Efficient Lambda Logic Based Optimisation Procedure to Solve the Large Scale Generator Constrained Economic Dispatch Problem

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Abstract – A simple and efficient Lambda logic (λ -logic) based algorithm is proposed for the solution of the generator constrained economic dispatch problem when the generating units having prohibited zones. The proposed method solves the economic dispatch (ED) problem that takes into account ramp-rate limits, transmission losses and prohibited operating zones in the power system operation. The proposed method uses a simple heuristic rule based on average power of prohibited operating zones which produces the feasibility of solution for the restricted operating units. The effectiveness of the algorithm is tested on five different test systems and the performance compared with other relevant methods reported in the literature. In all the cases, the proposed algorithm performs better than the previous existing algorithms with a less computational burden.

Keywords: Economic Dispatch, Large Scale Power systems, average power of prohibited operating zones.

1. Introduction

Economic dispatch (ED) is the process of allocating the generation levels to the various generating units in the system so as to meet the load demand in the most economic way without violating any system or individual unit constraints. The importance of economic load dispatch is to get maximum usable power using minimum resources. The purpose of ED is to determine the optimal combination of power generations that minimizes the total generation cost while satisfying the constraints. It is difficult to solve the ED problem since the ED problem is a nonlinear, non-convex, discrete optimization problem. However, good solutions of the ED problem would result in great economical benefits. In recent years, a lot of researches have been done and various mathematical programming optimization methods have been employed for solving ED problems. Many techniques such as the lambda iteration method, base point and participation method, and dynamic programming [1-3] have replaced obsolete techniques made as the best point loading and base load methods [1]. Although the most commonly used method in software is the lambda iteration [2] owing to its ease of implementation, its application to a large-scale model is not feasible due to oscillatory problems. Conventionally, the economic dispatch problem of a power system is solved in the environment of unit commitment and real time operation plants by assuming that each of the dispatchable on-line units can be regulated continuously between its minimum generation limit, $P_{i\min}$ and its maximum generation limit,

$P_{i\max}$. In practical systems, however some of the on-line units may have prohibited operating zones due to the physical limitations of power plant components such as vibrations in a shaft bearing in a certain operating region etc. For a unit with prohibited zones, its operating region, $[P_{i\min}, P_{i\max}]$, will be broken into several isolated sub-regions [4]. It can only be dispatched to one of the isolated sub-regions in practical operation.

The isolated sub-regions will form multiple decision spaces and result in a very challenging task for determining the optimal economic dispatch. Several methods have been proposed in the literature [4-16], to solve ED Problem considering transmission constraints and prohibited operating zones. This paper presents a simple and efficient algorithm based on ' λ -logic' for determining the optimal loading of generators having prohibited zones and ramp-rate limits, which uses a simple heuristic rule to determine the advantageous spaces. Recently, Meta-heuristic approaches that use Particle Swarm Optimisation (PSO) [8] and genetic algorithms (GAs) [9] have been successfully used in the solution of nonconvex ED problems with prohibited zones. However, these approaches involve a large number of iterations and are sensitive to the parameter settings. The method proposed in [7-16] made the authors to work on large scale systems. Lin et al. [12] have presented an approach that integrates EP, tabu search and quadratic programming methods, the so-called (ETQ) method to solve the ED problem with prohibited operating zones. A. Pereira-Neto et al. [16] proposed Evolutionary strategy optimisation (ESO) method to solve the ED problem with nonconvex functions and consider nonlinear generator characteristics, such as ramp-rate limits and prohibited operating zones in the power system operation.

In this paper, a ' λ -logic' based approach is used to determine the optimal loading of generators having prohib-

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ited zones. This method requires only two iterations of ‘λ-logic’ based approach for small as well as for large scale ED problems without considering transmission losses and a few iterations when transmission losses considering in to view. The proposed method uses a simple heuristic rule based on average power of prohibited operating zones which produces the feasibility of solution for the restricted operating units. This work has been tested with five test case systems to show its feasibility and effectiveness for ED with Prohibited operating zones, ramp-rate limits, spinning reserve constraints and transmission losses.

2. Problem Formulation

The objective of ED problem is to determine the generation levels for all on-line units which minimize the total fuel cost, while satisfying a set of various constraints.

