Reactive Power Control using Sine Cosine Algorithm for Active Power Loss Minimization with Voltage Profile Enhancement

R. Ravisekar, K. Srinivasan

Abstract: The major purpose of optimal reactive power dispatch (ORPD) is to detect control variables like the voltage ratings of the generator, switchable shunt condenser banks, and the tap ratio of the tap setting transformer to reduce the active power loss for fixed economic power planning when taking on a set of constraints. This paper introduces the application of the sine cosine algorithm (SCA) to find the novel solution for the reactive power dispatch of power systems with different test systems (Standard IEEE 14-bus, IEEE 57-bus and IEEE 118-bus) with specific cases like reducing active power losses and increasing bus voltages in test systems. Obtained results validate the high tone of the proposed algorithm, with better, fast and consistent results comparing with existing literatures.

Keywords: Active power loss reduction, Optimal reactive power dispatch, Sine cosine algorithm, Whale optimization algorithm, Ant lion optimizer.

I. INTRODUCTION

Optimal reactive power dispatch (ORPD) has recognized boundless consideration in the final few spans and has become a major concern to improve the performance of the power system's budget and safety. ORPD problem, which is a non-linear, non-convex also non-differentiable optimization problem, goals at minimizing the objective functions like voltage improvement [1-3] and system active power losses through the proper control parameters corresponding to generator voltages, switchable reactive sources, tap settings of transformers.

Mathematical algorithms were used in the initial stages to solve ORPD problems such as the Decomposition process, Newton approach, nonlinear programming, interior point Jacobian matrix, etc. [4-7]. These methods solve the objective function by linearizing the objective function. Since the ORPD problem has more than one local optima issues, also, it is a non-linear optimization problem. Therefore, finding the global optimum using mathematical algorithms is so complex. Nonetheless, in that regard, algorithms such as premature convergence and algorithmic complexity have few drawbacks. For these causes heuristic and meta-heuristic algorithms are developed to solve the problem of ORPD in Table 1.

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Table. 1 Literature review for the solution of ORPD problem

Approach	Reference	Objective	Test System
IEP	[8]	Active power loss	IEEE 118-bus system and a realistic power system in Western China
MAPSO	[9]	Active power loss	IEEE 30-bus and IEEE 118-bus
DE	[10]	Active power loss	IEEE 14, IEEE 30, and IEEE 118-Bus
DPSO	[11]	Active power loss and the costs of adjusting the control devices	IEEE 30-bus
SOA	[12]	Active power loss	IEEE 57-bus and IEEE 118-bus
CLPSO	[13]	Active power loss and voltage profile	IEEE 30-bus and IEEE 118-bus
DMSDE	[14]	Active power loss	IEEE 30-bus, IEEE 57-bus and IEEE 118-bus
HSA	[15]	Active power loss and voltage profile	IEEE 30-bus and IEEE 57-bus
MNSGA-II	[16]	Active power loss and voltage stability	IEEE 30-bus and IEEE 118-bus
BBO	[17]	Active power loss and voltage profile	IEEE 30-bus and IEEE 118-bus
MASRL	[18]	Active power loss	Ward-Hale 6-bus, IEEE 30-bus and IEEE 162-bus
GSA	[19]	Active power loss, voltage profile, and voltage stability	IEEE 30-bus, IEEE 57-bus and IEEE 118-bus
HDE	[20]	Active power loss and voltage profile	IEEE 30-bus, IEEE 57-bus and IEEE 118-bus

QOTLBO	[21]	Active power loss, voltage profile, and voltage stability	IEEE 30-bus and IEEE 118-bus
HFMOEA	[22]	Active power loss and voltage stability	IEEE24-busRTS
HMICA-IWO	[23]	Active power loss	IEEE 30-bus, IEEE 57-bus and IEEE 118-bus
OGSA	[24]	Active power loss, voltage profile, and voltage stability	IEEE 30-bus, IEEE 57-bus and IEEE 118-bus
HFA	[25]	Active power loss and voltage deviation	IEEE 30-bus and IEEE 118-bus
MGBTLO	[26]	Active power loss	IEEE 14-bus and IEEE30-bus
ICA-PSO	[27]	Active power loss and voltage deviation	IEEE57-bus and IEEE118-bus
HABC	[28]	Active power loss	IEEE 6-bus, IEEE14-bus, and IEEE 30-bus
2ArchMGWO	[29]	Active power loss and voltage profile	IEEE 30-bus, IEEE 57-bus and IEEE 118-bus
ABO-TRL	[30]	Active power loss and voltage deviation	IEEE118-bus and IEEE 300-bus
WOA	[31]	Active power loss	IEEE 14-bus, IEEE 30-bus, Algerian electric 114-bus
ABC-FF	[32]	Active power loss and voltage stability	IEEE 14 and IEEE 39 bus
DEEPSO	[33]	Active power loss	IEEE 30-bus, IEEE 57-bus and IEEE 118-bus
HSA	[34]	Active power loss	IEEE 14-bus and IEEE 57-bus

Recently, Sine Cosine Algorithm (SCA) has been proposed by Seyedali et al in 2016. SCA has a variety of benefits and is unique from other algorithms such as GSA etc. Those are shown in detail [35]. Moreover, in [35], SCA was tested on 19 different mathematical benchmark functions and aircraft design problem related with other algorithms such as the Flower Pollination Algorithm (FPA), Gravitational Search Algorithm (GSA), Firefly Algorithm (FA) and Bat Algorithm (BA). The results achieved by SCA in most cases offer better results comparable with other algorithms. The SCA's most important feature is that numerous initial random candidate solutions are generated to oscillate outward or toward the optimal solution using a mathematical equation of sine and cosine functions. This algorithm also combines several random and adaptive variables to highlight exploration and use of the search space in various signs of optimization. For all these reasons,

SCA is selected to solve the ORPD problem in this paper. The ORPD is determined by the constraints of equality and inequality as a non-linear optimization problem. To assess the dependability of the proposed algorithm, IEEE 14/57-bus and 118-bus test systems are tested with various objective functions reflecting active power losses and enhancement of the voltage profile, and results obtained from SCA were compared with those reported in the past.

