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Steady state load shedding to mitigate blackout in power systems using an improved harmony search algorithm

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Abstract Generation contingencies in a power system lead to under-frequency and low voltages owing to active and reactive power deficiencies. 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 music inspired optimization algorithm known as improved harmony search algorithm (IHSA). 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 and 118 bus test systems. The viability of the proposed method in terms of solution quality and convergence properties is compared with the other conventional methods reported earlier.

1. Introduction

Power systems are designed to be operated for normal conditions including a margin for emergencies. Under these conditions the generation and transmission capacities are adequate. The main objective of the power utility is to operate the power system without violating the system constraints and operational limits. But under certain situations such as sudden increase in system demand or unexpected outages, the system constraints and operational limits are violated. Load shedding is considered as a last resort to avoid cascaded tripping and blackout. It is defined as coordinated sets of controls that decrease the electric load in the system to restore the system back 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 of load shedding either in steady state or in transient state have been proposed. An optimal load shedding program finds a best steady-state stable operating point for a post contingency system with a minimum amount of load shed.

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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 has been formulated in [1]. A voltage dependent load model is used to express the active and reactive power demands. Systematic approaches toward 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 has 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. Corrective and preventive control strategies to mitigate power system voltage collapse during severe contingencies have been proposed in [20].

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 is not considered [13–22]. 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 improved harmony search algorithm (IHSA) 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:

- 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 IHS algorithm is discussed in Section 3. Results obtained for the test systems, namely, IEEE 14, 30-bus representing small and a 118-bus representing medium power 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].

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

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 loads. The weighting factors α_i and β_i are problem dependent constants. In order to validate the results obtained with those of other conventional methods considered for validation, flat values are assigned to the priorities of the loads.

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

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

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

where P_{Gi} and Q_{Gi} are the active and reactive powers generated at bus 'i'. The active and reactive power injections at bus i in terms of bus voltage magnitude and phase angle are expressed as

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

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

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

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

$$Q_{Gi}^{\min} \leqslant Q_{Gi} \leqslant Q_{Gi}^{\max} \quad i = 1,\ldots,NG \quad (7)$$

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

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

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

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

$$P_{di} = \overline{P}_{di}\left[P_p + P_c\left(\frac{V_i}{\overline{V}_i}\right)^{N_1} + P_z\left(\frac{V_i}{\overline{V}_i}\right)^{N_2}\right] \quad (10)$$

$$Q_{di} = \overline{Q}_{di}\left[Q_q + Q_c\left(\frac{V_i}{\overline{V}_i}\right)^{N_3} + Q_z\left(\frac{V_i}{\overline{V}_i}\right)^{N_4}\right] \quad (11)$$

where P_p, P_c, P_z, Q_q, Q_c and Q_z are constants associated with this voltage dependent load model (VDLM) and N_1, N_2, N_3 and N_4 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

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

3. Improved harmony search algorithm

This section describes the proposed improved harmony search (IHS) algorithm. A brief overview of harmony search (HS) algorithm is given first and then the modification procedures of the proposed IHS algorithm are stated.

3.1. Harmony search algorithm

In recent years for solving complex engineering optimization problems, the heuristic and/or meta-heuristic methods, also called nontraditional optimization methods, have emerged as a powerful and popular method to obtain better solutions. These methods are versatile in solving multidimensional and complex non-linear equations. This algorithm is inspired by the music improvisation process in which the musician seeks for harmony and continues to tune the pitches to obtain a better harmony [23]. The effort of musicians to find the harmony in music is analogous to the search for a best state (i.e., global optimum) in an optimization process. The HS algorithm has several advantages compared to the traditional optimization techniques and has been very successful in solving a wide variety of optimization problems [24,25].

The design parameters of the HS algorithm are as follows:

Harmony is the set of the values of all the variables of the objective function. Each harmony is a possible solution vector.
Harmony memory(*HM*) is the location where harmonies are stored.
Harmony memory size (*HMS*) is the number of solution vectors in the harmony memory.
Harmony memory considering rate (*HMCR*) is the probability of selecting a component of the solution vector in *HM*.
Pitch adjusting rate (*PAR*) determines the probability of mutating a component of the solution vector from the *HM*.

The HS algorithm consists of the following steps:

Step 1: Initialization of the optimization problem and algorithm parameters

The problem to be optimized is formulated in the structure of optimization problem, having an objective function and constraints as

$$\begin{aligned} &Minimise(or\ Maximise) f(\vec{x}) \\ &subject\ to\ x_i \in X_i, \quad i = 1, \ldots, N \end{aligned} \tag{13}$$

where $f(\vec{x})$ is the objective function with $\vec{x}$ as the solution vector composed of decision variables x_i, and X_i is the set of feasible range of values for each decision variable $x_i({}_Lx_i \leqslant X_i \leqslant {}_Ux_i)$, where ${}_Lx_i$ and ${}_Ux_i$ are the respective lower and upper limits for each decision variable. N is the number of decision variables of the problem. The values of the various parameters of HS algorithm such as *HMS*, *HMCR*, *PAR* and the maximum number of iterations are also specified in this step.

Step 2: Initialization of the Harmony Memory (HM)

The harmony memory is initialized by randomly generating *HMS* number of solution vectors for the formulated optimization problem. Each component of the solution vector in *HM* is initialized using the uniformly distributed random number between the lower and upper bounds of the corresponding decision variable $[{}_Lx_i, {}_Ux_i]$, for $1 \leqslant i \leqslant N$. The ith component of the jth solution vector is as follows:

$$x_i^j = {}_Lx_i + ({}_Ux_i - {}_Lx_i) \cdot rand[0,1] \tag{14}$$

where $j = 1, 2, \ldots, HMS$ and $rand$ [0, 1] is a uniformly distributed random number between 0 and 1.

