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GSO based optimization of steady state load shedding in power systems to mitigate blackout during generation contingencies

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Abstract Load shedding is considered as a last alternative to avoid the cascaded tripping and blackout in power systems during generation contingencies. It is essential to optimize the amount of load to be shed in order to prevent excessive load shedding. To minimize load shedding, this paper proposes the implementation of nature inspired optimization algorithm known as glowworm swarm optimization (GSO) algorithm. The optimal solution of steady state load shedding is carried out by squaring the difference between the connected and supplied power (active and reactive). The proposed algorithm is tested on IEEE 14, 30, 57, 118 and Northern Regional Power Grid (NRPG)-(India) 246 bus test systems. The viability of the proposed method in terms of solution quality and convergence properties is compared with the conventional methods, namely, projected augmented Lagrangian method (PALM), gradient technique based on Kuhn–Tucker theorem (GTBKTT) and second order gradient technique (SOGT).

1. Introduction

Power systems with adequate generation and transmission capacity are well designed to operate under normal operating condition and also with some small perturbation. Under these conditions, the main objective of the power utility is to operate the power system without violating the system constraints and operational limits. However, under certain situations like unexpected generation loss and sudden increase in system demand, the system constraints and operational limits are violated. Load shedding is considered as an emergency control action that is necessary to prevent a blackout in the power system by relieving overload in some parts of the system. Load shedding is defined as coordinated sets of controls that decrease the electric loads in the system so as to restore the system to its normal operating condition. By carrying out load shedding, the perturbed system can be forced to settle to a new equilibrium state. Different methods have been proposed in literature for load shedding in steady state or transient state. An optimal load shedding method finds a best steady state

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stable operating point for a post fault system with a minimum amount of load shed.

The optimal steady state load shedding problem that uses the sum of squares of the difference between the connected active and the reactive load and the supplied active and reactive power have been formulated in [1]. A voltage dependent load model is used to express the active and reactive power demands. Systematic approaches towards minimizing the curtailment of service in a power system after a severe fault have been discussed in [2]. Here, a feasible steady state solution defining the priority schedules for the post fault condition is obtained first and then the minimum load to be shed is obtained by gradient technique. Newton–Raphson technique and Kuhn–Tucker theorem are used to solve the power flow equations and the optimization problem respectively. The active and reactive powers of loads are assumed to be independent of bus voltages.

In [3], second order gradient technique (SOGT) has been proposed to minimize the load curtailment during a sudden major supply outage or tripping of tie-line breakers. Here, the generator control effects and the voltage and frequency characteristics of loads are considered during optimization. Optimal load shedding policy with generator control effects and voltage and frequency characteristics of loads has been suggested in [4]. Here, power generation is considered as dependent variable in the dynamic problem formulated.

Optimal load shedding using the sum of squares of the difference between the connected active and reactive load and the supplied active and reactive power has been presented in [5], which considers the supplied active and reactive power as dependent variables and modeled as a function of bus voltages only. A sensitivity based approach to solve the load shedding problems and to minimize the loss of loads has been proposed in [6]. In order to limit the size of the load being dropped, different priorities to loads are assigned using a weighted error criterion. The method overlooks equipment and operational limitations.

In [7,8], a non-linear optimization problem has been formulated for the optimal load shedding and rescheduling of generators during an emergency state. The non-linear problem has been approximated by an accurate sensitivity model which takes into account the real and reactive nodal injections, voltage magnitudes and angles. Loads' sensitivity to voltage magnitudes is also considered. An upper-bounding sparse, linear programming algorithm is used to solve the problem. To improve the computational efficiency, reduced size problems are considered in the iterative procedure. In [9,10], two different methods for generation rescheduling and load shedding to alleviate line overloads, based on the sensitivity of line overloads to bus power increments have been developed. In [11], a mesh approach has been developed for the formulation of the network equations in the load flow analysis. A hybrid approach using a combination of an impedance matrix method and a nodal-admittance matrix method which exploits the salient characteristics of the impedance and admittance method is developed.

A new power flow model for the steady state behavior of large complex power system that allows the study of power flow under normal and abnormal operating conditions has been developed in [12]. In [13], differential evolution algorithm has been implemented for optimal allocation of repair times and failure rates in meshed distribution system. An optimal under-voltage load shedding scheme to provide long term voltage stability using a new hybrid particle swarm based simulated annealing optimization technique has been presented in [14]. The technical and economic aspects of each load are considered by including the sensitivities of voltage stability margin into the cost function. In [15], a new voltage stability margin index considering load characteristics has been introduced in under-voltage centralized load shedding scheme. Quantum inspired evolutionary programming has been implemented in [16] for the optimal location and sizing of distributed generations (DGs) in radial distribution system. In [17], an optimal load shedding scheme have been proposed to monitor the load-generation unbalance in the plants with internal co-generation and to quickly initiate shedding of an optimal amount of load during a contingency.

DC optimal load shed recoveries with transmission switching model have been presented in [18]. This model reduces the amount of load shed required during generation and/or transmission line contingencies, by modifying the bulk power system topology. An approach based on parallel-differential evolution has been proposed in [19] for the optimal load shedding against voltage collapse. The non-linearity of the problem is fully considered in this approach and thereby able to escape from local optima and not limited to system modeling.

Basically, the optimal load shedding strategies are classified into two types, namely, centralized load shedding and de-centralized or distributed load shedding. Centralized load shedding strategies are solved based on stability margin sensitivities. These methods are based on the assumptions of linearity and constancy of the sensitivities [21], and depend on linear programming techniques to solve the comprehensive optimization problem. In actual practice, these assumptions are not realistic [22], particularly when the non-linear characteristics of the system components, such as, reactive power generation limits, actions of switched shunt devices load-tap changers and so on are considered. A multi-stage method to solve the non-linear optimal load shedding problem stage by stage has been presented in [22]. Here, each stage corresponds to a linearized sub-problem based on sensitivity analysis. Usually these methods do not consider priorities for the loads to be shed, whereas, in distributed load shedding schemes priorities for the loads are being considered. Moreover, in the mathematical formulation of optimal load shedding schemes, reactive power of loads to be shed are not considered [13–23]. Also, the loads are considered to be independent of the system voltage, but in actual practice, the real and reactive power of the loads depends on the system voltage [1].

The contribution of this paper consists of proposing an alternative approach based on glowworm swarm optimization (GSO) algorithm for efficiently and globally optimizing the steady state load shedding problem. The proposed scheme makes use of distributive load shedding with priorities for the significant loads. In this scheme, the active and reactive power demands of the system are expressed using a polynomial function of the bus voltage. In addition, the reactive powers of the loads to be shed are also considered during the problem formulation, which minimizes the amount of load shed required for the contingencies considered.

The significant features of the proposed approach are as follows:

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- Able to solve the non-linear optimization problem formulated for the minimization of load shedding.
- It adapts to generation loss and generation deficit contingencies considered.
- It is capable of obtaining a high quality solution in terms of the amount of load shed and the supplied active power.
- Adaptive to all the test systems viz., small, medium and large test systems (when applied to generation loss and generation deficit contingencies).
- Able to converge in minimum number of iterations.

The organization of the paper is as follows. In Section 2, the description of the problem is presented. The flowchart of the GSO algorithm is discussed in Section 3. Results obtained for the test systems, namely, IEEE 14, 30, 57, 118 and Northern Regional Power Grid (NRPG) of Power Grid Corporation of India Limited (PGCIL) 246 bus systems, are analyzed and validated in Section 4. Finally, conclusion is drawn in Section 5.

2. Problem formulation

The mathematical formulations of the non-linear optimization problem for the load shedding are as follows:

- The objective function during emergency conditions is to minimize the difference between the connected load and the supplied power subjected to equality and inequality constraints [1].

$$F = \sum_{i=1}^{NB} \left[\alpha_i \left(P_{di} - \overline{P}_{di} \right)^2 + \beta_i \left(Q_{di} - \overline{Q}_{di} \right)^2 \right] \quad (1)$$

where NB is the number of buses in a system, P_{di}, and Q_{di} are the active and reactive powers supplied to the load. $\overline{P}_{di}$, and $\overline{Q}_{di}$ are the connected active and reactive load. The weighting factors α_i and β_i are problem dependent constants.

