Application of a Novel Modified Hybrid Algorithm for Solving Dynamic Economic Dispatch Problem with Practical Constraints

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Abstract. *Dynamic Economic Dispatch (DED) is a highly complex nonlinear optimization problem with practical constraints. The aim of DED is to optimize dynamically the active power of generating units over operating time considering practical constraints such as valve point effect, prohibited zones, ramp rate limits and total power losses. In order to overcome the drawback of the two standard metaheuristics such as Firefly Algorithm (FA) and Time Varying Acceleration based Particle Swarm Optimization (PSOTVAC), a hybrid method called FAPSOTVAC is proposed to improve the solution of DED. The main idea introduced towards combining FA and PSOTVAC is to create a flexible equilibrium between exploration and exploitation during search process. The robustness of the proposed hybrid method is validated on many practical power systems (10 and 30 units) to minimize the total fuel cost considering all practical constraints. The results found prove the efficiency of the proposed FAPSOTVAC in terms of solution quality and convergence characteristics.*

Keywords

A hybrid algorithm, dynamic economic dispatch, FA-PSOTVAC, prohibited operating zones, ramps rate constraints, valve point effect.

1. Introduction

Nowadays electric energy resembles a vital artery to our daily life and the main engine for any economic or commercial activity. Such occupied position renders it irreplaceable due to its credibility when compared with any other natural energy. The electric energy demand in our economic has multiplied by 3.2 in 37 years to reach 19738 TWh in 2010. This colossal number indicates the salient position it occupies in the current world economy.

The energy system is composed of power station interconnected with transmission lines transporting the produced energy to consumers after several operation and control stages. The non-stocked aspect of this form of energy obliges us to produce it in the time of consumption. The balance between production and consumption should be respected in real time and within the capacity of power generating units. This problem is generally called the problem of Static Economic Dispatch (SED).

The main task of electric power system is to ensure instantaneously the equilibrium between production and demand. The determination of the optimal state of each generator interconnected with the electric network during the twenty-four hours complicates the solution of the faced problem. Rather than being more static, this problem becomes dynamic in time, in other contexts wherein the complexity of nowadays network increases vis a vis its size that holds hundreds of bus-bars and hundreds of thousands of kilometers of transmission lines, in addition to highly complicated structure of the interconnected network.All these factors make the optimization of the total fuel cost complex and vital objective.

In this context, new practical constraints, attached mainly to the construction of thermal units, on the one hand, and to the conditions imposed by the strategy of exploitation, on the other hand, should be respected.

The opening of fuel's valves perturb the quadratic form of cost's objective operation by introducing a highly non-linear form. Furthermore, another new constraint can be added to complicate the (DED) problem. The latter is generators ramp constraint that does not allow the adjustment of the generated active power only by a pre-imposed value. In [1], Ramp-rate limits have been considered in unit commitment and economic dispatch incorporating rotor fatigue effect. This study explains how the violation of such constraints can highly minimize rotor's life and increments the maintenance cost. Since the constraints are highly non-linear, they add prohibited operating zones, which are attached directly to the equilibrium of the thermal generating units. The latter should operate away from certain intervals called "Prohibited Operating Zones" to avoid some dangerous vibration at the level of machine's bearing [2]. In such situation, the form of objective function must be modified and adapted to take into consideration the effects of these prohibited zones.

Several mathematical methods have been applied for solving such non-linear problem. Most of them have exploited the mathematical characteristics of the cost function function for discovering the continuity and hessian derivation,..etc. In this sense, authors in [3] made a comparison between the solution of the iterative Lamda method and the metaheuristic algorithm "Brent method" for solving the problem of dynamic economic dispatching with losses and ramp constraints. Moreover, authors in [4] have applied the dynamic programming in order to find the solution to the same problem by considering the prohibited operating zones. Whereas, reserve constraints have been considered in [5] by applying Lagrange relaxation method. Besides, authors in [6] have applied the same method to investigate unit commitment problem. All these methods are swift and all what they need is one launch either to find the optimum solution or stay inapt towards the different mentioned constraints. The ordinary methods of optimization cannot cover the entire space designed for research in order to find a low cost for they can be trapped at a local rather than a global optimum following an exaggerated time that can never be applied in real time.

The application of artificial intelligence methods present an alternative to the conventional methods, which leads to the development and the application of many techniques such as Genetic Algorithms (GA) [7], Particle Swarm Optimization (PSO) [8] and their modified versions. Authors in [9] used the modified version of PSO which they called Modulated particle swarm optimization to solve the problem of muti-objective dynamic economic dispatch. In addition, a kenetic gas molecule optimization algorithm has been proposed in [2] to solve the static and dynamic economic dispatch problems. Whereas, authors in [10] applied the Modified Real Coded Genetic Algorithm (MRCGA) to solve the problem of multi-objective Dynamic Economic Dispatch (DED). Furthermore, authors in [11] solved the large scale problem DED by using the Crisscross optimization algorithm. Meanwhile, authors in [12] suggested the Alternating Direction Method of Multipliers (ADMM) for solving environmental economic dispatch. In [13] Differential Evolution (DE) algorithm was applied to solve the DED problem considering ramp rates constraints.

