SARFI$_X$ improvement for distribution system by dynamic voltage restorer considering its limited current

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***Abstract*—The paper introduces a new method for optimizing the placement of a Dynamic Voltage Restorer-DVR for voltage sag mitigation in distribution systems. The location of DVR is optimally selected on the basis of minimizing the system average RMS variation frequency index – SARFI$_X$ of the system of interest. The problem of optimization is introduced where the modeling of DVR using Norton's equivalent circuit in short-circuit calculation and voltage sag calculation using the Thevenin's superposition principle are combined for determining the objective function which is the SARFI$_X$ of the system with the presence of one DVR. The DVR's effectiveness of system voltage sag mitigation is considered in the case of a given maximum current generated by DVR. 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.**

***Index Terms*—Distribution System, Voltage Sag, SARFI$_X$, Dynamic Voltage Restorer-DVR.**

1 INTRODUCTION

Voltage sag/dip [1] is one of power quality (PQ) issues that occurs rather frequently because its main cause is the fault in power systems. A single voltage sag event may not cause serious problems to a large number of customers, but its high frequency of occurrence still results in costly damage, especially in distribution systems. With the recent development of power electronic application, the phenomenon can be effectively mitigated by using the custom power device (CPD) [2, 3] under two approaches named "distributed improvement" [4] and "central improvement" [5]. The first is mainly considered for protecting a single sensitive load while the latter is introduced for systematically improving PQ in the power system that is mainly interested by utilities.

Among CPD based solutions for voltage sag mitigation, using the Dynamic Voltage Restorer (DVR) is proved to be effective for "distributed improvement" [6, 7, 8] with regard mainly to DVR's controller design improvement for mitigating PQ issues at a specific load site. When DVR is used for "central improvement" of PQ in general, the problem of optimizing its placement and size always needs to be solved and [5] overviews various researches for modeling and solving the problem. However, the number of reports for "central improvement" of PQ using CPD, especially DVR is much fewer than that for "distributed improvement" of PQ. The main difficulties for researches on "central improvement" solutions are: i. To find suitable steady-state or short-time modeling of CPD for systematically mitigating different PQ issues, ii. To optimize the use of CPD (sizing and locating). Regarding DVR's application, the research review can be summarized by remarkable reports as follows: [9] introduced an interesting research for optimizing DVR's location and size, but the objective function implies the improvement of system reliability with regard to the events of supply interruption only. [10] also considered the optimization of DVR's location, but it's used for individual fault events. [11] introduced the solving of the optimization problem for the application of Static Compensator (Statcom) under "central improvement" approach that is probably applicable to other CPD like DVR. This research deals with the mitigation of various PQ issues including

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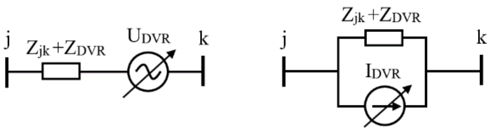
voltage sag and multi-objective optimization approach for Statcom locating, but such an optimization problem can rarely get the best performance for voltage sag mitigation only. References [13, 14] deal directly with the voltage sag mitigation using FACTS devices, but the modeling of FACTS devices for short-circuit calculation still needs to be further improved.



a) Voltage source model of DVR   b) Norton's equivalent current source model

U_{DVR}: Series voltage source of DVR
I_{DVR}: Current injected by DVR
Z_{DVR}: Internal reactance of DVR
Z_{jk}: Impedance of the branch j-k

Fig. 1. Norton's equivalent current source model for DVR

This paper introduces a novel method for estimating the effectiveness of system voltage sag mitigation by the presence of a DVR in the short-circuit of a distribution system. This method optimizes the placement of DVR basing on minimizing a well-known system voltage sag index – SARFIX that allows considering 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 modeling of DVR compensating system voltage sag in short-circuit events is introduced and discussed. The research uses the IEEE's 33-bus distribution system as the test system. Short-circuit calculation for the test system as well as the modeling and solving of the problem of optimization are all programmed in Matlab.

For this purpose, the paper is structured as the following parts: Section 2 introduces the modeling of DVR's effectiveness for system voltage sag mitigation in the problem of short-circuit calculation in a distribution system. Section 3 introduces the problem of optimization where objective function and constraints are defined and the modeling of DVR is built in the test system modeling for short-circuit calculation. Finally, the results for different scenarios of DVR's parameters are analyzed in Section 4.

