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Optimal Power Flow using Fuzzy-Firefly Algorithm

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Abstract—**Development of Metaheuristic Algorithm in engineering problems grows really fast. This algorithm is commonly used in optimization problems. One of the metaheuristic algorithms is called Firefly Algorithm (FA). Firefly Algorithm is a nature-inspired algorithm that is derived from the characteristic of fireflies. Firefly Algorithm can be used to solve optimal power flow (OPF) problem in power system. To get the best performance, firefly algorithm can be combined with fuzzy logic. This research presents the application of hybrid fuzzy logic and firefly algorithm to solve optimal power flow. The simulation is done using the MATLAB environment. The simulations show that by using the fuzzy-firefly algorithm, the power losses, as well as the total cost, can be reduced significantly.**

***Keywords*- Firefly algorithm, Fuzzy logic system, Optimal power flow.**

I. INTRODUCTION

Many power plants such as thermal and hydropower plant are located far away from the load center. Water as a turbine power plant is located either in foothills or mountains as well as in the lake. While petroleum, gas, and coal which is the source of the thermal power plant are generally placed near ports or other places due to the transportation cost [1].

Power plants that located far away from the load center require long transmission line to supply electrical energy to the load center. This long transmission line could cause a huge amount of power loss. This losses resulting in generating units generate power beyond the total load demand that should be borne to compensate for the power loss. The thermal plant is using unrenewable energy such as fuel as the source of energy. The trend in fuel prices on the market fluctuates and the trends continue to increase so that the fuel consumption needs to be minimized due to the high cost for generating electricity [1].

Since the electrical load is a function of generating costs, it is necessary to find solutions to optimally operate the generating units by reducing fuel costs to a minimum and maintaining continuity of service to consumers and still paying attention to the operational constraints. This method is commonly called the optimal power flow (OPF) [2].

The purpose of OPF is to achieve the load demand with a minimum cost production without neglecting physical and operational limits. OPF can be easily done by using conventional mathematical approach. The application of conventional mathematical approach such as Gaussian Message Passing Iterative detection for solving optimization problems is reported in [3, 4]. However, with the more fluctuation of load demand and the fuel prices, the conventional mathematical approach of OPF sometimes do not give optimal results. Hence solving OPF based metaheuristic algorithm approach can be proposed.

The application of metaheuristic algorithm approach for solving a complex problem in power system application has developed significantly over the few decades. Application of differential evolution algorithm (DEA) for designing battery energy storage systems (BESS) and solving the modal interaction problems are reported in [5, 6]. The application of particle swarm optimization (PSO) for solving load frequency control and optimizing redox flow batteries (RFB) is investigated in [7, 8]. In [9] the application of craziness PSO for mitigating low-frequency oscillatory stability is investigated. Optimizing parameter of blade pitch angle wind turbine using hybrid differential evolution algorithm-particle swarm optimization is explained in [10]. Application of imperialist competitive algorithm for designing capacitive energy storage parameter as load frequency controller of micro hydro is described in [11].

Designing RFB based on ant colony optimization (ACO) approach for solving small disturbance angle stability problems is described in [12]. Optimization of RFB and power system stabilizer (PSS) for small signal stability enhancement of power system using cuckoo search algorithm is presented in [13]. Designing a linear quadratic regulator for enhancing the frequency performance of the power system using artificial Immune System via clonal selection is investigated in [14]. Optimal coordination of superconducting magnetic energy storage (SMES) and PSS using firefly algorithm (FA) for dynamic stability enhancement on the power system is reported in [15]. Among a numerous number of metaheuristic algorithm, FA is becoming more popular due to simplicity and less computational burden. Furthermore, the alpha coefficient in FA is played important role in the firefly algorithm as reported in [16]. So by modified the alpha coefficient of FA, the optimal value can be achieved as the alpha coefficient can reduce the randomness of fireflies [17].

Hence this paper proposed the application of firefly algorithm for solving optimal power flow problems. To get the best performance, the fuzzy logic system is used as a hybrid with the FA method. The rest of the paper is organized as follows: Section II provides a fundamental theory of optimal power flow, firefly algorithm, and fuzzy logic systems. Section III focused on designing hybrid fuzzy logic and firefly algorithm for solving optimal power flow. Result and discussion are presented in section IV. Finally, section V highlight the contribution, conclusions and future direction of this work.

