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Comparison of Constraints Handling Methods for Economic Load Dispatch Problem using Particle Swarm Optimization Algorithm

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***Abstract*— The main goal of economic load dispatch (ELD) problem is to find an optimal operating condition for the committed generating units in order to minimize total operational cost while satisfying the constraints. The ELD problem becomes more complicated and non-convex when valve point effects of the generator are considered. The penalty function approach (PFA) is widely used to handle the constraints in ELD problem due to simple implementation. However, it requires a proper penalty factor tuning and provides inconsistent result. This paper investigates the performances of modification of infeasible particle (MIP) method based on particle swarm optimization (PSO) for solving ELD problem. The performances of MIP and PFA methods have been compared in terms of optimal result, convergence characteristic and robustness. The proposed MIP and PFA have been tested on three standard test systems (consists of 3, 6 and 40 generating units) to validate their effectiveness. The simulation result confirmed that MIP has better convergence characteristic and more robust compared to PFA. Therefore, the MIP approach can be applied in any optimization algorithm for solving constraint ELD problem effectively.**

***Keywords*— Constraints Handling; Economic Load Dispatch; Particle Swarm Optimization; Valve Point Effect**

I. INTRODUCTION

ELD is an important optimization problem in power system operation and planning [1]. The main objective of ELD is to schedule power generator output with respect to the load demand as well as operational constraints at lower operation cost. The input-output characteristics of modern generators are nonlinear by nature because of the valve-point loadings, prohibited operating zone, multi-fuel options and rate limits [2]-[4]. Thus, the characteristics of ELD problems become multimodal, discontinuous and highly nonlinear.

The particle swarm optimization (PSO) is a population based stochastic optimization technique. This is based on the concept of swarms and their intelligence as well as their movement. This algorithm was developed in 1995 by James Kennedy and Russell Eberhart [5]. It comprises of a group of creatures (particles) performing the same action in a search space. The swarms are basically the groups that serve the same purpose like food hunting.

The PSO is inspired from the relative behaviour of the creatures that live and move in groups like swarm of birds or bees [5]. The PSO algorithm has been effectively used for solving many non-linear and non-convex optimization problems [6]–[9] . Unlike the mathematical optimization methods, this algorithm does not required any gradient information about the objective. Thus it can obtain the best optimal solution effectively [10]-[13].

The ELD problem consists of several equality and inequality constraints such as power balance, generation limits and prohibited operating zones which required a proper constraints handling during optimization process. Currently, the penalty function approach (PFA) is widely used due to simple implementation and less complexity [14],[15] . However, it required a proper penalty factor tuning to satisfy the constraints especially the power balance constraint.

In this paper, a modification of infeasible particle (MIP) is proposed as a mechanism to handle the constraints in ELD problem using PSO algorithm. Its performances are compared with the PFA for solving ELD problem. It has been tested on three different test systems which are 3-unit test system, 6-unit test system and 40-unit test system.

This paper is organized as fallows, section 2.0 presents the problem formulation ELD. Section 3.0 briefly review the constraint handling approaches. Section 4.0 discusses the implementation of PSO algorithm for solving ELD problem. Section 5.0 discusses the performances of MIP and PFA based on PSO algorithm on three different test systems. The obtained results are also compared with the reported results for verification. Finally, the conclusion are drawn in section 6.0.

II. MATERIAL AND METHOD

A. Problem Formulation of Economic Load Dispatch

The main objective of economic load dispatch is to minimize the total fuel cost (C_t) of each generating unit while satisfying the total power demand and operational constraints. The objective function of ELD problem is defined as follows:

$$Min \quad C_t = \sum_{i=1}^{Ng} C_i(P_i) = a_i + b_i P_i + c_i P_i^2 \qquad (1)$$

where a_i, b_i and c_i are the cost coefficients, n_g is the number of generator, C_i is the cost of ith generator and P_i is the real power output of ith generator.

