A Novel Analytical Study on Voltage Instability Mitigation Using Multiple Severity Functions by Optimal Placement of SVC in N-2 Contingency Analysis Using Gravitational Search Algorithm

S P MANGAIYARKARASI* T SREE RENGA RAJA**
Department of Electrical and Electronics Engineering
Anna University– BIT Campus Tiruchirappalli
Tiruchirappalli, Tamilnadu
INDIA 620024
*mangaisowmeya@gmail.com **renga_raja@rediffmail.com

Abstract: - Voltage stability analysis based on the number of limit violating buses apart from considering the voltage magnitude violations using several severity functions is performed in this work. Deviating from existing works in literature, the double line contingency is considered based on the three types of severity functions: discrete, continuous and percentage of violation severity functions. The severity functions are analyzed and their merits and drawbacks are discussed. The N-2 line outage comprising of all the 820 possible combinations of contingency states in the IEEE 30 bus system is effectively analyzed and contingency ranking is done based on the severity. FACTS devices are utilized to improve the voltage profile of the system during line outages. The Static VAr Compensator (SVC) is considered here, as the compensating device. A multi-objective optimization, with the objective of minimizing the voltage deviation and also the number of limit violating buses with optimal reactive power support is achieved through the Gravitational search algorithm (GSA). The effectiveness of the proposed work is tested on IEEE 30 bus system under double line contingencies. The results of the work are compared with several optimization methods and the results substantiate the effectiveness of the proposed methodology.

Key-Words: - Voltage Stability, Severity Functions, N-2 line contingency, FACTS, Static VAr Compensator, Gravitational Search Algorithm.

1 Introduction

Deregulation, restructuring and open access policies have enforced transmission corridors to operate in highly stressed operating conditions. This in turn has resulted in establishment of a monitoring authority to look into the problems of transmission line congestion, overloading patterns and the unpredictable operating margins of power system to overcome voltage instability. Voltage instability has become a major concern of interest nowadays and therefore there is an increased need to look into the security level of the power system operations. Voltage collapse is usually caused by either of two types of power system disturbances namely load variations and contingencies [1]. Several measures are developed to identify the closeness of system voltage violation towards voltage collapse. PV curves and QV curves are reliable measures for determining the proximity to voltage collapse but are expensive to compute [2]. Singular value and Eigen value decomposition techniques were proposed in [3] but is not a good indicator of proximity to collapse point. Multiple load flow solution methods [4], bifurcation methods [5] and energy methods [6] were introduced to assess voltage stability. Becovic et al in [7] have used local measurements for voltage stability assessment. Tangent vector technique was proposed in [8] to study the voltage stability margin.

All the methods cannot be used on-line as they suffer from the disadvantage of high computational time. Hence the need of voltage stability indices that could be used on line to identify the weakest bus and the most critical line becomes inevitable. Voltage magnitude alone cannot be an index for determining the imminence to voltage collapse [9]. Arya in [10] have developed an index that would become half at voltage collapse point. Fast voltage stability index [11], Voltage collapse index [12] and new voltage stability index [13] are some of the indices available in literature to identify voltage instability.

Decrease in voltage magnitude is mainly due to deficient reactive power supports. Adequate reactive power supports at critical buses can provide voltage stability enhancement which can be achieved by the use of FACTS devices. Different FACTS controllers for voltage stability improvement have been discussed in [14]. SVC is a shunt compensated device which can be made to generate or absorb reactive power and can be used for voltage control applications. Placement of FACTS devices and optimal amount of MVAR generated or absorbed by the device has a great impact on voltage stability augmentation [15].

Different optimization techniques are available in literature to find the optimal location of FACTS devices. Evolutionary algorithms have the inherent ability to explore a set of possible solutions simultaneously [16].Genetic Algorithm [17], Non dominated sorted GA [18], Particle swarm optimization [19], Simulated annealing [20] and Tabu search [21] have been adopted to find the optimal location of FACTS devices. Other methods such as fuzzy method [21], weighted method [22], projection method [23] and [24] normalization method are also proposed to solve optimization problems. A metaheuristics algorithm, Gravitational Search Algorithm, inspired by Newtonian theory of gravity was proposed by Rashed et al in 2009 [25]. Table 1 summarizes the available literature in finding the optimal location of FACTS devices.