II. FUNDAMENTAL THEORY

A. Optimal Power Flow

The idea of optimal power flow was developed by Carpentier in 1962. OPF is used to determine the optimal set of variables that have various constraint boundaries. The development of OPF has been increasing significantly due to the development of advanced computing technology. The problem of highly complex power system optimization can be solved using OPF without needing any huge amount of time. Conventional OPF is one of the optimization problems in the power system to meet the required load demand at the minimum production cost. The cost of generating electricity has increased significantly, as a result of the increasing fuel prices. It is important to find ways to generate electrical energy at minimum cost in power system as well as achieving the physical and constrained provisions in operation. The mathematical representation of OPF to minimize the cost of generation can be described in (1) [2].

$$\min F(x) = \sum_{i=1}^{N} C_i\left(P_{Gi}\right) = \sum_{i=1}^{N}\left(C_2 P_{Gi}^2 + C_1 P_{Gi} + C_0\right) \tag{1}$$

In (1), *F(x)* is the total cost of generation, while C_0, C_1, C_2 are cost function coefficient. Furthermore, P_{Gi}, N are active power generation and the number of the generator. The concept of OPF has only one restriction that is, the total power generated is proportional to the load plus the loss of power. That restriction can be expressed in the mathematical equation in (2) [2].

$$L = \sum F\left(P_i\right) + \lambda\left(P_{load} + P_{losses} - \sum P_i\right) \tag{2}$$

The equation that representing "generation equal to load plus power loss" is described in (3) with equality and inequality constraint described in (4) and (5) [2].

$$P_{load} + P_{losses} - \sum P_i = 0 \tag{3}$$

$$\begin{aligned} P_{Gi} - P_{Di} &= V_i \sum_{j=1}^{NB} V_j (G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)) \\ Q_{Gi} - Q_{Di} &= V_i \sum_{n=1}^{NB} V_j (G_{ij}\sin(\theta_i - \theta_j) + B_{ij}\cos(\theta_i - \theta_j)) \end{aligned} \tag{4}$$

$$\begin{aligned} &P_{Gi\_\min} \le P_{Gi} \le P_{Gi\_\max} \\ &Q_{Gi\_\min} \le Q_{Gi} \le Q_{Gi\_\max} \\ &P_{m\_\min} \le V_m \le V_{m\_\max} \\ &S_L \le S_{L\_\max} \end{aligned} \tag{5}$$

In (4) and (5)

V_i: Voltage magnitude bus i

P_{Gi}: Active power bus i

Q_{Gi}: Reactive power bus i

G_{ij}, B_{ij}: Transmission admittance m-n

Θ_i: Voltage phase angle bus m

Θ_j: Voltage phase angle bus n

B. Firefly Algorithm

FA is a metaheuristic algorithm inspired by the flashing behavior of fireflies. This algorithm was developed by Dr. Xin-She Yang at Cambridge University to solve optimization problems. FA has three important parts as described in the following rule [18-20]:

- All fireflies are unisex, so a firefly will be attracted to other fireflies regardless of their sex.
- The attraction is proportional to the brightness of the fireflies. Fireflies with lower brightness levels will be attracted and move to fireflies with higher brightness. Brightness may decrease with increasing distance and the absorption of light due to air factor. If there are no fireflies with the most brightness light, the fireflies will move randomly.
- The brightness or intensity of the firefly is determined by the value of the objective function of the given problem.

There are two things that are related and very important in FA namely light intensity and attractiveness function. In this case, we assume that the attractiveness is influenced by the degree of light intensity. The degree of light intensity on a firefly x can be stated as (6).

$$I(x) = f(x) \tag{6}$$

In (6), I indicated the level of light intensity on x fireflies that is proportional to the solution of the objective function *(f(x))*. β is the attractiveness coefficient that has relative value due to the light intensity that must be seen and assessed by other fireflies. Hence, the result of the assessment will differ depending on the distance between the fireflies. In addition, the light intensity will decrease from the source due to the air factor (γ). Hence, the mathematical representation of the attractiveness function is presented in (7).

$$\beta(r) = \beta_0 * \exp\left(-\gamma r^m\right), \left(m \ge 1\right) \tag{7}$$

The distance between fireflies *i* and *j* at the locations *x*, *xi* and *xj* can be determined when they are placed at the point where fireflies are dispersed randomly in the Cartesian diagram as presented in (8). Where the different location of firefly *i* to firefly *j* is the distance between those two (*rij*).

