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Optimal reactive power dispatch using a novel optimization algorithm

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Abstract

The problem of optimal reactive power dispatch (ORPD) is one of the most popular and widely discussed problem in power system engineering all over the world. Optimal reactive power dispatch is one of the sub-problems of the optimal power flow which is complex and nonlinear problem, which can be formulated as both single- and multi-objective. In this paper, the problem has been formulated as a single-objective problem to minimize the active power losses in the transmission lines. A recently proposed powerful and reliable meta-heuristic algorithm known as the JAYA algorithm has been applied to solve the ORPD problem. The algorithm has been applied on the standard IEEE 14, 30, 57 and 118 bus systems. The simulation results using the proposed algorithm when compared with the results from other algorithms and few others reported in the literature prove that the JAYA algorithm is the most superior among all.

Keywords: Active power loss, JAYA algorithm, Optimization problem, ORPD, Particle swarm optimization, Variants of PSO, Transmission line losses

Introduction

The major challenges in power system engineering nowadays is the large expansion of power and the system stability accompanied with it. The large variation in the time variant load demand results in system instability leading to voltage collapse and blackout. Another major problem is the increase in the active power losses in the transmission line, which results in low efficiency of the system and thus restrict the expansion of power to a certain limit. The ORPD problem is a complex and nonlinear problem in power system engineering which helps in enhancing the security of the power system and improving its economy largely. The solution of the ORPD problem is to minimize the objective function by satisfying the operating constraints. It helps in optimally redistributing the reactive power in the system resulting in minimization of transmission line active power losses and improving the voltage profile in the system. Due to this nonlinearity of the problem, many conventional techniques of optimization like the Newton method, quadratic programming, linear programming and interior point methods have failed to solve the ORPD problem due to their low accuracy, complexity, inability to find the local and global optima and thus resulting in secure converge [1–4]. Thus, to overcome these disadvantages, many modern stochastic and meta-heuristic techniques have been developed in the recent past such as the genetic algorithm (GA) [5], improved GA

[6], particle swarm optimization (PSO) [7], evolutionary programming (EP) [8], hybrid evolutionary strategy [9], seeker optimization algorithm (SOA) [10], bacterial-foraging optimization (BFO) [11], gravitational search algorithm (GSA) [12], differential evolution (DE) [13] and Artificial Bee colony algorithm (ABC) [14]. to solve the ORPD problem. Recently in [15], the Whale optimization algorithm inspired from the bubble-net hunting technique of the humpback whales has been used to solve the ORPD problem. Shaheen et al. [16] proposed a backtracking search optimizer (BSO) where five diversified generation strategies of mutation factor have been applied to solve the ORPD problem. In [17], Lenin proposed an algorithm named Enhanced Red Wolf Optimization which is a hybrid of wolf optimization (WO) and particle swarm optimization (PSO) algorithm to solve the ORPD problem. In [18], an improved social spider optimization (ISSO) has been used for determining the optimal solution to the power loss in ORPD problem. Li et al. [19], proposed an Antlion optimization algorithm (IALO) top solve the ORPD problem for three bus systems. In [20], two different algorithms namely the Moth-Flame optimizer and Antlion optimizer have been used to optimize the ORPD problem.

In this paper, a novel algorithm named the JAYA algorithm, developed by Rao [21] has been applied to solve the ORPD problem. It is a newly developed optimization technique and has capability in optimizing any objective function under any possible constraint. Many other algorithms such as PSO and its many other different variants, which are R-PSO, L-PSO, PSO-CFA, Improved PSO Based on Success Rate (IPSO-SR) [22], Fruit Fly optimization algorithm (FOA) [23] and Modified Fruit Fly optimization algorithm (MFOA) [24] are also tested along with JAYA algorithm. The objective of this work is to minimize the transmission line power loss by optimal allocation of the control variables within the system without violating the equality and inequality constraints. The control variables are the generator voltage, tap position of the tap-changing transformer and the VAR outputs of the reactive power compensating devices situated at few specific buses. The algorithms have been used to solve the ORPD problem under four different test cases, IEEE 14, 30, 57 and 118. Here, two different limits of the control variables for the IEEE 30, 57 and 118 bus systems each have been used as per the literature survey to solve the ORPD problem. The results for each cases are compared to determine the best technique among them in terms of convergence rate, ability to determine the optimal solution and robustness.

Problem formulation

This paper aims at minimizing the active power loss in the transmission lines by determining the optimal solutions to the ORPD problem. The proposed JAYA algorithm helps in determining the optimal values of the control variables while simultaneously satisfying all the constraints in the system. The objective function of the ORPD problem is shown below [25]:

$$f_n = \min\left(P_{\text{loss}}\right) = \sum_{k=1}^{Nl} G_k\left(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij}\right) \tag{1}$$

where, Nl represent the total number of transmission lines, the conductance of the kth branch is shown as G_k, V_i and V_j represent the magnitudes of the bus voltage for the buses i and j, respectively, and δ_{ij} stand for the phase difference between V_i and V_j.

Constraints

The following shows the different constraints of the objective function:

Equality constraints

$$P_{gi} - P_{di} - V_i \sum_{j=1}^{Nb} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) = 0 \tag{2}$$

$$Q_{gi} - Q_{di} - V_i \sum_{j=1}^{Nb} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) = 0 \tag{3}$$

The above constraints depict the load flow equations, where Nb represent the total number of buses, P_{gi} and Q_{gi} represent the active and reactive power generation and P_{di} and Q_{di} are the active and reactive power load demands at the ith bus, respectively. G_{ij} and B_{ij} represent the conductance and susceptance between two different buses (i.e., ith and jth), respectively, and θ_{ij} is the angle between the ith and jth bus.

Inequality constraints

- Generator constraints

The generator active power, reactive power and voltage magnitudes are restricted within their limits and must not be violated during solving the problem. The limits are shown below:

$$V_{gi}^{\min} \le V_{gi} \le V_{gi}^{\max}, \quad i = 1, \ldots, N_g \tag{4}$$

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max}, \quad i = 1, \ldots, N_g \tag{5}$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}, \quad i = 1, \ldots, N_g \tag{6}$$

where, N_g represent the total number of generator buses, $V_{gi}^{\min}$, $P_{gi}^{\min}$ and $Q_{gi}^{\min}$ are the minimum limits and $V_{gi}^{\max}$, $P_{gi}^{\max}$ and $Q_{gi}^{\max}$ are the maximum limits of the generator bus voltages, active and reactive power, respectively. V_{gi}, P_{gi} and Q_{gi} are the amount of voltage, active and reactive power generation at the ith bus.

- Transformer constraints

The minimum and maximum limits of the settings of the tap-changing transformer are given by:

$$T_i^{\min} \le T_i \le T_i^{\max}, \quad i = 1, \ldots, N_T \tag{7}$$

where, N_T shows the number of tap-changing transformers in the system. T_i is the tap-setting position value of the tap-changing transformer at the ith bus and $T_i^{\min}$, $T_i^{\max}$ are its minimum and maximum limits.

- VAR compensator constraints

The limits of the reactive power to be injected by the VAR compensators are given as:

$$Q_{ci}^{\min} \leq Q_{ci} \leq Q_{ci}^{\max}, \quad i = 1, \ldots, N_C \tag{8}$$

where, N_C represent the total number of shunt compensators at the buses and $Q_{ci}^{\min}$, $Q_{ci}^{\max}$ are the minimum and maximum limits of the reactive power injection Q_{ci}, respectively.

- Operating constraints

The voltage at the load buses and the apparent power at the branches must remain within a specified limit. Their limits are shown below:

$$V_{Li}^{\min} \leq V_{Li} \leq V_{Li}^{\max}, \quad i = 1, \ldots, N_{PQ} \tag{9}$$

$$S_{Li} \leq S_{Li}^{\max}, \quad i = 1, \ldots, NL \tag{10}$$

where, N_{PQ} depict the total number of load buses, and $S_{Li}^{\max}$ is the maximum value of the apparent power flow at the ith bus where S_{Li} is the apparent power at that branch. V_{Li} is the magnitude of the voltage at the ith load bus and $V_{Li}^{\min}$, $V_{Li}^{\max}$ are its minimum and maximum limits.