Table 1 Literatures for application of Optimization Techniques for Optimal Placement of FACTS Devices

Ref. No	Optimization Method	Year
[16]	Evolutionary Algorithms	2003
[17]	Genetic Algorithm	2002
[18]	Non- Dominated Sorted Genetic Algorithm	2001
[19]	Particle Swarm Optimization	2005
[20]	Simulated Annealing	2004
[21]	Tabu Search	1996

In this work, the different severity functions dealt in [26] are analyzed and severity of the N-2 contingencies is studied. Contingency ranking is done based on not only on the voltage violations but also on the severity of the contingencies. Contingency severity for all possible 820 combinations of N-2 contingencies is done for IEEE 30 bus system. SVC is considered for voltage profile improvement. Gravitational Search Algorithm is adopted to achieve the optimal location and sizing of the SVC, thereby improving the voltage profile and reducing the number of limit violating buses.

2 Severity Indices

Three types of severity index function for low voltage are detailed in [26]. The following are the c

2.1 Discrete Severity Function (DSF)

If the voltage magnitude of the bus is lower than its low voltage rating, the severity function is assigned a value 1 or else a value of 0 is assigned to the severity function.

$$Sev(V_i) = \begin{cases} 0, & V_i \geq V_i^c \\ 1, & V_i < V_i^c \end{cases} \quad \text{... (1)}$$

where V_i^c is the low voltage rating of Bus 'i' and V_i is the voltage magnitude at bus 'i'.

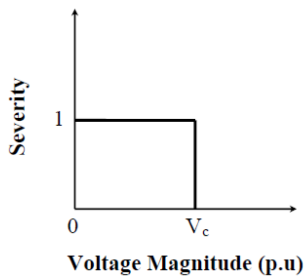

Fig 1. Discrete Severity Function

2.2 Percentage Violation Severity Function (PSF)

The severity function uses the percentage of violation to define the severity of the low voltage problem. The severity function may be stated as

$$Sev(V_i) = \begin{cases} \dfrac{0.95 - V_i}{0.95}, & V_i \leq 0.95 \\ 0 \quad , & V_i > 0.95 \end{cases} \quad \text{... (2)}$$

where V_i is the magnitude of voltage in p.u at bus 'i'.

2.3 Continuous Severity Function (CSF)

For each bus, the severity function takes a value of 1.0 at the deterministic low voltage limit and the severity function increases linearly as the decrease in magnitude of the bus voltage. In this case, when the bus voltage magnitude stays equal or above the nominal value of the bus, then the severity magnitude is zero. For voltage magnitude values smaller than 1.0, severity is a linear function with 1.0 corresponding to a voltage of 0.95 p.u.

$$Sev(V_i) = \begin{cases} 0, & V_i \geq V_i^b \\ \left(\frac{1}{V_i^c - V_i^b}\right) V_i + \frac{V_i^b}{V_i^b - V_i^c}, & V_i < V_i^b \end{cases} \quad ...(3)$$

where V_i^b is the nominal voltage of the bus 'i', V_i^c is the low voltage rating of the bus 'i' and V_i is the voltage magnitude of the bus 'i'.

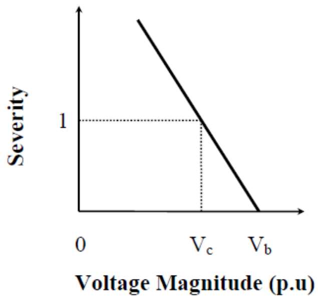

Fig.2 Continuous Severity Function

3 N-1 and N-2 contingencies

According to northern Electric Reliability Council (NERC), a catastrophic failure, defined as one that results in the outage of a sizable amount of load, may be caused by dynamic instabilities in the system or exhaustion of the reserves in transmission due to a sequence of line tripping leading to voltage collapse. NERC-compliance studies address the issue of assessing power system performance following normal and contingency conditions.

