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Power Exchange Algorithm for Improving Answers of Meta-heuristic Methods in Economic Dispatch

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Abstract

The main purpose of solving economic dispatch problem in power network is to plan the generation of thermal units in order to meet the network demanded load at minimum operating cost while satisfying constraints of system. The represented algorithm in this paper tends to promote the results of economic dispatch problem. This algorithm implements a solution to reach an optimal point near the initial point addressed by meta-heuristic algorithms by using power exchange in units based on incremental cost. Real model of cost function in thermal units is a non-convex function; therefore, gradient-based methods could not be useful in solving mentioned problem. Although lots of meta-heuristic methods for solving economic dispatch problem with constraints Such as genetic algorithm, imperial competition algorithm, tabu search and particle swarm optimization have been presented and all of them have been succeeded in finding optimal solution, none of them could ensures that there wouldn't be a better point for the problem. Proposed algorithm tends to provide possibility for finding optimal point without calculation burden. This algorithm has been tested on three systems with 10, 13 and 40 thermal units and the results are presented. The conclusions have shown that in the most of the cases, total cost reduced by implementing power exchange algorithm.

Keywords: Economic Dispatch, Gradient-based Algorithm, Incremental Cost, Meta-heuristic Algorithms, Power Exchange Algorithm

1. Introduction

Economic dispatch is a dynamic problem for minimizing fuel cost of thermal units considering power system constraints which should iteratively be solved by changing load demand in network[1]. Different methods have been proposed for solving this problem and their goal was to reach best solution in least possible time. Fuel cost function for thermal units is a quadratic convex function[2,3]. Considering valve loading effect, a sinusoidal term with limited range is added to this quadratic function which makes fuel cost function non-convex[3,5].

Gradient-based Algorithms have been studied for solving economic dispatch. Lambda iteration method[2,6], base point and participation factors method[2,6] and gradient method[2,7] are common methods, and among them Lambda iteration was more under consideration. Because non-convex functions have more than one extremum, Gradient-based Algorithms lose their efficiency in solving EDP with Non-Convex Fuel Cost and Intelligent Stochastic Search Algorithms are used for solution. Various articles have considered EDP with Meta-Heuristic Algorithms like genetic algorithm[8,11], particle swarm algorithm[12,15], tabu search algorithm[16], Simulated Annealing[17], Evolutionary Programming[18], Ant Colony Algorithm[19], Bacteria Foraging Algorithm[20], Hopfield Neural Network[21,22] but these algorithms, because of their stochastic search to a point which might not be the absolute minimum point in problem space. This paper shows that generally there is a better point

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near to optimal point which is not found by intelligent algorithms, because by imposing iteration limit in this algorithms for compromising between minimum cost and solution time, algorithms stops after certain number of iterations until optimal iteration point is reached.

Meta-heuristic methods potential is in escaping local minima. All Meta-heuristic algorithms have a factor for escaping local minima. In genetic algorithm, mutation is an escape way; in PSO a coefficient is obtained in speed updating vector using uniform distribution which leads to escape local minima. In other algorithms there are factors for escape but these algorithms are unable to find optimal points in continuous and differentiable functions with one extremum compared to gradient-based algorithms.

Assuming that there is a better point near the best obtained point by intelligent algorithms that it could not find it, presented algorithm finds the best point near obtained point of meta-heuristic algorithms. Initial point changes to optimal point in that neighborhood by some modifications which also meet constraints of EDP.

2. Economic Dispatch

Purpose of economic dispatch is calculating produced power of thermal units for supplying load and network losses such that minimizes sum of fuel cost in thermal units.