Among all the mentioned variables, the load bus voltages, the reactive power generation and apparent power flow are the dependent variables considered. These variables are constrained using penalty coefficients to the objective function in Eq. (1). Thus, the objective function modified as,

$$f = P_{\text{loss}} + \lambda_V \sum_{i=1}^{N_V \text{lim}} \left(V_i - V_i^{\text{lim}} \right)^2 + \lambda_Q \sum_{i=1}^{N_Q \text{lim}} \left(Q_{gi} - Q_{gi}^{\text{lim}} \right)^2 \tag{11}$$

The limits of V_i^{lim} and Q_{gi}^{lim} are:

$$V_i^{\text{lim}} = \begin{cases} V_i^{\min}, \text{ if } V_i < V_i^{\min} \\ V_i^{\max}, \text{ if } V_i > V_i^{\max} \end{cases} \tag{12}$$

$$Q_{gi}^{\text{lim}} = \begin{cases} Q_{gi}^{\min}, \text{ if } Q_{gi} < Q_{gi}^{\min} \\ Q_{gi}^{\max}, \text{ if } Q_{gi} > Q_{gi}^{\max} \end{cases} \tag{13}$$

where, λ_V and λ_Q are penalty coefficients, N_V^{lim} is the number of buses on which the voltages are outside limits and N_Q^{lim} is the number of buses on which the reactive power generations are outside limits.

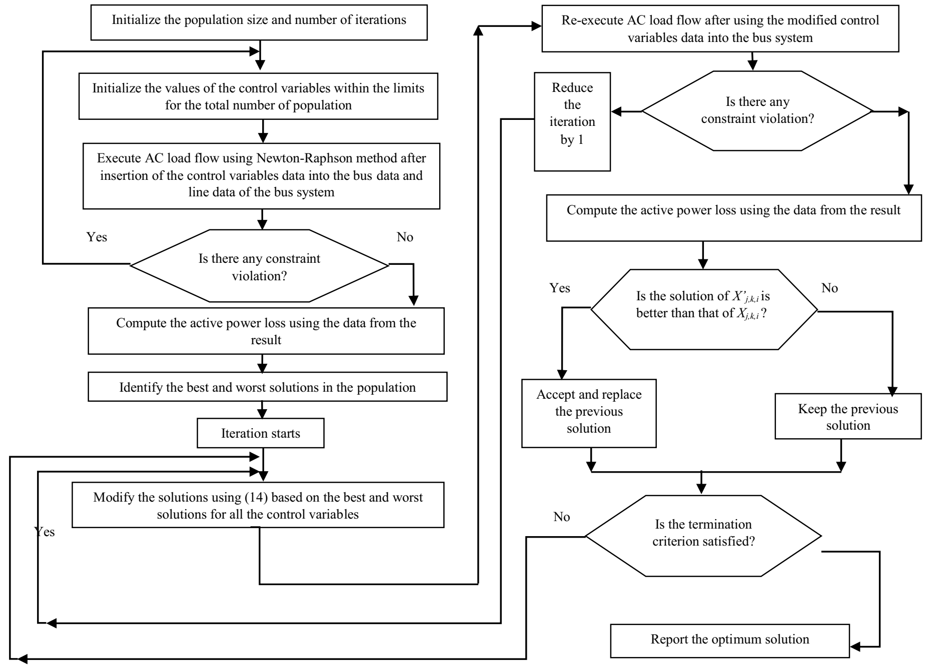

Fig. 1 Flowchart of JAYA algorithm implemented on ORPD problem

JAYA algorithm

The JAYA algorithm is a newly proposed meta-heuristic algorithm by Rao [21], which is used for solving any complex, nonlinear and stochastic problem like the ORPD. This algorithm has the ability to find a quick optimal solution to any problem and has a very high convergence rate. It has a high success rate in determining the best solution to the problems compared to many other algorithms as it has a tendency to move toward the best solution in every iteration and move away from the worst. Thus, this reduces the chance of the algorithm to be stuck into the global optima and keeps updating its solution comparing with the best.

For an objective function *f(x)*, let there be '*m*' number of design variables (i.e., $j = 1, 2,\ldots, \mathrm{m}$) and '*n*' number of populations ($k = 1, 2,\ldots, \mathrm{n}$) for *i*th iteration. Let the population having the best solution of *f(x)* (i.e., $f(x)_{\text{best}}$) be called the best candidate and for the population having the worst solution to the objective function (i.e., $f(x)_{\text{worst}}$) be called worst. Let the value for the *j*th variable for the *k*th population in the *i*th iteration be represented as $A_{j,k,i}$. Then, the value is modified as given in Eq. (14).

$$A'_{j,k,i} = A_{j,k,i} + r_1\left(A_{j,\text{best},i} - \left|A_{j,k,i}\right|\right) - r_2\left(A_{j,\text{worst},i} - \left|A_{j,k,i}\right|\right) \tag{14}$$

where, $A_{j,\text{best},i}$ and $A_{j,worst,i}$ are the best and the worst solution of the objective function of the *j*th variable, respectively. r_1 and r_2 are two random numbers in the range [0, 1]. The equation for updating the variable shows the tendency of the algorithm to move closer to the best solution and the tendency of the variable to move away from the worst solution. Thus, this helps in updating the control variables much more accurately and results in obtaining the most optimal result for the optimizing

Table 1 The comparative results of G01–G24 benchmark functions using different algorithms

Function		PSO	BBO	DE	ABC	HTS	TLBO	JAYA
G01	Best	−15	−14.977	−15	−15	− 15	−15	−15
(−15.00)	Mean	−14.71	−14.7698	−14.555	−15	−15	−10.782	−15
G02	Best	−0.669158	−0.7821	−0.472	−0.803598	− 0 .7517	−0.7835	−0.803605
(−0.803619)	Mean	−0.41996	−0.7642	−0.665	−0.792412	−0.6437	−0.6705	−0.7968
G03	Best	1	−1.0005	−0.99393	−1	−1.0005	−1.0005	−1.005
(−1.0005)	Mean	0.764813	−0.3957	−1	−1	−0.9004	−0.8	−1
G04	Best	−30,665.539	−30,665.539	−30,665.539	−30,665.539	−30,665.539	−30,665.539	−30,665.539
(−30,665.539)	Mean	−30,665.539	−30,411.865	−30,665.539	−30,665.539	−30,665.539	−30,665.539	−30,665.539
G05	Best	5126.484	5134.2749	5126.484	5126.484	5126.486	5126.486	5126.486
−5126.486	Mean	5135.973	6130.5289	5264.27	5185.714	5126.5152	5126.6184	5126.5061
G06	Best	−6961.814	−6961.8139	−6954.434	−6961.814	−6961.814	−6961.814	−6961.814
(−6961.814)	Mean	−6961.814	−6181.7461	−6954.434	−6961.813	−6961.814	−6961.814	−6961.814
G07	Best	24.37	25.6645	24.306	24.33	24.3104	24.3101	24.3062
−24.3062	Mean	32.407	29.829	24.31	24.473	24.4945	24.837	24.3092
G08	Best	−0.095825	−0.095825	−0.095825	−0.095825	−0.095825	−0.095825	−0.095825
(−0.095825)	Mean	−0.095825	−0.95824	−0.095825	−0.095825	−0.095825	−0.095825	−0.095825
G09	Best	680.63	680.6301	680.63	680.634	680.6301	680.6301	680.6301
−680.6301	Mean	680.63	692.7162	680.63	680.634	680.6329	680.6336	680.6301
G10	Best	7049.481	7679.0681	7049.548	7053.904	7049.4836	7250.9704	7049.312
−7049.28	Mean	7205.5	8764.9864	7147.334	7224.407	7119.7015	7257.0927	7052.7841
G11	Best	0.749	0.7499	0.752	0.75	0.7499	0.7499	0.7499
−0.7499	Mean	0.749	0.83057	0.901	0.75	0.7499	0.7499	0.7499
G12	Best	−1	−1	−1	−1	−1	−1	−1
(−1)	Mean	−0.998875	−1	−1	−1	−1	−1	−1
G13	Best	0.085655	0.62825	0.385	0.76	0.37319	0.44015	0.003625
(−0.05394)	Mean	0.569358	1.09289	0.872	0.968	0.66948	0.69055	0.003627
G14	Best	−44.9343	54.6679	−45.7372	−44.6431	−47.7278	−46.5903	−47.7322
(−47.764)	Mean	−40.871	175.9832	−29.2187	−40.1071	−46.4076	−39.9725	−46.6912
G15	Best	961.715	962.664	961.715	961.7568	961.715	961.715	961.715
−961.715	Mean	965.5154	1001.4367	961.7537	966.2868	961.75	962.8641	961.715
G16	Best	−1.9052	−1.9052	−1.9052	−1.9052	−1.9052	−1.9052	−1.9052
(−1.9052)	Mean	−1.9052	−1.6121	−1.9052	−1.9052	−1.9052	−1.9052	−1.9052
G17	Best	8857.514	9008.5594	8854.6501	8859.713	8853.5396	8853.5396	8853.5396
−8853.5396	Mean	8899.4721	9384.268	8932.0444	8941.9245	8877.9175	8876.5071	8872.5402
G18	Best	−0.86603	−0.65734	−0.86531	−0.86603	−0.86603	−0.86603	−0.86603
(−0.86603)	Mean	−0.8276	−0.56817	−0.86165	−0.86587	−0.77036	−0.86569	−0.86602
G19	Best	33.5358	39.1471	32.6851	33.3325	32.7132	32.7916	32.6803
−32.6555	Mean	36.6172	51.8769	32.768	36.0078	32.7903	34.0792	32.7512
G20	Best	0.24743	1.26181	0.24743	0.24743	0.24743	0.24743	0.24139
−0.204979	Mean	0.97234	1.43488	0.26165	0.80536	0.25519	1.22037	0.24385
G21	Best	193.7311	198.8151	193.7346	193.7343	193.7264	193.7246	193.5841
−193.274	Mean	345.6595	367.2513	366.9193	275.5436	256.6091	264.6092	193.7219
G22	Best	−258.74	−267.15	−249.12	−243.43	−272.78	−248.78	−242.45
−236.4309	Mean	−255.55	−254.44	−249.46	−251.33	−265.66	−252.56	−239.05
G23	Best	−105.9826	2.3163	−72.642	−43.2541	−390.6472	−385.0043	−391.5192
(−400.055)	Mean	−25.9179	22.1401	−7.2642	−4.3254	−131.2522	−83.7728	−381.2312
G24	Best	−5.508	−5.508	−5.508	−5.508	−5.508	−5.508	−5.508
(−5.5080)	Mean	−5.508	−5.4982	−5.508	−5.508	−5.508	−5.508	−5.508

