Comparison of the evolutionary algorithm's performances on power flow analysis

Evrimsel algoritma performanslarının güç akışı analizinde karşılaştırılması

1 Introduction

The optimal operation of the electricity grid in Carpentier’s work since 1962 has become a topic of continuous improvement [1]. As technology developing, the customers need more energy and the optimal power flow (OPF) problem becomes more important. Therefore, many researchers have interested growingly in optimizing OPF problem [2]-[9]. In general, objective of the OPF problem is to minimize total fuel cost by adjusting optimal power system control variables while satisfying given set of power system constraints.

Several conventional optimization methods have been used to reduce the overall production cost for power flow problems in the literature [2]-[4]. Some of these methods have disadvantages because of the OPF problem which is nonlinear, non-convex and multimodal. In most cases, these methods have slow convergence, may suffer from local minima and they have unpredictable run time if number of variables increases. To overcome these deficiencies and limitations in conventional methods, evolutionary algorithms are developed. The major advantage of the evolutionary algorithms is that they can be applicable to various problems without getting stuck in local minima as well as have the ability to self-adapt a solution space when improving a solution as compared with conventional methods. Genetic algorithm (GA), differential evolution algorithm (DE), particle swarm optimization algorithm (PSO), simulated annealing algorithm (SA), and harmony search algorithm (HS) are often used in solution of OPF problem in several studies [5]-[9]. However in the studies above related to solving OPF problems, the algorithms may not show own efficiency and robustness. When these studies are analyzed in terms of population size, number of execution and initial point, it is seen that different population size is preferred in some of studies and different number of execution is used as the stopping criterion. On the other hand, it is not possible to use same beginning point in different computers due to nature of algorithms which initial randomly. Using same initial seed gives support to algorithms for making comparison uniform. The aim of this study is to detailed comparative analysis in between recently-used eight optimization algorithms to solve power flow problems. All the algorithms were performed on the same platform to prevent misjudgment of the algorithms employed. By using same initial values, population size and number of execution, eight different algorithm analyses were carried out on IEEE-30 test bus system for two different cases of OPF problem.

This paper is organized as follows: In Section 2, formulation of OPF problem is declared. In Section 3, general structure of evolutionary algorithms is defined. In Section 4, implementation of OPF problem is described. Finally, In Section 5, simulation results are shown and discussed.
2 Problem formulation

2.1 Optimal power flow

Optimal power flow optimization is a nonlinear constrained optimization problem and defined as follows:

Minimize $f(x, u)$

Subject to $g(x, u) = 0$ and $h(x, u) \leq 0$

In this context, $x$ represents the state variables that can be seen in Eq. 3 and $u$ represents the control variables as shown in Eq. 4.

$$x^T = [P_{\text{slack}}, V_g, Q_g, S_e]$$

In Eq. 3, $x$ consists of slack bus $P_{\text{slack}}$, load bus voltage $V_g$, generator reactive power $Q_g$ and transmission line loading (line flow) $S_e$.

$$u^T = [P_g, V_g, Q_g, T]$$

Where $P_g$ is generator active power, $V_g$ is generation bus voltage, $Q_g$ is shunt VAR compensation and $T$ is transformers tap settings.

$$0 = P_{gi} - P_{ai} - \sum_{j=1}^{C} V_j \{ G_{ij} \cos(\Theta_{ij}) + B_{ij} \sin(\Theta_{ij}) \}$$

$$i = 1 \ldots C$$

(5)

$$0 = Q_{gi} + Q_{ai} - \sum_{j=1}^{C} V_j \{ G_{ij} \sin(\Theta_{ij}) - B_{ij} \cos(\Theta_{ij}) \}$$

$$i = 1 \ldots C$$

(6)

$g(x, u)$ is the function of equality constraints and relies on typical load flow equations which are formulated in Eq. 5 and Eq. 6, where $P_{ai}$ and $Q_{ai}$ are the active and reactive load demand of $i$th line and $C$ is the number of buses in power system. $G_{ij}$ and $B_{ij}$ are real (conductance) and imaginary (susceptance) part of admittance matrix of power system. $\Theta_{ij}$ is the difference in voltage angle between bus $i$ and bus $j$ [7]. $h(x, u)$ is inequality constraints of the OPF problem. System operating constraints reflect the limits on physical devices in the power system. These constraints are given as follows:

$$p_{gimin} \leq P_{gi} \leq p_{gimax} \quad i = 1 \ldots C_g$$

(7)

$$Q_{gimin} \leq Q_{gi} \leq Q_{gimax} \quad i = 1 \ldots C_g$$

(8)

$$V_{imin} \leq V_i \leq V_{imax} \quad i = 1 \ldots C$$

(9)

$$T_{imin} \leq T_i \leq T_{imax} \quad i = 1 \ldots C_T$$

(10)

$$Q_{cinmin} \leq Q_{ci} \leq Q_{cinmax} \quad i = 1 \ldots C_C$$

(11)

Where $C_g$, $C_T$ and $C_C$ are the total number of generators, transformers and compensator devices, respectively. $p_{gimin}$, $p_{gimax}$ are lower and upper limits of active power for each generator. $Q_{gimin}$, $Q_{gimax}$ are lower and upper limits of reactive power for each generator. $V_{imin}$, $V_{imax}$ are lower and upper limits of voltage for each bus. $T_{imin}$, $T_{imax}$ are lower and upper limits of the transformer tap setting for each transformer [7].

