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A Novel Hybrid Fuzzy-JAYA Optimization Algorithm for Efficient ORPD Solution

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ABSTRACT This paper is concerned with the application of hybrid fuzzy-JAYA optimization algorithm to find the solution of non-linear optimal reactive power dispatch (ORPD) problem in power systems. The proposed hybrid optimization algorithm combines the merits of fuzzy principle and the Jaya optimizer. Fuzzification of the ORPD variables is employed by pseudo goal strategy. Two technical objectives are minimized individually and simultaneously to enhance the overall power systems performance. These objectives are transmission active power losses and voltage deviation at load buses. The ORPD objectives are optimized considering both inequality and equality constraints that reflect the operation needs. The hybrid fuzzy-JAYA is established as efficient optimization method that is achieving the global optimal solution. The effectiveness of the proposed hybrid algorithm for solving the ORPD problem is proven by using three standard IEEE test networks. An assessment of the proposed hybrid algorithm is carried out compared with other optimization algorithms those reported in the literature. The simulation results assure that the fuzzy Jaya hybrid algorithm leads to significant power system performance enhancement for different scale power systems.

INDEX TERMS Fuzzy logic, jaya optimization algorithm, hybrid strategy, ORPD, pseudo goal strategy, minimization of transmission power losses, enhancement of load buses voltage profile.

I. INTRODUCTION

Solving the optimal reactive power dispatch (ORPD) problem is an urgent task in the era of power systems. This problem has several objectives to be optimized such as the minimization of the transmission power losses, enhancing the voltage profile at load buses by reducing the voltage deviation. These objectives are achieved by finding the optimal adjustment of defined control variables like the voltages at generator buses, tapping settings of transformers and allocation of reactive power resources i.e shunt VAR compensator. When the ORPD is solved, equality and inequality constraints are preserved within their acceptable operating limits [1]–[6].

The ORPD is non-linear complex optimization problem that was resolved by many classical methods [7]–[12] including linear programming (LP) [7], interior point method [8], quadratic programming (QP) [9], dynamic programming (DP) and Newton-Raphson [10]. The classical methods have many idrawbacks such as consuming large amount of numerical iterations, huge computations and therefore take a long time to produce results without approximations and assumptions that lead to local optimum solutions. Therefore, these methods failed to handle with the non-linear and complex problems such as the ORPD problem. In the last decades, continuous development of modern optimization techniques led to the existence of wide range of optimization solvers that have been solved for different applications in power systems. In this regard, several methods have been developed for obtainig the ORPD solution such as hybrid particle swarm optimization and imperialist competitive algorithms [4], wind driven optimization algorithm [5], genetic algorithm [11], ant colony optimizer [12], gravitational based search optimizer [13], [14], brain storm optimization algorithm (BSOA) [15], fuzzy linear programming [16], seeker optimization algorithm [17], differential evolution algorithm (DEA) [2], [3], [18], hybrid evolutionary programming (HEP) [19], bacteria foraging optimization (BFO) [20], cuckoo search algorithm (CSA) [21], [22],

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firefly algorithm [23], and several improvements based on the particle swarm optimization (PSO) technique in [6], [24]–[26], and. In [27], genetic algorithm (GA) is developed for improving the voltage stability as an important issue in ORPD frameworks. By dynamic PSO, the real power loss minimization is employed in [28]. An efficient differential evolutionary approach is introduced for ORPD in [29]. Modified DEA algorithm with adaptive penalty factor for reduction of the MW power losses and enhance the shape of voltages at load buses is introduced in [30]. Modified bat algorithm is presented for solving ORPD in [31]. Backtracking search optimization algorithm is enhanced with several strategies for solving the ORPD problem [32]. Evolutionary and teaching-learning-based optimization algorithm for solving ORPD problems were presented in [33] and [34], respectively. In [35] and [36], the thyristor-controlled series compensators are added the system performance by using seeker optimization algorithm. In [37], the controlled switches called Soft Open Points were developed to control the reactive power flow in distribution systems.

JAYA optimizer is an optimization technique presented by R. Venkata Roa in August 2015 [38]. JAYA is Sanskrit word meaning victory [39]. The JAYA optimizer solves the constrained and unconstrained optimization problems. It aims to find the best solution by moving towards the true solution and ignore the worst one by moving far from the false positions [40]. Several applications for Jaya optimization algorithm are reported in [40]–[46].

In this paper, a new hybrid optimization algorithm called fuzzy-JAYA algorithm is investigated for optimizing the settings of control variables defined in the ORPD problem. The effects of this algorithm on the control variables and objective functions are introduced. Although the existence of new optimization algorithms, JAYA technique is considered as a simple, effective tool, easy to be implemented, and high efficiency compared to other optimization algorithms. Therefore, this paper is concerned on obtaining the optimal control variables that reduce the system real power losses as well as enhancing the voltage shape at load nodes. Applications on three standard IEEE systems are passed to demonstrate the capability of the planned hybrid algorithm. Single and multi-objectives case studies are considered.

The rest of this paper is organized as follows: In Section 2, the formulation of the ORPD problem is presented. The proposed hybrid fuzzy-Jaya algorithm is illustrated in Section 3. In Section 4, simulation results are investigated for the IEEE 14, 30 and 118 power systems. Section 5 concludes the main outputs of this research.

II. PROBLEM FORMULATION

The generalized form of the ORPD problem includes the optimization of a non-linear objective function while maintaining different types of operational restrictions. Mathematically, it was expressed as follows:

$$\text{Min } F(x, u) \tag{1}$$

$$\text{Subject to: } g(x, u) = 0 \qquad h(x, u) \leq 0 \tag{2}$$

where, F is the considered objective function, u and x are the control and dependent variables, respectively.