Table 2 Typical parameters of the bus systems

Control variables	IEEE 14 bus system	IEEE 30 bus system	IEEE 57 bus system	IEEE 118 bus system
Buses	14	30	57	118
Generators	5	6	7	54
Transformers	3	4	15	9
Shunt compensators	2	3	3	14
Transmission lines	20	41	80	186
Control variables	10	13	27	77
Base P_{loss} (MW)	13.49	5.66	27.8637	132.45

Table 3 Simulation results on IEEE 14 bus system using different algorithms

Control Variables (p.u.)	PSO	R-PSO	L-PSO	PSO-CFA	IPSO-SR	FOA	MFOA	JAYA
V_{G1}	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
V_{G2}	1.1	1.1	1.1	1.1	1.0863	1.1	1.1	1.0859
V_{G3}	1.0701	1.0696	1.0703	1.0702	1.0578	1.1	1.1	1.0568
V_{G6}	1.1	1.1	1.1	1.0605	1.0575	0.9	1.1	1.1
V_{G8}	1.1	1.1	1.1	1.1	1.0726	0.95	1.1	1.1
$T_{4\text{-}7}$	0.9285	0.9551	1.1	1.1	0.9685	1.1	1.1	0.9492
$T_{4\text{-}9}$	1.1	1.1	0.9	0.9	1.1	0.935	1.1	1.0766
$T_{5\text{-}6}$	1.1	1.0179	1.0047	1.1	1.1	1.1	1.1	1.0031
Q_{sc9}	0.2332	0.3	0.2643	0.015	0.2134	0.000328	0.0443	0.3
Q_{sc14}	0.0555	0.0604	0.0	0.0641	0.0634	0.000296	0.0443	0.0594
Total P_{loss} (MW)	12.4268	12.3585	12.4041	12.416	12.2957	12.5992	12.7531	12.2270
DE[25]	ABC[25]	ACOR [25]	TLA [25]	DE [25]	MTLA [25]	MTLA-DDE [25]	LCA [25]	CSS [25]
13.1053	12.9333	13.1226	12.9229	13.1053	12.9106	12.8978	12.9891	12.9748
BRCFF [25]	BB–BC [25]	PBIL [25]	DDE [25]	TLBO [28]	BBPSO [28]	BBDE [28]	GBTLBO [28]	MGBTLBO [28]
12.9264	13.0039	13.0008	12.9286	12.9878	12.9919	12.9973	12.4152	12.3105
PSO [15]	PSO-TVAC [15]	WOA [15]	MDE [16]	SARGA [16]	RTS [16]	EP [16]	BSO 1 [16]	BSO 2 [16]
12.381	12.279	12.255	13.0532	13.21643	13.236	13.3462	12.4633	12.4672
BSO 3 [16]	BSO 4 [16]	BSO 4 [16]						
12.4651	12.4588	12.4699						

problem compared to many other modern meta-heuristic algorithms. Hence, the JAYA algorithm is one of the most competitive algorithms among the newly developed meta-heuristic optimization algorithms in the recent past. The procedure for the implementation of the JAYA algorithm in solving the ORPD problem is shown in the flowchart in Fig. 1 [26].

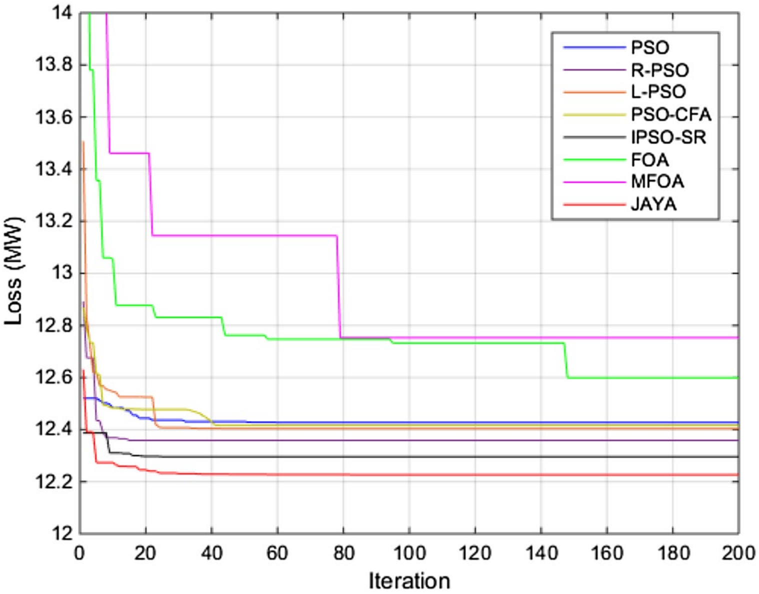

Fig. 2 Convergence characteristic of the algorithms for IEEE 14 bus system

Table 4 Control variable limits (p.u.) for different test cases

Case no	V_g^{min}	V_g^{max}	V_{PQ}^{min}	V_{PQ}^{max}	T^{min}	T^{max}	Q_c^{min}	Q_c^{max}
1	0.9	1.1	0.95	1.05	0.95	1.05	-0.12	0.36
2	0.95	1.1	0.95	1.1	0.9	1.1	0	0.36

Simulation results and discussion

Before going in to the ORPD problem, the proposed JAYA algorithm has been tested on different standard constrained benchmark functions to inspect the optimizing capability of the algorithm. The test have been done to determine the best and the mean values of the solutions for all the respective optimizing functions. The results are compared with many other popular optimization techniques and are shown in Table 1. The results show that the JAYA algorithm has given the best results compared to the others, and is the most consistent in optimizing any objective function with minimum deviation of the solutions as the mean values are very close to the best solutions for every corresponding functions.