- The power flow equations of the networks are the equality constraints. These equations of a network with NB number of nodes can be written as

$$P(V) = P_{Gi} - P_{di}(V) - P_i(V, \delta) = 0 \quad (2)$$

$$Q(V) = Q_{Gi} - Q_{di}(V) - Q_i(V, \delta) = 0 \quad (3)$$

The active and reactive power injections at bus i in terms of bus voltage magnitude and phase angle are expressed as

$$P_i(V, \delta) = V_i \sum_{i=1}^{NB} V_j Y_{ij} \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \quad (4)$$

$$Q_i(V, \delta) = V_i \sum_{i=1}^{NB} V_j Y_{ij} \sin\left(\delta_i - \delta_j - \theta_{ij}\right) \quad (5)$$

- The inequality constraints are the limits of real and reactive power generations, bus voltage magnitudes and angles, and line flows, which are expressed as

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad i = 1, \ldots NG \quad (6)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad i = 1, \ldots, NB \quad (7)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 1, \ldots, NB \quad (8)$$

where $P_{Gi}^{\min}$ and $Q_{Gi}^{\min}$ are the minimum real and reactive power generations, respectively, and $P_{Gi}^{\max}$ and $Q_{Gi}^{\max}$ are the maximum available real and reactive power generations, respectively. $V_i^{\min}$ and $V_i^{\max}$ are the minimum and maximum limits of bus voltages of the system, respectively.

Either current magnitude constraint due to thermal considerations or electrical angle (difference in voltage angle across a line) constraint due to stability considerations can be considered for transmission line loading limits. In the present formulation the electrical angle inequality constraint is used, which can be expressed as

$$LF = \left|\delta_i - \delta_j\right| \le \epsilon_{ij} \qquad i = 1, \ldots NB - 1; \quad j = i + 1, \ldots NB \quad (9)$$

where δ_i and δ_j are the voltage angles at bus i and bus j, and ϵ_{ij} is the maximum voltage phase angle difference between i and j.

- The system active and reactive power demands can be expressed using different load models in terms of bus voltage and system frequency. A polynomial function of the bus voltage is used in this formulation to express the active and reactive power demands at any given bus as

$$P_{di} = \overline{P}_{di} \left[P_p + P_c \left(\frac{V_i}{\overline{V}_i} \right)^{N1} + P_z \left(\frac{V_i}{\overline{V}_i} \right)^{N2} \right] \quad (10)$$

$$Q_{di} = \overline{Q}_{di} \left[Q_q + Q_c \left(\frac{V_i}{\overline{V}_i} \right)^{N3} + Q_z \left(\frac{V_i}{\overline{V}_i} \right)^{N4} \right] \quad (11)$$

where P_p, P_c, P_z, Q_q, Q_c and Q_z are constants associated with this voltage dependent load model and $N1$, $N2$, $N3$ and $N4$ are the powers of polynomial.

- The optimal load curtailment problem can be described by Eqs. (1)–(11). Substituting Eqs. (2) and (3) into Eq. (1), a modified objective function in terms of P_{Gi} and P_i is given by,

$$J = \sum_{i=1}^{NB} \left[\alpha_i \left(P_{Gi} - P_i - \overline{P}_{di} \right)^2 + \beta_i \left(Q_{Gi} - Q_i - \overline{Q}_{di} \right)^2 \right] \quad (12)$$

3. Glowworm swarm optimization (GSO) algorithm

The GSO algorithm which is inspired by swarm intelligence has been developed by Krishnanand and Ghose [23]. This algorithm is improved from ant colony algorithm (ACO). The actions which are based on neighbor interactions and local information from the environment that is exhibited by biological swarms like ants, termites, bees, wasps and bacteria are called as swarm intelligence [24]. In the GSO algorithm, the agents (glowworm) are initially deployed randomly in the objective function space and the agents in the GSO algorithm carry a luminescence quantity called luciferin along with them [25]. The luciferin level is associated with the objective function value of the agent's position. Agents are thought of as glowworms that emit a light whose intensity of luminescence (brightness) is proportional to the associated luciferin. The luciferin of each glowworm is used to (indirectly) communicate the function-profile information at its current location to the neighbors. Each agent carries the light on two dimensional works space and has its own vision, called local-decision range.

The agent is only attracted towards a neighbor whose luciferin intensity is higher than its own within the local decision range and then the agent flies towards this neighbor. The local decision range depends on the number of neighbors. This range is increased if the number of neighbors is low in order to find more neighbors, otherwise the range is reduced. The direction of movement of the agent always changes towards the selected neighbor. The higher luciferin level the neighbor has, the more attraction it gains.

The three main phases of GSO are

(i) luciferin update phase
(ii) movement phase and
(iii) decision range update phase

These main phases of GSO can be briefly described as

3.1. Luciferin update phase

At the starting of the iteration process same luciferin value is assumed for all the agents. The updating of the luciferin value of each agent in the successive iterations depends on the value of objective function obtained at their current position and also on the luciferin value it has during the previous iteration. Each glowworm adds its previous luciferin level. At the same time, the luciferin level of glowworm is subtracted from the previous luminescence value to simulate the decay in luminescence. The luciferin update rule is given by:

$$l_i(t+1) = (1-\rho)l_i(t) + \gamma J_i(t+1) \tag{13}$$

where $l_i(t)$, represents the luciferin level associated with glowworm i at time t, $\rho$is the luciferin decay constant $0 < \rho < 1$, γ is the luciferin enhancement constant, and J_i represents the value of objective function at agent i's location at time t.

3.2. Movement phase

During the movement phase, each glowworm uses a probabilistic mechanism to decide a movement of a neighbor that has a luciferin value more than its own. Glowworms are attracted by neighbors that glow brighter. For each glowworm i, the probability of moving toward a neighbor j is given by:

$$P_{ij} = \frac{l_j(t) - l_i(t)}{\sum_{k \in N_i(t)} (l_k(t) - l_i(t))} \tag{14}$$

where $j \in N_i(t), N_i(t) = \{j : d_{ij}(t) < r^i_d(t); l_i(t) < l_j(t)\}$ is the set of neighborhood of glowworm i at time t. $d_{ij}(t)$ represents the Euclidean distance between glowworms i and j at time t, and $r^i_d(t)$ represents the variable neighborhood range associated with glowworms i at time t. Let glowworm i select a glowworm $j \in N_i(t)$ with $P_{ij}(t)$ is given by Eq. (14). Then, movements of glowworms can be stated as:

$$x_i(t+1) = x_i(t) + s\left(\frac{x_j(t) - x_i(t)}{\left\|x_j(t) - x_i(t)\right\|}\right) \tag{15}$$

where s is the step-size. $\|\ \|$ represents the Euclidean norm operator.

3.3. Neighborhood range update rule

Each agent i is associated with a neighborhood of radial range r^i_d, which is dynamic in nature $0 < r^i_d < r_s$. Where r_s represents the radial range of the luciferin sensor. Here the neighborhood range cannot be fixed because of the fact that a priori information about the objective function (e.g., number of peaks and inter-peak distances) is not available. So it is difficult to fix the value of the neighborhood range that performs well for different function landscapes. The fact is that a chosen neighborhood range r_d for a particular objective function will work better only if the minimum inter-peak distance is more than r_d.

Therefore, GSO uses an adaptive neighborhood range in order to detect the presence of multiple peaks in a multimodal function landscape. A substantial enhancement in performance is noticed by using the rule given below:

$$r^i_d(t+1) = \min\{r_s, \max\{0, r^i_d(t) + \beta(nt - |N_i(t)|)\}\} \tag{16}$$

where β is a constant parameter and nt is a parameter used to control the numbers of neighbors. The computational procedure of the basic GSO algorithm can be summarized in Fig. 1 [26].

The implementation of GSO algorithm to optimal load shedding problem can be explained in the following steps. The real and reactive power load to be shed at each bus is considered as the variables of the optimal load shedding problem. Each glowworm corresponds to a solution vector of the load shedding problem.

Step 1: The parameters of the algorithm are initialized.
Step 2: A population of 'n' glowworms is generated randomly in the search space of the decision variables.
Step 3: Same luciferin values are assumed for all the glowworms at the beginning of the iteration.
Step 4: With the newly generated solution the objective function is calculated using Eq. (12).
Step 5: The luciferin value associated with each glowworm is updated using Eq. (13).
Step 6: Each glowworm selects a neighbor that has a luciferin value higher than its own within a variable neighborhood range $r^i_d(t)$ $(0 < r^i_d < r_s)$ to make up the $N_i(t)$.
Step 7: Probability of movement of each glowworm i towards a neighbor j is calculated using Eq. (14).
Step 8: Using the roulette method glowworm i selects a neighbor j and move towards it. Then the location of the glowworm i is updated using Eq. (15).
Step 9: The value of the variable neighborhood range is updated using Eq. (16).
Step 10: The steps 5 to 9 are repeated until maximum number of iterations are reached.