For being able to cover the whole research area, limited by an important number of constraints as well as the huge non-linearity, on one hand, and to solve the problem of a large size DED on the other hand, many hybrid algorithms have been suggested. These hybrid techniques have been developed to overcome the drawback of the standard metaheuristic methods by creating flexible equilibrium between diversification and intensification during search process. Authors in [14] used Modified Particle Swarm Optimization and Genetic Algorithm (MPSO-GA) for solving the problem of static economic dispatch with prohibited operation zones, ramp constraints and multi fuel. Besides, authors in [15] proposed the hybrid method (MILP-MDSD) to solve the problem of dynamic economic dispatch with valve points effects. Authors in [16] have used the Improved Dynamic Programming (IDP), which is a recursive of a dynamic programming to solve the problem of economic dispatch with prohibited zones and ramp rate constraints. In addition in [17] a Chaotic self-adaptive Differential Harmony Search algorithm (CDHS) applied in order to solve the problem of dynamic economic dispatch wherein, the prohibited operation zones and ramp-rate constraints are taken into consideration simultaneously. Authors in [18] proposed metaheuristic Two Stage Mixed Integer Linear Programming (TSMILP) as a method to solve the problem of dynamic economic dispatch considering the effects of valves and transmission losses. On the other hand authors in [19] used Fast Evolutionary Programming with Swarm Direction for solving DED problem. Whereas, authors in [20] applied the hybrid technique of Cross-Entropy Method and Sequential Quadratic Programming to solve the same problem.

This article intends to solve the problem of multi constraints non-linear dynamic economic dispatch to investigate valves point effects, ramps constraints, by introducing prohibited operating zones that have never been treated together before according to review of literature. The huge number of constraints and complication problem obliged us to introduce new hybrid algorithms such as FA-PSOTVAC and BBO-PSOTVAC to achieve the desired low cost by respecting all the practical operation constraints imposed.

2. Nomenclature:

BBO:	Biogeography-Based Optimization algorithm.
C_{it}:	The unit i production cost at time t.
DED:	Dynamic Economic Dispatch.
FA:	Firfly algorithm.
ng:	The number of generation units.
n_i:	The number of prohibited operating zones in the ith generating unit.
$P_d(t)$:	Load demand at time t.
P_i^{min}, P_i^{max}:	The maximum and the minimum production of unit i.
P_{it}:	Power output of unit at time t.
P_{loss}:	Transmission losses.
PSOTVAC:	Particles Swarm Algorithm with a variable acceleration coefficient.
T:	The total number of hours in the operation period.
TC:	Total Cost ($).
UR_i, DR_i:	The ramp up and the ramp down rate limit's respectively.

3. Mathematical Formulation

3.1. Objective Function

The objective function of (DED) problem is to minimize the total production cost over the operation period, which can be written as [21]:

$$\min TC = \sum_{t=1}^{T}\sum_{i=1}^{ng} C_{it}(P_{it}), \tag{1}$$

where C_{it} is the cost of ith generating unit at time t, ng is the number of generation units and P_{it} is the power output of it unit at time t. T is the total number of hours in the operation period. The fuel cost function of generating units considering valve-point effect can be expressed using the following equation [15]:

$$\begin{aligned} F(Pg_i) = \sum_{i=1}^{ng} a_i + b_i Pg_{it} + c_i Pg_{it}^2 \\ +|e_i \sin(f_i(Pg_{it}^{\min} - Pg_{it}))|, \end{aligned} \tag{2}$$

where a_i, b_i, c_i, e_i, f_i are the cost coefficients of i^{th} power generating units. This objective function should be minimized considering the following equality and inequality constraints [22].

3.2. The Equality Constraints:

$$\sum_{i=1}^{ng} P_{it} = P_d(t) + P_{loss}, \qquad t = 1, 2, ..., T. \tag{3}$$

3.3. Inequality Constraints [23] and [24]

$$P_i^{\min} \le P_{it} \le P_i^{\max}, \quad i = 1, ..., ng \quad t = 1, ..., T. \tag{4}$$

$P_i^{\min}, P_i^{\max}$ are the minimum and the maximum of unit's production.

1) Ramp Rate Constraints [25]

$$P_{it} - P_{i(t-1)} \le UR_i, \tag{5}$$

$$P_{i(t-1)} - P_{it} \le DR_i. \tag{6}$$

2) Prohibited Operation Zone

The Prohibited Operation Zones [26] and [27] are mathematically expressed by the following equation:

$$P_i \in \begin{cases} P_i^{\min} \le P_i \le P_{i1}^{L}, \\ P_{ik-1} \le P_i \le P_{ik}^{L}, \\ P_{izi}^{u} \le P_i \le P_i^{\max}, \end{cases} \tag{7}$$

where: n_i is the number of prohibited operating zones in the i^{th} generating unit. k is the index of the prohibited operating zones of the i^{th} generating unit. P_{iK}^{L}, P_{iK}^{U} are the lower and upper bounds of k^{th} prohibited operating zones of unit i.

