Optimal Power Flow in Uncertain Power System

Namami Krishna Sharma, S. C. Choube

Abstract: Due to the increasing demand of electricity in ever-growing electricity market, it is necessary to observe the nature of load and map the effects of load uncertainties on the operation of power system. These uncertainties have also led to voltage instability which is sooner or later considered to be a fundamental cause of blackouts. The distributed generation sources can also be regarded as the source of uncertainties at the load ends of power systems. Along with the load uncertainties, wind turbine generation (WTG) and solar plants have also been used as a source of uncertainties in this paper. The load uncertainties have been incorporated in the system by designing a dynamic load flow program. Corresponding to all uncertain inputs critical case has been identified by the singularity property of load flow jacobian. For the optimal load flow a multi-objective optimization problem aiming to constrained objective function to enhance voltage stability, improve stability index value, reduce system losses and increase reactive reserve margins at generator buses has been formulated. Black hole algorithm has been used to achieve the optimal values of control variables and hence optimal load flow. The aforementioned problem has been tested on standard IEEE-14 bus system.

Keywords: Load uncertainty, distributed generation, Reactive compensation, optimal power flow, BHA.

NOMENCLATURE

A. Parameters

N Normal Distribution
\( \text{exp} \) Exponential Distribution
\( db \) Base Case load deviation
\( \Psi \) Uncertain load parameter
\( \xi \) Uncertainty results on the output parameters
\( \mu \) Average Value
\( \sigma \) Standard Deviation
\( \lambda \) linearly distributed parameter

B. Constants

\( P_\text{cl}^i \) Active power load in MW at \( i^{th} \) bus at Base case
\( Q_\text{cl}^i \) Reactive power load in Mvar at \( i^{th} \) bus at Base case
\( G_i \) Real part of shunt admittance of line ‘k’ in pu
\( Y_i \) Shunt admittance of the line
\( \theta_y \) Angle in degree of \( Y_y \)
\( A \) wind turbine’s cross-sectional area in \( m^2 \)
\( \Phi \) WTG Power Factor angle
\( \rho \) density of air in kg/m3 (1.225)
\( C_P \) Turbine coefficient (0.5926)

\( V_{\text{cut in}} \) Cut-in speed of wind (3.5m/s)
\( V_{\text{cut out}} \) Cut-out speed of wind (20m/s)
\( V_r \) Rated wind speed (11m/s)

C. Variables

\( P_{\text{cl}}(\psi) \) Uncertain Real loading at \( i^{th} \) bus
\( Q_{\text{cl}}(\psi) \) Uncertain Reactive loading at \( i^{th} \) bus
\( V^\epsilon \) Voltage magnitude in pu due to \( \psi \) uncertainties
\( V^\delta \) Base case Voltage magnitude
\( \delta^\delta \) Voltage angle due to \( \psi \) uncertainties
\( P_{\text{cl}G_i} \) Base case real power generation at \( i^{th} \) generator bus
\( Q_{\text{cl}G_i} \) Base case reactive power generation at \( i^{th} \) bus
\( P_{\text{cl}G_i}^d \) Real power generation at \( i^{th} \) bus due uncertain loads
\( Q_{\text{cl}G_i}^d \) Reactive power generation \( i^{th} \) bus due to uncertain loads
\( V^\gamma \) Voltage magnitude at \( i^{th} \) bus in pu due to uncertain load
\( P_{\text{WTGi}} \) Real Power supplied by WTG in MW
\( Q_{\text{WTGi}} \) Reactive Power drawn by WTG in Mvar
\( Q_{\text{WTGi}} \) Resultant Reactive Power load in Mvar at \( i^{th} \) PQ bus

