GA Based Multi-Objective Optimizing Size and Location of One D-STATCOM for Global Voltage Sag Mitigation in Distribution System

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ABSTRACT

In this paper, a novel method for solving the problem of optimizing the size and position of D-Statcom for global voltage sag mitigation in distribution systems is introduced. In application of a solution for power quality mitigation, the difficulty of integrating the investment of power quality solution and the benefits from power quality mitigation in a single objective function is overcome by introducing the Genetic Algorithm based multi-objective optimization where the objective functions are to minimize either the system voltage sag index – SARFIX of the system of interest and D-Statcom investment. In this problem, voltage sag is assumingly caused only by faults. In modeling the fault condition of a distribution network where a D-Statcom device is placed, global voltage sag mitigation by the D-Statcom device is modeled using Thevenin superposition theorem. The effectiveness for global voltage compensation by D-Statcom is considered with regard to its limited injected current. IEEE 33-buses test system is taken for testing the method and related analysis. Case studies for influential parameters are also considered and discussed.

1. INTRODUCTION

Nowadays, various research for mitigating voltage sag [1, 2] due to short-circuits in the power system have been introduced. Solutions are based on two approaches namely “distributed improvement” and “central improvement” [3]. While the early is popular for individually protecting sensitive loads, the latter generally considers global power quality (PQ) improvement for the whole system. Rapid development of power electronics application has introduced a lot of advanced solutions for effective voltage sag mitigation by using D-FACTS devices [4]. The paper puts a new effort on the research of applying the distribution static synchronous compensator (D-Statcom) for globally mitigating (central improvement) voltage sag caused by faults in distribution systems.

Regarding the problem of optimizing the size and position of the D-FACTS device for PQ mitigation in distribution system, [3] gives a rather comprehensive review on various research where D-Statcom applications cover both two “distributed improvement” and “central improvement” approaches. Although almost publications discussed on “distributed improvement” approach, a huge development on “central improvement” research has been introduced. However, two challenging issues for “central improvement” research are

- Introducing a suitable steady-state modeling of D-FACTS devices for globally mitigating different PQ issues,
- Proposing a suitable tool for optimizing the use of D-FACTS device.

For steady-state operation modeling, some research [5-8] estimates D-Statcom’s capability for either voltage quality improvement and loss reduction in distribution system operation. Some others [9-11] work on its capability of PQ mitigation either in steady-state and short-time operations. Concretely, [9] uses studies the D-Statcom based solution for mitigating a number of PQ issues including voltage sag mitigation. Multi-objective optimization approach is used. However, because the objective functions are set for simultaneously mitigating various PQ issues, and thus the best voltage sag mitigation is rarely reached. [10] deals directly with the problem of voltage sag improvement using D-Statcom, however some room is still there for improvement for the modeling of D-Statcom in network fault condition analysis. Another modeling of a D-FACTS device installed in distribution network is introduced in [11] also for global voltage sag mitigation, but the D-FACTS device is the dynamic voltage restorer (DVR) and the DVR sizing and positioning is optimized basing on event index only. [12] uses direct search method for optimizing the D-Statcom’s location, but only the benefit of voltage sag improvement by D-Statcom

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is discussed. No cost for D-Statcom's investment is taken into account.

This paper works on a novel method for optimizing D-Statcom application for globally mitigating voltage sags due to faults of distribution system. In this method, D-Statcom's size and position are found optimally basing on the problem of multi-objective optimization (MOO) where either the system voltage sag index or D-Statcom's investment are minimized.

The structure of this paper is as follows: The Section 2 briefly presents the simulation of one D-Statcom globally mitigating voltage sag due to short-circuit in distribution system. Basing on that modeling, Section 3 proposes the MOO problem and solution. The results for various scenarios of D-Statcom parameters and MOO problem are finally analysed and discussed in the Section 4.

2. MODELING OF GLOBAL VOLTAGE SAG MITIGATION BY ONE D-STATCOM

D-Statcom belongs to the family of D-FACTS devices. It is in parallel connected with the load for its protection or the source generating PQ issues for preventing its harmful injection to the power grid. A D-Statcom is modeled popularly as a current source [2] that injects a current in the bus where voltage is expected to compensate.