The *HM* matrix with *HMS* number of solution vectors is expressed as

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \ldots x_{N-1}^{HMS-1} x_N^{HMS-1} & & \\ & x_1^{HMS} & x_2^{HMS} \ldots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \tag{15}$$

The value of the objective function is calculated for each solution vector of this *HM* matrix

Step 3: Improvisation of new harmony from the HM

HM is improved by generating a new harmony vector $\bar{x}' = (x_1' x_2' x_3' \cdots x_N')$.

Each component of the this vector is generated using

$$x_i' \leftarrow \begin{cases} x_i' \in HM(i) & with\ probability\ HMCR \\ x_i' \in X_i & with\ probability\ (1 - HMCR) \end{cases} \tag{16}$$

where $HM(i)$ is the ith column of the *HM*, *HMCR* is already defined as the probability of selecting a component from the *HM* members and $(1 - HMCR)$ is, therefore, the probability of randomly generating a component within the range of values. After the generation of x_i' from the *HM* it is further mutated (pitch adjustment) according to *PAR* which determines whether the generated component is to be adjusted or not. The pitch adjustment for a generated x_i' is given as

$$x_i' \leftarrow \begin{cases} x_i' \pm rand[0,1] \cdot bw & with\ probability\ PAR \\ x_i' & with\ probability\ (1 - PAR) \end{cases} \tag{17}$$

where *bw* is an arbitrary distance bandwidth for the continuous design variable.

Step 4: Updating the HM

For updating the *HM*, the value of the objective function is calculated using the newly generated harmony vector $\bar{x}_i'$.

If this new value is better than the worst harmony in the *HM*, judged in terms of the objective function value, then the *HM* is updated by replacing the worst harmony by the new harmony.

The steps 3 and 4 are repeated until the maximum number of iterations is reached. Finally, the best solution is chosen from the final *HM* and it is considered as the optimal solution for the formulated optimization problem.

3.2. Proposed improved harmony search algorithm

The parameters *HMCR*, *PAR* and *bw*, given in Step 3, help the algorithm to find globally and locally improved solutions [25,26]. In HS algorithm *PAR* and *bw* are very important parameters in fine-tuning of the optimal solution vectors and adjusting the convergence rate of the algorithm effectively. So it is of great interest in the fine adjustment of these parameters. In HS algorithm the values of both *PAR* and *bw* are fixed in the initialization step (Step 1) and cannot be varied during new generations.

In order to improve the performance of the algorithm and to reduce the computational time needed to find the optimal solution, initially a large *bw* with small *PAR* must be considered to increase the diversification (or exploration) of the search. However in the final iterations the value of PAR must be large with small bw to improve the intensification (or exploitation) of the search. Therefore having fixed values of PAR and bw in HS algorithm will deteriorate the performance of the algorithm and also increase the computation time. This main drawback of HS algorithm can be eliminated by IHS algorithm reported in [27]. In IHS algorithm, the values of PAR and bw are dynamically updated in each iteration.

IHS consists of the same steps as those in HS algorithm except Step 3, where the value of parameter PAR is increased linearly and the value of parameter bw is decreased exponentially with the number of iterations. The mathematical expression for PAR and bw is given by Eqs. (18) and (19) respectively.

$$PAR(iter) = PAR_{\min} + (PAR_{\max} - PAR_{\max}) \cdot \left(\frac{iter}{Maxiter}\right) \tag{18}$$

where $PAR_{\min}$ is the minimum pitch adjustment rate, $PAR_{\max}$ is the maximum pitch adjustment rate, $iter$ is the current iteration and $Maxiter$ is the maximum number of iterations.

$$bw(iter) = bw_{\max} \cdot \exp\left[\left\{\ln\left(\frac{bw_{\min}}{bw_{\max}}\right)\right\} \cdot \left(\frac{iter}{Maxiter}\right)\right] \tag{19}$$

where $bw_{\min}$ is the minimum bandwidth and $bw_{\max}$ is the maximum bandwidth.The value of $bw_{\min}$ and $bw_{\max}$ greatly influences the performance of the algorithm.

3.2.1. Implementation of proposed IHS algorithm to optimal load shedding problem

The implementation of the IHS algorithm to the proposed problem can be explained in the following steps.

The active and reactive power loads to be shed at each bus are considered as the variables of the optimal load shedding problem. Each harmony corresponds to a solution vector of these variables. These values of the variables are stored in a location called harmony memory. The number of these solution vectors in the harmony memory is the harmony size.

Step 1: The solution vectors are randomly initialized. With the generated solutions the value of the objective function is calculated using Eq. (12).
Step 2: The HM is improved by generating new solution vector using Eq. (16).
Step 3: The generated solution is further mutated based on pitch adjustment rate using Eq. (17). Here the values of PAR and bw are calculated using Eqs. (18) and (19) respectively.
Step 4: With the newly generated solution the objective function is calculated using Eq. (12).
Step 5: The HM is updated by replacing the worst harmony by the new harmony.
Step 6: The steps 3–5 are repeated until maximum number of iterations are reached.

4. Simulation results and analysis

The proposed IHS algorithm has been verified on two small systems – IEEE 14-bus and 30-bus and one medium system – IEEE 118-bus test system. The results obtained by the proposed approach are compared with those obtained by using conventional methods reported earlier, such as projected augmented lagrangian method (PALM) implemented using MINOS – an optimization package [1,4], gradient technique based on Kuhn-Tucker theorem (GTBKTT) [2] and second order gradient technique (SOGT) [3]. Since there are no recent researches that have considered this objective function, we have validated our results with [1–3] and [4]. As these works use conventional methods they are ideal for validation. The single line diagram and the detailed data of IEEE-14, 30 and 118-bus systems are given in [11]. The software was written in Matlab and executed on 2.4 GHz, Intel i3 processor with 2 GB RAM PC.

The decision variables of this problem are the active and reactive power loads 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 remaining 20% of the load is reserved for emergency conditions. The violation of the inequality constraints is penalized in the objective function.