When considering the valve-point effect of the thermal generator, the cost function can be described as superposition of sinusoidal function and quadratic function. As a results, the cost function become non-smooth and non-linear function as shown in Fig. 1. The formulation of cost function with valve-point effect as follows:

$$C_i(P_i) = a_i + b_i P_i + c_i P_i^2 + \left| e_i \times \sin(f_i \times (P_i^{\min} - P_i)) \right| \qquad (2)$$

where e_i and f_i are the cost coefficients for ith generator reflecting valve-point effect.

The minimization of equations (1) and (2) is subjected to the power balance and power limit constraints as follows:

1) Power Balance Constraint: The total power generated must be equal to total power demand (P_D) and transmission loss (P_L) as follows:

$$\sum_{i=1}^{Ng} P_i = P_D + P_L \; ; i=1,2,\ldots N_g \qquad (3)$$

The total transmission loss is a function of unit power output that can be calculated using B-coefficient. The simplest quadratic form of transmission loss is as follows:

$$P_L = \sum_{i=1}^{Ng} \sum_{j=1}^{Ng} P_i B_{ij} P_j \qquad (4)$$

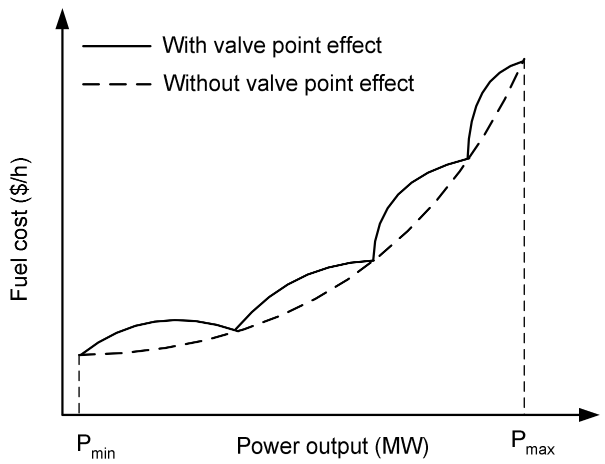

Fig. 1 Fuel cost characteristic with valve point effect

An formula extended formula that contains a linear term and a constant term is referred to Kron's loss formula as follows:

$$P_L = \sum_{i=1}^{Ng} \sum_{j=1}^{Ng} P_i B_{ij} P_j + \sum_{i=1}^{Ng} B_{i0} P_i + B_{00} \qquad (5)$$

where B_{ij} B_{0j} and B_{00} are transmission loss coefficients matrix.

2) Power Limit Constraint: To ensure the generator in stable condition, the power generated by ith generator should restricted to the minimum (P_i^{min}) and maximum (P_i^{max}) limits as follows:

$$P_i^{\min} \le P_i \le P_i^{\max} \qquad (6)$$

B. Particle Swarm Optimization for ELD Problem

PSO is a population-based algorithm which search the optimal solution in parallel using a swarm of particles. In the swarm, each particle represents a potential solution of the optimization problem. The searching behaviour of PSO is inspired by birds flocking or fish schooling for finding the food source. Each bird or fish positions is represents as particle for possible solution (x) in searching area. The movement of these particles are guided by personal best position (*pbest*) and global best position (*gbest*).

Local leader or the personal best position (*pbest*) represents the best position found by the ith particle itself. The global leader or the global best position (*gbest*) represents the global best position found by neighbours of this particle so far. Acceleration coefficients (C_1 and C_2) are non-negative constants which control the influence of *pbest* and *gbest* on during searching process. The r_1 and r_2 are two independent random numbers between 0 and 1.

In every iteration, the velocity of the ith particle (v_i^{k+1}) is updated according to the following formula [12], [13], [15]:

$$v_{id}^{k+1} = w^k v_{id}^k + c_1 r_1 (pbest_{id}^k - x_{id}^k) + c_2 r_2 (gbest_d^k - x_{id}^k) \qquad (7)$$

where d is the number of problem variable (number of generator), v_i^k is the velocity of ith particle at iteration k and x_i^k is the current position of ith particle at kth iteration.