2 MODELING OF DVR WITH LIMITED CURRENT FOR SHORT-CIRCUIT CALCULATION

2.1 DVR's basic modeling

DVR is a FACTS device that is connected in series 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 DVR in the steady-state calculation is popularly given as a voltage source [3] connected in series with the impedance of the branch as Figure 1.a. In modeling the power system for short-circuit calculation, the method of bus impedance matrix is often used and such DVR's model of a series connected voltage source is difficult to apply. However, the problem can be eased by replacing the voltage source model with the Norton's equivalent current source as shown in Figure 1.b.

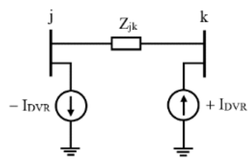


Fig. 2. Model for DVR for steady state analysis

In power system modeling for steady-state calculation, the Norton's equivalent current source model of the DVR can be represented as a load current at the output node (j) and a current source at the input node (k) as shown in Fig. 2 [15].

Note that the node k is the position of which the voltage is compensated by DVR. In the radial distribution system, node j is nearer to the source while node k is farer to the source (i.e. nearer to the load side).

2.2 Modeling of DVR for system voltage sag mitigation

2.2.1 Modeling the test system in a short-circuit event

For modeling the effectiveness of the DVR for system voltage sag mitigation, the paper also introduces the application of the superposition principle according to the Thevenin theorem for the problem of short-circuit calculation in distribution system [10]. It's assumed that the initial state of the test system is the short-circuit without the presence of DVR. Thus, we have the system bus voltage can be calculated as follows

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

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).

$$[U^0] = \begin{bmatrix} \dot{U}_{sag.1} \\ \vdots \\ \dot{U}_{sag.k} \\ \vdots \\ \dot{U}_{sag.n} \end{bmatrix} \quad (2)$$

$$[I^0] = \begin{bmatrix} \dot{I}_{f1} \\ \vdots \\ \dot{I}_{fk} \\ \vdots \\ \dot{I}_{fn} \end{bmatrix} \quad (3)$$

$[Z_{bus}]$: 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 DVR, according to Thevenin theorem, the bus voltage equation should be modified as follows [16]:

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

where

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

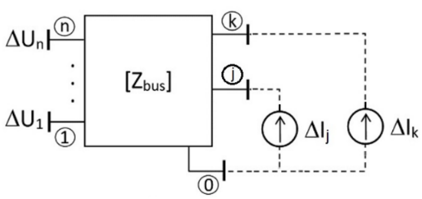


Fig. 3. Test system modeling using [Zbus] with the presence of one DVR

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

ΔU_i: Bus i voltage improvement (i=1÷n) after adding the custom power devices in the system.

ΔI_i: Additional injected current to the bus i (i=1÷n) after adding the custom power devices like DVR in the system.

*2.2.2*Modeling the test system with the presence of DVR

Assuming a DVR is placed on the branch j-k. Basing on the DVR modeling in Fig. 3, in the matrix of additional injected bus current (6), there're only two elements that do not equal zero (Fig.3). They are $\Delta I_k = + I_{DVR}$ and $\Delta I_j = -I_{DVR}$. Other elements equal zero ($\Delta I_i = 0$ for i=1÷n, i≠j and i≠k).

Replace the assumed values of ΔI_i in (6), we get

$$\begin{aligned}\Delta\dot{U}_k &= Z_{kk} \times \Delta\dot{I}_k + Z_{kj} \times \Delta\dot{I}_j \\ &= (Z_{kk} - Z_{kj}) \times \dot{I}_{DVR} \end{aligned} \quad (7)$$

According to the DVR modeling in Fig. 2, the voltage of bus k is compensated up to the desired value. [10] proposes the desired value is 1pu. It means the bus k voltage is boosted by DVR from $U_k^0 = U_{sag.k}$ to U_k = 1p.u.

