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Optimal Load Shedding Model based on Sensitivity Analysis for Line Overload Mitigation using Sine Cosine Algorithm

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ABSTRACT: Load shedding as control action plays vital role in preventing the system from cascaded outages and then blackout. Thereby, this approach helps in maintaining secure and reliable functioning of power network. In case contingency arises or predicted loading in forthcoming interval threatens system security, then in such a situation load shedding scheme ought to be planned in anticipation. Load shedding is to be carried out at some suitable buses as it would not be appropriate to perform load shedding at all the buses because it causes inconvenience to the consumer. Therefore, this work presents a model for determining optimum shedding of load at preferred locations to mitigate line overloading. In order to select the buses where the load shed is to be performed, sensitivity analysis is carried out. Sine Cosine Algorithm (SCA) has been applied to determine the optimum load shed as this algorithm possesses the ability to reach the global minimum and requires tuning of only one algorithm-specific parameter. The scheme has been implemented over the IEEE-14 and IEEE-39 bus system. For demonstrating the efficacy, the comparison of results has been carried out. It has been presented that the proposed technique offers superior results pertaining to amount of load shed and successfully alleviates line overloading.

Keywords: Line Overloading Sensitivity; Load Shedding; SCA, Sine-Cosine Algorithm.

Abbreviations: LS, Line Sensitivity; LOS, Line Overload Sensitivity; LOSI, Line Overloading Sensitivity Index; SCA, Sine Cosine Algorithm.

I. INTRODUCTION

The electricity demand has enhanced to a large extent in the last few decades. Numerous factors have an influence on this rapid growth of electricity demand. The transmission network role turns out to be very decisive for proper operation with this rise in demand. Especially under the contemporary market-based environment where for achieving higher economic benefits, often power transmission lines are functioned close to their operational limits.

Since the operating conditions in power network keep on changing and at any instant abnormal situation such as abrupt rise in system loading, outage of network component (generator or transmission line) may take place. Therefore under these circumstances, operational limits may violate and transmission lines may get overloaded. Consequently, suitable means are required to deal with the issues of transmission line overloading.

Load shedding during the abnormal situations is one among the crucial control actions in planning the secure and reliable operation of power systems. Load shedding can be defined as the set of controls through which the decline of load demand can be attained to reach a new balanced state [1]. Load shedding implementation becomes essential to avoid the incident such as line overloading and voltage collapse as these occurrences may lead to cascade outages and then blackout. Load shedding is regarded as a preferred option to stay away from the system-wide blackouts [2].

Therefore, it turns out to be essential to perform load shedding in power network restoration at some preferred buses. Load shedding is to be performed at some suitable buses so that inconvenience faced by the consumers is kept minimum and should not greatly affect the consumers in a localized area. [3].

Optimal load shedding schemes have been proposed in [4-5]. An optimization based means for minimizing load curtailments that are necessary to reinstate equilibrium condition with relaxation of restrictions has been discussed in [6]. To minimize total load shed with consideration of voltage deviation limits and line flows constraints has been presented in [7]. Chattopadhyay and Chakrabarti (2003) proposed load shed scheme taking into consideration load dynamics for preventing voltage collapse [8]. Amraee *et al.,* (2007) utilized static voltage stability margin based severity index with its sensitivity for deciding optimal load sheds at suitable buses [9]. Arya *et al.,* (2013) applied differential evolution to build an optimum load shedding scheme that offers load shed at suitable buses in anticipation for the next predicted loading conditions [10]. Sun *et al.*, (2013) presented a flexible load shedding approach taking into account real time dynamic thermal line rating technology and implemented in operations for improving transmission line capacity, such that congestion costs and/or risk of load shedding can be reduced [11]. Reddy (2016) proposed a new multi objective optimization based scheme with generation rescheduling and load shedding. The author in this paper adopted voltage-dependent loads modeling [1]. Zhang *et al.,* (2018) presented a sensitivity analysis based load shedding

model. In this model, sensitive buses for individual overloaded lines is determined [12].
Further from the review of literature it can be understand that anticipatory load shedding for the mitigation of transmission line overloading has been considered by few papers. Therefore, this work aims to develop a model for determining optimum shedding of system loading at preferred locations to mitigate line overloading in predicted loading condition as well as contingency situations. Additionally this work determines sensitive buses with respect to all the overloaded lines concurrently. A novel SCA algorithm developed in recent times has been applied to determine the optimum load shed. Sine Cosine Algorithm (SCA) possesses the ability to reach the global minimum and requires tuning of only one algorithm-specific parameter. Sensitivity analysis has been carried out in order to determine suitable buses where load shedding can be performed. In order to validate the obtained results, comparison of results has also been presented.