II. PROBLEM STATEMENT

Minimization of active power losses

The main objective of multi-objective optimization is to reduce the active power loss in the transmission network, as described below [8-34]:

$$F_1 = \sum_{k=1}^{NT} P_{loss,k} = \sum_{k=1}^{NT} G_k (V_i^2 + V_j^2) - 2V_i V_j \cos(\delta_i - \delta_j) \quad (1)$$

Where NT is the number of transmission lines, G_k is the conductance of the k^{th} line, V_i and V_j are the voltage magnitude of the i^{th} and j^{th} buses, and δ_i and δ_j are the voltage phase angles of i^{th} and j^{th} buses.

Dependent (x) and control variables(u)

For the Eq. (1), x and u are vectors of dependent and control variables, respectively. The vector of dependent variables x can be expressed as

$$x^T = [P_{G1}, V_{L1} \dots V_{LNPQ}, Q_{G1} \dots Q_{GNPV}] \quad (2)$$

Where, P_{G1} denotes the real power of slack bus, V_L is the voltage at the PQ buses, Q_G is the reactive power of generator buses, NPV defines the number of voltage controlled (PV) buses, NPQ is the number of PQ buses.

The vector of control variables u can be represented as

$$u^T = [V_{G1} \dots V_{GNPV}, Q_{C1} \dots Q_{CNC}, T_1 \dots T_{NT}] \quad (3)$$

Where, NT and NC are the number of tap changing transformers and shunt VAR compensators, respectively. V_G defines the terminal voltages at the PV bus, T is the tap ratio of the tap changing transformers and Q_C is the output of shunt VAR compensators.

Improvement of voltage profile

Another aim of this problem is to improve the voltage profile which is formulated mathematically as follows [13,17,19-21,24,29],

$$F_2 = \sum_{i=1}^{NPQ} |V_{i,spec} - V_i| \quad (4)$$

Where NPQ is the number of load buses in the power system and V_i is the reference value of the voltage magnitude of the i^{th} bus which is equal to 1.0 (pu)

By combining the Eq. (1) and Eq. (2) leads to the main objective function as follows:

$$F_{obj} = F_1 + F_2 = \left(\sum_{k=1}^{NT} P_{loss,k} \right) + \left(\sum_{i=1}^{NPQ} |V_{i,spec} - V_i| \right) \quad (5)$$

Constraints

Equality constraints

These constraints, which are load flow equations, are described as follows

$$P_{Gi} - P_{Di} - \sum_{j \in NB} V_i V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) = 0 \quad (6)$$

$$Q_{Gi} - Q_{Di} - \sum_{j \in NB} V_i V_j (G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij}) = 0 \quad (7)$$

Where NB is the number of buses, P_{Gi} and Q_{Gi} are generated real and reactive power, P_{Di} and Q_{Di} are load real and reactive power, G_{ij} is the transfer conductance and B_{ij} is the transfer susceptance between i^{th} bus and j^{th} bus, respectively.

Equality constraints

Generator constraints

Generator voltages, reactive outputs ought to be restricted by their lower and upper limits as follows

$$Q_{G,i}^{\min} \leq Q_{G,i} \leq Q_{G,i}^{\max} \quad i \in NG \quad (8)$$

$$V_{G,i}^{\min} \leq V_{G,i} \leq V_{G,i}^{\max} \quad i \in NG \quad (9)$$

Transformer constraints

Transformer tap setting are bounded as follows:

$$T_i^{\min} \leq T_i \leq T_i^{\max} \quad i \in \text{No. of transformers} \quad (10)$$

Shunt VAR compensator constraints

Shunt VAR compensators should be constrained as follows by their lower and upper limits

$$Q_{C,i}^{\min} \leq Q_{C,i} \leq Q_{C,i}^{\max} \quad i \in NC \quad (11)$$

Security constraints

These include the voltage constraints at load buses and the loading of the transmission line as follows:

$$V_{L,i}^{\min} \leq V_{L,i} \leq V_{L,i}^{\max} \quad i \in NPQ \quad (12)$$

$$S_{L,i} \leq S_{L,i}^{\max} \quad i \in NT \quad (13)$$

Where $S_{L,i}$ is the apparent power flow in the transmission line i , $S_{L,i}^{\max}$ is the maximum limits of apparent flow in the transmission line. NT is the number of transmission lines in the system.

Dependent variables are considered as constraints to the objective function using penalty values. Therefore, Eq. (1) and Eq. (2) are combined as:

$$F_{new} = F_{obj} + \lambda_V \sum_{i=1}^{NPQ} (V_i - V_i^{\lim})^2 + \lambda_Q \sum_{i=1}^{NG} (Q_{G,i} - Q_{G,i}^{\lim})^2 \quad (14)$$

$x^{\lim}$ is the limit value of the dependent variable $x = (V_i \text{ and } Q_G)$ and given as:

$$x^{\lim} = x^{\max} \text{ if } x > x^{\max}, \text{ and } x^{\lim} = x^{\min} \text{ if } x < x^{\min}$$

Where λ_V and λ_Q are the weighting factors to enhance the objective function.

III. SINE COSINE OPTIMIZATION ALGORITHM

Regardless of the variances in the field of optimization between optimization algorithms, the green is the divergence of the optimization system into two phases: exploration versus exploitation. In the previous step, an optimization algorithm blends unexpectedly random solutions in the set of solutions with a high rate of randomness in order to find the shining sections of the search space. However, there are incremental changes in random solutions in the development phase, and random differences are significantly lower than in the exploration stage.

In this SCA [35], the following position updating equations is proposed for both phases:

$$X_i^{t+1} = X_i^t + r_1 \times \sin(r_2) \times \|r_3 P_i^t - X_i^t\| \quad (15)$$

$$X_i^{t+1} = X_i^t + r_1 \times \cos(r_2) \times \|r_3 P_i^t - X_i^t\| \quad (16)$$

Where X_i^t is the position of the current solution in i^{th} dimension at t^{th} iteration, $r_1/r_2/r_3$ are random numbers, P_i is position of the destination point in i^{th} dimension, and $\|$ indicates the absolute value.

