The performance of COR optimization using different constraint handling strategies to solve ELD

Azralkmin Azmi¹, Samila Mat Zali², Mohd Noor Abdullah³, Mohammad Faridun Naim Tajuddin⁴, Siti Rafidah Abdul Rahim⁵
¹,²,⁴School of Electrical System Engineering, Universiti Malaysia Perlis (UniMAP), Malaysia
³Green and Sustainable Energy (GSEnergy) Focus Group, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Malaysia

ABSTRACT
This research compares the performance of Competitive Over Resources (COR) optimization method using a different type of constraint handling strategy to solve the economic load dispatch (ELD) problem. Previously, most research focused on proposing various optimization techniques using the Penalty Factor Strategy (PFS) to search for a better global optimum. The issue using the penalty factor is that it is difficult to find the correct tune of constant value that influences the algorithm to find the solution. The other technique is using Feasible Solution Strategy (FSS), the idea of which is to locate the infeasible particle to the feasible solution and avoid being trapped by the unsuccessful condition of constraint. This paper investigates the performance of PFS and FSS on the COR optimization method for solving ELD. Both strategies have been tested on two standard test systems to compare the performance in terms of a global solution, robustness and convergence. The simulation shows that FSS is a better solution compared to PFS.

Keywords:
Competitive over resources
Constraint handling
Economic load dispatch
Feasible solution strategy
Optimization

Corresponding Author:
Azralkmin Azmi,
School of Electrical System Engineering,
Universiti Malaysia Perlis (UniMAP),
Kampus UniMAP Pauh Putra, 02600 Arau, Perlis, Malaysia.
Email: azralkmin@unimap.edu.my

1. INTRODUCTION
The economic load dispatch (ELD) of generation is one of the most crucial tasks in modern power systems. It promises better dispatch scheduling to mitigate the increasing cost of fuel for various types of thermal power plant. Solving the ELD problem is a potentially significant economic solution to power system planning and operations. ELD’s goal is to commit the required power consumption by planning the different types of power generation units such that secure total cost production is the cheapest possible while fulfilling the system’s equality and inequality constraints. It keeps the cost of producing electricity to a minimum price by properly allocating workloads among the generating units of the plants with various operating efficiencies, type of fuel cost and total transmission losses of systems. This optimum solution to the problem of generating power contributes significant economic benefits to the operation of the power plant.

Initially, the ELD problem was solved using traditional techniques such as linear, quadratic and nonlinear programming methods as provided in [1-5]. The conventional techniques have a higher probability of becoming trapped in local minima solution due to the complex fuel cost function problem related to the highly nonlinear characteristic of present power generating units such as ramp rate limit and prohibited operating zones. Nowadays, in order to handle the nonlinear fuel cost function, many advanced optimization techniques based on nature-inspired meta-heuristic has been implemented on ELD such as
The performance of COR optimization using different constraint... (Azralmukmin Azmi)

2. ELD PROBLEM FORMULATION

The ELD issue, which deals extensively with financial concerns, refers to the amount of power to be assigned from all generators in an attempt to minimize the cost of supplying the required electrical energy subject to several constraints of multiple generating units. The ELD’s mathematical optimization has three primary parts, which are the optimization variable of the problem, the goal of the objective function and constraints.

2.1. Optimization Variable

The optimized input variable is the real output power of generating units,

\[ P = [P_1, P_2, \ldots, P_{Ng}] \]  

(1)

Where, \( Ng \) is the total number of generating unit in the power system.

2.2. Objective Function

The objective function of ELD is to supply power via each generator unit for the request demand load with minimum generation total fuel cost. ELD’s objective function can be expressed through the problem of mathematical optimization,

\[ \text{minimize } F_{\text{cost}} = \sum_{j=1}^{Ng} F_j(P_j) \]  

(2)

Where

\[ F_j(P_j) = \text{generation cost of the } j^{th} \text{ generator (S/h)} \]
\[ P_j = \text{power of the } j^{th} \text{ generator (MW)} \]

Moreover, the cost coefficient of each generator stated as,

\[ F_j(P_j) = \alpha_j + \beta_j P_j + \gamma_j P_j^2 \]  

(3)

Where,
\( \alpha_j, \beta_j \) and \( \gamma_j \) = coefficients of the \( j^{th} \) generating unit
2.3. Constraints

To achieve ELD’s optimum value, the objective function has been subject to the following limitation constraints:

2.3.1 Power Demand Constraint

Total power generation must be satisfied with the total power demand and power losses as follows,

\[ \sum_{j=1}^{N_g} P_j = P_D + P_L \]  

(4)

Where,

- \( \sum_{j=1}^{N_g} P_j \) = Total power generation (MW)
- \( P_D \) = Total power demand (MW)
- \( P_L \) = Total power transmission loss (MW) using Kron’s loss formula

The total power transmission losses calculated as follows,

\[ P_L = \sum_{j=1}^{N_g} \sum_{k=1}^{N_g} P_{jk} B_{jk} P_k + \sum_{j=1}^{N_g} P_{j0} B_{j0} \]  

(5)

Where,

- \( B_{jk}, B_{j0}, B_{00} \) = B-coefficients or loss coefficients.

