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Firefly Algorithm based on Fuzzy Mechanism for Optimal Congestion Management

Aref Jalili[1], Mansour Hosseini Firouz[1], Noradin Ghadimi[2]*

1Department of Engineering, Ardabil Branch, Islamic Azad University, Ardabil, Iran
2Young Researchers and Elite club, Ardabil Branch, Islamic Azad University, Ardabil, Iran
**Author for Correspondence*

ABSTRACT

This paper presents optimal congestion management in an electricity market using Firefly Algorithm (FA) and Fuzzy mechanism. The FA is a meta-heuristic, nature-inspired, optimization algorithm which is based on the social (flashing) behavior of fireflies, or lighting bugs, in the summer sky in the tropical temperature regions. Transmission pricing and congestion management are the key elements of a competitive electricity market based on direct access. They also focus of much of the debate concerning alternative approaches to the market design and the implementation of a common carrier electricity system. This paper focuses on the tradeoffs between simplicity and economic efficiency in meeting the objectives of a transmission pricing and congestion management scheme. The effectiveness of the proposed technique is applied on 30 and 118 bus IEEE standard power system in comparison with CPSO, PSO-TVAC and PSO-TVIW. The numerical results demonstrate that the proposed technique is better and superior than other compared methods.

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Introduction

The emerging energy markets take on various forms. Depending on particular regional characteristics some markets admit centralized day-ahead and hour-ahead markets for wholesale trading and a real-time energy market for balancing while others only offer one or two centralized markets, and still other offers only bilateral contracts among market participants with no centralized markets. The model of Multilateral Transaction is based on bilateral transactions between market participants without the presence of centralized market. The system operator, upon receiving the proposed transactions, makes decisions to have allowed or not to the transactions based on analysis of transmission network constraints. Only when the proposed transactions violate transmission limits, the operator interferes of system and suggests necessary modifications needed to the transactions through "loading vector" [1-2].

Optimal Power Flow (OPF) has probably been the most significant technique for obtaining minimum cost generation patterns in a power system with existing transmission and operational constraints [3]. The problem of dispatch has been formulated with two different objective functions: cost minimization and minimization of transaction deviations. The congestion charges can be calculated in both the cases. These can then be incorporated in the problem of OPF to efficiency the incremental/decremental change in the generator outputs. Similarly, in the bilateral market mode case, every transaction contract can include a compensation price that the buyer-seller pair is willing to accept should its transaction be curtailed [4].

Actually, several OPF based congestion management schemes for multiple transactions have been proposed recently. The minimum total modification to the favorable transactions for relieving congestion is presented in [5]. In [6] a number of Congestion management approaches are presented. Congestion factor of distribution network is described in [7]. Ranking zone categorized by sensitivity index is divided to active and reactive power. This technique in computational aspect is complex. A variant of this least modification approach [8] used a weighting scheme with the weights being the surcharges paid by the transactions for transmission usage in the congestion-relieved network. In [9], an OPF which minimizes cost of congestion and service costs is proposed. A new working of congestion management in multilateral transaction networks has been developed based on physical flows [10].

In this paper, hybrid FA with fuzzy mechanism is proposed for re-dispatching system with congestion management to minimize cost, congestion lines for overload condition and satisfied production constraints and generator loads. The FA is a meta-heuristic, nature-inspired, optimization algorithm which is based on the social (flashing) behavior of fireflies, or lighting bugs, in the summer sky in the tropical temperature regions. The effectiveness of the proposed technique is applied on 30 and 118 bus IEEE standard power system in comparison with CPSO, PSO-TVAC and PSO-TVIW [14]. Proposed method has a high convergence rate and placed in local areas.

I. PROBLEM EXPRESSION

The optimal congestion management minimizing re-dispatch cost can be expressed as [4]:

$$Min \sum_{g=1}^{Ng} Ic_g\,(\Delta P_g)\Delta P_g \quad (1)$$

Where,

ICg = Incremental and decremental cost of generator g
ΔPg = Active power adjustment at bus g
g = Participating generator
Ng = Number of participating generators.

