# Central Improvement of Voltage Sags in the IEEE 33-Bus Distribution System by a Number of D-STATCOMS

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**Abstract**

*The paper introduces a novel method for "central improvement" of voltage sags due to short-circuits in distribution system using multiples of D-Statcoms. D-Statcom's effectiveness for 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 newly considers the case of using a multiple of D-Statcoms with a proposed voltage compensating principle that can be practical for large size of distribution system. A multiple of D-Statcoms are optimally located and sized on the basis of minimizing the system bus voltage deviation with regard to the constraint of D-Statcom's size. The paper uses the IEEE 33-buses distribution feeder as the test system for voltage sag simulation and results discussion.*

Keywords: Distribution System, Voltage Sag, System Voltage Deviation, Distribution Synchronous Compensation – D-Statcom

## 1. Introduction

Voltage sag, according to IEEE1159 [1], 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. Short-circuits in the power systems account for more than 90% of voltage sag events. Various solutions for voltage sag mitigation [2, 3] have been introduced, particularly for distribution system, and they are basically clustered into two groups [4] named "distributed improvement" and "central improvement". While the first are mainly applied for protecting a single sensitive load, the later are introduced for systematically (or totally) enhancing PQ in the distribution system (i.e. not only for a single load, but also for many loads). These solutions, especially that use custom power devices (CPD) like the distribution static synchronous compensator (D-Statcom) [2], have recently attracted more and more interest from utilities as the cost of solutions has gradually declined.

When CPDs are used for totally improving PQ in distribution system, the problem of optimally selecting their location and size is always concerned and [4] summarizes various researches for modeling and solving the problem by using CPDs for "central improvement" of PQ in general. For PQ problems using the shunt compensator like D-Statcom, besides researches on dynamic modeling of D-Statcom with main regard to the design of controller of D-Statcom [5-8] for mitigating PQ issues at a specific load site, there have been researches on using D-Statcom [9-14] as a systematic solution of PQ. However, no researche deals a multiple of D-Statcom mitigating voltage sag due to faults in distribution system.

This paper introduces a novel method for system voltage sag mitigation by the presence of a number of D-Statcoms in a distribution system. This method optimizes the size and placement of a multiple of D-Statcoms basing on the improved system voltage deviation index during a short-circuit in the system of interest. The research uses the IEEE 33-bus distribution system as the test system. Short-circuit calculation for the test system as well as the modeling and solution of the problem of optimization are all programmed in Matlab.

Toward the above purpose, the paper is organised as follows: The Section 2 presents the proposal of the modeling of D-Statcom for short-circuit calculation in distribution system. The Section 3 defines the problem of optimization where the modeling of a multiple of D-Statcoms is built in short-circuit calculation and

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system voltage sag quantification. Finally, the results for different scenarios of short-circuit events are analysed in the Section 4.

## 2. Modeling of D-Statcom for Short-circuit Calculation in Distribution System

### *2.1 Generality*

D-Statcom is a FACTS device that is popularly described as a current source that injects the required current in the bus needed for voltage compensation [3].

It's assumed that the initial state of the test system is the short-circuit without custom power devices in general. Thus, we have the system bus voltage equation (1) as follows

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

where

$$[U^0] = \begin{bmatrix} \dot{U}_{sag.1} \\ \vdots \\ \dot{U}_{sag.k} \\ \vdots \\ \dot{U}_{sag.n} \end{bmatrix} \quad (2); \qquad [I^0] = \begin{bmatrix} \dot{I}_{f1} \\ \vdots \\ \dot{I}_{fk} \\ \vdots \\ \dot{I}_{fn} \end{bmatrix} \quad (3)$$

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

*[$I^0$]:* Initial injected bus current matrix (Short-circuit current).

*[$Z_{bus}$]*: 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 D-Statcoms, according to the Thevenin theorem, the bus voltages should be calculated as follows [15]:

$$\begin{aligned}[U] &= [Z_{bus}] \times ([I^0] + [\Delta I]) \\ &= [Z_{bus}] \times [I^0] + [Z_{bus}] \times [\Delta I] \\ &= [U^0] + [\Delta U] \end{aligned} \quad (4)$$

where

$$[\Delta U] = [Z_{bus}] \times [\Delta I] \quad (5)$$

or

$$\begin{bmatrix} \Delta\dot{U}_1 \\ \vdots \\ \Delta\dot{U}_k \\ \vdots \\ \Delta\dot{U}_n \end{bmatrix} = [Z_{bus}] \times \begin{bmatrix} \Delta\dot{I}_1 \\ \vdots \\ \Delta\dot{I}_k \\ \vdots \\ \Delta\dot{I}_n \end{bmatrix} \quad (6)$$

*$\Delta U_i$*: Bus i voltage improvement (*i=1,n*) after adding the CPD in the system.