The typical control variables involve the voltages of generators, tap settings of transformers and the injected reactive power from connected reactive power sources i. e. shunt capacitors. The control variables are expressed in the vector form as:

$$u^T = [V_{G_1} \ldots V_{G_{NGen}}, Q_{C_1} \ldots Q_{C_{NCom}}, T_1 \ldots T_{NTr}] \tag{3}$$

The dependent variables are expressed in the vector form as:

$$x^T = [V_{L_1} \ldots V_{L_{NLB}}, Q_{G_1} \ldots Q_{G_{NGen}}, S_{l_1} \ldots S_{l_{Nline}}] \tag{4}$$

The primary ORPD objective function aims to achieve the highest reduction of the real power losses as much as possible can while with satisfying the system equality and inequality constrains. Solving the ORPD problem finds the optimal adjustments of the controlled variables in Eq. (3). These variables are voltages levels at generator bus, settings of transformer taps, and shunt compensator reactive power outputs. According to these adjustments, the dependent variables in Eq. (4) like the MW power generation at slack bus, VAR produced at generation buses and voltages' levels of load buses. The ORPD problem is expressed as in [47]–[50] as:

A. OBJECTIVES

In this study, two objectives, called minimization of system real power losses and minimizing the voltage deviation, which aims at enhancing the voltage profile, are considered. The first objective function that minimizes the real power loss in the transmission network is expressed as:

$$\min P_{L=} \sum_{k \in N_l} P_k^{loss} = \sum_{k \in N_l} G_k (V_i^2 + V_j^2 - 2V_i V_j \cos \theta_k) \tag{5}$$

where, V_i *and* V_j are the bus voltage magnitude at bus i and j, respectively, G_k is mutual conductance between bus i and j, θ_k is the voltage angle difference between bus i and j.

The 2nd objective function aims to minimize the voltage deviation. In a power framework, it is attractive to keep up the load bus voltages (NL) inside determined deviation restrict for the most part inside ±5% of the nominal degree. In this regard, the 2nd objective F_2, which minimizes the bus voltage deviation (VD), can be expressed as:

$$\text{Min } F_2 = VD = \sum_{i=1}^{N_{Load}} |V_i - V_{ref}| \tag{6}$$

where, V_{ref} is the specified reference voltage of buses which is normally equal to 1 p.u, and N_{Load} is the number of load buses.

In this study, the multi-objective framework combines the previous two objectives in their normalized form into single objective function. Therefore, the combined fitness function is expressed by the weighting sum method as follows:

$$\text{Min } F_3 (\text{VD}, \text{P}_{\text{loss}}) = \omega_1 \frac{P_L}{P_L^{\max}} + \omega_2 \frac{VD}{VD^{\max}} \tag{7}$$

where ω_1, ω_2 are weighted values for the fitness functions in the range [0, 1]. The maximum values of $P_L^{\max}$ and $VD^{\max}$ are obtained from single objective cases.

B. SYSTEM CONSTRAINTS

1) THE EQUALITY CONSTRAINTS

For minimizing the objective function, the equality constraints must be achieved as:

$$P_{gi} - P_{di} - V_i \sum_{j=1}^{N_B} V_j (G_k \cos\theta_k + B_k \sin\theta_k) = 0 \tag{8}$$

$$Q_{gi} + Q_{ci} - Q_{di} - V_i \sum_{j=1}^{N_B} V_j (G_k \sin\theta_k - B_k \cos\theta_k) = 0, \quad i \in N_{pq} \tag{9}$$

where, B_k is susceptance between bus i and j, P_{gi} and Q_{gi} are the real and reactive power generation at bus i, P_{di}, Q_{di} are the active and reactive power demand at bus i, Q_{ci} is the capacitive or inductive power of existing VAR source installed at bus i, N_B is the total number of buses and N_{pq} is the total number of load buses.

2) THE INEQUALITY CONSTRAINTS

Equation (10)-(15) represent the operational inequality constraints which must be maintained within their permissible limits as follow:

$$V_i^{\min} \le V_i \le V_i^{\max}, \quad i \in N_B \tag{10}$$

$$T_m^{\min} \le T_m \le T_m^{\max}, \quad m \in N_t \tag{11}$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}, \quad i \in N_{pv} \tag{12}$$

$$Q_{ci}^{\min} \le Q_{ci} \le Q_{ci}^{\max}, \quad i \in N_c \tag{13}$$

$$P_s^{\min} \le P_s \le P_s^{\max} \tag{14}$$

$$S_k \le S_k^{\max}, \quad k \in N_l \tag{15}$$

where, T_m is the tapping change of transformer m, N_{pv} is the total number of voltage-controlled buses, N_t is the total number of on-load tap changing transformers. N_c is the number of shunt capacitor compensators, N_l is the number of all transmission lines in the system, P_s is the active power at slack bus, $P_s^{\min}$ and $P_s^{\max}$ are the minimum and maximum limits at slack bus and S_l is the apparent power flow.

III. PROPOSED HYBRID FUZZY-JAYA ALGORITHM

A. THE JAYA OPTIMIZER CONCEPT

To optimize the function $f(x)$, assume the number of control variables (n) for ($j = 1, 2, \ldots\ldots, k$), the number of candidate solutions (k) for population size ($p = 1, 2, \ldots\ldots, k$) and the number of iteration (i). The solutions are modified according to the following equation:

$$x'_{j,k,i} = x_{j,k,i} + r_1(x_{j,best,i} - |x_{j,k,i}|) - r_2(x_{j,worst,i} - |x_{j,k,i}|) \tag{16}$$

B. FUZZIFYING THE POWER DISPATCH PROBLEM BY THE PSEUDO GOAL STRATEGY

Two strategies were used for solving multi-objective problem. The first is Pareto-based methodology that leads to several non-dominated solutions while the other strategy is aggerating the number of single objectives into single function that is optimized. A fuzzy based on pseudo goal function is proposed for solving the multi-objective problem is this section. The principle of fuzzy decision introduced by Bellman and Zadeh [51], [52].