The constants and the powers of the polynomial associated with the load model given in Eqs. (10) and (11) were taken from [3] as

$$P_p = 0.2, P_c = 0.3, P_z = 0.5; \quad Q_q = 0.2, Q_c = 0.3 \text{ and } Q_z = 0.5; \quad N1 = 1, N2 = 2, N3 = 1 \text{ and } N4 = 2.$$

The optimal values of the design parameters of IHS algorithm used in this paper are $HMCR = 0.95$, $PAR\min = 0.4$, $PAR\max = 0.9$, $bw\min = 0.00001$, $bw\max = 1.0$ [27].

4.1. Application to small size systems

IEEE 14, 30-bus test systems are considered here. The two cases of contingencies analyzed are loss of generation and generation deficits. The HMS of the proposed IHS algorithm for these test systems is 100.

4.1.1. IEEE 14-bus system

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

$$0 \leqslant P_{G1} \leqslant 200, \quad 0 \leqslant P_{G2} \leqslant 200$$

The generated reactive power limits are

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

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

The supplied powers obtained using GTBKTT method in [2], SOGT method of [3] reported in [4] and PALM method in [4] are 259.0 MW, 258.81 MW and 258.59 MW respectively

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

Bus	GTBKTT [2]		SOGT[3] reported in [4]		PALM [4]		NR method with VDLM	
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(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	GTBKTT [2]		SOGT [3] reported in [4]		PALM [4]		NR method with VDLM	
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(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

for a connected load of 259 MW. In [1] the supplied power is 258.59 MW for the same connected load. The deficit in the supplied power obtained in this paper and in [1,3,4] represents the effect of using 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 0.9321 pu to 1.035 pu in [2], 0.9765 pu to 1.016 pu in SOGT method [3] reported in [4] and 0.98 pu to 1.07 pu in [1,4]. The main aim of optimal load shedding is to return the system to normal state following generation loss and generation deficit contingencies by minimum load shedding.

4.1.1.1. Loss of generation contingency. The results obtained when an abnormal operating condition representing the loss of generation of 72 MW or 26% of normal generation at bus #2 are presented in Tables 3–5. The connected load is 259.0 MW.

In Table 3 the active and reactive power supplied by the proposed method is compared with those obtained with the other methods. The amount of load shed obtained using the proposed IHS approach is 66.5 MW or 25.676% of the nominal load and the supplied active power is 192.51 MW, whereas the load shed and the supplied active power reported in [2] are 67.0 MW or 25.87% of nominal load and 192 MW respectively. For the same generation loss, the amount of load shed and the active supplied power in [1] and [4] are 71.11 MW or 27.45% of the nominal load and 187.89 MW respectively. It can be observed that the proposed approach has yielded lower amount of load shed and higher supplied active power when compared with other methods reported in [2,1,4].

In [1] it is reported that the method of [3] fails to converge for this contingency. At the end of the optimization the active power supplied is 231.57 MW the system generation being 200 MW. This shows that the system generation is less than the supplied power. Therefore the active power loss becomes negative in this work (Table 5).

Table 4 shows the comparison of the active and reactive power generations obtained by the proposed approach with the other methods. This table shows that the generator at bus # 1 is utilized to its full capacity of 200 MW. 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.

Fig. 1 shows the convergence characteristics of the proposed IHS algorithm for the test system under loss of generation of 72 MW. The maximum number of iterations required by the proposed approach to converge is 16. The values of bus voltages before and after the load shedding for this contingency are shown in Fig. 2. The figure shows that the voltage profile after load shedding has improved when compared with that before load shedding. The bus voltages vary between 1.06 pu and 1.1 pu in the proposed approach, whereas the voltages vary from 1.04883 pu to 1.1 pu in [2] and 0.8065 pu to 0.917 pu in [1,4]. The proposed approach yields better bus voltage profile as compared with other approaches.

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	GTBKTT [2]		SOGT [3] reported in [4]		PALM [4]		Proposed IHS approach	
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(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	17.51	10.562
3	69.53	14.02	84.39	17.02	75.24	15.18	72.298	15.672
4	35.48	−2.90	43.74	−3.57	35.21	−2.87	32.25	−2.603
5	5.66	1.19	7.02	1.48	5.64	1.19	5.630	1.232
6	8.34	5.59	9.83	6.59	7.03	4.71	7.462	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	20.276	11.930
10	6.68	4.31	7.87	5.08	5.75	3.71	7.543	4.217
11	2.60	1.34	3.06	1.58	2.20	1.13	2.682	1.842
12	4.53	1.19	5.29	1.39	3.73	0.98	4.576	1.138
13	10	4.30	11.61	4.99	8.22	3.53	12.041	4.874
14	10.98	3.69	12.62	4.23	9.04	3.03	11.081	3.914
Total	192	54.59	231.57	65.2	187.89	51.13	192.51	59.410

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	GTBKTT [2]		SOGT [3] reported in [4]		PALM [4]		Proposed IHS approach	
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(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	0.0	43.6
3	0.0	0.0	0.0	22.73	0.0	63.34	0.0	25.1
6	0.0	10.15	0.0	25.70	0.0	5.59	0.0	12.7
8	0.0	0.0	0.0	14.71	0.0	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] (MW)	SOGT [3] reported in [4] (MW)	PALM [4] (MW)	Proposed IHS approach (MW)
Normal	12.8454	11.3274	10.6685	13.2
Abnormal	7.9952	−31.5814	12.1111	7.49

4.1.1.2. Range of generation deficits 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 maximum number of iterations required for the proposed approach to converge is 29. 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 shows that better voltage profile is obtained after load shedding as compared with that before load shedding for the generation of 160 MW. For this generation contingencies the maximum bus voltage obtained by the proposed method remains constant at 1.06 pu and the minimum voltage varies between 1.01 pu and 1.022 pu, whereas in [1,4] 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. In [2] the maximum voltage remains constant at 1.2 pu and the minimum voltage increases from 1.1165 pu to 1.1387 pu. The variation in the minimum and maximum voltages obtained in the proposed method is less as compared to those obtained in [1,4,2].