*$\Delta I_i$*: Additional injected current to the bus i (*i=1,n*) after adding CPDs like D-Statcoms in the system.

### *2.2. Placing two D-Statcoms in the test system*

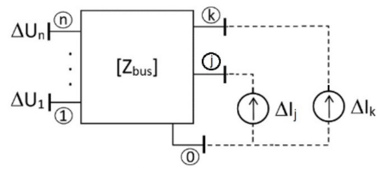


**Fig. 1.** Test system short-circuit modeling using [$Z_{bus}$] with presence of two D-Statcoms

In the case of using two D-Statcoms (Fig. 1) assumed to connect to bus j and k (such as *k>j*), the matrix of additional injected bus current only has two elements at bus j and bus k that do not equal zero *($\Delta I_j = I_{DSj} \neq 0$ and $\Delta I_k = I_{DSk} \neq 0$).* Other elements equal zero ($\Delta I_i = 0$ for ∀i≠j,k). Therefore, (6) can be rewritten as follows

$$\begin{cases} \Delta\dot{U}_j = Z_{jj} \times \dot{I}_{DSj} + Z_{jk} \times \dot{I}_{DSk} \\ \Delta\dot{U}_k = Z_{kj} \times \dot{I}_{DSj} + Z_{kk} \times \dot{I}_{DSk} \end{cases} \quad (7)$$

The injected currents to bus j and bus k, their bus voltages can boost $U_j$ and $U_k$ from $U_j^0 = U_{sag.j}$ and $U_k^0 = U_{sag.k}$ up to desired value, say 1p.u. That means

$$\begin{cases} \Delta\dot{U}_j = 1 - \dot{U}_{sag.j} \\ \Delta\dot{U}_k = 1 - \dot{U}_{sag.k} \end{cases} \quad (8)$$

replace (8) to (7) and solve this system of two equations, we get

$$\begin{cases} \dot{I}_{DS.k} = \dfrac{Z_{kj}\times(1-\dot{U}_{sag.j}) - Z_{jj}\times(1-\dot{U}_{sag.k})}{(Z_{kj}\times Z_{jk} - Z_{jj}\times Z_{kk})} \\ \dot{I}_{DS.j} = \dfrac{Z_{jk}\times(1-\dot{U}_{sag.k}) - Z_{kk}\times(1-\dot{U}_{sag.j})}{(Z_{kj}\times Z_{jk} - Z_{jj}\times Z_{kk})} \end{cases} \quad (9)$$

The power of corresponding D-Statcoms placed at buses j and k

$$\begin{cases} \dot{S}_{DS.j} = \dot{U}_j \times \hat{I}_{DS.j} \\ \dot{S}_{DS.k} = \dot{U}_k \times \hat{I}_{DS.k} \end{cases} \quad (10)$$

The voltage upgrade at other buses i (i≠j,k) can also be calculated

$$\Delta\dot{U}_i = Z_{ij} \times \dot{I}_{DS.j} + Z_{ik} \times \dot{I}_{DS.k} \quad (11)$$

Finally, the voltage at other buses i (i≠j,k) after placing two D-Statcoms at buses j and k

$$\dot{U}_i = \Delta\dot{U}_i + \dot{U}_i^0 = \Delta\dot{U}_i + \dot{U}_{sag.i} \quad (12)$$

### *2.2.3. Placing m D-Statcoms in the test system*

Assume that M is the set of m buses to connect to D-Statcom (Fig. 2), so the column matrix of bus injected current [*$\Delta I$*] in (6) has m non-zero elements and n-m zero elements. From (6), we have

$$\Delta\dot{U}_k = Z_{kk} \times \dot{I}_{DS.k} + \sum_{j\in M, i\neq k} Z_{jk} \times \dot{I}_{DS.j} \quad (13)$$

For bus *k*, $k \in M$, the rule of voltage compensation is as follows

$$\Delta\dot{U}_k = \dot{U}_k - \dot{U}_{sag.k} = 1 - \dot{U}_{sag.k} \qquad (14)$$

Replace (14) to (13) we have m equations to calculate m variables $I_{DS.k}$ of m D-Statcoms. Solve this system of m equations, we get m values of $I_{DS.k}$.