2.1 Generation operation constraints

In this study, the ramp-rate limits and prohibited operating zone constraints are considered.

A. Ramp-rate limit constraints: As mentioned in Section 1, the actual operating range of all on-line units is restricted by their corresponding ramp-rate limits. Fig. 1 shows three possible situations in which a unit is on-line from time interval $t-1$ to t [9]. Fig. 3a shows the unit operating in steady-state conditions, Fig. 3b shows the unit increasing its power generation whereas Fig. 3c shows the unit decreasing the power generation output.

According to [9] and [14], the inequality constraints due to ramp-rate limits can be rewritten as:

- If generation increases:
- $$P_i^t - P_i^{t-1} \leq UR_i \quad (1)$$
- If generation decreases:

$$P_i^{t-1} - P_i^t \leq DR_i \quad (2)$$

Where P_i^t is the present output power and P_i^{t-1} is the previous output. UR_i is the up ramp-rate limit of the i th generator (in MW/ time period). DR_i is the down ramp-

Fig. 1. Three possible situations of an on-line generation unit

- (a) Steady-state operation
- (b) Increasing the level of power generation
- (c) Decreasing the power output

rate limit of the i th generator (in MW/time period).

B. Prohibited operating zones: References [4], [9], and [14] have shown the input-output performance curve for a typical thermal unit with many valve points. These valve points generate many prohibited zones. In practical operation, adjusting the generation output P_i^t of a unit must avoid unit operation in the prohibited zones.

2.2 Problem formulation for ED problem with various constraints

The objective is to minimize overall generation cost while satisfying load demand and all constraints. Considering this, the ED problem can be formulated as a constrained optimisation problem of the form

$$\min : F_T = \sum_{i=1}^n F_i = \sum_{i=1}^n a_i + b_i P_i + c_i P_i^2 \quad (3)$$

This model is subject to follow constraints:

1. Power balance constraint:

$$\sum_{i=1}^n P_i = P_D + P_L \quad (4)$$

With

$$P_L = \sum_{i=1}^n \sum_{j=1}^n P_i B_{ij} P_j + \sum_{i=1}^n B_{0i} P_i + B_{00} \quad (5)$$

2. Ramp-rate limits constraint:

$$\max(P_i^{\min}, P_i^{t-1} - DR_i) \leq P_i^t \leq \min(P_i^{\max}, P_i^{t-1} + UR_i) \quad (6)$$

3. Prohibited operating zones constraint:

$$\begin{aligned} P_{i,\min} &\leq P_i \leq P_{i,1}^j \\ P_{i,j-1}^u &\leq P_i \leq P_{i,j}^j, j = 2, 3, \dots, m_i \\ P_{i,m_i}^u &\leq P_i \leq P_{i,\max} \end{aligned} \quad (7)$$

4. Spinning reserve constraints:

$$\sum_{i=1}^n S_i \geq S_R \quad (8)$$

For set of on-line units without prohibited operating zones

$$S_i = \min\{(P_{i,\max} - P_i), S_{i,\max}\} \quad (9)$$

For set of on-line units with prohibited operating zones

$$S_i = 0 \quad (10)$$

where n is the total number of generating units; F_T is the total generation cost; F_i is the power generation cost function of the i th unit; a_i, b_i and c_i are the cost coefficients of the i th generating unit; P_D is the total demand; P_i is real power output of the i th generating unit; $P_{i,\min}$ and $P_{i,\max}$ are the minimum and maximum power outputs of the i th generating unit, respectively; P_L is the total transmission network loss as function of the unit power outputs and the Bmatrix coefficients (transmission loss

matrix coefficients); B_{ij} is the ij^{th} element of the loss coefficient matrix, B_{0i} the i^{th} element of the loss coefficient vector, B_{00} is the loss coefficient constant, m_i is the number of prohibited zones of unit i ; j is the index of prohibited zones of a unit i ; $P_{i,j}^{l/u}$ is the lower/upper bounds of the j^{th} prohibited zone of unit i , S_i is the Spinning Reserve Contribution of unit i , S_R is the System Spinning Reserve Requirement, and S_{imax} is the Maximum Spinning Reserve Contribution of Unit i .