2.1 Cost Function of Thermal Units with Multiple Fuels

Equation (1) shows thermal units fuel cost model with multiple fuels. Considering loading effect adds a sinusoidal term to quadratic function. In Equation (1), $FC_i(P_i)$ is fuel cost of i th thermal unit and $a_{i,k}$, $b_{i,k}$, $c_{i,k}$, $e_{i,k}$, $f_{i,k}$, are coefficients of k th fuel in i th generator. In multiple fuel models certain fuel is used in each thermal unit depending on produced power of each thermal unit.

$$FC_i(P_i) = \begin{cases} a_{i,1}p_i^2 + b_{i,1}p_i + c_{i,1} + \left|e_{i,1}\sin\left(f_{i,1}\left(p_i^{min} - p_i\right)\right)\right| \\ \quad p_i^{min} \le p_i \le p_{i,1} \qquad fuel\ type\ 1 \\ a_{i,2}p_i^2 + b_{i,2}p_i + c_{i,2} + \left|e_{i,2}\sin\left(f_{i,2}\left(p_i^{min} - p_i\right)\right)\right| \\ \quad p_{i,1} \le p_i \le p_{i,2} \qquad fuel\ type\ 2 \\ \quad \vdots \\ a_{i,k}p_i^2 + b_{i,k}p_i + c_{i,k} + \left|e_{i,k}\sin\left(f_{i,k}\left(p_i^{min} - p_i\right)\right)\right| \\ \quad p_{i,k-1} \le p_i \le p_i^{max} \qquad fuel\ type\ k \end{cases} \tag{1}$$

Purpose of EDP is minimizing thermal units cost based on equation (2).

$$Min\ TC(P) = \sum_{i=1}^{N} FC_i(p_i) \tag{2}$$

$$P = [p_1, p_2, \ldots, p_N] \tag{3}$$

In which TC(P) is total cost of thermal units, N is number of thermal units and P is optimization problem variable.

2.2 Economic Dispatch Constraints

One of EDP constraints is equality of load demand with total generated power of all thermal units. Equation (4) shows this constraint.

$$\sum_{i=1}^{N} p_i = P_D + P_L \tag{4}$$

In which P_D, P_L show consumed power and loss power of network, respectively.

Another constraint is power bound of units which is as equation (5) in which p_i^{min}, p_i^{max}, is power bound of i th generator.

$$(p_i^{min} \le p_i \le p_i^{max}) \tag{5}$$

Sum of network losses is expressed by a quadratic function of generators' output power as equation (6):

$$P_L = \sum_{i=1}^{N_g}\sum_{j=1}^{N_g} p_i B_{ij} p_j + \sum_{i=1}^{N_g} B_{0i} p_i + B_{00} \tag{6}$$

In which B_{ij} is ij th element of B coefficient matrix.

2.3 Prohibited Operating Zones Constraints

Errors in generators, pumps, boiler and other equipment may create instability in certain range of generator output power. Because of these errors generator is prohibited from power generation on that area. In fact, there is no operational production unit on that area. This makes non-continuous fuel cost function. The Prohibited Operating Zones (POZs) create constraint[7] for EDP.

$$p_j \in \begin{cases} p_j^{min} \le p_j \le p_j^{LB_1} \\ p_j^{UB_{K-1}} \le p_j \le p_j^{LB_K} \qquad j = 1, \ldots, N_g \\ p_j^{UB_K} \le p_j \le p_j^{max} \end{cases} \tag{7}$$

Figure 1 shows a typically fuel cost function with considering valve effect, prohibited operating zone and multiple fuels.

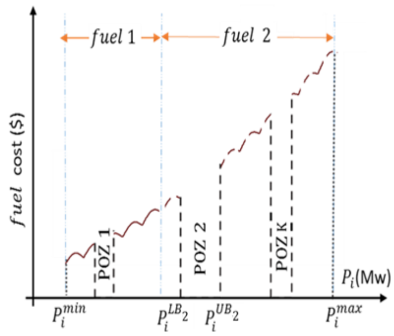

Figure 1. Fuel Cost Curve with Considering Multi-Fuel and POZ.

3. Gradient Base Methods

If fuel cost function for thermal units is convex, we can solve EDP with gradient based methods. Using equality of incremental costs for thermal units in optimal point, gradient method and Lagrangian method are common methods for solving EDP[23].

