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Research Article

Optimal Placement of Static Compensators for Global Voltage Sag Mitigation and Power System Performance Improvement

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Abstract: This study presents a new multi-objective approach for optimal placement of Static Compensator (STATCOM) for global (overall) voltage sag mitigation as well as for power system performance improvement. The problem is formulated as a non linear constrained multi-objective optimization problem and solved using Genetic Algorithm (GA). The proposed method determines optimal locations of STATCOMs which simultaneously minimizes the overall voltage sags at network buses, bus voltage deviation and system real power loss and maximizes the voltage stability margin of the system. The proposed approach has been applied on IEEE 24-bus Reliability Test System (RTS) and IEEE 57-bus test systems. The details of implementation and simulation results are presented. The application results are promising and encouraging.

Keywords: Power quality, Static Compensator (STATCOM), voltage sag, voltage sag mitigation

INTRODUCTION

Modern power systems are operating under stressed operating conditions with associated problems related to system security and power quality. Also, deregulation in the power industry and opening of the market to deliver cheaper energy to the customers is creating additional requirements for the performance improvement of power systems (Thukaram and Yesuratnam, 2008). One of the major problems that may associate with such a stressed system is the voltage instability or collapse. Therefore under stressed operating conditions, the most effective way to improve the performance of the system is to provide reactive power support by FACTS controllers (Thukaram and Yesuratnam, 2008; Hingorani and Gyugyi, 1999; Yan and Sekar, 2005; Cai and Erlich, 2005). FACTS devices have been developed to improve the performance of long-distance AC transmission system (Hingorani and Gyugyi, 1999; Garbex *et al*., 2001). Excellent operating experiences are available worldwide and also FACTS technology became mature and reliable (Thukaram and Yesuratnam, 2008). Providing adequate reactive power support at the appropriate location not only leads to reduction in the power loss and improvement in the voltage profile, but also solves voltage instability problems. However, to obtain good performance from these controllers proper placement of these controllers is crucial (Cai *et al*., 2004; Saravanan *et al*., 2007; Rahimzadeh *et al*., 2010; Kumar *et al*., 2007; Phadke *et al*., 2012).

There are several methods proposed in literature for placement of FACTS devices for power system performance improvement and voltage stability enhancement. In recent years, multi-objective approaches based on evolutionary optimization techniques have become popular. The intelligent optimization techniques such as Genetic Algorithm (GA) (Cai and Erlich, 2005; Garbex *et al*., 2001; Rahimzadeh *et al*., 2010), Particle Swarm Optimization (PSO) (Saravanan *et al*., 2007), Fuzzy logic (Jeevarathinam, 2006) etc. are used to determine the optimal location of FACTS controllers. In these approaches the objective or fitness function is based on multiple objectives, such as minimization of power loss, voltage deviation and maximization of voltage stability margin enhancement.

Another serious problem is the occurrence of voltage sag in the system under fault conditions but comparatively little attention has been devoted to this problem. With the rapid development of science and technology, more and more sensitive equipments, such as Programmable Logic Controllers (PLCs), Adjustable Speed Drives (ASDs), Personal Computers (PCs) and AC-Contactors (ACCs), are widely used in modern industrial applications. These equipments are very sensitive to voltage sags (Bollen, 1999) which lead to disruptions of industrial processes and poor quality or even faulty products, resulting in significant economic

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and investment losses (Xiao *et al*., 2010; Gomez and Morcos, 2001). Therefore, the mitigation of the voltage sags has become the focus of power quality research to minimize its severe economical impact (Lamoree *et al*., 1994; Alabduljabbar and Milanovi, 2010; Goswami *et al*., 2011). Haque (2001) dealt with placement of FACTS devices for voltage sag mitigation but it is mostly oriented towards the load where the device is connected and simulations were focusing on the individual connected bus. This approach however, tends to ignore the effect of FACTS devices on the whole network. In Zhang and Milanovic (2010) a GA based approach for optimal placement of FACTS controller for global voltage sag mitigation is proposed. However this approach does not consider steady state performance improvement and voltage stability margin enhancement.

In the existing literature, the placement of FACTS devices is considered either for performance improvement and voltage stability enhancement or for voltage sag mitigation under fault condition. However, no effort has been made to obtain optimal locations of these controllers for performance improvement, voltage stability margin enhancement and simultaneously for voltage sag mitigation under fault conditions.

In the light of above discussion, this paper addresses the problem of optimal placement of Static Compensator (STATCOM) as a multi-objective optimization problem which simultaneously minimizes the number of voltage sags, bus voltage deviation, system real power loss and also maximizes voltage stability margin of the system. This multi-objective problem is solved using GA.

METHODOLOGY

Multi-objective formulation for placement of Static Compensator (STATCOM): Static compensator connected at the appropriate location results in overall voltage sag performance improvement, better voltage profile, reduction in total active power loss and also maximizes voltage stability margin of the system. The problem for placing static compensator can be formulated as a multi-objective problem with the following objectives and constraints.

Voltage sag mitigation: The Flexible AC Transmission System (FACTS) devices like STATCOMs are well-developed mature technologies which have been widely applied in power systems around the world to restore bus voltages either in certain part/area of the system or at the load side (Ali *et al*., 2012).