$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \qquad (8)$$

The movement of fireflies that move towards the best level of light intensity can be described as (9) [18-20].

$$x_i = x_i + \beta_0 * \exp\left(-\gamma r_{ij}^2\right) * \left(x_j - x_i\right) + \alpha * \left(rand - \frac{1}{2}\right) \qquad (9)$$

In (9), x_1 indicated the initial position of fireflies located at *x*, while alpha is a variable that has a range between 0 and 1. All the variables formed on (9) ensure the fast algorithm work toward the optimal solution [20]

C. Fuzzy logic systems

Fuzzy logic was introduced in 1965 by Lofti Zadeh. The fuzzy or gray concept (vague, unclear) is based on obscurity limits and provides a mechanism for representing linguistic constructions such as “many,” “low,” “medium,” “often,” “multiple”. The fuzzy set provides a meant to model the uncertainties associated with obscurity inaccuracy and lack of information about a problem or plant. Suppose the meaning of a “short” person. For *X* individual short people may have a heigh <4’25”, for *Y* individuals <3’90”. The term “short” informs the same meaning as the individuals of *X* and *Y*, but neither of the gives a distinctive definition [21].

Lofti Zadeh proposed the idea of a set of membership set to make the appropriate decisions when the uncertainty occurred. Like the word “short”, if we take “short” as high equal to or less than 4 feet, then 3’90” easily becomes a member of the “short” set and 4’25” does not belong to the “short” set. The membership value is “1” if a member of the set or “0” if it is not a member of the set. This can be mathematically described as given in (10) [21].

$$X_A(x) = \begin{cases} 1; x \in A \\ 0; x \notin A \end{cases} \qquad (10)$$

In (6), *Xa(x)* is the member of element *x* in the set *A*, while *A* value itself is the whole set of universes. Membership expanded to have various “degrees of membership” at a real continuous interval [0.1]. Zadeh forms a fuzzy set like the set of the universe *X* that can accommodate the “degree of membership” [21].

III. DESIGN FUZZY-FA FOR SOLVING OPF

A. Designing Fuzzy for FA

Fuzzy interference is used to set the value of alpha. Alpha value has an important role on FA. Hence, in this research, the alpha value is designed as random value based on the Takagi-Sugeno fuzzy formula.

The membership function for fuzzy input is used trapezoidal type and has one input which is the minimum value of total fuel cost at each iteration. The linguistic value of the input variables consists of four fuzzy sets of *VS* (very small), *S* (small), *M* (medium), and *L* (large). While the value of crisp output consists of four linear equations. The coefficient values a1-a4 and J1-J6 are obtained by try and error. The value of a1, a2, a3 and a4 are 0.0010465, 0.0021665, 0.003227 and 0.00427 [1]. Table 1 illustrates the membership function of this paper [1].

Table 1 The membership function of fuzzy interference.

Linguistic	**Value**	**Value**	**Value**	**Value**
Very small	797	801.7	802.9	807.6
Small	802.9	807.6	808.8	813.5
Medium	808.8	813.5	814.7	819.4
Large	814.7	819.4	820.6	825.3

The rule base is used to control the fuzzy adaptation. In this paper the rule base of the fuzzy system can be described in below [1]:

R_1 : *If* min(*J*) very small (VS) then $u_1 = a_1 \min(J)$

R_2 : *If* min(*J*) small (S) then $u_2 = a_2 \, min \, (J)$

R_3 : *If* min(*J*) medium (M) then $u_3 = a_3 \min(J)$

R_4 : *If* min(*J*) large (L) then $u_4 = a_4 \min(J)$

Furthermore, since the input is just one of the input is directly stated as defuzzification [22]. In the process of defuzzification, the weighted average is used to find the output of fuzzy.