3.1 Equal Incremental Cost Method

If we consider fuel costs of thermal unit as a quadratic function without valve effect, it is naturally a convex function and we can solve it with equal incremental cost method, with considering equality constraint and power range of generators. In this method, sum of fuel cost minimizes when incremental fuel cost of all units are equal together. Optimal power is obtained by solving equation set (8) with N linear equations.

$$\begin{cases} \frac{dFC_1}{dp_1} = \frac{dFC_2}{dp_2} = \cdots = \frac{dFC_N}{dp_N} \\ \sum_{i=1}^{N} p_i = P_D \end{cases} \qquad (8)$$

These steps should be implemented for considering output power constraint[23]:

- Without considering output power constraint, we solve Equation (8) to obtain output power of all units.
- We change power of units that are out of range to their maximum and minimum power.

if $p_t \geq p_t^{max} \rightarrow p_t = p_t^{max}$

if $p_t \leq p_t^{min} \rightarrow p_t = p_t^{min}$

- Out of range units are considered as negative load and we modify equality constraint as equation (9).

$$\sum_{\substack{i=1 \\ i \neq t}}^{N} p_i = P_D - \sum_{i=1}^{N_t} p_i \qquad (9)$$

- Go to Step 1 and calculate other units' power from Equation (8). We repeat it until we reach to a power which is permissible for all units.

3.2 Gradient Descend Method

If cost function of thermal units is a convex function with more than quadratic degree, we can use gradient descend method for solving economic dispatch with considering output power range and production and consumption equality constraints[23]. This method is based on changing power from initial point in gradient descend direction. We should consider one generator as slack generator for meeting production and consumption equality constraint and express power of N[th] generator based on other generators power as in (10).

$$p_N = P_D - \sum_{\substack{i=1 \\ i \neq s}}^{N-1} p_i \qquad 10$$

As a result, sum of thermal units costs is obtained by Equation (11) which is a variable function based on $N-1$.

$$TC = \sum_{i=1}^{N-1} C_i(p_i) + C_N\left(P_D - \sum_{i=1}^{N-1} p_i\right) \qquad 11$$

In which N^{th} unit is slack.

Equation (12) shows Gradient vector of units cost.

$$\nabla C = \left[\frac{dTC}{dp_1}, \frac{dTC}{dp_2}, \ldots, \frac{dTC}{dp_{N-1}}\right]^T \qquad 12$$

Using Equation[13] we update generators' power along with gradient function reduction form initial point P^0 to a point that gradient vector becomes zero.

$$P^{k+1} = P^k - \varepsilon \nabla C^k \qquad 13$$

In Equation[13], ∇C^k shows gradient function value for each P^k and ε is gradient function effect on updating generators' power. If ε dynamically reduces in iterations based on a certain function, it is possible to reach optimal unit with high speed. Low ε slows algorithm and if higher value allocates to it, it creates fluctuation in generators power near optimal point.

4. Comparison of Non-convex and Convex Cost Function

Cost Function of thermal units with considering valve effect is a continuous non-convex function and if effect of prohibited units considered in generator output power, Cost function becomes piecewise continuous. Non-convex cost function leads to various extermums in cost function. Plurality of extermums trap gradient-based algorithm in local minima and meta-heuristic algorithm were used for solving economic dispatch. Figures 2 and 3 show fuel cost function for two thermal units without considering valve effect and with considering it in 3-dimensional space based on both units' power.

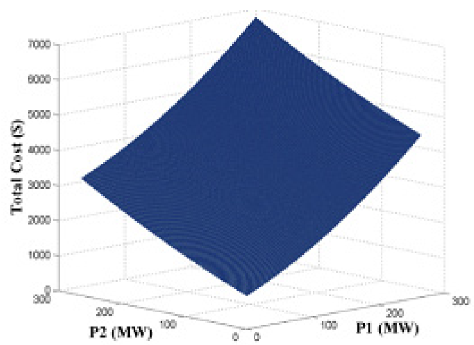

Figure 2. Smooth total cost function.

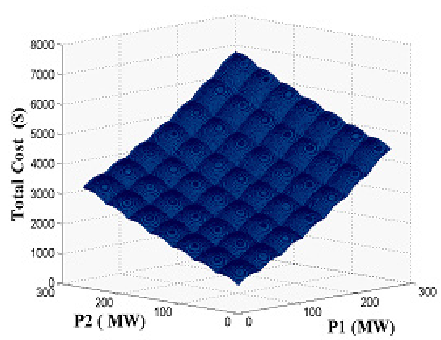

Figure 3. Non-smooth total cost function.