4. Simulation results and analysis

The aim of optimal load shedding is to restore normal operating conditions following loss of generation contingencies by shedding minimum load. The proposed GSO approach has been verified on two small systems – IEEE 14-bus and IEEE 30-bus, two medium systems – IEEE 57-bus and IEEE 118-bus and one large system – 246-bus NRPG of PGCIL. The results obtained by the proposed approach for the small and

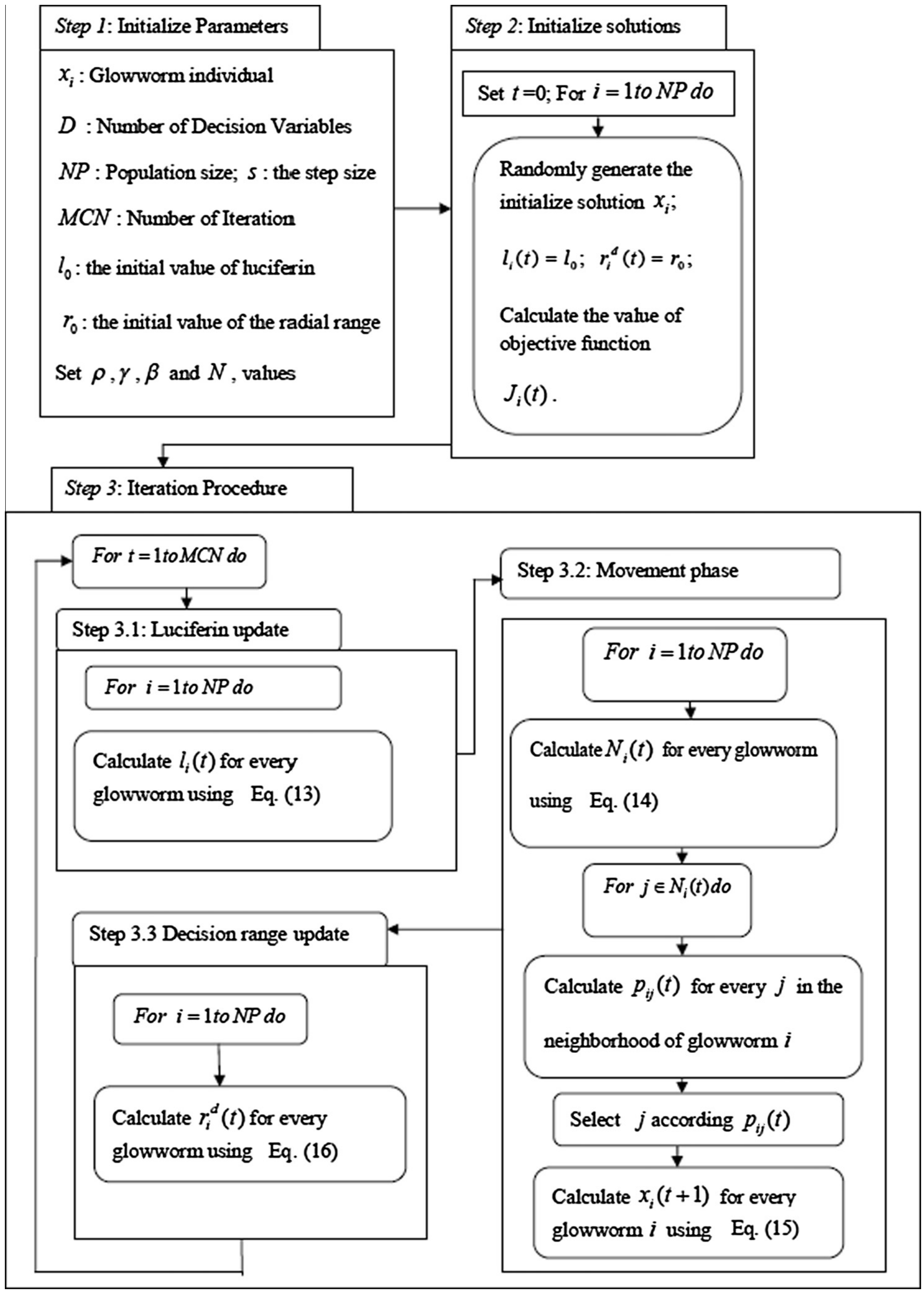

Figure 1 Flow chart of glowworm swarm optimization algorithm.

medium systems are compared with those obtained by using conventional methods reported earlier, such as projected augmented Lagrangian method (PALM) implemented using MINOS – an optimization package [1,5], gradient technique based on Kuhn–Tucker theorem (GTBKTT) [2] and second order gradient technique (SOGT) [3]. The single line diagram and the detailed data of IEEE 14, 30, 57 and 118 – bus systems are given in [11] and for the NRPG 246 bus Indian system the data are taken from [27]. The software was written in Matlab and executed on 2.4 GHz, Intel core i3 processor with 2 GB RAM PC.

The decision variables of this problem are the real and reactive power load to be shed at each bus. Thus, for a 14-bus system the number of decision variables will be 28. The permissible amount of load shed in each bus is assumed as 10–80% of the total load connected at each bus. The rest 20% of the load is reserved for emergency conditions. The violation of the inequality constraints is penalized in the objective function. In order to validate the results obtained with that of the results reported in [1–2,5]; flat values are assigned to the priorities of the loads. The constants and the powers of the polynomial associated with the load model given in Eqs. (10) and (11) is as follows [3]:

$P_p = 0.2, P_c = 0.3, P_z = 0.5, Q_q = 0.2, Q_c = 0.3$ and

$Q_z = 0.5; \quad N1 = 1, N2 = 2, N3 = 1$ and $N4 = 2$.

The assumed values of the design parameters of GSO algorithm used in this paper are as follows:

$\rho = 0.4, \gamma = 0.6, \beta = 0.08, l_0 = 5, s = 0.03, n_t = 5$

4.1. Application to small size systems

IEEE 14, 30 – bus test systems are considered here. The two cases of generation contingencies are analyzed for these test systems. The population size, *NP* of the proposed GSO algorithm applied for these test systems is assumed as 100.

4.1.1. IEEE 14-bus system

This system consists of 20 lines, two generators, three synchronous condensers, three transformers and one static capacitor. The generated active power limits are:

$0 \le P_{G1} \le 200 \quad 0 \le P_{G2} \le 200$

The generated reactive power limits are:

$$-150 \le Q_{G1} \le 150 \quad 0 \le Q_{G2} \le 140, \quad 0 \le Q_{G3} \le 140 \quad 0 \le Q_{G6} \le 140, \quad 0 \le Q_{G8} \le 140$$

Tables 1 and 2 present a comparison of the active and reactive power supplied and generated for the test system under normal operating conditions obtained in this paper with other methods. The active and reactive power supplied at each bus obtained by Newton Raphson (NR) method used here, is almost the same as those obtained by other methods in Table 1. The connected load for this test system is 259 MW. The supplied power to the connected load is 258.801 MW under normal operating conditions using NR method for the active power generation of 272 MW.

For a connected load of 259 MW, the supplied powers obtained using GTBKTT, SOGT and PALM are 259.0 MW, 258.81 MW and 258.59 MW, respectively. The deficit in the supplied power obtained using the proposed approach, PALM and SOGT represents the effect of using a voltage dependent load model (VDLM) to express the active power. The bus voltages vary between 1.01 pu and 1.08 pu in the NR method with VDLM, whereas the voltages vary from 0.98 pu to 1.07 pu in PALM, 0.93 pu to 1.035 pu in GTBKTT and 0.9765 pu to 1.016 pu in SOGT.

4.1.1.1. Loss of generation contingency. An abnormal operating condition representing the loss of generating unit – 2 generating 72.0 MW or 26% of normal generation is the contingency considered here. The results obtained are presented in Tables 3–5. The connected load in this case is 259.0 MW.

Table 1 Comparison of the active and reactive power supplied under normal operating conditions for the IEEE 14 – bus test system.