Fig. 5(a) shows the total supplied power obtained by the proposed approach decreases from 249.694 MW at 260 MW generations to 154.292 MW at 160 MW generations. Fig. 5(b) shows the corresponding active power loss decrease from 10.306 MW to 5.709 MW, whereas the total supplied power in [1,4] decreases from 249.30 MW at 260 MW generations to 153.78 MW at 160 MW generation with corresponding active power loss decrease from 10.70 MW to

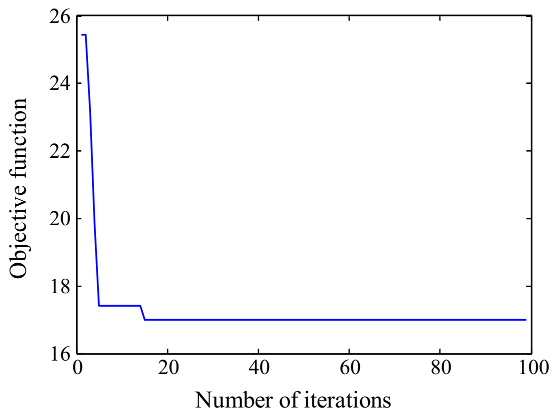

Figure 1 Convergence characteristics of IHS approach for IEEE under loss of generation of 72 MW.

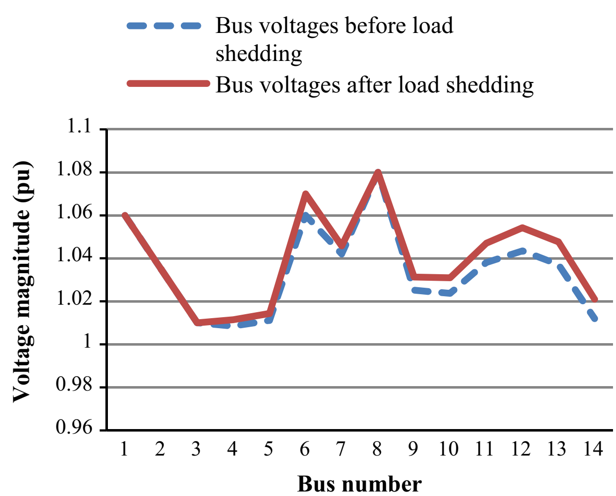

Figure 2 Bus voltages before and after load shedding for IEEE 14-bus system under loss of generation of 72 MW.

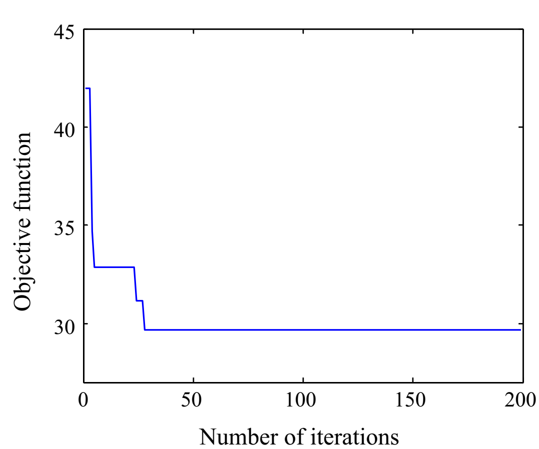

Figure 3 Convergence characteristics of IHS approach for IEEE 14-bus system under generation deficit contingency.

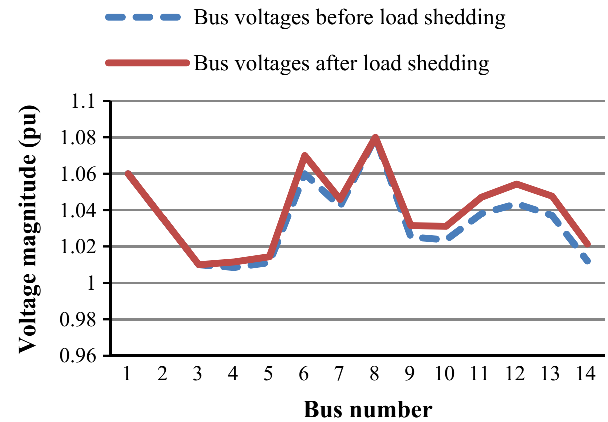

Figure 4 Bus voltages before and after load shedding for IEEE 14-bus system under generation deficit contingency.

6.22 MW. In [2] 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 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 buses 3 and 4 by the proposed IHS approach are 90.6 MW and 45.640 MW respectively. In [1,4] the supplied powers at bus 3 and bus 4 are 85.52 MW and 39.70 MW respectively. The supplied powers at bus 3 in [2] are 78.02 MW and at bus 4 it is 36.69 MW. The proposed approach supplies more power to the heavily loaded buses as compared to [1,2,4].

4.1.2. IEEE 30-bus system

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

$$0 \leqslant P_{G1} \leqslant 175,\ 0 \leqslant P_{G2} \leqslant 70 \text{ and } 0 \leqslant P_{G5} \leqslant 75$$

The generated reactive power limits are

$$-20 \leqslant Q_{G1} \leqslant 43,\ -10 \leqslant Q_{G8} \leqslant 30,\ -20 \leqslant Q_{G2} \leqslant 43,\ -10 \leqslant Q_{G11} \leqslant 45,\ -20 \leqslant Q_{G5} \leqslant 50 \ \text{ and } \ -10 \leqslant Q_{G13} \leqslant 50$$

Tables 6 and 7 present the active and reactive power supplied and generated for the test system under normal operating conditions obtained in this paper and the other methods. The supplied power by the NR method with VDLM used here under normal operating conditions is 281.579 MW for a connected load of 283.40 MW, while the active power generation is 290 MW.