The voltage sag magnitude has been identified as the most influential (on equipment performance), most frequently and reliably recorded available parameter. Therefore, it is used in this study as the parameter in the optimization procedure. Thus the first objective is to reduce the overall voltage sags which includes the number of sags in different magnitude ranges and relevant weighting factors can be expressed as (Zhang and Milanovic, 2010):

$$\min \quad f_1 = w_1 N_1 + w_2 N_2 + w_3 N_3 \tag{1}$$

where, w_1, w_2 and w_3 $(w_1 + w_2 + w_3 = 1)$ are weighting coefficients specifying the desired shift of sags from a particular magnitude range., N_1, N_2 and N_3 are the numbers of voltage sags in a particular voltage magnitude range. As per recommendations of IEC 61000-4-11: (2004) the voltage magnitude values used are 0, 40 and 70%, respectively of nominal, for equipment testing against voltage sags and short interruptions. Therefore, it motivates the author to analyze the number of voltage sags in these magnitude ranges i.e., 0-0.4, 0.4-0.7, 0.7-0.9 p.u., Thus, N_1, N_2 and N_3 are selected as follows:

N_1 = Number of voltage sag in the magnitude range 0.7 to 0.9 p.u.
N_2 = Number of voltage sag in the magnitude range 0.4 to 0.7 p.u.
N_3 = Number of voltage sag in the magnitude range 0 to 0.4 p.u.

In this study, the values of w_1, w_2 and w_3 are taken as 0.1, 0.2 and 0.7, respectively.

Voltage deviation: Excessively low voltages can lead to an unacceptable service quality and can create voltage instability problems. STATCOMs connected at the appropriate location are playing a leading role in improving voltage profile and avoiding the voltage collapse in the power system. Therefore, the second objective selected is to minimize bus voltage deviation. This objective function can be expressed as:

$$\min \quad f_2 = \sum_{m=1}^{k} \left| \frac{V_{mref} - V_m}{V_{mref}} \right| \tag{2}$$

where, f_2 is voltage deviation in p.u., V_m is the voltage magnitude at bus *m*, V_{mref} is the nominal voltage of bus *m* and *k* is the number of buses for which bus voltage limit is violated. Low value of f_2 indicates flat voltage profile.

Active power loss: Apart from reducing number of voltage sags and voltage deviation, a good STATCOM reinforcement scheme should contribute to reducing the system active power loss (I^2R). Static compensator connected at the appropriate location, results in maximum decrease in active power loss. Therefore active power loss reduction is, in fact, in a way linked with the optimal location of static compensator. Thus, the third objective selected is to minimize the total system active power loss which can be expressed as:

$$\min f_3 = P_{loss}(x, u) \tag{3}$$

where, x is a vector of dependant variables consisting of slack bus power P_{G1}, load bus voltages V_L and generator reactive power outputs Q_G and u is the vector of independent variables consisting of generator voltages V_G, generator real power outputs P_G except the slack bus power P_{G1} and shunt VAR compensations Q_C.

Voltage stability margin enhancement: One of the major problems that may associate with a stressed system is the voltage instability or collapse. Many incidents of system blackout due to voltage collapse have been reported worldwide (Kundur *et al*., 1994). Voltage stability is the ability of a power system to maintain steady voltages at all buses in the system after being subjected to disturbance from a given initial operating condition (Kundur *et al*., 2004).

Various analytical tools based on different concepts have been proposed to get a measure of the margin between the current operating point and the voltage collapse point. This measure can be in the form of an index. The index proposed by Kessel and Glavitsch (1986) gives a scalar number for each load bus, called the L-index. L-index describes the stability of the complete system and it varies in a range between 0 (no load) to 1 (voltage collapse) (Kessel and Glavitsch, 1986). Consider a system where n is the total number of buses with 1, 2, ..., g, generator buses and g + 1, g + 2, ..., n, the load buses. Using the power flow results the L-index can be computed as:

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \left(V_i / V_j \right) \right| \tag{4}$$

where, $j = g + 1, \ldots, n$ and the values of F_{ji} can be computed from the Y bus matrix as:

$$F_{ji} = -\left[Y_{LL}\right]^{-1} \left[Y_{LG}\right] \tag{5}$$

The L-indices for a given load condition are computed for all load buses. The maximum value of L-indices (L_{max}) is an indicator of the proximity of the system to voltage collapse and the corresponding bus is the most critical or weakest bus in the system. Low value of f_4 indicates greater voltage stability margin.

Thus the fourth objective selected is voltage stability margin enhancement which can be expressed as:

$$\min f_4 = \sum_{m=1}^{n} L_m \tag{6}$$

where,
L_m = L index value for bus m
n = Total number of buses

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

Load constraint: The load constraints are the active and reactive power balance equations which can be expressed in a compact form as:

$$g(x,u) = 0 \tag{7}$$

where, g is the equality constraint representing typical load flow equations.

Operational constraint: These constraints can be represented in a compact form as:

$$h\,(x, u) \le 0 \tag{8}$$

where, h is the system operating constraint that includes generator voltages, their real and reactive power outputs and shunt VAR compensations. These are restricted by their limits as follows:

$$V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max}, \quad i = 1, \ldots.., NG \tag{9}$$

$$P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}, \quad i = 1, \ldots.., NG \tag{10}$$

$$Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}, \quad i = 1, \ldots.., NG \tag{11}$$

$$Q_{C_i}^{\min} \le Q_{C_i} \le Q_{C_i}^{\max}, \quad i = 1, \ldots.., NC \tag{12}$$

where, NG and NC are the total number of generators and shunt compensators, respectively.

Problem formulation: Considering the objectives and constraints the problem of optimal placement of static compensator can be mathematically formulated as a non linear constrained multi-objective optimization problem as follows:

$$\left.\begin{array}{ll} \min & f_1 = w_1 N_1 + w_2 N_2 + w_3 N_3 \\ \min & f_2 = \sum_{m=1}^{k} \left| \dfrac{V_{mref} - V_m}{V_{mref}} \right| \\ \min & f_3 = P_{loss}(x, u) \\ \min & f_4 = \sum_{m=1}^{k} L_m \end{array}\right\} \tag{13}$$

Subject to:

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

and,

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

It is very difficult to solve this non linear constrained multi-objective optimization problem using traditional techniques. Additionally, there are difficulties with finding the derivatives of the objective function with respect to parameters. Therefore, in this paper, evolutionary optimization technique i.e., Genetic Algorithm (GA) is applied to solve this problem. The multi-objective optimization problem is converted into a single objective optimization problem and solved by applying GA. To appreciate the application of GA to solve the multi-objective optimization problem, a brief description of GA and its implementation is presented in the next section.