This concept states that the multi-objective problem is converted into a single-objective model. Then, the minimum degree of satisfaction among the membership degrees the optimized objective functions is while the conditional constraints are added with banality functions. The fuzzification process aims to convert regular variables and functions into their fuzzy counterpart. Fuzzy variable is defined by the pair of of (v, μ) where v is the value set of the variable and μ is the membership function combined with these values. Furthermore, fuzzy objective functions and the constraints are defined basing on the notation of fuzzy variable. This procedure converts the objective function $\text{F}_\text{i}(\text{x})$ and conditional constraints $\text{C}_\text{i}(\text{x})$ into pseudo goals like (F_i, μ_{F_i}) and (C_i, μ_{C_i}) respectively. For a problem containing "L" objectives and "M" constraints, the following notations can be defined:

$$\begin{cases} Objectives: (F_1, \mu_{F_1}), (F_2, \mu_{F_2}), \ldots, (F_L, \mu_{F_L}) \\ Constraints: (C_1, \mu_{C_1}), (C_2, \mu_{C_2}), \ldots, (C_M, \mu_{F_M}) \end{cases} \tag{17}$$

The process of fuzzification calculates the optimal function membership degree via combining all the pseudo goals and constraints. To proceed the fuzzy principle for maximizing certain functions, all membership functions are combined by the (and) or minimum operator. Afterwards, the optimal value x* is calculated by the maximum operator. The proposed methodology can be declared using Eqs. (18) and (19) as:

$$\mu_F(x) = \min\left(\mu_{f_1}(x), \mu_{f_2}(x), \ldots\ldots\mu_{f_L}(x), \mu_{C_1}(x), \mu_{C_2}(x) \ldots\ldots\mu_{C_M}(x)\right) \tag{18}$$

$$\max(\mu_F(x)) = \max\left(\min\left(\mu_{f_1}(x),\right) \mu_{f_2}(x), \ldots\ldots\mu_{f_L}(x), \mu_{C_1}(x), \mu_{C_2}(x) \ldots\ldots\mu_{C_M}(x)\right) \tag{19}$$

$$\text{X}^* = \frac{\int Best\_Sol_F * \max(\mu_F)\, dF}{\int \max(\mu_F)\, dF} \tag{20}$$

where $\mu_F(x)$ is the membership degree of the optimum compromised objective function.

Based on fuzzy optimization theory illustrated above, the problems stated as $\text{F}_1, \text{F}_2, \text{F}_3$ along with their corresponding constraints described in Eqs. 6-13 would be transformed into single-objective models by maximizing the minimum membership of satisfaction within the objectives. For the various target functions in F_1, F_2, F_3, a reasonable membership function μ_{fi} is characterized for every objective f_i shown in Fig. 1a–c. The membership degrees represent the

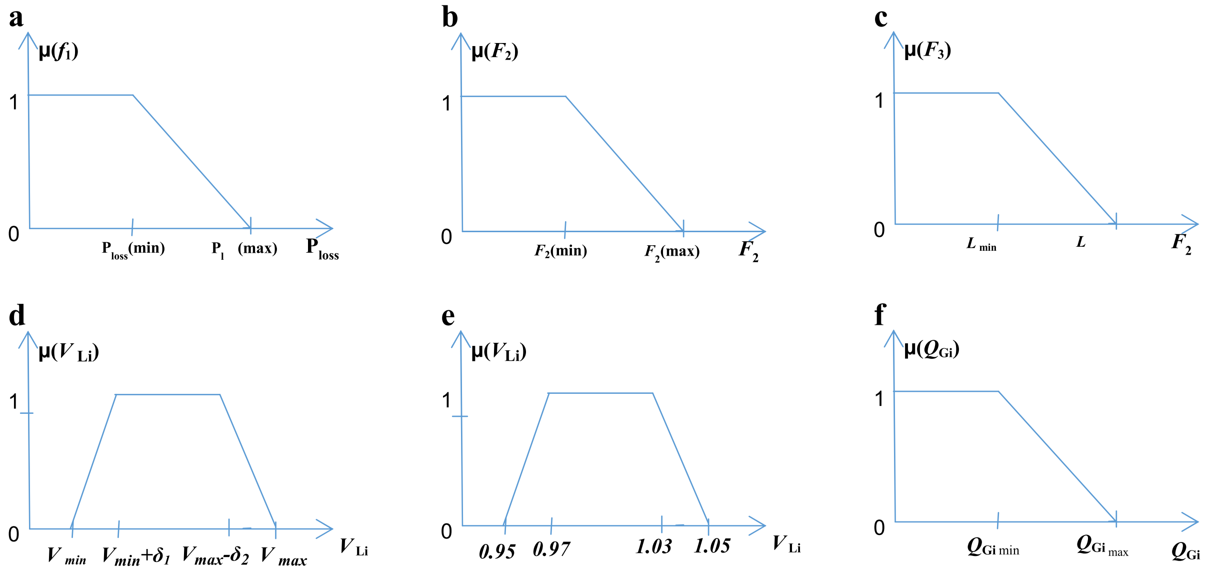


FIGURE 1. Fuzzy modeling of objectives and constraints.

level of fulfillment for the objective functions. f_{imax} is the initial estimation of objective function and f_{imin} is the optimum value when an optimization problem with $f_i(x)$ as the single-objective function is illuminated. Trapezoidal membership function would suit load bus voltage constraints, as shown in Fig. 1d. V_{Lmin} and V_{Lmax} corresponding to those in (8) . δ_1 and δ_2 can be characterized as the satisfaction of the limitation. Fig. 1e presents an case of these values for $V_{Lmin} = 0.95\ p.u.$, $V_{Lmax} = 1.05\ p.u.$ and $\delta_1 = \delta_2 = 0.2$. The logic of this capacity is that the voltages within ±0.03 p.u of per unit are generally in the same performance. Outside of this interval, the adequacy of a voltage diminishes until outside of the ±0.05 p.u range the voltage level is inadmissible. A bus with high voltage deviation gets a low degree and a bus with low voltage deviation gets a high degree of participation. The membership capacity of generator reactive power output constraints Q_{Gi} is exhibited in Fig. 1f. The constraints connected to the control vector u $=[V_{Gi}Q_{Ci}T_i]^T$ are demonstrated as crisp unequal imperatives. Thus, the multi-objective optimization problem is written in terms of equality and inequality constraints as:

$$\begin{aligned} &\text{Min } (X^*) \\ &\textit{subject to}: H(x, u) = 0 \\ &\qquad\qquad C(x, u) \leq 0 \end{aligned} \tag{21}$$

where, X* is obtained using Eqs. (18)-(20), are the objective functions and M is the number of conditional constraints, $H(x, u) = 0$ are the equality constraints and the $C(x, u) \leq 0$ are the inequality constraints

C. THE PROPOSED FUZZY JAYA OPTIMIZATION ALGORITHM

The fuzzy Jaya is an integrated hybrid algorithm that combines the Zadeh extension principle [53] with the conventional Jaya optimization algorithm [38] to find optimal solutions for fuzzy constrained optimization problems [51], [52]. The fuzzy Jaya utilizes the benefits of the Jaya algorithm which tends to move toward the best solution and keep away from the worst solution, while maintaining the ability of the Zadeh principle to work in an ambiguous and vague environment.