- Power balance constraint:

$$\sum_{g=1}^{Ng} \Delta P_g = 0 \quad (2)$$

- Operating limit constraints:

$$\Delta P_g^{\min} \le \Delta P_g \le \Delta P_g^{\max};\, g = 1,2,...,Ng \quad (3)$$

Where,

$$\Delta P_g^{\min} = P_g - P_g^{\min}\, and\, \Delta P_g^{\max} = P_g^{\max} - P_g \quad (4)$$

- Line flow constraints:

$$\sum_{g=1}^{Ng} (GS_g^{ij}.\Delta P_g) + F_l^0 \le F_l^{\max}\quad, l=1,2,\dots,n \quad (5)$$

A. *Re-dispatched Generators Selecting*

The Generator Sensitivity (GS) technique indicates the change of active power flow due to change in active power generation which is explained between *i* and *j* buses as [8]:

$$GS_g^{ij} = \frac{\Delta P_{ij}}{\Delta P_{Gg}} = \frac{\partial P_{ij}}{\partial \theta_i}\cdot\frac{\partial \theta_i}{\partial P_{Gg}} + \frac{\partial P_{ji}}{\partial \theta_j}\cdot\frac{\partial \theta_j}{\partial P_{Gg}} \quad (6)$$

The equation for derivation of power flow on congested lines can be described as:

$$\frac{\partial P_{ij}}{\partial \theta_i} = -V_iV_j.G_{ij}.\sin(\theta_i - \theta_j) + V_iV_j.B_{ij}.\cos(\theta_i - \theta_j)$$

$$\frac{\partial P_{ij}}{\partial \theta_j} = +V_iV_j.G_{ij}.\sin(\theta_i - \theta_j) + V_iV_j.B_{ij}.\cos(\theta_j - \theta_i) = -\frac{\partial P_{ij}}{\partial \theta_i} \quad (7)$$

For the related equation between the change in active power at each bus and voltage phase angles can be written as:

$$[\Delta P]_{n\times1} = [\mathrm{H}]_{n\times n} \times [\Delta\theta]_{n\times1}$$

$$[\mathrm{H}]_{n\times n} = \begin{bmatrix} \frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial \theta_2} & \cdots & \frac{\partial P_1}{\partial \theta_n} \\ \frac{\partial P_2}{\partial \theta_1} & \frac{\partial P_2}{\partial \theta_1} & \cdots & \frac{\partial P_2}{\partial \theta_n} \\ : & : & & : \\ . & . & & . \\ \frac{\partial P_n}{\partial \theta_1} & \frac{\partial P_n}{\partial \theta_2} & \cdots & \frac{\partial P_n}{\partial \theta_n} \end{bmatrix}_{n\times n} \quad (8)$$

Where, $[M] = [\mathrm{H}]^{-1}$ therefore $[\Delta\theta]_{n\times1} = [M]_{n\times n} \times [\Delta P]_{n\times1}$. Since bus 1 is the reference bus, the first row and first column of [M] can be eliminated. Therefore, the modified [M] is written as:

$$[\Delta\theta]_{n\times1} = \begin{bmatrix} 0 & 0 \\ 0 & [\mathrm{M}-1] \end{bmatrix}_{n\times n} \times [\Delta P]_{n\times1} \quad (9)$$

The modified [M] represents the values of $\frac{\partial \theta_i}{\partial P_{Gg}}$ and $\frac{\partial \theta_j}{\partial P_{Gg}}$ to calculate GS values. Large GS generators will be selected for re-dispatched since they are more influential on the congested line.

II. HYBRID METHOD

A. *Firefly Algorithm*

The Firefly Algorithm (FA) is a meta-heuristic, nature-inspired, optimization algorithm which is based on the social (flashing) behavior of fireflies, or lighting bugs, in the summer sky in the tropical temperature regions and introduced by Xin-She Yang [17]. Although FA has many similarities with other algorithms which are based on the so-called swarm intelligence; it is indeed much simpler both in concept and implementation.