II. PROBLEM FORMULATION

A. Selection of buses for Load Shedding
Line overloading severity index for any particular loading condition is defined as follows.

$$LOSI = \frac{1}{2}\sum_{i \in OL}\left(\frac{S_i}{S_{i-limit}}\right)^2 \quad (1)$$

where,
S_i = actual apparent power flow in i[th] line
$S_{i-\mathrm{limit}}$ = apparent power flow limit ofi[th] line
OL= Set of lines which are overloaded
Load shed performed at any bus results in change of power flow through transmission lines. Thereby the overloading of line is also gets affected. If all the load buses are considered during optimization to remove overloading then size of problem becomes very large. At the same time, all the buses are not having the same impact on reduction of overloading. Due to the mentioned reasons, it is required to identify the few buses at which by performing load shedding overloading can be alleviated with a small amount of load shedding. In order to determine the suitable buses, line overload sensitivity (LOS) which represents the change in LOSI with respect to change in load at P_l has been considered and is defined as:

$$LOS_l = \frac{\partial LOSI}{\partial P_l} = \sum_{i \in OL}\left(\frac{S_i}{{S_{i-limit}}^2}\right) * \frac{\partial S_i}{\partial P_l} = \sum_{i \in OL}\left(\frac{S_i}{{S_{i-limit}}^2}\right) * LS_{i-l} \quad (2)$$

where,
LS_{i-l} = the sensitivity of line i with respect to load shedding at bus l.
As active power dominates in the system compare to reactive power Line Sensitivity (LS) is defined with respect to active power only.

$$LS_{i-l} = \frac{\partial S_i}{\partial P_l} \approx \frac{\partial P_i}{\partial P_l} \quad (3)$$

where,
P_i = active power flow in i[th] line.
Active power flow in i[th] line connected between bus m and bus n is presented as follows:

$$P_i = P_{mn} = -{V_m}^2 G_{mn} + V_m V_n G_{mn}\cos(\delta_m - \delta_n) + V_m V_n B_{mn}\sin(\delta_m - \delta_n) \quad (4)$$

Derivatives of $P_{mn}$with respect to δ_m and δ_n

$$\frac{\partial P_{mn}}{\partial \delta_m} = -\frac{\partial P_{mn}}{\partial \delta_n} = -V_m V_n G_{mn}\sin(\delta_m - \delta_n) + V_m V_n B_{mn}\cos(\delta_m - \delta_n) \quad (5)$$

Using Eqns. (3) and (5) LS_{i-l} can be represented as follows.

$$LS_{i-l} = \frac{\partial P_{mn}}{\partial \delta_m} * \frac{\partial \delta_m}{\partial P_l} + \frac{\partial P_{mn}}{\partial \delta_n} * \frac{\partial \delta_n}{\partial P_l} \quad (6)$$

Where, terms $\frac{\partial \delta_m}{\partial P_l}$ and $\frac{\partial \delta_n}{\partial P_l}$ can be extracted from inversion of Jacobian matrix at conversed solution.
Using Eqns. (2) and (6), line overload sensitivities for all the load buses have been calculated. It is evident that if LOS value is more negative than the amount of load shed required will be less. Hence calculated LOS of all load buses are arranged in increasing order and few top buses are selected for performing optimal load shedding.

B. Optimization Problem Formulation
The aim of considered problem is to alleviate the line overloading by exercising load shedding. From economical as well as from customer satisfaction point of view amount of load shedding should be as low as possible. Hence the objective of optimization problem is to minimize the total amount of load shed at selected buses which can be written as follow.

$$Obj = \sum_{t \in SB} \Delta P_t \quad (7)$$

Where, SB is set of buses selected for load shedding and ΔP_t represents amount of load shedding at t[th] bus.
The optimal load shedding problem is subjected to following equality and inequality constraints.
(i) Equality constraint: During optimization problem load flow equations (Eqn. 8 and 9) which are based on active and reactive power balance should be satisfied at each and every bus of the system.

