Modified Firefly Algorithm in Solving Economic Dispatch Problems with Practical Constraints

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***Abstract*—This paper presents a modified Firefly Algorithm (MFA) for solving economic dispatch (ED) problems. ED is one of the most challenging problems of power system since it is difficult to determine the optimum generation scheduling to meet the particular load demand with the minimum fuel costs while all constraints are satisfied. In addition the practical ED problems which are involving objective functions with quality and inequality constraints including the practical operation constraints of generators such as ramp rate limit, prohibited operating zones and generation limits make it harder to find the global optimum results of ED. To demonstrate the effectiveness and feasibility of MFA in solving ED, two well-known ED test systems with non-convex solution features have been tested and compared with some of the most recently published ED solution methods in literatures. The results of this research show that MFA is able to find more economical solution than those determined by other methods.**

Keywords-economic dispatch; firefly algorithm; optimization; swarm intelligence

I. INTRODUCTION

Power system is one of the complex systems of human's invention. One of the most important issue emerged in power system complexity is economic dispatch (ED) problem. ED is the fundamental issue which aims to find the optimal power generation to match with the demand at minimum cost by satisfying all the system constraints. In addition, by taking the consideration of practical and operational constraints, it will make ED highly nonlinear constrained optimization problem, especially for larger systems. Small improvements in determining the optimal output scheduling can contribute to significant cost savings. Thus, there are a lot of researches that have been proposed to solve ED problem.

To date, the application of artificial intelligence, swarm intelligence and optimization techniques becoming the choice of many researchers in solving ED problem. The application of particle swarm optimization (PSO) into ED problem has been proposed in [1]. The modification of PSO namely quantum-behaved PSO (QPSO) [2] and self-organizing hierarchical PSO (SOH_PSO) [3] also have been tempted to solve ED. In evolutionary computation technique to solve ED, GA has been proposed by using string structure scheme which is to prevent GA trapping into infeasible solution [4]. The real-coded GA (RCGA) [5] also has been done in solving ED.

Affijulla and Chauhan [6] proposed an application of Gravitational Search Algorithm (GSA) into ED problem with valve point loading and Kron's loss formula. This technique modifies the Newton's gravitational law and laws of motion which can become a powerful optimizer. An application of Honey Bee Mating Optimization algorithm to ED has been proposed in [7]. The other technique based on swarm of bees, bee colony optimization also has been done in solving ED problem [8].

Although the said methodologies have been developed for ED, the complexity of the task reveals the necessity for development of efficient algorithms to accurately locating the optimum solution [9]. In this paper, the modification of Firefly Algorithm (MFA) to solve ED problem is proposed. FA is a meta-heuristic algorithm which is inspired by the flashing behavior of fireflies [9]. The results demonstrate that the proposed method gives the good solution quality and efficiency in solving the ED problem. This paper is organized as follows. The ED problem is briefly discussed in Section 2. The concept of MFA is presented in Section 3. In Section 4, the case study including discussion is presented. Finally, conclusion is stated in Section 5.

II. ECONOMIC DISPATCH PROBLEMS

Economic dispatch is the operation of generation to produce energy at the lowest cost by fulfilling the demand within several limits. This is not an easy task since there are a lot of factors need to be considered especially in the large interconnected power systems. The objective function is to minimize the overall generating cost which normally expressed as polynomial function as follows:

$$F_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i P_i^2 \quad (1)$$

where P_i is the output power of generator i for dispatched hour, $F_i(P_i)$ is the fuel cost function of generator i, and α_i, β_i and γ_i are the coefficients of the fuel cost function for generator i.