Furthermore, this proposed technique is very efficient and can outperform other conventional algorithms, for solving many optimization problems; where the statistical performance of the firefly algorithm was measured against other well-known optimization algorithms using various standard stochastic test functions [17]. For simplicity, summarize of these flashing characteristics as the following three rules:

- All fireflies are unisex, so that one firefly is attracted to other fireflies regardless of their sex.
- Attractiveness is proportional to their brightness, thus for any two flashing fireflies, the less bright one will

move towards the brighter one. The attractiveness is proportional to the brightness and they both decrease as their distance increases. If no one is brighter than a particular firefly, it moves randomly.

- The brightness of a firefly is affected or determined by the landscape of the objective function to be optimized.

B. Attractiveness

The form of attractiveness function of a firefly is the following monotonically decreasing function [17]:

2 $$(\beta_r) = \beta_0^{*} \exp(-\gamma r^{m}), with m \geq 1,$$

1

3

Where, r is the distance between any two fireflies, β_0 is the initial attractiveness at $r = 0$.

γ, is an absorption coefficient which controls the decrease of the light intensity.

C. Distance

The distance between any two fireflies i and j, at positions x_i and x_j , respectively, can be defined as:

4 $$r_{ij} = \left\| x_i - x_j \right\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2}$$

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Where $x_{i,k}$ is the k_{th} component of the spatial coordinate x_i of the i_{th} firefly and d is the number of dimensions.

However, the calculation of distance r can also be defined using other distance metrics, based on the nature of the problem, such as Manhattan distance or Mahalanobis distance.

D. Movement

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

5 $$x_i = x_j + \beta_0 * \exp(-\gamma r_{ij}^2) * (x_j - x_i) + \alpha * (rand - \frac{1}{2})$$

1□

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 used for the random movement of a firefly in case there are not any brighter ones. Actually α is a randomization parameter determined by the problem of interest between [0, 1].

E. Fuzzy Mechanism

Upon having the Pareto-optimal set of non-dominated solution, the proposed approach presents one solution to the decision maker as the best compromise solutions. Due to imprecise nature of the decision maker's judgment, the i^{th} objective function is represented by a membership function μi defined as [18]:

$$\mu_i(p_{gi}) = \frac{f_i^{\max} - f_i(p_{gi})}{f_i^{\max} - f_i^{\min}} \qquad (13)$$

Where, f_i^{max} and f_i^{min} are the maximum and minimum values of i^{th} objective, respectively.

$$FDM_i(p_{gi}) = \begin{cases} 0 & \mu_i(p_{gi}) \leq 0 \\ \mu_i(p_{gi}) & 0 < \mu_i(p_{gi}) < 1 \\ 1 & \mu_i(p_{gi}) \geq 1 \end{cases} \qquad (14)$$

For each non-dominated solution k, the normalized membership function FDM^k is:

$$FDM^{k} = \left[\frac{\sum_{i=1}^{2} FDM_i^{k}(p_{gi})}{\sum_{j=1}^{M}\sum_{i=1}^{2} FDM_i^{j}} \right] \qquad (15)$$

The best compromise solution of congestion management problem is the one having the maximum value of FDM^k as fuzzy decision making function where M is the total number of non-dominated solutions [25]. Then, all the solutions are arranged in descending order according to their membership function values which will guide the decision makers with a priority list of non-dominated solutions in view of the current operating conditions. Fig. 1 shows the membership structure μ_c for the fuzzy logical variable signifying total fuel cost $f_i(P_{gi})$.