The modeling about how one D-Statcom can mitigate voltage sag globally in fault conditions of distribution system [13] is performed by using the Thevenin theorem's superposition principle (Fig. 1).

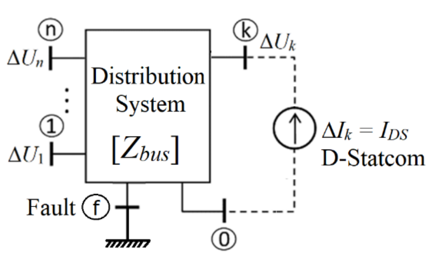

Fig. 1. Modeling of one D-Statcom mitigating globally voltage sag in a fault condition of power system.

In this modeling, for a given fault event i (i∈n, n: total events) the initial state of the system is the short-circuit condition without D-Statcom. The corresponding bus voltage is calculated by the equation (1) as follows

$$[U^0]_i = [Z_{bus}] \times [I^0]_i \quad (1)$$

where, $[U^0]_i$ is initial bus voltage (voltage sag) matrix; $[I^0]_i$ is initial bus current matrix (Fault current); $[Z_{bus}]$ is system bus impedance matrix. $[Z_{bus}] = [Y_{bus}]^{-1}$, in which $[Y_{bus}]$ is system bus admittance matrix.

The next state of the system is that with one D-Statcom is connected, and the bus voltage equation should be calculated by the Thevenin theorem as follows [13]:

$$[U]_i = [Z_{bus}] \times ([I^0]_i + [\Delta I]_i) = [U^0]_i + [\Delta U]_i \quad (2)$$

where

$$[\Delta \mathrm{U}]_i = [\mathrm{Z_{bus}}] \times [\Delta \mathrm{I}]_i \quad (3)$$

or

$$\begin{bmatrix} \Delta U_1 \\ \vdots \\ \Delta U_k \\ \vdots \\ \Delta U_n \end{bmatrix}_i = [Z_{bus}] \times \begin{bmatrix} \Delta I_1 \\ \vdots \\ \Delta I_k \\ \vdots \\ \Delta I_n \end{bmatrix}_i \quad (4)$$

ΔU_j is voltage variation of bus j (j=1,N) with the presence of the D-Statcom; ΔI_j is additional current injected in bus j (j = 1, N) with the presence of the D-Statcom.

When a D-Statcom is connected to bus k (Fig. 1), let's look at (4), the column maxtrix of additional injected bus current has only one non-zero element that is the bus k current ($\Delta I_k \neq 0$). All other elements are zero ($\Delta I_j = 0$ for j=1,N; j≠k).

If the voltage of bus k is compensated from $U_k = U_k^0 = U_{sag.k}$ up to the desired value, say $U_k = 1$p.u., then the required $\dot{I}_{DS}^*$ that is injected to the bus k is obtained as follows

$$\dot{I}_{DS} = \dot{I}_{DS}^* = \Delta \dot{I}_k = \frac{\Delta \dot{U}_k}{Z_{kk}} = \frac{1}{Z_{kk}} \times \left(1 - \dot{U}_{sag.k}\right) \quad (5)$$

However, it's very likely that bus k is near the short-circuit position, and thus, the above calculated required $\dot{I}_{DS}^*$ of the D-Statcom is even higher than a given limited current I_{DSmax}. Therefore, if I_{DSmax} is smaller than I_{DS}^*, the voltage of bus k is only compensated upto a certain value less than 1pu for $I_{DS} = I_{DSmax}$.

$$\dot{U}_k = \Delta \dot{U}_k + \dot{U}_{sag.k} = \dot{I}_{DS} \times Z_{kk} + \dot{U}_{sag.k} < 1 \quad (6)$$

Finally, other bus voltages ($\dot{U}_j$, j=1,N; j≠k) are calculated by (4) as follows

$$\dot{U}_j = \Delta \dot{U}_j + \dot{U}_j^0 = Z_{jk} \times \dot{I}_{DS} + \dot{U}_{sag.j} \quad (7)$$

From above presented modeling of one D-Statcom located at bus k that mitigates voltage sag for the fault event i, we can calculate the $SARFI_X$ by considering all the fault events n of short-circuit i (i∈n) in the system of interest.