These studies ensure that the transmission system performance meets NERC Reliability Standards, and that the upgrades to meet future system needs are developed such that reliable and secure operation of the system is maintained. Transmission Planning (TPL) standards define reliable system performance following a loss of single bulk electric element, two or more bulk electric elements, or following extreme events. NERC, under its transmission planning standards.[27]

A new NERC TPL standard TPL-001-1 (Transmission System Planning Performance Requirements) that is scheduled to be submitted to the regulatory authorities for approval in 1Q2010 requires a more systematic and diligent contingency analysis, including exhaustive N-2 contingency analysis (loss of two elements simultaneously), N-1-1 contingency analysis (loss of two elements consecutively), and assessment of cascading outages. The need to provide the system planner with fast and automated process to effectively perform NERC-compliance studies is vital and growing more acute. In addition, this process should be used to assist planners in optimizing transmission system expansion which will reduce blackout risk and improve transmission system reliability.[28-29]

The traditional N-1 security criterion provides only a limited perspective on the actual level of security of a power system and a risk-based approach to security assessment, provides considerably more information on which operating decisions are to based.[30-31].

4 SVC Modelling

SVC is used in power system for voltage control to attain system stabilization. SVC can be viewed as an adjustable reactance with either firing angle limits or reactance limits. SVC is treated as a shunt connected variable susceptance (B_{SVC}) in this model as shown in fig.3.

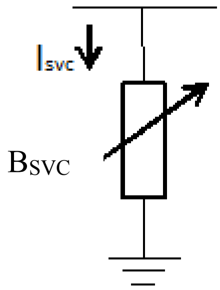

Fig 3: Equivalent Circuit of Static VAr Compensator

Current drawn by the SVC is

$$I_{SVC} = B_{SVC} V_i \quad ...(4)$$

Reactive power injected at bus 'i' is negative of the reactive power drawn by the SVC. Therefore,

$$Q_{SVC} = Q_i = -V_i^2 B_{SVC} \quad ...(5)$$

The bus to which SVC is connected is a voltage controlled bus and is called a PVB type bus, in which voltage magnitude, active and reactive power are specified and equivalent susceptance B_{SVC} is taken as the state variable.

The linearized equation of SVC is

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}^m = \begin{bmatrix} 0 & 0 \\ 0 & Q_i \end{bmatrix}^m \begin{bmatrix} \Delta Q_i \\ \Delta B_{SVC}/B_{SVC} \end{bmatrix} \quad ...(6)$$

At the end of iteration m, variable susceptance B_{SVC} is updated as:

$$B_{SVC}^{(m)} = B_{SVC}^{(m-1)} + \left(\frac{\Delta B_{SVC}}{B_{SVC}}\right)^{(m-1)} B_{SVC}^{(m-1)} \quad \dots(7)$$

Eqn (7) represents total SVC susceptance necessary to maintain nodal voltage magnitude at the specified value.

5 Gravitational Search Algorithm

The Gravitational Search Algorithm (GSA) is inspired from the Newton's theory that states: Every agent in the universe attracts every other agent with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. GSA method employs a collection of candidate solutions as agents that have their masses proportional to their fitness functions. During each generation, as per Newtonian law, each agent attracts each other agent with a force that is directly proportional to their masses or in other words their fitness function. Heavier the mass, the heavier is the force of attraction of an agent towards other agents. Hence the agent with better fitness function extends a higher attracting force on other agents towards it. The movement of an agent for the next iteration is dependent on the attractive force exerted on it due to all other agents.

In GSA, all masses are randomly initialized and each mass is considered as a candidate solution. Velocities for all masses are defined after initialization. The gravitational constant, total forces and accelerations are calculated using corresponding equations respectively and finally the positions of masses are calculated.

5.1 GSA Algorithm Implementation

Step 1:
Initialize all agents randomly in the search space within the search area limits.

Step 2:
Calculate the fitness of all agents based on its position in the search space using fitness function.

Step 3:
Calculate Gravitational force and gravitational constant.

$$GF_{mn}(t) = G(t)\frac{M_{pm}^{(t)} * M_{an}^{(t)}}{R_{mn}^{(t)+\varepsilon}} \quad \dots(8)$$

Where $GF_{mn}(t)$ is the gravitational force from agent 'm' on agent 'n' at time 't', $G(t)$ is gravitational constant at time 't', ε is constant of very low value, $M_{pm}^{(t)}$ is passive gravitational mass related to agent 'm', $M_{an}^{(t)}$ is active gravitational mass related to agent 'n'. Gravitational constant can be computed by:

$$G(t) = G_0 * \exp\left(-\alpha * \frac{N}{N_m}\right) \quad \dots(9)$$

Where G_0 is initial value, α is descending co-efficient, N is the current iteration, N_m is maximum number of iterations.