So, $\Delta\dot{U}_k = 1 - \dot{U}_{sag.k}$ (8)

Replace (8) into (7), we get I_{DVR}

$$\dot{I}_{DVR} = \Delta\dot{I}_k = \frac{\Delta\dot{U}_k}{Z_{kk}-Z_{kj}} = \frac{1-\dot{U}_{sag.k}}{Z_{kk}-Z_{kj}} \quad (9)$$

However, [10] only considers individual fault positions because the objective function is a kind of event index [17]. If we consider all possible fault positions in the system for calculating a system index like $SARFI_X$, it's obvious that there's fault position that is very close to DVR's location and to boost the voltage to 1p.u., it needs a large inject current from DVR that possibly exceeds its maximum value, say I_{DVRmax}. Therefore, this paper newly assumes the condition for voltage sag mitigation by a given limited current injected by DVR as follows

- If I_{DVR} calculated by (9) is not greater than a given I_{DVRmax}, the voltage of bus k is boosted up to 1p.u. And the upgraded voltage for another bus i (i=1÷n; i≠k) in the test system can be calculated as follows

$$\begin{aligned}\Delta\dot{U}_i &= Z_{ik} \times \Delta\dot{I}_k + Z_{ij} \times \Delta\dot{I}_j \\ &= (Z_{ik} - Z_{ij}) \times \dot{I}_{DVR} \end{aligned} \quad (10)$$

- If I_{DVR} calculated by (9) is greater than I_{DVRmax}, the voltage of bus k is calculated as follows

$$\dot{U}_k = (Z_{kk} - Z_{kj}) \times \dot{I}_{DVRmax} + \dot{U}_{sag.k} < 1\text{p.u.} \quad (11)$$

The upgraded voltage for other bus i (i=1÷n; i≠k) in the test system can be calculated as follows

$$\Delta\dot{U}_i = (Z_{ik} - Z_{ij}) \times \dot{I}_{DVRmax} \quad (12)$$

Finally, bus voltages with the presence of DVR

$$\dot{U}_i = \Delta\dot{U}_i + \dot{U}_{sag.i} \quad (13)$$

3 PROBLEM DEFINITION

3.1 The problem of optimization

3.1.1 Objective function and constraints

In this research, the use of DVR for total voltage sag mitigation is assessed based on the problem of optimizing the location of DVR 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 [17].

$$SARFI_X = \frac{\sum_{i=1}^{N} n_{i.X}}{N} \Rightarrow Min \quad (14)$$

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.

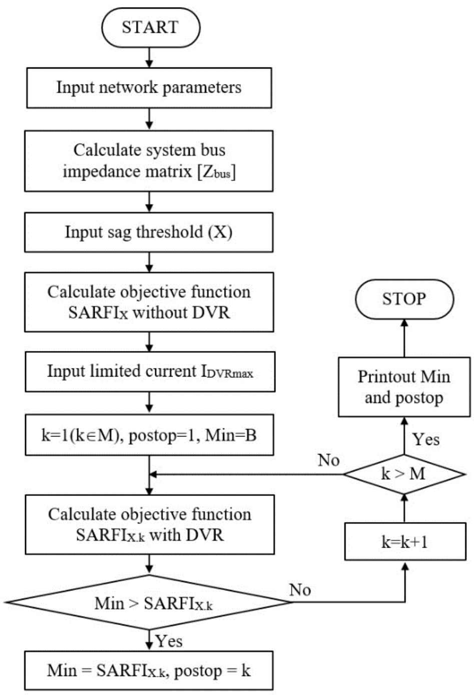


Fig. 4. Block-diagram of solving the problem of optimization

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

For this problem of optimization, the main variable is the scenario of positions (branches) where the DVR are placed. The test system has 33 buses so it features 32 branches for possible DVR connection. Each candidate scenario to be tested is a branch on which the DVR is series connected.

The problem of optimization has no constraint, but there're two important assumptions that are being considered during estimating each candidate scenario: Firstly, a DVR's parameter which is the limited current of DVR is in-advance given. The modeling about how DVR with a limited current can compensate system voltage sag is introduced in Section 2.2.2. Secondly, the DVR's operation is assumed [6, 7, 8] that DVR only works if it is placed on the branch that is not a part of fault current carrying path (from the source to the fault position). In this case, the bypass switch is actually closed to disable DVR's operation.

3.1.2 Problem solving

For such a problem of optimization, with preset parameters (X%, and DVR's limited current), the objective function – $SARFI_X$ is always determined for any candidate scenario of DVR's placement. So, we use the method of direct search and testing all scenarios of DVR positions. The block-diagram of solving this problem in Matlab is given in Fig.5.

