Optimal Reactive Power Dispatch Considering SSSC Using Grey Wolf Algorithm

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Abstract— **Static Synchronous Series Compensator (SSSC) is an efficient member of Flexible AC Transmission Systems (FACTS) devices. SSSC is connected in series with transmission lines to control the active and reactive power flow in these lines. In this paper, Grey Wolf Optimization (GWO) algorithm is developed for solving the optimal reactive power dispatch (ORPD) problem. The ORPD problem is solved with incorporating SSSC for improving the voltage profile and enhancing voltage stability of the electric system. The optimal location and parameter setting of SSSC controller is determined under a contingency state. The developed algorithm is validated using standard IEEE 30-bus test system and the obtained results are compared with the particle swarm optimization (PSO) algorithm. The simulation results demonstrate the effectiveness of the developed algorithm for solving the ORPD problem with determining the optimal location and parameter setting of SSSC. In addition superiority results are obtained with incorporating SSSC in the power systems.**

Keywords—opimal reactive power flow; optimization; Static Synchronous Series Compensator; FACTS.

I. INTRODUCTION

The optimal reactive power dispatch (ORPD) problem is a non-linear optimization problem. Solving of the ORPD problem became a strenuous task to adjust the power system at its secure and economical regions. The main purpose of ORPD solution is determining the best secure operating settings of the electric systems such as generator voltages, transformer taps and the shunt compensation units with satisfying operating constraints in of the electric system. The control variables are optimized for a certain objective function such as voltage profile improvement, voltage stability enhancement and power losses minimization.

The optimal reactive power dispatch problems has been solved by using many conventional methods such as; Linear programming (LP) [1], non-linear programming(NLP) [2], Quadratic programming (QP) [3] and the interior point (IP) [4]. The main shortage of the conventional methods are difficult to be applicable with nonlinear or non-convex objective functions moreover, these methods can trapped on local minima of the objective functions.

Recently, many new meta-heuristic optimization techniques have been applied to solve the optimization problem. These techniques have been developed to overcome the main drawbacks in conventional methods and these methods are successfully applied to solve the ORPD problem such as particle swarm optimization (PSO) [5], genetic algorithm (GA) [6], ant colony algorithm (ACO) [7] and gravitational search algorithm (GSA) [8], etc.

Flexible Alternating Current Transmission Systems (FACTS) devices have been widely used in electrical power systems to control different variables such as; bus voltage magnitude, active power, reactive power, and transmission line impedance. Hence, FACTS devices can be applied for enchanting power system operation, security and stability [9-10]. However, the main purpose of ORPD problem is determining the control variables for the voltage profile improvement, voltage stability enhancement and power losses minimization but it should point out here that the solving of OPRD with including the SSSC compensator in power system can significantly enhanced these values. Static Synchronous Series Compensator (SSSC) is an elegant that can be connected in series with transmission lines to control on the active power and reactive power flow through transmission lines separately or simultaneously. SSSC provide the required controllability by injecting an AC voltage with controllable magnitude and phase angle in series with transmission line [11-13].

Grey wolf optimizer (GWO) algorithm is an efficient optimization technique proposed by S. Mirjalili. GWO has been applied successfully for solving many optimization problems [14-17]. GWO simulates the social hierarchy and hunting behavior of grey wolves where the wolves in the pack follow the leader wolves in hunting process.

In this paper the GWO algorithm is applied to solve ORPD problem for improving the voltage profile and enhancing the stability index of the system in presence of SSSC controller. The ORPD is solved with and without embedding SSSC. The optimal location and parameter setting of SSSC is determined successfully for the required objective functions.

II. MODELING OF SSSC CONTROLLER

SSSC converter is series connected controller where, it can inject controllable AC voltage in series with line to control on the active and reactive powers flow through transmission line. SSSC consists of inverter, diodes, DC capacitor link and coupling transformer. Referring to Fig. 1 SSSC is connected between two buses (*i,j*) where *i* represents the send bus and *j* represents the receiving end bus.

SSSC is represented by voltage sources (V_{se}) connected in series with the coupling transformer impedance (Z_{se}) as shown in Fig. 2. An axiulary bus *k* is added which represents terminal of the SSSC controller.

