OPTIMAL SIZING AND PLACEMENT OF STATCOM IN TRANSMISSION SYSTEMS USING GRAVITATIONAL SEARCH ALGORITHM

P.RamaSubba Reddy[1], A.Lakshmi Devi[2]

[1]*M.Tech, Dept. of EEE, SVUCE, Sri Venkateswara University, Tirupati, India.*
[2]*Professor,Dept. of EEE, SVUCE, Sri Venkateswara University, Tirupati, India.*

ABSTRACT

A nature inspired Gravitational Search Algorithm (GSA) has been proposed for optimal placement of STATCOM to maximize the voltage stability margin and also improve voltage profile by minimizing the total voltage deviation in the power system. The proposed nature inspired evolutionary approach has been performed using two steps. As the first step, the weakest buses selected for placement of STATCOM using modal analysis. In the second step GSA is applied, to select the optimal allocation of STATCOM considering these selected weakest buses. The proposed GSA has been tested on the standard IEEE 30-bus system considering the stressed condition as well as contingencies during stressed condition. To establish the superiority of proposed GSA approach, the results using with and without STATCOM were compared.

Keywords: *Gravitational Search Algorithm, STATCOM, Voltage Stability Margin*

---

1. INTRODUCTION

Power systems usually consist of generators, transmission lines, transformers, compensators, switches, real and reactive power loads. Power system networks are complex, dynamic, non linear, and are prone to various types of faults/ disturbances. Due to day-by-day increase in load demand, power systems are operated near to their operating limits. Such stressed conditions and various contingencies sometimes may lead to poor voltage profile and voltage instability.

In the last decades, efforts have been made to find the ways to assure the security of the system in terms of voltage stability. It is found that flexible AC transmission system (FACTS) devices are good choices to improve the voltage profile in power systems that operate near their steady-state stability limits and may result in voltage instability.

Different types of devices have been developed. Three categories of FACTS controllers may be distinguished:

- Series controllers
- Shunt controllers
- Combined series-shunt controllers.

Inside a category, several FACTS devices exist and each one has its own properties and may be used in specific contexts. The choice of the appropriate device is important since it depends on the goals to be reached. For improving the voltage profile and voltage stability, statcom, a shunt FACTS Controller is more effective in compare to series FACTS Controller. But due to high cost of statcom, optimal statcom placement is very important task for power system engineers.

Various heuristic approaches have been adopted by researches including genetic algorithm, simulated annealing, ant colony and particle swarm optimization. These algorithms have been proven to be very effective for static and dynamic optimization problems. Study on the use of heuristic approaches to seek the optimal location of FACTS devices in a power system is carried out by the researches around the world. In this paper a new optimization algorithm is used known as Gravitational Search Algorithm (GSA). The proposed optimization algorithm is based on gravitational law and laws of motion based on following definition by English mathematician Sir Isaac Newton in 1687: every particle in the universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

2. MODELING OF STATCOM

The first static synchronous shunt compensator (statcom) was installed by Tennessee Valley Authority (TVA) in 1995 [13]. Statcom is a voltage source converter which is used to offer reactive power support to maintain the voltage magnitude of load bus within their voltage security limit. Statcom is always placed on a PQ bus and this PQ bus is converted in to PV bus. Therefore statcom is worked as a (alternator) synchronous generator. The real power output of synchronous generator is zero and its voltage is set to some reference value [14]. The model equation of statcom used here is defined in [15]. The model equation signifies the flow of active and reactive power to and from the statcom. The voltage at the statcom bus is expressed as

$$V = V_{ref} \pm IX_{SL} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, V_{ref} is reference voltage and X_{SL} is the controller droop. In equation (1), the inductive mode and capacitive mode of statcom is identified by using the positive and negative sign respectively.

3. PROBLEM FORMULATION

A. Objective Function:

- Voltage stability margin Maximization:

For improving the voltage stability margin, it is required to maximize the distance between the current operating point and voltage collapse point. Saddle-node bifurcation or voltage collapse point is determined using the zero Eigen value associated with the power system Jacobian. Hence to enhance voltage stability margin, it is required to maximize the minimum Eigen value of the power system Jacobian. Hence the first objective function is represented by using the following equation,

$$max f_1 = min\big(eig(J_R)\big) \ldots\ldots\ldots\ldots (2)$$

Where min (eig(J_R)) is the minimum Eigen value of reduced Jacobian matrix from power flow solution.