Brief description of Genetic Algorithm (GA) and its implementation: The GA has become a well-accepted technique for solving complex search problems. It is based on the principles of genetic variation and natural selection and is considered to offer a high probability of finding the global or near global optimum solution of difficult optimization problems with objective functions that do not possess nice properties such as continuity, differentiability etc. The theoretical development of GAs is largely credited to the work of Holland (1975) and Goldberg (1989). Since then, the GA has evolved and found applications in almost every area of optimization, especially those areas involving problems where the search space is not very well understood. The increasing popularity enjoyed by GA can be attributed in part to its simplicity, elegance, ease of implementation and its proven ability to often find good solutions for difficult high-dimensional function optimization or combinatorial problems with continuous or discrete variables (Goldberg, 1989; Haput and Haput, 2004).

Fitness function: GAs is essentially unconstrained search procedure within a given representative space. Therefore, it is very important to construct an accurate fitness function as its value is the only information available to guide the search. In this problem, as mentioned in the previous section, there are four objectives to be achieved. When there are multiple objectives to be satisfied simultaneously, a compromise has to be made to obtain the best solution. In large practical systems, the above objectives may be conflicting, i.e., the static compensator connected at a particular bus cannot provide maximum improvement

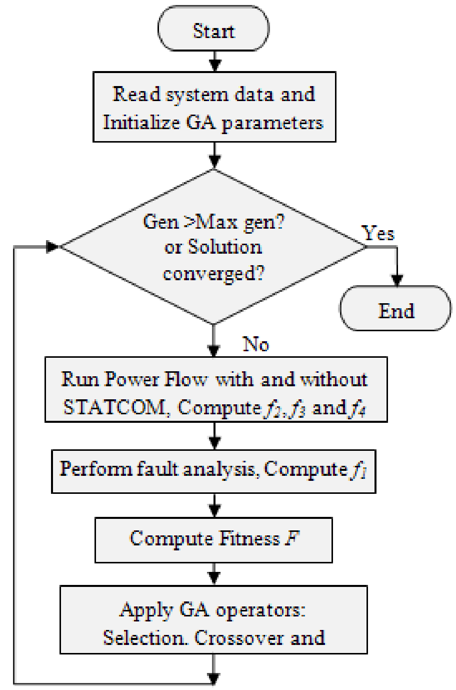

Fig. 1: Flow chart for GA implementation

in voltage sag performance, voltage profile and minimum active power loss. Here, the objective is to determine the best location of the static compensator which simultaneously optimizes the above objectives. At the same time minimum degree of satisfaction among the objectives must be guaranteed. Thus based on the objectives described by (1) to (4) the fitness function can be defined as:

$$F = M_1 \cdot f_1 + M_2 \cdot f_2 + M_3 \cdot f_3 + M_4 \cdot f_4 \tag{14}$$

where, F represents the fitness function which is to be minimized using GA. M_1, M_2, M_3 and M_4 are the multiplying factors which reflect the relative importance of each objective. In this study, M_1, M_2, M_3 and M_4 are set to make all the four objectives comparable, i.e., equal importance is given to voltage sag mitigation, voltage deviation, active power loss and voltage stability margin enhancement.

GA implementation: In order to obtain optimal locations of STATCOMs, GA is applied to minimize the objective function F. The algorithm has been implemented using (MATLAB®, http://www.mathworks.com; Houck *et al*., 2008). The steps involved in finding the optimal locations of STATCOMs are given below and its flow chart is shown in Fig. 1:

- Read system data and set GA parameters.

- For each individual, solve load-flow equations and compute the performance of the system with STATCOMs connected at candidate buses.
- Form bus impedance and sequence impedance matrix.
- Perform fault analysis and calculate voltage sag magnitudes at different buses of the system by simulating faults at each bus one by one.
- Compute the objective/fitness function F given by (14).
- Solve the constrained optimization problem by applying GA operators: selection, crossover and mutation.
- If number of generations is less than maximum no. of generations or if the solution is not converged, repeat the above steps, else stop.

RESULTS AND DISCUSSION

The applicability of the proposed method has been tested on IEEE 24-bus Reliability Test System (RTS) and IEEE 57-bus system. The system data are obtained from (Wong *et al*., 1999; Power System Test Archive, year). Optimal locations of STATCOMs were determined by applying the proposed GA approach.

If the slope of the STATCOM characteristics is neglected, then the STATCOM can be modelled as a *PV* bus, with $P = 0$ and $V = V_{ref}$. In *PV* bus type model, limits are usually represented through limits in reactive power, i.e., if the reactive power generated/absorbed is within limits then the voltage at the STATCOM bus is maintained at $V = V_{ref}$ (Acha *et al*., 2004). Thus for power flow analysis, the STATCOM is modelled simply as a *PV* bus with reactive power limit of ±100 MVAR and V_{ref} is taken as 1 p.u., As shown in Fig. 2, at reduced voltage the STATCOM can continue to operate with rated leading (or lagging) current (even down to very low voltage) (Hingorani and Gyugyi, 1999). Thus in the simulation programme, the bus where STATCOM is installed can be represented as an infinite bus in the fault calculations program (Faried *et al*., 2005).

Table 1 shows the optimal locations of STATCOMs for IEEE 24-bus reliability test system and IEEE 57-bus systems for various symmetrical and unsymmetrical faults if only first objective, i.e., voltage sag mitigation is considered. It can be observed that optimal locations of two STATCOMs for different types of faults are almost identical. Thus, to reduce the computational burden in this study, while computing the first objective, only three phase symmetrical fault is considered. STATCOMs connected in the system should minimize overall voltage sags due to fault at any bus in the system. Thus fault at each bus in the system was simulated one by one and remaining voltages were calculated at all the buses to compute the objective f_1.