I. INTRODUCTION

The nondeterministic or uncertain behavior of loads in modern power systems need to be tackled carefully [1]. Under the presence of numerous uncertainties in the power systems the optimal power flow functionality is affected. At present, power system operators and planners are facing problems to maintain voltage stability due to uncertain increasing demand of electricity by the consumers. [2]. The sources of uncertainty in modern power systems includes, ambiguity in generation, transmission, distribution network, distributed generation, loads, energy reserve or economic factors. Alternators, power transmission lines and power transformer’s models have been ascertained in [3,4]. The model of uncertain load in randomness and time-varying distributed property, could be defined by single or many groups of mathematical equations. Precise load modelling has thus become one of the most worrying issue in power system research field [5, 6]. Under the uncertain environment for the proper and smooth functioning of system operation the available control actions must be utilized effectively and up to its maximum limit to ensure the stability and reliability of the system.
Sources of uncertainty include fuel price, generation convenience, market forces, capacity of transmission systems, nonlinear load demands, unplanned shedding, weather and other interruptions, etc. These uncertainties can be incorporated in the system by designing a proper probabilistic problem and the shortcomings of deterministic approach can also be overcome [7]. Since the deterministic approach does not account the randomness of the parameters, in such cases for the better handling of these randomness the researchers shifted their approaches from deterministic to probabilistic one. Uncertainties affect the operation of the power system in terms of power transfer capability and voltage stability limits and other operating parameters of the system. The inclusion of load uncertainties by designing a computational feasible method is shown in [9]. Due to the increasing demand of electricity and consequently the penetration of distributed generation [6-9], it has now also become imperative that these renewable energy resources are modelled along with loads. Solar photovoltaic (PV) installations is growing rapidly and affecting load profiles as it replaces a part of the load and/or is added to production units of distribution system. PV penetration affects the voltage profile, stability, and operation of system [20,21]. In this paper a dynamic load flow model has been developed to account the randomness of load uncertainties over a certain period of time [8]. Various modern optimization techniques have been used for solving the complex problem given in [10,11]. Black Hole optimization (BHA) technique proposed in [11] is the modified swarm optimization technique is being widely used for solving engineering optimization problem. A voltage stability enhancement analysis under the presence of load uncertainties and distributed generation has been carried out in this paper. A multi-objective optimization problem has been designed aiming to minimize the voltage deviation, L-Index and line losses has been designed in this paper and reactive shunt compensation has been used as control variable. The effectiveness of the proposed technique has been observed by calculating the voltage benefit factors, loss benefit factors and improvement in total reactive reserve in the system [16]. Deviation from base loading at different buses, normally distributed and exponentially distributed load models have been used in this paper [16]. Wind Turbine Generator (WTG) and Solar photovoltaic system have also been modelled in this paper to account the effect of uncertainties due to distributed generation. The stability index (minimum eigen value of load flow Jacobian matrix) has been used as an indicator to identify the critical or adverse case under the given sets of uncertain conditions. After identifying critical case black hole optimization technique has been employed to find optimum value of control variable (VAR compensation) which satisfies the objective functions and all the operating limits. The proposed technique has been implemented on IEEE-14 bus system.

In this paper the overview of Black hole optimization is given in section II. Uncertain load, WTD and solar modelling have been done in section III. Section IV covers the methodology and problem formulation of the proposed problem. Results have been shown in section V and the conclusions are given in the last section.

II. BLACK HOLE OPTIMIZATION

A. Overview

A. Hatamlou [11] has proposed the modified population-based optimization technique inspired from the ‘Black Hole’ phenomenon. In the journey of a star towards the blackhole, there may be a probability of crossing the event horizon. The stars or candidate solutions which crosses the event horizon they are sucked by the black hole. The black hole optimization problem is formulated as follows:

\[ r_i(k+1) = r_i(k) + \text{rand} \left( r_{BH} - r_i(k) \right) \]  

Where \( r_i(k+1) \) and \( r_i(k) \) are the locations of the star at iterations 't' and 't+1', respectively and \( r_{BH} \) is the location of the black hole in the search space, 'rand' is a random number in the interval [0-1]. N is the number of stars (candidate solutions). Every time a candidate (star) dies, it is sucked in by the black hole, another candidate solution (star) is born and distributed randomly in the search space and starts a new search. In the BHA algorithm the event horizon radius is calculated by following equation:

\[ r = \frac{F_{BH}}{\sum_{i=1}^{N} F_i} \]

Where ' \( f_{BH} \) ' is the fitness value of the black hole and ' \( f_i \) ' is the fitness value of the ' \( i^{th} \) ' star. When the distance between a candidate solution and the black hole (best candidate) is less than R, that candidate is collapsed and a new candidate is created and distributed randomly in the search space.

