P_i + c_i \; ; \qquad (4a)$$

With valve point loading

$$f_{1i}\left(P_i\right)= a_i P^2 + b_i P_i + c_i + \left| e_i \times Sin\left\{ f_i \times \left(P_i^{\min} - P \right) \right\} \right| \qquad (4b)$$

Transmission loss is defined by Kron's loss formula:

$$P_L = B_{00} + \sum_{i=1}^{Ng} B_{io} P_i + \sum_{i=1}^{Ng}\sum_{i=1}^{Ng} P_i B_{ij} P_j \qquad (5)$$

[III] ECONOMIC LOAD DISPATCH WITH RAMP RATE AND PROHIBITED OPERATING ZONE

In solving economic load dispatch problem, the unit generation output is usually assumed to be smoothly and instantaneously. Hence, the constraints like ramp rate and prohibited operating zones of generator must be taken into account to achieve the true economic operation.

3.1. Ramp Rate Limit:

Practically, the operating range of units is restricted by their ramp rate limits thus forcing the units operation continually between two adjacent specific operation periods. Inequality constraints due to ramp rate limits [12] for unit generation changes are given:

a. as generation increases: $P_i - P_i^0 \le UR_i$ (6)

b. as generation decreases: $P_i^o - P_i \le DR_i$ (7)

3.2. Prohibited Operating Zone:

The prohibited operating zones in the input-output curve of generator are due to steam valve operation or vibration in a shaft bearing. Since it is difficult to determine the prohibited operating zone by actual performance testing or operating records, so practically the best economy is achieved by avoiding operation in such areas during actual operation. The input-output performance curve for a typical thermal unit with many valve points generates many prohibited zones [12, 13]. The feasible operating zones of i^th unit can be described as:

$$P_i \in \begin{cases} P_i^{\min} \le P_i \le P_{i,1}^l \\ P_{i,j-1}^u \le P_i \le P_{i,j}^l,\ j = 2,3,\ldots,n_i, i = l,\ldots,m. \\ P_{i,n_i}^u \le P_i \le P_i^{\max} \end{cases} \quad (8)$$

The economic dispatch problem objective of units operating in power system considering ramp rate and prohibited operating zones limits is defined below:

Minimize operating cost

$$F(P_i) = \sum_{i=1}^{Ng} \left(a_i P_i^2 + b_i P_i + c_i \right) \quad (9a)$$

Subject to energy balance equation and operating limits of generating units as inequality constraints and are given by Eq. (2) and (3), respectively. Prohibited operating zone being additional constraint on the unit operating range are imposed and are given by Eq. (8). The generator ramp rate being inequality constraint is taken into account as:

$$\max(P_i^{\min}, P_i^o - DR_i) \le P_i \le \min(P_i^{\max}, P_i^0 + UR_i) \quad (9b)$$

[IV] ECONOMIC-EMISSION DIS-PATCH PROBLEM:

The economic-emission load dispatch problem is defined as to minimize the total operating cost and gaseous emission of a power system simultaneously meeting the total load plus transmission losses within generator limits [12]. Mathematically, the problem is defined as

Minimize operating cost

$$F_1(P_i) = \sum_{i=1}^{Ng} f_{1i}(P_i) \quad (10a)$$

Minimize NOX emission

$$F_2(P_i) = \sum_{i=1}^{Ng} f_{2i}(P_i) \quad (10b)$$

Subject to the constraints given by Eqs. (2) and (3).

The fuel cost function is defined by Eq. (4) and the amount of NO_X emission as a function of generator output is given by

$$f_{2i}(P_i) = \alpha_i P_i^2 + \beta_i P_i + \gamma_i + \eta_i \exp(\delta_i P_i) \quad (11)$$

To generate the non-inferior solution, the economic-emission load problem is converted into a scalar optimization problem and is stated below:

$$\text{Minimize} \sum_{m=1}^{2} w_m F_m(P_i) \quad (12)$$

Subject to constraints given by Eqs. (2) and (3)

$$\sum_{m=1}^{2} w_m = 1.0; \quad w_m \ge 0.0 \quad (13)$$

where w_1 and w_2 are the levels of the weighting coefficients assigned to economic and emission objectives respectively. This approach yields meaningful results to the decision maker when the weighting coefficients are varied systematically within 0 to 1.