3. DEFINITION OF OPTIMIZATION PROBLEM

Nowadays, we can easily find that there're plenty engineering problems involve the optimization of several objectives simultaneously. It is likely that the objectives are calculated in incomparable units such as the problem of applying a solution for PQ mitigation. In this problem, we often deal with two conflict ingredients. They are the investment for the PQ solution and its resulting benefit of PQ mitigation. While the first one is easily presented as a cost, the latter is not and that leads to the idea of using

MOO. For the problem of applying D-Statcom for global mitigation of voltage sag, the benefit of global PQ mitigation is the improvement of the system index – SARFIX that is hard to present as a cost. Therefore, this paper introduces the problem of sizing and locating one D-Statcom for global mitigation of voltage sag in distribution system as a MOO [15] as follows

1.1. Objective functions

Two objective functions are considered as follows

$$f_1 = C_{DS} \Longrightarrow \text{Min} \tag{8}$$

$$f_2 = SARFI_X = \frac{\sum_{j=1}^{N} M_{j.X}}{M} \Longrightarrow \text{Min} \tag{9}$$

where, C_{DS} is investment of D-Statcom that is proportional to its injected current limit I_{DSmax} for voltage sag mitigation; $SARFI_X$ is System Average rms Variation Frequency Index for a given rms voltage threshold X [14]; $M_{i.X}$ is the frequency of voltage sags lower than X% of the load j in the test system; and M is total of loads in the system.

For calculating the $f_2 = SARFI_X$, basing on the modeling of one D-Statcom location (bus k) with a given current limit IDSmax mitigating voltage sag as presented in Part 2, the process of calculating SARFIX of a distribution system (with a given fault rate distribution) is plotted in Fig. 2.

For this optimization problem, the main variables are the positions (buses) where D-Statcom can be placed and a given current limit (IDSmax) of the D-Statcom. For a given test system, the number of buses N is also the candidates for D-Statcom placement. For this problem, only one constraint is the current limit of the D-Statcom $I_{DSmax} \leq MaxI_{DS}$ (10).

1.2. Multi-Objective Optimization Using GA

To solve MOO problems, methods are generally classified as the mathematical based group and the evolutionary based group. For this problem, the MOO is solved by GA [17, 18] which belongs to the evolutionary based group.

GA based MOO solver uses the function *gamultiobj* in Matlab [19] and the outcome results are a set of so-called non-dominated solutions or Pareto optimal solutions. They are optimal options with different trade-offs among the objectives. For such a problem of two objective functions, Pareto optimal solutions are shown as a set of optimal points (Pareto front) on two-dimensions graphic. The function *gamultiobj* uses a controlled, elitist genetic algorithm (a variant of NSGA-II). In applying this function, the number of populations is set in advance or took the default value (say 200). A chromosome is defined as a string of N-bit format, for instance, "0 0.21 0 … 0 0", where "0" value means no D-Statcom placement and "non-zero" value (e.g. 0.21) means that a D-Statcom is installed at the given position (bus) with its current limit I_{DSmax} (in pu). N is the total of buses in the system of interest. From each generation, a non-dominated set of variables is derived and the corresponding fitness is calculated. The process of new generation reproduction is continued until the relative change in best fitness function values is not greater than the function tolerance.