- Total Voltage Deviation Minimization:

By keeping the bus voltage within their voltage security limits, the voltage profile can be improved. This can be accomplished by minimizing the total voltage deviation from their voltage security limit. Therefore second objective is to expressed as

$$min f_2 = \sum_{m=1}^{k} \left|V_{mref} - V_m\right| \quad \ldots\ldots.. (3)$$

Where, Vm is the voltage magnitude at PQ bus m, Vrnref is nominal voltage at PQ bus m and k is the no. of buses for which bus voltage security limit is disturbed. In this, acceptable bus voltage security limit ±6% (0.94 to l.06 p.u.) is considered. Low value of f_2 indicates that voltage profile.

- Minimize the capacity of statcom:

Due to the high cost of statcom, it should be optimally sized. The third important objective function is to have minimum possible capacity of statcom. This can be expressed as below and the total number of statcom is represented by sf.

$$min f_3 = \sum_{i=1}^{sf} C_i \ldots\ldots\ldots\ldots \quad (4)$$

B. Constraints:

During normal operation, power system is required to satisfy some constraints. These constraints are as described below.

$$g(x,u) = 0 \ldots\ldots\ldots\ldots (5)$$

Equation (5) shows the load constraints, where g is the load (equality) constraint representing typical load (power) flow equations, x is a vector of dependent variables consisting of slack bus power P_{G1}, PQ bus voltages V_L and generator reactive power outputs Q_G and u is a vector of independent variables comprising of generator real power outputs P_G, generator voltages V_G except the slack bus power P_{G1} and shunt VAR compensations Q_C.

$$h(x,u) \leq 0 \ldots\ldots\ldots\ldots (6)$$

Equation (6) shows the inequality constraints, where h is the system operating constraint comprising of generator voltages and their real and reactive power outputs and shunt VAR compensations. Considering the objectives and constraints, the optimization problem of optimal allocation statcom can be expressed Multi-Objective Optimization (MOO) problem (nonlinear constrained problem) as below

$$V = V_{ref} \pm IX_{SL}$$

$$max f_1 = min(eig(J_R))$$

$$min f_2 = \sum_{m=1}^{k} |V_{mref} - V_m|$$

Subject to

$$g(x,u) = 0$$

$$h(x,u) \leq 0$$

4. PROPOSED APPROACH

In this paper, Gravitational Search Algorithm (GSA) approach is proposed, to improve voltage profile and voltage stability by solving statcom placement and sizing problem. GSA was efficiently tested on SVC Allocation problem [17] and found that GSA provides high quality optimal solution compare to PSO. GSA approach was also applied for other power system engineering problems for example, reactive power dispatch problem [18], optimal power flow [19] and others. GSA provided good solutions for the above problems, in compare to c1assical optimization techniques and it is also reduced the computational work.

Gravitational Search Algorithm was proposed by Rashedi et al. [20] in 2009. GSA is based on the law of gravity and mass interactions. Assume a system n agents where position of ith agent is given by:

$Xi = (x_i^1, \ldots x_i^d, \ldots x_i^n)$ for i =1,2…. N.

x_i^d is the position of ith agent in dth dimension. Now at a particular time t force acting on mass i by mass j is given by:

$$F_{ij}^d(t) = G(t) \frac{M_{pi}(t) * M_{aj}(t)}{R_{ij}(t) + \varepsilon}$$

Where M_{aj} is the active gravitational mass related to agent j, M_{pi} is the passive gravitational mass related to agent i, G (t) is gravitational constant at time t, ε is a small constant, and $R_{ij}(t)$ is the Euclidian distance between two agents i and j. The total force which acts on agent i in a dimension d is the randomly weighted sum of dth components of the forces exerted from other agents:

$$F_i^d(t) = \sum_{j=1, j \neq i}^{N} rand_j F_{ij}^d(t)$$

Where $rand_j$ is a random number in the interval [0,1]. According to the law of motion, the acceleration of an agent is proportional to the result force and inverse of its mass, so the acceleration of all agents should be calculated as follow:

$$ac_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)}$$

Where M_{ii} is the inertial mass of the ith agent. Further, next velocity and next position of the agent can be calculated as:

$$v_i^d(t+1) = rand_i \times v_i^d + ac_i^d$$
$$x_i^d(t+1) = x_i^d + v_i^d(t+1)$$