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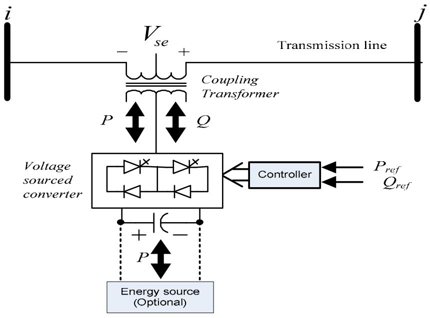


Fig. 1.SSSC schematic diagram

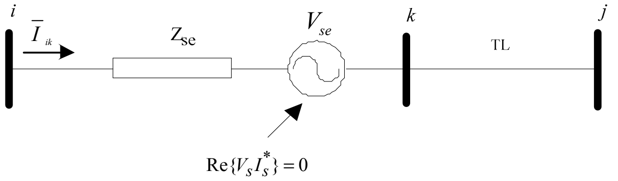


Fig. 2. SSSC equivalent circuit based on voltage source representation

The voltage source of SSSC in Fig. 2 can be converted to current sources in parallel with its impedance. The current source can be converted into two parallel injected sources at SSSC terminals as shown in Fig. 3.

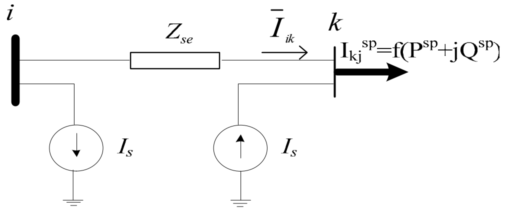


Fig. 3. Representation of SSSC with the shunt Injected currents.

The shunt injected current can be calculated as function of the required specified values (P^{sp},Q^{sp}) by applying Kirchhoff current law's at bus k

$$I_S = I_{kj} - I_{ik} = \left(\frac{S^{sp}}{V_k}\right)^* - \left(\frac{V_i - V_k}{Z_{se}}\right) \tag{1}$$

where,

$S^{sp} = P^{sp} + jQ^{sp}$

The injected current can be represented as injected loads according to (2) and (3) as shown in Fig. 4.

$$S_i = V_i(I_s)^* \tag{2}$$

$$S_k = -V_k(I_s)^* \tag{3}$$

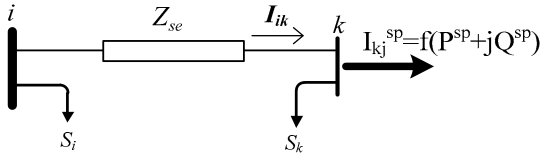


Fig. 4. SSSC Model based on injected loads

III. PROBLEM FORMULATION

ORPD is an optimization problem which can be formulated as follows:

$$Min\ F(x, u) \tag{4}$$

Subjected to

$$g_j(x, u) = 0 \quad j = 1,2, \dots, m \tag{5}$$

$$h_j(x, u) \leq 0 \quad j = 1,2, \dots, p \tag{6}$$

where F is the required objective function, x is a vector represents the dependent variables (state variables), u is a vector represents the independent (the control) variables, g_j and h_j represent equality and inequality constraints, respectively. m and p are number of equality and inequality constraints, respectively.

3.1 Objective functions

3.1.1 Voltage profile improvement

Improving the voltage profile can be achieved by minimizing the voltage deviations of load bus from a certain voltage hence, the objective function can be formulated as follows:

$$F_1 = \sum_{i=1}^{NPQ} \left|(V_i - V_{ref})\right| \tag{7}$$

where, NPQ is number of the load buses. V_{ref} is the reference voltage for the load buses which equals to 1 p.u for all studied cases.