4. Optimization Algorithms

4.1. Particles Swarm Algorithm with a Variable Acceleration Coefficient PSOTVAC

Particle Swarm Optimization with Time Variable Acceleration (PSOTVAC) is a dynamic variant of the standard PSO algorithm. This algorithm presents a modified version of the basic algorithm PSO, though it somewhat differs from the standard algorithm by its cognitive and social coefficients that change during search process. The dynamic behavior of these two coefficients allows to create equilibrium between exploration and exploitation [28] and [29]. The position and the speed of each particle are presented in the following equations:

$$\begin{cases} V(t+1) = w * V(t) + \alpha_1 rand_1 * (P_i - X(t)) + \\ \qquad +\alpha_1 rand_2 * (Pb - X(t)), \\ X(t+1) = X(t) + (t+1), \end{cases} \tag{8}$$

$$\begin{cases} \alpha_1 = (c_{1f} - c_{1i})\frac{iter}{iter_{\max}} + c_{1i}, \\ \alpha_1 = (c_{2f} - c_{2i})\frac{iter}{iter_{\max}} + c_{2i}, \end{cases} \tag{9}$$

$$w = (w_{\max} - w_{\min}) * \frac{(iter_{\max} - iter_{\min})}{iter_{\max}} + w_{\min}, \tag{10}$$

where $x(t)$ is the initial position of the particle. $v(t)$ presents the initial speed of the particle. $v(t+1)$ is the new speed of the particle. $x(t+1)$ is the new position of the particle. Pi is the best local solution. Pb is the best global solution. w is the inertia factor presented by $0.4 \leq w \leq 0.9$. $iter$ is the iteration number. $iter_{max}$ is the maximum iteration number. α_1, α_2 are respectively the cognitive and the social factors. $C_{1i}, C_{2i}, C_{1f}, C_{2f}$ represents the initial and final values of the cognitive and the social factors which are respectively 2.5, 0.5, 0.5 and 2.5. The flowchart of the PSOTVAC is shown in Fig. 1.

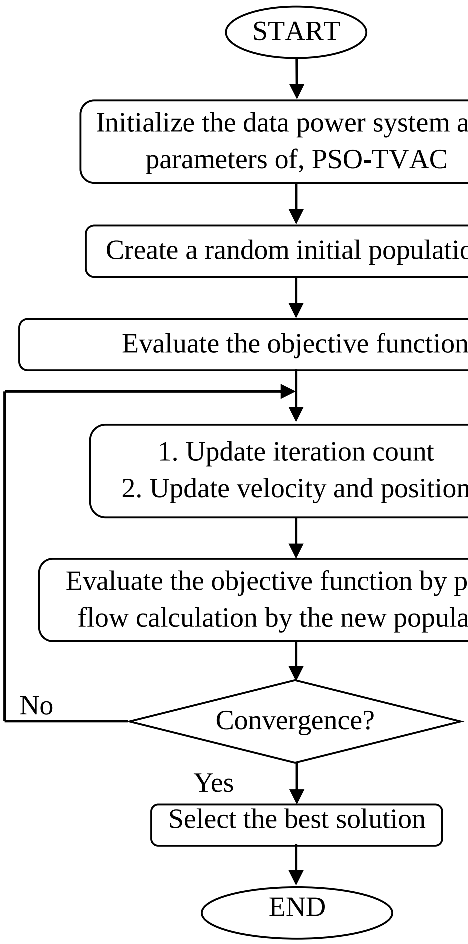

Fig. 1: Flowchart of PSOTVAC.

4.2. Firefly Algorithm

This algorithm is inspired by and based on the principle of attraction between fireflies in nature, which gives many similarities with other metaheuristic methods based on group collective intelligence such as PSO algorithm. Based on the pseudo code of the FFA shown in Alg. 1, the FA algorithm is governed by the three following rules:

- All the fireflies are unisex; they will move towards more attractive and brighter ones regardless their sex.
- The degree of attractiveness of a firefly is proportional to its brightness which decreases as the distance from the other firefly increases.
- Fireflies luminosity is determined by an objective function (an optimized one).

Algorithm 1 Firefly Algorithm.

Ensure: : Initialize population of m fireflies, x_i, $i = 1, 2, 3, \ldots m$.
Ensure: : Compute Light intensity $f(x_i)$, for $i = 1, 2, \ldots m$.

```
while stopping criteria is not met do
  for i = 1 to m do
    for j = 1 to m do
      if (f(x_i) > f(x_j)) then
        return Move firefly i towards j (eq 13)
      end if
    end for
  end for
  Update Light intensity f(x_i) for i = 1,2,...m.
  Rank the fireflies and find the current best
end while
```

1) Attractiveness

The attractiveness function between fireflies is expressed by the following equation:

$$\beta(r) = B_0 exp(\gamma r^m), \quad \text{with} \quad m \geq 1, \tag{11}$$

where r is the distance between any two fireflies, B_0 is the initial attractiveness at $r = 0$, and γ is an absorption coefficient which controls the decrease of the light intensity.