Step 4:
Calculate inertia mass constant

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad \dots(10)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)} \quad \dots(11)$$

Step 5:
Update G{t}, best{t}, worst{t} and $M_i(t)$
For minimization problems,

$$best(t) = \min_{j\in\{1,\dots,N\}} fit_j(t) \quad \dots(12)$$

$$worst(t) = \max_{j\in\{1,\dots,N\}} fit_j(t) \quad \dots(13)$$

Step 6:
Calculate total force acting on agent 'm'

$$F_m^d(t) = \sum_{n=1, n\neq m}^{N} rand_n F_{mn}^d(t) \quad \dots(14)$$

Where d is the dimension, $rand_n$ is random number in the interval [0, 1], F_m^d is the total force acting on agent 'm' and F_{mn}^d is the Force acting on agent 'm' due to agent 'n'.

Step 7:
The mass of each agent is calculated by

$$m_m(t) = \frac{presentfitness_i(t) - 0.9 * worst(t)}{best(t) - worst(t)} \quad \dots(15)$$

Step 8:
Calculate acceleration of all agents. Acceleration of all agents is given by

$$ac_m^d(t) = \frac{F_m^d(t)}{m_m(t)} \quad \dots(16)$$

where $ac_m^d(t)$ is the acceleration of the agent 'm' at time instant 't'.

Step 9:
Finally velocity and position of all agents are updated and the steps are repeated until convergence is achieved.

The generalized flowchart for the application of Gravitational Search Algorithm for N-2 contingency Analysis is given in Figure 4. The Newton Raphson method is used to perform load flow analysis and to determine the voltage levels at all buses.

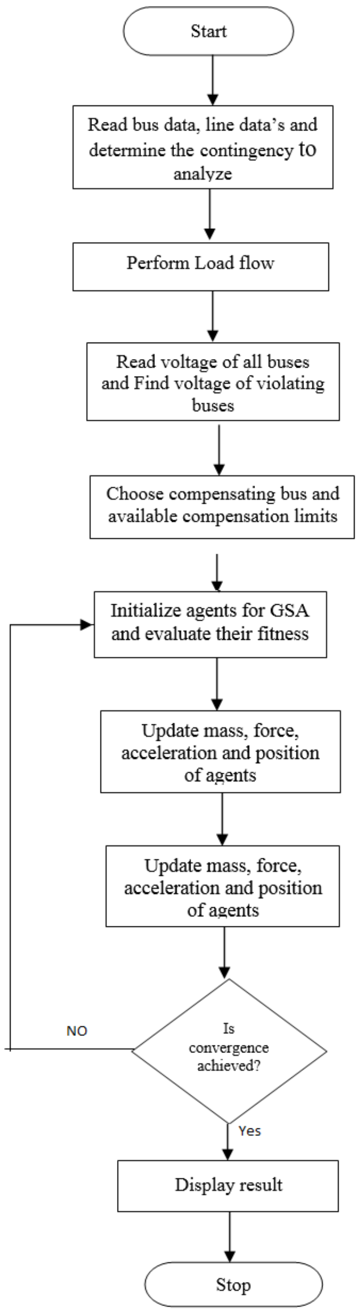

Fig 4. Flowchart for implementation of GSA for Contingency Analysis

6 Optimization Problem Formulation

The multi- objective function (J) is to reduce the severity index value (J_1) and to minimize the voltage deviation (J_2) by optimally placing the SVC.

6.1 Minimization of the Severity index:

The security level of the system is identified by the severity of the contingency. For stable operation, the severity of the contingency must be minimized.

$$Min\, J_1 = Min\,\{Sev(V_i)\} \qquad \dots(17)$$

where J_1 is the severity of the contingency to be minimized.

6.2 Minimization of Voltage Deviations

The deviation of voltage from the nominal value is to be minimized and is given by

$$Min\, J_2 = \sqrt{\sum_{i=0}^{N_{bus}} (V_i - 1)^2} \qquad \dots(18)$$

where J_2 is the voltage deviation to be minimized, V_i is the magnitude of the bus 'i', and V_{nom} is the nominal operating value of the bus 'i'.V_{nom} =1.0

The net objective function J to be minimized is:

$$\min J = w_1 J_1 + w_2 J_2 \qquad \dots(19)$$

where w_1 and w_2 are the weights attached to individual functions.

Three different types of cases are analysed on the subsystem based on the weights value assigned to w_1 and w_2.