Where $rand_i$ is a uniform random variable in the interval [0, 1]. The value of gravitational constant G is not constant and will reduce with time to have a control over the search accuracy.

$$G(t) = G(G_0.t)$$

The gravitational masses are updated by the following equations:

$$M_{ai} = M_{pi} = M_{ii} = M_i \quad i = 1,2, \ldots..N$$
$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)}$$
$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)}$$

Where $fit_i(t)$ is the fitness value of agent i at time t and for the current minimization problem best(t) and worst(t) are given as follows:

$$best(t) = min_{j\epsilon\,(1,2,..N)} fit_j(t)$$
$$worst(t) = max_{j\epsilon\,(1,2,..N)} fit_j(t)$$

Following are the various steps of the GSA approach:

Step 1: Identify the search space.
Step 2: Randomly initialize the agents.
Step 3: Calculate the fitness of agents
Step 4: Update G(t), best(t), worst(t) and Mi(t) for 1, 2, 3 ...... N.
Step 5: Evaluate the force on agents.
Step 6: Calculate acceleration and velocity of agents.
Step 7: Position and velocity of agents are updated.
Step 8: Repeat steps 3-7 until stop criteria is reached.
Step 9: Stop.

5. RESULTS AND DISCUSSION

Gravitational Search Algorithm (GSA) is applied for finding the optimal placement and sizing of statcom in IEEE 30-bus system. The line and bus data is given [12]. In IEEE 30- bus system bus no. 1 is slack bus, bus nos. 2, 5, 8, 11 and 13 are generator buses, and remaining buses are load buses. The IEEE 30 bus system comprising of two synchronous compensators connected at bus 11, 13, including four generators which are connected at bus no. 1, 2, 5 and 8. Synchronous compensators are used to provide support of reactive power. There are 41 branches with transformer tap setting between buses 6-10, 9-11, 4-13 and 4-12. Under the base case condition, the connected load is 283 MW and 109 MVAR and voltage magnitude at all buses are within their voltage security limit (0.94 p.u.to l.06 p.u.). Therefore power system is secured. However during severe stressed condition as well as critical contingencies under stressed condition, voltages at some buses violating from their voltage security limit.

In this paper, two cases are considered. Case A is stressed condition and Case B is critical contingencies under stressed condition with and without statcom. For optimally placement of statcom, the 5 load buses (bus nos. 23, 24, 25, 26 and 27) have been selected using modal analysis, as possible locations, to improve voltage profile and voltage stability. As a first step, load flow analysis and modal analysis have been performed for the base case condition. This has been observed that this test system has a satisfactory voltage profile with TVD (Total Voltage Deviation) is 0.3520 and thus needs no StatCom. From modal analysis, the minimum Eigen value for this system is found to be 2.777l. Load flow analysis and modal analysis have also been performed during Case A and Case B for calculating minimum Eigen values. Contingency selection and ranking is carried out to find out the most severe condition which is given in table l. On this basis three most critical single line outage contingencies, outage of line (LO) nos. 14 and 16 are found critical line outages during Case B. The reduction in power loss with the help of optimal sizing and placement of StatCom in IEEE 30 bus system is shown in below Table 1.

Table 1: Real and Reactive Power Losses

Type of losses		P loss (MW)	Q loss (Mvar)
Normal case		17.557	67.690
Without Statcom	Stressed condition	18.212	69.980
	Line Outage 16(LO 16)	22.918	87.560
	Line Outage 14 (LO 14)	20.646	79.300
With Statcom	Stressed condition	11.382	43.320
	Line Outage 16(LO 16)	10.300	41.140
	Line Outage 14 (LO 14)	9.995	37.180

Table2. Result analysis of IEEE 30 bus system system without statcom.