Bus number	GTBKTT [2]		SOGT [3]		PALM [5]		Proposed method (this work)	
	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)
1	0.0	0.0	0.0	0.0	0.0	0.0	0	0
2	21.7	12.7	21.55	12.62	21.66	12.68	21.971	12.859
3	94.2	19.0	94.19	19.00	94.20	19.0	94.20	19
4	47.80	−3.90	47.96	−3.91	47.84	−3.90	47.746	−3.896
5	7.60	1.60	7.67	1.62	7.64	1.61	7.614	1.603
6	11.20	7.50	11.44	7.66	11.65	7.80	11.20	7.5
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	29.50	16.60	29.57	16.64	29.71	16.72	29.668	16.132
10	9	5.80	8.96	5.77	8.93	5.76	8.789	5.664
11	3.50	1.8	3.51	1.81	3.52	1.81	3.458	1.778
12	6.10	1.60	6.10	1.6	6.09	1.60	6.088	1.597
13	13.50	5.80	13.41	5.76	13.30	5.71	13.45	5.778
14	14.90	5	14.45	4.85	14.05	4.72	14.617	4.905
Total	259.0	73.50	258.8100	73.4200	258.5900	73.5100	258.801	72.9200

Table 2 Comparison of the active and reactive power generation under normal operating conditions for the IEEE 14 – bus test system.

Bus number	GTBKTT [2]		SOGT [3]		PALM [5]		Proposed method (this work)	
	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)
1	200	8.56	135	0.51	69.25	−64.43	200.0	−16.5
2	71.85	0	135	−60	200	0	72.0	43.6
3	0.0	0.0	0.0	48.47	0.0	47.50	0	25.1
6	0.0	0.0	0.0	60.02	0.0	61.26	0	12.7
8	0.0	0.0	0.0	31.22	0.0	34.84	0	17.6
Total	271.85	8.56	270	80.220	269.250	79.1700	272.00	82.50

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Table 3 Comparison of the active and reactive power supplied under abnormal operating conditions (loss of generation) for the IEEE 14 – bus test system.

Bus number	GTBKTT [2]		SOGT [3]		PALM [5]		Proposed method (this work)	
	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	16.28	9.53	20.11	11.77	16.55	9.69	16.179	10.562
3	69.53	14.02	84.39	17.02	75.24	15.18	75.268	15.672
4	35.48	−2.90	43.74	−3.57	35.21	−2.87	35.988	−2.603
5	5.66	1.19	7.02	1.48	5.64	1.19	4.483	1.232
6	8.34	5.59	9.83	6.59	7.03	4.71	6.831	5.994
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.683
9	21.92	12.33	26.03	14.64	19.28	10.85	21.719	11.930
10	6.68	4.31	7.87	5.08	5.75	3.71	6.273	4.217
11	2.60	1.34	3.06	1.58	2.20	1.13	2.277	1.842
12	4.53	1.19	5.29	1.39	3.73	0.98	3.996	1.138
13	10	4.30	11.61	4.99	8.22	3.53	9.241	4.724
14	10.98	3.69	12.62	4.23	9.04	3.03	9.880	3.914
Total	192	54.59	231.57	65.2	187.89	51.13	192.135	59.3050

Table 4 Comparison of the active and reactive power generation under abnormal operating conditions (loss of generation) for the IEEE 14 – bus test system.

Bus number	GTBKTT [2]		SOGT [3]		PALM [5]		Proposed method (This work)	
	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)
1	200	−31.72	200	4.81	200	−6.65	200	−16.5
2	0.0	0.0	0.0	0.0	0.0	0.0	0	43.6
3	0.0	0.0	0.0	22.73	0.0	63.34	0	25.1
6	0.0	10.15	0.0	25.70	0.0	5.59	0	12.7
8	0.0	0.0	0.0	14.71	0.0	0.0	0	17.6
Total	200	−21.75	200	67.950	200	62.280	200	82.50

Table 5 Comparison of the active power losses (MW) under normal and abnormal operating conditions (loss of generation) for the IEEE 14 – bus test system.

Condition	GTBKTT [2] Real power (MW)	SOGT [3] Real power (MW)	PALM [5] Real power (MW)	Proposed method (this work) Real power (MW)
Normal	12.8454	11.3274	10.6685	13.2
Abnormal	7.9952	−31.5814	12.1111	7.865

In Table 3 the active and reactive power supplied by the proposed method is compared with other methods. The amount of load shed using the proposed GSO approach is 66.865 MW or 25.816% of the nominal load and the supplied active power is 192.135 MW. Whereas using PALM, the load shed and the supplied active power are 71.11 MW or 27.45% of the nominal load and 187.89 MW respectively.

For the same generation loss, the amount of load shed and the active supplied power obtained using GTBKTT are 67.0 MW or 25.87% of nominal load and 192 MW respectively. It can be observed that the proposed approach has yielded lower amount of load shed and higher supplied active power demand when compared with other methods. Table 4 shows the comparison of the active and reactive power generations obtained by the proposed approach with the other methods. Table 5 shows the comparison of the active power loss obtained for the 14-bus test system under normal operating condition and abnormal operating condition representing loss of generating unit – 2.

The bus voltages vary between 1.06 pu and 1.1 pu in the proposed approach whereas using PALM and GTBKTT, the bus voltages vary from 0.8065 pu to 0.917 pu and from 1.04883 pu to 1.1 pu respectively. The proposed approach yields better bus voltage profile as compared with other approaches. Fig. 2 shows the convergence characteristic of the proposed GSO algorithm for the test system operated under the generation contingency considered here. The number of iterations required for the proposed approach is 3 iterations.

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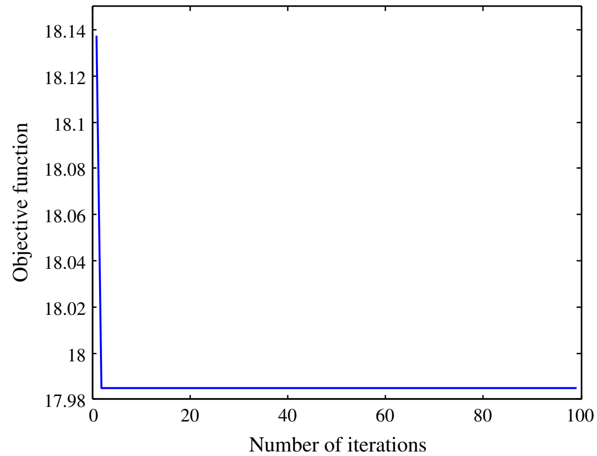

Figure 2 Convergence characteristics of GSO approach for IEEE 14 – bus system under loss of generation contingency.

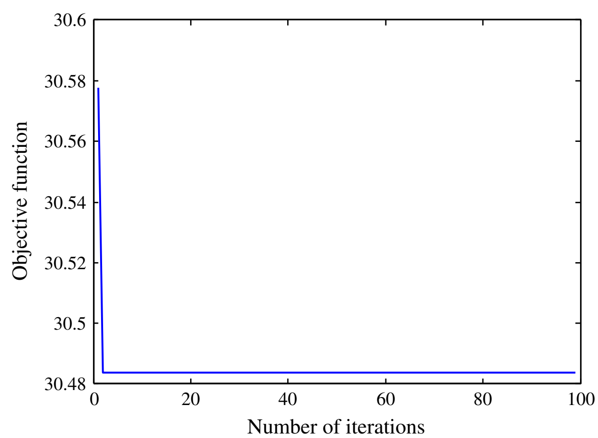

Figure 3 Convergence characteristics of GSO approach for IEEE 14 – bus system under generation deficit contingency.

4.1.1.2. Range of generation deficit contingencies. The test system is also subjected to contingencies characterized by generation deficits. The range of generation is varied from 260 MW to 160 MW, with a connected load of 259 MW, which means, the resulting generation deficit varies from 0 to 99 MW. Fig. 3 shows the convergence characteristics of the proposed approach for the generation of 160 MW. The number of iterations required for the proposed approach to converge is 5. Since the severity of the contingency considered in this case is increased as compared with previous case (Generation loss of 72 MW), the number of iterations needed to converge is increased.

Fig. 4(a) shows the decrease of total supplied power obtained by the proposed approach from249.663 MW at 260 MW generations to 154.262 at 160 MW generations. Fig. 4(b) shows the corresponding active power loss decrease from 10.337 MW to 5.578 MW. The total supplied power using PALM decreases from 249.30 MW at 260 MW generation to 153.78 MW at 160 MW generation with corresponding active power loss decrease from 10.70 MW to 6.22 MW. However, using GTBKTT, the supplied power decreases from 252.92 MW to 157.22 MW with the corresponding active power loss decrease from 7.08 MW to 2.78 MW for the same range of generation deficits. For this generation deficits contingency the maximum bus voltage obtained by the proposed method remains constant at 1.04 pu and the minimum voltage varies between 1.01 pu and 1.022 pu. Whereas in PALM the maximum voltage decreases from 1.062 pu to 0.85838 pu and the minimum voltage magnitude decreases from 0.9507 pu to 0.77 pu.