Although Meta-heuristic Algorithms are able to search whole problem space and it is not trapped in local minima, but if we assume that there is only one extermum for this function, meta-heuristic algorithms parameters which escape from local extermums, not only cannot improve solution but slow down its convergence. If problem has one extermum, gradient-based algorithms can quickly calculate extremum point and this calculated answer is necessarily best solution which is the absolute extremum. While in all meta-heuristic methods, even in cases where there is one extremum, there is no certainty that the obtained solution is the best solution and there can be a better point in the neighborhood of the found solution. Figure 4 shows fuel cost function for 13 thermal units which are magnified around optimal solution obtained from meta-heuristic methods and optimal power of each unit is specified as a vertical line. According to Figure 4, cost function gradient which is incremental fuel cost is lower in units 4, 5 and 6 than units 3 and 11. Increasing units 4, 5 and 11 power and instead reducing units 3 and 11 power decreases total fuel cost. Therefore, it is clear that there are better points near obtained powers.

5. Presented Algorithm

In proposed algorithm, all thermal units power obtained from Meta-heuristic algorithms enter as input to algorithm and incremental fuel cost of units arrange from low to high. Units with maximum and minimum incremental fuel cost that are far from their maximum and minimum range with δ magnitude and are not in prohibited operating zone will selected for power exchange. Power exchange is as follows: Power of unit with minimum incremental fuel cost which is at least δ amount lower than its maximum power, is increased by δ and power of unit with maximum incremental fuel cost which is at least δ amount higher than its minimum power, is reduced by δ. This increase and decrease in power in two selected units with minimum and maximum incremental fuel cost ensures satisfying generation and consumption equality constraint in EDP.

This algorithm which is based on incremental fuel cost ensures calculation of optimal point near the point obtained by Meta-heuristic methods. Algorithm steps are as follows:

Step 1: Entering value of initial point $P^0 = [p_1^0 \dots p_i^0 \dots p_N^0]$ which is obtained by solving EDP using Meta-heuristic methods.

Step 2: Calculating incremental fuel cost of all units in i^{th} iteration (λ^{it}) for each $P^{it} = [p_1^{it} \dots p_i^{it} \dots p_N^{it}]$

Step 3: Selecting units with minimum and maximum incremental fuel cost which can exchange power.

$$\forall\, mn \in \{1,..,N\} \;\exists\, mn \,\Big|\, \left\{ \begin{array}{c} \lambda_{mn} = Min[\lambda^{it}],\; p_{mn}^{it} \le p_{mn}^{max} - \delta\,, \\ p_{mn}^{it} \notin POZ_j\,, j \in \{1,..,k\} \end{array} \right\} \quad (14)$$

$$\forall\, mx \in \{1,..,N\}\ \exists\, mx \left| \begin{Bmatrix} \lambda_{mx} = Max[\lambda^{it}],\ p_{mx}^{it} \le p_{mx}^{min} - \delta\,, \\ p_{mx}^{it} \notin POZ_j\,, j \in \{1,..,k\} \end{Bmatrix} \right. \quad (15)$$

In which

- mn: Unit which has minimum incremental fuel cost and is at least δ lower than its maximum and is not in POZs.
- mx: Unit with maximum incremental fuel cost and is at least δ higher than its generation and is not in POZs.
- $\lambda_{mx}, \lambda_{mn}$: Maximum and minimum incremental fuel cost
- p_{mx}^{it} , p_{mn}^{it}: Generators power with minimum and maximum incremental fuel cost.
- p_{mx}^{min} , p_{mn}^{max}: Maximum and minimum power in units' mnth and mxth

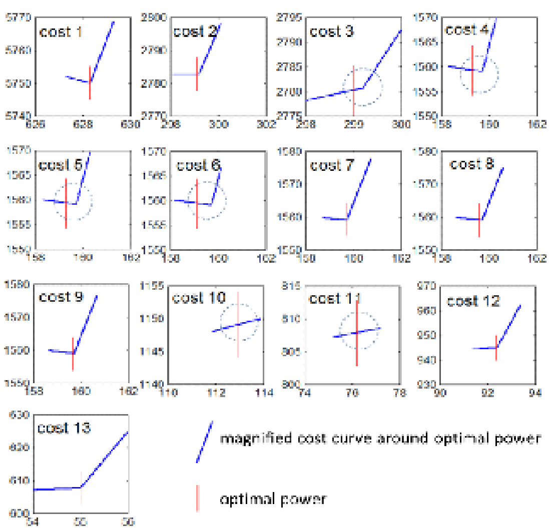

Figure 4. Fuel cost function of 13 thermal units.