By combining the Eq. (15) and Eq. (16), it will be used as,

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin(r_2) \times \|r_3 P_i^t - X_i^t\| & r_4 < 0.5 \\ X_i^t + r_1 \times \cos(r_2) \times \|r_3 P_i^t - X_i^t\| & r_4 \geq 0.5 \end{cases} \quad (17)$$

Where r_4 is a random number in $[0,1]$. From the Eq. (17), there are four main parameters in the SCA: r_1, r_2, r_3 and r_4 .

Fig. 1 Properties of Sine and Cosine on the next position region

Sine and Cosine's property on Esq. (15) and (16) are shown in Fig. 1. This act illustrates how the proposed equations describe a space in the search space between two solutions. It should be noted that, although a two-dimensional case is illustrated in Fig. 1, this formula can be applied to higher dimensions.

The solutions should also be able to search outside the space between their corresponding destinations in order to investigate the search space. This can be done by modifying the functions of sine and cosine. Fig. 2 shows a conceptual model of the effects of sine and cosine functionalities with the scope in $[-2, 2]$.

Fig. 2 Sine and cosine with range of $[-2,2]$

The following equation is used to update the value of r_1 in Eqs. (15) to (17),

$$r_1 = a - t \frac{a}{T} \quad (18)$$

Fig. 3 Sine and cosine function with the range in $[-2,2]$ allow a solution to go around the destination

Fig. 4 Flow chart for the SCA Algorithm - ORPD problem

Where t is the current iteration, T is the maximum number of iterations, and a is a constant.

It can be inferred from Fig. (3) the search space is explored by the SCA algorithm when the sine and cosine function ranges are in $(1,2)$ and $[-2, -1)$. All the same, when the ranges are in $[-1,1]$ interval, this algorithm exploits the search space.

Implementation of Sine Cosine Optimization Algorithm for ORPD with FACTS devices

Step 1: Initialization the set of search agents (control variables) (X).

$$X^T = [V_{G1} \dots V_{GNPV}, Q_{C1} \dots Q_{CNC}, T_1 \dots T_{NT}]$$

Step 2: Perform Newton Raphson load flow analysis, and ascertain the solution using Eq. (14) for the initialized set of search agents from step 1.

Step 3: Save the best solutions obtained so far, assigns it as the final tip ($P=X^*$), and update the other solutions with respect to it.

Measure 4: Meanwhile, the sine and cosine function ranges (r_1, r_2, r_3 , and r_4) are updated to emphasize search space development as the iteration counter increases.

Pace 5: Check the termination criteria (SCA algorithm ends the optimization process in this study when the iteration counter is higher than the default upper limit number of iterations). If its satisfied, publish the best solution (objective function and control variables) else Update the status of search agents using Eq. (17) and GOTO step 2.

IV. TEST SYSTEMS

Sine, cosine algorithm is given in this paper to standard IEEE 14, IEEE 57 and IEEE 118 test systems for solving the traditional ORPD problem [35,36]. 25 Test runs were also performed for each of the processes and for comparison the best results of each process were presented. In each case, the maximum number of iterations was taken at 1000. One line diagram of all the test systems was given in Fig. (9), (10) and Fig. (11) with its description is depicted in Table 2. All the necessary details about the test systems were taken from MATPOWER tool box [37].

Fig. 5 Single line diagram - IEEE-14 bus system

Fig. 6 Single line diagram - IEEE-57 bus system

Fig. 7 Single line diagram - IEEE-118 bus system

Table. 2 Summary of test systems – Base case

Description	IEEE 14-bus	IEEE 57-bus	IEEE 118-bus
Buses	14	57	118
Generators	5	7	54
Transformers	3	15	9
Shunts	2	3	14
Branches	20	80	186
Control variables	10	25	77
Base case P_{Load} (MW)	259.00	1250.80	4242
Base case Q_{Load} (MVar)	73.50	336.40	1438
Base case P_{Loss} (MW)	13.49	28.462	132.283

V. RESULTS AND DISCUSSION

Test system 1: Standard IEEE-14 bus system

The standard IEEE 14-bus system consists of 20 transmission lines for 4-7, 4-9 and 5-6 transformer branches, five generators at 1, 2, 3, 6 and 8 and 15 branches under load tap setting. Busses 9 and 14 consider the reactive power sources. Details of the system, variable limits, and initial control variables values were presented in [26,36]. Initially, P_{Load} is 259 MW and Q_{Load} is 73.50 MVar before optimization. The upper and lower limits of the test system's control variable limits are given separately in Table 6-8.

Table. 3 Minimum and Maximum limits of control variables for IEEE 14 bus system

Generator		Transformer		Reactive power	
V_G^{min}	V_G^{max}	T_i^{min}	T_i^{max}	Q_C^{min}	Q_C^{max}
0.95	1.1	0.9	1.1	-0.3	0.3

Fig. 8 Convergence curve of IEEE-14 bus system

The proposed approach is used to minimize active power losses with the objective function of improving the voltage profile. Table 1 shows the optimal values of the control variables obtained from the proposed SCA method. The minimum active power loss obtained from the proposed SCA approach is 12.2715 MW from the 13.49 MW active power loss in the base case. Fig. 3 Represents the SCA convergence characteristic for the objective function proposed. It proves that the SCA finds the better convergence compared with WOA and ALO. Table 6 shows the effects obtained from the proposed SCA technique compared to the other methods in the literature with each algorithm's computational time. It can be seen that both the power loss and the computing time of the SCA are less than the other algorithms mentioned in the literature.