2.2 Objective function

$(x, u)$ refers to the desired objective function to be minimized and represents total fuel cost in Eq. 12:

$$f(x, u) = \sum_{i=1}^{C_g} (a_i P_{gi}^2 + b_i P_{gi} + c_i)$$

(12)

Where, $a_i$, $b_i$ and $c_i$ are the cost coefficients of $i$th generator. Objective function $f$ is considered as the total fuel cost. Total fuel cost depends on the power of each generator and the cost coefficients.

2.3 Valve point effect

Considering the valve point effects of generators, a recurring rectifying sinusoidal term is joined to the principal quadratic cost function, as follows in Figure 1. With the valve point effects, cost function has some ripples because of these ripples; the number of local optima is increased in solution space [10]. Figure 1 represents the cost function of generators with/without the valve point effect [11]. Total fuel cost with valve point loading is given by Eq. 13.

$$f(x, u) = \sum_{i=1}^{C_g} (a_i P_{gi}^2 + b_i P_{gi} + c_i + |d_i \sin(e_i (p_{gimin} - P_{gi}))|)$$

(13)

Where, $d_i$ and $e_i$ are coefficients from valve point effect of $i$th generator [11].

Figure 1: Cost function with and without valve point effect.

3 Evolutionary algorithms

In Table 1, the structure of algorithms used in OPF problems are summarized:

4 Implementation of the algorithms to OPF problem

This part makes a general statement of the all algorithms which is about how to solve OPF problem using objective function as gathered from Eq. 12. To solve this problem, algorithms generally follow these steps:

Step 1: Define algorithm parameters and load input data from IEEE 30 bus test system.

Step 2: Initialize algorithm randomly with initial population $X_M$, as follows:
Table 1: Evolutionary algorithms used in OPF problem.

| Artificial Bee Colony algorithm (ABC) [12] | Cuckoo Search algorithm (CS) [13] |
|-------------------------------------------|-----------------------------------|
| 1. Define number of colony size and limit value. | 1. Define number of nests and probability of discovery egg by the host bird. |
| 2. Generate initial food source positions. | 2. Generate initial population of host nests. |
| 3. Calculate initial nectar amounts. | 3. Calculate Cuckoo solutions. |
| 4. Is the termination criteria satisfied? | 4. Apply replacing process and determine Cuckoo societies. |
|   a. If satisfied: | 5. Find current best Cuckoo. |
|   • Final food positions are best food positions. | 6. Is the termination criteria satisfied? |
|   b. (Else) If not satisfied: | a. If satisfied: |
|     • Determine the new food positions. | • The best Cuckoo solution is found. |
|     • Calculate the nectar amounts and apply selection process. | b. (Else) If not satisfied: |
|     • Memorize the position of best food source so far. | • Go to Step 3. |
|     • Go to Step 3. | |

| Firefly algorithm (FF) [14] | Real Coded Genetic algorithm (RCGA) [15] |
|----------------------------|----------------------------------------|
| 1. Define number of fireflies, largest degree of attraction, degree of light attenuation and step factor. | 1. Define population size, mutation probability and crossover probability. |
| 2. Generate initial population randomly. | 2. Generate initial population randomly. |
| 3. Calculate the relative brightness and attraction between fireflies. | 3. Calculate the fitness values of individuals. |
| 4. Find best Firefly. | 4. Is the termination criteria satisfied? |
| 5. Is the termination criteria satisfied? | a. If satisfied: |
|   a. If satisfied: | • Choose best individual. |
|   • Obtained minimum location from best Firefly. | b. (Else) If not satisfied: |
|   b. (Else) If not satisfied: | • Generate new population via selection, crossover and mutation processes. |
|     • Test brightness for moving and update position. | • Go to Step 3. |
|     • Go to Step 3. | |