3. Solution Methodology

3.1 Proposed overall Algorithm for ED with Prohibited operating zones (considering transmission losses):

The proposed method for ED consists of two executions of 'λ-logic' and the various steps involved in the proposed approach are outlined below.

Step 1: Read the input data $a_i, b_i, c_i, P_{imin}, P_{imax}, n, UR_i, DR_i, P_i^{t-1}, m_i, S_{imax}, P_D, B_{ij}, B_{0i}, B_{00}$ and prohibited operating zone limits.

Step 2: Calculate the average power of unit prohibited zones ($P_{av(i,j)}$) for all the m_i zones. This determines the exact advantageous space of prohibited operating zones (produced first time in literature).

$$P_{av(i,j)} = \frac{P_{i,j}^l + P_{i,j}^u}{2} \quad (11)$$

Step 3: Solve the constrained ED problem without considering prohibited operating regions using 'λ-logic' based algorithm (First execution). If the real power output satisfies the constraints (4), (5), (6), (7) and (8) and prohibited operating zone limits, then optimum dispatch is obtained. Calculate the total generation cost and print the results else Go to step 4.

Step 4: check the unit which is having prohibited zone and the power limits of remaining units are fixed. If a unit i falls in a zone j , compare the output power of that unit with average power of prohibited operating zone ($P_{av(i,j)}$). If it falls below average power of prohibited operating zone choose the operating ranges of power between ($P_{i,j-1}^u \leq P_i \leq P_{i,j}^l$) for that corresponding unit i . If it falls above average power of prohibited operating zone choose the operating ranges of power between ($P_{i,j}^u \leq P_i \leq P_{i,j+1}^l$).

Step 5: After setting the inequality constraints of each unit as in step 4, Solve the constrained ED problem iteratively using 'λ-logic' based algorithm (second execution) and print the results. The obtained real output power of each unit is the optimal power output of each unit which

satisfies the inequality constraints (6, 7), equality constraints (4), transmission loss constraints (5) and spinning reserve constraints (8).

Step 6: Calculate the Total generation cost (\$/h).

3.2 Algorithmic steps involved in 'λ-logic' approach (without considering transmission losses)

Step 1 Pre-prepared Power Demand data (PPD)

- a) Calculate the Incremental cost of all known Power limits of each unit as follows

$$\lambda_{imin} = (dF_i/dP_i) \text{ at } P_i = P_{imin} \quad (12)$$

$$\lambda_{imax} = (dF_i/dP_i) \text{ at } P_i = P_{imax} \quad (13)$$

For $i = 1$ to n units.

Where n - no. of units present in the system.

- b) Arrange λ -vector in ascending order for all units
c) Now calculate total power demand for the known λ_j of the λ_{asc} vector. For this, the following fundamental observation of ED condition is used.

$$\text{If } P_i^J < P_{imin} \text{ then } P_i^J = P_{imin} \quad (14)$$

$$\text{If } P_i^J > P_{imax} \text{ then } P_i^J = P_{imax} \quad (15)$$

$$P_i^J = (\lambda_J - a_i) / (\beta_i) \quad (16)$$

Where $J = 1$ to $2*n$ units.

The calculations of PPD_J are performed only once and tabulated against corresponding values of incremental fuel cost. This information can be treated as static system data and can be supplied as input data along with the coefficients of fuel cost functions. The steps a, b, c completes the first step of the 'λ-logic' method. This part can be done offline and λ_{asc} and PPD_J would remain as static data.

Step 2 Estimation of optimum generation for specified P_D

Say P_D is system demand and look in to PPD if it is present in the PPD, then it is the optimal generation for the generating units. If it is not present in any of the J^{th} location, then Scan PPD_J and identify the interval J and $J+1$ corresponding to P_D .

Calculate λ_{final} by using the following equations.

$$\lambda_{final} = \lambda_J + \left(\frac{(\lambda_J - \lambda_{J+1})(P_D - PPD_J)}{PPD_J - PPD_{J+1}} \right) \quad (17)$$

and eq. (17) can be applied to find optimal generation incorporating (14, 15, 16).

3.3 Algorithmic steps involved in 'λ-logic' approach (Considering transmission losses)

Step 1 Read all the input data.