Function Evaluate _ Fitness_of_POP (X, X_Mem)
1: Input:$(Xnew_{pd})$
2: Output: Fitness, Membership
3: Fitness← P(X₁ x X₂ x … x Xₙ) → P(Y)
4: Membership $\leftarrow_{y=f(x_1,x_2,\ldots x_{pd})}^{max}$ $\{\min[\mu(x_1), \mu(x_2), \ldots, \mu(x_n)]\}$
5: Return Fitness, Membership

FIGURE 2. Pseudo code for fitness function computation.

The proposed algorithm uses the Zadeh extension principle pseudo goal function to solve the multi-objective problem. The fuzzy-Jaya algorithm begins with initializing the population by fuzzy numbers for control variables.

$$Individuals = \begin{bmatrix} (x_1^1, \mu_1^1) & (x_2^1, \mu_2^1) & \ldots & (x_d^1, \mu_d^1) \\ (x_1^2, \mu_1^2) & (x_1^2, \mu_1^2) & \ldots & (x_d^2, \mu_d^2) \\ (x_1^3, \mu_1^3) & x_1^3, \mu_1^3 & \ldots & (x_d^3, \mu_d^3) \\ \vdots & \vdots & \vdots & \vdots \\ (x_1^N, \mu_1^N) & (x_2^N, \mu_2^N) & \ldots & (x_d^N, \mu_d^N) \end{bmatrix} \tag{22}$$

The Zadeh principle defines the membership function for the control fuzzy variables. Then, declares the Cartesian product for all possible combinations of the control variables and their corresponding membership degree. Figure 2 presents the pseudo-code for fitness function computation. Afterwards, it computes the fuzzy objective function F_i according to the problem defined and the membership degree of F_i by the

TABLE 1. ORPD problem solution for Cases 1-3 of IEEE 14-bus test system.

Variables	Initial	BSO4[32]	MGBTLBO [34] [38]	PSO [34]	DDE [34]	MTLA-DE[34]	Proposed procedure	Fuzzy	Jaya
							Case 1	Case 2	Case 3
V_{g1} (p.u)	1.06	1.0999	1.1	1.06	1.07431	1.07531	1.1	1.0190	1.1000
V_{g2} (p.u)	1.045	1.0763	1.0791	1.0443	1.05616	1.05734	1.0862	1.0207	1.0815
V_{g3} (p.u)	1.01	1.0401	1.0484	1.0138	1.02662	1.02847	1.0571	1.0008	1.0489
V_{g6} (p.u)	1.07	1.054	1.0553	1.1	1.04696	1.05057	1.0597	1.0227	1.0153
V_{g8} (p.u)	1.09	1.0557	1.0326	1.0882	1.04019	1.03535	1.1000	1.0631	1.0430
Tap4--7	0.947	0.99	1.01	1.07	1.04	1.08	1.0000	1.0531	1.0671
Tap4--9	0.952	0.99	1.01	1.04	0.97	0.91	1.0000	1.0001	1.0000
Tap5--6	0.909	0.98	1.03	1.0	1.01	1.01	1.0545	1.0087	1.0639
Q_{c9} (MVar)	18	15	0.3	0.18	0.3	0.3	2.9986	2.9999	2.7803
Q_{c14}(MVar)	18	6	0.07	0.06	0.07	0.08	2.9999	2.4504	2.9993
P_{loss} (MW)	13.6337	12.4592	12.6070	14.3076	13.1876	13.1451	**12.2886**	14.8300	**12.3918**
VD (p.u)	0.3582	0.3037	0.2480	0.3491	0.1606	0.1713	0.3826	**0.0333**	**0.1388**

Function Defuzz (Best _Sol, Membership)
1: Input: Best _Sol, Membership)
2: Output: Sol
3: $Sol = \frac{\int \text{Best\_Sol}_z * \text{Membership}_z \, dz}{\int \text{Membership}_z \, dz}$
4: Return Sol
4: End Fun

FIGURE 3. Pseudo code for defuzzification process computation.

minimum between all the membership degrees of the control variables.

$$Fitness = \begin{bmatrix} (F^1, \mu^1) \\ (F^2, \mu^2) \\ \vdots \\ (F^N, \mu^N) \end{bmatrix} \tag{23}$$

The Jaya algorithm picks up the best F_{best} and the worst F_{worst} solutions and uses them to update the individuals in the population using Eq. (16). Defuzzification the fuzzified objective function, shown in Fig. 3, is implemented using the centroid function to get the scalar solution Z* of the problem using Eq. (20) which is rewritten as follows:

$$F^* = \frac{\int \mu_c (F) \cdot FdF}{\int \mu_c (F) \, dF} \tag{24}$$

The flowchart of the proposed Fuzzy Jaya is shown in Fig. 4 as:

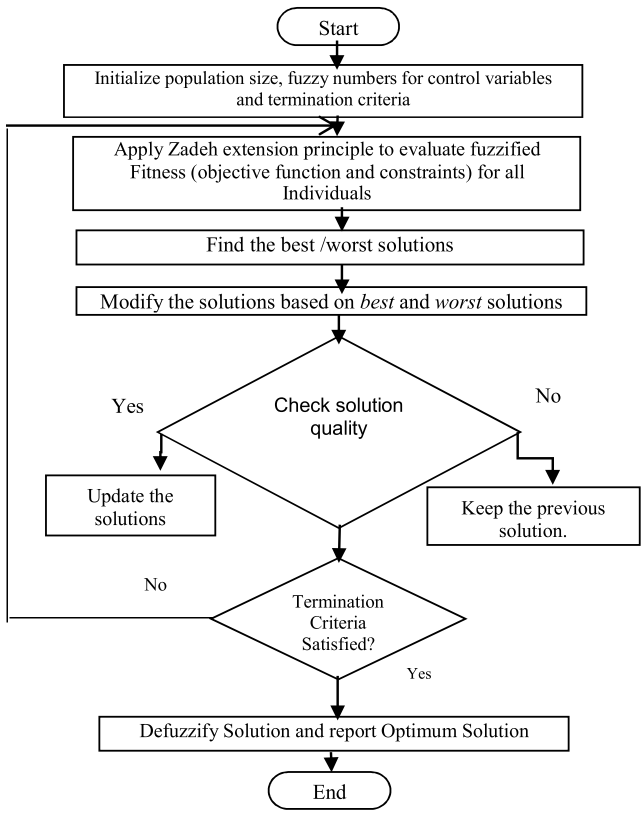
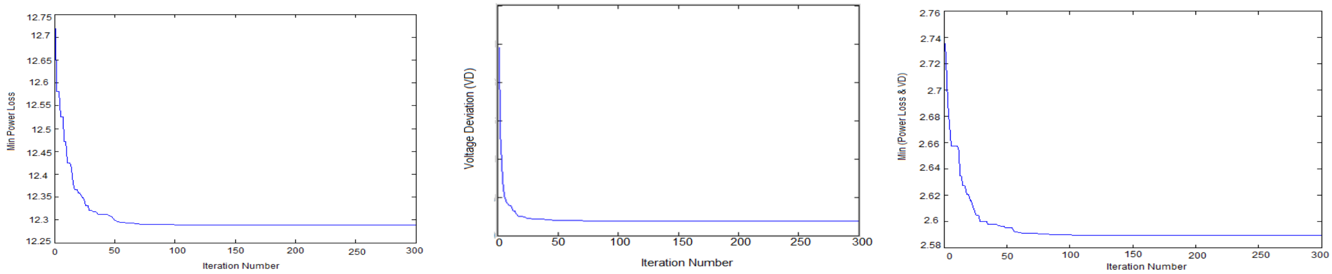


FIGURE 4. Flowchart of the proposed hybrid fuzzy-JAYA algorithm to solve the ORPD problem.

IV. SIMULATION RESULTS AND DISCUSSION

A. TEST SYSTEMS

Three test systems, IEEE 14-bus, 30-bus and 118-bus systems, are selected to investigate the capability of the proposed hybrid Fuzzy-JAYA optimization algorithm and other recent optimization algorithms for solving the ORPD problem. The first test system is the IEEE 14-bus system, which contains 5 generation buses, 11 loads, 20 branches, 3 tap changers and 2 shunt capacitors. The second test system is 30- bus; it has 6 generation buses, 21 loads, 41 branches, 4 tap changers and 3 shunt capacitors. The third test system is IEEE 118-bus, it contains 54 generation buses, 99 loads, 186 branches, 9 tap changers and 14 shunt capacitorsWith a specific end goal to actualize the proposed fuzzy-Jaya hybrid algorithm. Jaya algorithm is tested on three IEEE test frameworks, for example, IEEE 14-, 30- and 118- bus test framework for comprehending the ORPD Problem. For the three frameworks, three target capacities, for example, minimizing reactive power



a: Case 1   b: Case 2   c: Case 3

FIGURE 5. convergence curves for Case 1-3 of IEEE 14-bus test system.

TABLE 2. ORPD problem solution of IEEE 30-bus test system for Case 1 (minimizing P_L only).

Control variables		Initial	CLPSO [57]	DE [18]	BBO [58]	FA [59]	ABC [60]	BFOA[61]	PSO[62]	Proposed Fuzzy -Jaya
Voltages bus	1	1.05	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
	2	1.04	1.1	1.093	1.0944	1.0644	1.0615	1.0261	1.1	1.0955
	5	1.01	1.0795	1.074	1.0749	1.07455	1.0711	1.0696	1.085	1.0777
	8	1.01	1.1	1.076	1.0768	1.0869	1.0849	1.1	1.0838	1.0795
	11	1.05	1.1	1.1	1.0999	1.09164	1.1	1.1	1.1	1.0996
	13	1.05	1.1	1.1	1.0999	1.099	1.0665	1.1	1.1	1.099
T11		1.078	0.9154	1.047	1.0435	1	0.97	0.98	1.1	1.0053
T12		1.069	0.9	0.91	0.9011	0.94	1.05	0.94	0.9	0.9791
T15		1.032	0.9	0.987	0.9824	1	0.99	1.05	1.02	1.0027
T36		1.068	0.9397	0.969	0.9691	0.97	0.99	0.98	0.99	1.0002
QC10		0	4.9265	5	4.9998	3	5	3.1	1.1	4.9021
QC12		0	5	5	4.987	4	5	4.6	0.4	18.1659
QC15		0	5	5	4.9906	3.3	5	5	0.7	3.9186
QC17		0	5	5	4.997	3.5	5	2.1	5	6.1739
QC20		0	5	4.406	4.9901	3.9	4.1	3.7	4.7	3.6118
QC21		0	5	5	4.9946	3.2	3.3	2.3	1	9.8777
QC23		0	5	2.8	3.8753	1.3	0.9	1.9	3	1.0879
QC24		0	5	5	4.9867	3.5	5	2.3	0.8	8.0869
QC29		0	5	2.598	2.9098	1.42	2.4	0.1	1.2	3.5074
P_loss		**5.8324**	**4.9824**	**4.5458**	**4.5477**	**5.6417**	**5.7906**	**10.0111**	**4.6827**	**4.5479**
VD		0.6893	1.7957	1.1904	1.2374	1.7020	0.9183	0.9894	0.945	1.218525

loss(case1), minimizing voltage deviation(case2) and minimizing power loss while maintaining voltage deviation to its minimum rate(case3) are contemplated.

B. RESULTS OF TEST SYSTEMS

Case Study 1 (Simulation Results of IEEE 14 Bus Power System): The first tested power network is the standard IEEE 14 bus test system. This system is composed of 5 generators at the buses 1, 2, 3, 6, and 8; 20 transmission lines; three under load tap changing transformers (ULTCs) and two shunt capacitive sources (SCSs) at buses 9 and 14. The bus and line data are referenced by MATPOWER [54].