Considering the imprecise nature of the decision maker's judgment, it is normal to assume that the decision maker has fuzzy goals for each participating objectives. Degree of membership in certain fuzzy sets is defined by values from 0 to 1. The value of the membership function indicates how much, in scale of 0 to 1, a solution is satisfying the F_i objective. By taking account of the minimum and maximum values of each objective function together with the rate of increase of membership satisfaction, the decision maker must determine the membership function in a subjective manner is defined as:

$$\mu(F_i)=\begin{cases} 1 & ; F_i \le F_i^{min} \\ \dfrac{F_i^{max}-F_i}{F_i^{max}-F_i^{min}} & ; F_i^{min} \le F_i \le F_i^{max}; i=1,2 \\ 0 & ; F \ge F_i^{max} \end{cases} \quad (14)$$

F_i^{min} and F_i^{max} are the minimum and maximum values of ith objective function in which the solution is expected. The decision regarding the best solution is made by the selection of min-max of membership function defined as below:

$$\mu_D = Min\left(\mu\left(F_i\right); i=1,2.\right) \quad (15)$$

[V] CALCULATIONS FOR SLACK GENERATOR

The power outputs of the Ng generating units at a particular time period has to satisfy energy balance constraints, operating limit constraints, ramp rate and prohibited operating limit constraints. So, the committed Ng generating units delivers the power output subject to their respective energy balance constraints represented by Eq. (2), and the capacity constraints given Eq. (3). A dependent unit P_d is selected arbitrarily from the committed Ng units to meet the equality constraints and is named as slack generator. The power output of the slack unit is computed by rewriting the energy balance Eq. (2).

5.1 Transmission Losses are neglected (P_L=0):

$$P_d = PD - \sum_{\substack{i=1 \\ i \ne d}}^{Ng} P_i \quad (16)$$

5.2 Transmission Losses are considered:

Considering equation 5, equation 2 can be rewritten as

$$XP_d^2 + YP_d + Z = 0 \quad (17)$$

where $X = B_{dd}$ (18a)

$$Y = \sum_{\substack{j=1 \\ j \ne d}}^{Ng} \left(B_{id} + B_{di}\right)P_j + B_{do} - 1 \quad (18b)$$

$$Z = P_D + \sum_{\substack{i=1 \\ i \ne d}}^{Ng}\sum_{\substack{i=1 \\ i \ne d}}^{Ng} P_i B_{ij} P_j + \sum_{\substack{i=1 \\ i \ne d}}^{Ng} B_{io} P_i - \sum_{\substack{i=1 \\ i \ne d}}^{Ng} P_i + B_{do} P_d + B_{oo} \quad (18c)$$

The positive roots of the equation are obtained as:

$$P_d = \frac{-Y \pm \sqrt{Y^2 - 4XZ}}{2X}$$

where $Y^2 - 4XZ \ge 0$ (19)

The positive root of equation is considered.

[VI] SEARCH IN POLAR COORDI-NATE SYSTEM

The proposed search method is explored to search the power generation pattern and weight pattern to find the non-inferior solution, in polar coordinate system. In this method, a combination of exploratory move and pattern move is made on position of phasor iteratively to search out the optimum solution for the problem. In the exploratory move the current angle is perturbed in positive and negative directions for each variable one at a time and the best position of phasor is recorded. The exploratory move is a success if the perturbed position of phasor is different from the starting position, otherwise the exploratory move is a failure. In case the exploratory move fails, the perturbation factor is reduced to continue the process. On achieving successful exploratory move, two best points are used to perform the pattern move. This process is repeated until some termination criterion is met.

6.1 Generation Search in Polar Coordinates

In this paper, a search method in polar coordinate system is proposed to solve the economic load dispatch and economic emission load dispatch problems without any restriction to the fuel cost characteristics and constraints.

6.1.1 Exploratory Move:

Generation of the committed unit is defined by a phasor which is rotated through 0 to 180 degree having amplitude such that minimum and maximum operating limits of generator are satisfied. Let an imaginary circle which is drawn for each committed generating unit except the slack unit such that the diameter of the circle represents the minimum and maximum operating range of generating unit. Minimum and maximum operating limits of the generating unit lie diametrically opposite. The centre of the circle C_{pi} and radius R_{pi} is given by Eqs. (20) and (21), respectively. The radius of circle acts as amplitude of phasor and position of this phasor is decided by the angular displacement with respect to the real axis.

$$C_{pi} = \frac{P_i^{\max} + P_i^{\min}}{2} \; ; i = 1,2,..., Ng \; , i \neq d \tag{20}$$

$$R_{pi} = \frac{P_i^{\max} - P_i^{\min}}{2} \; ; i = 1,2,..., Ng \; ; i \neq d \tag{21}$$

At zero angle, maximum power, $P_i^{\max}$ is obtained and at 180^0 angle minimum power, $P_i^{\min}$ is acquired. The power between these limits is calculated by drawing a projection on the real axis and is given by:

$$P_i = 0.5\left[P_i^{\max}(1+\cos\delta_i) + P_i^{\min}(1-Cos\,\delta_i)\right]; \quad i = 1,2,...,Ng\,; i \neq d \tag{22a}$$

The centre of the circle is taken as starting point for representing power to initiate the iterative process. So, initially δ_i is taken as 900 for each circle representing generation so that generation of each unit lies in the middle of the operating limits of each. An angle Δ is selected as suitable angular step angle for the search. The angle is perturbed by subtracting and adding step angle into first and second quadrant of ith generator circle. The corresponding value of power P_i^- and P_i^+ is obtained as:

$$P_i^- = 0.5\left[\begin{array}{l} P_i^{\max}(1+\cos(\delta_i - \Delta)) \\ \quad + P_i^{\min}(1-Cos(\delta_i - \Delta)) \end{array}\right]; i \neq d$$

$$P_i^+ = 0.5\left[\begin{array}{l} P_i^{\max}(1+\cos(\delta_i + \Delta)) \\ \quad + P_i^{\min}(1-Cos(\delta_i + \Delta)) \end{array}\right]; i \neq d$$