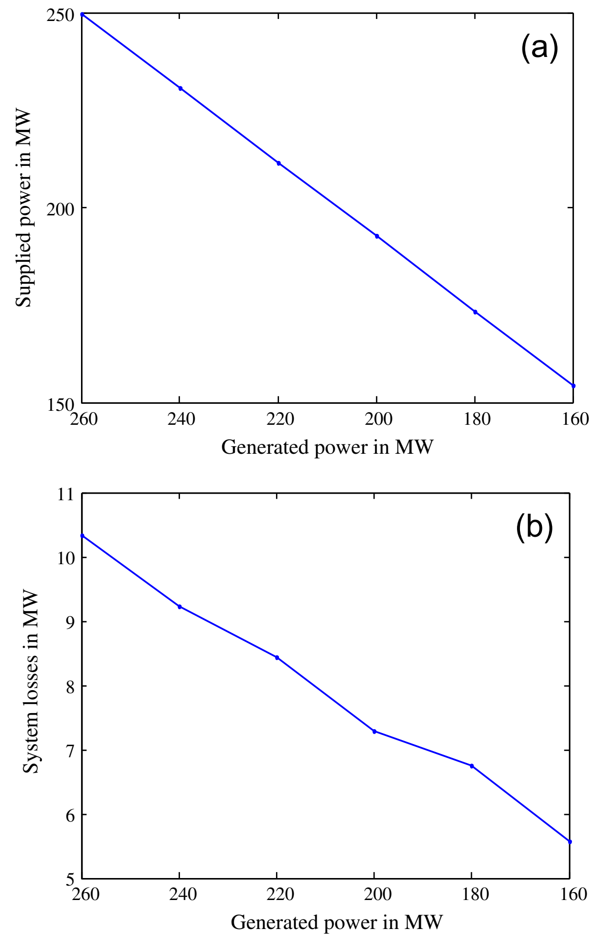

Figure 4 IEEE 14 – bus system under generation deficit contingencies (a) – optimal supplied load, (b) – system losses.

For IEEE 14 – bus system, bus 3 is the bus with heaviest load and bus 4 is the bus with second heaviest load. The supplied powers at bus 3 and bus 4 by the proposed GSO approach are 87.4 MW and 44.20 MW respectively. The supplied powers at bus 3 and bus 4, using PALM, are 85.52 MW and 39.70 MW respectively. The supplied powers at bus 3 and bus 4, using GTBKTT are 78.02 MW and 36.69 MW respectively. The proposed approach supplies more power at the heaviest loaded buses – bus 3 and bus 4- as compared to PALM and GTBKTT.

4.1.2. IEEE 30 – bus system

This system consists of 41 lines, three generators, three synchronous condensers, two static capacitor and three transformers. The generated active power limits are:

Table 6 Comparison of the active and reactive power supplied under normal operating conditions for the IEEE 30 – bus test system.

Bus number	GTBKTT [2]		SOGT [3]		PALM [5]		Proposed method (this work)	
	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	21.7	12.70	21.67	13.27	22.02	12.89	21.7	12.7
3	2.40	1.20	2.54	1.27	2.50	1.25	2.414	1.207
4	7.60	1.60	7.65	1.67	7.87	1.66	7.651	1.611
5	94.20	19.00	94.20	19.09	94.23	19.01	94.2	19
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	22.80	10.90	22.03	11.01	22.68	10.84	22.901	10.948
8	30	30	30	30.67	30.27	30.27	30	30
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	5.80	2	5.91	2.04	5.91	2.04	5.675	1.957
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	11.20	7.50	11.23	7.55	11.28	7.55	11.104	7.436
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	6.20	1.60	6.04	1.58	6.02	1.55	6.128	1.582
15	8.20	2.50	8.08	2.46	7.92	2.42	8.093	2.467
16	3.50	1.80	3.51	1.80	3.48	1.79	3.451	1.775
17	9	5.80	9.05	5.84	8.98	5.79	8.823	5.686
18	3.20	0.90	3.05	0.88	3.05	0.86	3.149	0.886
19	9.50	3.40	9.31	3.33	9.07	3.25	9.323	3.337
20	2.20	0.70	2.18	0.69	2.13	0.68	2.157	0.686
21	17.50	11.20	17.47	11.18	17.20	11.01	17.102	10.945
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	3.20	1.60	3.02	1.56	3.02	1.51	3.142	1.571
24	8.70	6.70	8.13	6.51	8.15	6.27	8.484	6.533
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	3.50	2.30	3.273	2.15	3.04	2	3.433	2.256
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	2.40	0.90	2.24	0.84	2.08	0.78	2.352	0.882
30	10.50	1.90	9.73	1.74	8.95	1.60	10.297	1.846
Total	283.30	126.20	280.313	127.130	279.85	125.02	281.5790	125.3110

Table 7 Comparison of the active and reactive power generations under normal operating conditions for the IEEE 30 – bus test system.

Bus number	GTBKTT [2]		SOGT [3]		PALM [5]		Proposed method (this work)	
	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)
1	170.62	70	170.35	21.61	144.41	−18.91	145	−18.910
2	70	−3.21	60.69	−40	70	−20	70	−20
5	0.0	1.24	0.0	40	0.0	47.33	0.0	47.330
8	0.0	13.60	0.0	21.69	0.0	20.54	0.0	20.540
11	54.22	29.86	61.03	40	75	46.58	75	46.58
13	0.0	10.00	0.0	40	0.0	50	0.0	50
Total	294.840	121.4900	292.070	123.30	289.410	125.540	290	125.540

$0 \le P_{G1} \le 175, \quad 0 \le P_{G2} \le 70 \quad 0 \le P_{G5} \le 75$

The generated reactive power limits are:

$-20 \le Q_{G1} \le 43, \quad -10 \le Q_{G8} \le 30, \quad -20 \le Q_{G2} \le 43,$
$-10 \le Q_{G11} \le 45, \quad -20 \le Q_{G5} \le 50, \quad -10 \le Q_{G13} \le 50,$

The supplied power by the NR method with VDLM used in the proposed approach under normal operating conditions is 281.579 MW for a connected load of 283.40 MW, while the active power generation is 290 MW.

For the same connected load, the supplied powers obtained using PALM, GTBKTT and SOGT are 279.85 MW, 283.30 MW and 280.313 MW respectively. The deficit in the supplied power obtained in this paper, PALM and SOGT represents the effect of using a VDLM to express the active power. The bus voltages vary between 0.970 pu and 1.082 pu in the proposed approach whereas using PALM, GTBKTT and SOGT, the voltages vary from 0.9349 pu to 1.10 pu, from 0.9247 pu to 1.10 and from 0.9319 pu to 1.088 pu respectively.

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Tables 6 and 7 present the active and reactive power demands and generations for the test system under normal operating conditions obtained in this paper and the other methods. The active and reactive power demands at each bus obtained by NR method with VDLM used here, is almost the same as those obtained in other methods in Table 6.

The test system is subjected to the same generation contingencies that has been considered by the earlier approaches referred here.

4.1.2.1. Loss of generation contingency. The results obtained when an abnormal operating conditions representing the loss of 60 MW or 20.35% of normal generation are presented in Tables 8–10. The connected load in this case is 283.40 MW. In Table 8 the active and reactive power supplied by the proposed GSO approach are compared with other methods. The amount of load shed obtained using the proposed method is 40.602 MW or 14.326% of the nominal load and the active supplied power is 242.798 MW. Whereas the load shed and the active supplied power, using PALM are 42.69 MW or 15.07% of the nominal load and 240.60 MW respectively. For the same generation loss, the amount of load shed and the supplied power using GTBKTT are 40.73 MW or 14.38% of the nominal load and 242.67 MW respectively.

It can be observed that the proposed approach has yielded lower amount of load shed and higher active supplied power demand when compared with other methods. Table 9 shows the comparison of the active and reactive power generations under abnormal operating condition, obtained by the proposed approach with the other methods. The real power loss obtained for this test system under normal operating condition and abnormal operating condition representing loss of generation of 60 MW, by the proposed approach and the other methods are tabulated in Table 10. The bus voltages vary between 0.9907 pu and 1.0820 pu in the proposed approach whereas using PALM and GTBKTT, the voltages vary from 0.8920 pu to 1.0630 pu and from 0.99806 pu to 1.10 pu respectively.