2) Distance

During the search process, the distance between two fireflies i and j at location x_i and x_j can be defined by the following expression:

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d}(x_{i,k} - x_{j,k})^2}, \tag{12}$$

where r_{ij} is the distance between two fireflies and d is the dimension of the problem.

3) Movement

The movement of a firefly i which is attracted by a more attractive firefly j is given by the following equation:

$$x_i^{t+1} = x_i^t + B_0 \exp(-\gamma r_{ij}^2) * (x_i - x_j) + \alpha(rand - 0.5), \tag{13}$$

where the first term is the current position of a firefly, the second term is used for considering a firefly's attractiveness to light intensity seen by adjacent fireflies, and the third term is for the random movement of a firefly in case there are not any brighter ones. i and j are two variables which reflect the light intensity that is associated with a specified fitness function of particles to be evaluated [30].

4.3. BBO Algorithm

BBO is relatively a new metaheuristic method introduced by (Simon, 2008) [31] and [32]. This method is inspired by migration of species among islands. The fitness of a geographical area is assessed by a Habitat Suitability Index (HSI). Habitats which are more suitable for species to reside are said to have a high HSI. Similarly, habitats which are less suitable for species to reside are said to have low a HIS (Bansal et al., 2016) [33]. In BBO, a solution is represented by an island consisting of solution features named Suitability Index Variables (SIV), which are represented by real numbers. It is represented for a problem with nd decision variables as:

$$\text{island} = [SIV_1, SIV_2, SIV_3, ..., SIV_{nd}]. \tag{14}$$

The suitability of sustaining larger number of species of an island can be modeled as a fitness measure referred to Suitability Index (SI) in BBO as:

$$SI = f(\text{island}) = f(SIV_1, SIV_2, SIV_3, ..., SIV_{nd}). \tag{15}$$

High SI represents a better quality solution and low SI denotes an inferior solution. The aim is to find optimal solution in terms of SIV that maximizes the SI. Each island, representing a solution point, is characterized by its own immigration rate λ and emigration rate μ. A good solution enjoys a higher μ and lower λ and vice-versa. The immigration and emigration rates are the functions of the number of species in the island as well shown in Fig. 2, and defined for the k^{th} island as [34].

$$\mu_k = f\left(\frac{k}{n}\right), \tag{16}$$

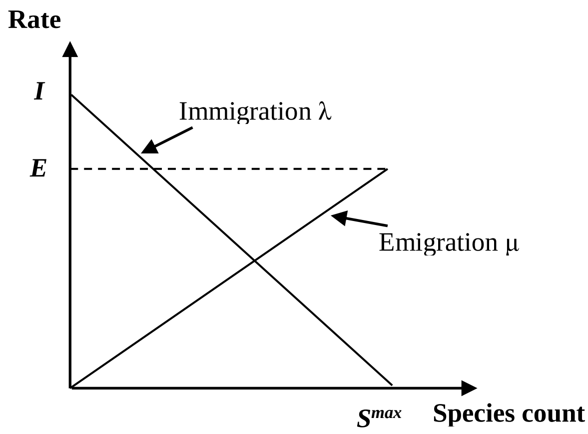

Fig. 2: Species model of an island.

$$\lambda_k = I\left(1 - \frac{k}{n}\right), \tag{17}$$

when $E = I$, the immigration and emigration rates can be related as:

$$\lambda_k + \mu_k = E. \tag{18}$$

4.4. Proposed Hybrid FA-PSOTVAC

In order to exploit the best proprieties of the two well known algorithms, the FA and PSOTVAC, a hybrid method is proposed to improve the solution of DED. The mechanism search of the standard FA is characterized by its possibility to locate the best solution but at high number of iteration. The PSOTVAC algorithm is characterized by its fast convergence, however the solution achieved is not competitive in particular when considering large DED problems. The proposed FA-PSOTVAC is adapted and applied to solve the DED of large test system considering simultaneously the prohibited zones, the valve point effect and ramp-rate limits. The flowchart of the proposed hybrid algorithm is shown in Fig. 3.

