FPA applied to the resolution of the economic dispatch problem with operational limits of maximum and minimum power of the generating units

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Abstract. This paper presents an application analysis of a computational intelligence (CI) technique based on flower pollination (FPA - Flower Pollination Algorithm) to solve an Economic Dispatch (ED) problem, aiming to minimize the total generation costs, considering operational restrictions of maximum and minimum generation power and the power balance. The algorithm will be tested, in two systems the first one with three generating units and the second with fifteen generating units. Both studies are available in the current literature. Finally, the obtained data will be compared with others already released, where the authors applied a Directional Search Genetic Algorithm (DSGA) to solve the problem. The good results achieved demonstrate the applicability of the proposed technique.

Keywords: Economic Dispatch, FPA, Operating Limits, Optimization first keyword.

1 Introduction

The ED problem dates to the early 1920's when engineers were concerned with the problem of generation or the more adequate load division among available generating units [4].

According to [6] the ED problem is the distribution of the demand for total power requested by the electricity grid among available generation units, so that the cost of generating energy is minimized. [6] also points out the importance of respecting the power balance of the network as well as the physical and operational limits. And as can be seen in [8], bioinspired optimization methods have been widely used to solve this kind of problem.

In this line, several methods using meta-heuristics have already been studied to solve the ED problems, among them: Genetic Algorithm [9], Particle Swarm [3] and Ant Colony [5]. Furthermore, some of them have been modified and / or improved and applied in this kind of problem, like the Directional Search Genetic Algorithm for example [1].

For this paper, the FPA algorithm was selected because it is a technique that can further explored to solve the ED problem and, as can be seen in [12], shows excellent performance when compared to other widely studied metaheuristics such as PSO (Particle Swarm Optimization) and GA (Genetic Algorithm).

Another study that presents data that corroborates with the fact that the FPA is a promising technique to solve the ED problem and also collaborates with the motivation of this work to expand this kind of research, it's presented by [10] that performs an analysis and obtain satisfactory results comparing the technique with the GA and PSO regarding the quality of the results and computational time. In this study [10] use as one of the justifications for the application of the FPA the fact that it has only one key input parameter p (switching probability), which makes the algorithm easier to be implemented and faster to reach the ideal solution. Moreover, this transferring switch between local and global pollination contributes to the algorithm to escape the local minimum solution.

Following this context, the present article aims to study the problem of economic dispatch (ED) with operational limits applying the flower pollination algorithm (FPA), in addition to comparing its results with the results of the DSGA presented in the study of [1]. Thus, allowing to evaluate if the technique will present satisfactory results in the resolution of the studied problem and it makes sense, in future complementary studies using FPA, the inclusion of other non-linearities such as prohibited zones, multiple fuels and distribution network aspects.

2 Problem formulation

As can be seen in [11], to solve ED problem, it is necessary to optimize the function regarding the generation cost of all available generating units. The restrictions established by the maximum and minimum power capable of generating each unit, equation (3) and the power balance of the system, equation (2), must also be considered. Therefore, the system can be mathematically represented as follows:

Minimize:

$$F_T = \sum_{i=1}^{N} F_i(P_i) \tag{1}$$

Subject to:

$$\sum_{i=1}^{N} P_i = P_D \tag{2}$$

$$P_i^{min} \leq P_i \leq P_i^{max} \tag{3}$$

Where, N is the number of units, F_T is the total fuel cost, F_i and P_i are the cost function and the real power output of the unit i, P_D is the total demand. P_i^{min} and P_i^{max} are the lower and upper bounds of the unit i.

2.1 Classical approach

For [10] and [11], traditionally, the fuel cost of a generator is usually defined by a quadratic cost function, following the characteristics presented below in the equation 4:

$$F_i(P_i) = a_i + b_iP_i + c_iP_i^2 \tag{4}$$

Where a_i, b_i e c_i are operating cost coefficients of the generating units i.