Table 1 outlines the results of the three studied cases for the fuzzy-Jaya algorithm. The acquired outcomes are contrasted with other algorithms found in literature like MGBTLBO [34], [38], [51], MTLA-DDE [34], [49], DDE [49], PSO [34] and BSO [32]. The comparison results prove the fuzzy-Jaya ability to reach the optimal solution for the three objective functions. The convergence rates for the algorithm to find solutions through 300 iterations are illustrated in Fig.5 a- c. It is obvious that the solutions for the IEEE 14 bus system objective functions are fast. The power loss achieved by the fuzzy-Jaya algorithm is 4.5479 MW, which is best among all other methodologies. It is observed that fuzzy-Jaya algorithm is able to reduce the real power loss by 21.7363% with respect to initial power loss [56], against 21.5109% with CLPSO [57], 21.61% with DE [18], 21.69% with BBO [58], 21.37% with FA [59], 20.80% with ABC [60], 20.44% with BFOA [61] and 19.80% with PSO [62].

Table 1 shows that generator voltages do not violate its lower and upper boundaries of 0.95 p.u. and 1.05 p.u. respectively. Thusly, the proposed solution avoids the infringement of load bus voltages. Moreover, in comparing the fuzzy jaya

TABLE 3. ORPD solution of second system for Cases 2 & 3.

Control variable	FA [59]	ABC [60]	BFOA [62]	PSO[62]	GSA [63]	HFA[50]	Case 2	Case 3
Vg1	0.9977	1.002536	0.95	1.006177	0.99298	1.003458	1.0001	1.0406
Vg2	1.0217	1.016158	1.0702	1.007507	0.95519	1.01638	1.0000	1.0307
Vg5	1.01672	0.9927	0.9645	1.00839	1.0189	1.019451	1.0165	1.0084
Vg8	1.001	1.0288	1.0258	1.039351	1.0189	1.018221	1.0142	1.0064
Vg11	1.0481	1.06469	1.0375	1.003456	1.01198	0.982272	1.0002	1.0279
Vg13	1.0191	1.0086	0.9914	1.04466	1.03598	1.01546	1.0412	1.0255
T11	1.04	0.97	0.98	0.99	1.0578	0.99	1.0040	1.0385
T12	0.9	1.03	0.96	0.9	1.05	0.9	0.9501	0.9503
T15	0.98	0.97	1.02	0.99	0.9	0.98	1.0002	1.0003
T36	0.96	0.95	0.99	0.95	1.05	0.96	1.0000	1.0002
QC10	3.6	2.5	4.8	4.4	0.966	3.2	4.9999	4.9400
QC12	1.3	0	1.3	0.9	4.5	0.5	0.0449	4.2945
QC15	2.7	5	4.5	1.2	2.5	4.9	4.9992	4.9998
QC17	0.9	0	2	1.9	1.4	0.1	4.9304	4.9394
QC20	4.2	5	4.3	1.1	4	3.8	4.9925	4.9937
QC21	2.7	5	3.9	1	3.8	5	4.9980	4.9505
QC23	3	5	4	0.9	2.9	5	4.9686	4.9402
QC24	1.7	4.7	4.5	1	2.5	3.9	4.9999	4.9998
QC29	1.8	0	3.4	0.9	3.1	1.5	4.9999	4.9851
Voltage Deviation	**0.1042**	**0.1309**	**0.1827**	**0.1371**	**0.4672**	**0.0708**	**0.0912**	**0.1244**
Powerloss(MW)	6.3548	6.3160	18.6745	6.5825	9.7668	6.1993	6.1291	**5.2191**

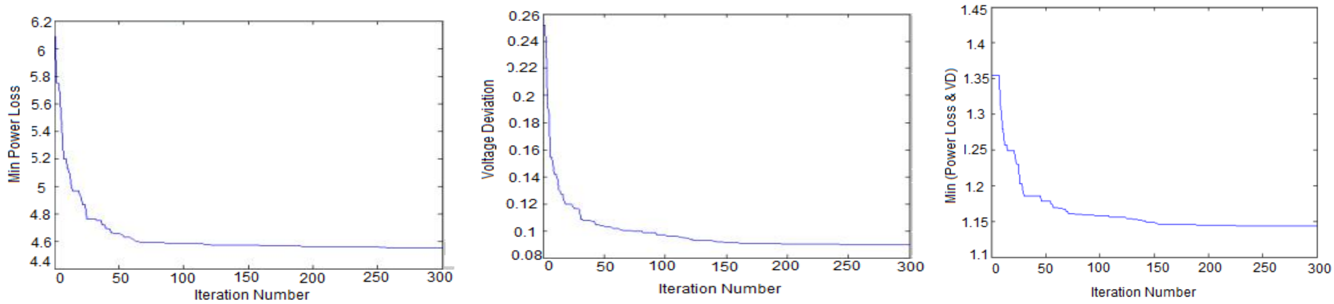
TABLE 4. Statistical study of the compared algorithms for PL and VD problems for cases 1 and 2.

Methods	Case 1				Case 2			
	Best	Average	Worst	Standard Deviation	Best	Average	Worst	Standard Deviation
PSO	4.661	4.8	4.702	0.0032	0.1535	0.158	0.161	9.02E-05
BFOA	4.623	4.68	4.64	0.00257	0.149	0.151	0.153	8.90 E-05
ABC	4.6022	4.63	4.61	0.00221	0.135	0.1367	0.138	8.89 E-05
FA	4.5691	4.59	4.578	0.002001	0.1157	0.11591	0.1162	8.74 E-05
Fuzzy Jaya	4.5479	4.5574	4.567	0.001986	2.9894e-005	0.06101	0.122	8.302 E-05

with well tested algorithms for solving the ORPD problem, the proposed fuzzy jaya algorithm achieved minimal voltage deviation for maintaining the second objective function. Furthermore, the fuzzy jaya obtained minimal reactive power loss while preserving the minimal voltage deviation rate for the third objective function.

Case Study 2 (Simulation Results for IEEE 30 Bus Power System): The second test system comprises 6 generators, 41 transmission lines, 4 tap changers and 9 shunt capacitors. The information for the test framework is taken from [55]. This framework has 19 control factors (6 generator voltages at buses 1, 2, 5, 8, 11 and 13, 4 transformers that are associated between the buses 6–9, 6–10, 4–12, and 28–27, plus the output of 9 shunt reactive power compensation devices located at 10,12,15,17,20,21,23,24 and 29. At 100 MVA base, the aggregate real power request is 2.834 p.u. The voltages of the heap buses and additionally generator buses have been obliged inside breaking points in the interval [0.95-1.10] p.u. The working scope of all tap transformers is in the range 0.9-1.05 with 0.01 step size. Table 2, 3 demonstrate detailed comparisons among the proposed algorithm and other algorithms like CLPSO [57], DE [18], BBO [58], FA [59], ABC [60], BFOA [61], PSO [62]. The fuzzy-Jaya competes other algorithms for the first objective function (minimization of power loss) and overcomes other algorithms in the second and third objective function.