Replace m values of $I_{DS.k}$ in (6), we can calculate the voltage upgrade of n-m buses without connecting to D-Statcoms

$$\Delta\dot{U}_i = \sum_{i=1}^{n} Z_{ik} \times \dot{I}_{DSk} \qquad (15)$$

Finally, we calculate voltages of all buses in the system after placing m D-Statcoms similar to (12).

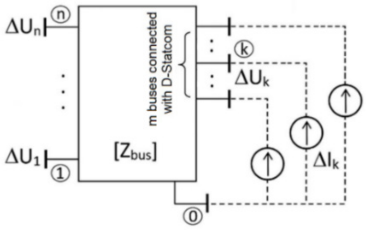


**Fig. 2.** Test system short-circuit modeling using [$Z_{bus}$] with the presence of m D-Statcoms (m<n)

## 3. Problem Definition

### *3.1. IEEE 33-Bus Distribution System*

This paper uses the IEEE 33-bus distribution feeder (Fig. 3) as the test system for the research. It features a balanced three-phase distribution system, with three-phase lines and loads. This research assumes: base values are 11kV; 100MVA. The system voltage is 1pu. System impedance is 0.1pu.

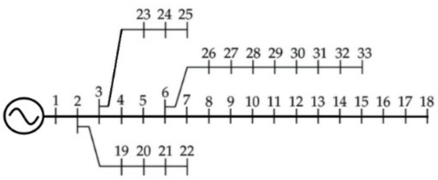


**Fig.3.** IEEE 33-bus distribution feeder

### *3.2. Short-circuit calculation*

According to point 2.2a, Section 2, we assume the initial status of the test system is a short-circuit in the system. The paper considers a number of short-circuit positions with different fault impedance $Z_f$. Three-phase short-circuit calculations are performed in Matlab using the method of bus impedance matrix and resulting bus voltage sags can be calculated.

With the calculation of system bus voltage in the short-circuit event with the presence of D-Statcom, we can define the problem of optimization as follows.

### *3.3. The problem of optimization*

#### *3.3.1. Objective function and constraints*

In this research, the problem of optimizing the location and size of a multiple D-Statcoms in the test system where the objective function is to minimize the total system voltage deviation, is established. It's seen as the index of system voltage sag energy [16].

$$F = \sqrt{\sum_{i=1}^{n}\left(U_{ref} - U_i\right)^2} \Rightarrow Min \qquad (16)$$

where

$U_{ref}$: Reference system voltage, equals 1p.u.

$U_i$: Bus i voltage calculated in (14).

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

$$T_m = C_n^m = \frac{33!}{m! \times (33-m)!} \qquad (17)$$

For example, if we consider the placement of 2 D-Statcoms in the test system, *m*=2, the total scenarios for placing these two D-Statcoms is as follows

$$T_2 = C_{33}^2 = \frac{33!}{2! \times (33-2)!} = 528.$$

Each candidate scenario to be tested is a pair of buses number k and l out from 33 buses where the two D-Statcoms are connected (e.g. 1,2; 1,3;…).

The only constraint is that the size of D-Statcom is limited to a certain maximum value ($S_{DS.max}$). In this research D-Statcom's size is not greater than 0.1p.u. (or 10MVA). For each bus where D-Statcom can be connected, if $S_{DS} > S_{DS.max}$, this bus is not qualified for D-Statcom placement.

#### *3.3.2. Problem solving*

For such a problem of optimization, under the assumption of a fault event, the objective function and the constraint are always determined. So, we use the method of direct search and testing all candidate scenarios in the set of scenarios of $T_m$. The flowchart of solving this problem in Matlab is given in Fig. 4.

Each candidate scenario *k* defines positions where D-Statcoms are connected. According to this method, we have to determine the whole set of candidate scenarios $T_m$ (17). For a candidate scenario *k*, we can calculate the D-Statcom's power (size) and objective function $F_k$. We can sweep all candidate scenarios in $T_m$ for constraint verification and minimization of the objective function.