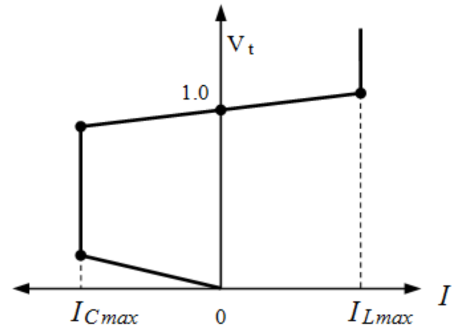

Fig. 2: V-I characteristic of STATCOM

Table 1: Optimal locations of STATCOMs for IEEE 24-bus and IEEE 57-bus systems for various faults considering first objective only

Type of fault	Optimal locations of STATCOM-1 and STATCOM-2 IEEE 24-bus system	IEEE 57-bus system
Symmetrical fault	Bus no. 9 and 17	Bus no. 13 and 38
Line to ground fault	Bus no. 9 and 17	Bus no. 13 and 38
Line to line fault	Bus no. 9 and 19	Bus no. 13 and 38
Double line to ground fault	Bus no. 9 and 17	Bus no. 13 and 38

Table 2: Optimal locations of STATCOMs for IEEE 24-bus reliability test system to achieve various objectives

Objective	Optimal locations of STATCOMs
Voltage sag mitigation (f_1)	Bus no. 9 and 17
Voltage deviation (f_2)	Bus no. 3 and 8
Real power loss (f_3)	Bus no. 8 and 10
Voltage stability margin enhancement (f_4)	Bus no. 9 and 10
Multi-objective (F)	Bus no. 3 and 10

Example 1: IEEE 24-bus Reliability Test System (RTS): The IEEE 24 bus Reliability Test System has ten generator buses, five transformers, 33 transmission lines and a synchronous condenser at bus number 14. The proposed method which is based on GA has been applied to obtain the best locations of two STATCOMs in IEEE 24-bus reliability test system. The fitness function F was computed at a loading factor of 0.3 p.u., in order to consider generator reactive power limits and nonlinearity. Figure 3 shows the variation of the best value of fitness function F with respect to the number of generations. Best locations of STATCOMs in IEEE 24-bus reliability test system for various objectives are shown in Table 2.

The importance of multi-objective formulation proposed in this paper can be observed from Table 2. It can be seen from this table that the objectives considered here are conflicting. However, the method proposed in this study finds the locations of STATCOMs for simultaneous optimization of all the four objectives.

In order to highlight the effectiveness of the proposed method, the results are obtained for voltage

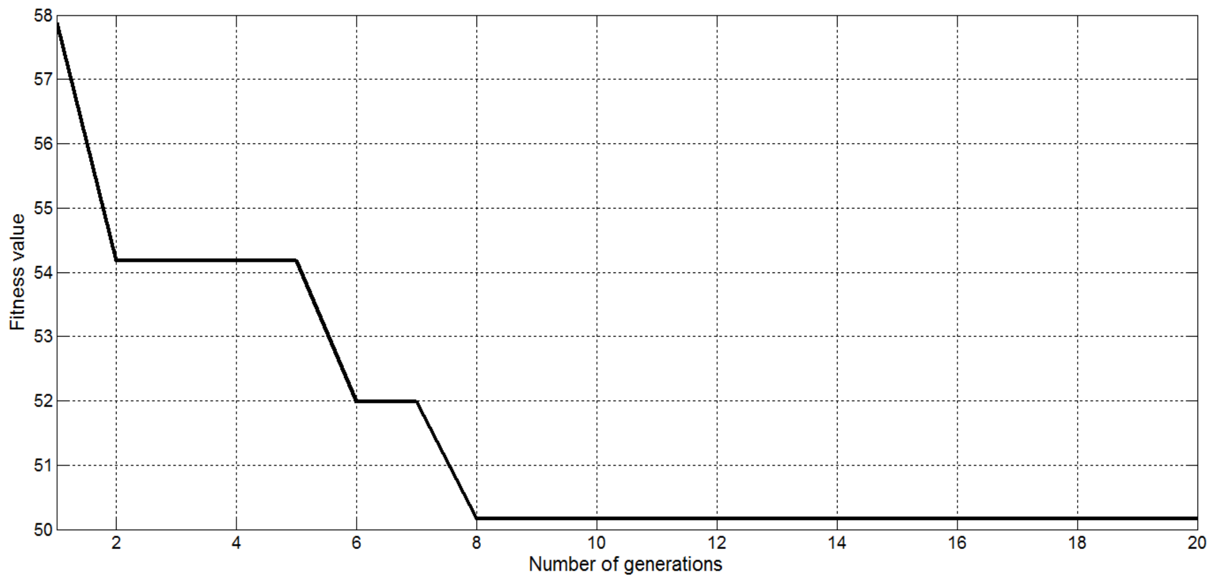

Fig. 3: Evolution of the fitness function with respect to number of generations in IEEE 24-bus system