The proposed JAYA algorithm along with few other algorithms as discussed in the literature, are tested on four standard IEEE bus systems, IEEE 14, 30, 57 and 118 bus systems are used as test systems to solve the ORPD problem for active power loss minimization in the transmission lines. In order to get a better comparison between the algorithms, two different cases each for IEEE 30, 57 and 118 bus systems are taken by changing the lower and upper limits of the control variables. The results are tabulated for all the different cases and are compared to establish the superiority of the proposed algorithm among the others in optimizing this minimization problem of ORPD. The software used for this problem is

Table 5 Simulation results on IEEE 30 bus system using different algorithms for case 1

Control Variables (p.u.)	**PSO**	**R-PSO**	**L-PSO**	**PSO-CFA**	**IPSO-SR**	**FOA**	**MFOA**	**JAYA**
V_{G1}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G2}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0946
V_{G5}	1.1	1.0881	1.1	1.1	1.1	0.9	0.9	1.0753
V_{G8}	1.0895	1.1	1.0904	1.0903	1.1	0.9	0.9	1.0771
V_{G11}	1.1	1.1	1.1	1.1	1.1	1.1	0.9	1.1
V_{G13}	1.1	1.1	1.1	1.1	1.1	1.0124	0.9	1.1
$T_{6\text{-}9}$	1.05	1.05	1.05	1.05	1.05	0.95	0.95	1.0318
$T_{6\text{-}10}$	1.05	1.05	1.05	0.9956	1.05	0.95	0.95	0.95
$T_{4\text{-}12}$	1.05	1.05	1.05	1.05	1.05	0.95	0.95	0.9500
$T_{28\text{-}27}$	1.05	1.05	1.05	1.05	1.0025	0.9	0.95	0.955
Q_{sc3}	−0.0124	−0.0081	−0.0122	0.0012	−0.0092	0.0002	−0.12	0.0807
Q_{sc10}	−0.1725	0.1543	0.1602	0.0842	0.2177	0.0005	−0.12	0.2806
Q_{sc24}	0.1137	0.1165	0.1181	0.1202	0.1016	0.0011	−0.12	0.0985
P_{loss} (MW)	4.8578	4.8488	4.8571	4.8523	4.8304	7.1480	4.8585	**4.5990**
ACO_R [25]	ABC [25]	LCA [25]	CSS [25]	BRCFF [25]	BB–BC [25]	PBIL [25]	TLA [25]	DE [25]
4.9147	4.9064	4.9092	4.9062	4.9059	4.9080	4.9144	4.9047	4.9121
MTLA [25]	DDE [25]	MTLA-DDE [25]	TLBO [28]	BBPSO [28]	BBDE [28]	GBTLBO [28]	MGBTLBO [28]	SGA [29]
4.8616	4.8623	4.8596	4.8787	4.8922	4.9015	4.8685	4.7802	4.9800
MAPSO [29]	HSA [30]	ICA [31]	IWO [31]	MICA-IWO [31]	BSO 1 [16]	BSO 2 [16]	BSO 3 [16]	BSO 4 [16]
4.8747	4.9059	4.8637	4.9344	4.8599	4.6847	4.6826	4.6728	4.6499
BSO 5 [16]								
4.634								

MATLAB 2014b, where the algorithms are tested taking the population size to be 100 for all the cases mentioned in the paper. The system data of these test systems are obtained from [27]. The total number of individual parameters used for the test systems are listed in Table 2.

IEEE 14 bus system

The IEEE-14 bus has five generators at the buses 1 (which is the slack bus), 2, 3, 6 and 8. It has three tap-changing transformers placed branches between the lines (4–7, 4–9 and 5–6) out of the total 20 number of branches. The reactive powers are injected at buses 9 and 14. The limits of the control variables (p.u. value) for IEEE 14 bus system are as follows:

$0.95 \leq V_{gi} \leq 1.1$

$0.95 \leq V_{Li} \leq 1.05.$

$0.9 \leq T_i \leq 1.1$

$0 \leq Q_{ci} \leq 0.3$

The ORPD problem is solved using all the mentioned algorithms for determining the best solution of the real power loss for the optimal values of the control variables. The simulation results of the algorithms are shown in Table 3, and the convergence characteristic is shown in Fig. 2. The results describe the superiority

Table 6 Simulation results on IEEE 30 bus system using different algorithms for case 2

Control variables (p.u.)	**PSO**	**R-PSO**	**L-PSO**	**PSO-CFA**	**IPSO-SR**	**FOA**	**MFOA**	**JAYA**
V_{G1}	1.1	1.1	1.1	1.1	1.1	0.9757	0.95	1.1
V_{G2}	1.1	1.1	1.1	1.1	1.1	0.95	0.95	1.0945
V_{G5}	1.1	1.1	1.1	1.0806	1.1	0.95	0.95	1.0752
V_{G8}	1.1	1.1	1.1	1.0821	1.0882	0.95	0.95	1.077
V_{G11}	1.1	1.1	1.1	1.1000	1.1	1.1	0.95	1.1
V_{G13}	1.1	1.1	1.1	1.1000	1.1	1.1	0.95	1.1
$T_{6\text{-}9}$	0.9981	1.1	1.1	0.9777	0.9758	0.9	0.9	1.073
$T_{6\text{-}10}$	1.1	0.9	1.1	1.1	1.1	0.9	0.9	0.9001
$T_{4\text{-}12}$	0.9726	0.9729	1.0063	1.1	0.9553	0.9	0.9	0.9411
$T_{28\text{-}27}$	0.9896	0.9746	0.998	1.0041	0.9644	0.9	0.9	0.9522
Q_{sc3}	0.0	0.0	0.0	0.0	0.094958	0.0003	0.2993	0.0915
Q_{sc10}	0.36	0.2362	0.36	0.0954	0.36	0.0005	0.2993	0.2824
Q_{sc24}	0.0949	10.056	0.1032	0.107	0.0994	0.0003	0.2993	0.0978
P_{loss} (MW)	4.7915	4.7392	4.8655	4.7282	4.7190	6.2775	5.0957	**4.5983**
ICA [31]	IWO [31]	MICA-IWO [31]	C-PSO [32]	CI-PSO [32]	LDI-PSO [32]	B-DE [32]	R-DE [32]	SFLA [32]
4.6155	4.6287	4.5984	4.6801	4.6124	4.6124	4.6124	4.6675	4.6148
NMSFLA [32]								
4.6118								

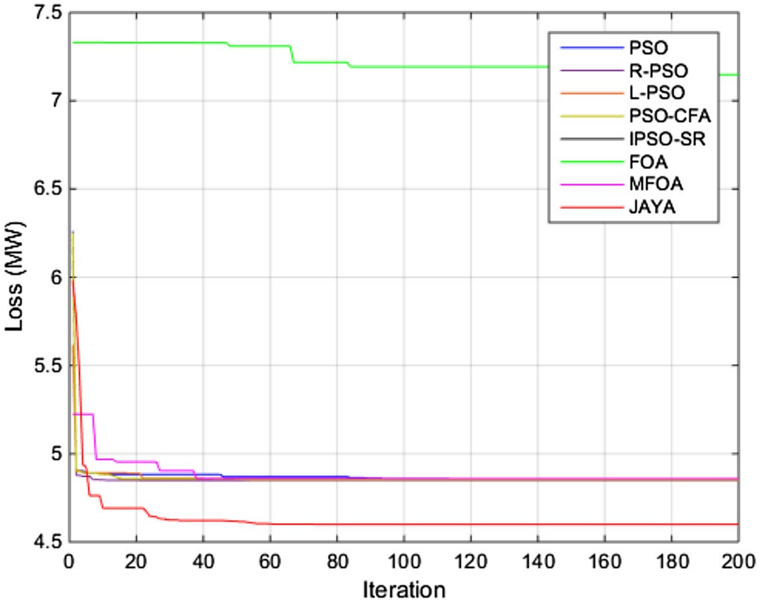

Fig. 3 Convergence characteristic of the algorithms for IEEE 30 bus system for case 1

of the JAYA algorithm among all the reported algorithms in determining the best solution to the ORPD problem. It has reduced the power loss to a level of 12.227 MW, which is the maximum reduction as reported in the literature. It has high

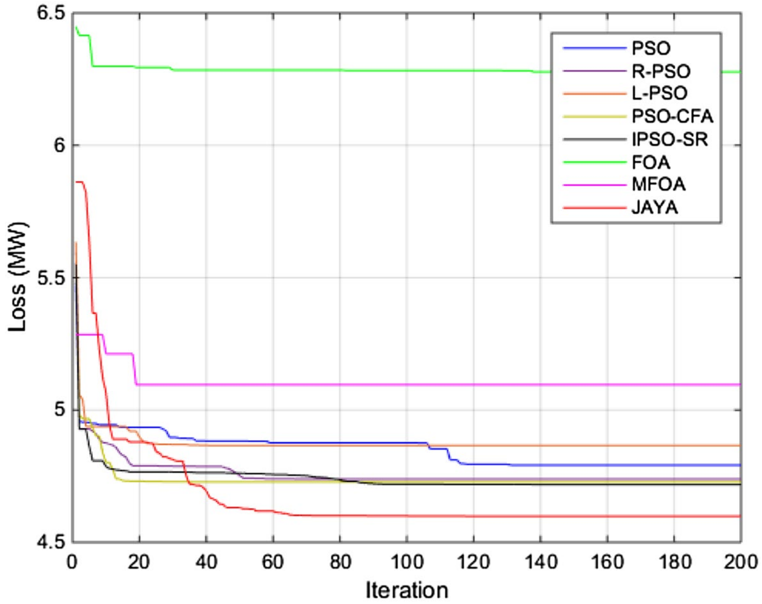

Fig. 4 Convergence characteristic of the algorithms for IEEE 30 bus system for case 2