The supplied powers obtained using GTBKTT method in [2], SOGT method of [3] reported in [4] and PALM method in [4] are 283.30 MW, 280.313 MW and 279.85 MW respectively for a connected load of 283.40 MW. The supplied power using PALM method in [1] is 279.85 MW. The active and reactive power supplied at each bus obtained in this paper, is almost the same as those obtained in other methods. The deficit in the supplied power obtained here and in [1,3,4] 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 the voltages vary from 0.92475

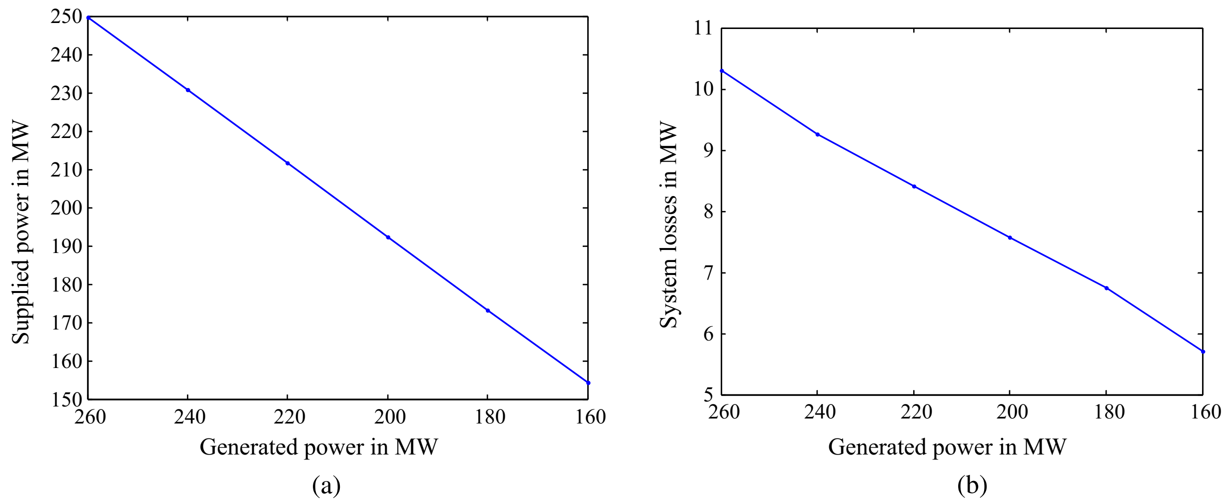

Figure 5 IEEE 14-bus system under generation deficit contingencies (a) – optimal supplied load, (b) – system losses.

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

Bus	GTBKTT [2]		SOGT [3] reported in [4]		PALM [4]		NR method with VDLM	
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(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

pu to 1.10 pu in [2], 0.9319 pu to 1.088 pu in SOGT method of [3] reported in [4] and 0.93493 pu to 1.10 pu in [1,4]. The test system is subjected to the same generation contingencies which 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. In Table 8 the active and reactive power supplied obtained by the proposed IHS approach is compared with

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

Bus	GTBKTT [2]		SOGT [3] reported in [4]		PALM [4]		NR method with VDLM	
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(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

other methods. The connected load is 283.40 MW. The amount of load shed obtained using the proposed method is 38.467 MW or 13.55% of the nominal load and the active supplied power is 243.8201 MW, whereas the load shed and the active supplied power in [2] are 40.73 MW or 14.38% of the nominal load and 242.67 MW respectively. For the same generation loss, the amount of load shed and the active supplied power in [1] and [4] are 42.69 MW or 15.07% of the nominal load and 240.60 MW respectively. It can be observed that the proposed approach has yielded lower amount of load shed and higher supplied active power when compared with other methods reported in [2]; [1] and [4]. As mentioned before, the method of [3] fails to converge for this case also. After the termination of the optimization process this method supplies 256.75 MW with a system generation of 250.00 MW. This shows that for this case also the system generation is less than the supplied power. Therefore the active power loss becomes negative in this method (Table 10).

Table 9 shows the comparison of the active and reactive power generations under abnormal operating condition (loss of generation), obtained by the proposed approach with the other methods. The active power loss obtained for this test system under normal operating condition and abnormal operating condition representing loss of generation of 60 MW, by the

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	GTBKTT [2]		SOGT [3] reported in [4]		PALM [4]		Proposed IHS approach	
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(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	18.7682	10.7817
3	2.07	1.04	2.32	1.16	2.24	1.12	2.0760	1.0196
4	6.53	1.38	7.29	1.54	7.03	1.48	6.4590	1.3158
5	80.41	16.22	83.05	16.75	77.95	15.72	82.4911	16.3026
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	20.2169	9.0008
8	25.8	25.73	28.65	28.66	27.98	27.98	25.9163	24.3288
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	4.9325	1.7070
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	9.0059	6.1845
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	5.2338	1.3239
15	7.02	2.14	7.35	2.24	6.57	2	7.2812	2.1228
16	3	1.54	3.19	1.64	2.91	1.50	3.0577	1.5337
17	7.73	4.98	8.26	5.33	7.74	4.99	7.2847	4.9727
18	2.74	0.77	2.86	0.80	2.58	0.73	2.6341	0.7242
19	8.13	2.91	8.5	3.04	7.76	2.78	7.7601	2.9861
20	1.89	0.60	1.99	0.63	1.83	0.58	1.9455	0.5675
21	15.01	9.61	15.97	10.22	15.02	9.61	14.8864	9.2291
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	2.8307	1.4026
24	7.44	5.73	7.73	5.95	7.08	5.45	7.3104	5.9551
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	2.9071	1.9637
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	2.1124	0.7906
30	9.02	1.62	8.99	1.61	8.03	1.44	8.7102	1.5933
Total	242.67	108.170	256.750	115.940	240.60	109.320	243.8201	105.8061