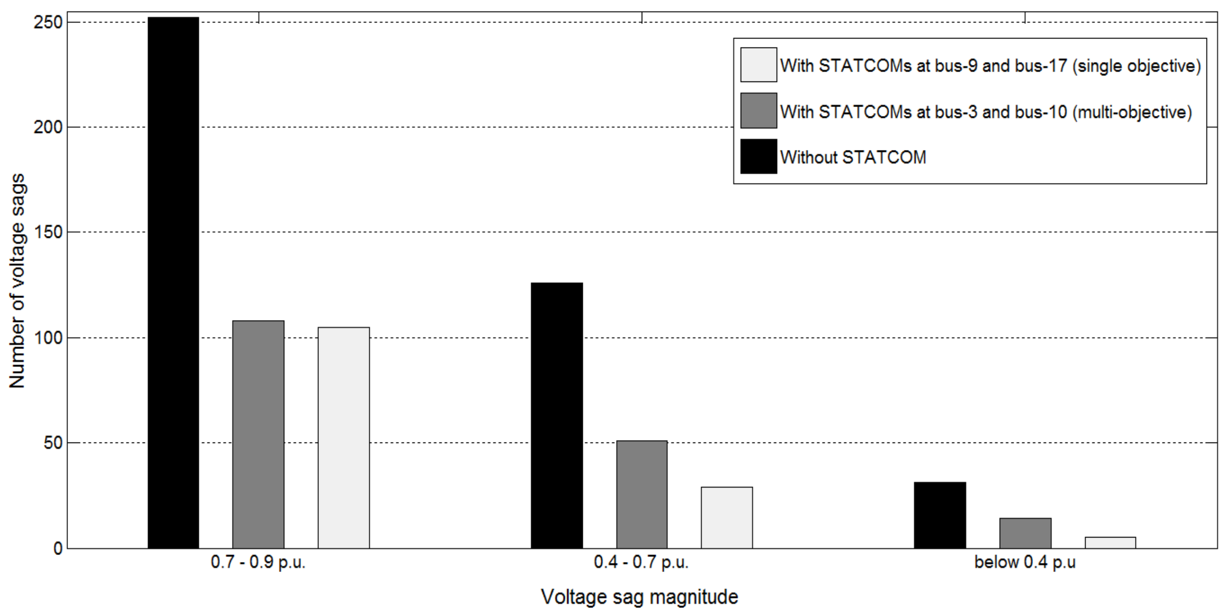

Fig. 4: Overall voltage sags in different voltage ranges without STATCOM and with STATCOMs at bus-3, bus-10 (multi-objective) and with STATCOMs at bus-9, bus-17 (single objective) in IEEE 24-bus system

sag performance, voltage profile, real power loss and *L*-index values at all the buses without STATCOM and with STATCOMs placed at optimal locations obtained from the proposed multi-objective Formulation (*F*) and also with STATCOMs placed at optimal locations considering single objectives, i.e., f_1, f_2, f_3 and f_4. The overall voltage sag performance improvement due to STATCOMs placed at bus-3, bus-10 (multi-objective) and with STATCOMs at bus-9, bus-17 (single objective) for symmetrical type of fault is shown in Table 3 and graphically represented in Fig. 4. The voltage sags at different buses in respective voltage magnitude range has been obtained after simulating symmetrical faults at bus no. 1 to 24, one bus at a time. From table it can be seen that most of the voltage sags in the range (<0.4, 0.4-0.7, 0.7-0.9 p.u.,) are mitigated with placement of STATCOMs. It can be observed that maximum voltage sag mitigation is provided by STATCOMs placed at bus-9 and bus-17 (single objective f_1). However, STATCOMs placed at bus-3 and bus-10 (multi-objective) also provide satisfactory voltage sag mitigation.

The voltage profile of the system without STATCOM and with STATCOMs at bus-3, bus-10

Table 3: Number of voltage sags without STATCOM and with STATCOMs at bus-3, bus-10 (multi-objective) and with STATCOMs at bus-9, bus-17 (single objective) in IEEE 24-bus system

	Number of voltage sags				
Voltage sag magnitude range	Without STATCOM	With STATCOM at bus-3 and bus-10	Reduction in no. of sags (%)	With STATCOM at bus-9 and bus-17	Reduction in no. of sags (%)
0.7 to 0.9 p.u.	252	108	57.14	105	58.33
0.4 to 0.7 p.u.	126	51	59.52	29	76.98
0 to 0.4 p.u.	31	14	54.84	5	83.87

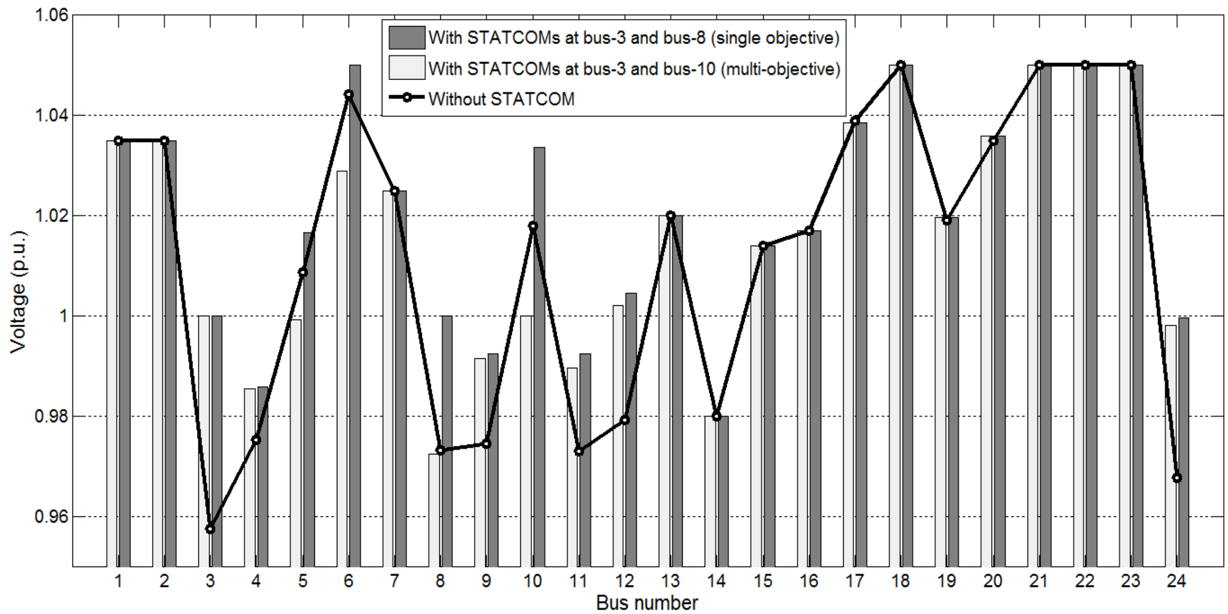

Fig. 5: Voltage profile of IEEE 24-bus system without STATCOM and with STATCOMs at bus-3, bus-10 (multi-objective) and STATCOMs at bus-3, bus-8 (single objective) at a loading factor of 0.3 p.u.