Table. 4 Best control variables settings and active power loss for IEEE 14 bus system

<i>Control variables</i>	<i>ORPD</i>					
<i>Optimization method</i>	<i>SCA (proposed)</i>	<i>WOA (proposed)</i>	<i>ALO (proposed)</i>	<i>HSA[34]</i>	<i>IHSA[34]</i>	<i>MGBTLBO [26]</i>
Generator voltage						
$V_1(pu)$	1.0931	0.9760	1.0515	1.0899	1.0932	1.1000
$V_2(pu)$	1.0116	1.0232	0.9930	1.0659	1.0650	1.0791
$V_3(pu)$	1.1000	1.0235	1.0177	1.0448	1.0461	1.0485
$V_6(pu)$	1.0865	1.1000	1.1000	0.9887	1.0703	1.0552
$V_8(pu)$	1.0580	1.0866	1.0753	1.0092	1.0362	1.0326
Transformer tap ratio						
T_{4-7}	1.0931	1.0589	1.0575	1.0458	1.0159	1.0100
T_{4-9}	1.0972	1.1000	1.0472	0.9544	1.0200	1.0100
T_{5-6}	1.0594	1.0354	0.9763	1.0866	0.9926	1.0300
Capacitor banks						
Q_{c-9} (MVar)	27.3476	25.5553	29.6613	12.7368	16.0675	30.0000
Q_{c-14} (MVar)	29.2124	25.9727	25.3325	10.4165	18.3021	7.0000
P_{Loss} (MW)	12.2715	12.2804	12.4443	12.8060	12.7890	12.3106

Table. 5 Best solutions of all algorithms for IEEE 14 bus system

<i>Algorithms</i>	<i>Best (pu)</i>	<i>Worst (pu)</i>	<i>Mean (pu)</i>	<i>Std. deviation</i>	<i>% P_{save}</i>
DE [10]	0.1324	0.1328	0.1325	1.61×10^{-4}	1.86
PSO [34]	0.1325	0.1340	0.1335	0.64×10^{-3}	1.75
ACOR[34]	0.1312	0.1357	0.1339	7.1854×10^{-2}	2.72
DE/best/2/bin[34]	0.1299	0.1301	0.1309	6.5036×10^{-4}	3.7
ABC[34]	0.1293	0.1312	0.1296	9.422×10^{-4}	4.13
LCA[34]	0.1299	0.1316	0.1305	5.5283×10^{-3}	3.71
CSS[34]	0.1297	0.1330	0.1312	4.206×10^{-2}	3.82
BRCFF[34]	0.1293	0.1298	0.1293	8.8191×10^{-5}	4.18
BB-BC[34]	0.1300	0.1323	0.1311	4.7604×10^{-3}	3.6
PBIL[34]	0.1300	0.1319	0.1309	9.7075×10^{-4}	3.63
TLA[34]	0.1292	0.1295	0.1293	9.0283×10^{-5}	4.2
MTLA [34]	0.1291	0.1292	0.1292	7.6832×10^{-5}	4.3
DDE [34]	0.1293	0.1293	0.1293	5.0065×10^{-5}	4.16
MTLA-DDE[34]	0.1290	0.1290	0.1290	6.486×10^{-6}	4.39
TLBO [26]	0.1299	0.1299	0.1299	9.28×10^{-5}	3.72
BBPSO [26]	0.1299	0.1300	0.1299	9.45×10^{-5}	3.69
BBDE [26]	0.1300	0.1311	0.1300	8.62×10^{-5}	3.64
GBTLBO [26]	0.1242	0.1242	0.1242	0.75×10^{-5}	7.97
MGBTLBO [26]	0.1231	0.1236	0.1232	0.42×10^{-5}	8.74
HAS [34]	0.1281	0.1283	0.1281	5.346×10^{-6}	5.07
IHSA [34]	0.1279	0.1288	0.1281	6.974×10^{-6}	5.20
ALO (proposed)	0.1244	0.1255	0.1261	5.98×10^{-6}	7.78
WOA (proposed)	0.1228	0.1288	0.1289	6.89×10^{-6}	8.96
SCA (proposed)	0.1227	0.1253	0.1228	5.73×10^{-6}	9.03

Test system 2: Standard IEEE-57 bus system

The standard IEEE 57-bus system consists of 80 transmission lines, 7 generators at 1, 2, 3, 6, 8, 9, 12 and branches under the transformer branches of the load tap setting. Busses 18, 25 and 53 are known as reactive power sources. In [12,17,19,23,24] the system line data, bus information, variable limits and initial control variables values were provided. This case system's search space has 25 dimensions including 7 voltages of generators, 15 taps of transformers and 3 reactive sources. The upper and lower

limits of the test system's reactive power generation and control variable limits are given respectively in Table 6-8. The total load of the system is 1250.8 MW and 336.4 MVar. The active power loss of the initial system is 28.462 MW.

Table. 6 Minimum and Maximum limits of control variables for IEEE-57 bus system

Reactive power sources (pu)														
Q_C^{min}								Q_C^{max}						
Bus No	1	2	3	6	8	9	12	1	2	3	6	8	9	12
Values	-1.4	-0.17	-0.1	-0.08	-1.4	-0.03	-1.5	2.0	0.5	0.6	0.25	2.0	0.09	1.55
Generator voltages (pu)								Transformer taps						
V_G^{min}			V_G^{max}					T_i^{min}		T_i^{max}				
0.95			1.1					0.9		1.1				

Table. 7 Best control variables settings and active power loss for IEEE 57 bus system