B. Solving OPF using Fuzzy-FA

Solving OPF using fuzzy-FA includes the following steps:

1. The input parameter of FA, data bus, transmission line, Pmin and Pmax power output.
2. Start firefly initialization.
3. Firefly is inputted as the parameter of optimal power flow for finding the fitness function.
4. Rank the firefly based on the fitness value and find the best fitness from the firefly.
5. Update firefly movement using Eq. 9 by changing the constant alpha value with fuzzy systems
6. Update the best fitness.
7. Update the firefly value.
8. Determine if the characterization is achieved. If not go back in step 3.
9. Print the output (The total generating capacity and cost of the generation).

IV. NUMERICAL RESULTS

Two cases study is considered in this paper in an attempt to test the effectiveness of the fuzzy-FA for solving optimal power flow problems. Comparison between fuzzy-FA, conventional FA and Lagrange is done to investigate the efficiency of the fuzzy-FA. All of the simulations are carried out using the MATLAB environment.

A. Case study 1

In the first case study, Java-Bali 500 kV is used as the test system. Fig. 1 depicts the one line diagram of Java-Bali system. This system consist of 25 buses with one slack bus, seven generator bus, and 17 bus loads. All of the data was taken from PT PLN (Persero) P3B Java, Bali on April 19, 2011 at 18.30 [23]. Generating units connected to the system Java-Bali 500 kV have limits minimum and maximum power generation as follows [23]:

Suralaya : $1.703 \leq P_1 \leq 3.287$ (MW)
Muaratawar : $1.191 \leq P_8 \leq 2.115$ (MW)
Cirata : $500 \leq P_{10} \leq 1.000$ (MW)
Saguling : $350 \leq P_{11} \leq 698$ (MW)
Tanjung Jati : $840 \leq P_{15} \leq 1.321$ (MW)
Gresik : $238 \leq P_{17} \leq 1050$ (MW)
Paiton : $1.664 \leq P_{22} \leq 3240$ (MW)
Grati : $150 \leq P_{23} \leq 827$ (MW)

With the cost function of each generating unit in this system are as follows [23]:

Suralaya $= -6{,}99\,P_1^2 + 385454{,}41P_1 + 51229002{,}4$
Muaratawar $= 137{,}924P_8^2 - 873046{,}208\,P_8 + 5375795990$
Cirata $= 6000\,P_{10}$
Saguling $= 5502\,P_{11}$
Tanjung Jati $= 10.114P_{15}^2 + 284810.35P_{15} + 18527152.74$
Gresik $= -6.3P_{17}^2 + 1021624.6\,P_{17} + 6477009$
Paiton $= 52.19P_{22}^2 + 37370.67P_{22} + 8220765.38$
Grati $= -100.79P_{23}^2 + 1726981.41P_{23} + 29938756.61$

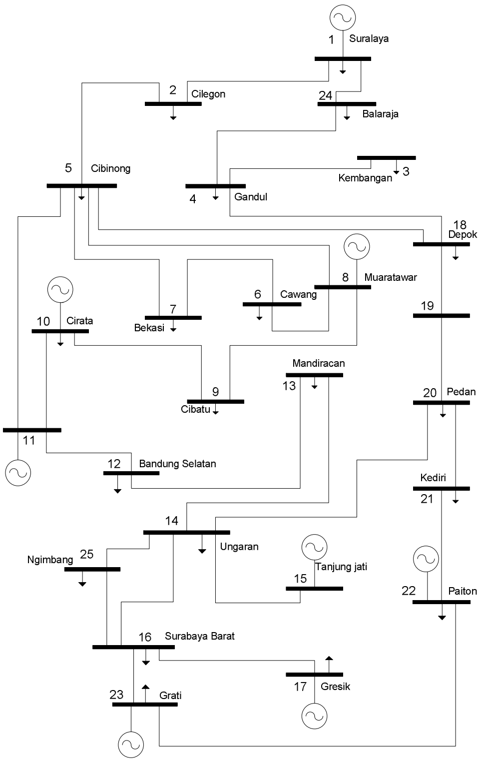

Fig. 1 Java-Bali 500 kV systems.

Table. 2 illustrates the comparison of generating capacity, power loss and cost of the system between a system with Lagrange method, conventional FA method and using the fuzzy-FA method. It is found that by using the Lagrange method, the total cost of the system is 756,570.63 USD and the power loss is 203.34 MW. By using the conventional FA method for solving OPF problems, the total cost can be reduced up to 126,905.87 USD and the power loss can be reduced up to 87.68 MW. Furthermore, the best performance is performed by combining fuzzy and FA. By using fuzzy-FA for solving OPF problems, the total cost becomes 629,664.76 USD.