Step 4: Power exchange between two selected units based on following equations.

$$p_{mn}^{it+1} = p_{mn}^{it+1} + \delta \quad (16)$$

$$p_{mx}^{it+1} = p_{mx}^{it+1} - \delta \quad (17)$$

Step 5: If total cost of thermal units decreases in power exchange, we return to step 2 and if it increases, we reduce δ to half and go to step 2 and study improvement of total cost of units with lower power exchange. It should be mentioned δ could be any value between 0 and 1. if it's close to zero the convergence would be slow, and if it's close to one fluctuations might be observed in the convergence, so an educated guess suggests to take the mean value i.e. 0.5, similar to the logic used in bisection method in root finding have high speed and low fluctuation in convergence. This trend continues until power exchange rate for improving total cost becomes lower than ε, which considering the small value of ε, this much power exchange has negligible influence on total costs. Figure 5 shows presented algorithm flowchart.

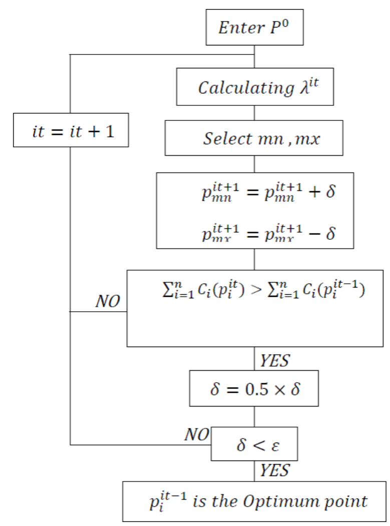

Figure 5. The flowchart of presented algorithm.

6. Case Studies

To show ability of power exchange algorithm in reaching optimal point near initial optimal point obtained from meta-heuristic algorithm it is tested on three case studies. System one includes 10 thermal units with multiple fuels and valve loading effect which its information presented in [10]. Second system has 13 thermal units considering valve loading which its data is presented in [24] and third system includes 40 thermal units with valve loading[24].

For solving these systems, algorithms are implemented in MATALB on a computer with 2.8GHZ processor and 4GB memory. 500kw is considered for initial power exchange and ε is considered 1kw to stop algorithm when power exchange goes below 1kw.

6.1 First System

This system has 10 thermal units with 3 types of fuel and valve loading effect. Optimal points for 10 units which

are obtained from solving EDP with methods ED-DE, RGA[25], DE[26], CGA-MU[10], IGA-MU[10], TSA and PSO[27], CIHBMO[28], SOH-PSO[29], CMSFLA[30], were input for this algorithm. Table 1 shows values for power and total cost of thermal units after using algorithm. Improvement rate in total costs (profit) which is the difference between total cost before and after using algorithm is shown in Table 1. Algorithm implementation time is dependent on number of iterations but its maximum time is less than 50ms.
Table 1. Best results for first case study