Bus No.	Normal Case (p.u. voltages)	Stressed Condition (p.u. voltages)	LO16 (p.u. voltages)	LO14 (p.u. voltages)
1	1.060	1.060	1.060	1.060
2	1.045	1.045	1.045	1.045
3	1.019	1.017	1.015	1.017
4	1.010	1.008	1.006	1.008
5	1.010	1.010	1.010	1.010
6	1.008	1.006	1.004	1.006
7	1.001	1.000	0.999	1.001
8	1.010	1.010	1.010	1.010
9	1.049	1.048	1.044	1.048
10	1.043	1.041	1.035	1.041
11	1.082	1.082	1.082	1.080
12	1.056	1.055	1.052	1.055
13	1.071	1.071	1.071	1.071
14	1.041	1.039	1.035	1.039
15	1.035	1.033	1.027	1.032
16	1.043	1.041	1.037	1.041
17	1.038	1.036	1.030	1.036
18	1.026	1.024	1.017	1.023
19	1.023	1.021	1.015	1.021
20	1.027	1.025	1.019	1.026
21	1.029	1.027	1.019	1.026
22	1.030	1.027	1.018	1.025
23	1.022	1.018	1.006	1.016
24	1.013	1.008	0.988	1.004
25	0.997	0.979	0.945	0.981
26	0.979	0.944	0.876	0.934
27	0.997	0.980	0.954	0.990
28	1.000	0.996	0.991	0.998
29	0.954	0.925	0.893	0.949
30	0.921	0.892	0.857	0.924

Table3. Result analysis of IEEE 30 bus system With statcom

Bus No.	Normal Case (p.u. voltages)	Stressed Condition (p.u. voltages)	LO16 (p.u. voltages)	LO14 (p.u. voltages)
1	1.0650	1.060	1.0600	1.0600
2	1.0450	1.045	1.0450	1.0450
3	1.0244	1.024	1.0259	1.0260
4	1.0159	1.016	1.0174	1.0177
5	1.0100	1.010	1.0100	1.0100
6	1.0136	1.014	1.0137	1.0146
7	1.0044	1.004	1.0060	1.0067
8	1.0100	1.010	1.0100	1.0100
9	1.0575	1.058	1.0540	1.0570
10	1.0565	1.057	1.0491	1.0548
11	1.0820	1.082	1.0820	1.0820
12	1.0631	1.063	1.0606	1.0635
13	1.0710	1.071	1.0710	1.0710
14	1.0508	1.051	1.0463	1.0505
15	1.0495	1.049	1.0434	1.0485
16	1.0546	1.055	1.0496	1.0536
17	1.0534	1.053	1.0468	1.0520
18	1.0452	1.045	1.0386	1.0440
19	1.0452	1.045	1.0382	1.0437
20	1.0472	1.047	1.0401	1.0456
21	1.0456	1.046	1.0360	1.0435
22	1.0466	1.047	1.0363	1.0444
23	1.0445	1.045	1.0330	1.0424
24	1.0411	1.041	1.0224	1.0375
25	1.0331	1.033	1.0078	1.0249
26	1.0208	1.021	0.9848	1.0023
27	1.0343	1.034	1.0106	1.0286
28	1.0109	1.011	1.0086	1.0110
29	1.0161	1.016	0.9961	1.0103
30	1.0085	1.008	0.9812	1.0027

From modal analysis, the minimum Eigen value for this system is found to be 2.777l. Load flow analysis and modal analysis have also been performed during Case A and Case B for calculating minimum Eigen values. Contingency selection and ranking is carried out to find out the most severe condition which is given in table l. On this basis three most critical single line outage contingencies, outage of line (LO) nos. 14 and 16 are found critical line outages during Case B. The comparison of voltages (p.u) in IEEE 30 bus system without and with StatCom during stressed condition and contingencies under stressed condition has shown in Table2 and Table3. In Fig1we have shown that the variation of voltages(p.u) during different conditions without statcom has been shown. The voltage variations using StatCom has been plotted in Fig2.