| Harmony Search algorithm (HS) [16] | Particle Swarm Optimization algorithm (PSO) [17] |
|---------------------------------|-------------------------------------------------|
| 1. Define harmony memory size, harmony memory consideration rate and pitch adjustment rate. | 1. Define number of the swarm particles, initial velocity, cognitive parameter, social parameter, initial weight and scaling factor for inertia weight. |
| 2. Initialize harmony memory randomly. | 2. Generate initial particles randomly. |
| 3. Calculate harmony memory solution. | 3. Calculate the fitness values of particles. |
| 4. Is the termination criteria satisfied? | 4. Is the termination criteria satisfied? |
|   a. If satisfied: | a. If satisfied: |
|     • Best harmony in the harmony memory is the solution. | • Choose best particle. |
|   b. (Else) If not satisfied: | b. (Else) If not satisfied: |
|     • Improve new harmony. | • Update velocity and position. |
|     • Update harmony memory. | • Go to Step 3. |
|     • Go to Step 3. | |

| Simulated Annealing algorithm (SA) [18] | Differential Evolution algorithm (DE) [19] |
|--------------------------------------|-------------------------------------------|
| 1. Define cooling schedule, initial and final temperatures. | 1. Define population size, crossover rate and scaling factor. |
| 2. Generate initial solutions. | 2. Generate initial population randomly. |
| 3. Create a candidate list of solutions. | 3. Calculate the fitness values of individuals. |
| 4. Evaluate solutions. | 4. Is the termination criteria satisfied? |
| 5. Find best admissible solution. | a. If satisfied: |
| 6. Is the termination criteria satisfied? | • Choose best individual. |
|   a. If satisfied: | b. (Else) If not satisfied: |
|     • Best solution is found. | • Generate new population via recombination and selection processes. |
|   b. (Else) If not satisfied: | • Go to Step 3. |
|     • Update the temperature. | |
|     • Go to Step 3. | |

\[ X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_M \end{bmatrix} \]

\[ X_i = [X_{i1}, X_{i2}, \ldots, X_{iD}] \quad i = 1, 2, \ldots, M \quad (14) \]

Where, \( M \) is the population size and \( D \) is the dimension of the problem. At the beginning, population is taken by algorithm randomly. It should be noted that whole algorithms use same initial population for equally comparison in this paper.

**Step 3:** Check the all constraints.

If any limit of constraint is violated, produce new individual \( X_i \) with respect to Eq. 14 and transform the constrained OPF problem into unconstrained one by adding penalty term to \( f(X_i, u) \) for each violated constraints.

Otherwise, go to Step 4.

**Step 4:**

a) Calculate the objective function in Eq. 12 using \( X_i \).

b) Process the algorithm according to the obtained results from objective function and own searching criteria. The structures of all algorithms can be shown in Section 3.
c) Choose best individual in the population that is found so far. This individual represents the variables of problem which are obtained from objective function.

Step 5: If the current number of execution reaches the predetermined maximum execution number, algorithm process is stopped, otherwise go to Step 4.

5 Simulation results

In this study, eight different algorithms are applied to OPF problem on IEEE 30-bus test system. Data of the 30-bus system can be achieved from [20]. As shown in Figure 2, IEEE 30-bus test system consists of four transformers and six generators, which has 283.4 MW total active demands, 126.2 MVar total reactive demands. Related data of generators for IEEE 30 bus system can be achieved from [20]. As shown in Figure 2, IEEE 30-bus test system is online available in [22].

All algorithms is performed with MATLAB [21] (computed with Intel(R) Core(TM) 2 Duo CPU 2.53 GHz, 3 GB RAM computer) independently 10 times and tested on IEEE 30-bus test system to compare each other for both cases. The best method is determined based on total fuel cost and related analysis.

Table 2: Fuel cost coefficients of generators for IEEE 30-bus test system [22].

| Generator Number | a   | b   | c   | d   | e   | P_max | P_min |
|------------------|-----|-----|-----|-----|-----|-------|-------|
| G1               | 0.00375 | 2   | 0   | 18  | 0.037 | 250   | 50    |
| G2               | 0.0175  | 1.75 | 0   | 16  | 0.038 | 80    | 20    |
| G5               | 0.0625  | 1    | 0   | 14  | 0.04  | 50    | 15    |
| G8               | 0.0083  | 3.25 | 0   | 12  | 0.045 | 35    | 10    |
| G11              | 0.025   | 3    | 0   | 13  | 0.042 | 30    | 10    |
| G13              | 0.025   | 3    | 0   | 13.5| 0.041 | 40    | 12    |

5.1 Case 1: OPF problem solution without valve point effect of generators

In the first case, OPF problem is solved without valve point effects by minimizing the objective function using Eq. 1. Active power outputs for generators found by each algorithm are given in Table 3. The obtained best, worst, mean values over 10 runs are shown in Table 4. It can be seen that in Table 3, there is no big difference (less than %1) in terms of fuel cost values of ABC, CS, FF, PSO, and DE. However, DE and PSO find lesser costs compared to other three algorithms.