Step 2 a) Calculate the Incremental cost of all known

Power limits of each unit as follows

$$\lambda_{imin} = (dF_i/dP_i) \text{ at } P_i = P_{imin} \quad (18)$$

$$\lambda_{imax} = p^* (dF_i/dP_i) \text{ at } P_i = P_{imax} \quad (19)$$

For $i = 1$ to n units.

Where n is the no. of units present in the system

p is the penalty factor, generally considered as

- 1 and varies only when Power demand (P_D) reaches towards P_{Dmax} (Total of P_i^{max}).
- b) Arrange λ -vector in ascending order for all units and calculate total power demand for the known λ_j of the λ_{asc} vector while incorporating eqns. (18) and eqns. (19).

$$\begin{bmatrix} \left(\frac{\beta_1}{\lambda_j} + 2B_{11}\right) & 2B_{12} & 2B_{1n} \\ & \left(\frac{\beta_2}{\lambda_j} + 2B_{22}\right) & \\ 2B_{n1} & & \left(\frac{\beta_n}{\lambda_j} + 2B_{nn}\right) \end{bmatrix} \begin{bmatrix} P_1' \\ P_2' \\ P_n' \end{bmatrix} = \begin{bmatrix} 1 - B_{01} - \frac{\alpha_1}{\lambda_j} \\ 1 - B_{02} - \frac{\alpha_2}{\lambda_j} \\ 1 - B_{0n} - \frac{\alpha_n}{\lambda_j} \end{bmatrix} \quad (20)$$

If $P_i' < P_{imin}$ then use (14)

If $P_i' > P_{imax}$ then use (15)

If $P_{imin} < P_i' < P_{imax}$ then P_i' is calculated value from (20).

The calculations of PPD_j are performed only once and tabulated against corresponding values of incremental fuel cost. This information can be treated as static system data for the ED problem. It can be supplied as input data along with the coefficients of fuel cost functions. The steps a, b, c completes the first step of the “ λ -logic” method. This part can be done off-line and λ_{asc} and $PPD_j = \sum_{i=1}^n P_i' - P_L^J$ would remain as static data.

Step 3 Estimation of optimum generation for specified P_D

Say P_D is system demand and look in to PPD if it is present in the PPD, then it is the optimal generation for the generating units. If it is not present in any of the J^{th} location, then Scan PPD_j and identify the interval J and $J+1$ corresponding to P_D .

Calculate λ_{new} by using the following equations.

$$\lambda_{new}^{iter} = \lambda_J + \left(\frac{(\lambda_J - \lambda_{J+1})(P_D - PPD_J)}{PPD_J - PPD_{J+1}} \right) \quad (21)$$

and use (22) to find optimal generation incorporating (14, 15 and 20).

Step 4 Calculate error $\varepsilon = |P_{gen}^{iter} - (P_D + P_L^{iter})|$ where

$$P_{gen}^{iter} = \sum_{i=1}^n P_i^{iter} \text{ and } P_L^{iter} = \sum_{i=1}^n \sum_{j=1}^n P_i^{iter} B_{ij} P_j^{iter} + \sum_{i=1}^n B_{0i} P_i^{iter} + B_{00}$$

If $\varepsilon \leq 0.0001$ stop else repeat step 5 until the goal reaches.

Step 5 Calculate λ_{final} by using

$$\lambda_{final} = \lambda_J + \left(\frac{(\lambda_J - \lambda_{new}^{iter})(P_D - (P_{gen}^{iter} - P_L^{iter}))}{PPD_J - (P_{gen}^{iter} - P_L^{iter})} \right) \quad (22)$$

and use (22) to find optimal generation by incorporating (14, 15 and 20).

4. NUMERICAL RESULTS

This section presents the results of simulations on five test cases to validate the proposed method. The results are compared with other relevant methods in the literature to show its performance. The Algorithm has been coded in MATLAB Version 7.0 using a PC PENTIUM IV, 2.4 GHz and 256 MB RAM as the test platform.

4.1 Description of the test cases:

1. Case 1. The First test system [13] consist of 20 generating units, when transmission loss constraint is incorporated. This case has been compared with Lambda iteration method [14] and new Hopfield neural network [13].