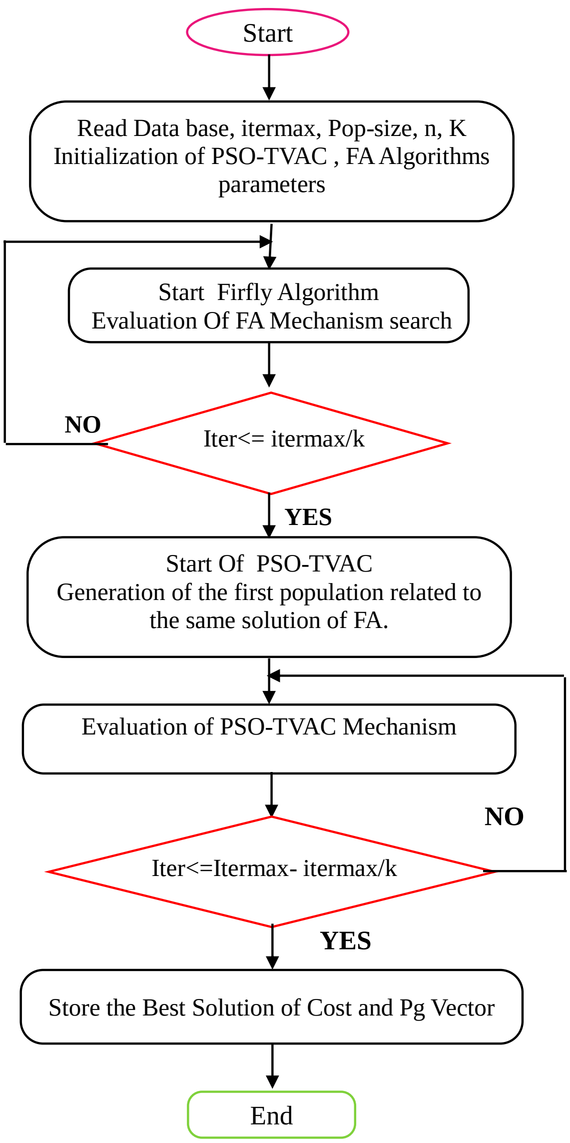

Fig. 3: Flow chart of the proposed hybrid algorithm based FA-PSOTVAC.

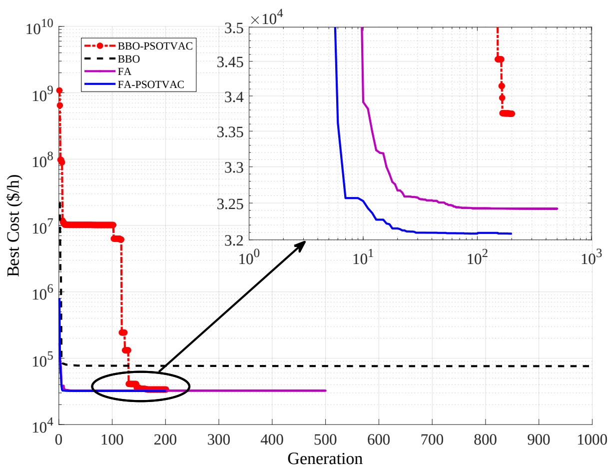

Fig. 4: Comparison of convergence characteristics of the proposed four algorithms for test system 1.

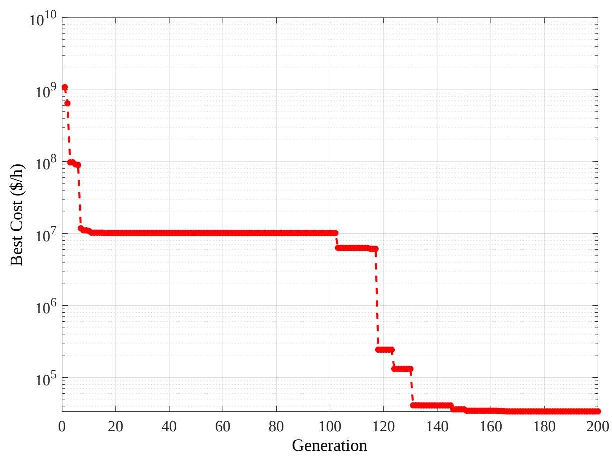

Fig. 5: Convergence characteristic of BBO-PSOTVAC for test system 1.

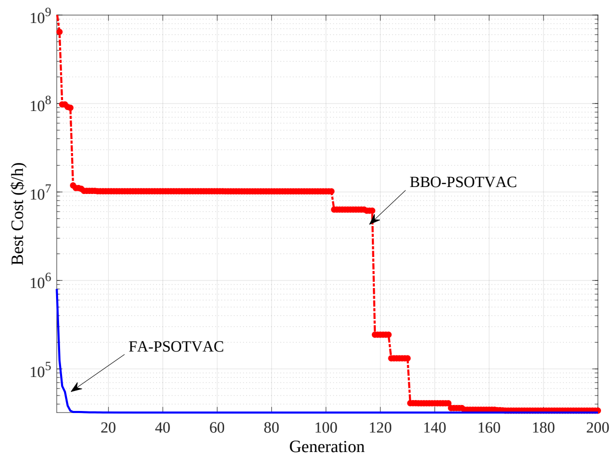

Fig. 6: Convergence characteristics of FA-PSOTVAC and BBO-PSOTVAC for test system 1.