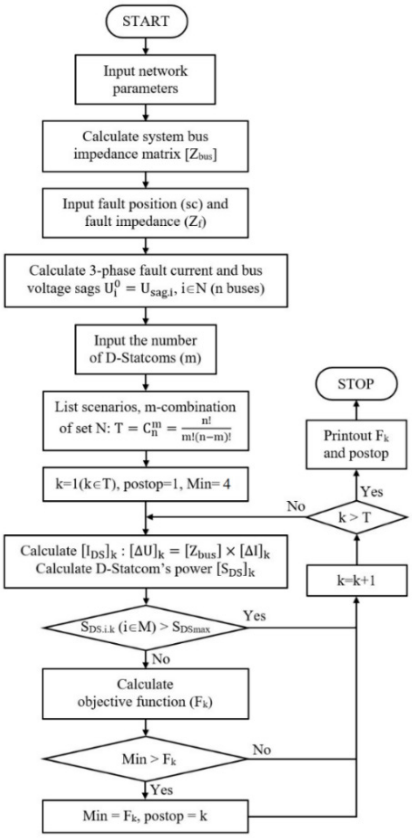


**Fig. 4.** Flowchart of the problem of optimization

In the flowchart, input data that can be seen as parameters are fault events. "postop" is the intermediate variable that fixes the optimal scenario of D-Statcom placement where the objective function is minimized. The initial solution of objective function Min equals 4 which is big value for starting the search process. The method sweeps all cadidate scenarios in the set of $T_m$ to find the global optimal solution.

## 4. Result Analysis

### *4.1. Fault event scenarios*

The research considers the following fault event scenarios that have significant influence on the D-Statcom's size and objective function:

Short-circuit type and fault impedance: Three-phase short-circuit through different values of fault impedances $Z_f$ is considered. Three alternatives of fault impedances $Z_f$ = 1.6(p.u.), 0.8(p.u.) and 0(p.u.) are considered for analysing its influences in the problem solutions. The paper mainly discusses the D-Statcom's effectiveness on voltage compensation in an event of short-circuit in general, thus, other short-circuit types are not considered.

Short-circuit positions: Two fault positions at buses 10 and 30 are considered.

### *4.2. Result analysis*

The proposed method of modeling the system voltage sag mitigation for the case of using multiples of D-Statcom in Section 2.2 can be illustrated for the case of using two D-Statcom. Followings are step-by-step clarification and analysis of the results.

For a better understanding, we consider the case of fault position at bus 10. The Fig.5 is 3D graphic of the objective function for all scenarios of placement of 2 D-Statcoms in case of $Z_f$ = 1.6p.u. A scenario is a point with its ordinates equal to D-Statcom's locations. Also, because we don't consider the permutation for the pair of D-Statcom's location (e.g. 1-2 is the same as 2-1), we only consider points on the triangle from the main diagonal of the matrix of scenarios of placement of 2 D-Statcoms. The points in the other triangle of the above said matrix are not considered and thus its objective function is given a high value (e.g. *F*=4p.u.). Besides, for the scenarios that result in the power of one or both two D-Statcoms greater than $S_{DSmax}$, they are also not considered as candidate scenarios and their objective function is also equal to 4p.u. Objective function gets its minimum of 0.1611p.u. for D-Statcoms placed at buses 9 and 13. The resulting system bus voltages are all upgraded above 0.8p.u. (Fig. 6).

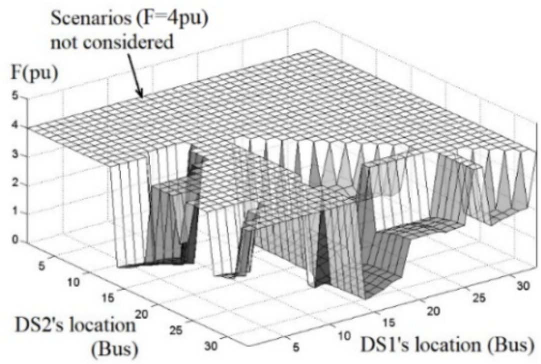


**Fig. 5.** Objective function for the placement of two D-Statcoms for fault position at bus 10, $Z_f$ = 1.6p.u.

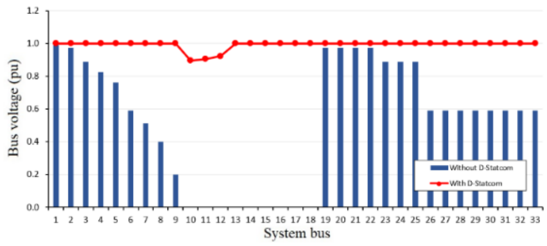


**Fig.6.** System bus voltage without and with D-Statcoms for short-circuit at bus 10, $Z_f$ = 1.6p.u.

The main results are summarized in the Table 2. The system bus voltage before and after placing two D-Statcoms are also depicted in Fig. 7.