The fitness function in (1) is subject to the following constraints:

A. Power balanced constraints

The total power output of generators must always equal to the sum of the power demands and the network losses as shown in the following:

$$\sum_{i=1}^{n_G} P_i = P_D + P_L \qquad (2)$$

where P_D is the total load demand, P_L is the total loss and n_G is the total number of committed generator during the dispatched hour. Since the power loss is cannot avoided in interconnected power system, it must be taken into account to achieve as closed as practical economic dispatch by using the B-coefficient method [10], as follows:

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} \qquad (3)$$

B. Ramp rate limits

In ED, several studies simplified the problem with the assumption that unit generation output can be adjusted instantaneously. This is not happened when the practical or actual operating process is taken into consideration. The operating range of all online units is restricted by their ramp rate limits [10]. Fig. 1 shows three possible situations when a unit is online from hour t-1 to hour t where the unit is in a steady state, increasing and decreasing power generation operation status in Fig. 1 (a) , (b) and (c) respectively.

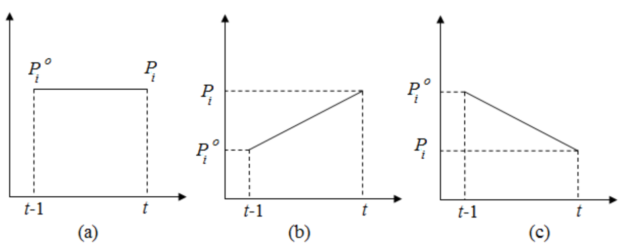

Figure 1. Three possible situations of an online unit.

Thus, the inequality constraints due to ramp rate limits are expressed as:

$$P_i - P_i^o \le UR_i \text{ if generation is increases} \qquad (4)$$

$$P_i^o - P_i \le DR_i \text{ if generation is decreases} \qquad (5)$$

where P_i^o is the previous power generation of unit *i*. UR_i and DR_i are the up-ramp and down-ramp limits in MW/h of the *i*-th generator, respectively. The generator operation constraints with the ramp rate limit now becomes as:

$$\max(P_i^{\max}, UR_i - P_i^o) \le P_i \le \min(P_i^{\max}, P_i^o - DR_i) \qquad (6)$$

C. Prohobited operating zones

The prohibited operating zones in the curve due to steam valve operating in shaft bearing [10] are being considered in determining the optimum ED in this paper. Since the shape of the input-output curve in the neighborhood of the prohibited zone is difficult to determined, the best economical approach is achieved by avoiding the operation in these areas. The typical input-output curve of a thermal unit is shown in Fig. 2. The feasible operating zones of a unit can be expressed as follow [4]:

$$\begin{cases} P_i^{\min} \le P_i \le P_{i,1}^{lower} \\ P_{i,j-1}^{upper} \le P_i \le P_{i,j}^{lower}, \; j = 2,3,\ldots, PZ_i \\ P_{i,PZ_i}^{upper} \le P_i \le P_i^{\max} \end{cases} \qquad (7)$$

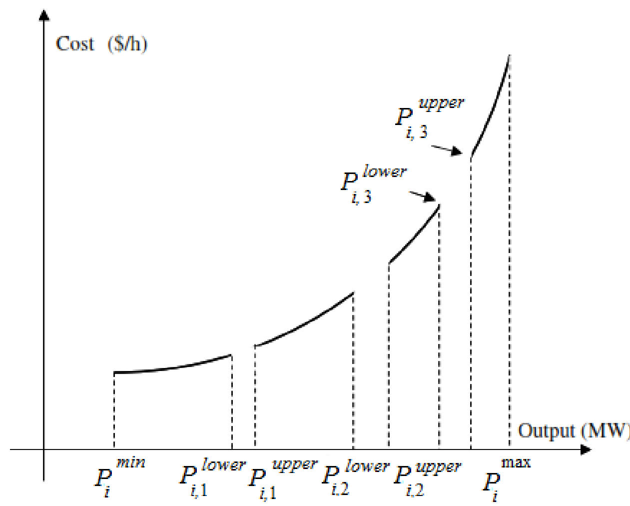

Figure 2. The prohobited operating zones and generation limits for a generator [4].