2.3.2 Generation Constraint

Each generator’s power generation must be within its operating limits as follows,

\[ P_{j\min} < P_j < P_{j\max} \]  

(6)

Where, \( P_{j\min} \) and \( P_{j\max} \) is minimum and maximum generation limit in MW.

2.3.3 Prohibited Operating Zones

The system involves certain restricted areas related to physical component constraints as follows,

\[ P_{POZ,j}^{\min} \leq P_{POZ,j} \leq P_{POZ,j}^{\max} \]

(7)

Where,

- \( P_{POZ,j}^{\min} \) = minimum border of \( k^{th} \) restricted zone of the \( j^{th} \) generator
- \( P_{POZ,j}^{\max} \) = maximum border of \( k^{th} \) restricted zone of the \( j^{th} \) generator
- \( n_j \) = number of restricted zones of the \( j^{th} \) generator

2.3.4 Ramp Rate Limits

The operating range of all operating units is restricted by their ramp rate limits in the actual power generation process for each unit. An increase or decrease of power generation is as follows,

\[ P_{RRL,j} - P_{RRL,j}^{\max} \leq UR_j \]
\[ P_{RRL,j}^{\min} - P_{RRL,j} \leq DR_j \]
\[ \max \left( P_{RRL,j}^{\max} - P_{RRL,j}, P_{RRL,j}^{\min} - DR_j \right) \leq R_{RRL,j} \leq \min \left( P_{RRL,j}^{\max} - UR_j, P_{RRL,j}^{\max} - DR_j \right) \]  

(8)

Where,

- \( UR_j \) = up ramp limit of the \( j^{th} \) generator (MW/h)
- \( DR_j \) = down ramp limit of the \( j^{th} \) generator (MW/h)
- \( P_{RRL,j} \) = previous output power of the \( j^{th} \) generator (MW/h)
3. COR OPTIMIZATION ALGORITHM FOR ELD

The COR begins at each year with the groups divided based on the food supply for each territory. At this stage, each group is looking for food in its territory. An active participant will periodically remove the weaker participant from the same region throughout the process so that the final process will consist of excellent competitors only. When food sources in a particular field are reduced, the members of the group will also be decreased. Members possibly will migrate to join a group in regions where there is plenty of food resources. Finally, the group with fewer resources is eliminated at the end of the year, leaving only the group with the most food resources. Figure 1 shows the pseudo-code of the COR optimization algorithm implementation to solve the ELD problem.

3.1. Initialisation

Identify parameters of COR such as minimum ($P_{\text{min}}$) and maximum ($P_{\text{max}}$) generation limit of each unit, number of iterations ($N_{\text{iter}}$), number of population ($N_{\text{pop}}$), number of groups ($N_{\text{group}}$), rate of death ($d_{\text{rate}}$) outer searching factor ($D_{\text{sch}}$) and population ratio between inner/outer neighborhood ($P_{\text{sch}}$). The generator’s active power generation is identified as an ELD problem input variable. Then, the population was randomly distributed, ranging over their maximum and minimum limit according to the generator limit stated in (6).

3.2. Evaluation of Generation Cost with Constraint Handling Technique

The fitness of each population is assessed with the objective function in (2) using the Penalty Factor Strategy (PFS) or Feasible Solution Strategy (FSS). The result of the fitness cost calculation is graded from the highest to the lowest solution. Then, the agents were equally distributed into the number of groups, $N_{\text{group}}$ and the best solution was identified as the best group agent for each group.

