Preparation A Novel Method for the Improvement of SARFI$_X$ of Distribution System Using One D-STATCOM Considering Its Limited Current

Khanh Quoc Bach

Abstract— *In the paper, a novel method for optimizing the placement of D-Statcom for system voltage sag mitigation in distribution systems is introduced and discussed. The D-Statcom's placement is optimally selected from a problem of optimization where the objective function is to minimize the system voltage sag index – SARFI$_X$ that allows dealing with all possible fault events in the system of interest. In solving the problem of optimization, D-Statcom's effectiveness for system voltage sag mitigation is modeled basing on the method of Thevenin's superimposition for the problem of short-circuit calculation in distribution systems. The paper considers the case of using one D-Statcoms with a proposed voltage compensating principle that considers the limited injected current from the D-Statcom. The paper uses the IEEE 33-buses distribution feeder as the test system for voltage sag simulation and influential parameters to the outcomes of the problem of optimization are considered and discussed.*

Keywords— **Distribution System, Voltage Sag, SARFI$_X$, Distribution Synchronous Compensation – D-Statcom.**

1. INTRODUCTION

Voltage sag/dip is a phenomenon of power quality (PQ) in which the rms value of the voltage magnitude drops below 0.9 p.u. in less than 1 minute, according to IEEE1159 [1]. It's known that the main cause which is account of more than 90% voltage sag events is the short-circuit in the power systems. Nowadays, voltage sag issues can be mitigated by various solutions for [2, 3] that have been effectively introduced under two approaches [4] named "distributed improvement" and "central improvement". The first was early introduced and mainly seen as the solution for protecting a single sensitive load. The latter have been recently introduced for systematically improving PQ in the distribution system that attracts a lot of interests from utilities. With the recently significant decrease in the cost of power electronic devices, the solutions for system voltage sag mitigation by using custom power devices such as inverter-based voltage sources like the distribution static synchronous compensator (D-Statcom) [2] have become more and more popular.

The problem of optimally selecting the location and size of the custom power devices for totally improving PQ in distribution systems, is always concerned when its application is introduced and [4] gives an overview of various researches for modeling and solving the problem by using custom power devices for "central improvement" of PQ in general. For D-Statcom's application, researches have been also performed according to the two above said approaches. The "distributed improvement" approach have normally worked on dynamic modeling of D-Statcom with main regard to D-Statcom's controller design improvement [5-8] for mitigating PQ issues at a specific load site. In the mean times, the approach of "central improvement" have been also introduced [9-14]. challenges for the researches on "central improvement" solutions are

i. To find suitable steady-state or short-time modeling of custom power device for systematically mitigating different PQ issues,

ii. To optimize the use of custom power device for its application.

In steady-state operation, some researches [9-11] deal with D-Statcom's effectiveness for voltage quality as well as loss reduction. Some other researches [12-14] consider its effectiveness on PQ issues either in steady-state operation and short-time operations. Concretely, [12] deals with the D-Statcom based solution for mitigating various PQ issues including voltage sag using multi-objective optimization approach, but such an optimization can rarely get the best performance for voltage sag mitigation only. [13] considers directly the problem of voltage sag mitigation using D-Statcom, but there's still some room for improvement to the modeling of D-Statcom for short-circuit calculation. A good modeling of a customer power device for systematic voltage sag mitigation in distribution system was introduced in [14], but it considers the dynamic voltage restorer (DVR) and the optimization of DVR application is just based on voltage sag event index.

This paper introduces a novel method for estimating the effectiveness of system voltage sag mitigation in the short-circuit of distribution system by the installation of a D-Statcoms. This method optimizes the D-Statcom placement basing on minimizing the system voltage sag index – SARFI$_X$ that allows to consider not only a single short-circuit event but also all possible short-circuit events in a system of interest. In solving the problem of optimization, the new modeling of a D-Statcom with

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limited current that compensates system voltage sag in short-circuit events is introduced and discussed. The research uses the IEEE 33-bus distribution system as the test system. The problem of optimization is solved by considering all candidate scenarios of D-Statcom placement and verifying the objective function that minimizes the $SARFI_X$. Short-circuit calculation for the test system as well as the modeling and solution of the problem of optimization are all programmed in Matlab.