In this block-diagram, M = 32 (branches) is the set of candidate scenarios of DVR location. $SARFI_X$ of the system without DVR is first calculated as shown in Fig. 5 without the part surrounded by the dashed line.

For each scenario of DVR's placement (each branch), calculating $SARFI_X$ of the test system with the presence of DVR is performed by adding the part surrounded by dash line where the DVR's location is first checked to see if the DVR-connected branch is on the fault current carrying path for disabling the DVR. After that, the condition of voltage sag mitigation in case of DVR's limited current as introduced in Section 2.2.2 is performed for calculating system bus voltage and the corresponding $SARFI_X$ is calculated.

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 DVR's location 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 parameters of fault events are considered.

3.2 Short-circuit Calculation

The paper only considers voltage sags caused by the fault. Because the method introduced in this paper considers $SARFI_X$, 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 the 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 DVR can be calculated for different scenarios of influential parameters as analyzed in Section 4.

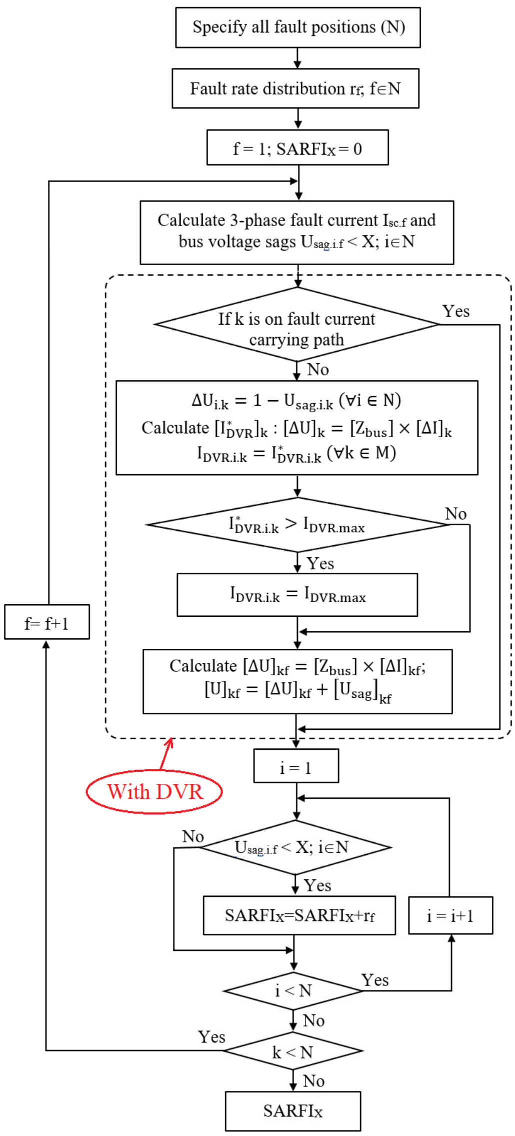


Fig. 5. Block-diagram of the part of SARFIX calculation without or with the presence of DVR

4 SIMULATION RESULTS

4.1 *Test System*

For simplifying the introduction of the method in the paper, the IEEE 33-bus distribution feeder (Fig. 6) is used as the test system because it just features a balanced three-phase distribution system, with three-phase loads and three-phase lines.

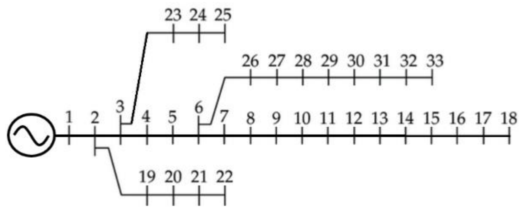


Fig. 6. IEEE 33-bus distribution feeder as the test system

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.

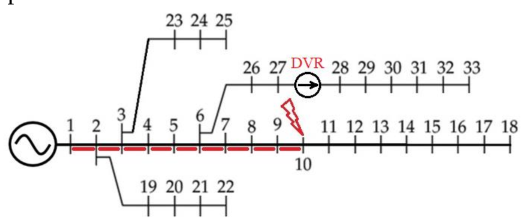


Fig. 7. Checking the locations where DVR is disabled for a give fault position

4.2 *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 [18] and fault rate = 1 time per unit period of time at a fault position (each bus).