$$P_{Gm} - P_{Dm} = V_m \sum_{n=1}^{nb} V_n[G_{mn}\cos(\delta_m - \delta_n) + B_{mn}\sin(\delta_m - \delta_n)] \quad (8)$$

$$Q_{Gm} - Q_{Dm} = V_m \sum_{n=1}^{nb} V_n[G_{mn}\sin(\delta_m - \delta_n) - B_{mn}\cos(\delta_m - \delta_n)] \quad (9)$$

where,
P_{Gm} = active power generation at m[th] bus
Q_{Gm} = reactive power generation at m[th] bus
P_{Dm} = active power demand at m[th] bus
Q_{Dm} = reactive power demand at m[th] bus
G_{mn} = conductance of the line connected between bus m and n
B_{mn} = susceptance of the line connected between bus m and n
V_m = Voltage magnitude of bus m
δ_m = Angle of voltage of bus m
N_b = number of buses in the system
(ii) Inequality constraints
(a) **Voltage magnitude**
During optimization problem voltage magnitude of the buses alter and hence it is necessary to make sure that its value at every bus is within the maximum and minimum limit.

$$V_{m-min} \le V_m \le V_{m-max} \quad (10)$$

Where, V_{m-min} and V_{m-max} refer the minimum and maximum limit of voltage magnitude at m[th] bus and V_m represents actual voltage of m[th] bus.

(b) Line flow limit: Line flow in each and every line should be kept within the limit during optimization which can be written as follows.

$$S_j \leq S_{j-limit} \quad (11)$$

Where, S_j and $S_{j-limit}$ refer the actual and limit of apparent power flow respectively through j[th] line.

(c) Load shed limit: Amount of load shed at any bus should lie in the limit of minimum and maximum value specified at that bus which can be represented as follows.

$$\Delta P_{m-max} \leq \Delta P_m \leq \Delta P_{m-min} \quad (12)$$

Where, ΔP_{m-min} and ΔP_{m-max} refer the minimum and maximum limit of load shed at m[th] bus and ΔP_m represents actual load shed of m[th] bus

III. SINE-COSINE ALGORITHM (SCA)

Mirjalili (2016) has developed the meta-heuristic method [13] by adopting the properties of sine-cosine functions. The main feature of this algorithm is that it balances exploration and exploitation for finding the optimal solution. Initially the search agents at its position creates the local solution and there after it deviates its position through this adapted mathematical model. To initialize, population of search agents are generated and consequently updated in the search criteria with the sole purpose of finding the optimal solution. In order to update the solution following equations have been considered:

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \sin(r_2) \left| r_3 P_i^t - X_i^t \right|, & r_4 < 0.5 \\ X_i^t + r_1 \cos(r_2) \left| r_3 P_i^t - X_i^t \right|, & r_4 \geq 0.5 \end{cases} \quad (13)$$

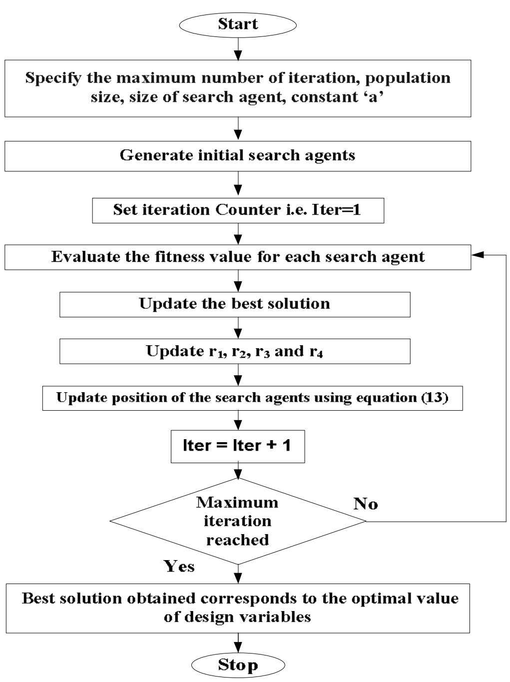

Fig. 1. Flowchart of Sine Cosine Algorithm.

Where, $X_i^t = \{X_1^t, X_2^t, \ldots, X_n^t\}$ is position of the i[th] search agent for the t[th] iteration; r_2, r_3, r_4 is random parameters; r_2 is random parameter in the range of $[0, 2\pi]$; r_3 is random parameter in the range of [0,2]; r_4 is random number in the range of [0,1] and P_i^t is best solution out of the population of m search agents in the t[th] iteration.