The paper is organized as follows: The Section 2 introduces the modeling of the system voltage sag mitigation by a D-Statcom in short-circuit calculation of distribution system. The Section 3 defines the problem of optimization where the modeling of a D-Statcom is built in the test system modeling for short-circuit calculation and $SARFI_X$ quantification. The results for different scenarios of D-Statcom's parameters are finally presented and analysed in the Section 4.

2. MODELING OF D-STATCOM IN SHORT-CIRCUIT CALCULATION

2.1 Basic modelling of D-Statcom

D-Statcom is theorically described as a FACTS device connected in parallel with the load that needs to be protected or connected to the source generating PQ issues to limit its bad influence to the power grid operation. The description of the D-Statcom in the steady-state calculation is popularly given as a current source [3] that injects the required current in the bus that is needed for voltage compensation.

For voltage sag mitigation, the load voltage during a singe sag event can be seen as the superposition of the voltage due to the system and the voltage change due to the injected current by D-Statcom as shown in Fig. 1.

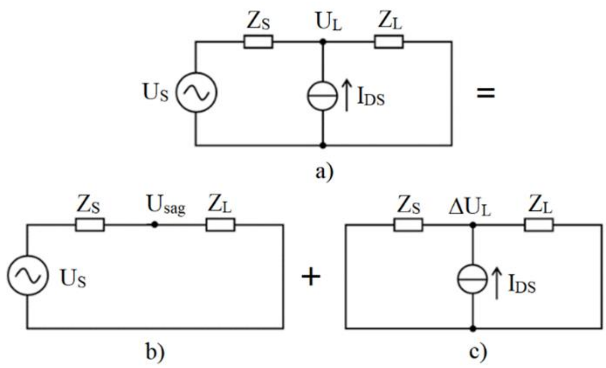

Fig.1. Modeling D-Statcom for voltage dip mitigation.

Fig. 1a is the simple network with one source (Source voltage: U_S, Source impedance: Z_S) and one load (Load impedance: Z_L) that is voltage compensated by a D-Statcom. In the event of voltage sag, the load voltage (U_{sag}) can be compensated ΔU_L by D-Statcom's injected current I_{DS} so that after-compensated load voltage U_L can be within voltage tolerance (e.g. U_L = 1p.u.).

$$U_L = U_{sag} + \Delta U_L \qquad (1)$$

From Fig. 1c, we have

$$I_{DS} = \frac{\Delta U_L}{Z_{th}} = \frac{(U_L - U_{sag})}{Z_{th}} = \frac{(1 - U_{sag})}{Z_{th}} \qquad (2)$$

where Z_{th}: Thevenin impedance of the system seen from the D-Statcom (equals Z_S in parallel with Z_L)

However, with regard to all possible sag events due to faults, the above voltage compensation is not always guaranteed because for fault locations that are very close to the D-Statcom's location, a large D-Statcom's injected current may be needed for boosting its terminal voltage to 1p.u. For a given limited current of the D-Statcom, maybe the voltage can be upgraded to somewhere between U_{sag} and 1p.u. as follows

$$|\Delta\dot{U}_L| = |\dot{I}_{DSmax} \times Z_{th}| = |\dot{U}_L - \dot{U}_{sag}| < |1 - \dot{U}_{sag}| \qquad (3)$$

2.2 Modeling of a D-STATCOM with limited current for voltage sag mitigation

To model the effectiveness of D-Statcom for voltage sag mitigation, the paper introduces the application of the superposition principle according to the Thevenin theorem for modeling the voltage sag mitigation with the presence of D-Statcom (Fig. 2) [16].