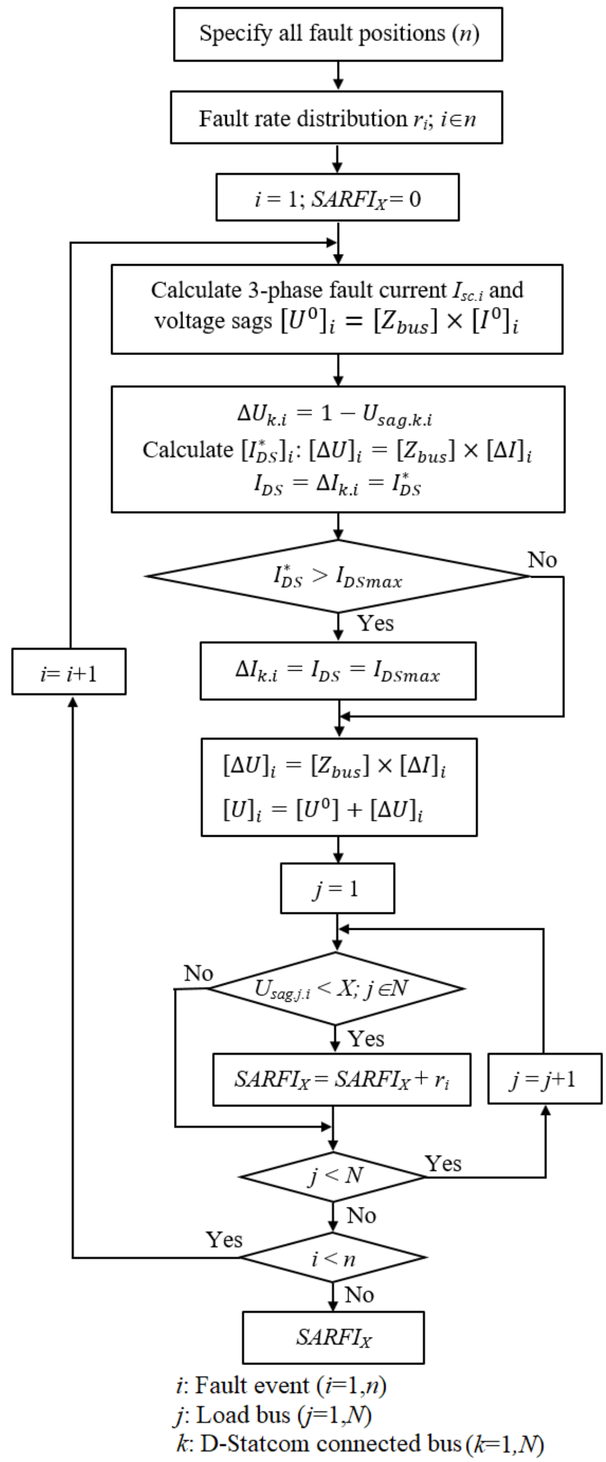

Fig. 2. $SARFI_X$ calculation for the distribution system with the presence of one D-Statcom.

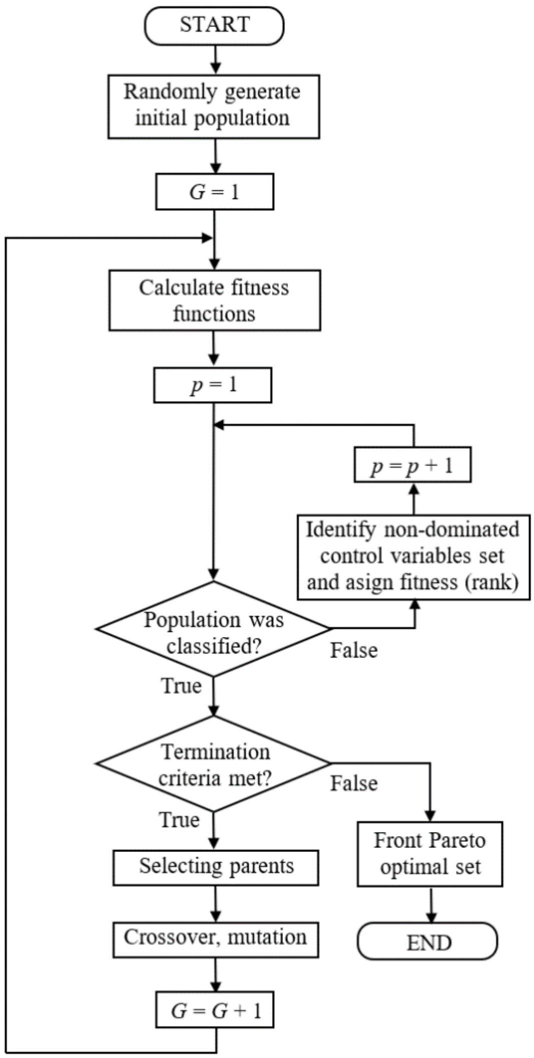

Fig. 3. The diagram of solving multi-objective optimization problem using GA.

The maximum generation is noticed and the set of Pareto optimal solutions is obtained. The step-by-step procedure of solving the GA based multi-objective optimization is shown in the block-diagram in Fig. 3.