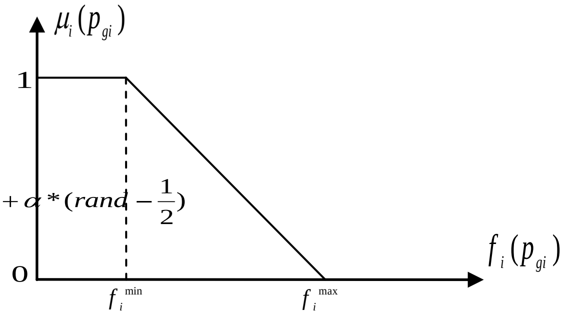

Fig. 1. Membership function of fuzzy fuel cost.

III. COMPUTATIONAL RESULTS

A. IEEE 30-bus system

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The IEEE 30-bus power system with six generators and forty one lines is tested as a first case study. The system configuration of the proposed case study is shown in "Fig. 2". Bus 1 is considered as the reference bus/slack. A congested line between buses 1 and 2 exists as shown in "Table 1".

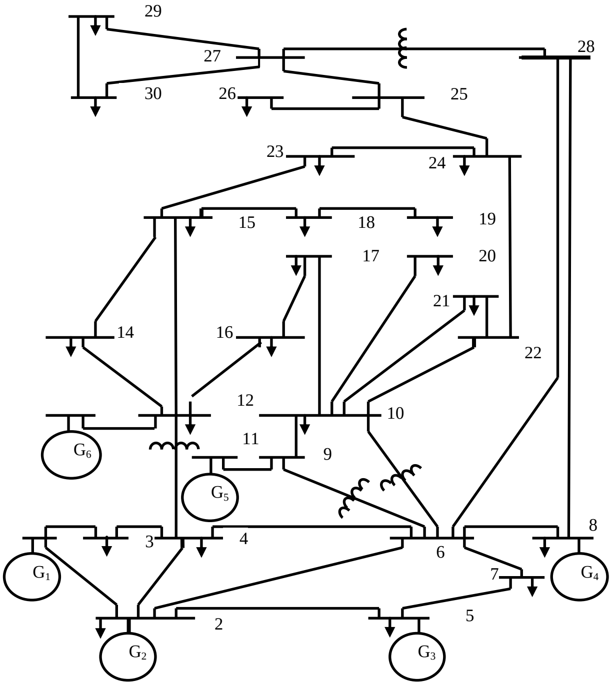

Figure 1. The IEEE 30-bus system configuration

TABLE I. A CONGESTED LINE ON THE IEEE 30-BUS SYSTEM

Congested line	**Active power flow (MW)**	**Line limit (MVA)**	**Overload (MW)**
1 to 2	170	130	40

The values of GS for 6 generation units are presented in Table. 2. Considering GS values which have high values, all generators are selected for re-dispatch. To achieve this goal, selected group of generators having the largest GS values may be used to save the computational effort. Accordingly, these values for first case study are presented in “Fig. 3”.

TABLE II. COMPARISON OF FA+FUZZY MECHANISM SOLUTIONS ON THE IEEE 30-BUS SYSTEM

Algorithm	**MW**	ΔP_1	ΔP_2	ΔP_5	ΔP_8	ΔP_{11}	ΔP_{13}	***Total*** ΔP	***Cost ($ /h)***
CPSO	Max	-66.1	28.9	23.3	18.1	6.2	3.7	146.3	403.1
	Min	-47.9	18.6	16.5	11.3	2.8	0.1	97.2	240.3
	Mean	-55.9	22.6	16.2	10.5	5.6	2.6	113.2	287.1
	SD	8.3	7.6	3.5	3.3	3.2	3.3	15.9	48.2
PSO-TVIW	Max	-58.5	16.7	13.0	11.8	8.6	5.7	114.2	288.0
	Min	-47.3	20.1	14.5	10.5	4.8	0.5	97.7	239.2
	Mean	-50.1	18.9	13.2	9.2	5.9	4.1	101.4	253.1
	SD	2.8	3.5	5.4	3.3	3.5	6.1	13.3	3.8
PSO-TVAC	Max	-51.1	22.0	14.7	8.8	6.2	1.0	103.8	254.9
	Min	-47.3	25.1	16.0	7.6	0.6	0.0	96.7	237.9
	Mean	-49.3	17.5	14.0	9.9	6.8	3.0	100.5	247.5
	SD	0.8	2.1	2.1	2.2	2.3	2.4	4.6	1.6
Proposed	Max	-41.40	20.00	10.45	8.11	7.98	0.22	88.16	214.2288
	Min	-40.30	17.18	12.22	8.45	7.20	0.34	85.69	208.2267
	Mean	-42.43	21.56	11.13	8.08	6.42	0.19	89.81	218.2383
	SD	0.64	1.78	1.64	1.91	2.05	2.14	3.25	1.11