Case 1: Least System Severity Solution

Here the multi-objective optimization function is modified to serve a single objective function of reducing the overall system severity. Hence the weightages assumed are w_1 =1 and w_2 =0.

Case 2: Least Voltage Deviation Solution

Here the multi-objective optimization function is modified to lay emphasis on system with least possible voltage deviations in all buses. Hence the weightages assumed are w_1 =0 and w_2 =1.

Case 3: Combined Solution

In this the multi-objective function is modified to find an optimal compromise solution to achieve the best possible solutions for reduction in voltage severity and voltage deviations combined together. The weightages assigned here are w_1 =1 and w_2 =1.

7 Test System Data

The test system used for the proposed work is the standard IEEE 30 bus system. The IEEE 30 bus system consists of 6 generators, 41 transmission lines with a total real power demand of 189.2 MW and a reactive power demand of 107.2 MVAR. The test system has six generators at the buses 1, 2, 5, 8, 11 and 13 and four transformers with off-nominal tap ratio at lines 6-9, 6-10, 4-12, and 28-27. The N-1 line contingency analysis in IEEE 30 bus system involves the analysis of 41 contingency states whereas N-2 line contingency analysis in IEEE 30 bus system involves the analysis of 820 contingency states. The schematic of the standard IEEE 30 bus system is shown in figure 5.

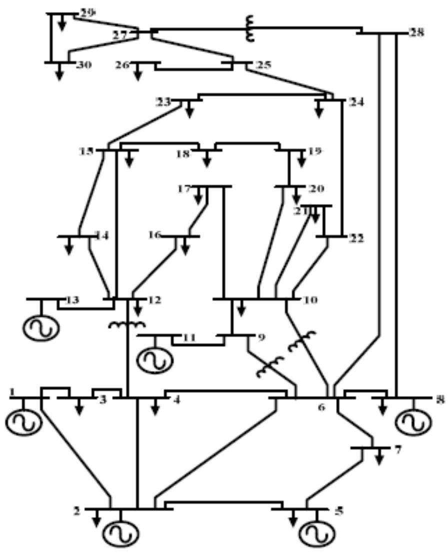

Fig. 5 IEEE 30 Bus System Schematic

8 Results and Discussion

In order to effectively manage the system stability, the N-1 contingency analysis cannot serve the entire purpose, since the loss of one line leading to voltage level violations in a bus may upset the balance of the power flow in the system, leading to the outage of another line of the system. Hence N-2 contingency analysis was done on all possible 820 states in the IEEE 30 Bus system using all the three different severity functions as discussed in section 2.

Table 2 shows the list of Top 5 severe contingencies determined by the discrete severity function. The Newton Raphson load flow analysis was used to determine the voltage at all the 30 Buses after the occurrence of a particular contingency state. The average computation time for the calculation of voltage at all buses using Newton Raphson method for a particular contingency is 0.0351 seconds.

Table 2 List of Top 5 Severe Contingencies based on Discrete Severity Function

Outage Lines		Severity of Contingency	Number of Voltage Violating Buses
Line 1	Line 2		
1	3	8	8
1	36	8	8
10	39	8	8
30	36	7	7
31	36	7	7

Table 3 List of Top 5 Severe Contingencies based on Percentage Severity Function

Outage Lines		Severity of Contingency	Number of Voltage Violating Buses
Line 1	Line 2		
31	36	1.492	7
10	39	1.287	8
30	36	0.595	7
1	36	0.578	8
14	36	0.561	6

Table 3 shows the list of Top 5 severe contingencies determined by the percentage severity function. It can be seen from Table 2 and Table 3 that the ranking of contingencies determined by each of the severity functions are different. Table 4 provides the list of Top 5 contingencies determined using the continuous severity function.

Table 4 List of Top 5 Severe Contingencies based on Continuous Severity Function

Outage Lines		Severity of Contingency	Number of Voltage Violating Buses
Line 1	Line 2		
10	39	40.051	8
31	36	36.106	7
1	36	29.729	8
14	36	23.340	6
1	3	22.383	8

The ranking of contingencies by continuous severity function given in Table 4 is different from ranking by percentage severity function in Table 4 and the ranking done by discrete severity function give in Table 2. In conclusion it may be summarily noted that each of the severity functions lay emphasis on certain features of voltage violation conditions resulting in various ranking.