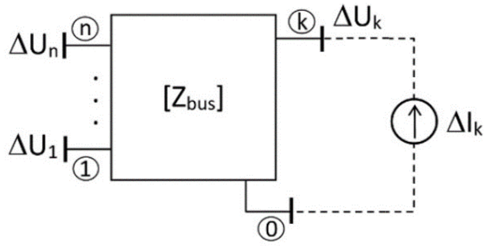

Fig.2. Modeling the D-Statcom's effectiveness for voltage sag mitigation in short-circuit of power system.

It's assumed that the initial state of the test system is the short-circuit without custom power device. Thus, we have the system bus voltage equation (3) as follows

$$[U^0] = [Z_{bus}] \times [I^0] \qquad (3)$$

where

- $[U^0]$: Initial bus voltage matrix (Voltage sag at all buses during power system short-circuit)
- $[I^0]$: Initial injected bus current matrix (Short-circuit current).

$$[U^0] = \begin{bmatrix} \dot{U}_{sag.1} \\ \vdots \\ \dot{U}_{sag.k} \\ \vdots \\ \dot{U}_{sag.n} \end{bmatrix} \quad (4) \quad ; \quad [I^0] = \begin{bmatrix} \dot{I}_{f1} \\ \vdots \\ \dot{I}_{fk} \\ \vdots \\ \dot{I}_{fn} \end{bmatrix} \qquad (5)$$

where $[Z_{bus}]$: System bus impedance matrix calculated from the bus admittance matrix: $[Z_{bus}] = [Y_{bus}]^{-1}$. If the short-circuit is assumed to have fault impedance, we can add the fault impedance to $[Z_{bus}]$.

With the presence of the custom power device, according to the Thevenin theorem, the bus voltage equation should be calculated as follows [16]:

$$[\mathrm{U}] = [\mathrm{Z_{bus}}] \times ([\mathrm{I}^0] + [\Delta \mathrm{I}])$$
$$= [\mathrm{Z_{bus}}] \times [\mathrm{I}^0] + [\mathrm{Z_{bus}}] \times [\Delta \mathrm{I}] = [\mathrm{U}^0] + [\Delta \mathrm{U}] \quad (6)$$

where

$$[\Delta \mathrm{U}] = [\mathrm{Z_{bus}}] \times [\Delta \mathrm{I}] \ (7) \text{ or } \begin{bmatrix} \Delta \mathrm{U}_1 \\ \vdots \\ \Delta \mathrm{U}_k \\ \vdots \\ \Delta \mathrm{U}_n \end{bmatrix} = [\mathrm{Z_{bus}}] \times \begin{bmatrix} \Delta \mathrm{I}_1 \\ \vdots \\ \Delta \mathrm{I}_k \\ \vdots \\ \Delta \mathrm{I}_n \end{bmatrix} \ (8)$$

where

$\Delta \mathrm{U_i}$: Bus i voltage improvement (i=1,n) after adding the custom power device in the system.

$\Delta \mathrm{I_i}$: Additional injected current to the bus i (i=1,n) after adding the custom power device in the system.

Assuming a D-Statcom is placed at bus k, according to D-Statcom modeling in Part 2.1 as well as Fig. 2, that means the matrix of additional injected bus current only have one element at bus k that does not equal zero ($\Delta \mathrm{I_k} \neq 0$). Other elements equal zero ($\Delta \mathrm{I_i} = 0$ for i=1,n; i≠k).

If we want the bus k voltage to increase from $\mathrm{U_k} = \mathrm{U_k^0} = \mathrm{U_{sag.k}}$ up to desired value, say $\mathrm{U_k} = 1$p.u., the required $\dot{\mathrm{I}}^*_{\mathrm{DS}}$ to be injected to the bus k is calculated by (8) as follows

$$\dot{\mathrm{I}}_{\mathrm{DS}} = \dot{\mathrm{I}}^*_{\mathrm{DS}} = \Delta \dot{\mathrm{I}}_{\mathrm{k}} = \frac{\Delta \dot{\mathrm{U}}_{\mathrm{k}}}{\mathrm{Z_{kk}}} = \frac{1}{\mathrm{Z_{kk}}} \times \left(1 - \dot{\mathrm{U}}_{\mathrm{sag.k}}\right) \quad (9)$$