Table 7 Statistical analysis for case 2 of IEEE 30 bus system

Algorithm	Best (MW)	Worst (MW)	Mean (p.u.)	Standard deviation (SD)	% of Power save
C-PSO [31]	4.68017	5.69149	5.14339	2.8854×10^{-3}	17.3114
CI-PSO [31]	4.61244	4.87635	4.64732	5.834×10^{-4}	18.5081
LDI-PSO [31]	4.61243	4.93822	4.62908	4.851×10^{-4}	18.5083
B-DE [31]	4.61243	4.61333	4.61281	2.6×10^{-6}	18.5083
R-DE [31]	4.66755	4.98274	4.75088	6.54×10^{-4}	17.5344
SFLA [31]	4.61483	4.97653	4.72213	9.973×10^{-4}	18.4659
NMSFLA [31]	4.61181	4.61749	4.61264	9.8×10^{-6}	18.5192
ICA [31]	4.6155	4.6624	4.6397	2.7613×10^{-3}	18.4541
IWO [31]	4.6287	4.9206	4.7813	3.1584×10^{-2}	18.2208
MICA-IWO [31]	4.5984	4.6009	4.5991	8.006×10^{-6}	18.7562
PSO	4.7915	4.9387	4.9053	9.08×10^{-3}	15.3445
R-PSO	4.7392	5.0006	4.8695	8.707×10^{-3}	16.2686
L-PSO	4.8655	5.0222	4.9496	5.1176×10^{-3}	14.0371
PSO-CFA	4.7282	4.9185	4.8334	6.668×10^{-3}	16.4629
IPSO-SR	4.719	4.9316	4.84455	6.668×10^{-3}	16.6254
FOA	6.2775	6.3832	6.3605	5.3887×10^{-3}	−10.9099
MFOA	5.0957	5.1424	5.13425	1.724×10^{-3}	9.97
JAYA	4.5983	4.5986	4.5984	9.4281×10^{-5}	18.7579

convergence rate and enormous capability of searching the optimal result to the objective function.

Table 8 Frequency of convergence for IEEE 30 bus system case 2 in 50 trial runs

Algorithms	4.59–4.60	4.61–4.70	4.71–4.80	4.81–4.90	4.91–5.0	5.01–5.10	5.11–5.20	> 6.01
PSO	0	0	1	30	19	0	0	0
R-PSO	0	0	11	33	6	0	0	0
L-PSO	0	0	3	25	22	0	0	0
PSO-CFA	0	0	18	27	5	0	0	0
IPSO-SR	0	0	4	29	17	0	0	0
FOA	0	0	0	0	0	0	0	50
MFOA	0	0	0	0	0	1	49	0
JAYA	50	0	0	0	0	0	0	0

Table 9 Control variable limits (p.u.) for the test cases

Case no	V_g^{min}	V_g^{max}	V_{PQ}^{min}	V_{PQ}^{max}	T^{min}	T^{max}
Limits of voltages and tap-settings (p.u.)						
1	0.94	1.06	0.94	1.06	0.9	1.1
2	0.9	1.1	0.94	1.06	0.9	1.1
Bus no		**18**		**25**		**53**
Limits of the reactive power sources (p.u.) for both the cases						
Q_c^{min}		0		0		0
Q_c^{max}		0.1		0.059		0.063

IEEE 30 bus system

The IEEE 30 bus system has six number of generators at buses 1, 2, 5, 8, 11 and 13 out of which bus number 1 is the slack bus. It has 41 transmission lines where four number of tap-changing transformers are situated at branches 6–9, 6–10, 4–12 and 28–27. The VAR injection is done at buses 3, 10 and 24. Two different case studies have been done for this test case depending upon the limits of the control variables. The ORPD problem is solved, and the optimal values of the control variables are determined using the different algorithms mentioned in the literature.

The case details along with the limits of the control variables are listed in Table 4. The simulation results of the algorithms for cases 1 and 2 are shown in Tables 5 and 6, and the convergence characteristic is shown in Figs. 3 and 4, respectively.

The results show that the minimum power loss has been observed for the case 2, and the JAYA algorithm has given better results compared to the other reported algorithm for all the cases. The convergence rate of JAYA algorithm has proved to be much faster and more accurate compared to the others in determining the power loss. The JAYA algorithm has obtained the best solution of 4.5983 MW for the case 2 by saving the power to 18.7579%, which is very impressive and is the highest recorded power saving in the ORPD problem for this test case under similar condition and constraint.

Table 7 shows the statistical analysis of the algorithms used in this paper for case 2 of the IEEE 30 bus system. The table compares the best (Best) and worst (Worst) values of the solutions of the ORPD problem along with the standard deviation (std.) and mean of the results for the different algorithms individually. The comparison of

Table 10 Simulation results on IEEE 57 bus system using different algorithms for case 1

Control variables (p.u.)	**PSO**	**R-PSO**	**L-PSO**	**PSO-CFA**	**IPSO-SR**	**FOA**	**MFOA**	**JAYA**
V_{G1}	1.06	1.06	1.06	1.06	1.06	0.9704	1.06	1.06
V_{G2}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G3}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0495
V_{G6}	1.06	1.06	1.0497	1.06	1.06	0.94	1.06	1.0436
V_{G8}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G9}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0450
V_{G12}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0411
T_{4-18}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9
T_{4-18}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9
T_{21-20}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9829
T_{24-26}	1.1	1.0822	1.0308	1.0273	1.1	0.9	0.9	0.9875
T_{7-29}	1.1	1.1	1.1	1.046	1.1	0.9	0.9	0.9
T_{34-32}	0.9692	0.9693	1.1	1.1	1.1	0.9	0.9	0.9743
T_{11-41}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9
T_{15-45}	0.995	1.0023	1.1	1.0042	0.9	0.9	0.9	0.9
T_{14-46}	1.0091	1.0078	1.0518	1.0095	0.9164	0.9	0.9	0.9
T_{10-51}	1.1	1.1	1.1	1.1	0.9345	0.9	0.9	0.9110
T_{13-49}	0.9745	0.9778	1.0122	0.9795	0.9	0.9	0.9	0.9
T_{11-43}	1.1	1.1	1.1	1.1	0.9	0.9	0.9	0.9
T_{40-56}	1.1	1.1	1.1	1.1	1.0733	0.9095	0.9	1.0156
T_{39-57}	1.1	1.1	1.1	1.1	1.0412	0.9	0.9	0.9838
T_{9-55}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9006
Q_{sc18}	0.10	0.10	0.0138	0.094	0.10	0.0009	0	0.0999
Q_{sc25}	0.059	0.059	0.059	0.059	0.059	0.007	0	0.059
Q_{sc53}	0.063	0.063	0.063	0.063	0.063	0.0015	0	0.063
P_{loss} (MW)	26.1507	26.1354	26.7281	26.1826	25.3875	31.6433	24.9314	**23.4710**
HSA [30]	SGA [30]	DMSDE [30]	DE [30]	CLPSO [30]	AGA [30]	CGA [30]	ICA [31]	IWO [31]
24.5612	25.03	24.266	25.0862	25.0684	24.4857	24.8853	24.4799	24.5939
MICA-IWO [31]	SOA [10]	PSO-w [10]	L-SaDE [10]	ABC [34]	MVMO [33]	DE [34]	JADE [34]	JADE-vPS [34]
24.25684	24.26548	24.27052	24.26739	24.1846	24.8512	24.8360	24.8493	24.8451
FA [20]	GWO [20]	SOA [20]	CSA [20]	ALO [20]	MFO [20]			
24.4587	24.7523	24.2677	24.2619	24.7621	24.2529			

the results prove that the JAYA algorithm has obtained the best solution to the problem and is also the most consistent and robust as it has very impressive standard. compared to most of the other algorithms. It has the best solution and has been able to reduce the active power loss to almost 18.7579% (4.5983 MW), which is the maximum reduction compared to the others as reported in the literature.