2. Case 2. The second tests data [4] consist of two different 15 generating units, when all the constraints mentioned in Section 2 (except transmission losses and ramp-rate limits) are incorporated. This case has been compared with GA proposed in [12], an ETQ proposed in [12] and an ESO proposed in [15, 16].

3. Case 3. The third test data consist of a) six thermal units, 26 buses, and 46 transmission lines from [8] and b) 3 generating units from [7,9]. Both case a) and b) considers prohibited operating zones and ramp-rate limits. Case (a) has been compared with the PSO method proposed in [8], GA elitist search method in [8] and case (b) has been compared with GA [9] and 2-Phase neural network [7].

4. Case 4. The fourth test data consists of 15 thermal units from [4]. This case also considers prohibited operating zones and ramp-rate limits, as well as transmission network losses [8]. This case has been compared with the PSO method proposed in [8] and with a GA elitist search method in [8].

5. Case 5. The fifth test data consists of 40, 80, 120, 160 and 240 thermal units from [10]. In this case, prohibited operating zones and losses are released. This case has been compared with Classical Method [10] and PHN [10]. This case is tested with 40 units [8, 9] which consider prohibited operating zones and ramp-rate limits, as well as transmission network losses.

4.2 Tests with case 1

In this test, the proposed algorithm is compared with a conventional Lambda iteration method [13] and with a new Hopfield Neural Network [13]. To verify the effectiveness of the proposed approach, a twenty-unit test system is employed. This test system supplies a total load demand of 2500MW. The fuel cost coefficients, generation limits for each unit and the loss formula coefficients of (5) are taken from [13]. The proposed method shown similar results to those of lambda-iteration method, new Hopfield Neural Network[13] and the proposed method are given in Table 1. Computational results from test case 1 confirm that the proposed method is more efficient than the methods available from [13]. Basically, the proposed method is computationally faster than the Lambda-iteration method.. However,

the difference of CPU time required between these methods varies, because the computational requirement of the lambda-iteration method is related to its initial value of λ guessed. The best generation cost reported until now is 62456.6341\$/h [13] and losses are 91.9669MW [13]. The generation cost produced by the proposed method is optimal as 62456.6333\$/h and losses are 91.9666MW.

Table 1. Comparison of three methods (Best solution) (Case 1)

Unit Power output, MW	Lambda-iteration Method[13]	New Hopfield Neural Network[13]	Proposed method
P ₁	512.7805	512.7804	512.78176
P ₂	169.1033	169.1035	169.10151
P ₃	126.8898	126.8897	126.89073
P ₄	102.8657	102.8656	102.86724
P ₅	113.6836	113.6836	113.6829
P ₆	73.5710	73.5709	73.572038
P ₇	115.2878	115.2876	115.29003
P ₈	116.3994	116.3994	116.39986
P ₉	100.4062	100.4063	100.4049
P ₁₀	106.0267	106.0267	106.02737
P ₁₁	150.2394	150.2395	150.23853
P ₁₂	292.7648	292.7647	292.76584
P ₁₃	119.1154	119.1155	119.11422
P ₁₄	30.8340	30.8342	30.831525
P ₁₅	115.8057	115.8056	115.80594
P ₁₆	36.2545	36.2545	36.254365
P ₁₇	66.8590	66.8590	66.859193
P ₁₈	87.9720	87.9720	87.971228
P ₁₉	100.8033	100.8033	100.80266
P ₂₀	54.3050	54.3050	54.304833
P _L (MW)	91.9670	91.9669	91.9666
Total output Power(MW)	2591.9670	2591.967	2591.9666
Total cost(\$/h)	62456.6391	62456.6341	62456.6331
CPU time (sec)	0.033757	0.006355	0.001255

Fig. 2. Incremental cost (\$/MWh) Vs No. of iterations for 20 unit system

4.3 Tests with case 2

Case 2 considers a 15-unit system, in which four units (units 2, 5, 6 and 12) have prohibited operation zones, which are listed in Table II. Additional data can be found in [4]. The remaining 11 units will contribute with regulating reserves. This system supplies a 2650MW load demand with 200MW as spinning reserve.

Table 3 shows the average power of prohibited operating zones ($P_{av(i,j)}$) which is used first time in literature.