4. RESULTS ANALYSIS

4.1. Test system and short-circuit assumptions

Similar to [12], this paper tests the method with the IEEE 33-bus distribution feeder as Fig. 4. This network is of balanced three-phase where all loads and line segments are three-phase.

Base system, system voltage and impedance are assumed similar to [12].

Because voltage sags are assumed to be caused by fault, short circuit calculation is needed for calculating SARFIX. For the purpose of the method introduction, only three-phase short-circuit is considered. For practical applications, other types of short-circuits can be taken into account.

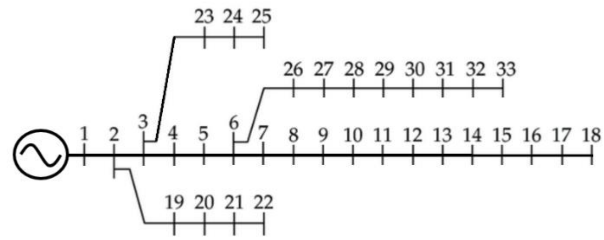

Fig. 4. The test system of IEEE 33-bus distribution feeder.

4.2. Input parameters

In this test, the following input parameters should be considered:

- For $SARFI_X$ calculation, the fault performance assumption is needed. The fault distribution is assumed to be uniform as per [16] and fault rate equals once per unit period of time at each fault position (buses in the system).

- For the sag threshold X, with reference from the power acceptability curve SEMI F47 (modified ITIC curve [2]), X values are considered as 90, 80, 70, 50% of U_n.

- For (12), the paper assumes $MaxI_{DS}$ = 0.5p.u.

- Regarding GA parameters, the research set the number of populations as 200.

4.3. Results analysis

By solving the MOO problem with assumed constraints and GA parameters, followings are remarked results.

Let's start considering X=50%. Calculating $SARFI_X$ (Fig. 2) without D-Statcom placement, we have the $SARFI_{50}$ = 13.73. For the case of placing one D-Statcom with $MaxI_{DS}$ = 0.5pu, the GA runs through 102 generations to get the Pareto optimal set with the process of non-dominated sorting and rank assigning for each generation and reproduction of new generations to solve the MOO problem. The resulting 70 Pareto solutions is mentioned in Table 1. It's noticed that the selection of population number is important for the algorithm to converge. A greater population number can help the algorithm converge easier, but the calculation time is longer.

As an example, taking a solution, say solution 9, bus 12 is the optimal location of D-Statcom, I_{DSmax} = 0.1322pu and $SARFI_{50}$ = 5.73. Fig. 5 shows the profile of sag 50% frequency (X > 50%) at all buses without D-Statcom (Blue) and with D-Statcom placed at bus 12 (Red) that remarks a significant improvement.

With the presence of one D-Statcom at bus 12, the required current injected from D-Statcom (I_{DS}^*) is only 0.0735pu (which is less than I_{DSmax} = 0.1322pu) for boosting the voltage at bus 12 to 1pu. Therefore, for the given I_{DSmax}, nodal voltage at a number of buses (bus 9 to bus 18, near the bus 12 in Fig. 6) is upgraded to 1pu, and sag frequency for X > 50% is zero.

Table 1. Optimal solutions for D-Statcom's size and location for voltage sag level X = 50%