In order to investigate how frequently the results from the different algorithms converge within different range of solutions, a comparison has been done for case 2 of IEEE 30 bus system. This is a comparison of the frequency of convergence and is shown in Table 8. The table shows the number of times each algorithm has produced the solution within a specified range when ORPD problem is run for 50 times each for every single algorithm that has been worked out in this paper. The results show

Table 11 Simulation results on IEEE 57 bus system using different algorithms for case 2

Control Variables (p.u.)	**PSO**	**R-PSO**	**L-PSO**	**PSO-CFA**	**IPSO-SR**	**FOA**	**MFOA**	**JAYA**
V_{G1}	1.1	1.1	1.1	1.1	1.1	0.9127	0.9	1.1
V_{G2}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0991
V_{G3}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0888
V_{G6}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0834
V_{G8}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G9}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0848
V_{G12}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0806
T_{4-18}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9
T_{4-18}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9
T_{21-20}	1.1	1.1	1.1	0.9918	1.1	0.9	0.9243	0.9824
T_{24-26}	1.0036	1.1	1.015	0.9971	1.0642	0.9	0.9	0.9865
T_{7-29}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9
T_{34-32}	0.9671	1.1	0.9688	0.9662	1.1	1.1	0.9	0.9751
T_{11-41}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9
T_{15-45}	1.1	1.0046	1.1	1.1	1.0133	0.9	0.9	0.9
T_{14-46}	1.1	1.0095	1.1	1.1	1.0176	0.9	0.9	0.9
T_{10-51}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9101
T_{13-49}	1.1	0.9823	1.0333	1.1	0.9895	0.9	0.9	0.9
T_{11-43}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9
T_{40-56}	1.1	1.1	1.1	1.027	1.1	0.9	0.9	1.0111
T_{39-57}	1.1	1.1	1.1	0.9829	1.1	0.9	0.9	0.9841
T_{9-55}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9002
Q_{sc18}	0.0	0.0	0.0	0.10	0.0616	0.0012	0.008	0.0976
Q_{sc25}	0.059	0.059	0.059	0.059	0.059	0.0026	0.0059	0.059
Q_{sc53}	0.063	0.063	0.063	0.063	0.063	0.0014	0.0059	0.063
P_{loss} (MW)	24.8254	24.2539	24.5676	24.5873	24.2012	33.5557	23.0158	**21.5481**
ALC-PSO [16]	BBO [16]	GSA [16]	CPVEI HBMO [16]	HBMO [16]	OGSA [16]	BSO 1 [16]	BSO 2 [16]	BSO 3 [16]
23.39	24.544	24.439	22.78	23.24	23.43	24.5025	24.4856	24.4492
BSO 4 [16]	BSO 5 [16]	SGA (F_{f1}) [35]	SGA (F_{f2}) [35]	PSO [36]	ICA [36]	PSO-ICA [36]	MOALO [37]	DSA [38]
24.3744	24.6431	23.836	24.325	24.7742	24.1607	24.1386	26.593	23.35
BSO [16]	WCA [39]	GBWCA [39]	GSA [40]	CSA [40]	MCBOA [40]	BA [41]	FPA [41]	
24.3744	24.82	23.27	24.4922	24.2619	23.6943	24.9254	24.8419	

the JAYA algorithm is undoubtedly the only one to produce all the result within the minimum range of 4.59–4.60 MW, and no other algorithm has obtained any solution within this range. Moreover, the MFOA technique is also quite consistent, as it has frequently obtained the solution within the range of 5.11–5.20 MW (49 times). However, the algorithm has failed to optimize the function to lower limits. Thus, the results prove that the JAYA algorithm has the capability of converging most frequently to the minimum solution.

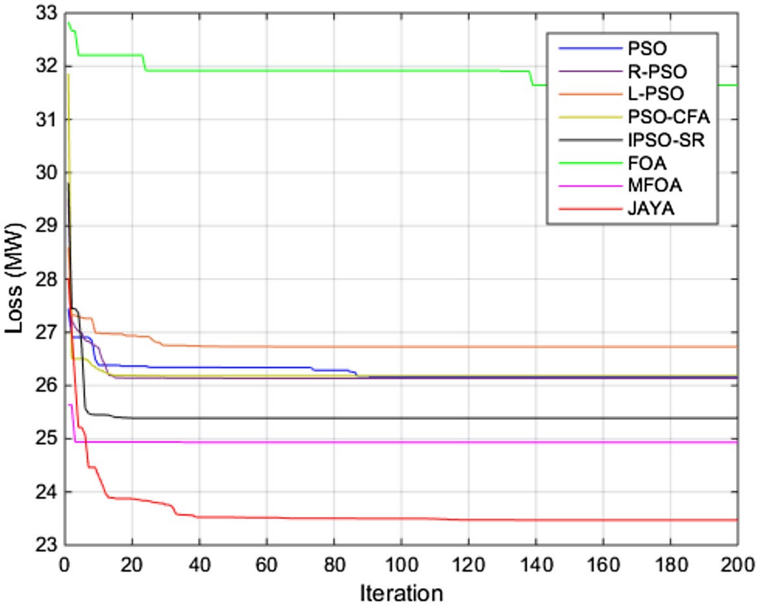

Fig. 5 Convergence characteristic of the algorithms for IEEE 57 bus system for case 1

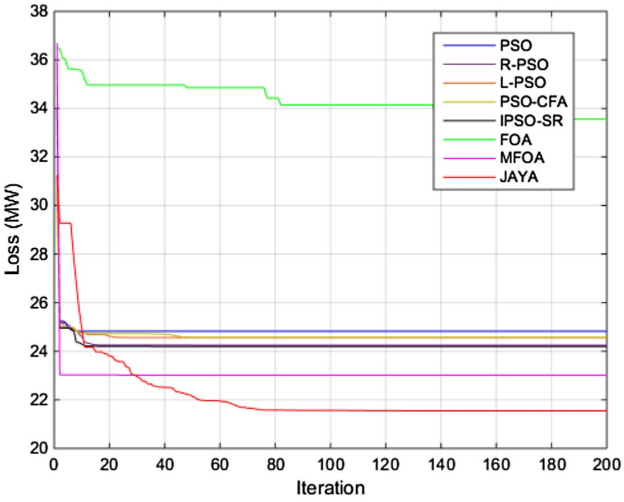

Fig. 6 Convergence characteristic of the algorithms for IEEE 57 bus system for case 2

IEEE 57 bus system

The IEEE 57 bus system has seven generators situated at the buses 1, 2, 3, 6, 8, 9 and 12 where bus number 1 is the slack bus. It has tap-changing transformers connected to the 15 out of the total 80 branches. The transformers are connected between 21–20, 24–26, 7–29, 34–32, 11–41, 15–45, 14–46, 10–51, 13–49, 11–43, 40–56, 39–57 and 9–55. The reactive powers sources are injected at the buses 18, 25 and 53. Here, two case studies have been done to solve the ORPD problem and determine the optimal solution for each case individually. The upper and lower limits of the control variables are given in Table 9. The simulation results for both case 1 and case 2 using

Table 12 Control variable limits (p.u.) for the test cases

Case no	V_g^{min}	V_g^{max}	V_{PQ}^{min}	V_{PQ}^{max}	T^{min}	T^{max}
Limits of voltages and tap-settings (p.u.)						
1	0.94	1.06	0.94	1.06	0.9	1.1
2	0.9	1.1	0.94	1.06	0.9	1.1

Bus no	5	34	37	44	45	46	48
Limits of the reactive power sources (p.u.) for both the cases							
Q_c^{min}	−0.4	0	−0.25	0	0	0	0
Q_c^{max}	0	0.14	0	0.1	0.1	0.1	0.15
Bus no	74	79	82	83	105	107	110
Q_c^{min}	0	0	0	0	0	0	0
Q_c^{max}	0.12	0.2	0.2	0.1	0.2	0.06	0.06

all the algorithms are represented in Tables 10 and 11, and the comparative convergence characteristics are shown in Figs. 5 and 6, respectively.

The results show that the power loss for case 2 has been minimized the most by JAYA algorithm, to almost 22.67% (21.5481 MW). It has obtained the best solution due to its high capability in searching for the best solution in every iteration and avoiding the risk of being stuck in to the local optima unlike the other algorithms in caparison. The comparison of the results establish the superiority of the proposed algorithm in determining the optimal results for the problem. Thus, it is more consistent, accurate and most effective in minimizing the loss in the problem compared to the other reported algorithms.