Table 2. Optimal power flow result on Java-Bali interconnection.

No	**Unit**	***Lagrange***	**Fuzzy-FA**	**FA**
		Power output (MW)	**Power output (MW)**	**Power output (MW)**
1	Suralaya	2006.86	2006.86	2972.69
2	Muarata war	1673.00	1673.00	2115.00
3	Cirata	1000.00	1000.00	1000.00
4	Saguling	499.00	499.00	660.21
5	Tanjung Jati	1291.00	1291.00	1151.55
6	Gresik	900.00	900.00	238.00
7	Paiton	3198.00	3198.00	2740.74
8	Grati	548.00	548.00	150.00
Total power		11115.85	11029.71	11028.18
Power loss (MW)		203.34	117.19	115.66
Total cost ($/hours)		**756,570.63**	**629,064.35**	**629,664.76**

B. Case study 2

IEEE 30 bus is used as a test system in the second case study. Fig. 2 depicts the single line diagram of IEEE 30 bus systems. This system consists of 30 buses with one slack bus, 5 generator bus, and 24 bus loads. All of the data was taken from reference [24]. The maximum and minimum limits of the power generation in IEEE 30 bus is described as follows [24]:

G1: $50 \leq P_1 \leq 200$ (MW)
G2: $20 \leq P_2 \leq 80$ (MW)
G3: $15 \leq P_5 \leq 50$ (MW)
G4: $10 \leq P_8 \leq 35$ (MW)
G5: $10 \leq P_{10} \leq 30$ (MW)
G6: $12 \leq P_{13} \leq 40$ (MW)

With the cost function of each generating unit in this system are as follows [23]:

$F_1 (P_1) = 0 + 2P_1 + 0.0037P_1^2$
$F_2 (P_2) = 0 + 1.75P_2 + 0.0175P_1^2$
$F_5 (P_5) = 0 + 1P_5 + 0.0625P_5^2$
$F_8 (P_8) = 0 + 3.25P_8 + 0.0083P_8^2$
$F_{10} (P_{10}) = 0 + 3P_{10} + 0.025P_{10}^2$
$F_{13} (P_{13}) = 0 + 3P_{13} + 0.025P_{13}^2$

Table. 3 illustrates the comparison of generating capacity, power loss and cost of the system between a system with Lagrange method, conventional FA method and using the fuzzy-FA method. It is found that by using the Lagrange method, the total cost of the system is 803.20 USD and the power loss is 9.59 MW. By using the conventional FA method for solving OPF problems, the total cost can be reduced up to 24.89 USD and the power loss can be reduced up to 3.66 MW. Furthermore, the best performance is performed by combining fuzzy and FA. By using fuzzy-FA for solving OPF problems, the total cost becomes 771.70 USD.

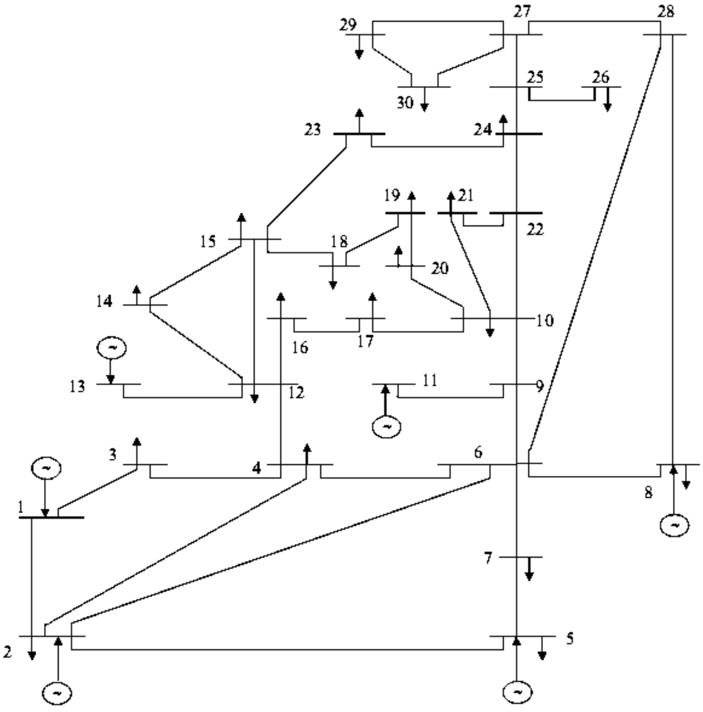

Fig. 2 IEEE 30 bus systems.