3.2.1 Penalty Factor Strategy (PFS)

This strategy penalizes ineffective solutions by multiplying a persistent penalty for these alternatives that violate the limitations. To satisfy constraint limitation and disallow the workable area, the individual population’s fitness performance is measured using (9), which is the combination of objective function equation between (2) and PFS linked with related constraints. This evaluation feature is used to obtain the smallest cost generation value while fulfilling the limitation of equality and non-equality constraint problem, as stated in (4-8).

$$f(P) = \sum_{i=1}^{N_{\text{pop}}} \left[ k_1 \sum_{j=1}^{N_{\text{group}}} \left( P_{\text{group}}^j + \frac{P_{\text{group}}^j}{P_{\text{pop}}} \right) \right] + k_2 \sum_{i=1}^{N_{\text{pop}}} P_{\text{group}}^i + k_3 \sum_{i=1}^{N_{\text{pop}}} P_{\text{group}}^i$$

(9)

Where:

$k_1, k_2, k_3 = \text{constraint constant value}$

3.2.2 Feasible Solution Strategy (FSS)

The PFS technique does not ensure that all solutions generated by the optimization algorithm meet the limitations of equality constraint because it is exceedingly difficult to obtain when considering nonlinear problems in ELD. Using FSS, handling constraints based on the repair of the unfeasible solution is implemented to guarantee that all the solutions generated are satisfactory through the optimization process. The details of FSS procedure is shown in Figure 2.
Step 1: calculate power balance error (ΔP) using
\[ ΔP = P_D - (\sum(P_G) + P_L) \]
where:
- \( P_D \) = power demand
- \( P_G \) = power generation
- \( P_L \) = transmission losses

Step 2: randomly select generator using
\[ n = \text{fix}((\text{rand} \times d) + 1) \]
where \( d \) is the number of generators

Step 3: while ( |ΔP| > 0.00001)
- Updated new generation for select generator using
  \[ P_G(n) = P_G(n) - |ΔP| \]
- Check \( P_G(n) \) if exceeds the maximum or minimum generator operating limits
  then assign value to its limits
- Check \( P_G(n) \) if located between trapped area POZ then assign value to nearest it is boundaries
- Calculate ΔP using the new value of \( P_G \) and \( P_L \)
- Randomly select generator \( n \)
end while

Step 4: Update value of \( P_G \)

Figure 2. Constraint handling based on FSS

3.3. Determination of Territory
Each group’s territory is described by using the Euclidean distance among the most excellent agents in the group. The minimum value of the distance between territories, \( d_{\text{min}} \), is the option rate to specify inner territory. The maximum and minimum power generation boundary for inner territory determined in (10),

\[
\begin{align*}
P_{\text{inner min}} &= P_j - d_{\text{min}} \\
P_{\text{inner max}} &= P_j + d_{\text{min}}
\end{align*}
\]

(10)

The maximum and minimum power generation for outer territory determine in (11),

\[
\begin{align*}
P_{\text{outer min}} &= P_j - (d_{ncb} \times l) \\
P_{\text{outer max}} &= P_j + (d_{ncb} \times l)
\end{align*}
\]

(11)

Where \( l \) is the different value between \( P_{\text{max}} \) and \( P_{\text{min}} \) and \( d_{ncb} \) is the option rate of the outer space search capability between 0 and 1.

3.4. New Population Generation and Evaluation
The population quantity between the inner and outer territories of each group must be determined using the ratio of inner and outer neighbourhoods, \( P_{sch} \). Some quantity of the agent’s new population in the group was produced randomly using the inner territory to locate a prospective optimum area within the group boundary. The left agent is obtained randomly using the identified outer territory with a larger searching space area to raise the opportunities of a random agent discovering optimal region outside group margins.

Finally, the new generated agents are set to the maximum and minimum boundary shown in (6). Then, all agents are evaluated using the process details in step 3.2 and update the position of the new best group agent.

3.5. Update Group Members
The group with the highest results from one of the group members will add a new member to its community while the poorest-performing group will eliminate one of its members. The competitive organization will increase its population from this process, to discover potential wealthy assets and the least productive organization will reduce its members.
The performance of COR optimization using different constraint... (Azralmukmin Azmi)
4.2. 15-Unit Test System

This case study consists of 15 generating units of large-scale test systems with a total active load demand of 2630MW. It also considers the ramp rate limits, real power balanced with transmission losses, prohibited operating zones, and generating limits. The parameters of this test system are obtained from [22], and the results are compared with the cases of GA [22], PSO [22], ABC [24] and GA-API [25].

The statistical results of maximum, minimum and average cost achieved after 30 individual runs of PFS and FSS are based on the COR algorithm and compared with other methods as shown in Table 2. The result shows that COR-FSS obtained the best global solution with the value of 32,704.4499 $/h, followed by COR-PFS by 32,717.0105 $/h. Both techniques satisfied the limitation set by the test system constraints. It observed that the COR-FSS technique could produce better quality solution generation cost and the lowest value of standard deviation among all stated technique.

The COR-FSS technique produced the lowest standard deviation (SD) with the value of 3.3154x10^{-4} compared to COR-PFS. However, COR-PFS’ value of standard deviation is higher than GA, PSO, ABC and GA-API. COR-PFS demonstrated its capability to obtain robust and consistent minimum results of cost generation solution.