III. Modified Firefly Algorithm

Firefly Algorithm (FA) is invented by Yang *et al.* [9] for solving ED problem. The development of FA is based on flashing behavior of fireflies. There are about two thousand firefly species where the flashes often unique for a particular species. The flashing light is produced by a process of bioluminescence where the exact functions of such signaling systems are still on debating. Nevertheless, two fundamental functions of such flashes are to attract mating partners (communication) and to attract potential prey.

For simplicity, the following three ideal rules are introduced in FA development [9]: 1) all fireflies are unisex so that one firefly will be attracted to other fireflies regardless of their sex, 2) attractiveness is proportional to their brightness, thus for any two flashing fireflies, the less brighter one will move towards the brighter one, 3) the brightness of a firefly is affected by the landscape of the objective function. For maximization problem, the brightness can simply be proportional to the value of the objective or fitness function.

The basic steps of the FA can be summarized as the pseudo code which is depicted in Fig. 3 [9].

```
Firefly Algorithm
Objective function f(x),   x = (x1,...,xd)^T
Generate initial population of fireflies xi ( i=1, 2..., n)
Light intensity Ii at xi is determined by f(xi)
Define light absorption coefficient γ
while ( t < MaxGeneration)
for i = 1: n all n fireflies
    for j = 1: i all n fireflies
            if (Ij > Ii), More firefly i towards j in d-dimension; end if
              Attractiveness varies with distance r via exp[-γr]
              Evaluate new solutions and update light intensity
    end for j
end for i
Rank the fireflies and find the current best
end while
Post process results and visualization
```

Figure 3. Pseudo code of the FA

The movement of a firefly i is attracted to another brighter firefly j is determined by [9]:

$$x_i^{t+1} = x_i^t + \beta_0 e^{-\gamma r_{ij}^2}\left(x_i^t - x_j^t\right) + \alpha\varepsilon_i^t \qquad (7)$$

where β_0 is the attractiveness at $r = 0$, the second term is due to the attraction, and the third term is randomization from Gaussian distribution [9].

The modified FA was proposed in this paper to improve the exploration of the searching optimum solution. Two modifications have been done. Firstly, instead of using Cartesian distance of r_{ij}, the modification was done by finding the minimum variation distance between fireflies i and j. Secondly, to improve the exploration or diversity of the candidate of solution, the simple mutation corresponds to α in (7) is adopted in the FA process. Thus it will enhance the optimum results in solving ED. The proposed modifications can be summarized as the pseudo code which is depicted in Fig. 4.

```
Modified Firefly Algorithm
Objective function f(x),   x = (x1,...,xd)^T
Generate initial population of fireflies xi ( i=1, 2..., n)
Light intensity Ii at xi is determined by f(xi)
Define light absorption coefficient γ
while ( t < MaxGeneration)
for i = 1: n all n fireflies
    for j = 1: i all n fireflies
            if (Ij > Ii), More firefly i towards j in d-dimension; end if
               Find the minimum variation distance of all fireflies
               r = min (Σ(firefly i –firefly j))
               Attractiveness varies with distance r via exp[-γr]
               Evaluate new solutions and update light intensity
    end for j
end for i
randnum
Mutation if randnum < probability of mutation
Rank the fireflies and find the current best
end while
Post process results and visualization
```

Figure 4. Pseudo code of the MFA

IV. SIMULATION RESULTS AND DISCUSSION

The proposed MFA has been tested on two well-known test systems viz. 6-units and 15-units systems which can be obtained in [1].

A. 6-units system

The system consists of six thermal units, 26 buses and 46 transmission lines. The load demand is 1263 MW. The characteristics of the six thermal units are given in Tables I and II. The loss coefficients B can be obtained in [1].