The inertia weight (w) is used to control the exploration capability of particles in the search space. To enhance the exploration capability of PSO. The inertia weight is varies according to the incremental of iteration number as follows:

$$w^k = w_{\max} - \left(\frac{w_{\max} - w_{\min}}{k_{\max}} \right) \times k \qquad k=1,2,\ldots k_{max} \qquad (8)$$

where w_{min} and w_{max} are the predefined minimum and maximum value of weights respectively, k is the current iteration number and k_{max} is the maximum iteration number.

The current position or possible solution (x_{id}^{k+1}) is updated according to the updated velocity in (7) and (8) as follows:

$$x_{id}^{k+1} = x_{id}^k + v_{id}^{k+1} \qquad (9)$$

The constraints handling is an important factor in order to ensure that optimization algorithm (such as PSO) to satisfy all the equality and inequality constraints in (3) to (6). Therefore, this paper propose an effective constraint handling named modified infeasible particle (MIP) for solving ELD problem effectively instead of penalty factor approach (PFA). The details explanation of both methods are described in next section.

C. Implementation Steps of PSO for Solving ELD Problem

The following steps describe the implementation of PSO for solving the ELD problem:

Step 1: **Read input data**
Input data consists of generator cost coefficients, power limits and network losses coefficients.

Step 2: **Initialization**
Set the parameters setting for PSO (swarm size, initial velocity and maximum iteration). Then, the particle are randomly generated according to power limit constraints.

Step 3: **Evaluation function**
The fitness of each individual is evaluated by the evaluation function using (2) and (11) for MIP and PFA methods respectively.

Step 4: **Initialization of *pbest*, *gbest***
Initial particles are set as initial *pbest* values, while the best fitness function among the *pbest* value is defined as *gbest*

Step 5: **Update the swarm**
The velocity and position are updated using equations (7) and (9).

Step 6: **Constraints handling**
Apply the constraints handling techniques either MIP or PFA as described in next subsection.

Step 7: **Update *pbest* and *gbest***
Evaluate the fitness of particle as in **Step 3**. If the current value is better than the previous *pbest*, the current value is stored as *pbest*. Otherwise, it remained similar to the previous *pbest*. The *gbest* value is the best value of the current *pbest*.

Step 8: **Stopping Condition**
Repeat the Steps 4 to 8 until the maximum iteration is reached.

Step 8: Display the final results

1) Penalty Function Approach (PFA): The PFA is widely used to handle the equality constraints by converting into unconstraint problem. This approach penalized the infeasible solutions by multiplying a constant penalty for those solutions are violated the considered constraints such as power balance constraint. The penalized objective function combined the objective function with the penalized function. In general, the penalty function for a problem with *m* constraints can be described as follows [16]:

$$f_p(x) = f(x) + \sum_{i=1}^{m} K_i(x_i) \qquad (10)$$

where $f_p(x)$ is the penalized objective function, $f(x)$ is the objective function, K_i is a constant imposed for violation of *i*th constraint and *m* is the number of considered constraints.

In ELD problem, the PFA is integrated with the objective function in order to satisfy the power balance constraint in (3). The violated power balance constraint will be penalized and the evaluation function ($f(p_i)$) can be minimize until the constraint is satisfied. In this approach, the penalty parameter must be chosen carefully to distinguish between feasible and infeasible solutions. The evaluation function based on PFA for satisfying power balance constraints in ELD problem can be defined as follows [14],[15],[17]:

$$f(P_i) = \sum_{i=1}^{Ng} F_i(P_i) + K \times abs\left(\sum_{i=1}^{Ng} P_i - (P_D + P_L) \right) \qquad (11)$$