Table 3. Optimal power flow result on IEEE 30 bus systems.

No	Unit	*Lagrange* **Power output (MW)**	**Fuzzy-FA** **Power output (MW)**	**FA** **Power output (MW)**
1	G1	193.73	186.28	187.21
2	G2	48.10	47.21	47.40
3	G3	19.47	19.19	19.31
4	G4	11.06	10.43	11.15
7	G5	10.00	10.01	10.00
8	G6	12.00	12.00	12.00
Total power		294.36	285.12	287.06
Power loss (MW)		9.59	1.72	3.66
Total cost ($/hours)		**803.20**	**771.70**	**778.31**

To test the efficiency of fuzzy-FA for solving optimal power flow, comparative study with another algorithm is essential. Fig. 3 illustrates the comparison of the total cost in IEEE 30 bus systems under different tuning, while Fig. 4 shows the comparison of power loss of IEEE 30 bus systems under different tuning method. From Figs. 3 and 4, it is noticeable that the proposed method (fuzzy-FA) could provide minimum cost and power losses.

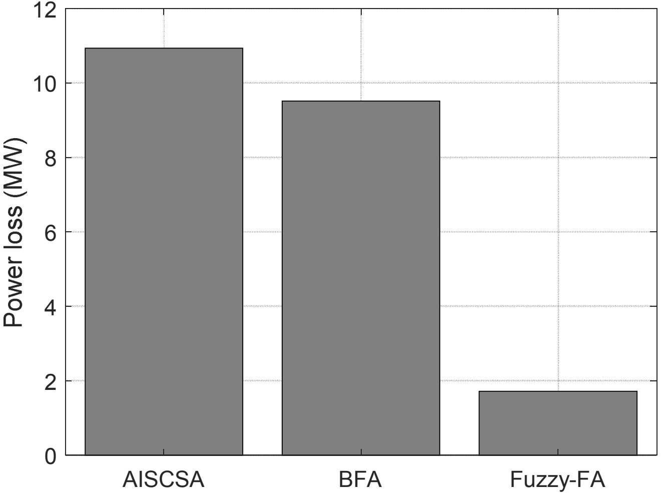

Fig. 3 Power loss comparison.

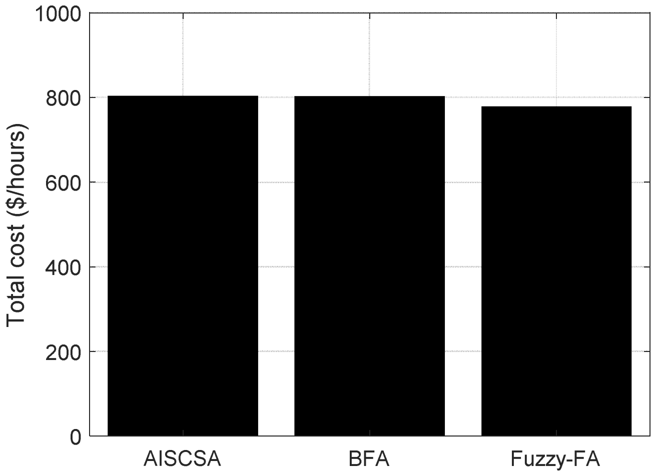

Fig. 4 Total cost comparison.

V. CONCLUSIONS

This paper proposed a method for solving optimal power flow by combining fuzzy logic and firefly algorithm. From the investigated study case, it is found that by using the proposed method, the total cost of both the Java-Bali and IEEE 30 bus system can be reduced. Furthermore, by using the proposed method, the total power loss can also be reduced in both test systems. However, in the case study one, it is found that the loss of Java-Bali by using regular FA is better than using fuzzy-FA. Further research needs to be conducted by considering the ramp rate of the generator, for analyzing dynamic optimal power flow.

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