3.1.2 Voltage stability enhancement

Voltage stability index L is an important value proposed by Kessel and Glavitsch to indicate system stability [17]. This value is calculated for all load buses, which vary between 0 (no load case) to 1 maximum loading point (voltage collapse case) hence, the minimizing of this value keeps the system far away from voltage collapse of power system. However, this objective function can be formulated as follows:

$$F_3 = \min(L_{max}) = min(max(L_j)) \tag{8}$$

where, L_j is the voltage stability index of bus *jth* and it can be calculated as follows:

$$L_j = \left|1 - \sum_{i=1}^{NPV} F_{ij} \frac{V_i}{V_j}\right| \tag{9}$$

where,V_i is the voltage of i^{th} generator bus and V_j is the voltage of load bus.F_{ij}can be obtained from system Y_{bus} matrix as follows:

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{10}$$

where I_G, $I_L$are the complex currents and V_G, $V_L$arethecomplex voltages vectors at the generator and load buses. Y_{GG},Y_{LL}, Y_{GL},Y_{LG} are sub-matrices of system $Y_{bus}$by making some manipulation in(14)

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{11}$$

where,$F_{ij} = [F_{LG}] = -[Y_{LL}]^{-1}[Y_{LG}]$.

3.2 System constraints

3.2.1 Equality constraints

The equality constrains represent the balanced load flow equations as follows:

$$P_{Gi} - P_{Di} = |V_i| \sum_{j=1}^{NB} |V_j| \left(G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}\right) \qquad (12)$$

$$Q_{Gi} - Q_{Di} = |V_i| \sum_{j=1}^{NB} |V_j| \left(G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij}\right) \qquad (13)$$

where, P_{Gi} and Q_{Gi} are the generated active and reactive power at bus i, respectively. P_{Di} and Q_{Di} are the active and reactive load demand at bus *i*, respectively. G_{ij} and B_{ij} are the conductance and susceptance between bus i and bus *j*, respectively.

3.2.2 Inequality constrains

The inequality constrains can be classified as follows:

1) Generators active power output
   $$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \quad i = 1,2,\ldots,NPV \qquad (14)$$
2) Generators bus voltages
   $$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max} \quad i = 1,2,\ldots,NPV \qquad (15)$$
3) Generators reactive power output
   $$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \quad i = 1,2,\ldots,NPV \qquad (16)$$
4) Transformer tap settings
   $$T_i^{min} \le T_i \le T_i^{max} \quad i = 1,2,\ldots,NT \qquad (17)$$
5) Shunt VAR compensator
   $$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max} \quad i = 1,2,\ldots,NC \qquad (18)$$
6) Apparent power flow in transmission lines
   $$S_{Li} \le S_{Li}^{min} \quad i = 1,2,\ldots,NTL \qquad (19)$$
7) Voltage magnitude of load buses
   $$V_{Li}^{min} \le V_{Li} \le V_{Li}^{max} \quad i = 1,2,\ldots,NPQ \qquad (20)$$
8) SSSC controller constraints
   $$V_{se}^{max} \le V_{se} \le V_{se}^{min} \qquad (21)$$
   $$\theta_{se}^{max} \le \theta_{se} \le \theta_{se}^{min} \qquad (22)$$

where P_G is output active power of generator,V_G is voltage of generation bus,Q_C is the injected reactive power of shunt compensator, T is tap setting of transformer,NG is number of generators,V_L is voltage of load bus,Q_G is the generator reactive power output, S_{TL} is the apparent power flow in transmission line, NPQ is number of load buses,NPV is number of generation buses and NTL is number of transmission lines.

the operating constrains of these values must be considered in the objective function. These variables can be easily limited in optimization solution by using the quadratic penalty formulation of objective function for all dependent variables; therefore the generalized objective function can be expressed as follows:

$$F_g(x,u) = F_i(x,u) + R_G\left(P_{G1} - P_{G1}^{lim}\right)^2 + R_Q \sum_{i=1}^{NPV}\left(Q_{Gi} - Q_{Gi}^{lim}\right)^2 + R_V \sum_{i=1}^{NPQ}\left(V_{Li} - V_{Li}^{lim}\right)^2 + R_S \sum_{i=1}^{NTL}\left(S_{Li} - S_{Li}^{lim}\right)^2 + R_F(V_{se} - V_{se}^{lim})^2 + R_t(\theta_{se} - \theta_{se}^{lim})^2 \qquad (23)$$

where R_G,R_V,R_Q, R_S, R_F and R_t are the penalty factors, these values are high positive .x^{lim}acts the limit value of dependent

$$x^{lim} = \begin{cases} x^{max}; & x > x^{max} \\ x^{min}; & x < x^{min} \end{cases} \qquad (24)$$

Three control variables related to SSSC (P^{sp},Q^{sp}, and location of SSSC) are included in the GWO optimization technique, moreover two variables (V_{se},θ_{se}) are considered as dependent variables.