2) Modification of Infeasible Particle (MIP): The PFA method is not guarantee the all the possible solutions produced by optimization algorithm satisfied the equality constraints. This is because the equality constraint are most difficult to obtained when nonlinear problem are considered such ELD with valve point effect [18]. Therefore, the modification infeasible particle (MIP) is proposed to be applied in ELD with nonlinear characteristic without penalty factor. The MIP works by repairing the infeasible solution (violated the power balance constraints) into feasible solution that satisfied the considered constraints. It can ensure that all the possible solution generated by optimization algorithm are satisfied the constraint. The details pseudo code of MIP as follows:

Input: updated particle (P_i^{k+1}), total power demand (P_D) and transmission loss coefficients
Begin (MIP Approach)
Step 1: Calculate power balance error (ΔP): $\Delta P = P_D - \sum(P_i) - P_L$
Step 2 Choose any *j*th generator number between 1 and N_g: j = fix(rand*N_q +1)
Step 3 **While** (the $|\Delta P| > \varepsilon$; ε is very small positive number, i.e ε=0.00001)
Set P(i,j) = P(i,j) + ΔP.
Check power limit for each generator
If (P(i,j) > P_i^{max}
P(i,j) = P_i^{max}
end
If (P(i,j) < P_i^{min}
P(i,j) = P_i^{min}
end
Calculate transmission loss (P_L) using (5)
Calculate ΔP
Choose another *j*th number of generator (without repeat its own number)
End While
End (MIP approach)
Output: Feasible updated particle (P_i^{k+1})

III. RESULTS AND DISCUSSION

The MIP and PFA constraints handling approaches for ELD problem have been tested on two standard different test systems in order to reveal their performances. Both constraints handling methods are employed in PSO algorithm. The parameters setting for PSO is as follows: acceleration coefficients (C_1 and C_2) are set to 2 and the swarm size is 30. The maximum iteration number is to 100 for both test systems. The Test Systems 1 and 2 are taken from [17] considering the valve-point effect and transmission losses. All the simulation works have been performed using MATLAB software.

A. Test System 1: 6-Bus 3-Unit Test System with Valve-Point Effect

Firstly, the PFA and MIP have been tested the standard 3-Unit Test System [17]. It consists of 3 generating units with total power demand of 210 MW. In this test system, valve-point effect are considered where the fuel cost coefficients and transmission loss coefficients are taken from [17].

Table I shows the statistical results of both methods obtained after 30 runs. It can be seen that minimum cost produced by MIP and PFA are same for this test system. However, the average and standard deviation (SD) results achieved by MIP method is better than PFA. The optimal generator output produced by MIP and PFA are tabulated in Table II.

Fig. 2 compared the convergence characteristic both methods for finding the best cost. It clearly shows that the MIP approach reach to the lowest cost faster than PFA. In the early iteration it shows that PFA generate a very high cost of generation due to penalty for not satisfying the power balance constraints. However, the MIP solution capable lower cost since the constraints have been satisfied in every iterative process. Fig. 3 shows the MIP method can provide consistent results compared to PFA after 30 runs, thus reveal the robustness of MIP method for solving this test system.

The solution obtained by using PFA and MIP are compared with the results of existing algorithm that using the hybrid of GA-APO and NSOA [18] approach for the same test system as shown in Table III. It is found that the cost obtained by PSO is lower than the GA-APO. Therefore, the PSO with MIP constraint handling method capable to produce lower cost as well as consistent results with smallest standard deviation.

TABLE I
STATISTICAL RESULT AFTER 30 RUNS FOR PD = 210MW (TEST SYSTEM 1)

Cost ($/h) / Methods	PFA	MIP
Minimum	3199.01	3199.01
Average	3231.67	3199.01
Maximum	3262.75	3199.01
SD	**27.5249**	**0.0006**

*SD is standard deviation

TABLE II
COMPARISON OF OPTIMAL COST OBTAINED BY PSO WITH PFA AND MIP METHODS (TEST SYSTEM 1)

Power Output / Methods	PFA	MIP
P_1 (MW)	50.0000	50.0000
P_2 (MW)	76.0015	76.0015
P_3 (MW)	90.8627	90.8627
$\sum P_i$ (MW)	216.8641	216.8641
P_L (MW)	6.8641	6.8641
Cost ($/h)	**3199.01**	**3199.01**