Table 4: Active power loss in IEEE 24-bus system without STATCOM and with STATCOMs at bus-3, bus-10 (multi-objective) and with STATCOMs at bus-3, bus-8 (single objective) at a loading factor LF = 0.3

Operating condition	Total active power loss (p.u.)
Without STATCOM	0.6811
STATCOMs at bus-3 and bus-8	0.4171
STATCOMs at bus-3 and bus-10	0.4593

(multi-objective) and STATCOMs at bus-3, bus-8 (single objective f_2) at a loading factor of 0.3 p.u., is shown in Fig. 5. From this figure it may be observed that STATCOMs connected at bus-3 and bus-10 (multi-objective) provide good improvement in voltage profile with slight compromise in results as compared to single objective formulation.

Table 4 shows the total active power loss of the system without STATCOM and with STATCOMs at bus-3, bus-10 (multi-objective) and with STATCOMs at bus-3, bus-8 (single objective f_3) at a loading factor $LF = 0.3$. Table 4 clearly shows that the STATCOMs connected at bus-3 and bus-10 (multi-objective) give considerably reduced active power loss.

In Fig. 6, L-indices for various buses with and without STATCOMs at bus-3, bus-10 (multi-objective) and with STATCOMs at bus-9, bus-10 (single objective f_4) are plotted at a loading factor $LF = 0.3$. It can be observed from this figure that the placement of STATCOMs at selected buses results in voltage stability enhancement of the system. In this case also, with slight compromise in results, multi-objective formulation has been achieved.

Example 2: IEEE 57-bus system: The system consists of seven synchronous machines including three synchronous condensers. Synchronous condensers connected at bus 2, 6 and 9 are used only for reactive power support. Four generators are located at bus no. 1, 3, 8 and 12. There are 80 branches and 57 buses with 42 loads totaling 1250.8 MW and 336.4 MVAR at base case. The proposed method based on GA has been applied to obtain the best locations of two STATCOMs in IEEE 57-bus system. The fitness function F was computed at a loading factor of 0.2 p.u., in order to consider generator reactive power limits and nonlinearity. Best locations of STATCOMs in IEEE 57-bus system to achieve various objectives are shown in Table 5. Table 5 again shows the importance of proposed multi-objective formulation which simultaneously optimizes all the four objectives maintaining minimum degree of satisfaction among these objectives.

The overall voltage sag performance improvement due to STATCOM placement at bus-13, bus-35 (multi-

Table 5: Optimal locations of STATCOMs for IEEE 57-bus system to achieve various objectives

Objective	Optimal locations of STATCOMs
Voltage sag mitigation (f_1)	Bus no. 13 and 38
Voltage deviation (f_2)	Bus no. 14 and 34
Real power loss (f_3)	Bus no. 15 and 36
Voltage stability margin enhancement (f_4)	Bus no. 13 and 15
Multi-objective (F)	Bus no. 13 and 35

objective) and with STATCOMs at bus-13 bus-38 (single objective) for symmetrical type of fault is shown in Table 6 and graphically represented in Fig. 7. The voltage sags at different buses in respective voltage magnitude range have been obtained after simulating symmetrical faults at bus no. 1 to 57, one bus at a time. From the table it can be seen that most of the voltage sags in the range (<0.4, 0.4-0.7, 0.7-0.9 p.u.) are mitigated with placement of STATCOMs at bus-13 and bus-35. Thus, with slight compromise in voltage sag mitigation performance, multi objective formulation gives satisfactory performance.

The voltage profile of the system without STATCOM and with STATCOMs at bus-13, bus-35 (multi-objective) and with STATCOMs at bus-14, bus-34 (single objective) at a loading factor of 0.2

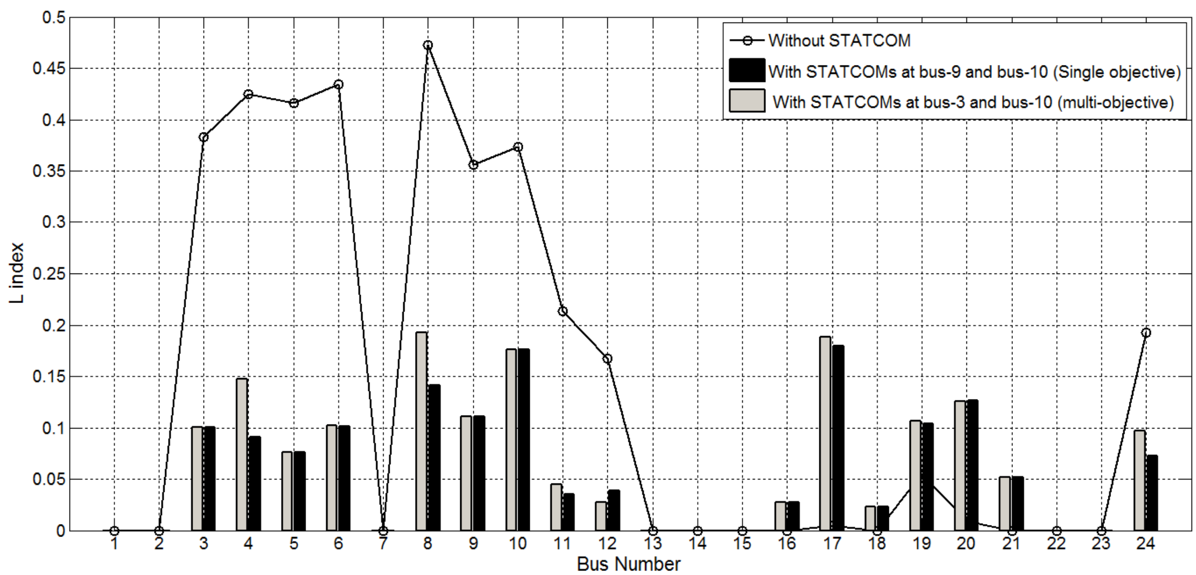

Fig. 6: L index at various buses in IEEE 24-bus system without STATCOM and with STATCOMs at bus-3, bus-10 (multi-objective) and with STATCOMs at bus-9, bus-10 (single objective) at a loading factor LF = 0.3