The discrete severity function does not quantify the amount by which the voltage has violated the lower voltage limit of the bus. Hence the severity of the contingency described by the discrete severity function is always equal to the number of voltage violating buses. In percentage severity function, the emphasis is laid on the quantity of violation in voltage violating buses alone which is expressed as a percentage of the lower violation limit of the bus. Hence the severity value expressed is comparatively small in numerical terms with respect to the other two functions. The continuous severity function quantifies the severity based on deviation of the voltage value from the nominal operating voltage of all buses irrespective of voltage limit violations. Hence the numeric quantification by the continuous severity function has numerically higher value than other two functions.

Table 5 gives various voltage violating buses for all the discussed contingencies in Table 2, Table 3 and Table 4.

Table 5 List of Voltage Violating Buses for N-2 Contingencies

Outage Lines		Number of Voltage Violating Buses	Violating Buses
Line 1	Line 2		
10	39	8	23,24,25,26,27,28,29,30
1	36	8	3,4,24,25,26,27,29,30
1	3	8	3,4,6,7,26,28,29,30
31	36	7	23,24,25,26,27,29,30
30	36	7	23,24,25,26,27,29,30
14	36	6	24,25,26,27,29,30

The proposed Gravitational Search Algorithm approach was used to find the optimal reactive power supply by a FACTS device such as SVC at a particular bus so as to reduce the severity of the contingency. Table 6 gives the results of GSA based approach for the most severe contingency as determined using Discrete Severity function. All the three different cases are numerically equivalent when applied to the discrete severity function since the severity of the system is equal to the number of voltage violating buses. The optimization problem was hence set to run for case 2.

The choice of the compensating bus depends on the physical considerations of the system and its capabilities. Form Table 6 it can be inferred that the severity and the number of voltage violating buses after compensation depends both on the location of the SVC and also on the reactive power support by the SVC. Table 7 provides the optimal compensation support required for all the highly sever contingencies as determined by the Discrete Severity Function.

Table 6 Reactive Power Support found by GSA for outage of Line 1 & Line 3 using DSF for Case 2

Compensating Bus	Optimal Reactive Power Support in MVAr	After Compensation	
		Severity	No. of Voltage Violating Bus
3	81.4724	0	0
4	81.4724	0	0
6	81.4724	0	0
7	95.7505	0	0
26	81.4724	2	2
28	81.4724	0	0
29	81.4724	2	2
30	81.4724	2	2

Table 7 GSA based Optimal Reactive Power Support for severe contingencies determined using DSF

Outage Lines		Bus	Compensating MVAr	After Compensation	
Line 1	Line 2			Severity	No. of Voltage Violating Buses
1	3	8	81.4724	0	0
1	36	24	81.4724	0	0
10	39	24	95.7507	0	0
30	36	24	81.4724	0	0
31	36	27	81.4724	0	0

Table 8 Reactive Power Support found by GSA for outage of Line 31 & Line 36 using PSF for Case 1

Compensating Bus	Optimal Reactive Power Support in MVAr	After Compensation	
		Severity	No. of Voltage Violating Bus
23	91.8621	0	0
24	36.5208	0	0
25	74.0121	0	0
26	81.4724	0	0
27	53.0576	0	0
29	74.284	0	0
30	40.4133	0	0

Table 9 GSA based Optimal Reactive Power Support for severe contingencies determined using PSF

Outage Lines		Bus	Compensating MVAr	After Compensation	
Line 1	Line 2			Severity	No. of Voltage Violating Buses
31	36	24	36.5208	0	0
10	39	27	49.8851	0	0
30	36	24	35.734	0	0
1	36	26	2.1423	0.512	8
14	36	29	3.3971	0.483	6

Table 8 provides the optimal reactive power requirement found by GSA for the contingency of outage of Line 31 and Line 36 using Percentage Severity Function in Case 1. The optimization algorithm was designed to reduce the severity of the system after compensation. The severity of this contingency state before compensation is 1.492. Table 9 lists the optimal value of support for all top 5 contingencies determined by percentage severity function for case 1.

Table 10 provides the optimal reactive power requirement found by GSA for the contingency of outage of Line 10 and Line 39 using Continuous Severity Function in Case 3. The severity of the contingency before compensation was 40.051. Table 11 lists the optimal value of support for all top 5 contingencies determined by continuous severity function for case 3.