IEEE 118 bus system

In order to test the effectiveness of the JAYA algorithm in a larger scale, this ORPD problem has been solved on the IEEE 118 bus system. This test system has 54 generators, 14 shunt compensators, 9 tap-changing transformers and 186 transmission lines. The limits of the control variables are given in Table 12. Two different cases have been considered for solving the ORPD problem where the upper and lower limits of the generator voltages are chosen differently. This has been done depending upon the different cases considered by the researchers in recent past for solving the ORPD problem the same bus system. Thus, the different test cases are considered here in order to investigate the capability of the proposed JAYA algorithm in solving the ORPD problem for both the possible conditions and compare the results with those of the other reported in the literature . Thus, the algorithms are tested and the simulation results along with the comparative convergence characteristic are shown in Tables 13, 14 and Figs. 7 and 8 for both the cases, respectively.

The tables show the optimal values of the control variables for which the best solution of the power loss has been obtained. The comparison of the results show that the proposed JAYA algorithm is the best among the other reported algorithms in determining the better solution to the ORPD problem for both the cases. The convergence characteristics does reflect the slow convergence of the JAYA algorithm compared to others for this particular higher order system, but the efficiency

Table 13 Simulation results on IEEE 118 bus system using different algorithms for case 1

Control variables (p.u.)	PSO	R-PSO	L-PSO	PSO-CFA	IPSO-SR	FOA	MFOA	JAYA
V_{G1}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0434
V_{G4}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G6}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0545
V_{G8}	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
V_{G10}	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
V_{G12}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0516
V_{G15}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0512
V_{G18}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0535
V_{G19}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0503
V_{G24}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0528
V_{G25}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G26}	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
V_{G27}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.047
V_{G31}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0436
V_{G32}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0458
V_{G34}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G36}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0584
V_{G40}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0391
V_{G42}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0397
V_{G46}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0471
V_{G49}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G54}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0392
V_{G55}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0383
V_{G56}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0385
V_{G59}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G61}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G62}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0561
V_{G65}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G66}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G69}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G70}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0378
V_{G72}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0424
V_{G73}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0375
V_{G74}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0276
V_{G76}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0252
V_{G77}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0474
V_{G80}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G85}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G87}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0593
V_{G89}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G90}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0438
V_{G91}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0489
V_{G92}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G99}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0552
V_{G100}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G103}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0517
V_{G104}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0431
V_{G105}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0392

Table 13 (continued)

Control variables (p.u.)	**PSO**	**R-PSO**	**L-PSO**	**PSO-CFA**	**IPSO-SR**	**FOA**	**MFOA**	**JAYA**
V_{G107}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0261
V_{G110}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0355
V_{G111}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0434
V_{G112}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.0199
V_{G113}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
V_{G116}	1.06	1.06	1.06	1.06	1.06	0.94	1.06	1.06
T_{5-8}	0.9878	0.9877	0.9877	0.9878	0.9879	1.1	0.9	0.9904
T_{25-26}	1.1	1.1	1.1	1.1	1.1	1.0716	0.9	1.1
T_{17-30}	0.9946	0.9813	1.1	1.1	0.9945	0.9	0.9	0.9862
T_{37-38}	1.1	0.9787	0.9951	1.1	1.1	1.1	0.9	0.9822
T_{59-63}	1.1	1.1	1.1	0.9814	1.1	0.9	0.9	0.9818
T_{61-64}	1.1	1.1	1.1	1.0021	1.1	0.9	0.9	1.0031
T_{65-66}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9668
$T_{68\text{-}69}$	1.1	0.9227	0.9	1.1	1.1	0.9	0.9	0.9536
T_{80-81}	1.1	1.1	1.1	0.9768	0.9771	0.9	0.9	0.991
Q_{sc5}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0000
Q_{sc34}	0.0	0.0	0.0	0.0	0.0	0.0008	0.0557	0.1328
Q_{sc37}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0003
Q_{s44}	0.0	0.0	0.0	0.0	0.0	0.0011	0.0557	0.0930
Q_{sc45}	0.0	0.0	0.0	0.0	0.0	0.0015	0.0557	0.1000
Q_{sc46}	0.0	0.0	0.0	0.0	0.0	0.0009	0.0557	0.0972
Q_{sc48}	0.0	0.0	0.0	0.0	0.0	0.0016	0.0557	0.0760
Q_{sc74}	0.0	0.0	0.0	0.0	0.0	0.0015	0.0557	0.1199
Q_{sc79}	0.0	0.0	0.0	0.0	0.0	0.0011	0.0557	0.2000
Q_{sc82}	0.0	0.0	0.0	0.0	0.0	0.0008	0.0557	0.2000
Q_{sc83}	0.0	0.0	0.0	0.0	0.0	0.0008	0.0557	0.1000
Q_{sc105}	0.0	0.0	0.0	0.0	0.0	0.0005	0.0557	0.1841
Q_{sc107}	0.0	0.0	0.0	0.0	0.0	0.0022	0.0557	0.0151
Q_{sc110}	0.06	0.06	0.0	0.06	0.06	0.0027	0.0557	0.0057
P_{loss} (MW)	120.7712	118.8887	120.4271	119.6773	119.8839	147.4177	116.851	**113.9979**
ACO_R [25]	DE/best/2/bin [5]	ABC [25]	LCA [25]	CSS [25]	BRCFF [25]	BB–BC [25]	TLA [25]	MTLA [25]
122.9456	118.4267	117.9922	120.0662	119.1621	116.5817	122.1314	116.0682	114.2213
DMSDE [30]	PSO-w [30]	AGA [30]	ICA [31]	IWO [31]	MICA-IWO [31]	CGA [10]	CLPSO [10]	L-SaDE [10]
115.37	115.8328	123.9636	118.3219	137.2954	114.0457	139.4149	123.1522	116.9057
SOA [10]	MVMO [34]	DE [34]	JADE [34]	JADE-vPS [34]	RGA [42]	CMAES [42]	MOPSO [42]	NSGA-II [42]
114.95013	115.7932	125.0250	119.1614	119.2006	122.1400	119.2750	119.5813	119.5799
MNSGA-II [42]	L-SACP-DE [43]	HICA-PSO [36]	ERWO [17]					
119.2790	141.8	127.82	116.44					

of the algorithm ultimately enables it to determine the optimal solution which turns out to be the best result obtained among any other algorithms in comparison. The proposed algorithm has reduced the power loss to a value of 105.4821 MW for

Table 14 Simulation results on IEEE 118 bus system using different algorithms for case 2

Control variables (p.u.)	PSO	R-PSO	L-PSO	PSO-CFA	IPSO-SR	FOA	MFOA	JAYA
V_{G1}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0801
V_{G4}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G6}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0932
V_{G8}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G10}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G12}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0896
V_{G15}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0882
V_{G18}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0886
V_{G19}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0869
V_{G24}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0912
V_{G25}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G26}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G27}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0812
V_{G31}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0755
V_{G32}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0813
V_{G34}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0989
V_{G36}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.096
V_{G40}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0784
V_{G42}	1.1	1.1	1.1	1.1	1.1	0.9437	0.9	1.078
V_{G46}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0855
V_{G49}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0977
V_{G54}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0771
V_{G55}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0756
V_{G56}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0765
V_{G59}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0994
V_{G61}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0994
V_{G62}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0956
V_{G65}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G66}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G69}	1.1	1.1	1.1	1.1	1.1	0.956	0.9	1.0999
V_{G70}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0776
V_{G72}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.081
V_{G73}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0769
V_{G74}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0669
V_{G76}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0673
V_{G77}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0867
V_{G80}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0994
V_{G85}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0995
V_{G87}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G89}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G90}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0854
V_{G91}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0895
V_{G92}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G99}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0969
V_{G100}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.1
V_{G103}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0918
V_{G104}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.083
V_{G105}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.077

Table 14 (continued)