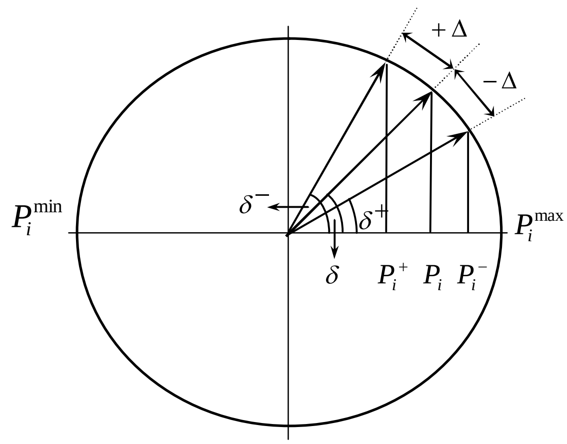

Fig. 1 Generation pattern search in polar coordinate system

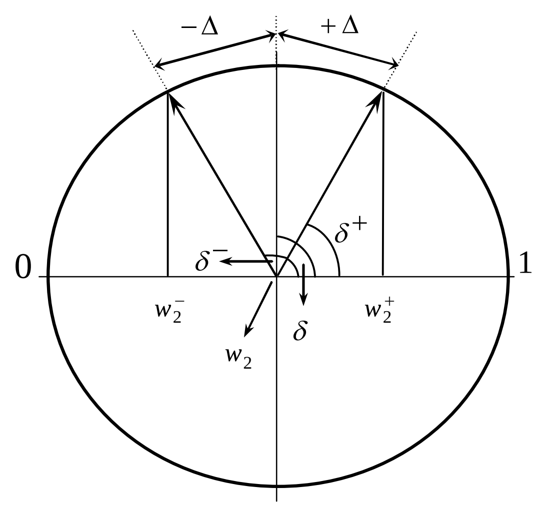

Fig. 2 Weight pattern search in polar coordinate system

Generation of slack generator is computed from Eq. (16a) or Eq. (16b) corresponding to $P_i^- and\; P_j\left(j = 1,2,..., Ng\,, j \neq i,\, j \neq d\right)$ and $P_i^+ and\; P_j\left(j = 1,2,..., Ng\,, j \neq i,\, j \neq d\right)$ respectively. The objective functions, F^- and F^+ are computed for $P_i^-, P_j(j = 1,2,..., Ng , j \neq i)$ and $P_i^+, P_j(j = 1,2,..., Ng , j \neq i)$ corresponding to change in position $-\Delta$ and $+\Delta$, respectively from the base position. The minimum value from F^k, F^- and F^+ is selected for next iteration. The process is continued till the minimum value is obtained for next iteration. The exploratory move is a success, if the new lower value is obtained.

6.1.2 Exploratory Move:

On successful exploratory move, pattern move is executed. A new point δ_i^{k+1} is found by jumping from the current minimum point δ_i^k along a direction connecting the previous best point δ_i^{k-1} as follows:

$$\delta_i^{k+1} = \delta_i^k + \left(\delta_i^k - \delta_i^{k-1}\right) \qquad (25a)$$

The corresponding power and fuel cost function is computed. The process is repeated till the new best point obtained which gives the minimum value in regards to the previous point. The detailed procedure to implement the exploratory and pattern move is depicted here:

***Algorithm 1*: Generation Search**

1: Compute Cpi and Rpi using Eq (20) and (21) for each generating unit.
   Set k = 0, $\delta_i^k = 90^\circ; (i = 1,2,...Ng; i \neq d)$
   Compute $P_i^k(i = 1,2,...Ng, i \neq d)$ from Eq.(22a).
   Compute P_d from Eq. (16) with $P_i^k(i = 1,2,...Ng, i \neq d)$ and
   Compute F^k corresponding to $P_i^k(i = 1,2,...Ng)$
2. Set k = 0,
3: Set k = k+1 and set $\delta_i^n = \delta_i^{k-1}; (i = 1,2,..., Ng; i \neq d)$ and $F^n = F^{k-1}$
4: Set counter i =0
5. Update i = i +1
6: IF ($i = d$) THEN GOTO 9
7: Update $\delta_i^+ = \delta_i^n + \Delta$, Compute P_i^+ from Eq.(22c)
   Compute P_d^n from Eq. (16) with P_i^+ and $P_j^n(j = 1,2,...Ng, j \neq d, j \neq i)$
   Compute F^+ corresponding to P_i^+ and $P_j^n(j = 1,2,..., Ng, j \neq i)$
8: Update $\delta_i^- = \delta_i^{k-1} - \Delta$, Compute P_i^- from Eq.(22b)
   Compute P_d^n from Eq. (16) with P_i^- and $P_j^n(j = 1,2,...Ng, j \neq d, j \neq i)$
   Compute F^+ corresponding to P_i^- and $P_j^n(j = 1,2,..., Ng, j \neq i)$
9: Find $F = Min\left(F^n, F^+, F^-\right)$ and save corresponding angle as δ_i^n
10: IF $\left(F < F^n\right)$ THEN begin set $F^n = F$ end
11: IF $(i < Ng)$ GOTO 5
12: Modify $\delta_i^k = \delta_i^n \; (i = 1,2,.., Ng, i \neq d)$ and $F^k = F^n$
13: IF $\left(F^k < F^{k-1}\right)$ THEN
Begin
13.1. Update
   $\delta_i^{k+1} = \delta_i^k + \left(\delta_i^k - \delta_i^{k-1}\right); (i = 1,2,...Ng; i \neq d)$
13.2. Compute P_d^{k+1} from Eq. (16) with $P_i^{k+1}(i = 1,2,...Ng, i \neq d)$
13.3. Compute F^{k+1} corresponding to $P_i^{k+1}(j = 1,2,..., Ng)$
13.4. IF $\left(F^{k+1} > F^k\right)$ GOTO 3
13.5. Set $\delta_i^{k-1} = \delta_i^k; (i = 1,2,..., Ng, i \neq d)$ and
   $F^{k-1} = F^k$
   $\delta_i^k = \delta_i^{k+1}; (i = 1,2,..., Ng, i \neq d)$
   and $F^k = F^{k+1}$

13.6. GOTO 12.1
End

14: Reduce step size $\Delta = \Delta / \beta$

15: IF $\|\Delta\| > \varepsilon$, THEN GOTO 2

16: STOP

[VII] WEIGHT SEARCH IN POLAR COORDINATE SYSTEM

Weights assigned to all the participating objectives except the prime objective is defined by a phasor which is rotated through 0 to 180 degree having amplitude such that weights remain normalized. Consider an imaginary circle named as weight circle, drawn to compute the weights between 0 and 1 by rotating weight phasor through 0 to 180 degree angle. The diameter of the circle is such that the minimum value (0) and maximum value (1) lie on the diametrically opposite sides of circle on real axis. The centre of circle, C_{wi} is 0.5 and radius of circle, R_{wi} is 0.5. The radius of circle acts as amplitude of weight phasor and position of this weight phasor is decided an angle giving a projection on the real axis representing actual weight. The weight w_2 is computed by a point representing the projection of weight vector on the real axis as:

$$w_2 = 0.5 + 0.5 Cos\ \delta \qquad (26)$$

and $w_1 = 1 - \sum_{m=2}^{2} w_m \qquad (27)$

Weight pattern search in polar coordinate system is employed to search preferred non-inferior solutions. The position of weight phasor is perturbed by subtracting and adding step angle into first and second quadrant of m^th weight circle. The corresponding value of power w_m^- and w_m^+ is obtained as:

$$w_2^- = 0.5\left(1 + Cos\ (\delta - \Delta)\right) \qquad (28)$$

$$w_2^+ = 0.5\left(1 + Cos\ (\delta + \Delta)\right) \qquad (29)$$

Corresponding to the perturbed weights non-inferior solutions are achieved. The maximum value from μ^k , μ^- and μ^+ is selected for next iteration. The process is continued till the maximum value is obtained. The exploratory move is a success, if the new higher value is obtained. On successful exploratory move, pattern move is executed.

The process is repeated till the new best point obtained which gives the maximum value in regards to the previous point. Stepwise procedure to find the non-inferior solution by searching the weight pattern is elaborated below:

***Algorithm 2*: Weight Search**

1: Set $\delta^o = 90^\circ$. Find w_2 and w_1=1-w_2.
Compute non-inferior solution implementing Algorithm 1 and μ_D^0

2. Set k=0

3: Set k=k+1 and $\mu_D^n = \mu_D^k$

4: Update $\delta_2^+ = \delta_2^n + \Delta$. Find w_2^+ and $w_1^+ = 1 - w_2^+$
Implement Algorithm 1 to find non-inferior solution. Compute μ_D^+

5: Update $\delta_2^- = \delta_2^n - \Delta$. Find w_2^- and $w_1^- = 1 - w_2^-$
Implement Algorithm 1 to find non-inferior solution. Compute μ_D^-

6: Find $\mu_D = Max\left(\mu_D^n, \mu_D^+, \mu_D^-\right)$

7: IF $\left(\mu_D > \mu_D^n\right) THEN\ begin$, set $\mu_D^n = \mu_D$ and save δ_2^n corresponding to μ_D^n end

8: Modify $\delta_2^k = \delta_2^n$ and $\mu_D^k = \mu_D^n$

9: IF $\left(\mu_D^k > \mu^{k-1}\right)$ THEN

Begin

9.1: Update $\delta_2^{k+1} = \delta_2^k + \left(\delta_2^k - \delta_2^{k-1}\right)$. Find w_2 and w_1=1-w_2