The proposed method provides minimum re-dispatch cost solution in comparison of other techniques which are presented in “Table 3”. Whereas, PSO-TVAC achieved $ 237.9/h, CPSO and PSO-TVIW provide $ 240.3/h and $ 239.2/h, respectively. The convergence characteristic of FA schemes on the IEEE 30-bus system is presented in “Fig. 4”.

TABLE III. GENERATION SENSITIVITY OF 6 UNITS ON THE IEEE 30-BUS SYSTEM

Gen no	**1**	**3**	**5**	**8**	**11**	**13**
GS 1_2	0	-0.8908	-0.8527	-0.7394	-0.7258	-0.6869

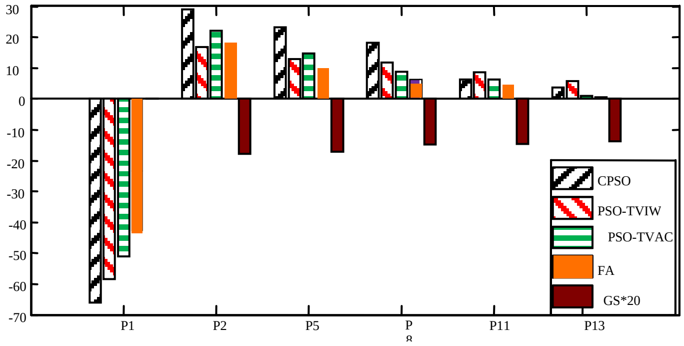

Figure 2. GS values and generation re-dispatch on the IEEE 30-bus system

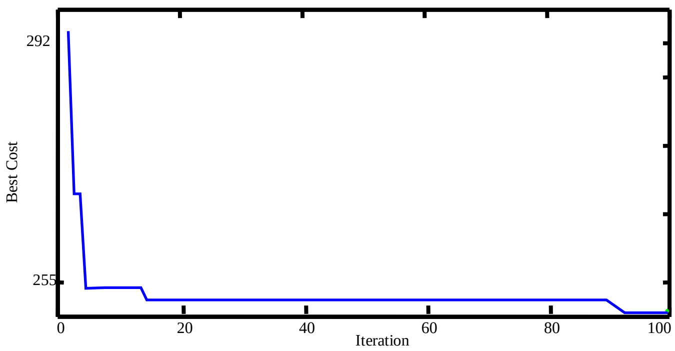

Figure 3. Convergence characteristics of Hybrid FA and Fuzzy mechanism schemes on the IEEE 30-bus system

B. *IEEE 118-bus system*

For the second test case the IEEE 118-bus system with 54 generators and 186 lines [19] is considered. Bus 1 is assigned as the reference bus. The congested line data is shown in "Table. 4".

TABLE IV. A CONGESTED LINE ON THE IEEE 118-BUS SYSTEM

Congested line	**Active power flow (MW)**	**Line limit (MVA)**	**Overload (MW)**
89 to 90	260	200	60

In this case, the numerical and diagram results of GS values are presented in "Table. 5" and "Fig. 4", respectively. These results show, the 85, 87, 89, 90, and 91 of generator buses are among the largest magnitude of GS. This implies that these generators could significantly affect to the congested line.