IV. GREY WOLF OPTIMIZER

Grey Wolf Optimizer (GWO) algorithm is Swarm Intelligence (SI) algorithms conceptualized from the social behavior and hunting process of the grey wolves. The grey wolves living together in groups called pack and the hierarchy leadership in the pack is divided as alpha, beta, delta and omega. Alpha wolf (α) is the first level in social hierarchy where it is considered the top leader and the other wolves in the pack follow his instructions. Beta wolf (β) is being in the second level of leadership where, the beta wolf assists the alphas for the activities of the pack. The third member in social hierarchy is the delta (δ) wolves which follow α and β wolves. The rest of wolves are the omegas (ω).The GWO algorithm based on depend upon three steps which are: (1) Searching, following and approaching the prey (2) Surrounding and harassing the prey (3) Attacking the prey.

Surrounding the prey by grey wolf can be mathematically modeled as follows:

$$D = \left|C.X_p(t) - X(t)\right| \qquad (25)$$

$$X(t+1) = X_p(t) - A.D \qquad (26)$$

where, t is the current iteration X_p is the position vector of the prey, and X indicates the position vector of a grey wolf. A and C are coefficient vector which can be calculated as follows:

$$A = 2a.r_1 - a \qquad (27)$$

$$C = 2.r_2 \qquad (28)$$

where a is a value decreased linearly from 2 to 0 with iterations. r_1 and r_2 are random numbers in range [0, 1]. In hunting process, the grey wolves can determine the location of prey. In the hunting process the pack is affected by α, β and δ hence, the first three best solutions are saved as best agents (α, β and δ) and the other search agents are updated their positions according to the best agents as follows**:**

$$D = \left|C.X_p(t) - X(t)\right| \qquad (29)$$

$$D_\alpha = |C_1.X_\alpha - X| \qquad (30)$$

$$D_\beta = |C_2.X_\beta - X| \qquad (31)$$

$$D_\delta = |C_3.X_\delta - X| \qquad (32)$$

$$X_1 = X_\alpha - A_1.(D_\alpha) \qquad (33)$$

$$X_2 = X_\beta - A_2.(D_\beta) \qquad (34)$$

$$X_3 = X_\delta - A_3.(D_\delta) \qquad (35)$$

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3} \qquad (36)$$

The gery wolves are fininshing the hunting by attacking the prey where the grey wolf attack when the prey stop moving. It can be achieve mathematically by reducing the value of a gradually from 2 to 0 consequently, A is varied randomly with variation of a and it will be in rang [-1, 1], hence the next location of search agents will be between its current position and the position of the prey. The grey wolf procedures are illustrated in Fig. 5.

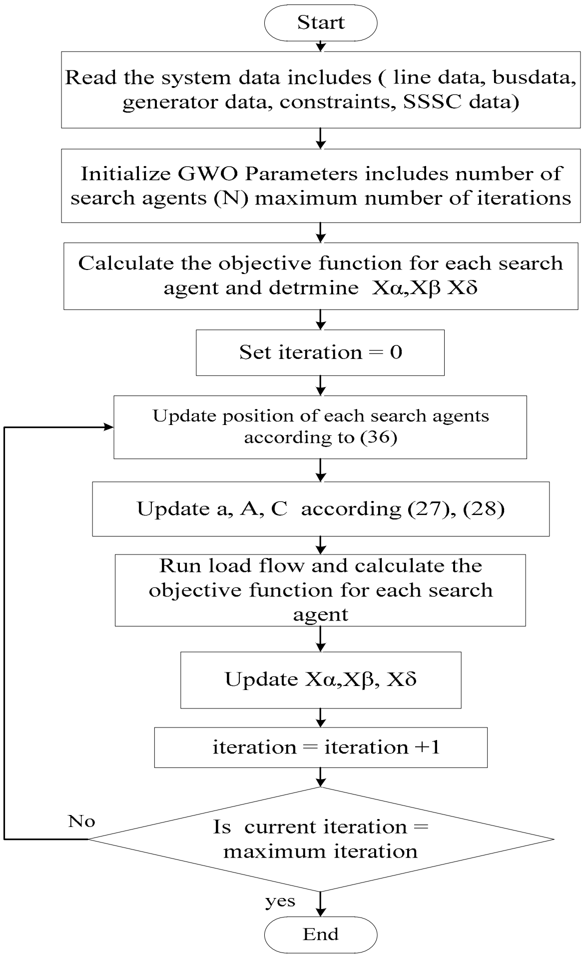


Fig. 5. Flowchart of the GWO algorithm.