For investigating the reliability and strength of the proposed Fuzzy-Jaya algorithm for optimizing the ORPD problem, 50 trials were implemented for each of the case studies. The measurements of average, best, worst and standard deviations present the efficiency of the Fuzzy-JAYA algorithm in reaching the optimum solutions. The statistical measures of various methods of solutions for IEEE 30 bus system are shown in Table 4. The average values and standard deviations of the proposed Fuzzy-Jaya algorithm are less, which indicate that the proposed algorithm has better effectiveness in finding



a: Case 1 b: case 2 c: case 3

FIGURE 6. Convergence curves for Cases 1-3 (IEEE 30-bus test system).

TABLE 5. ORPD solution of the large-scale test system for Case 1 (minimizing P_L only).

Var.	**V1**	**V4**	**V6**	**V8**	**V10**	**V12**	**V15**	**V18**	**V19**
Value	1.0396	1.0634	1.0285	1.0539	1.0887	1.0382	1.0525	1.0492	1.0398
Cont. var	**V24**	**V25**	**V26**	**V27**	**V31**	**V32**	**V34**	**V36**	**V40**
Value	1.0203	1.0387	1.0567	1.0007	0.9903	0.9883	1.0349	1.0147	1.0304
Cont. var	**V42**	**V46**	**V49**	**V54**	**V55**	**V56**	**V59**	**V61**	**V62**
Value	1.0306	1.0104	1.0349	1.0226	1.0209	1.0266	1.04	1.0364	1.027
Cont. var	**V65**	**V66**	**V69**	**V70**	**V72**	**V73**	**V74**	**V76**	**V77**
Value	1.0221	1.0356	1.0527	1.0099	1.0014	1.0162	1.0107	1.0131	1.0365
Cont. var	**V80**	**V85**	**V87**	**V89**	**V90**	**V91**	**V92**	**V99**	**V100**
Value	1.0473	1.066	1.0326	1.041	1.0387	1.0449	1.0256	1.0263	1.0331
Cont. var	**V103**	**V104**	**V105**	**V107**	**V110**	**V111**	**V112**	**V113**	**V116**
Value	1.0342	1.0113	1.0031	0.9868	1.02	1.0304	1.0078	1.0467	1.0453
Cont. var	**T8**	**T32**	**T36**	**T51**	**T93**	**T95**	**T102**	**T107**	**T127**
Value	0.9828	0.9999	1.0001	0.9728	0.9735	1.0211	0.9759	1.0569	1.0041
Cont. var	**QC5**	**QC34**	**QC37**	**QC44**	**QC45**	**QC46**	**QC48**	**QC74**	**QC79**
Value	-8.9805	10.8111	-10.9958	6.2817	6.0471	4.4053	8.3672	6.3656	10.7651
Cont. var	**QC82**	**QC83**	**QC105**	**QC107**	**QC110**	**Objectives PL (MW)**			
Value	4.6902	6.4522	13.9715	2.9778	2.9062	**123.0724**			

TABLE 6. ORPD solution of IEEE 118-bus test system or Case 2 (minimizing VD only).

Var.	**V1**	**V4**	**V6**	**V8**	**V10**	**V12**	**V15**	**V18**	**V19**
Value	1.0069	0.9872	1.0047	1.0054	1.0048	1.0036	0.9988	1.0222	0.991
Cont. var	**V24**	**V25**	**V26**	**V27**	**V31**	**V32**	**V34**	**V36**	**V40**
Value	1.0182	1.0233	1.0092	0.9931	0.9943	1.0014	0.9968	0.9926	0.9984
Cont. var	**V42**	**V46**	**V49**	**V54**	**V55**	**V56**	**V59**	**V61**	**V62**
Value	0.9955	0.9998	1.0019	1.0037	1.0304	1.0019	0.9991	1.0214	0.9987
Cont. var	**V65**	**V66**	**V69**	**V70**	**V72**	**V73**	**V74**	**V76**	**V77**
Value	0.9973	1.0146	0.9943	1.0038	0.9925	1.0263	1.0074	1.0166	0.9975
Cont. var	**V80**	**V85**	**V87**	**V89**	**V90**	**V91**	**V92**	**V99**	**V100**
Value	1.0225	1.0095	1.0045	1.025	1.0086	0.9977	1.0024	0.9947	1.0052
Cont. var	**V103**	**V104**	**V105**	**V107**	**V110**	**V111**	**V112**	**V113**	**V116**
Value	0.99	1.0085	1.0168	1.0205	1.0084	1.0263	1.0075	1.0007	1.0083
Cont. var	**T8**	**T32**	**T36**	**T51**	**T93**	**T95**	**T102**	**T107**	**T127**
Value	0.9966	0.9989	0.9996	1.0541	0.9982	1.008	1.0077	1.05	0.9887
Cont. var	**QC5**	**QC34**	**QC37**	**QC44**	**QC45**	**QC46**	**QC48**	**QC74**	**QC79**
Value	-20	4.0499	-3.326	6.4434	4.9562	5.1679	7.3223	0.9332	4.9973
Cont. var	**QC82**	**QC83**	**QC105**	**QC107**	**QC110**	**Objectives VD**			
Value	7.915	2.4427	10.141	3.0534	2.5748	**0.5778 @ PL=136.9293**			

optimal solution than other methodologies. The convergence rates of the three cases 1-3 are shown in Figs. 6a-c, which prove that the Fuzzy-Jaya finds the optimal solutions fast and steady.