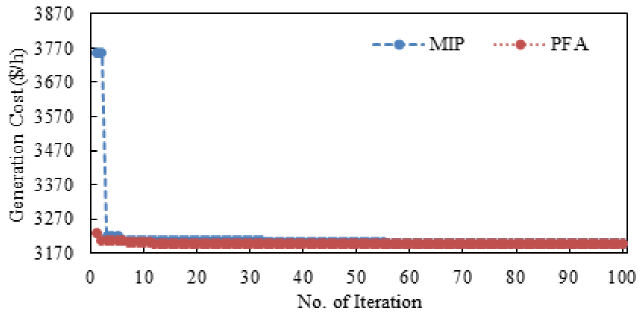

Fig. 2 Convergence characteristic of PFA and MIP (Test System 1)

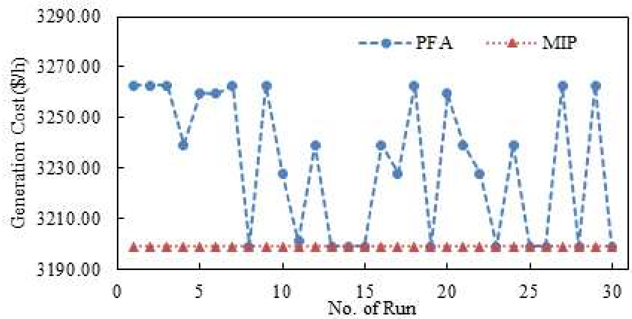

Fig. 3 Distribution of the minimum cost after 30 runs (Test System 1)

TABLE III
COMPARISON WITH GA-APO AND NSOA (TEST SYSTEM 1)

Power Output / Methods	GA-APO [18]	NSOA [18]	PFA	MIP
P_1 (MW)	61.6467	50.0000	50.0000	50.0000
P_2 (MW)	95.1632	86.0678	76.0015	76.0015
P_3 (MW)	60.5402	79.7119	90.8627	90.8627
$\sum P_i$ (MW)	217.3501	215.7797	216.8641	216.8641
P_L (MW)	7.3460	5.7797	6.8641	6.8641
Cost ($/h)	**3341.7710**	**3205.99**	**3199.01**	**3199.01**

B. Test System 2: IEEE 30-Bus 6-Unit Test System with Valve-Point Effect

The performances of the proposed constraint handling methods have been tested on the power system benchmark, IEEE 30-Bus 6-unit test system [17]. It consists of 6 generating units with valve point effect and the total power demand is 283.4 MW.

The simulation results show that MIP method can provide better result after 30 runs as shown in Table IV. The MIP method produce smallest standard deviation (SD=0.474979) compared to PFA method (SD=17.50099). The optimal generator output for both methods presented in Table V. It clearly shows that the MIP method produced lower cost compared to PFA. Thus, it shows the capability of proposed method for obtaining better generation cost with smallest standard deviation.

The convergence characteristic of PFA and MIP are shown in Fig. 4. It can be seen that the MIP achieved lower cost faster than PFA which is similar as in Test System 1. It is also capable to obtain consistent results with smallest standard deviation as shown in Fig. 5.

The comparison of MIP and PFA based PSO algorithm have been compared with the results of existing algorithm such as GA-APO, NSOA [18] and MSG-HP [17] algorithms in Table VI. It is found that the cost obtained by MIP method is lower than the GA-APO and PFA methods. It found that the PSO with MIP constraints handling method can produce better cost and lower standard deviation.