If the given $\mathrm{I_{DSmax}}$ is lower than $\mathrm{I^*_{DS}}$, the bus k voltage can only increase to a certain value $\mathrm{U_k} < 1$p.u. as $\mathrm{I_{DS}} = \mathrm{I_{DSmax}}$

$$\dot{\mathrm{U}}_{\mathrm{k}} = \Delta \dot{\mathrm{U}}_{\mathrm{k}} + \dot{\mathrm{U}}_{\mathrm{sag.k}} = \dot{\mathrm{I}}_{\mathrm{DS}} \times \mathrm{Z_{kk}} + \dot{\mathrm{U}}_{\mathrm{sag.k}} < 1\mathrm{p.u.} \ (10)$$

Other bus voltages ($\dot{\mathrm{U}}_{\mathrm{i}}$, i=1,n; i≠k) can be calculated for one placing the D-Statcom at bus k as follows

$$\dot{\mathrm{U}}_{\mathrm{i}} = \Delta \dot{\mathrm{U}}_{\mathrm{i}} + \dot{\mathrm{U}}_{\mathrm{i}}^0 = \mathrm{Z_{ik}} \times \dot{\mathrm{I}}_{\mathrm{DS}} + \dot{\mathrm{U}}_{\mathrm{sag.i}} \quad (11)$$

From the resulting system bus voltage, we can quantify the voltage sag using $\mathrm{SARFI_X}$.

3. PROBLEM DEFINITION

3.1 The test system

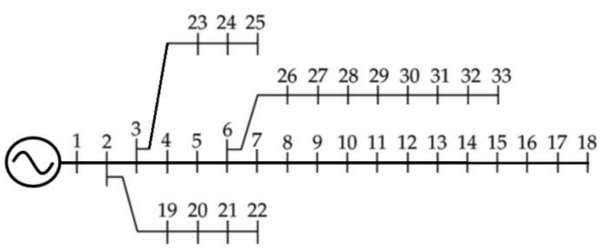

Fig.3. IEEE 33-bus distribution feeder as the test system.

For simplifying the introduction of the new method in the paper, the IEEE 33-bus distribution feeder (Fig. 3) is used as the test system because it just features a balanced three-phase distribution system, with three-phase loads and three-phase lines.

This research assumes base power to be 100MVA. Base voltage is 11kV. The system voltage is 1pu. System impedance is assumed to be 0.1pu.

3.2 Short-circuit calculation

The paper only considers voltage sags caused by fault. Because the method introduced in this paper considers $\mathrm{SARFI_X}$, we have to consider all possible fault positions in the test system. However, to simplify the introduction of the new method, we can consider only three-phase short-circuits. Other short-circuit types can be included similarly in the model if detailed calculation is needed.

Three-phase short-circuit calculations are performed in Matlab using the method of bus impedance matrix. The resulting bus voltage sags with and without the presence of D-Statcom can be calculated for different scenarios of influential parameters as analysed in Part 4.

3.3 The problem of optimization

3.3.1 Objective function

In this research, D-Statcom's effectiveness for total voltage sag mitigation is assessed basing on the problem of optimizing the location of one D-Statcom in the test system where the objective function is to minimize the System Average RMS Variation Frequency Index – SARFI-X where X is a given rms voltage threshold. [15].

$$\mathrm{SARFI_X} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{N}} \mathrm{n_{i.X}}}{\mathrm{N}} \Rightarrow \mathrm{Min} \quad (12)$$

where

$n_{i.X}$: The number of voltage sags lower than X% of the load i in the test system.

N: The number of loads in the system.

For a given fault performance (fault rate distribution) of a given system and a given threshold X, $\mathrm{SARFI_X}$ calculation is described as the block-diagram in Fig. 4.