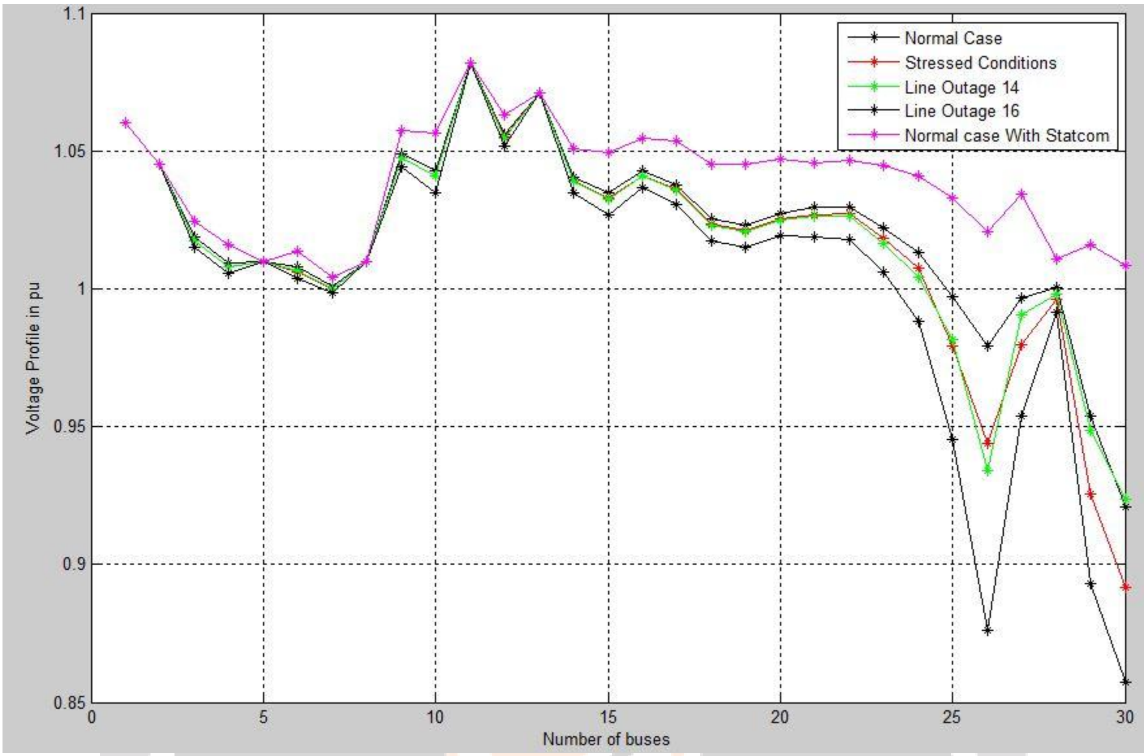

Fig1.comparison of voltages(p.u) without statcom

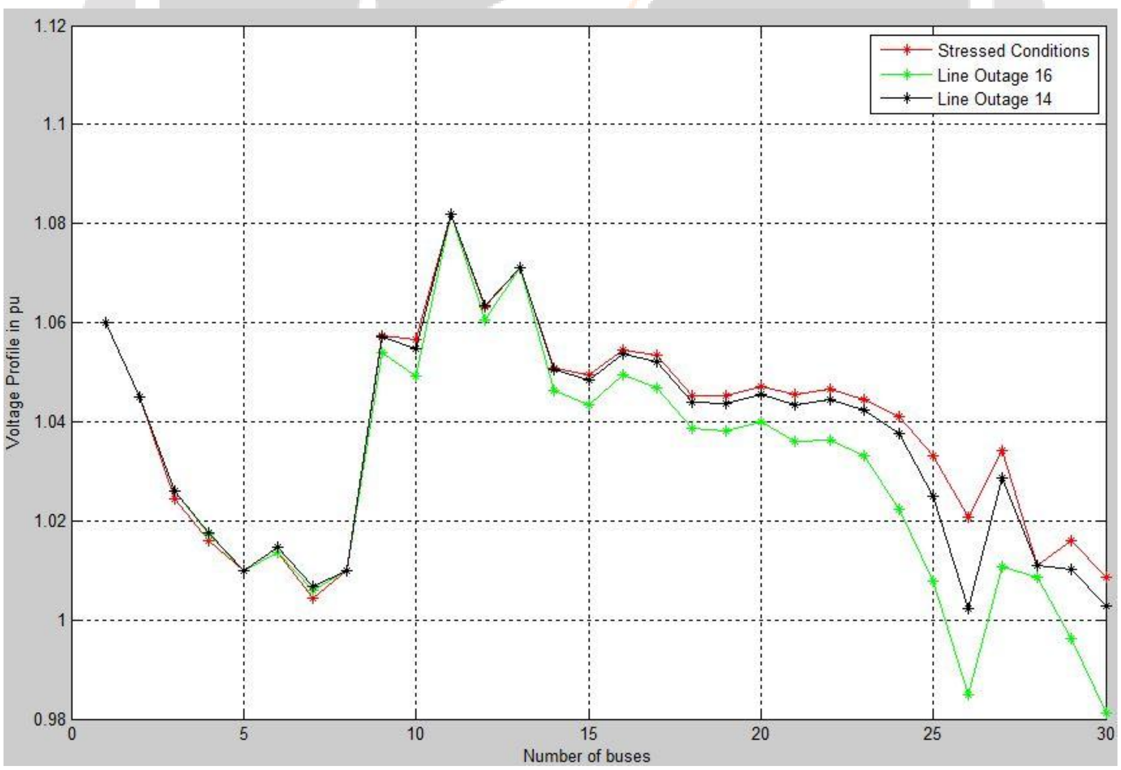

Fig2.comparison of voltages(p.u) with statcom

6.CONCLUSION

Gravitational Search Algorithm has been proposed for optimal placement and capacity of STATCOM, for voltages stability margin maximization and total voltage deviation minimization in a power system. For finding the optimal placement (location) and Size (Capacity) of STATCOM stressed condition, and contingencies under stressed condition are considered. Minimum Eigen value of reduced Jacobian matrix is considered for finding the severe condition in power system. This approach has been applied on standard IEEE 30-bus system. GSA quickly converges and provides high quality optimal solution as compare to GA. As the proposed GSA based approach is found to be faster and accurate, this can be implemented for practical power systems also.

7.REFERENCES

[1] Bharath Singh Rana and Laxmi Srivastava "Optimal statcom placement using gravitational search algorithm," *IEEE international conference on power electronics, intelligent control and energy systems,* July 2016.

[2] S. Gerbex, R. Cherkaoui and A. J. Germond "Optimal location of FACTS devices to enhance power system security," *IEEE Bologna Power Tech Conference proceedings,* vol. 3, pp. 7, 2003.

[3] W. Ongsakul and P. Jirapong "Optimal allocation of FACTS devices to enhance total transfer capability using evolutionary programming," *IEEE International Symposium on Circuits and System,* vol. 5, pp. 4175-4178, 2005.