III. UNCERTAIN LOAD, WTG AND SOLAR MODELLING

A. Normally distributed uncertain load

Various load models are given in [12,13,14,15]. The normally distributed load modelling is done as follows:

\[ P_{do}(\Psi_s) = \text{Normrnd}(\mu_1, \sigma_1, m, n) \]  

\[ Q_{do}(\Psi_s) = \text{Normrnd}(\mu_2, \sigma_2, m, n) \]

Bus no. 9 is selected for this modelling (with \( \mu_1=30 \) and \( \sigma_1=10 \), \( \mu_2=17 \) and \( \sigma_2=5 \)) and m, n is a (48x1) array. The real and reactive load variations are shown in figures 1 to 4.

Fig. 1: Variation of real load at bus no. 9
B. Exponentially distributed uncertain load

The exponentially distributed uncertain load can be modelled as follows [16]:

\[ f(P_{DL}) = \frac{e^{-\frac{(P_{DL} - \mu)}{b}}}{b} \]  

\[ P_{DL} \geq \mu \]  

\[ b > 0 \]  

(5)

\[ P_{DL}(\psi_{\exp}) = P_{DL}^0 + \frac{\exp(x - \mu)}{b} \]  

with \( x = \) linearly spaced numbers between \( 0 - P_{DL}^0 \)  

\[ b = 1.8 \]  

(6)

Similarly, for \( Q_{DL} \)

\[ Q_{DL}(\psi_{\exp}) = Q_{DL}^0 + \frac{\exp(x - \mu)}{b} \]  

(7)

Exponentially distributed loads are shown in figures 5 to 8:

C. Deviation from base case loading

Load at bus no. 10 is varying from rated to 150% of rated load values and the modelling is done as follows:

(i) Real power loading

\[ P_{D10}(\psi_{\Delta}) = P_{D10}^0(1 + \lambda) \]  

(8)

(ii) Reactive load modelling

\[ Q_{D10}(\psi_{\Delta}) = Q_{D10}^0(1 + \lambda) \]  

(9)
D. Modelling of wind turbine generator

The power generated by (WTG) is a direct function of air velocity and it consumes the reactive power from the grid at the same time [17]. WTG modelling are presented in [18-19]. The operating power factor of WTG is assumed to be constant at (0.95 lag). Placement of WTG units depends on the air flow and other physical parameters. Here bus no. 4 and 7 are chosen as candidate buses for the placement of WTG units.

\[
P_{WGT_{i}} = P_{WGT_{i}}^{0} - P_{DG_{i}}^{0}; \quad P_{WGT_{i}} \leq 9\text{MW} \tag{10}
\]

\[
Q_{WGT_{i}} = Q_{DG_{i}}^{0} + P_{WGT_{i}} \cdot \tan \phi \tag{11}
\]

(Cos \( \phi \) = 0.9 lagging)

\[
P_{WGT_{i}}^{'} = \begin{cases} 
\frac{1}{2} \rho_{a} A v_{c} \cdot C_p ; & v_{\text{cutin}} \leq v_{\text{rated}} \\
7.136\text{MW} ; & v_{\text{rated}} \leq v \leq v_{\text{cutout}} 
\end{cases} \tag{12}
\]

E. Modelling of solar photovoltaic system

Solar photovoltaic (PV) installations are growing rapidly and affecting load profiles as it replaces a part of the load and/or is as added to production units of distribution system. PV penetration affect the voltage profile, stability, and operation of system. The electricity generated by a solar photovoltaic system can be estimated as follows:

\[
E = A \times r \times H \times PR \tag{13}
\]

Where:
- E = Energy in KWh
- r = solar panel yield (electrical power of one solar panel divided by area of one solar panel in %)
- A = Total solar panel area
- H = annual average solar radiation
- PR = performance ratio (default value 0.75)

Solar output power is given by eq. (14) [20-21] and irradiance variation is taken from [21]. Active power generation at bus 14 where solar generator has been installed is shown in figure 13. Solar array area = 158 m² and r=14%.

\[
P_{PV} = \frac{A \times r \times H \times 10^{-6}}{24} \text{MW} \tag{14}
\]