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

Bus	GTBKTT [2]		SOGT [3] reported in [4]		PALM [4]		Proposed IHS approach	
	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(MVAR)	(MW)	(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] (MW)	SOGT [3] reported in [4] (MW)	PALM [4] (MW)	Proposed IHS approach (MW)
Normal	11.5363	10.6598	11.4053	8.421
Abnormal	7.4302	−6.7483	9.4087	6.180

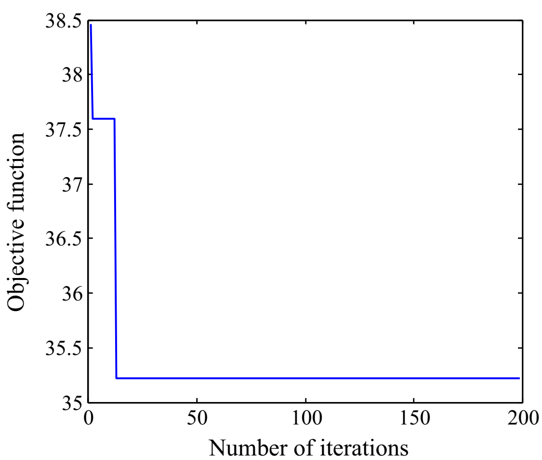

Figure 6 Convergence characteristics of IHS algorithm for IEEE 30-bus system under loss of generation of 60 MW.

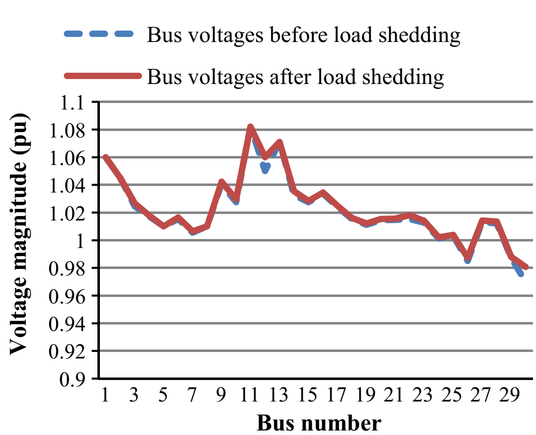

Figure 7 Bus voltages before and after load shedding for IEEE 30-bus system under loss of generation of 60 MW.

proposed approach and the other methods is tabulated in Table 10.

Fig. 6 shows the convergence characteristics of the proposed IHS approach for the test system operated under loss of generation of 60 MW. The number of iterations required for the proposed approach to converge is 13. The values of bus voltages before and after the load shedding for this contingency are shown in Fig. 7. The figure shows that the voltage profile after load shedding has improved when compared with that before load shedding. The bus voltages vary between 0.99842 pu and 1.105 pu in the proposed approach whereas the voltages vary from 0.99806 pu to 1.10 pu in [2] and 0.8920 pu to 1.0630 pu in [1,4].

4.1.2.2. Range of generation deficits contingencies. The test system is also subjected to contingencies characterized by generation deficits. The range of generation is varied from

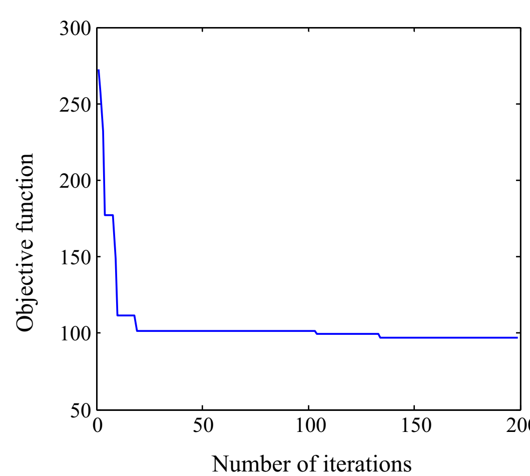

Figure 8 Convergence characteristics of IHS algorithm for IEEE 30-bus system under generation deficit contingency.

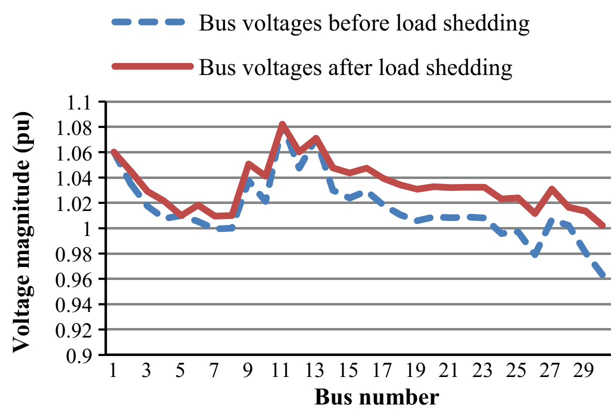

Figure 9 Bus voltages before and after load shedding for IEEE 30-bus system under generation deficit contingency.

300 MW to 190 MW, with a connected load of 283.3 MW, which means, the resulting generation deficit varies from 0 to 93.3 MW. The convergence characteristics of the proposed approach for the generation of 190 MW are shown in Fig. 8 and from the figure it can be observed that the maximum number of iterations required by the proposed approach to converge is 18. The number of iterations required is increased in this case because the severity of this contingency is more than that of the previous case representing loss of generation of 60 MW.

Fig. 9 shows better voltage profile is obtained after load shedding as compared with that before load shedding for the generation of 190 MW. For this generation contingency the maximum bus voltage obtained by the proposed method remains constant at 1.081 pu and the minimum voltage varies between 1.014 pu and 0.991 pu, whereas in [1] and [4] 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. In [2] the maximum voltage remains constant at 1.1 pu and the minimum voltage increases from 1.0125 pu to 0.9576 pu. The variation in the minimum and maximum voltage magnitude obtained in the proposed method is less as compared to those obtained in [1,4,2].