$P_{av(i,j)}$ helps to determine the advantageous enforcing limits in which optimal value of output power can be obtained.

Table 4 shows the performance comparison among the proposed algorithms, a GA approach [12], the ETQ method [12] and ESO method [15,16]. The proposed method performs better than the other methods in both the quality of the solution and the computational performance.

According to Table IV, it is observed that unit 2, unit 6 and unit 12 is in the fourth, fourth and second feasible operating regions respectively. Unit 5 is in prohibited operating zone 2. The output power of each unit in Table IV is calculated using Algorithm B under section III. Now apply the Algorithm A to set the new operating boundaries for all the units. Use (11) (i.e according to table III which has calculated by using (11)) to determine the operating regions of the units that consist of prohibited operating regions. According to average power of prohibited operating zone concept, limits of unit 2, 5, 6 and 12 are set to 4th, 2nd, 4th and 2nd region respectively. According to these regions the operating limits are [450 455], [200 260], [455 460] and [55 65] for unit 2, 5, 6 and 12 respectively. The power inequality constraints of remaining 11 units are same. But the reference [12], [15] and [16] has taken the upper operating ranges (i.e from [335 390] instead of [200 260]) which leads to the optimal power combination of units by using proposed algorithm. Thus the proposed method uses (11) to provide optimal feasible region which has been followed in all test cases.

Table 2. Prohibited operating zones (case 2)

Unit	No. of zones	Zone1(MW)	Zone2(MW)	Zone3(MW)
2	3	[185,225]	[305,335]	[420,450]
5	3	[180,200]	[260,335]	[390,420]
6	3	[230,255]	[365,395]	[430,455]
12	2	[30,55]	[65,75]	

Table 3. Average power of Prohibited operating zones (case 2)

Unit	No. of zones	Zone1(MW)	Zone2(MW)	Zone3(MW)
2	3	205.0	320.0	435.0
5	3	190.0	297.5	405.0
6	3	242.5	380.0	442.5
12	2	42.5	70.0	

Table 4. Comparison of proposed algorithm

Unit Power output, MW	Proposed method (without considering Prohibited operating zones)	Proposed method (Considering prohibited operating zones)
P ₁	455.0	455.00
P ₂	455.0	455.00
P ₃	130.0	130.00
P ₄	130.0	130.00
P ₅	295.2988	260.00
P ₆	460.00	460.00
P ₇	465.00	465.00
P ₈	60.00	60.00
P ₉	25.00	25.00
P ₁₀	20.00	20.00
P ₁₁	43.3731	70.00
P ₁₂	56.3279	65.00
P ₁₃	25.00	25.00
P ₁₄	15.00	15.00
P ₁₅	15.00	15.00
Total output Power(MW)	2650.00	2650.00
Total cost(\$/h)	32502.97	32506.18
Mean Computation Time(s)	0.0170	0.0320

Table 5 shows the performance comparison among the proposed algorithms, a GA approach [12], the ETQ method [12] and ESO method [15,16]. The proposed method performs better than the other methods in both the quality of the solution and the computational performance. The total generation cost using the proposed method reduced about 8.82 \$/h, 1.32 \$/h and 1.49 \$/h when compared with GA method, ETQ and ESO method respectively.

Table 5. Comparison of three methods (Best solution) (Case 2)

Unit Power output, MW	GA [12]	ETQ [12]	ESO [16]	Proposed method
P ₁	406.1	450.0	449.953	455.00
P ₂	453.8	450.0	450.054	455.00
P ₃	130.0	130.0	130.000	130.00
P ₄	130.0	130.0	130.000	130.00
P ₅	355.0	335.0	335.137	260.00
P ₆	456.8	455.0	455.393	460.00
P ₇	459.8	465.0	464.376	465.00
P ₈	60.0	60.0	60.013	60.00
P ₉	26.6	25.0	25.010	25.00
P ₁₀	21.6	20.0	20.000	20.00
P ₁₁	36.2	20.0	20.000	70.00
P ₁₂	59.0	55.0	55.059	65.00
P ₁₃	25.0	25.0	25.000	25.00
P ₁₄	15.0	15.0	15.000	15.00
P ₁₅	15.0	15.0	15.000	15.00
Total output Power(MW)	2649.9	2650	2649.995	2650.00
Total cost(\$/h)	32515.00	32507.50	32507.67	32506.18
Mean Computation Time (s)	398.5	15.8	13.8	0.0320

4.4 Tests with case 3

Case 3 a) considers a six-unit system in which all units are within the prohibited operating zones and ramp-rate limits. This system supplies a 1263MW load demand. The data for the individual units and the B matrix of the transmission loss coefficient (with a 100MVA base capacity) are taken from [8].