IV. METHODOLOGY

Following methodology has been adopted:

1. Load models for selected load buses have been developed and are incorporated in a dynamic load flow program.
2. WTG and solar photovoltaic modelling have been done for including the effect of distributed generation.
3. Run the load flow program for all the dynamic input values and observe the minimum eigen value of load flow Jacobian (exclude those results on which load flow did not converge).
4. After identifying the critical case an optimization problem based on ‘Black Hole Algorithm’ has been designed for maintaining system voltage stability and improving the performance of the system.
Fig. 13: Solar power output

(5) candidate buses for the placement of reactive shunt compensating units (SVCs) have been found out by L-index (bus) values [22]. L-index varies between 0 to 1. If the index value of any bus approaches to unity means that bus is operating near its stability limit. The buses having the higher value of indexes are chosen as candidate buses. L-index if the L-index approaches to unity means system is approaching towards voltage instability and consequently voltage collapse state.

\[ L_{index} = \max_{k \in j} \left| - \sum \beta_{ki} F_{kj} V_k \right| \]  

(15)

Where:
- \( \beta_{ki} \) is the set of load buses and \( \beta_{Gi} \) is the set of generator buses and \( F_{ki} \) is the subset of hybrid matrix, which has been generated by Y-matrix. Stability condition lies between 0 < L-index < 1.

V. PROBLEM FORMULATION

Objectives Functions

Minimum voltage deviation

\[ F_1 = \min (\text{abs}(1 - V_i^z)) \]  

(16)

Minimum real power loss

\[ F_2 = \min \sum_i G_i \left[ (V_i^z)^2 - (\delta_i^z)^2 - 2V_i^z \delta_i^z \cos(\delta_i^z - \delta_j^z) \right] \]  

(17)

Minimum L-index (bus)

\[ F_3 = \min (L_{index}) \]  

(18)

Subjected to

Equality constraints

\[ P_G^i - P_L^i + P_{DGi} = \sum_j |V_j^z| |V_j^z| |\cos(\delta_j^z - \delta_i^z)| \]  

(19)

\[ Q_{Ghi}^i - Q_{Lhi}^i - Q_{DGhi} = -\sum_j |V_j^z| |V_j^z| |\sin(\delta_j^z - \delta_i^z)| \]  

(20)

Inequality Constraints

\[ V_i^z \leq V_i^z \leq V_i \]  

(21)

\[ 0.95 < V_i < 1.05 \]  

(0.95 < V_i < 1.05)

\[ Q_{Gi}^z \leq V_i^z \leq Q_{Gi} \]  

(22)

The uncertainties can be limited by following:

\[ \Psi_{\min} \leq \Psi \leq \Psi_{\max} \]  

(23)

\[ Q_{Ghi} \leq Q_{Ghi} \leq Q_{Ghi} \]  

(24)

\[ (Q_{Ghi} \leq 0 \text{ and } Q_{Ghi} \leq 20 \text{ MVAR}) \]

\[ \min e_{\text{eig}}(J) > 0 \]  

(25)

\[ \Delta Q^{\text{rel}} = Q_{Gi}^{\text{max}} - Q_{Gi}^{\text{z}} \]  

(26)

Voltage benefit factor and loss benefit factors [16] have also been calculated for checking the effectiveness of the control action:

\[ VBF_i = \frac{V_i (Q_{Shi} - V_i)}{Q_{Shi}} \times 100\% \]  

(27)

\[ LBF_i = \frac{P_i (Q_{Shi} - V_i)}{Q_{Shi}} \times 100\% \]  

(28)

VI. RESULTS AND DISCUSSIONS

Base case load flow results and L-Index for buses of IEEE-14 bus system are shown in Table-I.