Fig. 5 shows the convergence characteristics of the proposed GSO approach for the test system operated under the abnormal operating condition representing loss of generation of 60 MW. The maximum iterations to converge for the proposed approach is 5 iterations.

4.1.2.2. Range of generation deficit contingencies. The test system is also subjected to contingencies characterized by generation deficits. The range of generation is varied from 300 MW to 190 MW, with a connected load of 283.3 MW, which

Table 8 Comparison of the active and reactive supplied power under abnormal operating conditions (loss of generation) for the IEEE 30 – bus test system.

Bus number	GTBKTT [2]		SOGT [3]		PALM [5]		Proposed method (this work)	
	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	18.69	10.94	20.67	12.10	19.77	11.57	18.695	11.041
3	2.07	1.04	2.32	1.16	2.24	1.12	1.993	0.913
4	6.53	1.38	7.29	1.54	7.03	1.48	6.3850	1.219
5	80.41	16.22	83.05	16.75	77.95	15.72	81.6641	16.907
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	19.51	9.33	20.82	9.95	19.76	9.45	18.592	9.042
8	25.8	25.73	28.65	28.66	27.98	27.98	26.503	25.563
9	0.0	0.0	0.0	0.0	0.0	0.0	−0.0001	−0.00
10	4.99	1.72	5.40	1.86	5.16	1.78	5.002	1.634
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000
12	9.61	6.44	10.23	6.85	9.13	6.11	9.340	6.616
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	5.31	1.37	5.56	1.43	4.94	1.28	5.409	1.206
15	7.02	2.14	7.35	2.24	6.57	2	7.154	1.993
16	3	1.54	3.19	1.64	2.91	1.50	3.014	1.369
17	7.73	4.98	8.26	5.33	7.74	4.99	7.406	4.655
18	2.74	0.77	2.86	0.80	2.58	0.73	2.723	0.652
19	8.13	2.91	8.5	3.04	7.76	2.78	8.279	2.814
20	1.89	0.60	1.99	0.63	1.83	0.58	1.733	0.484
21	15.01	9.61	15.97	10.22	15.02	9.61	15.205	9.494
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	2.74	1.37	2.84	1.42	2.56	1.28	2.496	1.302
24	7.44	5.73	7.73	5.95	7.08	5.45	7.610	5.538
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	2.98	1.96	3.01	1.98	2.70	1.77	3.004	1.843
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	2.05	0.77	2.07	0.78	1.86	0.70	1.944	0.627
30	9.02	1.62	8.99	1.61	8.03	1.44	8.647	1.566
Total	242.67	108.170	256.750	115.940	240.60	109.320	242.798	106.4780

Table 9 Comparison of the active and reactive power generation under abnormal operating conditions for the IEEE 30 – bus test system.

Bus number	GTBKTT [2]		SOGT [3]		PALM [5]		Proposed method (this work)	
	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)	Real power (MW)	Reactive power (MVAR)
1	175.0	−12.98	175.0	10.94	175.0	−6.22	175	−18.910
2	0.0	0.0	0.0	−2.62	0.0	0.0	0.0	−20
5	0.0	25.61	0.0	0.0	0.0	7.42	0.0	47.33
8	0.0	26.7	0.0	40	0.0	45.69	0.0	20.54
11	75	13.29	75	40	75	50	75	46.58
13	0.0	33.34	0.0	31.46	0.0	13.44	0.0	50.00
Total	250	85.960	250	119.780	250	110.33	250	125.540

Table 10 Comparison of the active power losses (in MW) under normal and abnormal operating conditions (Loss of generation) for the IEEE 30 – bus test system.

Condition	GTBKTT [2]	SOGT [3]	PALM [5]	Proposed method (this work)
	Real power (MW)	Real power (MW)	Real power (MW)	Real power (MW)
Normal	11.5363	10.6598	11.4053	8.421
Abnormal	7.4302	−6.7483	9.4087	7.202

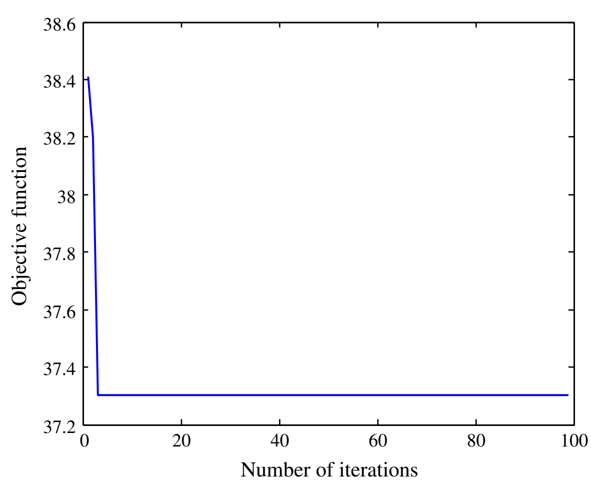

Figure 5 Convergence characteristics of GSO approach for IEEE 30 – bus system under loss of generation contingency.

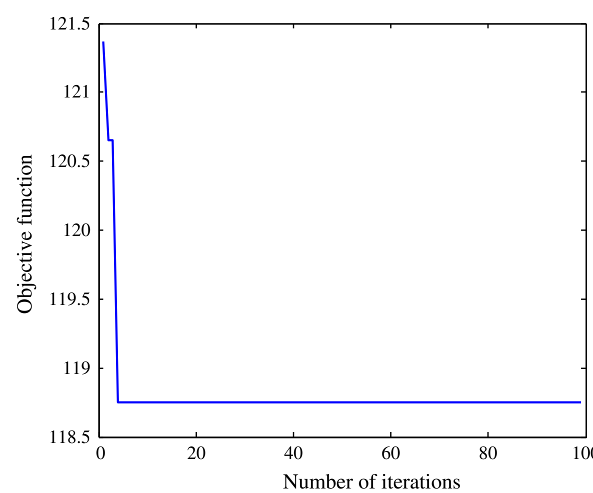

Figure 6 Convergence characteristics of GSO approach for IEEE 30 – bus system under generation deficit contingency.

means, the resulting generation deficit varies from 0 to 93.3 MW. Fig. 6 shows the convergence characteristics of the proposed approach for the generation of 190 MW. The minimum number of iterations required by the proposed approach is 8 corresponding to 190 MW generation. The number of iterations required is slightly increased in this case because the severity of the contingency considered here is more than the previous case representing loss of generation of 60 MW.

Fig. 7(a) shows the total supplied power obtained by the proposed approach decreases from 283.4 MW at 300 MW generations to 184.881 MW at 190 MW generations and Fig. 7(b) shows the corresponding active power loss decreases from 9.44 MW to 3.572 MW. Whereas the total supplied power using PALM decreases from 279.82 MW at 300 MW generation to 183.25 MW at 190 MW generation with corresponding active power loss decrease from 10.51 MW to 6.76 MW and using GTBKTT, the supplied power decreases from 283.3 MW at 300 MW generation to 186.06 MW at 190 MW generation with the corresponding active power loss decrease from 9.87 MW to 3.94 MW for the same range of generation deficits.

For this generation contingency the maximum bus voltage obtained by the proposed method remains constant at 1.082 pu and the minimum voltage varies between 1.00 pu and 1.08 pu. Whereas in PALM the maximum voltage decreases from 1.1 pu to 0.8786 pu and the minimum voltage magnitude varies from 0.9353 pu to 0.77 pu and in GTBKTT the maximum voltage is constant at 1.1 pu and minimum voltage magnitude increases from 0.9576 pu to 1.0125 pu.