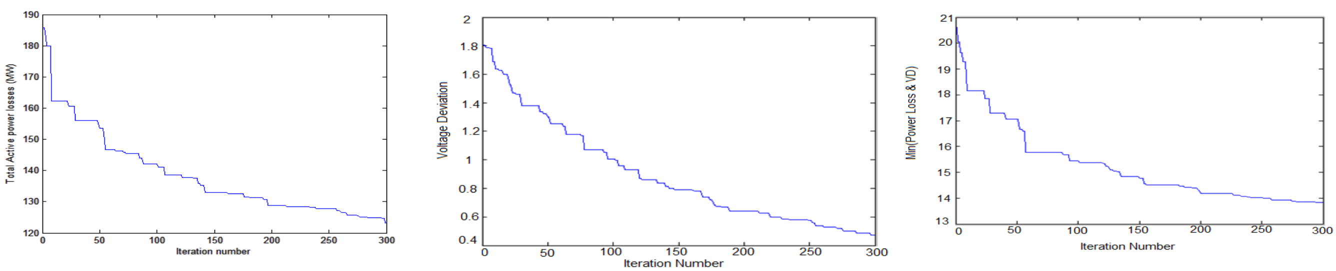
Case Study 3 (Simulation Results for the IEEE 118-Bus Test System): The IEEE 118-bus test system is considered as sample of large-scale test systems and whose date is presented in [50]. The entire load demand equals 4242 MW and the related power loss is 154.165 MW. For simulating Fuzzy Jaya algorithm on IEEE-118, a total of 77 control variables. The load buses voltages and generator buses were limited in the range of 0.95 p.u. and 1.10 p.u. The proposed hybrid fuzzy Jaya algorithm is used to obtain the optimal solution of ORPD problem for minimizing real power loss, minimizing voltage

TABLE 7. ORPD solution of large test system for Case 3 (minimizing P_L and VD simultaneously).

Cont. var	V1	V4	V6	V8	V10	V12	V15	V18	V19
Value	1.0242	1.0508	1.0319	1.0234	1.0174	1.0225	1.0189	1.0351	1.0066
Cont. var	V24	V25	V26	V27	V31	V32	V34	V36	V40
Value	1.0218	1.0278	1.0565	1.0261	1.0215	1.0201	1.0209	1.0282	0.9934
Cont. var	V42	V46	V49	V54	V55	V56	V59	V61	V62
Value	1.0103	1.0271	1.0153	1.0004	0.9988	0.996	1.0244	1.0303	1.0272
Cont. var	V65	V66	V69	V70	V72	V73	V74	V76	V77
Value	1.0326	1.0308	1.0452	1.0228	1.0104	1.0294	1.0027	1.0111	1.0172
Cont. var	V80	V85	V87	V89	V90	V91	V92	V99	V100
Value	1.034	1.0356	1.0237	1.042	1.0083	1.019	1.029	1.0125	1.0302
Cont. var	V103	V104	V105	V107	V110	V111	V112	V113	V116
Value	1.028	1.0187	1.0115	1.0202	1.0152	1.0252	1.0203	1.0239	1.0194
Cont. var	T8	T32	T36	T51	T93	T95	T102	T107	T127
Value	0.9574	0.9683	1.0054	1.001	0.9773	1.046	1.0156	1.0001	0.995
Cont. var	QC5	QC34	QC37	QC44	QC45	QC46	QC48	QC74	QC79
Value	-16.32	11.254	-11.841	7.1978	4.6193	4.3126	8.5493	5.2741	9.0743
Cont. var	QC82	QC83	QC105	QC107	QC110	Objectives			
Value	9.6848	5.0947	12.3116	2.9346	2.708		PL (MW)		VD p. u
							123.4583		0.9966

TABLE 8. Statistical study of the compared algorithms for cases 1 and 2 of IEEE 118-bus test system.

Methods	Case # 1				Case # 2			
	Worst	Average	Best	SD	Worst	Average	Best	SD
PSO[50]	138.67	138.6433	138.61	0.0091	-	-	1.1616*	8.30E-05
ABC[50]	137.2	137.001	136.99	0.009011	-	-	1.0774*	8.21E-05
FA[50]	135.48	134.447	135.42	0.008923	-	-	0.7400*	8.23E-05
HFA[50]	134.96	134.8499	134.24	0.008814	-	-	0.7800*	8.14E-05
Fuzzy Jaya	125.56	124.245	**123.0674**	0.007985	0.5789	0.57835	**0.5778**	7.54E-05



a. Case # 1 b. Case # 2 c. Case # 3

FIGURE 7. Convergence curves of the large-scale IEEE 118-bus test system for studied cases 1-3.

deviations and minimizing power loss while maintaining minimal voltage deviation. Tables 5-7 show the simulation results for IEEE 118-bus test system. The efficiency of the fuzzy Jaya algorithm is examined by conducting 20 runs of the simulation to judge the optimal values of the control variables. PSO, ABC, FA results are referenced by [50]. For each objective function, the Max iteration number was set to 300. Obviously, the Fuzzy Jaya algorithm gave the minimal value for the power loss of 123.0674 MW against other algorithms.

Table 8 presents the statistical measures of best, average, worst and standard deviation for the simulation results of minimizing the power loss (case 1). The VD (Case 2) is recalculated using the variables' values referenced in [50]. Therefore, the best VD is highlighted by * for the algorithms PSO, ABC, FA. The measures prove the efficiency of the fuzzy jaya algorithm by giving the lowest values. The convergence curves of the Fuzzy Jaya for cases 1-3 are presented in Fig. 7-a-c. The plot clarifies the fast convergence of the proposed algorithm along the iterations of the simulation.

V. CONCLUSION

This paper has presented a recent hybrid Fuzzy-Jaya optimizer for solving ORPD problem in power systems. The proposed algorithm is tested to three standard IEEE 14-, 30-, and 118-bus test systems. The competence of the proposed algorithm is proved for the real power loss reduction and the voltage profile. A comparative study between JAYA and other well-known methods in the literature has been carried out for solving the ORPD problem. This algorithm finds the best solution by moving towards the true one and ignores the worst solution by moving far from the worst one. From the results it is noticed that, the proposed algorithm can reach to a better and robust solution for solving the ORPD problem for the test systems. In addition, the results ensured that this algorithm could be used with small and large power systems. The future works are intended to cover new issues such as the scheduling of renewable energies in microgrids, finding the parameter of solar cells/modules and fuel cells. In the solution method viewpoint, other hybrid algorithms that enhance the solution quality such as hybrid fuzzy- sunflower optimization algorithm.

CONFLICT OF INTEREST

The authors state that are no conflict of interests.

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