For this problem of optimization, the main variable is the scenario of positions (buses) where D-Statcom is connected. We can see each main variable as the bus numbers with D-Statcom connection out of the set of n buses of the test system. Therefore, the total scenarios of D-Statcom placement to be tested is n=33.

For this problem, no constraint is set up. The D-Statcom's maximum current ($\mathrm{I_{DSmax}}$) is seen as a preset parameter.

3.3.2 Problem solving

For such a problem of optimization, with preset parameters (X%, and D-Statcom's limited current), the objective function – $\mathrm{SARFI_X}$ is always determined. So, we use the method of direct search and testing all 33 scenarios of D-Statcom positions. The block-diagram of solving this problem in Matlab is given in Fig.5.

For a candidate scenario k, we calculate the $\mathrm{I_{DS}}$ of D-Statcom for verifying the D-Statcom's limited current. The updated $\mathrm{I_{DS}}$ is then used for calculate system voltage with the presence of D-Statcom and the resulting $\mathrm{SARFI_X}$.

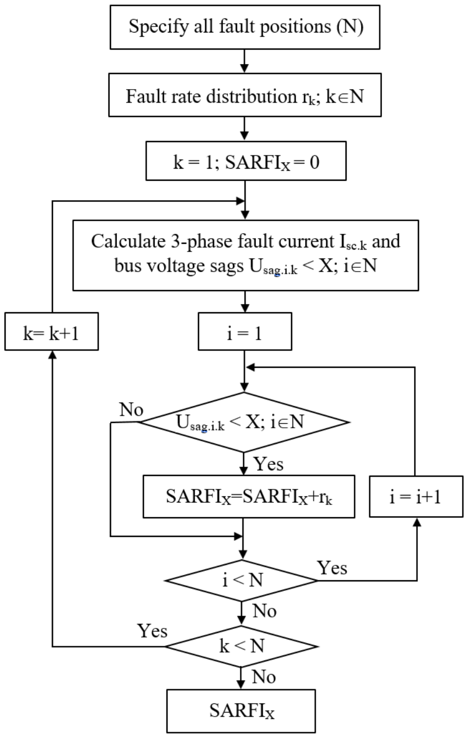

Fig. 4. $SARFI_X$ calculation

In the block-diagram, input data that can be seen as the above said preset parameters. "postop" is the intermediate variable that fixes the scenario of D-Statcom position corresponding to the minimum $SARFI_X$. The initial solution of objective function Min equals B (e.g. B=33) which is big value for starting the search process. All calculations are programmed in Matlab. The scenarios for preset parameters are considered.

4 RESULTS ANALYSIS

4.1. Preset parameters

The research considers the following preset parameters:

- For calculating $SARFI_X$, the fault performance which is fault rate distributed to all fault position. The paper uses uniform fault distribution as per [17] and fault rate = 1time per unit period of time at fault position (each bus).

- For rms voltage threshold, the paper considers voltage sags so X is given as 90, 80, 70, 50% of Un [15].

- For D-Statcom's limited current, the paper considers I_{DSmax} = 0.05, 0.1, 0.2p.u.

4.2. Results analysis

Solving the problem of optimization considering above said preset parameters, step-by-step results are introduced. Such as we consider sag X=80%, I_{DSmax} = 0.1p.u. the optimal location of D-Statcom is bus 14. Sag frequency at all buses without or with D-Statcom placed at bus 14 are plotted in Fig.6.

Values of SARFI-80 for all scenarios of D-Statcom placement are depicted in Fig. 7 for comparison. Minimum SARFI-80 = 12.0909 at bus 14.