Control variables	ORPD										
	SCA (proposed)	WOA (proposed)	ALO (proposed)	IHSA [34]	HSA[34]	GSA [19]	BBO [17]	SOA [12]	ICA[23]	IWO [23]	MICA-IWO [23]
V_1 (pu)	1.1000	1.1000	1.1000	1.0954	1.0938	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600
V_2 (pu)	1.1000	1.1000	1.0986	1.0814	1.0780	1.0600	1.0504	1.0580	1.0575	1.0591	1.0584
V_3 (pu)	1.0768	1.1000	1.0865	1.0688	1.0628	1.0600	1.0440	1.0437	1.0423	1.0472	1.0457
V_6 (pu)	1.0558	1.1000	1.0789	1.0743	1.0724	1.0081	1.0376	1.0352	1.0350	1.0382	1.0397
V_8 (pu)	1.0566	1.1000	1.1000	1.0951	1.0980	1.0550	1.0550	1.0548	1.0509	1.0593	1.0600
V_9 (pu)	1.0795	1.1000	1.0865	1.0704	1.0699	1.0098	1.0229	1.0369	1.0192	1.0273	1.0274
V_{12} (pu)	1.1000	1.1000	1.0826	1.0699	1.0649	1.0186	1.0323	1.0336	1.0287	1.0374	1.0350
T_{4-18}	0.9037	0.9000	1.0983	1.0699	1.0737	1.1000	0.9669	1.0000	0.9000	1.0500	1.0100
T_{4-18}	1.0765	1.1000	1.0996	1.0564	1.0509	1.0826	0.9902	0.9600	1.0100	1.0000	0.9500
T_{21-20}	1.0284	1.1000	1.0822	1.0440	1.0487	0.9220	1.0120	1.0100	1.0000	1.0700	1.0200
T_{24-26}	0.9033	0.9000	1.0274	1.0642	1.0683	1.0167	1.0087	1.0100	1.0100	1.0200	1.0100
T_{7-29}	0.9998	0.9000	1.0593	1.0225	1.0190	0.9963	0.9707	0.9700	0.9700	0.9700	0.9600
T_{34-32}	0.9000	1.1000	1.0299	1.0596	1.0605	1.1000	0.9687	0.9700	0.9800	0.9900	0.9800
T_{11-41}	0.9637	0.9658	1.0757	0.9695	0.9649	1.0746	0.9008	0.9000	0.9000	0.9000	0.9000
T_{15-45}	1.0515	0.9868	0.9911	0.9630	0.9573	0.9543	0.9660	0.9700	0.9600	0.9600	0.9500
T_{14-46}	1.0075	0.9075	1.0160	0.9399	0.9447	0.9377	0.9508	0.9500	0.9400	0.9500	0.9400
T_{10-51}	1.0257	0.9868	1.0395	0.9768	0.9783	1.0168	0.9641	0.9600	0.9500	0.9800	0.9500
T_{13-49}	1.0141	0.9000	0.9920	0.9401	0.9464	1.0526	0.9246	0.9200	0.9200	0.9300	0.9100
T_{11-43}	1.0432	0.9435	1.0431	1.0986	1.0896	1.1000	0.9502	0.9600	0.9500	0.9900	0.9500
T_{40-56}	0.9143	1.0554	0.9963	0.9517	0.9524	0.9800	0.9967	1.0000	1.0000	1.0100	1.0000
T_{39-57}	0.9753	1.0320	1.0450	1.0570	1.0557	1.0247	0.9629	0.9600	0.9600	1.0400	0.9700
T_{9-55}	0.9699	0.9410	1.0491	1.0001	1.0024	1.0373	0.9600	0.9700	0.9600	0.9600	0.9600
Q_{C-18} (MVar)	23.4334	26.5356	23.5968	13.3960	15.5030	7.8254	9.7820	9.9840	4.1000	4.4200	10.0000
Q_{C-25} (MVar)	13.2658	16.4014	18.6583	8.5066	6.8815	0.5869	5.8991	5.9040	5.9000	4.3300	5.9000
Q_{C-53} (MVar)	28.1163	15.4301	17.4103	18.9510	20.2430	4.6872	62.8900	6.2880	6.3000	6.1500	6.3000
P_{Loss} (MW)	21.8935	23.1152	23.7039	23.4480	23.7100	23.4611	24.5440	24.2655	24.4799	24.5939	24.2568

Fig. 9 Convergence characteristics of IEEE-57 bus system

Table. 8 Best solutions of all algorithms for IEEE 57 bus system

<i>Algorithms</i>	<i>Best (pu)</i>	<i>Worst (pu)</i>	<i>Mean (pu)</i>	<i>Std.Deviation</i>	<i>% P_{Save}</i>
NLP [16]	0.25902	0.30854	0.27858	1.167×10^{-2}	8.9934
CGA [16]	0.25244	0.27508	0.26294	6.295×10^{-3}	11.3059
AGA [16]	0.24565	0.26762	0.25128	6.006×10^{-3}	13.6925
PSO-w [16]	0.24271	0.26153	0.24726	7.014×10^{-3}	14.7266
PSO-cf [16]	0.24280	0.26033	0.24698	6.629×10^{-3}	14.6925
CLPSO [16]	0.24515	0.24781	0.24673	9.341×10^{-4}	13.8669
SPSO-07[16]	0.24430	0.25457	0.24752	2.833×10^{-3}	14.6925
L-DE [16]	0.27813	0.41909	0.33178	4.707×10^{-2}	13.8669
L-SACP-DE [16]	0.27916	0.36979	0.31033	3.223×10^{-2}	14.1647
L-SaDE [16]	0.24267	0.24391	0.24311	4.815×10^{-4}	14.2815
SOA [16]	0.24265	0.24280	0.24271	4.208×10^{-5}	14.7443
HSA [17]	0.24906	0.26965	0.25924	-	-
HAS [34]	0.23710	0.24272	0.23898	4.469×10^{-5}	16.6959
IHSA [34]	0.23448	0.24011	0.23755	4.177×10^{-5}	17.6165
ALO (proposed)	0.23704	0.24542	0.23753	4.077×10^{-5}	17.7170
WOA (proposed)	0.23115	0.24315	0.23557	3.489×10^{-5}	18.7864
SCA (proposed)	0.21894	0.22397	0.21673	3.178×10^{-5}	23.0740

Table 8 shows the outcome of the solution to minimize the objective when tabulating the best reactive power dispatch solutions for this objective. Table 8 compares the SCA-based findings with other recently reported optimization techniques in the literature like NLP [16]; CGA [16]; AGA [16]; PSO-w [16]; PSO-cf [16]; CLPSO [16]; SPSO-07[16]; L-DE [16]; L-SACP-DE [16]; L-SaDE [16]; SOA [16]; HSA [17]; HSA [34] and IHSA [34]. Also, SCA results are compared with ALO and WOA.