To balance the nature of exploration and exploitation to get the global best value, the algorithm must have some convergence criteria. To converge the mathematical model towards the global best value, with increase in iteration r_1 decreases its value which has been modelled as below:

$$r_1 = a - \frac{at}{T} \quad (14)$$

Where, t is the value of current iteration; T is the maximum iteration in which the optimal solution is needed and a is an integer with the positive value 2 hence the range of r_1 is [0, a]. The flow chart of the SCA algorithm has been depicted in Fig. 1.

IV. COMPUTATIONAL ALGORITHM FOR OPTIMAL LOAD SHED USING SCA

Step 1: Set maximum iteration count, size of search agent, number of search agent, algorithm specific constant 'a'.
Step 2: Initialize search agent in feasible region i.e. initial load shed value at selected buses within given range.
Step 3: Set iteration count iter = 1.
Step 4: Run load flow for each search agent and calculate objective value (Eqn. 7) for each search agent with consideration of penalty for voltage, line flow and load shed limit violation (Eqns. 10, 11 and 12).
Step 5: Find search agent which is having minimum load shedding with all constraints satisfied.
Step 6: Generate random variable r_1, r_3 and r_4 in the range specified in section III. Calculate the value of variable r_1 (equation 14).
Step 7: Using Eqn. 13 modified the position of search agents.
Step 8: Increase iteration count iter by one and repeat the Step 3 to 7 up to maximum iteration count.

V. RESULT AND DISCUSSION

In order to judge the effectiveness of the presented approach, it has been implemented on IEEE 14-bus and 39-bus system and comparison for IEEE 39-bus system has also been carried out. To perform the required computation, a computer with Intel Core i3 processor, 2.4 GHz, 4 GB RAM has been utilized.

A. Result for IEEE-14 Bus System

Data for IEEE 14-bus system have been taken from [14] and line loading limit in pu are provided in Appendix A. Under the line contingency (outage of line 5) few lines (2, 3 and 4) becomes overloaded. Using line overload sensitivity, selection of suitable buses for load shedding is carried out and tabulated with sensitivity value in Table 1.

Based on sensitivity values suitable buses are selected. At selected buses optimal load shedding is determined with adoption of sine cosine algorithm. During these optimization voltage at each bus is maintained between limits and line flow are also maintained within the limit (provided in appendix A).

During the load shedding optimization process the power factor at every selected bus is maintained as per the base case by maintaining ratio of reactive load shedding to real load shedding constant. Several trial runs have been executed and the best result obtained for the total optimal load shed is 0.1017pu as presented in Table 2. Load shedding at selected buses has been shown in Table 2. Voltage magnitude and line flow at base case and under contingency (without and with load shedding) has been shown in Table 3 and 4 respectively.

Table 1: Top ranked buses based on line overload sensitivity.

S.No.	Bus Number	Sensitivity	Ratio (Q/P)
1	5	-1.7300	0.210526
2	11	-1.6942	0.514286
3	12	-1.6473	0.262295

Table 2: Optimal load shedding at selected bus for best run for IEEE 14-Bus system.

S.No.	Bus number	Optimum load shed using SCA (pu)
1.	5	0.0057
2.	11	0.0350
3.	12	0.0610
Total optimum load shed		0.1017

Table 3: Voltage magnitude (pu) for different condition for IEEE 14-Bus system.

Bus No.	Base Case	Outage of line 5 (Without Load Shedding)	Outage of line 5 (With Load Shedding)
1	1.06	1.06	1.06
2	1.045	1.045	1.045
3	1.01	1.01	1.01
4	1.0186	1.0125	1.0146
5	1.0203	1.0113	1.0138
6	1.07	1.07	1.07
7	1.062	1.0594	1.0606
8	1.09	1.09	1.09
9	1.0563	1.0542	1.0554
10	1.0513	1.0496	1.0516
11	1.0571	1.0563	1.0604
12	1.0552	1.055	1.0626
13	1.0504	1.0502	1.0519
14	1.0358	1.0345	1.0359

Table 4: Line flow (pu) for different condition in IEEE 14-Bus system.