Table-I: Base case load flow results of IEEE-14 bus system

| Bus no. | IV1 (pu) | \( \delta \) (degree) | \( P_G \) (MW) | \( Q_G \) (MVAR) | L-index |
|---------|---------|----------------------|--------------|----------------|---------|
| 1       | 1.010   | 2.153                | 114.170      | 10.092         | -       |
| 2       | 1.000   | 0.000                | 102.289      | 37.590         | -       |
| 3       | 0.980   | -5.478               | 50.000       | 34.642         | -       |
| 4       | 0.957   | -5.216               | 0.000        | 0.000          | 0.0343  |
| 5       | 0.961   | -4.155               | 0.000        | 0.000          | 0.0233  |
| 6       | 1.000   | -10.422              | 0.000        | 19.355         | -       |
| 7       | 0.976   | -8.737               | 0.000        | 0.000          | 0.0443  |
| 8       | 1.000   | -8.737               | 0.000        | 13.637         | -       |
| 9       | 0.961   | -10.622              | 0.000        | 0.000          | 0.0785  |
| 10      | 0.960   | -10.913              | 0.000        | 0.000          | 0.0748  |
| 11      | 0.976   | -10.802              | 0.000        | 0.000          | 0.0422  |
| 12      | 0.982   | -11.396              | 0.000        | 0.000          | 0.0279  |
| 13      | 0.975   | -11.436              | 0.000        | 0.000          | 0.0376  |
| 14      | 0.947   | -12.165              | 0.000        | 0.000          | 0.0911  |
| Total \( P_G \)=266.459 MW | Total \( Q_G \)=115.316 MVAR |
| Total \( P_D \)=259.300 MW | Total \( Q_D \)=81.400 MVAR |
| Total \( P_{loss} \)=7.163 MW | Total \( Q_{loss} \)=33.918 MVAR |

L-index was presented by Kessel and Glavitsch [22], and developed by Jasmon and Lee [23]. The L-index of any branch connected between buses i and j can be expressed by eq. (29)

\[ L_{ij} = \left[ 4 \left( P_{ij} R_{ij} + P_{ij} X_{ij} V_i^z \right) V_i^z \right] \]  

(29)

L-index values have been calculated by eq. (29) and are given in table II. These values are calculated for base case to obtain the optimum locations for the placement of WTG. Buses 4 & 7 which connect the line 8 are chosen as candidate buses for the placement of WTGs because L-index value of line 8 is highest amongst all the line values.
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Table-II: L-index for lines corresponding to base case

| Line no. | L-index | Line no. | L-index | Line no. | L-index |
|----------|---------|----------|---------|----------|---------|
| 1        | 0.0309  | 8        | 0.1209  | 15       | 0.0542  |
| 2        | 0.1183  | 9        | 0.0563  | 16       | 0.0048  |
| 3        | 0.0255  | 10       | 0.0481  | 17       | 0.0512  |
| 4        | 0.1175  | 11       | 0.0939  | 18       | 0.0681  |
| 5        | 0.0123  | 12       | 0.0685  | 19       | 0.0283  |
| 6        | 0.0906  | 13       | 0.0952  | 20       | 0.1093  |
| 7        | 0.0173  | 14       | 0.1009  |          |         |

Minimum eigen value 0.5507

Table-III load flow results corresponding to critical case

| Bus no. | IVI (pu) | δ (degree) | P_G (MW) | Q_G (Mvar) | L-index |
|---------|----------|------------|----------|------------|---------|
| 1       | 1.010    | 2.030      | 114.170  | 14.551     |        |
| 2       | 1.000    | 0.000      | 121.165  | 63.537     |        |
| 3       | 0.980    | -5.516     | 50.000   | 8.909      |        |
| 4       | 0.950    | -5.713     | 0.000    | 0.000      | 0.038  |
| 5       | 0.953    | -4.595     | 0.000    | 0.000      | 0.027  |
| 6       | 0.990    | -11.909    | 0.000    | 7.451      |        |
| 7       | 0.966    | -10.396    | 0.000    | 0.000      | 0.055  |
| 8       | 1.000    | -10.396    | 0.000    | 13.332     |        |
| 9       | 0.944    | -12.976    | 0.000    | 0.000      | 0.101  |
| 10      | 0.941    | -13.251    | 0.000    | 0.000      | 0.096  |
| 11      | 0.961    | -12.731    | 0.000    | 0.000      | 0.053  |
| 12      | 0.972    | -13.037    | 0.000    | 0.000      | 0.030  |
| 13      | 0.964    | -13.137    | 0.000    | 0.000      | 0.041  |
| 14      | 0.932    | -14.364    | 0.048    | 0.000      | 0.106  |

Total P_G = 285.031 MW
Total Q_G = 134.845 Mvar

Jacobian

Corresponding to all uncertain inputs mentioned in section-III of this paper, the critical case has been identified by observing the minimum eigen value of load flow jacobian in each dynamic alteration. Figure 14 shows the variation of minimum eigen value of load flow jacobian. Minimum eigen value encountered is 0.5507 and corresponding load flow results are given in table III.