From Table 4, results based on SCA can be observed yielding optimum P_{Loss} value for this power network. In [19], the base case power loss is reported as 28.462 MW for this test power network. The percentage save of power loss shows that a power loss reduction of 23.07% (28.462 MW to 21.894 MW) is achieved by using the proposed SCA method, which is the highest power loss reduction than that obtained by the other literature approaches. Comparative

Convergence profiles based on ALO, WOA and SCA for this test power system are shown in Fig. 9. It can be observed from this figure that the convergence profile for this test system is capable of the proposed SCA-based approach.

Test system 3: Standard IEEE-118 bus system

A standard IEEE 118-bus test system is considered to analyze the proposed technique for solving large and complex power systems. This case system's control variables have 77 proportions, i.e. the 54 generator buses, 64 load buses, 186 transmission lines, 9 transformer taps, and 14 reactive power sources. Details of the system some are given in [19,23,25, 29]. Tables 10 and 11, respectively [25], show the lower and upper limits of reactive power sources, voltage, and tap-setting limits. The system loads are specified as follows $P_{load} = 4242$ MW., $Q_{load} = 1438$ MVar. The total power losses are as $P_{loss} = 132.283$ MW.

Table. 9 Minimum and Maximum limits of control variables for IEEE-118 bus system

Reactive power sources (MVar)														
Q_C^{min}								Q_C^{max}						
Bus No	5	34	37	44	45	46	48	5	34	37	44	45	46	48
Values	-40	0	-25	0	0	0	0	0	14	0	10	10	10	15
Bus No	74	79	82	83	105	107	110	74	79	82	83	105	107	110
Values	0	0	0	0	0	0	0	12	20	20	10	20	6	6
Generator voltages(pu)								Transformer tap						
V_G^{min}				V_G^{max}				T_i^{min}		T_i^{max}				
0.95				1.1				0.9		1.1

Fig. 10 Convergence characteristics of IEEE-118 bus system

Table. 10 Best control variables settings and active power loss for IEEE-118 bus system

Control variables	SCA (proposed)	WOA (proposed)	ALO (proposed)	ICA [23]	IWO [23]	MICA-IWO [23]	GSA [19]	PSO[19]	CLPSO[19]
V ₁ (pu)	1.0846	1.1000	1.1000	1.0080	0.9978	1.0419	0.9600	1.0853	1.0332
V ₄ (pu)	1.0996	1.0969	1.1000	1.0296	1.0378	1.0600	0.9620	1.0420	1.0550
V ₆ (pu)	1.0992	1.0769	1.1000	1.0149	1.0189	1.0542	0.9729	1.0805	0.9754
V ₈ (pu)	1.1000	1.1000	1.1000	1.0381	0.9922	1.0582	1.0570	0.9683	0.9669
V ₁₀ (pu)	1.1000	1.0960	1.1000	1.0600	1.0245	1.0600	1.0885	1.0756	0.9811
V ₁₂ (pu)	1.0937	1.0999	1.1000	1.0131	1.0087	1.0511	0.9630	1.0225	1.0092
V ₁₅ (pu)	1.0872	1.0784	1.1000	1.0006	0.9804	1.0498	1.0127	1.0786	0.9787
V ₁₈ (pu)	1.0865	1.0772	1.1000	0.9987	0.9883	1.0525	1.0069	1.0498	1.0799
V ₁₉ (pu)	1.0986	1.0715	1.1000	1.0036	0.9862	1.0490	1.0003	1.0776	1.0805
V ₂₄ (pu)	1.0993	1.0838	1.1000	1.0388	0.9673	1.0528	1.0105	1.0827	1.0286
V ₂₅ (pu)	1.0965	1.0906	1.1000	1.0600	1.0515	1.0600	1.0102	0.9564	1.0307
V ₂₆ (pu)	1.0949	1.0937	1.1000	1.0600	0.9948	1.0600	1.0401	1.0809	0.9877
V ₂₇ (pu)	1.0938	1.0798	1.1000	1.0093	0.9829	1.0466	0.9809	1.0874	1.0157
V ₃₁ (pu)	1.0984	0.9849	1.1000	0.9958	0.9461	1.0430	0.9500	0.9608	0.9615
V ₃₂ (pu)	1.0968	0.9638	1.1000	1.0016	0.9532	1.0453	0.9552	1.1000	0.9851
V ₃₄ (pu)	1.0909	0.9501	1.1000	1.0267	1.0099	1.0600	0.9910	0.9611	1.0157
V ₃₆ (pu)	1.0979	0.9681	1.1000	1.0257	1.0019	1.0584	1.0091	1.0367	1.0849
V ₄₀ (pu)	1.0869	0.9721	1.1000	1.0181	0.9886	1.0384	0.9505	1.0914	0.9830
V ₄₂ (pu)	1.1000	1.0610	1.1000	1.0285	0.9559	1.0398	0.9500	0.9701	1.0516
V ₄₆ (pu)	1.0939	0.9890	1.1000	1.0409	1.0205	1.0470	0.9814	1.0390	0.9754
V ₄₉ (pu)	1.0958	1.0083	1.1000	1.0535	1.0528	1.0600	1.0444	1.0836	0.9838
V ₅₄ (pu)	1.0921	0.9935	1.1000	1.0291	1.0146	1.0388	1.0379	0.9764	0.9637
V ₅₅ (pu)	1.0999	0.9825	1.1000	1.0285	1.0149	1.0380	0.9907	1.0103	0.9716
V ₅₆ (pu)	1.0959	1.0218	1.1000	1.0286	1.0162	1.0382	1.0333	0.9536	1.0250
V ₅₉ (pu)	1.0893	1.0441	1.1000	1.0478	1.0046	1.0600	1.0099	0.9672	1.0003
V ₆₁ (pu)	1.1000	1.0487	1.1000	1.0406	1.0468	1.0600	1.0925	1.0938	1.0771
V ₆₂ (pu)	1.1000	1.0964	1.1000	1.0346	1.0547	1.0559	1.0393	1.0978	1.0480
V ₆₅ (pu)	1.1000	1.0977	1.1000	1.0600	1.0547	1.0600	0.9998	1.0892	0.9684
V ₆₆ (pu)	1.0969	1.0624	1.1000	1.0600	1.0572	1.0600	1.0355	1.0861	0.9648
V ₆₉ (pu)	1.0972	1.0798	1.1000	1.0600	1.0599	1.0600	1.1000	0.9665	0.9574
V ₇₀ (pu)	1.0909	1.1000	1.1000	1.0371	1.0297	1.0377	1.0992	1.0783	0.9765
V ₇₂ (pu)	1.0934	1.0209	1.1000	1.0390	0.9832	1.0430	1.0014	0.9506	1.0243
V ₇₃ (pu)	1.0932	1.0082	1.1000	1.0411	1.0030	1.0374	1.0111	0.9722	0.9651
V ₇₄ (pu)	1.0919	1.0350	1.1000	1.0235	1.0239	1.0275	1.0476	0.9713	1.0733
V ₇₆ (pu)	1.0986	1.0520	1.1000	1.0107	0.9474	1.0253	1.0211	0.9602	1.0302
V ₇₇ (pu)	1.0972	1.0748	1.1000	1.0297	1.0311	1.0473	1.0187	1.0781	1.0275
V ₈₀ (pu)	1.0902	1.1000	1.1000	1.0389	1.0510	1.0600	1.0462	1.0788	0.9857
V ₈₅ (pu)	1.1000	1.0934	1.1000	1.0514	1.0070	1.0600	1.0491	0.9568	0.9836
V ₈₇ (pu)	1.0952	1.0565	1.1000	1.0417	0.9421	1.0600	1.0426	0.9642	1.0882
V ₈₉ (pu)	1.0973	1.0465	1.1000	1.0600	1.0562	1.0600	1.0955	0.9748	0.9895
V ₉₀ (pu)	1.0996	1.0879	1.1000	1.0340	1.0389	1.0445	1.0417	1.0248	0.9905
V ₉₁ (pu)	1.0926	1.0758	1.1000	1.0374	1.0198	1.0496	1.0032	0.9615	1.0288