As shown from Figure 3 which shows the convergence performance of different algorithms, CS is not more successful in solving case 1 of OPF problem compared with PSO and DE. Despite that, CS can converge to own optimum point (local solution) in lesser executions. On the other hand, ABC is more robust algorithm dealing with stability and accuracy. It can be also observed that SA and FF are not stable with big fluctuation and they make more number of executions to reach optimum point than other algorithms.

Results presented in Table 4 show that if accuracy of all algorithms are analyzed just based on best values, PSO is better choice to solve case 1 of OPF problem. It can be easily seen in Table 4, SA and RCGA find significantly worst solution than other algorithms.

Table 3: Power generations of all generators found by different algorithms for case 1.

| Algorithms | P_{g1} (MW) | P_{g2} (MW) | P_{g3} (MW) | P_{g4} (MW) | P_{g5} (MW) | P_{g6} (MW) | Fuel cost ($/h) |
|------------|-------------|-------------|-------------|-------------|-------------|-------------|----------------|
| ABC        | 176.720     | 48.830      | 21.477      | 21.673      | 12.099      | 12          | 801.937        |
| CS         | 176.787     | 48.802      | 21.490      | 21.591      | 12.134      | 12          | 801.938        |
| FF         | 175.951     | 50.704      | 19.197      | 24.926      | 10.006      | 12          | 802.539        |
| RCGA       | 170.893     | 47.952      | 20.473      | 22.385      | 13.918      | 16.786      | 803.046        |
| HS         | 176.357     | 48.499      | 21.823      | 21.714      | 12.329      | 12          | 801.941        |
| PSO        | 177.089     | 48.920      | 21.505      | 21.877      | 12.168      | 11.261      | 801.922        |
| SA         | 175.314     | 49.718      | 21.227      | 22.673      | 13.004      | 10.779      | 803.349        |
| DE         | 177.089     | 48.920      | 21.505      | 21.877      | 12.169      | 11.261      | 801.922        |
5.2 Case 2: OPF problem solution by considering valve point effect of generators

In this case, valve point effect is considered and the data is listed in Table 2. Active power outputs for generators are given in Table 5 and convergence performance of different algorithms related to case 2 is shown in Figure 5. Best, mean, worst values for the results of case 2 obtained by associated algorithms are given in Table 6. From the results in Table 6, best, mean, worst solutions found by each algorithm are different from the solution of case 1 due to valve point effect which increases computational costs of algorithms. As an example, without considering valve point effect, mean value of costs found by all algorithms is almost 803.22 $/h but considering this effect, the cost rises to almost 831.88 $/h.

As shown from Figure 5, HS, SA and FF have more number of executions (more than 80) to settle at the minimum point. Moreover, significant differences exist among these three algorithms for best cost values and HS gives better results compared with two of them.

As seen from Table 6 unlike to case 1, RCGA finds worst result and CS gives best result with small difference compared with ABC. On the other hand, similar to case 1 as shown in Figure 5, FF and SA don’t only make more numbers of executions but also give worse result compared to rest of algorithms. Of course, FF, SA and RCGA are not suitable for solving case 2 as compared to other algorithms. In general, if the balance between best and worst values of algorithms are analyzed which are shown in Table 6, the results of ABC, PSO, DE and HS are very identical and if small differences are not taken into account (less than %1), this problem can be solved with these four algorithms for case 2.
As shown in Figure 6, energy saving ratios according to initial cost values are very similar except RCGA but the number of executions taken to convergence solution is different when compared with each other.

Table 6: Best, mean and worst cost values for different algorithms in Case 2.

|       | Worst | Mean  | Best   |
|-------|-------|-------|--------|
| ABC   | 827.15 | 826.191 | 826.05 |
| CS    | 828.05 | 826.239 | 826.603 |
| FF    | 843.92 | 839.551 | 831.1  |
| RCGA  | 848.411 | 842.635 | 834.834 |
| HS    | 827.22 | 826.529 | 826.24 |
| PSO   | 827.53 | 826.412 | 826.04 |
| SA    | 855.07 | 841.394 | 826.61 |
| DE    | 827.04 | 826.138 | 826.04 |

![Energy saving ratio according...](image)

Figure 6: Energy saving ratio for case 2.

### 6 Conclusions

The OPF problems become difficult to solve because of large number of constraints and nonlinearity of OPF problems for mathematicians as well as for engineers. In this paper, eight different algorithms are successfully performed on two different cases of OPF problem. Discussing valve point effect and complex constraints create a challenge for algorithms to reach minimum cost. We have pointed out equal competition between algorithms in this challenge and also compared to all algorithms comprehensively on the OPF problem under equal conditions for both cases. The equally analysis showed that each algorithm has its own strength and weakness when dealing with OPF problem. The outcome of this research helps not only provide an equal comparison between whole algorithms but also helps to show us which algorithm works more efficiently on which cases.

### 7 References

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