[4] Y. Del Valle, J.C. Hernandez, G. K. Venayagamoorthy, R. G. Harley, "Optimal statcom sizing and placement using particle swarm optimization," *IEEE/PES Transmission and distribution conference and exposition,* pp. 1-6, 2006.

[5] B. Gao, GK. Morison, P. Kundur, "Voltage stability evaluation using modal analysis," *IEEE Transactions on Power systems,* vol. 7(4), pp. 1529-1542, 1992.

[6] C. A. Canizares, M. Pozzi, S. Corsi and E. Uzunovic, "Statcom modeling for voltage and angle stability studies," *Electrical Power and energy systems,* vol. 25, pp. 431-441, 2003.

[7] E. Rashedi, H. Nezamabadi-pour, S. Saryazdi and M.M. Farasangi, "Allocation of static VAR compensator using Gravitational search algorithm," *first joint congress on fuzzy and intelligent systems ferdowsi university of mashhad, Iran, 2007.*

[8] A. Bhattacharya and P.K. Roy, "Solution of multi objective optimal power flow using gravitational search algorithm," *IET Generation, Transmission, Distribution,* vol. 6, pp. 751-763, 2012.

[9] E. Rashedi, H. Nezamabadi-pour and S. Saryazdi, "GSA: A Gravitational Search algorithm, " *Information Sciences (179),* pp. 2232-2248, 2009.

[10] S. Duman, Y. Sonmez, U. Guvenc and N. Yorukeren "Application of Gravitational Search Algorithm for optimal reactive power dispatch problem," *International symposium on innovations in intelligent systems and applications,* pp. 519-523, 2011.