Reactive Power Control using Sine Cosine Algorithm for Active Power Loss Minimization with Voltage Profile Enhancement

V ₉₂ (pu)	1.0992	1.0468	1.1000	1.0470	1.0167	1.0600	1.0927	0.9568	0.9760
V ₉₉ (pu)	1.0993	1.0245	1.1000	1.0309	1.0588	1.0560	1.0433	0.9540	1.0880
V ₁₀₀ (pu)	1.0937	1.0029	1.1000	1.0257	1.0332	1.0600	1.0786	0.9584	0.9617
V ₁₀₃ (pu)	1.0913	1.0110	1.1000	1.0113	1.0141	1.0600	1.0266	1.0162	0.9611
V ₁₀₄ (pu)	1.0903	1.0215	1.1000	0.9949	1.0063	1.0518	0.9808	1.0992	1.0125
V ₁₀₅ (pu)	1.0973	0.9778	1.1000	0.9923	0.9945	1.0517	1.0163	0.9694	1.0684
V ₁₀₇ (pu)	1.0992	0.9643	1.1000	0.9800	0.9487	1.0389	0.9987	0.9656	0.9769
V ₁₁₀ (pu)	1.0881	0.9650	1.1000	0.9984	1.0441	1.0508	1.0218	1.0873	1.0414
V ₁₁₁ (pu)	1.0987	1.0598	1.1000	1.0080	0.9743	1.0600	0.9852	1.0375	0.9790
V ₁₁₂ (pu)	1.1000	1.0311	1.1000	0.9823	0.9863	1.0358	0.9500	1.0920	0.9764
V ₁₁₃ (pu)	1.1000	1.1000	1.1000	0.9786	0.9771	1.0600	0.9764	1.0753	0.9721
V ₁₁₆ (pu)	1.0862	1.0762	1.1000	1.0473	1.0566	1.0600	1.0372	0.9594	1.0330
T ₅₋₈	1.0516	1.0508	0.9855	0.9900	1.0400	1.0000	1.0659	1.0112	1.0045
T ₂₅₋₂₆	1.0894	0.9000	0.9869	1.1000	0.9900	1.1000	0.9534	1.0906	1.0609
T ₁₇₋₃₀	1.0306	1.0592	0.9869	1.0300	1.0800	0.9900	0.9328	1.0033	1.0008
T ₃₇₋₃₈	1.0938	1.0929	0.9825	1.0100	1.0400	0.9800	1.0884	1.0000	1.0093
T ₅₉₋₆₃	1.0614	1.1000	0.9821	0.9800	0.9500	0.9800	1.0579	1.0080	0.9922
T ₆₁₋₆₄	1.0970	1.0446	0.9869	1.0100	1.0200	1.0000	0.9493	1.0326	1.0074
T ₆₅₋₆₆	1.0919	0.9000	0.9840	0.9400	0.9500	0.9000	0.9975	0.9443	1.0611
T ₆₈₋₆₉	1.0940	1.0905	0.9869	0.9800	0.9300	0.9500	0.9887	0.9067	0.9307
T ₈₀₋₈₁	1.0887	0.9000	0.9869	0.9900	1.0300	0.9900	0.9801	0.9673	0.9578
Q _{c5} (MVar)	-10.8225	-14.4695	-9.8636	-0.0732	-0.2064	-0.4	0.0000	0.0000	0.0000
Q _{c34} (MVar)	12.3162	2.4322	13.3826	0.0477	0.1382	0.1400	7.4600	9.3639	11.7135
Q _{c37} (MVar)	-12.9499	-23.6278	0.0000	-0.1268	-0.0117	0.0000	0.0000	0.0000	0.0000
Q _{c44} (MVar)	7.1527	0.0000	8.9827	0.0000	0.0081	0.0429	6.0700	9.3078	9.8932
Q _{c45} (MVar)	6.1718	5.3532	9.7600	0.0505	0.0053	0.0073	3.3300	8.6428	9.4169
Q _{c46} (MVar)	6.9794	8.2046	4.3833	0.0669	0.0199	0.0697	6.5100	8.9462	2.6719
Q _{c48} (MVar)	9.5686	15.0000	14.3206	0.0321	0.1461	0.0368	4.4700	11.8092	2.8546
Q _{c74} (MVar)	8.9064	9.0147	11.4601	0.0000	0.0081	0.0000	9.7200	4.6132	0.5471
Q _{c79} (MVar)	16.6085	15.1698	19.1021	0.0000	0.1537	0.0000	14.2500	10.5923	14.8532
Q _{c82} (MVar)	5.5913	4.9987	18.7492	0.0000	0.0037	0.0000	17.4900	16.4544	19.4270
Q _{c83} (MVar)	7.2092	2.6740	8.9635	0.0260	0.0367	0.0000	4.2800	9.6325	6.9824
Q _{c105} (MVar)	9.2179	17.6632	19.1208	0.1995	0.0265	0.0001	12.0400	8.9513	9.0291
Q _{c107} (MVar)	1.3906	3.0503	0.1786	0.0235	0.0587	0.0016	2.2600	5.0426	4.9926
Q _{c110} (MVar)	3.3235	5.0448	5.7373	0.0483	0.0486	0.0002	2.9400	5.5319	2.2086
P _{Loss} (MW)	107.8154	110.8362	130.6457	118.32	137.30	114.05	127.760	131.990	130.960