- For RMS voltage threshold, the paper considers voltage sags so X is given as 90, 80, 70, 50% of U_n.

- For DVR's limited current, the paper considers I_{DVRmax} = 0.1, 0.2, 0.3 and 0.5p.u.

4.3 *Result analysis and discussion*

In solving the problem of optimization considering above said preset parameters, results are step-by-step introduced for better analysis and discussion. For a case of preset parameters, we initially consider sag X=80%, I_{DVRmax} = 0.2p.u. For calculating $SARFI_X$ of the test system with the presence of DVR at a certain location, we have to collect the sag frequency for all load buses (33 buses) caused by all possible fault positions (33 buses). For each fault position, firstly the algorithm will check to see whether the DVR is on the fault current carrying path or not. For example, if the fault occurs at the bus 10, branches on the path from bus 1 to bus 10 (marked in Fig. 7) are the locations DVR is disabled if it's placed on these branches.

If DVR is not on the fault current carrying path, for example, DVR is on the branch 27 (between bus 27 and bus 28), the bus voltage improvement is shown on Fig. 8 to illustrate the performance of DVR's model as introduced in Section 2.1 and 2.2.

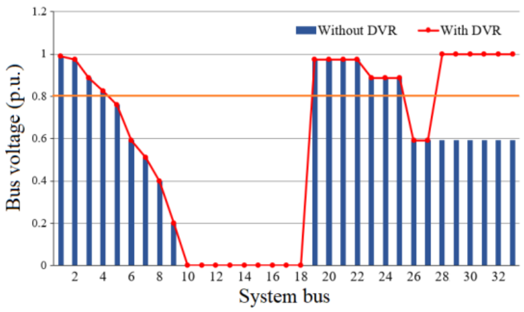


Fig. 8. Bus voltage without and with DVR placed on the branch 27 (27-28) for the short-circuit at bus 10

With the DVR placed on the branch 27, the voltage at bus 28 is boosted to 1pu and the required injected current from DVR is 0.3p.u. The buses from bus 28 to the end of this lateral tap are all compensated to 1p.u. Other bus voltages are unchanged.

For the X=80%, 22 buses experiencing voltage sag are counted. However, with the presence of DVR, only 16 buses having the voltage lower than 80% U_n are counted.

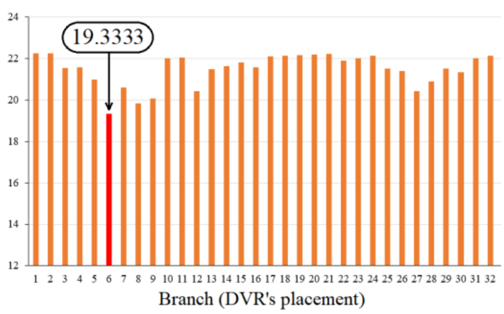


Fig. 9. $SARFI_{80}$ for all scenarios of DVR placement and the case I_{DVRmax} = 0.3p.u.

Similarly, the algorithm (as shown in Fig. 5) calculates the frequency of voltage sag for the magnitude X (resulted by all possible fault positions) at all buses and finally, the $SARFI_X$ is obtained. For all DVR's locations, the corresponding $SARFI_{80}$ is calculated. Values of $SARFI_{80}$ for all scenarios of DVR placement are depicted in Fig. 9 for comparison.

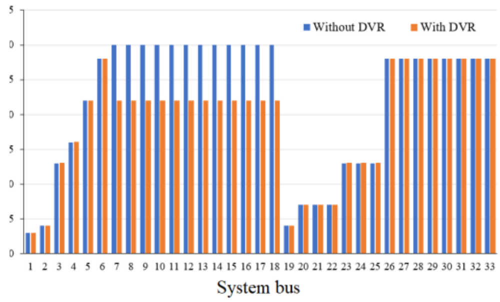


Fig. 10. Sag frequency for X=80% at all buses without and with DVR optimally placed on Branch 6, I_{DVRmax} = 0.3p.u.

The DVR's location resulting in the minimum $SARFI_X$ = 19.33 for the mentioned above case of preset parameters is at branch 6 (between bus 6 and bus 7). Sag frequency at all buses without or with DVR placed at branch 6 are plotted in Fig. 10.