Fig. 10(a) shows the total supplied power obtained by the proposed approach decreases from 287.14 MW at 293 MW generations to 188.252 MW at 190 MW generations and Fig. 10(b) shows the corresponding active power loss decreases from 9.25 MW to 3.12 MW, whereas the total supplied power in [1,4] 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 in [2] 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 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 IHS approach at bus 5 and bus 8 are 90.01 MW and 27.94 MW respectively at a generation of

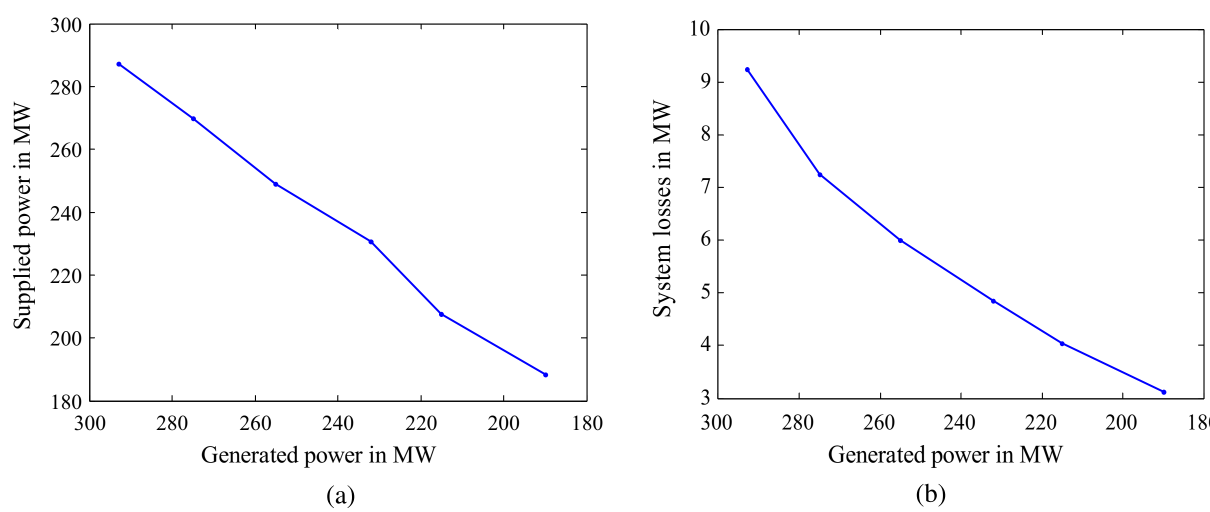

Figure 10 IEEE 30-bus system under generation deficit contingencies (a) – optimal supplied power, (b) – system losses.

Table 11 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 (vary between)
NR method with VDLM	3663.12	3.95	0.95 pu and 1.17 pu.
PALM [1]	3662.17	2.67	0.92 pu and 1.20 pu.
GTBKTT [2]	3668	4.706	0.914 pu and 1.20 pu.

Table 12 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)	294.812
P-DE [19]	305.1
SBM [20]	318.4
MSM [21,22]	318.8

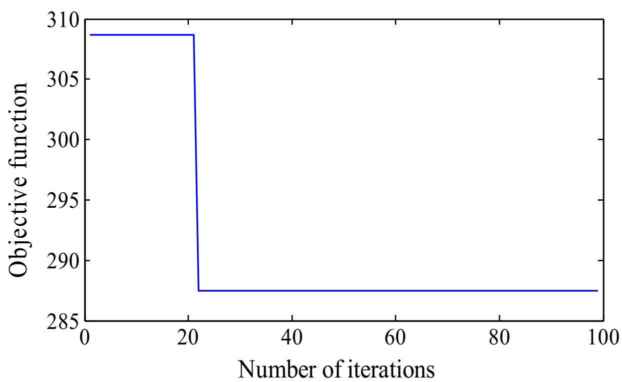

Figure 11 Convergence characteristics of IHS approach for IEEE 118-bus system under pre-contingency loadability margin of 130% of the base load of the test system.

250 MW. In [1,4] the supplied powers at bus 5 and at bus 8 are 88.46 MW and 26.89 MW respectively, whereas the supplied power at bus 5 in [2] is 80.70 MW and at bus 8 it is 25.80 MW. The proposed approach supplies more power to the heavily loaded buses as compared to [1,4,2].

4.2. Application to medium size system

IEEE 118-bus system is considered here and the data of this test system are taken from [11]. In this section the results obtained by the proposed approach under normal and abnormal operating conditions – generation contingencies – are compared with those results obtained in [1,2]. The *HMS* of the proposed IHS algorithm applied to these test systems is assumed as 50.

4.2.1. IEEE 118-bus system

The total connected load for the 118- bus system is 3668 MW with maximum available power generation of 4080 MW including spinning reserve. The connected load is 3666.6129 MW. Table 11 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 here and the results obtained by the other methods under normal operating condition. For this system two scenarios are analyzed. In the first scenario, no contingency is considered; however, the load-shed aims 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.

Table 13 Comparison of total load shedding, total system losses and bus voltages for the IEEE 118-bus test system under abnormal operating conditions (loss of generation) considered in both first case and second case.

Method	First case			Second case		
	Total load shed	Total system losses (% of the nominal load)	Bus voltage variation (vary between)	Total load shed	Total system losses (% of the nominal load)	Bus voltage variation (vary between)
Proposed IHS approach	182.2 MW or 4.969% of the nominal load	2.71	0.92 and 1.094 pu	561.6 MW or 15.3165% of the nominal load	3.908	0.94 pu and 1.1 pu.
PALM [1]	227.33 MW or 6.20% of the nominal load	4.34	0.95 and 1.09 pu	595.59 MW or 16.24% of the nominal load	2.93	0.90 pu and 1.08 pu.
GTBKTT [2]	189.66 MW or 5.17% of the nominal load	3.32	1.097 pu and 1.2 pu	563.40 MW or 15.36% of the nominal load	2.05	1.1 and 1.20 pu.