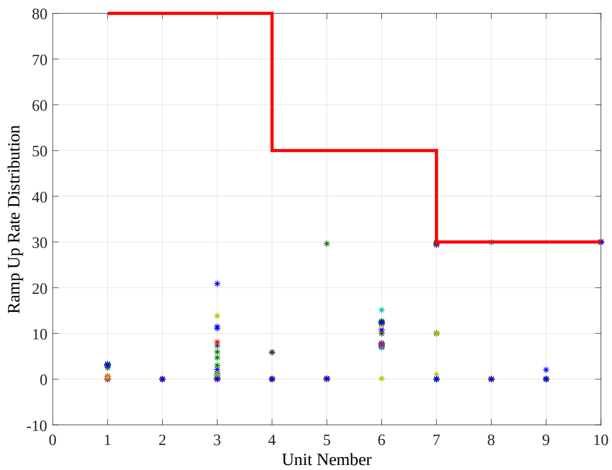

Fig. 7: Distribution of Ramp Up violation for 50 trials for test system 1.

Tab. 1: Best solution of FA for test system 1.

H	Pg1	Pg2	Pg3	Pg4	Pg5	Pg6	Pg7	Pg8	Pg9	Pg10	Cost
1	150.0000	309.5755	73.0000	60.0000	122.8639	122.4782	76.0961	47.0000	20.0000	55	28745
2	150.0000	309.5507	73.0999	60.0000	122.8885	149.3127	93.1691	47.0000	49.9658	55	30391
3	226.5853	309.6643	153.0568	60.0000	123.0489	140.4734	123.1521	47.0000	20.0000	55	33563
4	226.5508	309.5670	185.0731	100.5493	172.7406	159.9138	129.5695	47.0000	20.0159	55	36629
5	226.6134	309.5774	238.8934	120.4456	172.8045	159.9993	129.6077	47.0000	20.0537	55	38338
6	303.2963	309.6235	297.3994	120.4101	222.6227	122.9657	129.6770	47.0000	20.0000	55	41054
7	379.7484	309.5613	296.1865	120.2595	222.2314	122.4294	129.5911	47.0000	20.0000	55	42688
8	379.9163	309.5878	331.9346	120.3543	222.5364	160.0000	129.5783	47.0463	20.0414	55	44682
9	456.5803	309.5402	340.0000	170.3125	235.8224	160.0000	129.6444	47.0412	20.0000	55	48408
10	457.0786	389.4996	339.9167	220.2939	223.6654	159.9001	129.7003	47.0000	49.9592	55	52014
11	456.4682	460.0000	323.9527	241.3500	222.6343	160.0000	129.6314	76.9459	20.0000	55	53694
12	456.5319	460.0000	339.6460	291.1819	222.5952	160.0000	129.6202	85.3100	20.0792	55	55437
13	456.6231	459.9778	297.3991	241.2082	172.7557	154.0301	129.6521	85.3238	20.0016	55	51712
14	456.4936	396.7729	294.7512	191.2087	172.4486	122.5401	129.6818	85.1015	20.0000	55	47899
15	379.8663	396.7837	233.4647	180.8780	172.5976	122.5602	129.5828	85.2840	20.0000	55	44832
16	302.8660	316.7899	185.2285	130.9164	172.7174	155.4687	129.5770	85.4114	20.0461	55	40103
17	226.7340	309.5333	200.4338	120.5870	172.8071	160.0000	129.6007	85.2751	20.0000	55	38265
18	303.2308	309.5587	229.6569	120.5972	222.5535	122.5015	129.5881	115.2475	20.0000	55	41774
19	379.9181	309.4884	297.1465	119.7770	222.6016	122.4900	129.5685	120.0000	20.0000	55	44552
20	456.3717	389.4182	319.4344	169.7228	222.5600	159.8888	129.5937	120.0000	49.9539	55	51945
21	456.7414	309.6307	306.0718	181.1537	222.7390	122.9915	129.6789	120.0000	20.0000	55	48011
22	379.8686	229.6340	267.7906	131.2140	172.7559	122.2274	129.6219	119.8901	20.0000	55	41927
23	302.1687	222.1867	187.9891	81.3181	122.8433	120.9311	99.6632	119.8957	20.0000	55	35496
24	226.0974	222.2598	178.4508	60.0000	122.5708	80.0712	129.5932	89.9053	20.0000	55	32081
Total Cost ($)						**1024240**					

5. Simulation Results

In this study a comparative analysis is elaborated to validate the robustness of the proposed hybrid algorithm in solving the DED considering several practical constraints. Four algorithms are investigated, FA, BBO, PSOTVAC, FA-PSOTVAC, and BBO-PSOTVAC. Two test power systems are investigated to validate the efficacy of the proposed algorithms and in particular the hybrid method named FA-PSOTVAC.

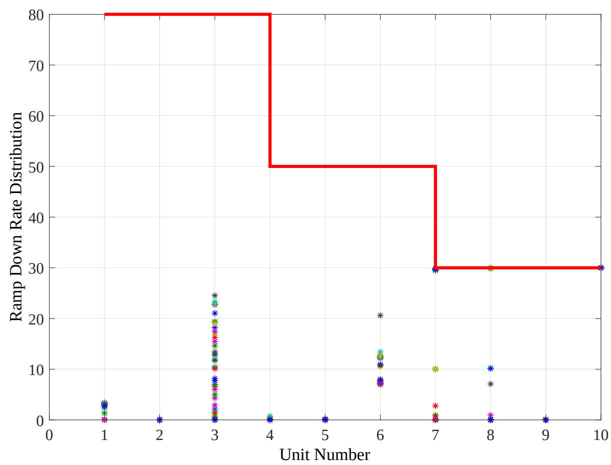

Fig. 8: Distribution of Ramp Down violation for 50 trials for test system 1.