Table 10 Reactive Power Support by GSA for outage of Line 10 & Line 39 using PSF for Case 3

Compensating Bus	Optimal Reactive Power Support in MVAr	After Compensation	
		Severity	No. of Voltage Violating Bus
23	3.555	35.496	7
24	97.239	1.964	0
25	45.430	4.485	0
26	64.580	5.121	0
27	40.035	6.216	0
28	0.4176	39.722	8
29	97.937	7.019	0
30	93.140	10.254	1

Table 11 GSA based Optimal Reactive Power Support for severe contingencies determined using CSF

Outage Lines		Bus	Compensating MVAr	After Compensation	
Line1	Line2			Severity	No. of Voltage Violating Buses
10	39	24	97.23	1.964	0
31	36	24	31.709	1.570	0
1	36	24	42.647	8.825	0
14	36	26	19.97	3.573	0
1	3	7	92.038	10.079	0

The voltage levels at all 30 buses in the test system after compensation by optimal MVAr found by GSA during the N-2 contingency outage of Line 10 and Line 39 is given in Figure 6. A comparison of voltage levels at all load buses after locating SVC at bus 26 in IEEE 30 bus system with other existing algorithms like Evolutionary programming, Particle Swarm Optimization and Tabu Search from [22] is made and shown in Table 12.

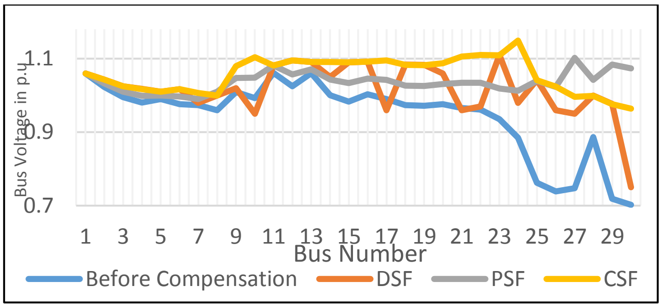

Fig. 6 Voltage Profile of System Before and After Compensation

Table 12 Comparison of Voltage levels at various buses after placement of SVC at Bus 26

Variable	EP	PSO	TS	GSA
V_1 (p.u)	1.009	1.049	1.05	1.06
V_2 (p.u)	1.006	1.037	1.0052	1.033
V_5 (p.u)	1.021	1.029	0.9506	1.00
V_8 (p.u)	0.998	1.020	0.973	1.01
V_{11} (p.u)	1.066	1.002	1.0147	1.082
V_{13} (p.u)	1.051	0.995	1.0158	1.071

9 Conclusion

The proposed work investigated for the N-2 contingencies and its associated voltage severity conditions on the basis of various severity functions available in literatures. A detailed analysis on all the 820 possible contingency states was done and the states were ranked based on the severity. The Gravitational Search Algorithm was designed and applied to find the optimal compensation at a particular bus to reduce the system severity.

Both the Percentage Severity Function and the Discrete Severity Function determines the severity value of the system only when there are voltage violating buses present in the system. It does not differentiate between the conditions where the voltage level of a bus is operating very close to the lower limits. Another serious drawback in all three severity functions is that the severity due to overvoltage conditions is not accounted in the severity function formulation. The Continuous Severity Function is comparatively a better methodology to effectively quantify the voltage violations as it takes the deviation of voltage value from its nominal voltage rather than the lower voltage limit. Further the severity value is calculated for all the buses irrespective of the presence of voltage violations.

The work may be extended to develop further augmented severity functions that combines the advantages of all the three mentioned severity functions and also to address their shortcomings.

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11 *Appendix*

The line details connecting various buses in the system under study is given below in Table 13.

Table 13 IEEE 30 Bus Transmission Line Configuration

Line	Between	
1	1	2
2	1	3
3	2	4
4	3	4
5	2	5
6	2	6
7	4	6
8	5	7
9	6	7
10	6	8
11	6	9
12	6	10
13	9	11
14	9	10
15	4	12
16	12	13
17	12	14
18	12	15
19	12	16
20	14	15
21	16	17
22	15	18
23	18	19
24	19	20
25	10	20
26	10	17
27	10	21
28	10	22
29	21	22
30	15	23
31	22	24
32	23	24
33	24	25
34	25	26
35	25	27
36	28	27
37	27	29
38	27	30
39	29	30
40	8	28
41	6	28