9.2: Implement Algorithm 1 to find non-inferior solution. Compute μ_D^{k+1}

9.3: IF $\left(\mu_D^{k+1} < \mu_D^k\right)$ GOTO 3

9.4: Set $\delta_2^{k-1} = \delta_2^k$, $\mu_D^{k-1} = \mu_D^k$ and

$\delta_2^k = \delta_2^{k+1}$, $\mu_D^k = \mu_D^{k+1}$ and GOTO 6.1

End

10: Reduce step size $\Delta = \Delta / \beta$

11: IF$\left(\|\Delta\| < \varepsilon\right)$, THEN GOTO step 2

12: STOP

[VIII] RESULTS AND DISCUSSION

The performance of proposed search method is tested on four different kinds of economic dispatch having various combinations of operating cost functions and constraints. The different case undertaken to validate the proposed technique are given below:

8.1 Economic Load Dispatch without valve loading

The results are demonstrated on economic load dispatch problem having quadratic operating cost function ignoring the effect of valve loading. Transmission losses are neglected and generators operating limits are considered. A practical test system consisting of 40-generating unit is under taken [10]. The results of economic load dispatch problem using proposed search method are depicted in Table 1 for 9,000 MW and 10,500 MW demands. The achieved results are compared to those obtained through Variable scaling hybrid differential evolution method [10]. The results obtained by proposed search method are better in respect of the operating cost achieved with 2 seconds of time.

8.2 Economic Load Dispatch with valve loading

The valve point loading has been undertaken into consideration while solving the economic load dispatch problem. Generators operating limits are considered as inequality constraints.

Transmission losses are neglected, to study three different systems consisting of 3-generators, 13-generators and 40-generators are considered for a load demand of 850 MW, 1,800 MW and 10,500 MW respectively [2]. Table 2 shows the result of economic load dispatch problem obtained by applying the proposed generation search in polar coordinate system and the results are compared to those obtained by classical evolutionary programming (CEP), fast evolutionary programming (FEP), mean fast evolutionary programming (MFEP) and improved fast evolutionary programming (IFEP) [2]. As depicted in Table 2, the proposed search method obtains lower operating cost than the CEP, FEP, MFEP and IFEP thus resulting in the higher quality solution as evident from the percentage deviation in operating cost depicted in Table 2. The generation schedules obtained by proposed generation search method are given in Table 1 for 3, 13 and 40-unit generating systems. The results depicted in Table 1 perform the comparison with the results obtained by particle swarm optimization with local random search. The results by the proposed generation search method are still better. Third unit is selected as dependent unit to obtain optimal value of operating cost for three unit systems.

8.2.1 Selection of slack generator

The optimal value of generation cost depends upon the selection of slack generator. Table 3 and 4 show the variation of generation cost and generation schedule with the selection of dependent generator for three unit and thirteen unit generation systems.

8.2.2 Considering Transmission loss

The value of scaling factor β and step size Δ was found as 1.2 and 31^0 respectively after experimental verification. The best solution is depicted in Table 5.

8.3 Economic Load Dispatch with ramp rate and prohibited operating zone

The economic load dispatch of committed generators with ramp rate limits as well as limit of prohibited operating zones has been solved with the proposed generation search in polar coordinate system. Generator’s operating limits are considered as inequality constraints along with transmission losses. Two systems, 6–generators [9] and 15–generators [9] for load demand of 1263

MW and 2630 MW are taken for test, respectively. Table 6 shows the results of economic load dispatch problem. Tables 6-7 show the results of economic load dispatch problem obtained by the proposed method and these results are compared to those obtained through particle swarm optimization [9]. As seen in Tables 6 and 7, the generation search in polar coordinate system obtains lower average generation cost than the genetic algorithms and particle swarm optimization method, thus resulting in the higher quality solution with lesser time.

8.4 Economic Emission Load Dispatch problem

The proposed generation search in polar coordinate system is also applied to test the economic-emission load dispatch problem. Weighting method is employed to convert the multi-objective optimization problem into scalar optimization problem. Weight pattern are searched is applied by searching weights of participating objectives in polar coordinates system. Two test problems are presented to illustrate the feasibility of proposed method and one test problem is compared with fuzzy logic controlled genetic algorithm [14] and results are depicted in Tables 8-10. Table 8 depicts the economic dispatch solution whereas Table 9 presents the minimum emission schedule. Best compromised solution for economic-emission dispatch is shown in Table10.

[IX] CONCLUSION

In this paper, a search strategy has been applied for optimal generation schedule which performs the exploratory move. The proposed method to search the generation of committed units in polar coordinate system has been successfully applied to economic dispatch problem as well to emission dispatch problems with all types of operating cost curves and a variety of constraints. Results show that the proposed method emerged as a better optimization tool. The main advantage of the method is that there is no need to compute the derivative of the functions and arrive at the solution with relative small known number of comparison and function evaluations.