Control variables (p.u.)	**PSO**	**R-PSO**	**L-PSO**	**PSO-CFA**	**IPSO-SR**	**FOA**	**MFOA**	**JAYA**
V_{G107}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0669
V_{G110}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0704
V_{G111}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0774
V_{G112}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0549
V_{G113}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0968
V_{G116}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0999
T_{5-8}	0.9905	1.1	1.1	1.1	1.1	0.9	0.9	0.9847
T_{25-26}	1.1	1.1	1.1	1.1	1.1	0.922	0.9	1.0967
T_{17-30}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	0.9964
T_{37-38}	1.1	1.1	1.1	1.1	0.9942	0.9	0.9	0.983
T_{59-63}	1.1	0.982	0.9820	0.9821	0.9667	0.9	0.9	0.9806
T_{61-64}	0.9859	0.9999	0.9999	1.0	1.1	0.9	0.9	1.005
T_{65-66}	1.1	1.1	1.1	1.1	1.1	0.9	0.9	1.0043
$T_{68\text{-}69}$	1.1	1.1	1.1	1.1	0.9257	0.9	0.9	0.9569
T_{80-81}	0.9789	1.1	1.1	0.9766	1.1	0.9	0.9	0.9915
Q_{sc5}	0.0	0.0	0.0	0.0	0.0	0.0000	0.0	-0.2340
Q_{sc34}	0.0	0.0	0.0	0.0	0.0	0.0017	0.14	0.0007
Q_{sc37}	0.0	0.0	0.0	0.0	0.0	0.0000	0.0	0.0
Q_{s44}	0.0	0.0	0.0	0.0	0.0	0.0007	0.1	0.0566
Q_{sc45}	0.0	0.0	0.0	0.0	0.0	0.0009	0.1	0.0979
Q_{sc46}	0.0	0.0	0.0	0.0	0.0	0.0019	0.1	0.0467
Q_{sc48}	0.0	0.0	0.0	0.0	0.0	0.0007	0.15	0.0015
Q_{sc74}	0.0	0.0	0.0	0.0	0.0	0.0008	0.12	0.0080
Q_{sc79}	0.0	0.0	0.0	0.0	0.0	0.0009	0.1604	0.1992
Q_{sc82}	0.0	0.0	0.0	0.0	0.0	0.0005	0.1604	0.2000
Q_{sc83}	0.0	0.0	0.0	0.0	0.0	0.0013	0.1	0.0741
Q_{sc105}	0.0	0.0	0.0	0.0	0.0	0.0008	0.1604	0.1991
Q_{sc107}	0.0	0.0	0.0	0.0	0.0	0.0013	0.06	0.0
Q_{sc110}	0.0	0.06	0.06	0.0	0.06	0.0028	0.06	0.0294
P_{loss} (MW)	111.7172	113.7233	113.7233	112.8162	112.6259	167.0409	107.9321	**105.4821**
CKHA [44]	PSO-TVIW [45]	PSO-TVAC [45]	SPSO-TVAC [45]	PSO-CF [45]	PG-PSO [45]	SWT-PSO [45]	PGSWT-PSO [45]	IPG-PSO [45]
110.79	116.8976	124.3335	116.2026	115.6469	116.6075	124.1476	119.4271	115.0605
GSA [46]	OGSA [47]	CLPSO [48]	EMA [49]	NGBWCA [39]	WCA [39]	SARCGA [18]	HEP [18]	QOTLBO [18]
127.76	126.99	130.96	126.22	121.47	131.83	113.12	115.58	112.2789
TLBO [18]	FPA [18]	CSA [18]	SSA [18]	MSSA [18]	HSSSA [18]	SSO [18]	ISSO [18]	MSFS [50]
116.4003	129.6524	121.2732	125.8324	124.0818	126.6992	179.1816	114.5297	114.6251
SARCGA [51]	HEP [51]	ALO [19]	IALO [19]					
113.12	115.58	116.86	114.795					

case 2, thus resulting in a reduction of power loss by 20.36%, which is the best obtained result among all the algorithms reported in the literature till date. Thus, it has proved to be the most efficient among all the reported algorithms in

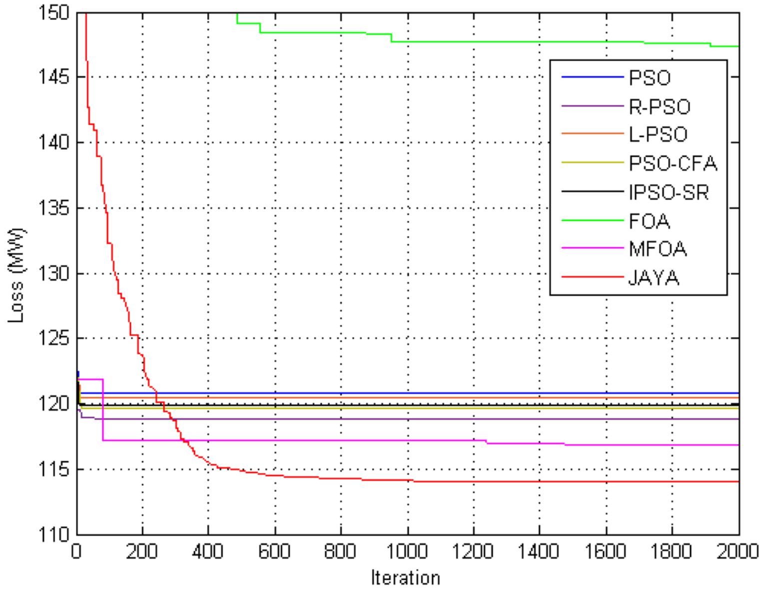

Fig. 7 Convergence characteristic of the algorithms for IEEE 118 bus system for case 1

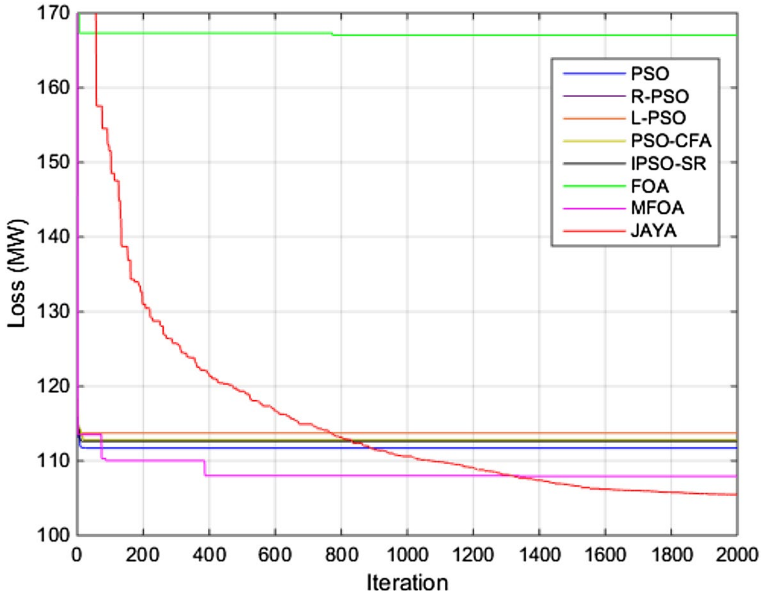

Fig. 8 Convergence characteristic of the algorithms for IEEE 118 bus system for case 2

comparison as it is capable of determining the best solution for the highly nonlinear optimization problem of ORPD even for higher order bus system.

Conclusion

In this paper, a recently proposed optimization technique named JAYA algorithm has been used to solve the ORPD problem for determining the minimum power loss for the optimal location of the control variables. It has been applied on IEEE 14, 30, 57 and 118 bus systems and the algorithm proved to be the best among the others compared in the literature in terms of robustness, efficiency and consistency as it has the highest frequency of convergence within small range of optimal solution. It is a novel meta-heuristic algorithm, which jumps into its optimal solution very fast and accurately compared to the other reported algorithms. Thus, this algorithm is able to find best solution to the ORPD problem and has reduced the transmission line power loss largely and most significantly compared to others under the similar constraints. It has consistently obtained best results for all the mentioned four IEEE standard bus system for different cases with different combination of limits of the control variables. Hence, it can be concluded that the JAYA algorithm is one of the most efficient modern competitive tool for solving the optimization problem of ORPD for smaller and larger scale of power systems, and can give consistent results under any condition without violating any equality and inequality constraint. As a result this optimization technique can be used to solve real life problems in power system related to power or energy saving and cost saving and even other fields of engineering as it very much competent in obtaining satisfying results with high convergence rate with minimum deviation of results.

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Authors' contributions
Mr. Tanmay Das carried out basic design, simulation work and prepared draft paper. Dr. Ranjit Roy and Dr. Kamal Krishna Mandal participated in checking simulation work, results and discussions, sequence of paper and helped to prepare the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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