Table 6 is a comparison of the best solutions obtained with the proposed method, PSO and GA methods, respectively. Notice that all methods obey the system constraints, such as ramp-rate limits and prohibited zones. Fig. 3 shows the number of iterations to hit global optimum for 6 units system.

Case 3 b) considers a 3-unit system in which all units are within the prohibited operating zones and ramp-rate limits. This system supplies a 300 MW load demand. The data for the individual units and their constraints are taken from [7,9]. Table VI is a comparison of the best solutions obtained with the proposed method, 2-Phase neural network and GA methods, respectively.

Table 6. Comparison of three methods (Best solution) (Case 3 (a))

Unit Power output, MW	PSO [8]	GA [8]	Proposed method
P ₁	447.95	474.81	447.5076
P ₂	173.32	178.64	173.3159
P ₃	263.47	262.21	263.4605
P ₄	139.06	134.28	139.0629
P ₅	165.47	151.90	165.4711
P ₆	87.13	74.18	87.13244
P _L (MW)	12.96	13.02	12.95
Total output Power(MW)	1275.96	1276.03	1275.95
Total cost(\$/h)	15450.000	15459.0	15449.796
Average CPU time (sec)	14.86	41.58	0.04687

Fig. 3. Incremental cost (\$/Mwh) Vs No. of iterations for 6 units system

Table 7. Comparison of two methods (Best solution) (case3 (b))

Unit Power output, MW	GA [9]	2-Phase neural network[7]	Proposed Method
P ₁	194.26	165.00	198.436
P ₂	50.00	113.40	80.362
P ₃	79.62	34.00	34.000
P _L , (MW)	24.01	12.45	12.798
Total output Power(MW)	323.89	312.45	312.798
Total cost(\$/h)	3737.20	3652.60	3634.874

From Table 7, it is observed that the optimal generation cost is obtained by the proposed method as 3634.874\$/h. The total generation cost using the proposed method reduced about 102.326 \$/h and 17.726 \$/h when compared with GA method and 2-Phase neural network method respectively.

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4.5 Tests with case 4

Case 5 considers a 15-unit system [4, 8] in which all the units obey the prohibited operating zones and ramp-rate limits. This system supplies 2630MW load demand. The characteristics of this case and the respective *B* transmission loss coefficients matrix are taken from [8].

Table 8. Comparison of three methods (Best solution) (Case 4)

Unit Power output, MW	PSO [8]	GA [8]	Proposed method
P ₁	439.12	415.31	455.0000
P ₂	407.97	359.72	380.0000
P ₃	119.63	104.42	130.0000
P ₄	129.99	74.98	130.0000
P ₅	151.07	380.28	170.0000
P ₆	459.99	426.79	460.0000
P ₇	425.56	341.32	430.0000
P ₈	98.56	124.79	60.0000
P ₉	113.49	133.14	56.87547
P ₁₀	101.11	89.26	160.0000
P ₁₁	33.91	60.06	80.0000
P ₁₂	79.96	50.00	80.0000
P ₁₃	25.00	38.77	25.0000
P ₁₄	41.41	41.94	15.0000
P ₁₅	35.61	22.64	28.07365
P _L , (MW)	32.42	38.28	29.9491
Total output Power(MW)	2662.41	2668.44	2659.9491
Total cost(\$/h)	32858.00	33113.00	32713.9510
Average CPU time (sec)	26.59	49.31	0.016

Fig. 4. Incremental cost (\$/Mwh) Vs No. of iterations for 15 units system

Table 8 compares the best solution of the proposed methods, PSO and GA, respectively. Table VIII lists the comparative performances for the generation cost and average CPU times. The total generation cost using the proposed method reduced about 144.049 \$/h and 399.049 \$/h when compared with PSO method and GA method respectively. Figure 4 shows how the Optimal Incremental Cost reaches iterations.