Figure 4 shows the convergence behaviour of COR-PFS and COR-FSS for a maximum iteration of 200. COR-FSS achieved the lowest cost generation in the early iteration of 20 and gradually move towards optimal results by the end of iteration, which is much faster compared with COR-PFS.

Table 2. Optimal Results for the 15-Unit Test System

| Power Generation (MW) | GA    | PSO   | ABC   | GA-API | COR-PFS | COR-FSS |
|-----------------------|-------|-------|-------|--------|---------|---------|
| G1                    | 415.31| 439.11| 454.2778| 454.70  | 454.7253 | 455.0000 |
| G2                    | 359.72| 407.97| 369.7131| 380.00  | 379.3048 | 380.0000 |
| G3                    | 104.43| 119.63| 124.3210| 129.53  | 129.7756 | 130.0000 |
| G4                    | 74.99 | 129.99| 163.1341| 170.00  | 169.1184 | 170.0000 |
| G5                    | 380.28| 151.07| 460.0000| 460.00  | 459.9703 | 460.0000 |
| G6                    | 426.79| 460.00| 460.0000| 460.00  | 459.9703 | 460.0000 |
| G7                    | 341.32| 425.56| 405.4317| 429.71  | 430.0000 | 430.0000 |
| G8                    | 124.79| 98.57 | 85.6483 | 75.35   | 103.7853 | 71.7561  |
| G9                    | 133.14| 113.49| 92.1289 | 34.96   | 48.9414  | 58.9054  |
| G10                   | 89.26 | 101.11| 157.4626| 160.00  | 133.7865 | 160.0000 |
| G11                   | 60.06 | 33.91 | 74.5293 | 79.75   | 79.2430  | 80.0000  |
| G12                   | 50.00 | 79.96 | 79.8057 | 80.00   | 79.8047  | 80.0000  |
| G13                   | 38.77 | 25.00 | 25.0000 | 34.21   | 25.0048  | 25.0000  |
| G14                   | 41.94 | 41.41 | 19.3117 | 21.14   | 18.2376  | 15.0000  |
| G15                   | 22.64 | 35.61 | 20.8153 | 21.02   | 18.7265  | 15.0000  |
| Total Power Generated | 2668.40| 2662.40| 2661.5795| 2660.36 | 2660.4030| 2660.6615|
| Power Losses (Ploss)  | 38.28 | 32.43 | 31.5795 | 30.36   | 30.4042  | 30.6615  |
| Total Generation Cost ($/h) | 33,113 | 32,858 | 32,787.8365 | 32,732.95 | 32,717.0105 | 32,704.4499 |
| Minimum Cost          | 33,113| 32,858| 32,787.8365| -       | 32,717.0105| 32,704.4499 |
| Maximum Cost          | 33,337| 33,331| -          | -       | 32,981.0896| 2,704.4535 |
| Average Cost          | 33,228| 33,039| 32,791.5366| -       | 32,794.4522| 32,704.4503 |
| SD                    | 0.0087| 0.0070 | 2.4746   | -       | 44.2100  | 3.315464  |

Figure 3. Convergence behaviour of COR-FSS and COR-PFS for 6-unit test systems
The performance of COR optimization using different constraint... (Azralmukmin Azmi)

5. CONCLUSION
This paper comparatively studies the performance of two types of constraint handling techniques, which are PFS and FSS on COR optimization technique to solve the issue of non-convex ELD problem considering generator limit, power balanced, ramp rate limits and prohibited zones. The two test system is used to testify the effectiveness of the proposed method. Based on this research, the constraint handling technique affects the optimization algorithm efficiency of finding better quality solutions. Comparing the outcomes acquired from the COR-PFS and COR-FSS demonstrated that the COR-FSS technique is highly efficient in continuously offering superior solutions in term of searching for a global solution, quick convergence and robustness for non-convex ELD issues compared to COR-PFS and other optimization techniques.

ACKNOWLEDGEMENTS
The author would like to acknowledge the Universiti Malaysia Perlis (UniMAP) and Ministry of Education Malaysia for supporting this research work under the Fundamental Research Grant Scheme (FRGS) with project code FRGS/1/2017/TK10/UNIMAP/02/10.