The harmful ecological effects caused by emissions of particulates and gaseous pollutants can be reduced by adequate distribution of load between the plants of a power system. However this leads to a noticeable increase in the operating cost of the plants. The solution set of the problem is non-inferior due to conflicting nature of the objectives and has been obtained through weighting method. Fuzzy decision making methodology is exploited to decide the 'best' generation schedule. When the weight combinations are simulated by giving suitable variation, the number of non-inferior solutions increases exponentially with the increase in the number of objectives. So the process of generation of non-inferior solution surface becomes very time consuming. Another limitation with the simulated weight problem is that the decision maker may not be provided with the weight set that corresponds to actual best solution, In order to overcome the limitation of the interactive method it is proposed to search the optimal pattern. In this method, the solution is guaranteed within the fixed number of iterations. The method is equally applicable to solve multi-objective optimization problems and falls in the category of interactive solution procedure.

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Table 1: Generation schedule by the proposed method

Generator Power output (MW)	9000 MW		10500 MW		10500 MW	10500 MW	1800 MW	850 MW
	Variable Scaling Hybrid Differential Evolution[10]	**Generation Search in Polar Coordinate**	Variable Scaling Hybrid Differential Evolution[10]	**Generation Search in Polar Coordinate**	Particle Swarm Optimization with Local Random Search [4]	**Generator Scheduling using Generation Search in Polar Coordinate method**		
P_1	79.63	79.94	80.00	79.99	111.9858	113.42	538.57	299.78
P_2	119.99	120.00	120.00	120.00	110.5273	113.42	75.55	150.33
P_3	189.98	190.00	190.00	190.00	98.5560	96.47	224.46	399.87
P_4	36.27	36.49	42.00	42.00	182.9266	187.21	109.87	
P_5	42.00	36.61	42.00	42.00	87.7254	96.24	109.87	
P_6	140.00	140.00	140.00	140.00	139.9933	111.77	109.87	
P_7	300.00	300.00	300.00	300.00	259.6628	222.22	109.87	
P_8	299.98	300.00	300.00	300.00	297.7912	295.81	109.87	
P_9	300.00	300.00	300.00	300.00	284.8459	294.45	109.87	
P_{10}	131.97	148.73	300.00	283.16	130.0000	218.38	77.41	
P_{11}	94.03	124.95	295.22	316.19	94.6741	296.20	77.40	
P_{12}	94.00	124.95	324.10	303.41	94.3734	242.45	92.40	
P_{13}	174.03	163.96	424.75	447.19	214.7369	283.16	55.00	
P_{14}	327.70	323.24	500.00	494.56	394.1370	394.26		
P_{15}	339.51	323.24	500.00	496.83	483.1816	394.26		
P_{16}	339.49	323.24	500.00	496.62	304.5381	394.26		
P_{17}	350.34	323.24	500.00	500.00	489.2139	497.90		
P_{18}	500.00	500.00	500.00	500.00	489.6154	462.99		
P_{19}	505.00	499.94	500.00	500.00	511.1782	513.96		
P_{20}	550.00	550.00	550.00	550.00	511.7336	513.96		
P_{21}	550.00	550.00	550.00	550.00	523.4072	447.50		
P_{22}	550.00	550.00	550.00	550.00	523.4599	447.50		
P_{23}	550.00	550.00	550.00	550.00	523.4756	471.23		
P_{24}	550.00	550.00	550.00	550.00	523.7032	471.23		
P_{25}	550.00	550.00	550.00	550.00	523.7854	471.23		
P_{26}	550.00	550.00	550.00	550.00	523.2757	471.23		
P_{27}	549.99	550.00	550.00	550.00	10.0000	10.16		
P_{28}	10.00	10.22	10.00	12.30	10.6251	10.16		
P_{29}	10.00	10.25	10.94	12.37	10.0727	10.12		
P_{30}	10.00	10.00	10.00	12.37	51.3321	96.37		
P_{31}	20.01	20.00	20.00	20.00	189.8048	189.94		
P_{32}	20.01	20.00	20.00	20.00	189.7386	189.94		
P_{33}	20.00	20.00	20.00	20.00	189.9122	189.94		
P_{34}	20.00	20.00	20.00	20.00	199.3258	158.46		
P_{35}	18.01	18.00	18.00	18.00	199.3065	168.82		
P_{36}	18.00	18.00	18.00	18.00	192.8977	172.78		
P_{37}	20.00	20.00	18.00	20.00	110.0000	89.44		
P_{38}	25.06	25.00	25.00	25.00	109.8628	89.44		
P_{39}	25.00	25.00	25.00	25.00	92.8751	89.44		
P_{40}	25.00	25.00	25.00	25.00	511.6883	512.22		
Cost ($/h)	**121253.01**	**121246.60**	**143943.90**	**143924.80**	**122035.79**	**121768.50**	**18025.06**	**8234.29**

Table 2: Comparison of results for different system with valve-point loading effect