Solution	$SARFI_{50}$	I_{DSmax} (pu)	DS pos.	Solution	$SARFI_{50}$	I_{DSmax} (pu)	DS pos.
1	5.45	0.1445	12	36	11.24	0.0380	15
2	7.52	0.0818	13	37	12.73	0.0001	1
3	11.76	0.0285	8	38	5.12	0.1937	9
4	8.67	0.0621	15	39	7.55	0.0798	13
5	5.82	0.1181	12	40	10.06	0.0452	17
6	5.00	0.2286	9	41	11.42	0.0327	8
7	5.21	0.1569	12	42	8.70	0.0606	15
8	3.30	0.2413	8	43	10.03	0.0471	17
9	**5.73**	**0.1322**	**12**	44	11.82	0.0267	8
10	9.18	0.0576	16	45	5.73	0.1322	12
11	6.79	0.0889	12	46	5.00	0.2286	9
12	9.91	0.0524	17	47	5.45	0.1445	12
13	11.18	0.0410	15	48	9.36	0.0530	16
14	12.73	0.0001	1	49	8.73	0.0577	15
15	10.64	0.0446	18	50	5.79	0.1223	12
16	8.21	0.0652	15	51	12.27	0.0176	9
17	5.15	0.1915	9	52	12.67	0.0103	13
18	7.24	0.0827	13	53	12.21	0.0189	9
19	6.45	0.0917	12	54	12.15	0.0213	10
20	12.09	0.0233	10	55	9.97	0.0489	17
21	12.70	0.0062	6	56	5.76	0.1289	12
22	6.09	0.1033	12	57	7.64	0.0779	13
23	5.12	0.1937	9	58	6.12	0.0996	12
24	10.12	0.0448	17	59	12.33	0.0163	10
25	7.82	0.0684	13	60	11.94	0.0233	8
26	3.33	0.2304	8	61	5.82	0.1181	12
27	12.61	0.0119	13	62	7.70	0.0737	13
28	12.45	0.0131	12	63	10.76	0.0419	18
29	11.48	0.0315	8	64	12.36	0.0144	11
30	7.61	0.0789	13	65	6.85	0.0867	12
31	8.24	0.0624	14	66	6.09	0.1033	12
32	11.30	0.0345	8	67	7.24	0.0827	13
33	9.24	0.0569	16	68	5.21	0.1569	12
34	9.30	0.0552	16	69	6.15	0.0945	12
35	7.76	0.0710	13	70	11.55	0.0315	13

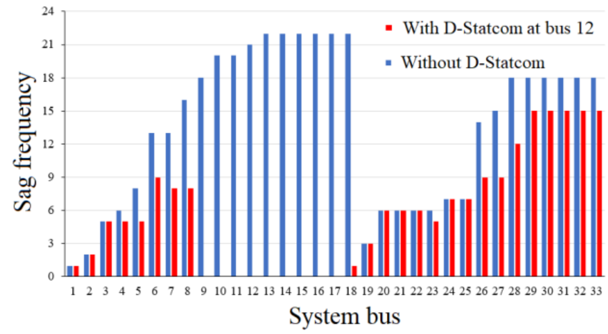

Fig. 5. Frequency profile of sag 50% at all buses without and with one D-Statcom placed at Bus 12, I_{DSmax} = 0.1322pu.

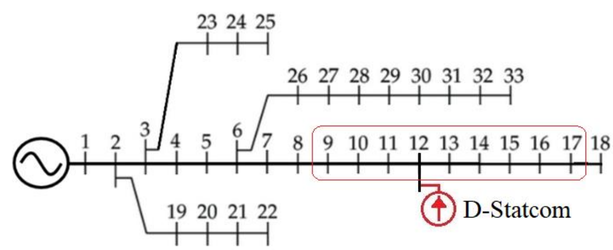

Fig. 6. One D-Statcom placed at Bus 12 boosts voltages at near buses.

Considering the $SARFI_{50}$ for other possible locations of D-Statcom placement we have Fig. 7. Placing one D-Statcom with I_{DSmax} = 0.1322pu at bus 12 results in the minimum value of $SARFI_{50}$.

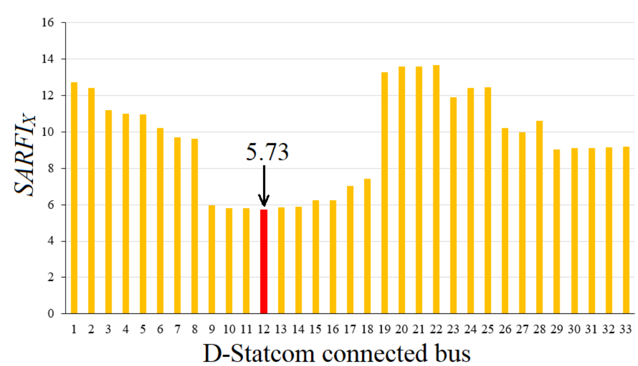

Fig. 7. $SARFI_{50}$ for all scenarios of D-Statcom placement, I_{DSmax} = 0.1322pu.

From the results in Table 1, the corresponding Pareto front for X = 50% is plotted in Fig. 8. From the Pareto front, we can find that most solutions are prone to low values of I_{DSmax} (less than 0.1pu) although a higher value of I_{DSmax} can result in a better $SARFI_X$. It is because of the objective function f_1, the small I_{DSmax} is preferable.