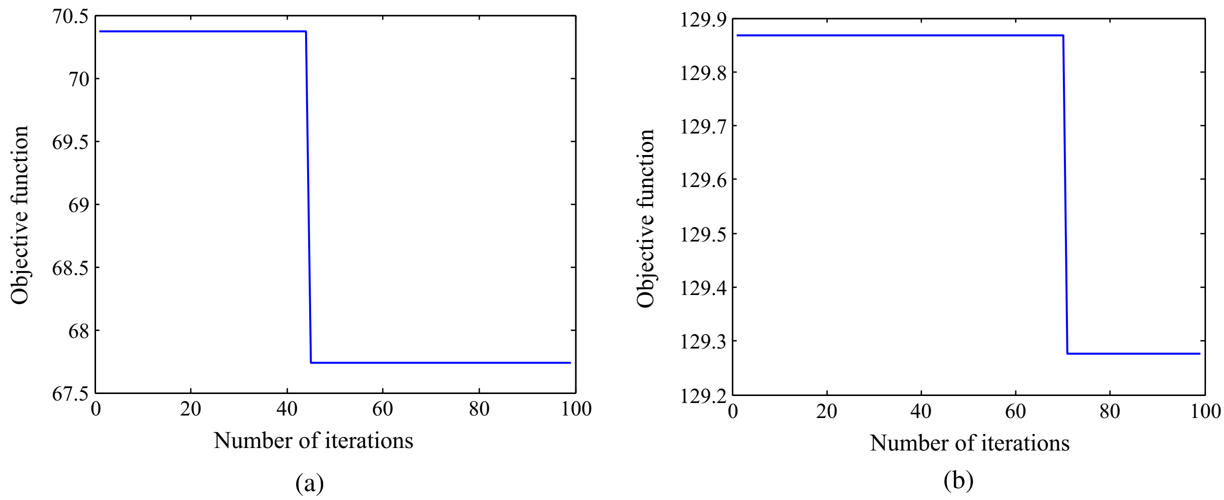

Figure 12 Convergence characteristics of IHS algorithm for 118-bus system under generation loss contingencies (a) – first case and (b) – second case.

4.2.1.1. Preventive control (first scenario). Table 12 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 12, 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 optimal load shedding problem. Fig. 11 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 21 iterations to converge.

4.2.1.2. Loss of generation contingencies (second scenario). Here, two cases of generation contingencies are considered. In the first case, loss of generating unit # 54 generates 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 of the loss of generating units 12, 54 and 111, it means loss of 900 MW or 22.05% of the available power, is considered. Table 13 shows the comparison of the total load shed, system losses and bus voltage variations for both the first and second cases. From the table it is observed that the total load shed obtained by the proposed approach for the first case is lower when compared with those reported in [1,2].

The corresponding convergence characteristic of the proposed approach is shown in Fig. 12(a) and from the figure it can be observed that the maximum number of iterations required by the proposed approach to converge is 47 iterations.

The second case of generation contingency considered for this test system represents a large disturbance where three units in the system are lost. From Table 13 it is observed that the total load shed obtained by the proposed approach for the second case is lower when compared with those obtained in [1,2]. The proposed approach took a maximum of 72 iterations to converge for this case and the corresponding convergence

Table 14 Comparison of total load shedding and bus voltages for the three test systems under abnormal operating conditions (loss of generation) with and without considering reactive power in the problem.

Test system	With reactive power		Without reactive power	
	Total load shed	Bus voltage variation (vary between)	Total load shed	Bus voltage variation (vary between)
IEEE 14-bus	66.5 MW or 25.676% of the nominal load	1.06 pu and 1.1 pu	68.4891 MW or 26.443% of the nominal load	1.01 pu and 1.09 pu
IEEE 30-bus	38.467 MW or 13.573% of the nominal load	0.99842 pu and 1.105 pu	42.6185 MW or 15.038% of the nominal load	0.9388 pu and 1.064 pu
IEEE118-bus (first case)	182.2 MW or 4.969% of the nominal load	0.954 and 1.094 pu.	190.5198 MW or 5.196% of the nominal load	0.8704 pu and 1.083 pu
IEEE 118-bus (second case)	561.6 MW or 15.3165% of the nominal load	0.94 pu and 1.085 pu.	605.2292 MW or 16.506% of the nominal load	0.9008 pu and 1.092 pu

characteristic is shown in Fig. 12(b). As the severity of generation contingency considered in the second case is more than that of the first case, the proposed algorithm requires more number of iterations to converge in this case as compared to the previous case.

4.3. Effect of considering reactive power in the proposed problem

As a point of interest a comparison is done for the results obtained with and without considering the reactive power in the formulated load shedding problem. Table 14 shows this comparison of the results obtained for all the three test systems considered here when subjected to loss of generation contingency. From the table it can be observed that when the reactive power is taken into account the required amount of load shed for the considered contingency is reduced as compared to those obtained without reactive power. Also the improvement in the voltage profile is better with reactive power than without it.

5. Conclusion

In this paper an optimal load shedding strategy using a heuristic technique-IHS approach has been presented. The proposed approach has been tested on IEEE 14, 30 and 118 bus test systems. The results obtained by the proposed approach are compared with those obtained by the conventional methods reported earlier. 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 graphical analysis and tabulated results show that for the considered optimization problem the proposed IHS approach has better performance in terms of convergence and ability to search for a near optimal solution as compared to other methods referred here.

In the proposed IHS algorithm, in addition to randomization, pitch adjustment rate () also controls the exploration characteristics of the algorithm, which is an important factor for its efficiency. Exploitation characteristics of the proposed algorithm are controlled by the harmony memory consideration rate (HMCR). Here, the randomization and HMCR explore the global search space effectively. Similarly, the exploitation is enhanced by the controlled pitch adjustment. Such interaction between various parameters of the algorithm is another important factor for the improved performance and success of the IHS algorithm over other existing algorithms.

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