Evaluation Method	3-UNIT SYSTEM 850 MW		13-UNIT SYSTEM 1800 MW		40-UNIT SYSTEM 10500 MW	
	Minimum Value	% age Deviation	Minimum Value	% age Deviation	Minimum Value	% age Deviation
Binary Genetic Algorithm [2]	8234.08	0.00267 %	---	---	---	---
Floating Point Genetic Algorithm [2]	8234.07	---	---	---	---	---
Classical Evolutionary Programming [2]	8234.07	---	18048.21	-0.2999	123488.29	- 1.3926
Fast Evolutionary Programming [2]	8234.07	---	18018.00	-0.1328	122679.71	- 0.7427
Mean Fast Evolutionary Programming [2]	8234.08	0.00267 %	18028.09	-0.1887	122647.57	- 0.7167
Improved Fast Evolutionary Programming [2]	8234.07	---	17994.07	---	122624.35	- 0.6979
Particle Swarm Optimization using local random search [4]	---	---	---	---	122035.79	-0.2195
Generation Search in Polar Coordinate	**8234.29**	**0.00255 %**	**18025.06**	**-0.1719**	**121768.50**	---
Scale Factor (β)	**2.9**		**1.20042**		**1.127239**	
Step Angle (△)	**7**		**34**		**22.345**	

Table 3: Variation in in Fuel Cost without transmission loss for 3-Units System with respect to slack unit selected

Unit Power Output	Fuel Cost of Dependent Unit		
	1	2	**3**
P_1(MW)	498.97	399.19	**299.78**
P_2(MW)	101.02	149.55	**150.33**
P_3(MW)	250.00	301.25	**399.87**
Total Power Output	849.99	850.00	**850.00**
Total Fuel Cost	8242.09	8366.81	**8234.29**

Table 4: Variation in operating cost with respect to slack unit chosen for 13-units system with valve-point loading for a load demand 1800 MW

Dependent Unit	1	2	3	4	5	6	7	8	9	10	11	**12**	**13**
P1(MW)	179.52	179.58	179.58	448.90	448.90	448.90	448.80	448.80	448.80	538.55	538.55	**538.57**	**538.57**
P2(MW)	299.30	299.18	299.07	223.70	223.70	223.70	150.01	150.01	150.01	75.46	75.46	**75.55**	**75.55**
P3(MW)	260.66	299.07	299.18	79.44	79.44	79.44	151.62	151.62	151.62	224.55	224.55	**224.45**	**224.46**
P4(MW)	111.51	109.82	109.82	159.72	110.36	110.36	110.04	110.04	110.04	109.87	109.87	**109.87**	**109.87**
P5(MW)	109.96	109.87	109.87	110.36	159.72	110.50	110.02	110.02	110.02	109.87	109.87	**109.87**	**109.87**
P6(MW)	118.96	109.86	109.86	110.50	110.50	159.72	109.96	109.96	109.96	109.87	109.87	**109.87**	**109.87**
P7(MW)	120.07	109.85	109.85	109.96	109.96	109.96	159.72	110.10	448.80	109.87	109.87	**109.87**	**109.87**
P8(MW)	120.07	109.85	109.85	110.10	110.10	110.10	110.10	159.72	109.75	109.87	109.87	**109.87**	**109.87**
P9(MW)	120.07	109.86	109.86	109.75	109.75	109.75	109.75	109.75	159.72	109.87	109.87	**109.87**	**109.87**
P10(MW)	92.98	103.90	103.90	77.23	77.23	77.23	77.23	77.23	77.23	40.01	77.40	**77.40**	**77.41**
P11(MW)	77.40	74.94	74.94	76.42	76.42	76.42	76.42	76.42	76.42	77.40	40.01	**77.40**	**77.40**
P12(MW)	95.14	91.81	91.81	91.71	91.71	91.71	91.71	91.71	91.71	92.41	92.41	**55.00**	**92.40**
P13(MW)	94.34	92.40	92.40	92.21	92.21	92.21	92.21	92.21	92.21	92.40	92.40	**92.40**	**55.01**
Total Fuel Cost	18776.78	18180.21	18180.21	18129.54	18076.30	18129.54	18129.54	18129.54	18129.54	18028.36	18028.36	**18025.06**	**18025.06**

Table 5: Result of 3-units system with transmission loss

P_1(MW)	324.3991
P_2(MW)	190.2858
P_3(MW)	498.9324
Power Output (MW)	1013.6170
Fuel Cost ($/h)	9813.728
Losses (MW)	163.6174