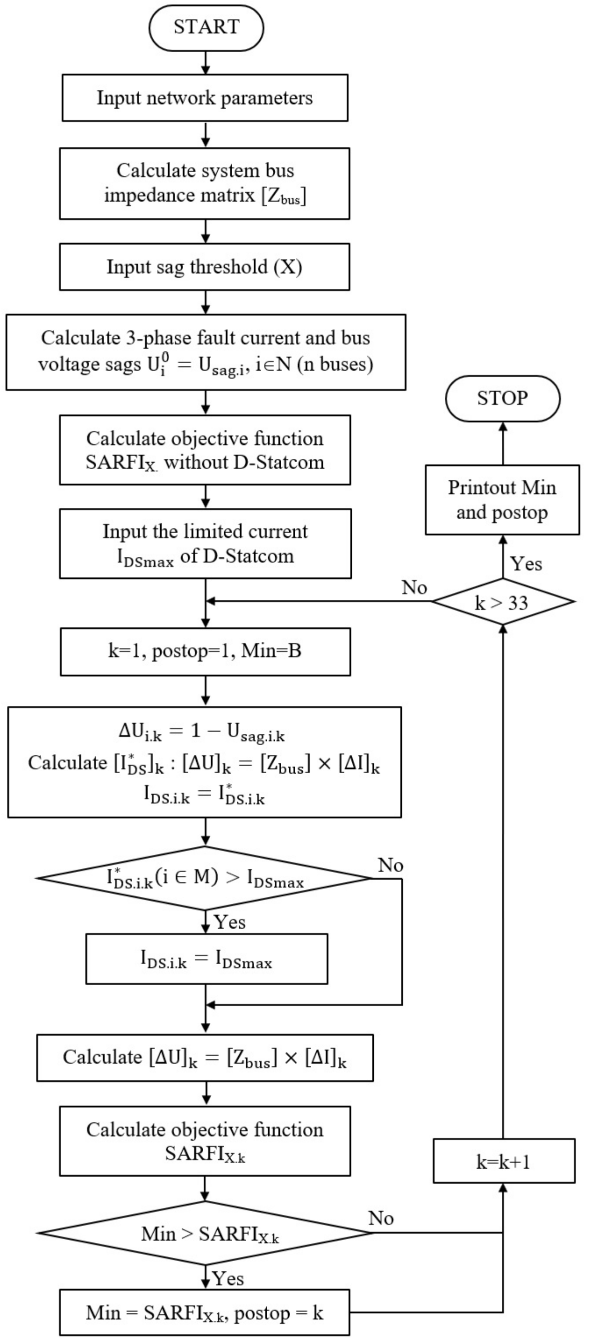

Fig. 5. Flowchart of the problem of optimization for selecting D-Statcom's location.

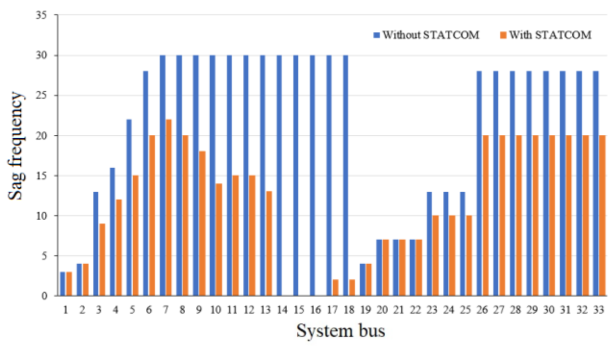

Fig.6. Sag frequency for X=80% at system buses without and with one D-Statcom placed at Bus 14, I_{DSmax} = 0.1p.u.

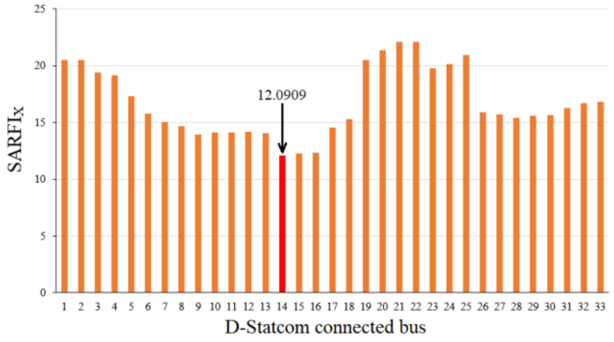

Fig.7. SARFI-80 for all scenarios of D-Statcom placement, I_{DSmax} = 0.1p.u.