V. RESULTS AND DISCUSSION

The proposed GWO optimization has been applied to solve ORPD problem. GWO is tested on IEEE 30-bus test system which consists of 6 generators , 4 transformers at 6–9, 6–10, 4–12 and 27–28, 41 transmission lines and Nine VAR compensation units at buses 10, 12, 15, 20, 23, 24 and 29.The the system data are given in [18,19]. The upper and lower limits of the transformer taps are 0.9 p.u and 1.1 p.u. The working rang of the VAR compensation unit is [0, 0.05] p.u. the upper and lower ranges of the PV bus voltage are 1.1 p.u and 0.95 p.u. The upper and lower ranges of the load bus voltage are 1.05 p.u and 0.95 p.u, respectively. The permission thermal loading limits of transmission lines are given in [18]. The Program code has been written in MATLAB-9 language and executed on a PC with core i3 processor, 2.50 GHz and 2 GB RAM. For all studied cases the selected number of agents and the maximum iterations of GWO are 20 and 200, respectively. The selected penalty factors are selected to be 100. The selecting operating ranges of the magnitudes and phase angle of the series injected voltage by SSSC are [0.001,0.2] p.u and [-π, π], respectively. The selected impedance of SSSC coupling transformer equals to j0.1 p.u. It should point out that all lines which have transformers are avoided for placement of SSSC controller. For verifying the effectiveness of SSSC controller, the ORPD problem is solved with and without incorporating SSSC in power system under line outage contingency state. The studied cases are performed with outage line (2–6) [20-21]. It should point out here that outage of line 2-6 is the more severe case compared to other lines outage contingencies based on stability index and voltage deviations which equal to 0.1391 p.u and 0.6318 p.u, respectively.

The studied cases are presented as follows:

5.1. Case1: Voltage profile improvement

Improving the voltage can be achieved by minimizing the voltage deviation of bus voltages. The results of initial case are listed in second column of Table I. The obtained results including the optimal control variables with and without incorporating SSSC using GWO and PSO for this case are listed in Table I and the bolded values highlight the best obtained results. The obtained voltage deviation without incorporating SSSC using GWO and PSO is reduced to 0.2884 p.u (54.35%) and 0.2989 p.u (53.69 %) respectively compared to initial case. In case of incorporating the SSSC, it is obvious that the voltage deviation is decreased to 0.1734 p.u (72.55 %) p.u and 0.1852 p.u (70.68%) p.u using GWO and PSO respectively, respectively compared to initial case. Hence, the obtained results demonstrate the effectiveness of SSSC for enhancing the voltage profile and superiority of the GWO algorithm. The optimal location and parameter setting of SSSC for this case are depicted in in Table I. The voltage profile with and without SSSC using GWO and PSO are shown in Fig. 6 and Fig. 7. It is obvious that the voltage profile using GWO is better than PSO. The convergence plot of GWO for the voltage profile using with and without SSSC is shown in Fig. 8.

5.1.2 Voltage stability enhancement

In this case, the voltage stability enhancement can be achieved by minimizing of the voltage stability index as depicted in (8). The optimal control variables obtained by GWO and PSO with and without incorporating SSSC are depicted on Table I. The obtained voltage stability index using GWO and PSO without incorporating SSSC are 0.1292 p.u and 0.1360 p.u, respectively, i.e., the voltage stability is enhanced by (7.11 %) and (2.22 %) using GWO and PSO respectively compared to the stability index in initial case. In case of incorporating SSSC, the voltage stability index is reduced to 0.1105 p.u. and 0.1301 p.u using GWO and PSO respectively, i.e., the stability index is reduced by (20.65 %) and (6.47 %) using GWO and PSO respectively compared to initial case. Hence, the obtained results reveal to the ability of SSSC for enhancing of the voltage stability moreover, the superiority of GWO over PSO in terms of the voltage stability improvement. The optimal placement and parameters setting of SSSC for this case are listed in in Table I. The convergence plot of GWO for stability index is illustrated in Fig. 9.