Table 6 Comparison of results for a 6-Units system for a demand of 1263 MW

Units	Genetic Algorithm Method [9]	Particle Swarm Optimization Method [9]	Particle Swarm Optimization using local random search [4]	New Particle Swarm Optimization [4]	New Particle Swarm Optimization using Local Random Search [4]	Generation Search in Polar Coordinate Method
P_1(MW)	474.8066	447.4970	447.4440	447.4734	446.96	448.23
P_2 (MW)	178.6363	173.3231	173.3430	173.1012	173.3944	173.60
P_3 (MW)	262.2089	263.4745	263.3646	262.6804	262.3436	263.24
P_4 (MW)	134.2826	139.0594	139.1279	139.4156	139.5120	138.81
P_5 (MW)	151.9039	165.4761	165.5076	165.3002	164.7089	165.52
P_6 (MW)	74.1812	87.1280	87.1698	87.9761	89.0162	86.00
Cost ($/h)	15459.00	15450.00	15450.00	15450.00	15450.00	15442.38
Tr. Loss(MW)	13.0217	12.9584	12.9571	12.9470	12.9361	12.4065

Table 7 Comparison of results for 15-Units system for a demand of 2630 MW

Units	Particle Swarm Optimization Method [4]	Genetic Algorithm Method [4]	Generation Search in Polar Coordinate method
P_1 (MW)	439.1162	415.3108	455.00
P_2 (MW)	407.9727	359.7206	380.00
P_3 (MW)	119.6324	104.4250	130.00
P_4 (MW)	129.9925	74.9853	130.00
P_5 (MW)	151.0681	380.2844	315.6957
P_6 (MW)	459.9978	426.7902	460.00
P_7 (MW)	425.5601	341.3164	430.00
P_8 (MW)	98.5699	124.7867	60.00
P_9 (MW)	113.4936	133.1445	25.00
P_{10} (MW)	101.1142	89.2567	58.2465
P_{11} (MW)	33.9116	60.0572	80.0
P_{12} (MW)	79.9583	49.9998	80.00
P_{13} (MW)	25.0042	38.7713	25.00
P_{14} (MW)	41.4140	41.9425	15.00
P_{15} (MW)	35.6140	22.6445	15.00
Cost ($/h)	32858.00	33113.00	32604.47
Tr. Loss (MW)	32.4306	38.2782	28.9580

Table 8: Comparison of Pure Economic dispatch results

Generation of Units	Fuzzy Logic Controlled Genetic Algorithm Method [14]			Generation Search in Polar Coordinate method		
	Demand (MW)			Demand (MW)		
	500	700	900	500	700	900
P_1 (MW)	49.47	72.14	101.11	52.13	76.03	103.28
P_2 (MW)	29.40	50.02	67.64	29.50	49.15	70.38
P_3 (MW)	35.31	46.47	50.39	35.00	45.20	60.46
P_4 (MW)	70.42	99.33	158.80	70.75	102.90	139.53
P_5 (MW)	199.03	264.60	324.08	192.57	266.34	325.00
P_6 (MW)	135.22	203.58	256.56	136.76	191.33	251.97
Loss (MW)	18.86	36.15	58.58	16.72	30.96	50.62
Cost ($/h)	28150.8	38384.09	49655.40	28079.33	38207.77	49298.35
Emission(Kg/h)	314.53	543.48	877.61	309.55	536.75	849.95

Table 9: Comparison of Pure Emission dispatch results

Generation of Units	Fuzzy Logic Controlled Genetic Algorithm Method [14]			Generation Search in Polar Coordinate system		
	Demand (MW)			Demand (MW)		
	500	700	900	500	700	900
P_1 (MW)	81.08	120.16	133.31	34.94	96.40	124.16
P_2 (MW)	13.93	21.36	110.00	40.36	78.89	111.17
P_3 (MW)	66.37	62.09	100.38	76.21	91.85	109.41
P_4 (MW)	85.59	128.05	119.27	72.96	112.66	141.29
P_5 (MW)	141.70	209.65	250.79	172.29	188.35	250.77
P_6 (MW)	135.93	201.12	251.25	130.82	170.69	225.24
Loss (MW)	24.61	42.44	65.00	27.60	38.84	62.59
Cost ($/h)	28756.71	39455.00	53299.64	28510.98	39310.00	50976.89
Emission(Kg/h)	286.59	516.55	785.64	286.14	463.59	750.07

Table 10: Comparison of economic-emission dispatch results

Generation of Units	Fuzzy Logic Controlled Genetic Algorithm Method [14]			Generation Search in Polar Coordinate system		
	Demand (MW)			Demand (MW)		
	500	700	900	500	700	900
P_1 (MW)	65.23	80.16	111.40	54.79	84.59	122.92
P_2 (MW)	24.29	53.71	69.33	36.34	57.04	79.98
P_3 (MW)	40.44	40.93	59.43	44.43	59.64	74.99
P_4 (MW)	74.22	116.23	143.26	76.39	105.01	142.59
P_5 (MW)	187.75	251.20	319.40	167.17	226.80	287.90
P_6 (MW)	125.48	190.62	252.11	137.52	197.81	238.86
Loss (MW)	17.41	32.85	54.92	16.64	30.89	47.27
Cost ($/h)	28231.06	38408.82	49674.28	28153.02	38367.04	49674.44
Emission(Kg/h)	304.90	527.46	850.29	289.73	494.35	785.14