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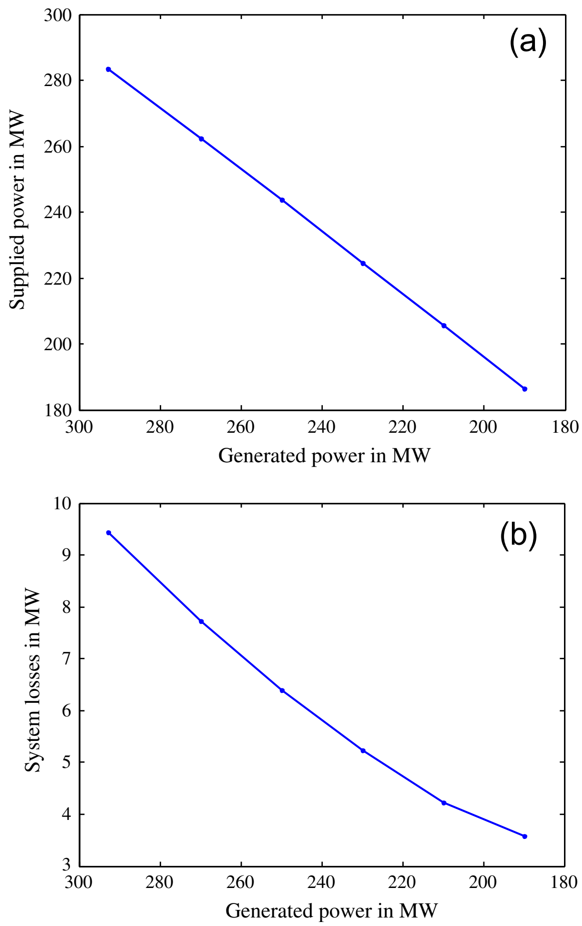

Figure 7 IEEE 30 – bus system under generation deficit contingencies (a) – optimal supplied power, (b) – system losses.

For IEEE 30 – bus system, bus 5 is the bus with heaviest load and bus 8 is the bus with second heaviest load. The supplied powers by the proposed GSO approach at bus 5 and bus 8 are 88.46 MW and 26.89 MW respectively at a generation of 250 MW, whereas the supplied powers using PALM and GTBKTT at bus 5 and at bus 8 are 88.46 MW and 26.89 MW respectively and 80.70 MW and 25.80 MW respectively. The proposed approach supplies more power at the heaviest loaded buses – bus 5 and bus 8 – as compared to the methods PALM and GTBKTT.

4.2. Application to medium size systems

IEEE 57- and 118-bus test systems are considered here. In this section the results obtained by the proposed approach under normal and abnormal operating conditions – generation contingencies – are compared with those obtained using PALM and GTBKTT.

The *NP* of the proposed GSO algorithm applied for these test systems is assumed as 50.

4.2.1. IEEE 57-bus system

The total connected active load for the 57 bus system is 1251.1 MW with maximum available power generation of 1440 MW including spinning reserve. Table 11 shows the comparison of the total supplied power to the connected load, the corresponding system losses and the bus voltages obtained by the NR method with VDLM used in the proposed approach with those obtained by the other methods under normal operating condition. The deficit in the supplied power obtained using the proposed approach and PALM represents the effect of using a VDLM to express the active power.

4.2.1.1. Loss of generation contingency. The results obtained when an abnormal operating conditions representing the loss of generating unit – 3 are presented in Table 12. In the table the total load shed, total system losses and bus voltage variations are compared with other methods. From the table it is observed that the total load shed obtained using the proposed approach is lower when compared with those obtained using PALM and GTBKTT.

The convergence characteristics of the proposed approach for this generation contingency is shown in Fig. 8 and from the curve it can be observed that the maximum number of iterations required to converge is 67.

4.2.2. IEEE 118 – bus system

The total connected load for the 118 – bus system is 3668 MW with maximum available power generation of 4080 MW

Table 11 Comparison of total supplied power, total system losses and bus voltages for IEEE 57 – bus system under normal operating conditions.

Method	Total supplied power (MW)	Total system losses (% of the nominal demand)	Bus voltage variation (pu)
Proposed method (this work)	1238.780	1.76	0.99–1.04
PALM [1]	1236.80	1.521	0.81–1.03
GTBKTT [2]	1251	1.835	0.90–1.14

Table 12 Comparison of total load shed, total system losses and bus voltages for IEEE 57 – bus system under abnormal operating conditions (loss of generation).

Method	Total load shed	Total system losses (% of the nominal demand)	Bus voltage variation (pu)
Proposed method (this work)	174.8135 MW or 13.97% of the nominal load	1.52	0.9800–1.04
PALM [1]	190.55 MW or 15.23% of the nominal load	1.554	0.80–0.96
GTBKTT [2]	183.36 MW or 14.66% of the nominal load	0.98	1.0125–1.2

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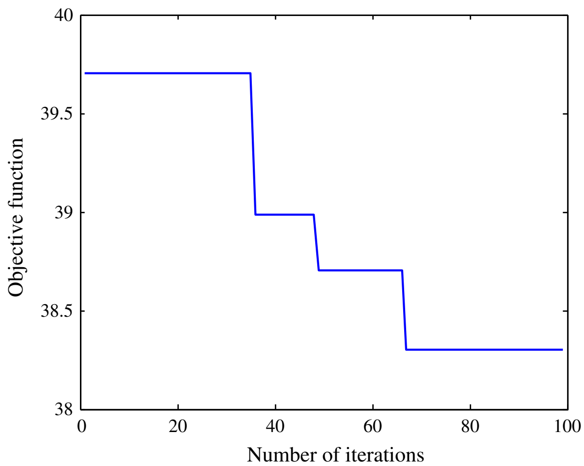

Figure 8 Convergence characteristics of GSO approach for 57 – bus system under loss of generation contingency.

Table 13 Comparison of total supplied power, total system losses and bus voltages for the IEEE 118 – bus test system under normal operating conditions.

Method	Total supplied power (MW)	Total system losses (% of the nominal load)	Bus voltage variation (pu)
Proposed method (this work)	3663.12	3.95	0.95–1.17
PALM [1]	3662.17	2.67	0.92–1.20
GTBKTT [2]	3668	4.706	0.914–1.20

including spinning reserve. Table 13 shows the total supplied power to the connected load, the corresponding system losses and the bus voltages obtained by the NR method with VDLM used in the proposed approach and the results obtained by the other methods under normal operating condition. The deficit in the supplied power obtained using the proposed approach and PALM represents the effect of using a VDLM to express the active power. For this system two scenarios are analyzed. In the first scenario, no contingency is considered, however, the load-shed aim to preventively increase the pre-contingency loadability margin to a level no less than 130%. Here, the objective is to minimize the total load shed. In the second scenario, loss of generation contingencies is considered.

4.2.2.1. Preventive control (first scenario). Table 14 shows the comparison of the total amount of load shed to increase the pre-contingency loadability margin of the test system to 130% of its base load, obtained by the proposed approach with those obtained by parallel differential approach (P-DE) [19], sensitivity based method (SBM) [20] and multi-stage method (MSM) [21,22]. From Table 14, it can be observed that the optimal load shed obtained by the proposed approach is less than those presented in the earlier works. This is due to the fact that the proposed objective function considers both active and reactive power of the loads to be shed, whereas, the methods P-DE [19], SBM [20] and MSM [21–22] have considered only the active power of the loads to be shed in the

Table 14 Comparison of total load shed for the IEEE 118 – bus system under pre-contingency loadability margin of 130% of the base load of the test system.

Method	Load shed (MW)
Proposed method (this work)	299.7599
P-DE [19]	305.1
SBM [20]	318.4
MSM [21,22]	318.8

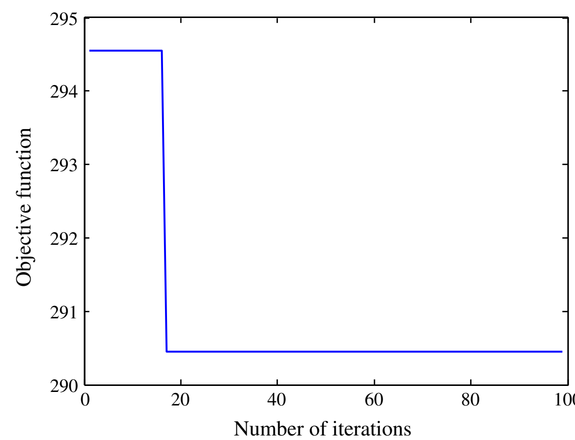

Figure 9 Convergence characteristics of GSO approach for IEEE 118 – bus system under pre-contingency loadability margin of 130% of the base load of the test system.

optimal load shedding problem. Fig. 9 shows the convergence characteristics of the proposed approach for this condition. From the curve, it can be observed that the proposed approach has taken a maximum of 18 iterations to converge.