Consider other X% and I_{DSmax}, the results of $SARFI_X$ and sag frequency at system buses are presented as follows:

- For the case of different I_{Dsmax} (0.05, 0.1, 0.2, 0.3p.u.) the Fig. 8 plotted the $SARFI_X$ at X=80% for all possible location (33 buses) of D-Statcom placement. At the corresponding optimal locations of D-Statcom for above said different I_{DSmax}, sag frequency at all system bus is depicted in Fig. 9.

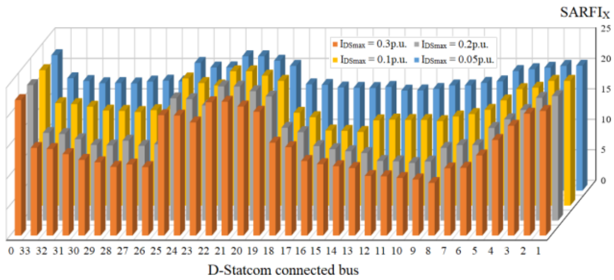

Fig.8. $SARFI_X$=80% for all scenarios of D-Statcom placement, I_{DSmax} = 0.05, 0.1, 0.2, 0.3p.u.

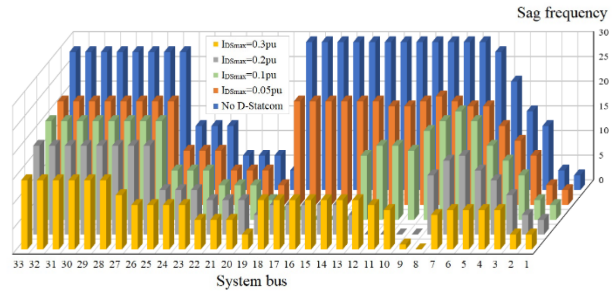

Fig.9. Sag frequency at system buses for X=80% without and with D-Statcom having I_{DSmax} = 0.05, 0.1, 0.2, 0.3p.u. placed at the optimal location.

- For the case of different X=50, 70, 80, 90%, $SARFI_X$ at all scenarios of D-Statcom placement are demonstrated in Fig. 10 for D-Statcom's I_{DSmax} = 0.1p.u. At the corresponding optimal locations of D-Statcom for above said different X thresholds, sag frequency at all system bus is depicted in Fig. 11.

Number "0" on horizontal axis in Fig. 8 and 10 means $SARFI_X$ without D-Statcom. The higher voltage threshold results in the larger SARFI in either with or without D-Statcom. Stronger injected current from D-Statcom can better support system voltage that helps reduce more SARFI. The optimal location of D-Statcom often fall to buses in the middle of the main feeder as it can support the voltage for almost buses in the system.

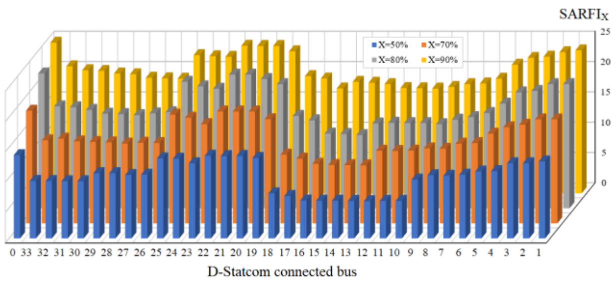

Fig.10. $SARFI_{X=50,\ 70,\ 80,\ 90\%}$ for all scenarios of D-Statcom placement, I_{DSmax} = 0.1p.u.