4.6 Tests with case 5

Case 5 considers five larger test systems are taken from [10]. In this tests, the system consists of 40 units in the realistic Taipower system that is large-scale and mixed generating system where coal-fired, oil-fired, gas-fired, diesel, and combined cycle are all present [10]. The load demand of the system is 9500 MW. The larger test systems 80, 120, 160 and 240 units have been created simply by expanding the 40 unit system. The load demand of the remaining test systems are 200000 MW, 31500 MW, 41000 MW and 57000 MW for the 80, 120, 160 and 240 unit systems respectively. In Table 8, this case releases the transmission losses in order to demonstrate the efficiency of the proposed approach. In Table 9, it is tested with 40 units which consider prohibited operating zones and ramp-rate limits, as well as transmission network losses. Due to lack of *B* loss coefficient data, the *B* loss coefficients matrix is generated randomly. The load demand of the system is 8550 MW.

Table 9. Comparison of three methods (Best solution) (Case 5)

No. of units	Load (GW)	Total cost (k\$/h)		
		CM[10]	PHN[10]	Proposed Method
40	9.5	128.4	129.1	128.4
80	20.0	271.9	272.8	271.9
120	31.5	431.7	432.6	431.7
160	41.0	559.5	560.7	559.6
240	57.0	770.55	774.98	770.54

Table 9 compares best solution of the proposed methods, classical method (CM) and PHN, respectively. From the Table 9, it is observed that the proposed method outperforms the PHN in all cases and it produces the optimal generation cost as similar to CM in all cases. From Table 10, it is observed that, the proposed method produces the feasible and optimal generation for large size systems even when Prohibited operating zones and transmission losses are considered. The optimal generation cost obtained is 129777.531620 \$/h with losses 87.403674 MW.

G. Global Comments

The test results show that Proposed ‘ λ -logic’ performs well, either matching or performing better than many of the previously reported methods. In test case 1, it matches with the Hopfield neural network with slighter reduction in generation cost. The proposed method takes just two iterations to reach the optimal cost for case 1. In test case 2 to case 4, it performs slightly better than the previously reported methods such as 2- Phase neural network, PSO, GA, ETQ and ESO by converging in 2 to 3 iterations. In test case 5, it performs better than the Hopfield neural network and matches with the classical method. It takes single iteration to converge when the transmission losses are neglected. Due to the proposed heuristic rule (Average power of prohibited operating zone), it finds the single advantageous space within single iteration. The solution for large size ED problem obtained without any convergence problem even when all the constraints are included.

Table 10. Optimised generation dispatch for 40-units problem with prohibited zones and transmission losses (case 5)

Unit	1	2	3	4	5	6	7
Output power (MW)	80	80	190	42	42	115	165
Unit	8	9	10	11	12	13	14
Output power (MW)	217	265	165	355	355	230	280
Unit	15	16	17	18	19	20	21
Output power (MW)	270	270	270	470	470	468	468
Unit	22	23	24	25	26	27	28
Output power (MW)	460	460	460	460	460	460	35.58
Unit	29	30	31	32	33	34	35
Output power (MW)	35.48	35.46	54.62	54.57	57.27	52.26	38.25
Unit	36	37	38	39	40		
Output power (MW)	47.25	48.96	50.36	50.16	50.11		

5. Conclusions

This paper presents an efficient and effective approach for solving the economic dispatch problem when the on-line generating units have prohibited operating zones. The proposed approach offers two execution of λ -logic method, which offers a best contribution in the area of economic dispatch. The proposed method uses a simple heuristic rule based on average power of prohibited operating zones which produces the feasibility of solution for the restricted operating units. In contrast to other conventional methods, this approach gives a promising value of power for providing improved economic dispatch. It reduces the computational burden and is superior to many of available techniques of economic dispatch. In most of the cases, the proposed algorithm outperforms other approaches reported in the literature, in that it provides higher-quality solutions with less computational burden. The method yields a good near-optimal solution for large scale systems without any convergence problems for convex functions which has been illustrated through numerical testing and a comparative analysis. This λ -logic method may be suggested for the solution for ED problems for on-line applications when the on-line units having prohibited zones.

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