4.2.2.2. Loss of generation contingencies (second scenario). Here, two cases of generation contingencies are considered. In the first case, loss of generating unit – 54 generating 300 MW along with decrease in the available generation at unit – 12 from 300 MW to 120 MW, which means the loss of 480 MW or 11.77% of the available power is considered. In the second case the loss of generating units 12, 54 and 111, which means loss of 900 MW or 22.05% of the available power, is considered. Table 15 shows the comparison of the total load shed, system losses and bus voltage variations for both the first case and second case. From the table, it is observed that for the first case the total load shed by the proposed approach is lower when compared with those obtained using PALM and GTBKTT. The corresponding convergence characteristics of the proposed approach is shown in Fig. 10(a) and from the curve it can be observed that the maximum number of iterations required by the proposed approach to converge is 25 iterations.

The second case of generation contingency considered for this test system represents a large disturbance where three units in the system are lost. The total load shed, total system losses and bus voltage variations for the second case obtained by the proposed method and various methods reported earlier are compared in Table 15. From the table it is observed that the total load shed by the proposed approach for this case is lower

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Table 15 Comparison of total load shed, total system losses and bus voltages for IEEE 118 – bus system under abnormal operating conditions (loss of generation) considered both in first case and second case.

Method	First case			Second case		
	Total load shed	Total system losses (% of the nominal load)	Bus voltage variation (pu)	Total load shed	Total system losses (% of the nominal load)	Bus voltage variation (pu)
Proposed method (this work)	185.5988 MW or 5.062% of the connected load	3.23	0.933–1.116	561.9143 MW or 15.3265% of the connected load	2.908	0.9–1.1098
PALM [1]	227.33 MW or 6.20% of the nominal load	4.34	0.95–1.09	595.59 MW or 16.24% of the nominal load.	2.93	0.90–1.08
GTBKTT [2]	189.66 MW or 5.17% of the nominal load	3.32	1.097–1.2	563.40 MW or 15.36% of the nominal load.	2.05	1.1–1.20.

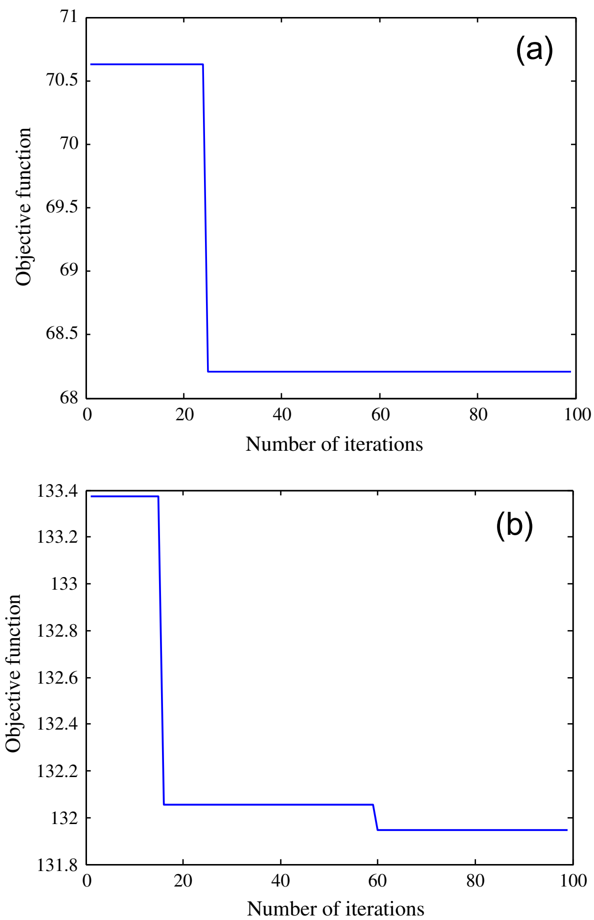

Figure 10 Convergence characteristics of GSO approach for 118 – bus system under generation loss contingencies (a) – first case, (b) – second case.

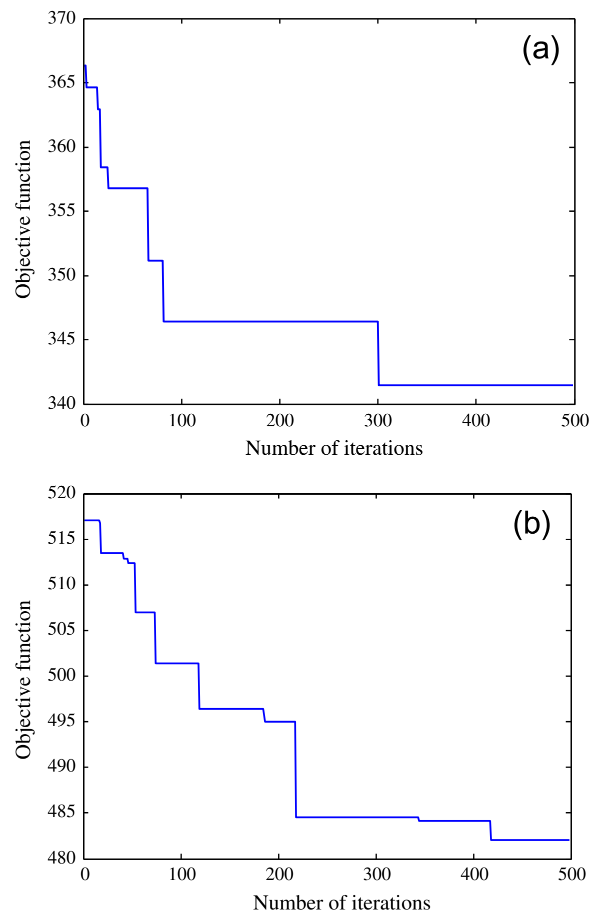

Figure 11 Convergence characteristics of GSO approach for 246 – bus system under generation loss contingencies (a) – first case, (b) – second case.

when compared with those obtained using PALM and GTBKTT.

The proposed approach took a maximum of 60 iterations to converge for this case and the corresponding convergence characteristic is shown in Fig. 10(b). The number of iterations required is increased in this case because the severity of the contingency considered here is more than the previous case.

4.3. Application to large size system

A large system of NRPG of Power Grid Corporation of India Limited is considered in this section. The reduced NRPG system (220 kV and 400 kV only) network consists of 246 buses, 376 branches (lines/transformers), 42 generating units and 40 shunt reactors. The total connected active load for this test system is 20,452 MW and the method dispatches an active power of 12,545 MW. Under normal operating conditions, for the 246-bus system the NR method with VDLM used in the proposed approach supplies 20,448 MW to the connected load with the corresponding system losses of 1753.781 MW which is 8.57% of the nominal load. The optimal bus voltages for the 246 bus test system vary between 0.8946 pu and 1.697 pu.

This test system is subjected to an abnormal operating condition representing the generation loss of 400 MW and 800 MW at buses 12 and 13 respectively in the first case and in the second case, an abnormal operating condition representing the generation loss of 1000 MW and 500 MW at buses 13 and 18 respectively are considered. The *NP* of the proposed GSO algorithm applied to this system is assumed as 20. For the abnormal condition considered in first case the proposed approach supplies 14,188.105 MW to the connected load after shedding a load of 6263.9 MW. The corresponding system loss is 590.337 MW. The system bus voltage varies between 0.9748 pu and 1.3157 pu. Fig. 11(a) shows the convergence characteristics of the GSO approach for the first case. The curve shows that the proposed approach requires 300 iterations to converge.

For the second case of abnormal condition the proposed approach supplies 13,196.044 MW to the connected load after shedding a load of 7256.0 MW. The corresponding system loss is 537.448 MW. Fig. 11(b) shows the convergence characteristics of the GSO approach for this case. Figure also shows that the proposed approach requires 425 iterations to converge. Compared to the small and medium system the proposed approach took more number of iterations to converge when applied to this system. This is because the number of decision variable is more in this test system when compared to the other test system. Also the number of iterations required for this case is more than that of the previous case.

5. Conclusion

In this paper, an optimal load shedding strategy using GSO algorithm has been presented. The proposed approach has been tested on IEEE 14, 30, 57, 118 and NRPG-Indian 246 – bus test systems. The results obtained by the proposed approach are compared with those obtained by conventional methods. The comparison is done on the basis of supplied power, system losses, total load shed and the minimum and maximum bus voltages. The results presented show that the proposed approach provides more supplied power and better voltage profile as compared with those of other methods. Also, the proposed method supplies more power to the heaviest load buses in the case of IEEE 14- and 30 – bus test systems, as compared with the power supplied by the other methods. The proposed approach has better convergence characteristics. Based on these results, it is concluded that the proposed GSO algorithm can be considered as an effective alternative approach for the optimal load shedding problem.

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