Therefore, they are chosen as re-dispatched generators. Using the largest GS values, only 6 generators out of 54 are used for re-dispatching by FA algorithm, requiring a much less computational effort.

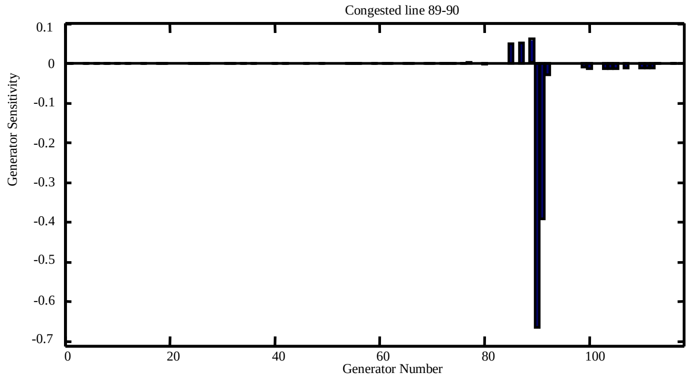

Figure 4. GS values of 54 units on the IEEE 118-bus system.

TABLE V. COMPARISON OF FA AND FUZZY MECHANISM SOLUTIONS ON THE IEEE 118-BUS SYSTEM

Algorithm	**MW**	ΔP_1	ΔP_2	ΔP_5	ΔP_8	ΔP_{11}	ΔP_{13}	**Total** ΔP	**Cost ($/h)**
CPSO	Max	-5.1	-6.4	-8.6	-122.9	117.8	18.9	279.8	1604.5
	Min	-5.1	-27.3	-27.5	-28.9	68.1	25.9	182.7	875.0
	Mean	-5.9	-15.3	-31.5	-62.0	85.1	26.8	226.6	1183.8
	SD	4.4	8.4	11.4	17.5	23.2	14.6	30.5	196.4
PSO-TVIW	Max	-2.7	-13.8	-23.4	-97.7	121.4	10.4	269.4	1497.8
	Min	-6.8	-18.2	-28.2	-33.1	78.3	8.9	173.5	853.8
	Mean	-5.5	-12.1	-28.2	-59.8	76.4	29.8	211.7	1088.4
	SD	4.3	6.7	10.7	16.9	21.1	13.5	26.3	165.8
PSO-TVAC	Max	-5.9	-6.2	-6.5	-96.2	80.1	30.5	225.5	1229.6
	Min	-0.8	-12.1	-13.9	-52.3	81.6	3.3	163.8	829.5
	Mean	-4.4	-10.3	-22.0	-58.5	69.4	24.7	189.3	970.7
	SD	2.9	5.0	10.0	15.1	9.8	16.1	16.5	94.5
Proposed	Max	-7.45	-19.45	-11.45	-39.46	85.16	5.87	168.84	844.2
	Min	-6.94	-17.64	-10.46	-38.46	75.76	6.97	156.23	781.15
	Mean	-4.43	-17.15	-15.17	-39.33	80.24	5.50	161.82	809.1
	SD	1.10	4.20	7.94	13.01	7.98	12.25	12.42	68.363

TABLE VI. GS VALUES OF 54 GENERATORS ON THE IEEE 118-BUS SYSTEM

Gen no.	***GS(10^-3)***	***Gen no.***	***GS (10^-3)***	***Gen no.***	***GS (10^-3)***
1	0	42	-0.0375	80	-0.9250
4	-0.0005	46	-0.0242	85	50.068
6	-0.0001	49	-0.0460	87	50.654
8	-0.0014	54	-0.0838	89	74.455
10	-0.0014	55	-0.0871	90	-701.15
12	0.0004	56	-0.0854	91	-427.90
15	0.0021	59	-0.1100	92	-28.411
18	0.0051	61	-0.1160	99	-9.391
19	0.0046	62	-0.1130	100	-12.915
24	0.1350	65	-0.1350	103	-12.737
25	0.0484	66	-0.0983	104	-12.854
26	0.0337	69	0.2120	105	-12.772
27	0.0451	70	0.3690	107	-12.202
31	0.0339	72	0.2326	110	-12.274
32	0.0477	73	0.3400	111	-12.07
34	-0.0323	74	0.5410	112	-11.747
36	-0.0329	76	0.8650	113	0.0110
40	-0.0343	77	0.0012	116	-0.1750