REFERENCES
[1] K. Iba, H. Suzuki, K. Ichiki Suzuki, and K. Suzuki, “Practical Reactive Power Allocation/Operation Planning using Successive Linear Programming," IEEE Trans. Power Syst., vol. 3, no. 2, pp. 558–566, May 1988.
[2] C. E. Lin and G. L. Viviani, “Hierarchical Economic Dispatch for Piecewise Quadratic Cost Functions,” IEEE Trans. Power Appar. Syst., vol. PAS-103, no. 6, pp. 1170–1175, Jun. 1984.
[3] A. Sasson, “Nonlinear Programming Solutions for Load-Flow, Minimum-Loss, and Economic Dispatching Problems,” IEEE Trans. Power Appar. Syst., vol. PAS-88, no. 4, pp. 399–409, Apr. 1969.
[4] J. P. Zhan, Q. H. Wu, C. X. Guo, and X. X. Zhou, “Fast lambda-Iteration Method for Economic Dispatch With Prohibited Operating Zones,” IEEE Trans. Power Syst., vol. 29, no. 2, pp. 990–991, Mar. 2014.
[5] R. Ramanathan, “Fast Economic Dispatch Based on the Penalty Factors From Newton’s Method,” IEEE Trans. Power Appar. Syst., vol. PAS-104, no. 7, pp. 1624–1629, Jul. 1985.
[6] H. Vennila, B. G. Malini, V. E. Jeba, and T. R. D. Prakash, “Economic Emission Dispatch of Thermal Generating Units using Genetic Algorithm Technique,” Int. J. Enterp. Netw. Manag., vol. 4, no. 4, p. 344, 2011.
[7] M. N. Abdullah, N. A. Rahim, A. H. A. Bakar, H. Mokhlis, H. A. Illias, and J. J. Jamian, “Efficient Evolutionary Particle Swarm Optimization Approach for Nonconvex Economic Load Dispatch Problem,” Przeglad Elektrotechniczny, pp. 139–143, 11-Jul-2013.
[8] M. N. Abdullah, M. A. Ismail, A. Azmi, N. H. M. Radzi, and J. J. Jamian, “Economic and Emission Load Dispatch Solution via Artificial Bee Colony Algorithm,” Adv. Sci. Lett., vol. 23, no. 11, pp. 11158–11161, Nov. 2017.
[9] M. N. Abdullah, A. F. A. Manan, J. J. Jamian, S. A. Jumaat, and N. H. Radzi, “Gbest Artificial Bee Colony for Non-convex Optimal Economic Dispatch in Power Generation,” Indon. J. Electr. Eng. Comput. Sci., vol. 11, no. 1, p. 187, Jul. 2018.

Figure 4. Convergence behaviour of COR-FSS and COR-PFS for the 15-unit test systems
N. A. Rahmat, I. Musirin, and A. F. Abidin, “Differential Evolution Immunized Ant Colony Optimization (DEIANT) Technique in Solving Economic Emission Dispatch,” in *2013 International Conference on Technology, Informatics, Management, and Environment*, 2013, pp. 198–202.

Z. M. Yasin, N. F. A. Aziz, N. A. Salim, N. A. Wahab, and N. A. Rahmat, “Optimal Economic Load Dispatch using Multiobjective Cuckoo Search Algorithm,” *Indones. J. Electr. Eng. Comput. Sci.*, vol. 12, no. 1, p. 168, Oct. 2018.

N. Karthik, A. K. Parvathy, and R. Arul, “Non-convex Economic Load Dispatch using Cuckoo Search Algorithm,” *Indones. J. Electr. Eng. Comput. Sci.*, vol. 5, no. 1, p. 48, Jan. 2017.

S. Mohseni, R. Gholami, N. Zarei, and A. R. Zadeh, “Competition Over Resources: A New Optimization Algorithm Based on Animals Behavioral Ecology,” in *Proceedings - 2014 International Conference on Intelligent Networking and Collaborative Systems, IEEE INCoS 2014*, pp. 311–315, 2014.

R. Gholami, S. Mohseni, B. Zakeri, and H. Abedi, “Driving Point Impedance Restriction in Synthesis of Linear Antenna Arrays using Competition over Resources Optimization Algorithm,” in *2014 4th International Conference on Computer and Knowledge Engineering (ICCKE)*, pp. 414–419, 2014.

A. Azmi, S. M. Zali, M. N. Abdullah, and M. F. N. Tajuddin, “Potential Competitive over Resources (COR) Optimization Method to Solve Economic Load Dispatch Problem,” *J. Electr. Syst.*, vol. 12, no. 3, pp. 529–540, 2016.

Z. N. Zakaria, A. Azmi, M. S. Laili, S. A. Syed Jamalil, and M. H. Sulaiman, “An Extension of Particle Swarm Optimization (E-PSO) Algorithm for Solving Economic Dispatch Problem,” in *Proceedings - 1st International Conference on Artificial Intelligence, Modelling and Simulation, AIMS 2013*, 2014.