TABLE I COMPARISON OF SIMULATION RESULTS OBTAINED BY DIFFERENT ALGORITHMS

Variable	**Initial case**	**Case 1: Voltage profile improvement**				**Case 2: Voltage stability enhancement**			
		without SSSC		**with SSSC**		**without SSSC**		**with SSSC**	
		GWO	***PSO***	***GWO***	***PSO***	***GWO***	***PSO***	***GWO***	***PSO***
V1(p.u)	1.060	1.0789	1.0808	1.0410	1.0490	1.0652	1.0940	1.0879	1.0951
V2(p.u)	1.043	1.0817	1.0230	1.0437	1.0485	1.0668	1.0414	1.0939	1.0213
V5 (p.u)	1.010	1.0794	1.0531	1.0812	1.0362	1.0991	1.0867	1.1000	1.0143
V8(p.u)	1.010	1.0273	0.9931	1.0078	1.0819	1.0647	0.9968	1.0079	1.0002
V11(p.u)	1.082	0.9867	1.0115	1.0508	1.0011	1.0997	1.0994	1.0998	1.0510
V13(p.u)	1.071	0.9917	1.0693	0.9754	1.0598	1.0978	1.0357	1.0995	1.0009
T11	0.932	0.9593	1.0021	0.9271	0.9840	1.0508	0.9077	0.9355	1.0308
T12	0.978	1.0114	1.0194	0.9806	1.0091	0.9593	0.9637	0.9637	1.0257
T15	0.969	0.9696	0.9680	0.9712	1.0165	0.9045	1.0121	0.9009	0.9469
T36	0.968	0.9992	0.9739	0.9994	1.0340	0.9914	0.9664	0.9621	0.9892
Q10(p.u)	0.19	0.0158	0.0274	0.0442	0.9952	0.0221	0.0358	0.0449	0.0162
Q12(p.u)	0	0.0303	0.0319	0.0213	0.0285	0.0463	0.0301	0.0490	0.0209
Q15(p.u)	0	0.0407	0.0053	0.0382	0.0181	0.0312	0.0186	0.0216	0.0234
Q17(p.u)	0	0.0289	0.0343	0.0196	0.0057	0.0142	0.0251	0.0043	0.0155
Q20(p.u)	0	0.0356	0.0292	0.0148	0.0352	0.0295	0.0315	0.0136	0.0169
Q21(p.u)	0	0.0137	0.0202	0.0217	0.0310	0.0208	0.0222	0.0320	0.0353
Q23(p.u)	0	0.0125	0.0281	0.0297	0.0135	0.0199	0.0303	0.0318	0.0474
Q24(p.u)	0.043	0.0204	0.0331	0.0173	0.0380	0.0289	0.0404	0.0110	0.0108
Q29(p.u)	0	0.0168	0.0278	0.0270	0.0348	0.0423	0.0478	0.0170	0.0397
VD (p.u)	0.6318	**0.2884**	**0.2989**	**0.1734**	**0.1852**	0.6047	0.9027	0.6119	0.6715
Lmax(p.u)	0.1391	0.1301	0.6023	0.1411	0.1416	**0.1292**	**0.1360**	**0.1105**	**0.1301**
Ploss(MW)	20.211	22.976	23.012	20.90	21.096	19.33	20.076	20.88	21.32
SSSC of parameters						-	-		
Location		-	-	27(10-22)	7(5-7)	-	-	9(6-8)	8(6-7)
P^{sp} (MW)		-	-	49.75	19.25	-	-	-14.65	-4.01
Q^{sp}(MAR)		-	-	38.75	6.76	-	-	-22.77	7.03
V_{se} (p.u)		-	-	0.1813 $\angle 17.42$	0.1228 $\angle 69.70$		-	0.1574 $\angle 2.25$	0.1554 $\angle -1.84$