**Table 1.** Remarked results for placing two D-Statcoms

| Fault impedance $Z_f$ (p.u.) | 1.6 | 0.8 | 0 |
|---|---|---|---|
| Short-circuit position at bus 10 | | | |
| Objective function (p.u.) | 0.1611 | 0.2825 | 0.3184 |
| Optimal placement of DS 1 | Bus 9 | Bus 8 | Bus 8 |
| Size (p.u.) of DS 1 | 0.0988 | 0.0822 | 0.0925 |
| Optimal placement of DS 2 | Bus 13 | Bus 13 | Bus 13 |
| Size (p.u.) of DS 2 | 0.0518 | 0.0858 | 0.0965 |
| Number of buses U > 0.8p.u. | 33 | 33 | 33 |
| Number of scena. $S_{DS} > S_{DS.max}$ | 310 | 358 | 423 |
| Short-circuit position at bus 30 | | | |
| Objective function (p.u.) | 0.1096 | 0.1247 | 1.8066 |
| Optimal placement of DS 1 | Bus 28 | Bus 28 | Bus 9 |
| Size (p.u.) of DS 1 | 0.0707 | 0.0793 | 0.0918 |
| Optimal placement of DS 2 | Bus 31 | Bus 31 | Bus 23 |
| Size (p.u.) of DS 2 | 0.0839 | 0.094 | 0.0589 |
| Number of buses U > 0.8p.u. | 0.1096 | 0.1247 | 1.8066 |
| Number of scena. $S_{DS} > S_{DS.max}$ | 366 | 381 | 404 |

The research considers the voltage tolerance of 0.8p.u. in Table 1 and 2 because we know that the voltage sag duration is basically defined by protection's tripping time and for distribution system, it's normally in the range of 0.1-10s. According to voltage ride through curve (e.g. ITIC [1]), the safe voltage magnitude is 0.8pu. That's why for the size of distribution system as the IEEE 33-bus system, we can only consider to use up to 2 D-Statcoms for system voltage sag mitigation.

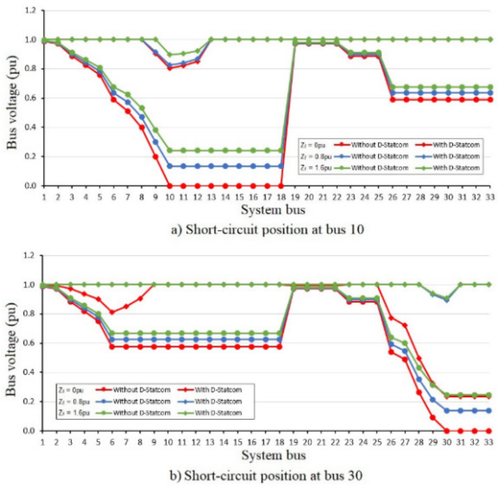


**Fig. 7.** System bus voltage without and with two D-Statcom placements for short-circuit at buses 10, 30

## 5. Conclusion

This paper introduces a new method for considering "central improvement" voltage sag mitigation by a multiple of D-Statcoms in distribution system. D-Statcom modeling for voltage sag mitigation in short-circuit calculation of power system is introduced basing on the application of Thevenin's superposition theorem. The problem of optimization is solved on the minimization of objective function which is the total system voltage deviation as per "central improvement" approach with regard to D-Statcom's power constraint. This method allows us to consider using a multiple of D-Statcoms in the case of large distribution system that helps improve totally system bus voltage in voltage sag events in distribution system. Different scenarios of fault event including short-circuit positions and fault impedances are taken into account for assessing their influence to the outcomes of the problem of optimization.

A cost model is not introduced for the problem of optimization because the benefice from system voltage sag mitigation is impossibly determined. Research can be developed with regard to different fault events in the same time for a better illustration for D-Statcom's system voltage sag mitigation.

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