Table 1. Best results for first case study

	ED-DE	DE	RGA	CGA-MU	IGA-MU
p_1	218.103	220.938	219.996	222.011	219.127
p_2	211.959	212.610	212.701	211.704	211.203
p_3	279.647	283.581	283.739	283.945	280.657
p_4	239.505	240.042	240.521	237.805	238.430
p_5	279.966	282.892	282.313	280.448	276.418
p_6	239.640	240.446	240.579	236.012	240.446
p_7	287.736	292.979	293.085	292.050	287.740
p_8	239.955	240.193	240.311	241.924	240.761
p_9	427.601	406.999	406.980	424.201	429.337
p_{10}	275.888	279.320	279.775	269.901	275.852
TP	2700	2700	2700	2700	2700
TC_{new}	624.089	624.456	624.529	624.359	624.119
TC_{old}	624.525	624.843	624.963	624.812	624.402
profit	0.4360	0.3873	0.4338	0.4532	0.2826
	TSA	PSO	CIHBMO	SOH-PSO	CMSFLA
p_1	219.496	225.573	218.105	206.809	219.066
p_2	206.709	208.224	211.722	206.275	211.225
p_3	291.353	278.806	280.657	265.537	279.658
p_4	237.673	238.027	239.686	235.743	239.417
p_5	279.248	282.414	279.937	258.369	280.097
p_6	237.355	239.639	239.642	236.552	239.505
p_7	277.960	285.427	287.728	268.763	287.738
p_8	238.968	239.092	239.505	236.058	240.042
p_9	429.926	425.586	427.149	332.059	428.173
p_{10}	281.313	277.212	275.869	253.834	275.078
TP	2700	2700	2700	2500	2700
TC_{new}	624.710	624.182	624.119	526.556	624.116
TC_{old}	624.993	624.304	624.524	526.963	624.544
profit	0.2837	0.1229	0.4055	0.4062	0.4277

Figure 6 shows results of total cost by increasing number of iterations. As figure shows after certain number of iterations, cost is stabilized and final optimal point is obtained.

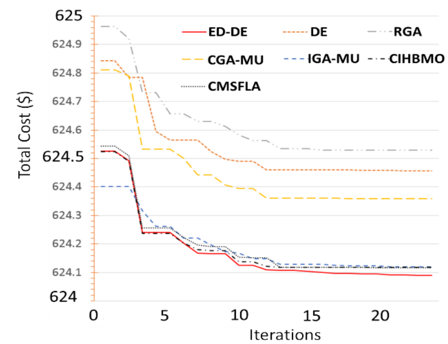

Figure 6. The process to obtain the tc for each iteration.

6.2 Second System

Second study system includes 13 thermal units which were solved considering valve loading effect for powers 1800MW and 2520MW. Power optimal points for 13 thermal units which are obtained by solving EDP by DSPSO-TSA and TSA and GA and PSO[27], FAPSO-NM[31] and ESO[32] methods, entered as input to algorithm. Table 2 shows obtained values for profit and total cost of thermal units before and after using algorithm. Maximum time for implementing algorithm is less than 50 milliseconds.

Table 2. Results for second case study

	FAPSO-NM	DSPSO-TSA	TSA
TP	1800	2520	2520
TC_{new}	17963.848	24169.907	24170.614
TC_{old}	17964.170	24169.992	24171.262
profit	0.32222	0.08452	0.64771
	GA	PSO	ESO
TP	2520	2520	2520
TC_{new}	24169.825	24169.910	24176.768
TC_{old}	24170.536	24170.126	24177.538
profit	0.71067	0.21579	0.77045

6.3 Third System

Third system includes 40 thermal units which are solved for 10500MW power demand considering valve effect. Optimal power points for 40 thermal units are obtained by solving EDP using FAPSO-NM[31], CIHBMO and NPSO[28], RCGA[33], which are inputs of algorithm. Power exchange algorithm is implemented. Table 3 shows results of third system. Implementation time is about 100 milliseconds.

Table 3. Results for third case study

	CIHBMO	NPSO	FAPSO-NM	RCGA
TC_{new}	121412.770	121696.503	121422.288	121424.409
TC_{old}	121412.781	121704.606	121425.048	121424.437
profit	0.01021	8.10331	2.76002	0.02780

7. Conclusion

This article introduced a method for finding absolute optimal points near optimal point obtained by Meta-heuristic methods. As Tables 1-3 show total fuel cost obtained by Meta-heuristic algorithms decreased, and in all cases a better point existed near the optimal point of meta-heuristic algorithms and this algorithm has found it in a small time. Reduction rate in total fuel cost depends highly on initial solution which was low in some samples and high in others.

Although this algorithms does not necessarily improve solution, but if there is an optimal point near initial point, which is generally so, presented algorithm can find it. This algorithm can be used to improve EDP results obtained by every Meta-heuristic algorithm.

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