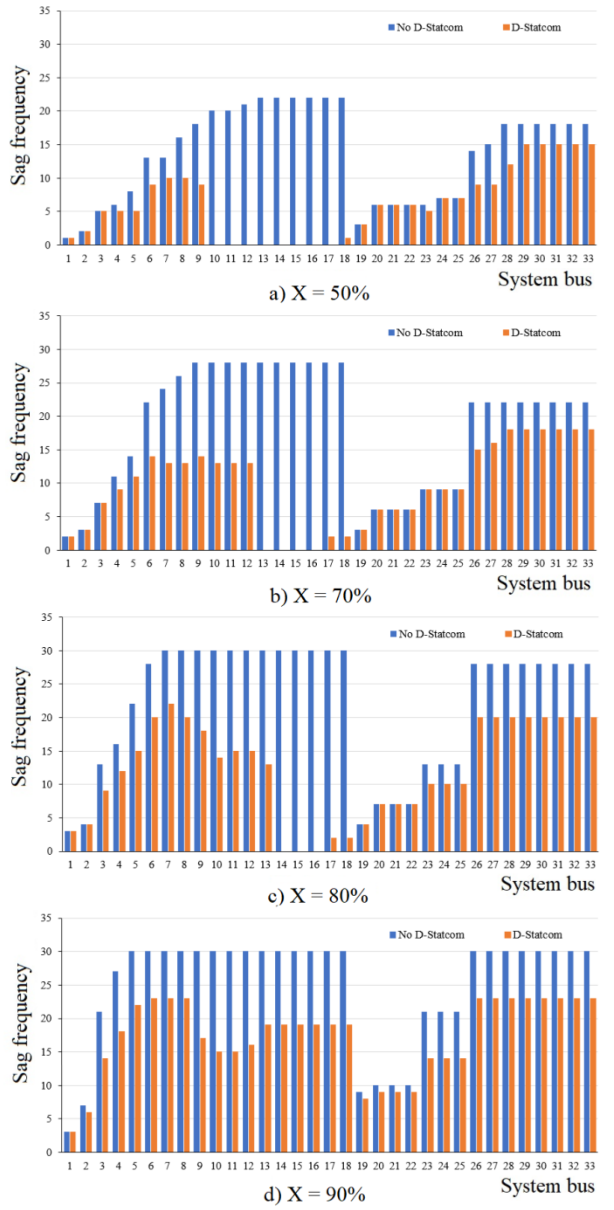

Fig. 11. Sag frequency at system buses for X=50, 70, 80, 90% without and with D-Statcom having I_{DSmax} = 0.1p.u. placed at the optimal location.

The remarkable results for all preset parameters are summarized in Table 1.

Table 1. Optimal location of D-Statcom and $SARFI_X$ for scenarios of preset parameters

I_{DSmax} (pu)	0.05	0.1	0.2	0.3
X = 50%				
$minSARFI_X$	9.9697	6.1212	5.1212	3.303
DS Opt. Loc.	Bus 17	Bus 12	Bus 9	Bus 8
X = 70%				
$minSARFI_X$	14.303	9.5758	7.4545	7.1818
DS Opt. Loc.	Bus 12	Bus 13	Bus 9	Bus 9
X = 80%				
$minSARFI_X$	16.4242	12.0909	9.4545	8.6364
DS Opt. Loc.	Bus 12	Bus 14	Bus 10	Bus 8
X = 90%				
$minSARFI_X$	20.7879	17.2727	12.4848	11.0909
DS Opt. Loc.	Bus 13	Bus 10	Bus 10	Bus 8

4. CONCLUSION

This paper introduces a novel method for optimally selecting the location of a D-Statcom with a given limited current for system voltage sag mitigation. The problem of optimization considers D-Statcom placement for minimizing the resulting $SARFI_X$ for given X threshold. The modeling of D-Statcom compensating system voltage sag in the problem of short-circuit using the Thevenin theorem's superimposition principle is introduced for calculating the $SARFI_X$ with the presence of D-Statcom. Preset parameters are considered in the research for a better demonstration of influences to the outcomes of the problem of optimization. The calculation can be developed further with all types of short-circuit are taken into account.

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