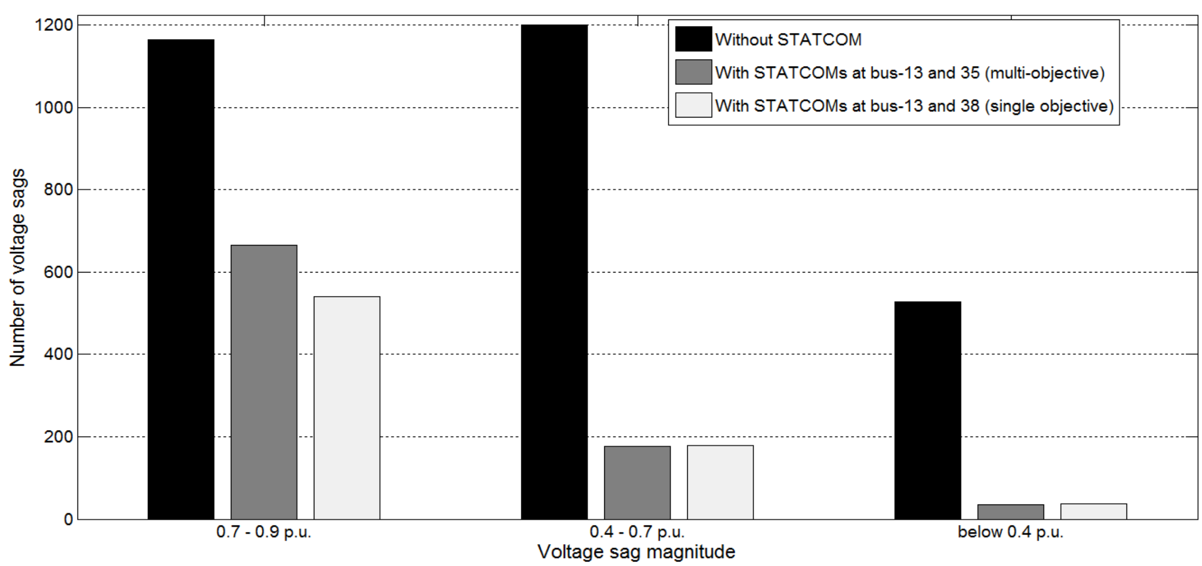

Fig. 7: Overall voltage sags in different voltage ranges without STATCOM and with STATCOMs at bus-13, bus-35 (multi-objective) and with STATCOMs at bus-13, bus-38 (single objective) in IEEE 57-bus system for symmetrical fault

Table 6: Number of voltage sags without STATCOM and with STATCOMs at bus-13, bus-35 (multi-objective) and with STATCOMs at bus-13 bus-38 (single objective) in IEEE 57-bus system

	Number of voltage sags				
Voltage sag magnitude range	Without STATCOM	With STATCOMs at bus-13 and bus-35	Reduction in no. of sags (%)	With STATCOMs at bus-13 and bus-38	Reduction in no. of sags (%)
0.7 to 0.9 p.u.	1165	665	42.92	540	53.64
0.4 to 0.7 p.u.	1201	176	85.34	178	85.18
0 to 0.4 p.u.	527	35	93.36	37	92.98

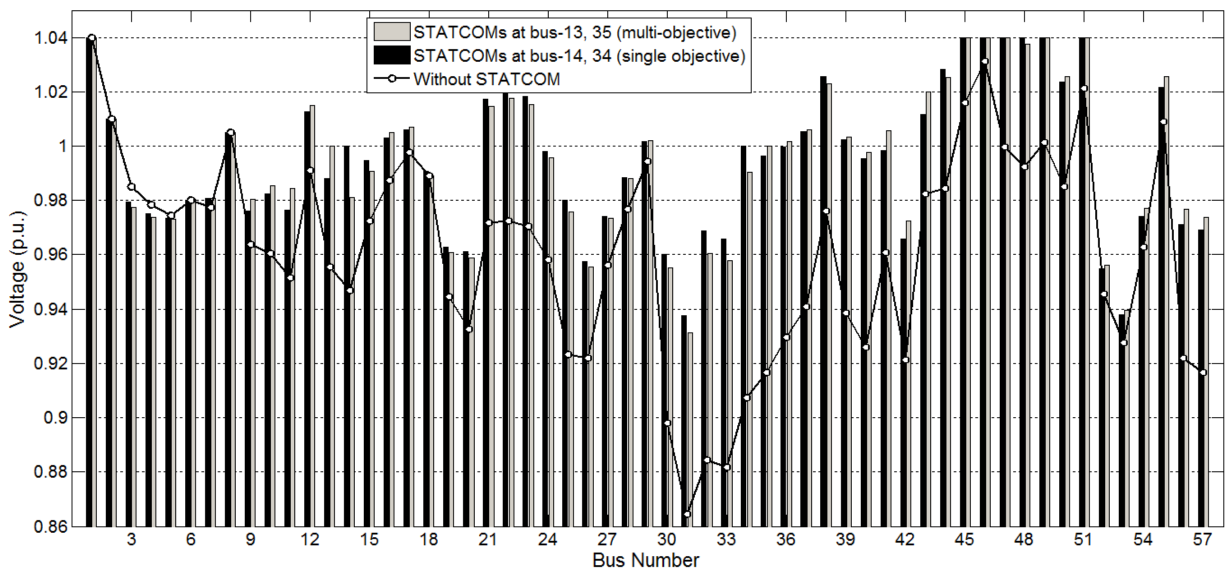

Fig. 8: Voltage profile of IEEE 57-bus system without STATCOM and with STATCOMs at bus-13, bus-35 (multi-objective) and with STATCOMs at bus-14, bus-34 (single objective) at a loading factor of 0.2 p.u.