The proposed FA technique over the IEEE 118-bus power system is compared with other meta-heuristic algorithms in “Table. 6”. Consequently, the proposed technique provides minimum re-dispatch cost solution of $ 809.1. The convergence characteristic of FA schemes on the IEEE 118-bus system is presented in “Fig. 6”.

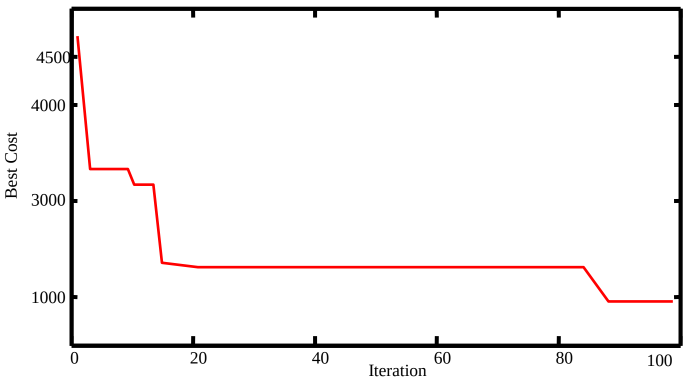

Figure 5. Convergence characteristics of FA schemes on the IEEE 118-bus system

As the GS at bus 85, 87, and 89 are positive, the generation output at these buses is reduced. By contrast, the generators at bus 90 and 91 have negative GS values, thus the generation is increased. Moreover, the GS magnitude affects to the amount of active power adjustment.

The reference bus is used to maintain the power balance. The relationship between GS values and power re-dispatch shown in the “Fig. 7”.

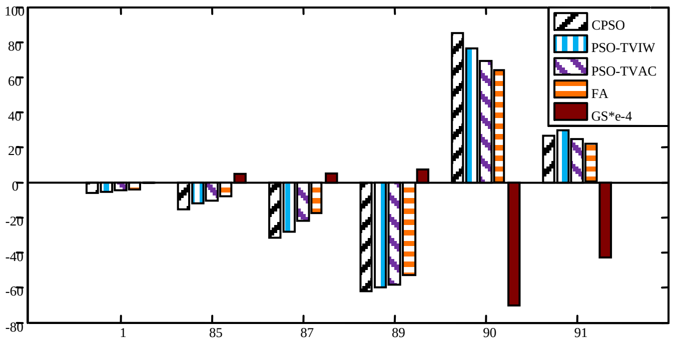

Figure 6. GS values and power re-dispatch on the IEEE 118-bus system

According to the presented results, it is clear that the proposed technique is superior and better than the other compared techniques in optimization problem of congestion management in electricity market regarding to distribution network constraints to reduce cost and increase efficiency and security of power system distribution network.

IV. CONCLUSION

The operational aspects of power systems pose some of the most challenging problems encountered in the restructuring of the electric power industry. In this research hybrid FA and fuzzy mechanism technique is applied for optimization problem of congestion management in electricity market regarding to distribution network constraints to reduce cost and increase efficiency and security of power system distribution network. Purposed algorithm had an appropriate convergence rate compared with other techniques. FA is a meta-heuristic, nature-inspired, optimization algorithm which is based on the social (flashing) behavior of fireflies, or lighting bugs, in the summer sky in the tropical temperature regions. The proposed technique convergence rate is really less than in comparison other methods in solving complex mathematical problems. The effectiveness of the proposed technique is applied over two IEEE standard power systems.

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