The convergence of all the objective functions which are mentioned in section-V are shown in figures 15,16 and 17 respectively. Variation of the weakest bus voltage is shown in figure 18. The load flow results after the optimization are given in table-V and noteworthy changes have been observed on the voltage magnitudes, L-index, losses and reactive reserve of the system.

Table-IV: Optimization Results

| Optimized value of control variables | Q_{sh14} = 15.8740 Mvar |
|-------------------------------------|-------------------------|
| Objective function-1                | 0.0208                  |
| Objective function -2               | 8.114                   |
| Objective function-3                | 0.0944                  |
| Total reactive support in the system| 32.156 Mvar             |
| Improvement in reactive reserve     | 28.3493 Mvar            |
| Total no. of iterations             | 100                     |
| Population size per iteration       | 100                     |
| CPU time                            | 18.091654 seconds       |
Table-V: Load flow results after optimization for critical case

| Bus no. | V1 (pu) | \( \delta \) (degree) | \( P_G \) (MW) | \( Q_G \) (Mvar) | L-index |
|------|--------|-----------------|--------------|----------------|--------|
| 1    | 1.010  | 2.026           | 114.170      | 11.782         | -      |
| 2    | 1.000  | 0.000           | 120.422      | 35.321         | -      |
| 3    | 0.980  | -5.846          | 50.000       | 35.218         | -      |
| 4    | 0.956  | -5.907          | 0.000        | 0.000          | 0.0380 |
| 5    | 0.958  | -4.735          | 0.000        | 0.000          | 0.0266 |
| 6    | 1.000  | -11.434         | 0.000        | 8.141          | -      |
| 7    | 0.983  | -10.317         | 0.000        | 0.000          | 0.0490 |
| 8    | 1.000  | -10.317         | 0.000        | 9.585          | -      |
| 9    | 0.978  | -12.634         | 0.000        | 0.000          | 0.0860 |
| 10   | 0.972  | -12.837         | 0.000        | 0.000          | 0.0821 |
| 11   | 0.982  | -12.283         | 0.000        | 0.000          | 0.0547 |
| 12   | 0.987  | -12.514         | 0.000        | 0.000          | 0.0267 |
| 13   | 0.984  | -12.772         | 0.000        | 0.000          | 0.0367 |
| 14   | 0.979  | -14.503         | 0.048        | 0.000          | 0.0944 |

Minimum Eigen value=0.5868

Total \( P_G =284.640 \text{ MW} \)
Total \( Q_G =100.048 \text{ Mvar} \)

Total \( P_D =276.528 \text{ MW} \)
Total \( Q_D =92.418 \text{ Mvar} \)

Total \( P_{loss} =8.114 \text{ MW} \)
Total \( Q_{loss} =39.789 \text{ Mvar} \)

Total reactive reserve 38.2732 Mvar

Table-VI: L-Index (Lines) before and after optimization

| Line no. | L-index Before optimization | L-index After optimization |
|----------|----------------------------|----------------------------|
| 1        | 0.0318                     | 0.0318                     |
| 2        | 0.1381                     | 0.1178                     |
| 3        | 0.0176                     | 0.0182                     |
| 4        | 0.1351                     | 0.1092                     |
| 5        | 0.1419                     | 0.1216                     |
| 6        | 0.1203                     | 0.0956                     |
| 7        | 0.0171                     | 0.0124                     |
| 8        | 0.0148                     | 0.0628                     |
| 9        | 0.0647                     | 0.0529                     |
| 10       | 0.0337                     | 0.0243                     |
| 11       | 0.1119                     | 0.0706                     |
| 12       | 0.0714                     | 0.0496                     |
| 13       | 0.1013                     | 0.0606                     |
| 14       | 0.1479                     | 0.0699                     |
| 15       | 0.0792                     | 0.0116                     |
| 16       | 0.0096                     | 0.0255                     |
| 17       | 0.0438                     | 0.0391                     |
| 18       | 0.0874                     | 0.0428                     |
| 19       | 0.0319                     | 0.0125                     |
| 20       | 0.1240                     | 0.0135                     |