TABLE I. GENERATING UNIT CAPACITY AND COEFFICIENTS

Unit	P_i^{min}	P_i^{axn}	α_i($)	β_i($/MW)	γ_i($/MW^2)
1	100	500	240	7.0	0.0070
2	50	200	200	10.0	0.0095
3	80	300	220	8.5	0.0090
4	50	150	200	11.0	0.0090
5	50	200	220	10.5	0.0080
6	50	120	190	12.0	0.0075

TABLE II. RAMP RATE LIMITS AND PROHIBITED ZOES OF GENERATING UNITS

Unit	P_i^0	UR_i (MW/h)	DR_i (MW/h)	Prohibited zones (MW)
1	440	80	120	[210 240] [350 380]
2	170	50	100	[90 110] [140 160]
3	200	65	100	[150 170] [210 240]
4	150	50	90	[80 90] [110 120]
5	190	50	90	[90 110] [140 150]
6	110	50	90	[75 85] [100 105]

The best result of MFA together with other methods [1, 3, 4, 5] is tabulated in Table III. From this table, it can be seen that all of the constraints mentioned in Tables I and II are all satisfied. It is also shown that the proposed MFA has a better solution quality in term of total cost generated compared to the others.

TABLE III. BEST SOLUTIONS OF 6-UNITS SYSTEM

Generator Output	MFA	SOH_PSO [3]	GA [4]	PSO [1]	RCGA [5]
P1	445.08	438.21	446.71	447.5	474.81
P2	173.08	172.58	173.01	173.32	178.64
P3	264.42	257.42	265	263.47	262.21

P4	139.59	141.09	139	139.06	134.28
P5	166.02	179.37	165.23	165.48	151.9
P6	87.21	86.88	86.78	87.13	74.18
Line Loss	12.41	12.55	12.733	12.958	13.022
Total Output	1275.4	1275.55	1275.73	1276.01	1276.03
Cost ($/h)	15,443	15,446	15,447	15,450	15,459

B. 15-units system

The system consists of 15 thermal units and the details parameters of the system can be accessed in [1]. In this test system, all the mentioned practical constraints and nonlinear characteristics of the ED problem are included. The load demand is 2630 MW. The prohibited operating zones embedded in the 4 units, viz. units 2, 5, 6 and 12.

The comparison of best, average and worst solutions of the proposed MFA and most recently published ED solution methods shown in Table IV. The comparison with the FA [9] also has been done and shown in this table. It can be seen that MFA offers an improved generation cost over the other methods. All mentioned constraints were satisfied and it can be said that MFA is superior compared to other methods. A detailed result of the optimal solution of the proposed MFA together with FA is tabulated in Table V. For this study, only 20 simulations have been executed to see the robustness of the proposed method. It can be noted that the better result is obtained for the proposed method.

TABLE IV. BEST, AVERAGE AND WORST SOLUTIONS OF 15-UNITS SYSTEM

Methods	**Generation Cost ($/h)**		
	Best	**Average**	**Worst**
PSO [1]	32,858	33,039	33,331
GA [5]	33,113	33,228	33,337
SOH PSO[3]	32,751	32,878	32,945
CPSO1 [11]	32,835	33,021	33,318
CPSO2 [11]	32,834	33,021	33,318
BF [12]	32,784.50	32,796.80	NA
FA [9]	32,704.50	32,856.10	33,175
MFA	32,697	32,703	32,713

TABLE V. BEST SOLUTIONS RESULTOF 15-UNITS SYSTEM

Unit	**MFA**	**FA [9]**
	Power (MW)	**Power (MW)**
1	454.9737	455
2	379.9481	380
3	130	130
4	129.9541	130
5	170	170
6	460	460
7	429.995	430
8	115.3589	71.745
9	43.6778	58.9164
10	126.6485	160
11	79.9884	80
12	79.8974	80
13	25	25
14	15.0288	15
15	18.456	15
Losses (MW)	29.5101	30.6614
Generation cost ($/h)	32,697	32,704.4501

V. CONCLUSION

The proposed MFA to solve ED problem by considering the practical constraints has been presented in this paper. The effectiveness of MFA was demonstrated and tested. From the simulations, it can be seen that MFA gave the best result of total cost minimization compared to the other methods. In future, the proposed MFA can be used to solve ED with considering the valve loading effect, which is still in the progress of the research works.

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