Bus No.	Base Case	Outage of line 5 (Without Load Shedding)	Outage of line 5 (With Load Shedding)
1	1.5815	1.4306	1.3667
2	0.7327	0.8235	0.8035
3	0.5618	0.7459	0.7067
4	0.7563	0.9152	0.8634
5	0.4152	0	0
6	0.2432	0.1611	0.1772
7	0.6362	0.3977	0.4125
8	0.4589	0.4361	0.3801
9	0.3021	0.317	0.2925
10	0.1736	0.1893	0.1821
11	0.1617	0.1673	0.1532
12	0.2868	0.2941	0.2703
13	0.0812	0.0781	0.0618
14	0.0678	0.0697	0.0485
15	0.0817	0.0813	0.0441
16	0.1913	0.1892	0.1723
17	0.1012	0.104	0.0945
18	0.0409	0.0382	0.0612
19	0.0177	0.0176	0.0438
20	0.0588	0.0562	0.0657

B. Result for IEEE-39 Bus System

Data pertaining to IEEE 39-bus system and predicted loading condition has been taken from [3]. Observation of Table 8 indicates that some of the lines (Line number 6, 7, 13 and 19) are overloaded. Selection of buses for load shed are based on the line overload sensitivity (LOS) index which has been calculated for all the load buses. Top ranked buses based on sensitivity values are 15, 16, 20, 21 and 23 as presented in Table 5.

Table 5: Top ranked buses based on line overload sensitivity.

S.No.	Bus Number	Sensitivity	Ratio (Q/P)
1.	15	-0.9542	0.478125
2.	23	-0.9351	0.341818
3.	20	-0.9260	0.164013
4.	21	-0.9251	0.419708
5.	16	-0.9184	0.098176

Based on sensitivity values suitable buses are selected. At selected buses optimal load shedding is determined with adoption of sine cosine algorithm. In that process voltage magnitude are restricted between 0.97 pu and 1.1 pu and line flows are also within the limit as provided in data [3]. Maximum and minimum load shedding limit for the selected buses are considered as 0.5 pu and 0 pu respectively. During the load shedding optimization process the power factor at ever selected bus is maintained as per the base case by maintaining ratio of reactive load shedding to real load shedding constant.

With population size of 30 and maximum iteration of 200, 30 independent runs are executed. The best result obtained for the total optimal load shed as 0.5893 pu and load shedding at selected buses has been shown in Table 6. Voltage magnitude and line flow at base case, predicted loading condition and after load shed are tabulated in Table 7 and 8 respectively.

Table 6: Optimal load shedding at selected buses for best run for IEEE 39 bus system.

S.No.	Bus number	Optimum load shed using SCA (pu)
1.	15	0.5000
2.	23	0.0000
3.	20	0.0000
4.	21	0.0000
5.	16	0.0893
Total optimum load shed		0.5893

Table 7: Voltage magnitude (pu) for different condition for IEEE 39 bus system.

Bus No.	Base case	Predicted load (Before load shed)	Predicted load (After load shed)
1	1.0653	1.0594	1.0612
2	1.0681	1.0636	1.0652
3	1.0536	1.047	1.0494
4	1.0233	1.015	1.0177
5	1.0199	1.011	1.0136
6	1.0214	1.013	1.0154
7	1.0092	0.9984	1.0013
8	1.0074	0.9957	0.9988
9	1.033	1.0212	1.0243
10	1.0314	1.0251	1.0273
11	1.027	1.02	1.0222
12	1.014	1.006	1.0084
13	1.0308	1.0241	1.0265

14	1.0327	1.0256	1.0287
15	1.0402	1.0343	1.0392
16	1.0567	1.0523	1.0553
17	1.0638	1.0584	1.0611
18	1.0594	1.0534	1.056
19	1.0597	1.0579	1.0589
20	0.9954	0.9937	0.9943
21	1.0522	1.0486	1.0507
22	1.0627	1.0607	1.0618
23	1.0583	1.0562	1.0573
24	1.0622	1.0583	1.061
25	1.0721	1.066	1.0677
26	1.0935	1.088	1.0899
27	1.0758	1.0698	1.0722
28	1.0869	1.0836	1.0846
29	1.0765	1.0742	1.0749
30	1.0475	1.0475	1.0475
31	0.982	0.982	0.982
32	0.9831	0.9831	0.9831
33	0.9972	0.9972	0.9972
34	1.0123	1.0123	1.0123
35	1.0493	1.0493	1.0493
36	1.0635	1.0635	1.0635
37	1.0278	1.0278	1.0278
38	1.0265	1.0265	1.0265
39	1.03	1.03	1.03

Table 8: Line flow (pu) for different condition in IEEE 39 bus system.