Similarly, we can consider other voltage sag levels X = 70%, 80% and 90%, Fig. 9, 10 and 11 show the corresponding Fareto fronts. For higher X values, the

$SARFI_X$ obviously increases while optimal values of I_{DSmax} remain almost unchanged. It's again explained as the result of the objective function f_1.

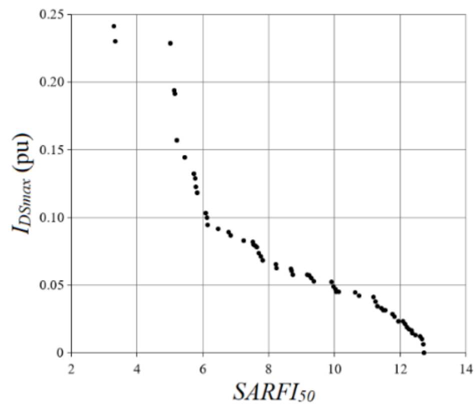

Fig. 8. Pareto front for voltage sag level X = 50%.

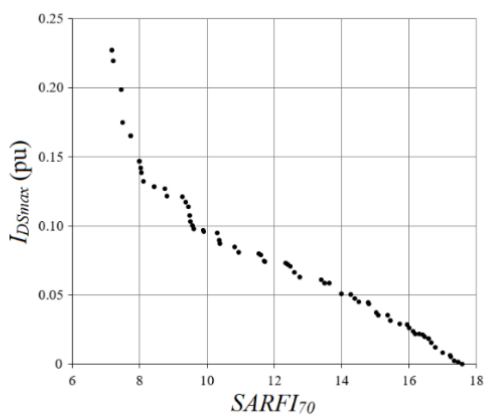

Fig. 9. Pareto front for voltage sag level X = 70%.

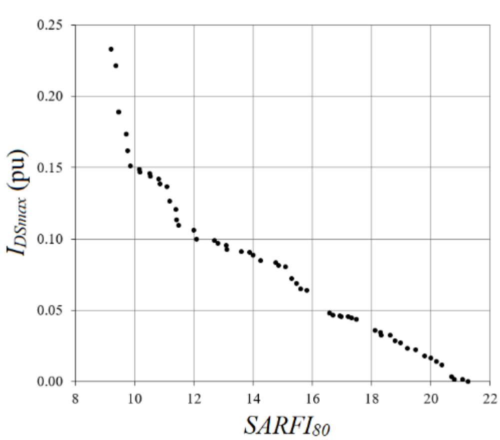

Fig. 10. Pareto front for voltage sag level X = 80%.

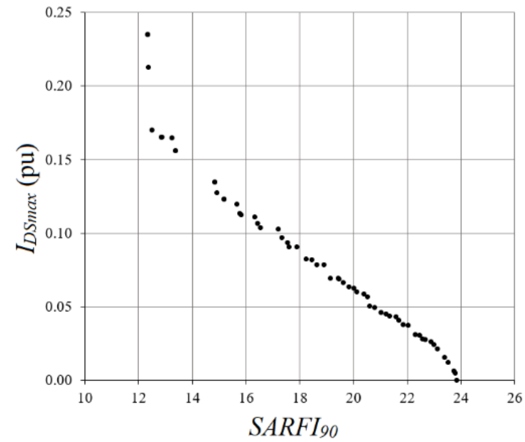

Fig. 11. Pareto front for voltage sag level X = 90%.

5. CONCLUSION

This paper proposes a novel method for optimally selecting the location and the size of a D-Statcom connected in a distribution network for global voltage sag mitigation. This method uses GA based MOO to solve the problem of optimization where either minimizing D-Statcom's investment and minimizing $SARFI_X$ of the test system is targeted. One D-Statcom compensating globally voltage sag is modeled using the Thevenin theorem's superposition principle in short-circuit calculation. The results should be a good reference for utilities in design "centre improvement" solutions for PQ mitigation. The method can be developed further if all types of short-circuit are taken into account as well as this method can be compared with other methods to see its advantages. The MOO problem can also be developed by considering more objective functions.

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