3 Flower Pollination Algorithm (FPA)

In this work we will apply the FPA (Flower Pollination Algorithm) optimization technique to minimize the total generation cost function. As defined in [13], in a simplified way, four rules are used to implement the FPA algorithm:

Rule 1: Biotic and cross-pollination can be regarded as a process of global pollination process, and pollen-carrying pollinators moves obeying Lévy flights.
Rule 2: Abiotic and self-pollination are regarded as local pollination.
Rule 3: Pollinators such as insects can develop a constant search for the same flowers, which is equivalent to the probability of reproduction that is proportional to the similarity of the flowers involved.
Rule 4: The variation in the search for solutions through abiotic or biotic pollinations can be controlled by a switch probability p ∈ [0,1].

As noted in [12], when these rules are transformed into equations, we have for the global pollination step

(Rule 1):

$$x_i^{t+i} = x_i^t + L(x_i^t - g_*) \quad (6)$$

Where, x_i^t represents the pollen of flower i or vector solution x_i at iteration t, g_* is the best solution option found among all solutions in the current generation / iteration and L is the step size obeying Lévy flight.

For the movement of pollinators using Lévy flights. Since insects can move long distances with different steps, we can use Levy's flight to simulate this feature efficiently. That is, we extracted L> 0 from a Levy distribution.

$$L \frac{\lambda \Gamma(\lambda) sin(\pi \lambda/2)}{\pi} \frac{1}{s^{1+\lambda}}, (s \gg s_0 > 0) \quad (7)$$

Here, $\Gamma(\lambda)$ is the standard gamma function, and distribution is valid for large steps s> 0.

The local pollination step (Rule 2) and flower constancy (Rule 3) can be represented as [12]:

$$x_i^{t+i} - x_i^t + \epsilon(x_j^t - x_k^t) \quad (8)$$

Where, x_j^t and x_k^t are pollens from different flowers of the same plant species. If x_j^t and x_k^t comes from the same species or they are selected from the same population, it becomes a local random walk if is ϵ drawn from a uniform distribution in [0,1] [12].

The activities of flower pollination may occur at local and global scale. Therefore, to switch between them, a switch probability or proximity probability (Rule 4) can be used [10].

Thus, according to [13], we can use the pseudo code shown in figure 1 below to represent the FPA algorithm:

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FOB definition, minimize or maximize f(x), x = (x_1, x_1, ..., x_d)
Start the population of n flowers / pollen gametes with random solutions
Search for a better g_* solution in the initial population
Definition of commutation probability p ∈ [0,1]
Definition of the criterion for interruption, such as the number of iterations t
While (t < Maximum number of Generation)
    For i=1 : n (all n flowers of the population)
        If rand < p
            Draw L step vector obey a Lévy distribution
            Conduct global pollination via x_i^{t+i} = x_i^t + L(x_i^t − g_*)
                Else
                    Select a random number ϵ between 0 and 1
                    Conduct local pollination via x_i^{t+i} − x_i^t + ϵ(x_j^t − x_k^t)
                End if
                Evaluation of new solutions
                If the new solution is better, then update the population
        End for
        Find the best g* solution
End while
Output with the best result found
```

Figure 1. Pseudo code of the Flower Pollination Algorithm (FPA)

4 Results and Comparisons

Applying, then, the FPA algorithm through the MATLAB® tool, following the pseudo code proposed by [13], the resolution was sought for the cases with three and fifteen generating units seen in [1], as well as the realization of a comparison between total generation costs results obtained in this study with FPA algorithm and study results whit the application of DSGA seen in [1]It is important to emphasize that for the tests carried out by this work, the restrictions of the prohibited zone addressed by the article by [1] were not considered.

First, the input data were defined by testing different configurations for flower population *n*, probability of local search *p* and number of maximum iterations *tmax*. Thus, we arrived at the input parameters *n* equal to 100, *p* equal to 0.4 and *tmax* equal to 500.

In order to deal with the equality restrictions of the ED problems treated in this article, an additive penalty strategy was used, which, as seen in [7], is about adding a penalty function to the objective function of disabled individuals. The most used method for additive penalties, which is also the method applied in this study, has its definition according to equation 9, such that $p\ (x) = 0$ if x obeys all restrictions of the problem.

$$F(x) = f(x) + p(x) \tag{9}$$

Where $F(x)$ is the expanded objective function to be minimized, $f(x)$ is the original objective function and $p(x)$ is the penalty value.

4.1 Test 1 – Case with 3 generating units

Once defined the input data and the strategy to be used to deal with the equality restrictions, the FPA algorithm was applied to solve the ED problem, for a system with three generating units and with three different load levels required by the system generation, 750 MW, 1,080 MW and 1,140 MW.

Table 1(a) shows the data of costs and operating limits for each generating unit of the case in question and table 1(b) shows the best results of optimum power for each generating unit, as well as the optimal costs of generation, obtained after 20 simulations of the problem.

Table 1. (a) Cost and operating limit data and (b) optimal generation levels and total cost obtained for the study with three generating units

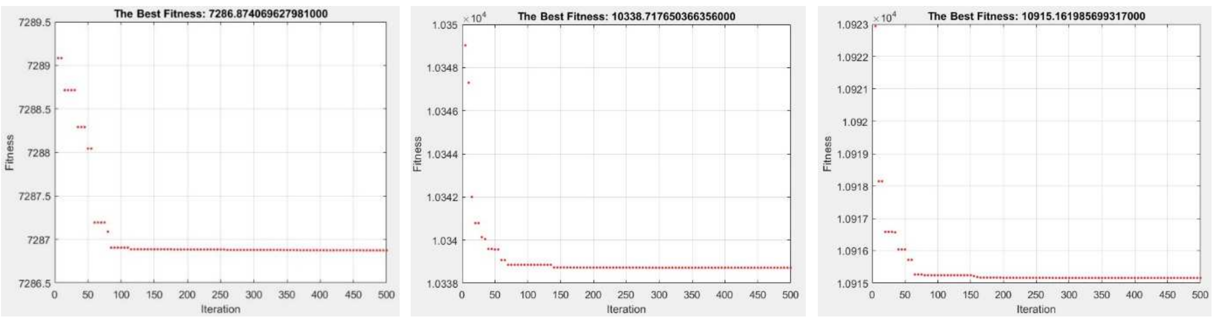
Units	a_i ($/hr)	b_i ($/hr)	c_i ($/hr)	P_{min} (MW)	P_{max} (MW)
1	561	7.92	0.001562	150	600
2	310	7.85	0.00194	100	400
3	78	7.97	0.00482	50	200

(a)

Units	750	1080	1140
1	346	518	563
2	298	400	400
3	106	162	177
Total Cost	7,286.87	10,338.71	10,915.16

(b)

Next, to complement the study with three generating units, it is presented in the figures 2(a), 2(b) and 2(c) the evolution graphs of the FPA algorithm convergence for the 3 load levels studied.



(a) (b) (c)

Figure 2. FPA convergence graph for the case with 3 generating units. (a) System with 750MW of load, (b) System with 1,080MW of load and (c) System with 1,140MW of load

Comparing the results obtained for the total cost of generation via FPA with the results presented by the DSGA in [1], we can verify that the presented results are satisfactory, demonstrating feasibility in the application of FPA to solve this case. It is important to remember that, as in the reference article, these simulations do not consider the restrictions of prohibited zones. Table 2 presents the comparative data:

Table 2. Comparative data of the total cost for the study with three generating units

Method	Total cost of generation ($/h) – System with 750 MW	Total cost of generation ($/h) – System with 1080 MW	Total cost of generation ($/h) – System with 1140 MW
DSGA [1]	7,286.76	10,338.77	10,915.41
FPA	7,286.87	10,338.71	10,915.16

4.2 Test 2 – Case with 15 generating units

Using the same input data, this time the FPA algorithm was applied to solve the ED problem for a system composed of fifteen generating units and with a required load of 2,650 MW.

Table 3(a) shows the parameters of costs and operating limits for each of the generating units in the case in question and table 3(b) shows the best results of optimum power for each generating unit, as well as the optimal costs of generation, obtained after 20 simulations of the problem.

Table 3. Cost data and operating limits and (b) optimal generation levels (without prohibited zones) and total cost obtained for the study with fifteen generating units

Units	a_i ($/hr)	b_i ($/hr)	c_i ($/hr)	P_{min} (MW)	P_{max} (MW)
1	671.03	10.07	0.000299	150	455
2	574.54	10.22	0.000183	150	455
3	374.59	8.8	0.001126	20	130
4	374.59	8.8	0.001126	20	130
5	461.37	10.4	0.000205	150	470
6	630.14	10.1	0.000301	135	460
7	548.2	9.87	0.000364	135	465
8	227.09	11.5	0.000338	60	300
9	173.72	11.21	0.000807	25	162
10	175.95	10.72	0.001203	20	160
11	186.86	11.21	0.003586	20	80
12	230.27	9.9	0.005513	20	80
13	225.28	13.12	0.000371	25	85
14	309.03	12.12	0.001929	15	55
15	323.79	12.41	0.004447	15	55

(a)

Units	Generation levels without prohibited zones 2650(MW)
1	455
2	455
3	130
4	130
5	317.803
6	460
7	465
8	60
9	25
10	20
11	20
12	57.196
13	25
14	15
15	15
Total Cost ($/h)	32,542.44

(b)

Next, to complement the study with fifteen generating units, it is presented in the figure 3 the evolution graph of the FPA algorithm convergence for load level studied.

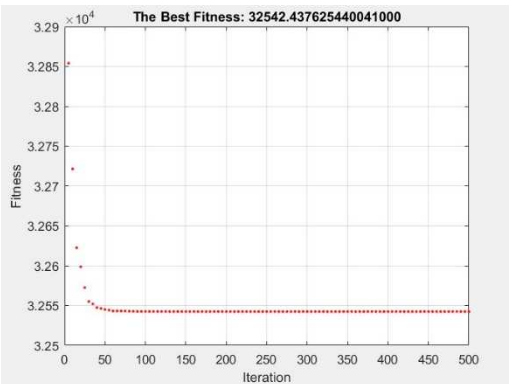


Figure 3. FPA convergence graph for the case with 15 generating units. System with 2,650 MW of load

Table 4 presents the results of generation levels without prohibited zones seen in [1], in addition to the individual cost data calculated using equation (4) and the calculated total cost which is the sum of the individual costs of the units.

Table 4. Generation levels without prohibited zones. Individual and total cost calculated for the study with 15 generating units seen in [1]

Load	2,650 MW	
Units	Generation levels without prohibited zones [1] (MW)	Calculation of the total cost considering the data of Optimal Generation without prohibited operation zones ($/h)
1	455	5,314.78
2	455	5,262.53
3	130	1,537.62
4	130	1,537.62
5	317.835	3,787.56
6	460	5,339.83
7	465	5,216.46
8	60	918.31
9	25	454.47
10	20	390.83
11	20	412.49
12	57.166	814.23
13	25	553.51
14	15	491.26
15	15	510.94
Total Cost ($/h)		32,542.45

In the second test presented in [1], the problem of prohibited zones for some generating units is considered. As the analysis of prohibited zones is not part of the initial objectives of this study, we use the proposed data in the article that disregard the prohibited zones for application of the FPA.

Thus, it is possible to observe that when we compare the total cost obtained via FPA, seen in table 3(b), with the total cost obtained through calculation using data collected in [1], seen in table 4, we obtained a satisfactory comparative result, demonstrating the feasibility of applying the FPA to solve this other case, which, due to the five times greater number of generating units, appears as a more complex economic dispatch problem than the previous one.

5 Conclusions

After completing the study, it is possible to conclude that the results obtained show that the FPA, in comparison with the DSGA [1], has the potential to solve ED problems with operating limits and active power balance satisfactorily. For future studies and improvement of the analysis it is suggested to perform other tests in cases with a larger number of generating units and including challenges related to real operating conditions, such as prohibited operating zones, multiple fuels and aspects of the transmission network.

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