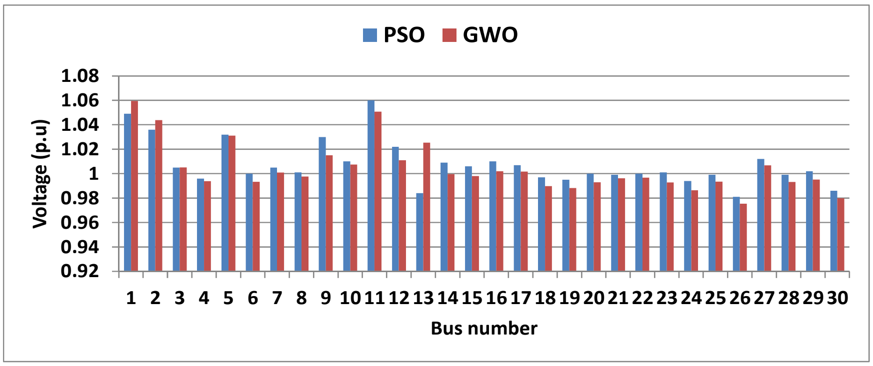


Fig. 6. System voltage profile without incorporating SSSC.

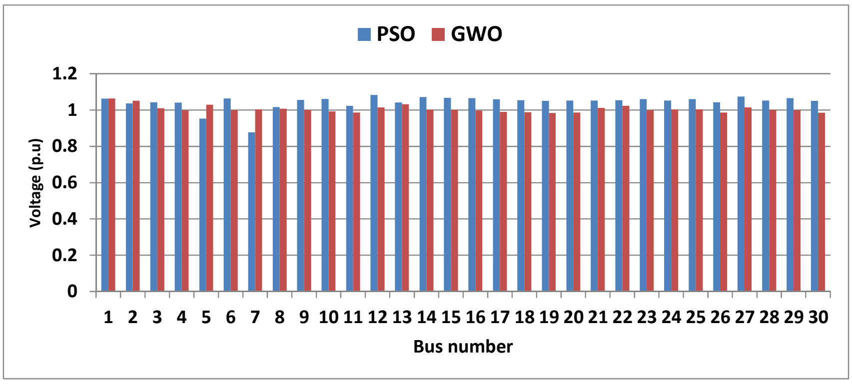
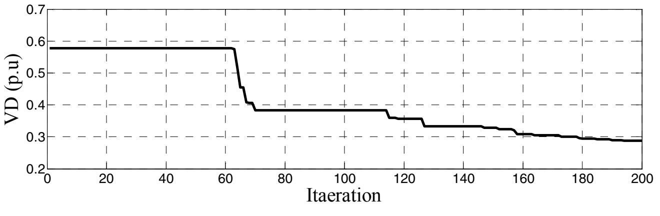
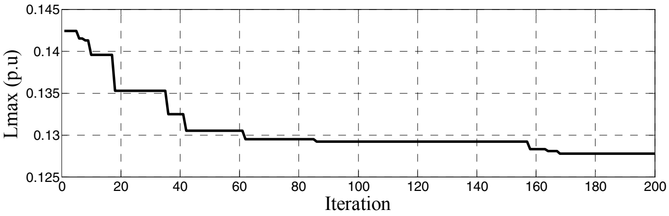


Fig. 7. System voltage profile with incorporating SSSC.



(a) Convergence plot without SSSC (b) Convergence plot with SSSC

Fig. 8. Convergence characteristic of GWO Case1 (a) without incorporating SSSC (b) with incorporating SSSC



(a) Convergence plot without SSSC (b) Convergence plot with SSSC

Fig. 9. Convergence characteristic of GWO for case2 (a) without incorporating SSSC (b) with incorporating SSSC

CONCLUSIONS

This paper has developed Grey wolf optimizer (GWO) algorithm for solving the optimal reactive power dispatch (ORPD) problem in presence of SSSC controller. The SSSC is incorporating in the system for improving the voltage profile and enhancing the stability index under contingency state (line outage). Standard IEEE 30-bus test system is used to verify the developed optimization technique with and without the SSSC. The developed technique has comprehensively compared with Particle swarm optimization algorithm. The simulation results proved the effectiveness of GWO technique for solving the ORPD problems moreover; superiority results are obtained for enhancing the voltage profile and the voltage stability with incorporating of SSSC optimally in electrical power system.

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