TABLE IV
STATISTICAL RESULT AFTER 30 RUN FOR PD = 283.4 MW (TEST SYSTEM 2)

Cost ($/h) / Methods	**PFA**	**MIP**
Minimum	927.2819	925.4947
Average	959.6878	925.5868
Maximum	984.6240	928.0992
SD	**17.50099**	**0.474979**

*SD is standard deviation

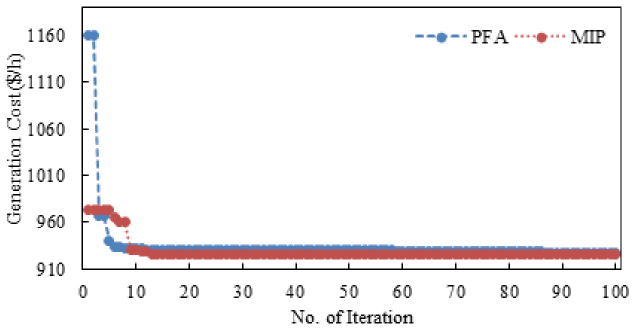

Fig. 4 Convergence characteristic of PFA and MIP (Test System 2)

TABLE V
COMPARISON OF OPTIMAL COST OBTAINED BY PSO WITH PFA AND MIP METHODS (TEST SYSTEM 2)

Generation / Methods	**PFA**	**MIP**
P_1 (MW)	200.0000	199.5996
P_2 (MW)	20.0000	20.0000
P_3 (MW)	25.0125	25.0000
P_4 (MW)	13.7709	18.5162
P_5 (MW)	21.3316	17.7581
P_6 (MW)	14.0555	13.5646
$\sum P_i$ (MW)	294.1705	294.4386
P_L (MW)	10.7725	11.0386
Cost ($/h)	**927.28**	**925.49**

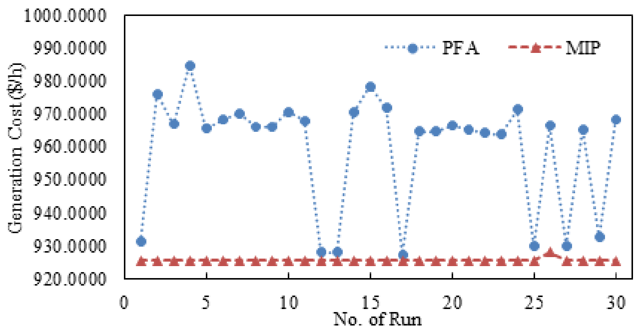

Fig. 5 Distribution of the minimum cost after 30 run (Test System 2)

IV. CONCLUSION

This paper investigated the performances of two different constraints handling methods which are modification of infeasible particle (MIP) and penalty factor approach (PFA) for solving constraint ELD problem with valve point effect. Both methods have been employed in PSO algorithm and compared with the reported results. Based on this study, it should be highlighted that the constraints handling method also influence the performance of optimization algorithm such as PSO. It found that the proposed MIP constraint handling is capable to provide good result (lower cost) compared to PFA method for solving ELD problem with valve point effect.

TABLE VI
COMPARISON WITH OTHER ALGORITHMS (TEST SYSTEM 2)

Generation / Methods	**GA-APO [18]**	**NSOA [18]**	**MSG-HP [17]**	**PFA**	**MIP**
P_1 (MW)	133.9816	182.4784	199.6331	200.0000	199.5996
P_2 (MW)	37.2158	48.3525	20.0000	20.0000	20.0000
P_3 (MW)	37.7677	19.8553	23.7624	25.0125	25.0000
P_4 (MW)	28.3492	17.1370	18.3934	13.7709	18.5162
P_5 (MW)	18.7929	13.6677	17.1018	21.3316	17.7581
P_6 (MW)	38.0525	12.3487	15.6922	14.0555	13.5646
$\sum P_i$ (MW)	294.1600	293.8395	294.5829	294.1705	294.4386
P_L (MW)	10.7563	10.4395	11.1830	10.7725	11.0386
Cost ($/h)	**996.04**	**984.94**	**925.64**	**927.28**	**925.49**

Moreover, the MIP also can produce consistent results with smallest standard deviation after 30 runs. Therefore, the MIP method is suitable to be implemented with any optimization algorithm for solving constraints ELD problem effectively.

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