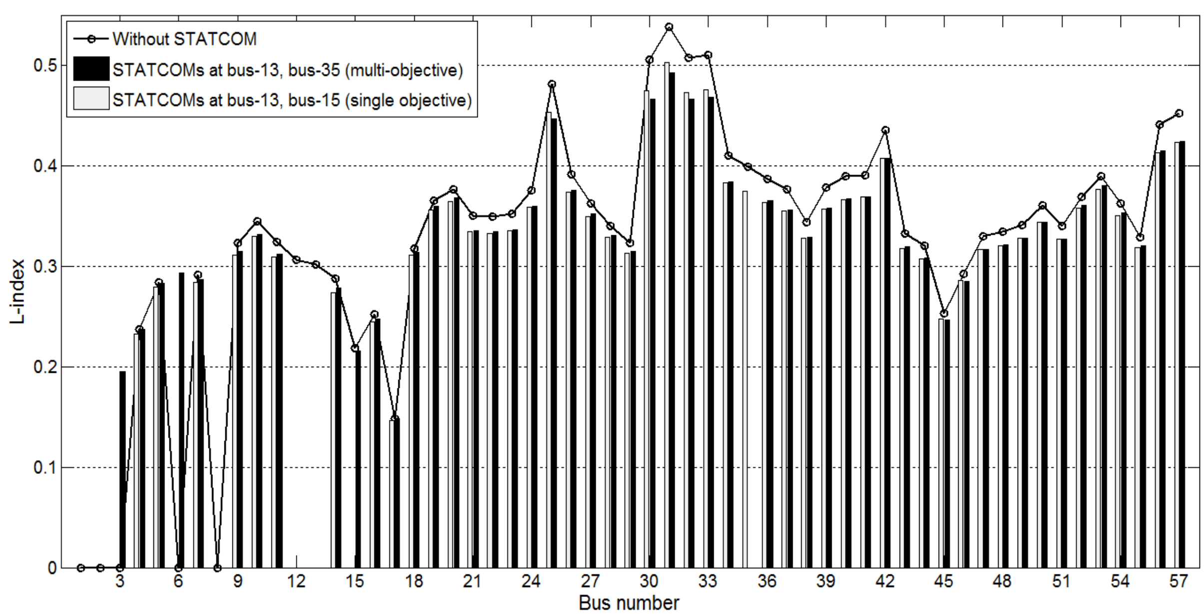

Fig. 9: L index at various buses in IEEE 57-bus system without STATCOM and with STATCOMs at bus-13, bus-35 (multi-objective) and with STATCOMs at bus-13, bus-15 (single objective) at a loading factor LF = 0.2 p.u.

p.u. is shown in Fig. 8. From this figure it may be observed that STATCOMs connected at bus-13 and bus-35 (multi-objective) provide good improvement in voltage profile with slight compromise in results as compared to single objective formulation, i.e., STATCOMs at bus-14 and bus-34.

Table 7: Active power loss of IEEE 57-bus system without STATCOM and with STATCOMs at bus-13, bus-35 (multi-objective) and with STATCOMs at bus-15, bus-36 (single objective) at a loading factor LF = 0.2 p.u.

Operating condition	Total active power loss (p.u.)
Without STATCOM	0.6082
STATCOMs at bus-13 and bus-35	0.5871
STATCOMs at bus-15 and bus-36	0.5796

Table 7 shows the total active power loss of the system without STATCOM and with STATCOMs at bus-13, bus-35 (multi-objective) and with STATCOMs at bus-15, bus-36 (single objective) at a loading factor *LF* = 0.2 p.u. This Table clearly shows that the STATCOMs connected at bus-3 and bus-10 (multi-objective) gives considerably reduced active power loss.

In Fig. 9, *L*-indices for various buses with and without STATCOMs at bus-13, bus-35 (multi-objective) and with STATCOMs at bus-13, bus-15 (single objective) at a loading factor *LF* = 0.2 p.u. are shown. It can be observed from this figure that the placement of STATCOMs at selected buses results in voltage stability enhancement of the system. Therefore, with slight compromise in results, multi-objective formulation has been achieved.

From the above results, it may be summarized in the context of chosen examples, that the proposed multi-objective method gives locations of STATCOMs which simultaneously minimizes voltage sag at all the buses, voltage deviation, active power loss and improves voltage stability margin of the system. The results presented show that in large systems these objectives are conflicting. However, the proposed method finds the buses for STATCOM placement which ensures effective voltage sag mitigation, good voltage profile, reduced real power loss and additional security to the system.

CONCLUSION

In this study a new multi-objective method has been proposed for placement of Static Compensator (STATCOM) to improve the overall performance of power system and also for global voltage sag mitigation under fault conditions. The proposed method optimizes the performance of the system with respect to the four identified objectives: minimum number of voltage sags, minimum voltage deviation, minimum active power loss and maximum voltage stability margin of the system. It is important to note that in large power systems these objectives are conflicting, i.e., the STATCOM connected at a particular bus cannot provide maximum improvement in all the objectives. However, the proposed method finds the best locations of STATCOMs to ensure good voltage profile, reduced active power loss, reduced overall voltage sags and increased voltage stability margin simultaneously at the same time the minimum degree of satisfaction among the objectives is also guaranteed. The proposed method has been tested on IEEE 24-bus RTS and IEEE 57-bus test systems. The results presented illustrate the effectiveness of the proposed method.

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