5.1. Test System 1

The first test system consists of 10 units, system data is takem from [35] and [17]. The optimized active power of thermal units during 24 H is achieved considering valve point effect, prohibited zones and ramp rate limits. For fair comparison between different methods, the population size for all methods is set to 50. Table 1 and Tab. 2 show the details of the optimized active power of 10 thermal units during 24 H. The FA achieves the best solution 1024200 $ at 500 iterations, the corresponding execution time is 41.8955 min, the convergence characteristics are shown in Fig. 4, the BBO achieves the best total cost 1044000 $ which is higher than FA, also this algorithm requires large number of iterations (1000), at a relatively reduced execution time (7.1236 min) compared to FA.

Table 3 depicts details about the performances of several algorithms in solving DED in terms of the best, the mean and the maximum value. Figure 4 shows the convergence behavior for total cost minimization for a period of 24 h for all proposed methods. As well shown in Fig. 5, the hybrid algorithm named BBO-PSOTVAC allows to achieve a total cost of 1055000 $ at a competitive time (0.9350 min). On the other side, the proposed hybrid algorithm based on combining the FA and PSOTVAC achieves a remarkable total cost of 1024163 $ at a reasonable execution time (8.4934 min), It is also important to confirm that the proposed algorithm is found to be better than other standard and combined algorithms in terms of

Tab. 2: Best solution of FA-PSOTVAC algorithm for test system 1.

H	Pg1	Pg2	Pg3	Pg4	Pg5	Pg6	Pg7	Pg8	Pg9	Pg10	Cost
2	150.0000	222.2977	119.9927	60.0000	172.7551	133.2690	129.6194	47.0684	20.0000	55	30220
3	226.6829	222.2649	199.8623	60.0000	172.7874	124.6362	129.7631	47.0000	20.0000	55	33106
4	303.2261	222.1884	273.8517	60.0000	172.7244	122.4197	129.5903	47.0000	20.0000	55	36316
5	379.9085	222.2685	297.4001	60.0000	122.8779	145.7868	129.7293	47.0000	20.0276	55	37912
6	379.9504	302.2682	300.9859	60.2773	172.7347	160.0000	129.6819	47.0126	20.0874	55	41268
7	379.9384	309.6140	317.8722	110.1765	172.7422	160.0000	129.6391	47.0000	20.0155	55	43089
8	379.7673	309.5442	339.5965	120.4278	222.6159	122.4767	129.6386	47.0000	49.9280	55	44764
9	456.4904	309.5325	297.2723	170.0277	222.2960	154.8207	129.5225	76.9843	52.0546	55	48421
10	468.5611	309.5358	340.0000	220.0197	223.7258	160.0000	129.8466	85.3120	80.0000	55	52581
11	456.5008	389.5146	339.9296	241.2453	236.7129	160.0000	129.7207	85.3177	52.0588	55	53679
12	456.5777	460.0000	340.0000	258.8141	222.6798	159.9631	129.5956	85.3123	52.0564	55	55608
13	456.4978	396.7024	297.2402	284.6130	222.5896	122.3767	129.6034	85.3192	22.0572	55	51452
14	456.5069	316.7464	300.2911	241.3478	222.6032	126.4383	129.7427	55.3223	20.0000	55	48255
15	456.4983	309.2706	251.9156	191.4026	222.5805	122.5846	99.7451	47.0000	20.0000	55	45245
16	379.8921	309.5309	182.2315	172.1561	172.6454	122.4838	93.0579	47.0000	20.0000	55	39961
17	303.2201	309.5034	180.3546	176.7481	172.6892	122.4267	93.0445	47.0000	20.0100	55	38312
18	303.2842	309.9226	260.3178	181.1381	172.7265	125.5862	123.0291	47.0000	49.9962	55	41938
19	379.8756	309.5352	328.4486	181.1280	172.7430	122.6920	129.5852	76.9929	20.0000	55	44915
20	456.5191	389.5333	328.8065	224.6494	222.5961	160.0000	129.5758	85.3189	20.0000	55	51778
21	379.9298	460.0000	317.9828	180.9005	172.7697	122.4799	129.6152	85.3121	20.0090	55	48296
22	303.2117	396.7645	297.3459	130.9016	122.8333	87.0071	129.6583	85.2567	20.0201	55	41694
23	226.6244	316.7646	251.9903	81.1457	73.1616	122.4624	129.5912	55.2591	20.0000	55	35449
24	150.0000	309.5334	185.1918	60.0000	73.0000	154.6855	129.5901	47.0000	20.0000	55	31501
Total Cost ($)						1024163					

Tab. 3: Best solution of FA, BBO, PSOTVAC, FA-PSOTVAC, BBO-PSOTVAC for test system 1.