Line No.	Base Case	Predicted load (Before load shed)	Predicted load (After load shed)
1	3.61	4.9067	4.5959
2	4.1589	5.22	4.9586
3	6.7993	7.5431	7.3276
4	0.9104	0.3613	0.4062
5	2.7182	2.7236	2.7121
6	1.1958	1.7395	1.5705
7	1.1496	1.6209	1.4904
8	2.3017	2.1608	2.306
9	1.9014	1.9686	1.9601
10	1.4548	1.5163	1.5085
11	2.2668	2.1847	2.2376
12	3.8219	3.5214	3.6552
13	0.9089	1.4148	1.2782
14	5.7745	7.0272	6.7268
15	5.912	7.0607	6.7786
16	3.8646	3.6137	3.732
17	2.7065	3.0082	2.8799
18	2.6692	2.9883	2.8595
19	0.8797	1.2719	1.1329
20	3.5341	3.3266	3.0532
21	1.1788	0.8693	0.9302
22	4.4522	4.128	4.135
23	3.0227	2.8217	2.8396
24	1.0561	1.1855	1.1436
25	1.0427	0.8162	0.9041
26	1.115	1.0733	1.0444
27	5.9792	5.9354	5.9297
28	0.8455	0.8886	0.8861
29	3.4414	3.3637	3.3711
30	2.5307	2.9352	2.8523
31	3.5522	3.6911	3.5932
32	1.6262	1.4868	1.5034
33	2.3067	2.1838	2.1999
34	3.6553	3.5994	3.607
35	0.4508	0.4693	0.4666
36	0.5459	0.5697	0.5734
37	1.0828	1.3889	1.3009
38	6.6473	6.7139	6.6899
39	6.3361	6.3461	6.34
40	5.2757	5.3011	5.2918
41	6.6094	6.6368	6.6211
42	5.6205	5.6284	5.624
43	5.5319	5.4762	5.4905
44	2.527	2.5764	2.5562
45	8.6255	8.5822	8.5952
46	1.8712	2.1821	2.1855

Various statistics are also tabulated for 30 independent run in Table 9. Obtained value of standard deviation is 0.00035977 which is indicating the capability of the optimization method to converge at global optimal or near to optimal value every time.

Table 9: Statistics for 30 independent run of load shedding using SCA for IEEE 39 bus system

S.No.	Statistical parameter	Obtained value using SCA
1.	Minimum value	0.5893
2.	Maximum value	0.5903
3.	Average	0.58967
4.	Standard deviation	0.00035977
5.	Frequency of convergence	0.433

In order to justify the competence of SCA pertaining to optimum load shed, comparison of results with other algorithm [3] is presented. Using teaching learning based optimization (TLBO) and bare bones particle swarm optimization (BBExp) optimal load shedding obtained for predicted loading condition is 0.68941 pu and 0.698812 pu respectively. Whereas with adoption of SCA, the total amount of load shed obtained is 0.5893 pu. This indicates that SCA offers superior results in comparison to other mentioned techniques.

VI. CONCLUSION

This work discusses about load shedding schemes for mitigating the overloading of the transmission line. Selection of buses to perform load shedding has been carried out based on sensitivity information. Sine cosine algorithm is utilized for determining the amount of optimum load shedding. During load shedding optimization different constraints like real and reactive power balance, voltage limits, apparent power flow limits of transmission lines and load shed limits are considered. This technique is tested on IEEE 14 and IEEE 39-bus system and in order to show effectiveness, the comparison of results with other techniques is provided with other techniques for IEEE 39-bus system. To indicate the ability of the considered method to reach the optimal or near to optimal value at every time, statistics information is also provided. It has been presented that the proposed technique offers superior results pertaining to amount of load shed and successfully alleviates line overloading.

VII. FUTURE SCOPE

The presented work can be formulated as multi objective optimization with consideration of minimum voltage deviation or minimum line losses. It can also be formulated with considering ZIP model of load.

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Conflict of Interest. No.

APPENDIX A

Line Flow Limit in IEEE 14-Bus System

Line number	Line loading limit (pu)	Line number	Line loading limit (pu)
1	1.6532	11	0.2158
2	0.8035	12	0.3541
3	0.7157	13	0.2134
4	0.8658	14	0.1789
5	0.5436	15	0.1679
6	0.3126	16	0.2456
7	0.7259	17	0.1693
8	0.5438	18	0.1274
9	0.3642	19	0.1587
10	0.2543	20	0.1642

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