The comparison of bus voltages and L-Index (bus) before and after the optimization are shown in figures 19 and 20 respectively. The Voltage benefit factors (VBF) and Loss benefit factor (LBF) are given in table-VII. These factors are calculated by using eq. (27) and (28) respectively.
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Table VII: %VBF and %LBF

| Bus no. | VBF (%) | Bus no. | VBF (%) |
|--------|---------|--------|---------|
| 4      | 1.866   | 11     | 6.531   |
| 5      | 1.555   | 12     | 4.665   |
| 7      | 5.287   | 13     | 6.020   |
| 9      | 10.573  | 14     | 14.616  |
| 10     | 9.640   |        | LBF=1.024% |

Fig. 20: L-Index (bus) before and after optimization

VII. CONCLUSION

The handling, representation and consequences of load uncertainties have been discussed in this paper. Along with uncertain loads distributed generations have also been considered as a source of load uncertainties. An optimal power flow has been achieved by designing a multi-objective optimization problem to improve system voltage stability and reduce the real power losses has been proposed in this paper. An optimal load Black Hole optimization algorithm has been used to solve the proposed problem. The propose technique has been implemented on IEEE-14 bus system.

APPENDIX

Air flow and Solar irradiance [24]

| S.no. | Air flow (m/s) | Solar irradiance (W/m²) | S.no. | Air flow (m/s) | Solar irradiance |
|-------|----------------|-------------------------|-------|----------------|------------------|
| 1     | 0.5            | 690.3                   | 25    | 18.0           | 635.3            |
| 2     | 1.1            | 735.2                   | 26    | 19.3           | 635.3            |
| 3     | 2.0            | 741.2                   | 27    | 20.0           | 623.5            |
| 4     | 2.5            | 758.8                   | 28    | 20.5           | 605.9            |
| 5     | 3.2            | 723.5                   | 29    | 21.0           | 600              |
| 6     | 3.5            | 758                   | 30    | 22.0           | 588.2            |
| 7     | 4.1            | 720.5                   | 31    | 23.0           | 588.2            |
| 8     | 5.0            | 705.9                   | 32    | 24.4           | 588.2            |
| 9     | 5.5            | 711.8                   | 33    | 25.0           | 588.2            |
| 10    | 6.0            | 700                    | 34    | 26.0           | 582.4            |
| 11    | 7.0            | 700                    | 35    | 27.0           | 564.7            |
| 12    | 7.8            | 694.1                   | 36    | 28.0           | 547.1            |
| 13    | 8.0            | 688.2                   | 37    | 29.3           | 541.2            |
| 14    | 9.0            | 682.4                   | 38    | 30.0           | 541.2            |
| 15    | 9.8            | 682.4                   | 39    | 30.6           | 541.2            |
| 16    | 10.2           | 682.4                   | 40    | 31.0           | 529.4            |
| 17    | 11.0           | 676.5                   | 41    | 32.3           | 529.4            |

18 12.0 664.7 42 33.0 517.6
19 13.0 664.7 43 34.0 511.8
20 14.5 670.6 44 34.8 500
21 15.0 658.8 45 35.0 482.4
22 16.2 652.9 46 36.7 441.2
23 16.5 652.9 47 38.0 423.5
24 17.0 647.1 48 40.0 394.1

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25. School of Energy and environment technology, RGPV Bhopal.

AUTHORS PROFILE

**Namami Krishna Sharma** is currently pursuing Ph.D. from UIT-RGPV Bhopal. His research areas are Power system stability & control, soft computing techniques and uncertainty analysis in power systems. He published several papers in reviewed journals and reputed conferences.

**Prof. S. C. Choube** is the Professor in Electrical & Electronics engineering department of UIT-RGPV, Bhopal. He published various research papers in Reputed journals and reputed conferences. His research area includes Power system voltage stability, modern optimization techniques, power system reliability and security analysis. He is the active member of various professional bodies.