Method	Pop Size	Max Iteration	Best Solution	Worst Solution	Mean Value	Min-Max of Balance Demande Violation	Time (min)
FA	50	500	1024200	8161000	1254900	0.0213-0.0658	41.8955
BBO	50	1000	1044000	53566000	4909400	0.0198-0.0162	7.1236
PSOTVAC	50	1000	-	-	-	Violation	-
FA-PSOTVAC	50	200	1024163	13793000	1794400	0.0023-0.0049	8.4934
BBO-PSOTVAC	50	200	1055000	1065600	1060000	0.0222-0.0150	0.9350

speed of convergence, standard deviation of generation cost, and computational time. Figure 6 shows the convergence characteristics of FA-PSOTVAC and BBO-PSOTVAC. Figure 7 and Fig. 8 show that the constraints related to ramp up and ramp down are verified. Figure 9 shows the ditribution of the best cost for 50 trials, this test demonstrates the robustness of the proposed hybrid method named FA-PSOTVAC.

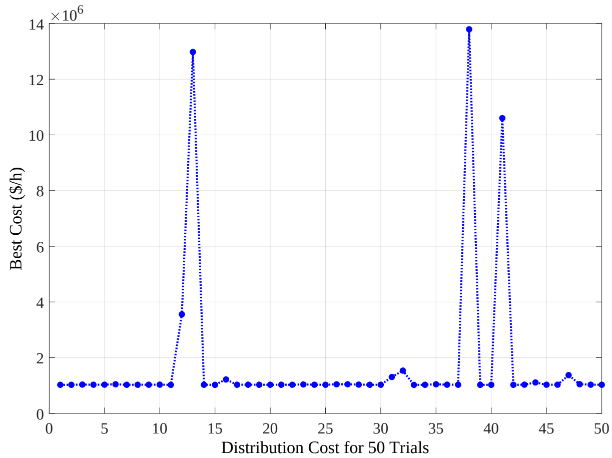

Fig. 9: Distribution of the best cost for 50 trials for test system 1.

5.2. Test System 2

In order to demonstrate the efficacy and performances of the proposed hybrid methods such as FA-PSOTVAC and BBO-PSOTVAC a large scale test system is considered. This second test system consists of 30 units, system data is takem from [11]. For fair comparison with other methods cited in the literature, only two constraints are considered, the valve point effects and ramp rate limits.

The best total cost achieved using the proposed algorithms are compared to various methods cited recently in the literature such as Evolutionary Programming (EP) [36], Differential Evolution (DE) [37], Criss Cross Optimization algorithm (CSO) [11], Harmony Search (HS) [38] and a modified hybrid EP-SQP approach (MHEP-SQP) [35], as well depicted in Tab. 4, it is found that by using the proposed hybrid method BBO-PSOTVAC the best total cost achieved is 3105700 $.

Tab. 4: Best solution of FA, BBO, PSOTVAC, BBO-PSOTVAC and FA-BBO for test system 2.

Method	Pop Size	Max Iteration	Best Solution	Worst Solution	Min-Max of Balance Demande Violation	Time (min)
FA	50	200	3119200	3153700	0.0982-0.0565	11.769
BBO	50	200	3192700	7297400	0.0121-0.0562	3.2391
PSOTVAC	50	1000	-	-	Violation	-
BBO-PSOTVAC	50	1000	3105700	3122200	0.0313-0.0360	3.4018
FA-BBO	50	200	3141960	3166200	0.1323-0.0623	20.001
CSO [11]	30	1000	3051260	3054960	-	1.797
EP [37]	-	-	3164531	-	NA	NA
DE [38]	-	-	3163000	3173100	NA	0.52
HS [39]	-	-	3143254	NA	NA	NA
MHEP-SQP [36]	-	-	3151445	3157738	NA	NA

It is also important to note that the obtained results were achieved at a competitive time.

6. Conclusion

In this study, four algorithms the FA, PSOTVAC, BBO, FA-PSOTVAC, BBO-PSOTVAC have been adapted and applied to solve the DED considering three practical constraints simultaneously such as the valve point effect, prohibited zones and ramp rate limits. The performances of the standard algorithms such as FA and BBO in terms of solution quality and number of generations required have been improved by hybridization. The main idea introduced in this study is to exploit the best properties of FA and PSOTVAC, the BBO and PSOTVAC by creating flexible balance between diversification and intensification during search process. The performances of the hybrid methods were validated on two practical test with 10 units and 30 units to solve the DED considering three practical constraints. The total cost achieved using the hybrid method named FA-PSOTVAC is competitive in terms of solution quality and convergence characteristics. Due to the competitive aspect of the proposed hybrid method, authors will strive to develop an extended hybrid variant to solve DED of modern power system characterized by the large integration of various types of renewable sources and FACTS devices.

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