Table. 11 Best solutions of all algorithms for IEEE 118 bus system

Algorithms	Best (pu)	Worst (pu)	Mean (pu)	Std. Dev	% Psave
ICA [23]	1.18322	1.21527	1.18970	6.4261 x 10 ⁻³	11.27
IWO [23]	1.37295	1.56288	1.45752	9.4227 x 10 ⁻²	-2.95
MICA-IWO [23]	1.14046	1.14976	1.14448	2.4288 x 10 ⁻⁴	14.48
RGA [23]	1.22140	1.26696	1.24089	1.791 x 10 ⁻²	-
CMAES [23]	1.19275	1.21860	1.20854	8.62 x 10 ⁻³	-
MOPSO [23]	1.19581	-	-	-	-
NSGA-II [23]	1.19580	-	-	-	-
MNSGA-II [23]	1.19279	-	-	-	-
DMSDE [23]	1.15370	-	1.16840	8.787 x 10 ⁻³	13.4879
PSO-cf [23]	1.15821	-	1.18827	1.7248 x 10 ⁻²	13.1496
PSO-w [23]	1.15833	-	1.20575	2.3574 x 10 ⁻²	13.1408
AGA [23]	1.23964	-	1.27827	2.0613 x 10 ⁻²	17.0438
MVMO [23]	1.15793	1.19358	1.16820	7.682 x 10 ⁻³	-
PSO [23]	1.20897	1.35372	1.25487	3.1634 x 10 ⁻²	-
DE [23]	1.25025	1.30229	1.27442	1.1337 x 10 ⁻²	-
JADE [23]	1.19161	1.32035	1.22677	3.0467 x 10 ⁻²	-
JADE-vPS [23]	1.19201	1.33344	1.25575	3.8943 x 10 ⁻²	-
CGA [23]	1.39415	1.49009	1.43548	2.6026 x 10 ⁻²	-
AGA [23]	1.24209	1.31078	1.27701	1.836 x 10 ⁻²	-
PSO-w [23]	1.15815	1.18214	1.16771	6.8971 x 10 ⁻³	-

PSO-cf [23]	1.15642	1.18058	1.16202	6.1864×10^{-3}	-
CLPSO [23]	1.23152	1.25499	1.24080	6.4325×10^{-3}	-
SPSO-07 [23]	1.39275	1.50244	1.46266	2.653×10^{-2}	-
L-DE [23]	1.51009	1.76614	1.62315	8.2443×10^{-2}	-
L-SACP-DE [23]	1.41799	1.76812	1.60679	1.0643×10^{-1}	-
L-SaDE [23]	1.16906	1.18862	1.17598	5.4041×10^{-3}	-
SOA [12]	1.14950	1.16347	1.15674	3.5908×10^{-3}	-
ALO (proposed)	1.30457	1.32023	1.31430	4.4041×10^{-3}	13.803
WOA (proposed)	1.10836	1.11017	1.10573	5.3434×10^{-3}	16.210
SCA (proposed)	1.07815	1.08476	1.07564	2.7675×10^{-3}	18.496

SCA based reactive power dispatch schedule for the trial system of power loss minimization objective is presented in Table 10 and the results obtained are compared to ICA [23]; IWO [23]; MICA-IWO [23]; GSA [19]; PSO [19]; CLPSO [19], ALO and WOA. This table shows that compared to other algorithms, the SCA yields optimal loss. Table 11 records the statistical comparison of effects obtained from SCA with existing results presented in the literature. From this table, it was noted that the standard deviation and median values are rather acceptable to SCA. From this Fig. 10, the respectable convergence profile of the SCA can be noted by its ability to reach the nearly optimal solution.

VI. CONCLUSION

The optimal problem of reactive power dispatch is cast as a nonlinear problem of optimization with the power system's inequality and equality limitations. Several methods of optimization have solved it, and on this ground the analysis and comparison has been carried out. The implementation of algorithms was carried out on the IEEE 14/57-bus and large 118-bus systems to obtain reactive power optimization. SCA has been one of different methods of optimization that has more beneficial effects. A comparison was performed on the results obtained from ALO, WOA and various literatures. The proposed SCA is thus capable of solving the problem of reactive power dispatch quickly and effectively and can be considered a promising expectation for future research.

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