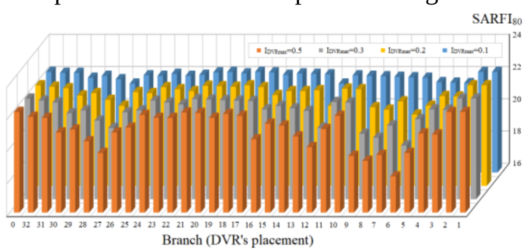


Fig. 11. $SARFI_X$ for X=80% for all scenarios of DVR placement, I_{DVRmax} = 0.1, 0.2, 0.3, 0.5p.u.

For analyzing the influence of DVR's limited current on $SARFI_X$, we consider other cases of I_{DVRmax} = 0.1p.u., 0.2p.u. and 0.5p.u. with X=80% in the same way, the $SARFI_{80}$ corresponding DVR's placement for different values of I_{DVRmax} are integrated in the same chart as shown in Fig. 11. "0" means the $SARFI_{80}$ for the case without DVR. Higher limited current results in better (smaller) SARFI improvement. The corresponding bus voltage improvement for the optimal location of DVR is plotted in Fig. 12. The low sag frequencies are found for buses from 18 to 25 because the points of common coupling for the lateral taps feeding to these buses are close to the source (bus 2 and 3).

For considering the improvement of SARFI for different levels of voltage sag magnitude X, the results of $SARFI_X$ for X=50%, 70%, 80% and 90% with the I_{DVRmax} = 0.3p.u. are shown in the Fig. 13. "0" means the $SARFI_X$ without DVR.

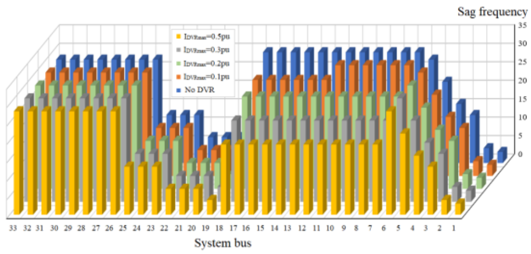


Fig. 12. Sag frequency at system buses for optimal scenario of DVR placement, I_{DVRmax} = 0.1, 0.2, 0.3, 0.5p.u.

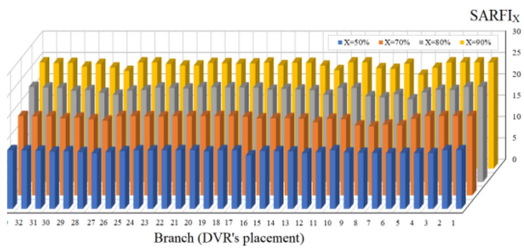


Fig. 13. $SARFI_X$ for all scenarios of DVR placement for different voltage sag magnitude (50%, 70%, 80% and 90%), I_{DVRmax} = 0.3p.u.

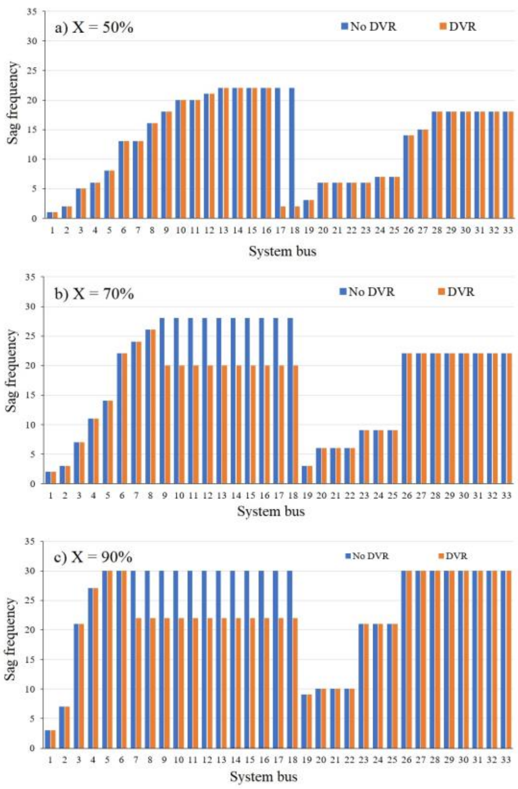


Fig. 14. Sag frequency at all buses for X=50, 70, 90% without or with DVR (at optimal placement), I_{DVRmax} = 0.3p.u

In more detail, the corresponding sag frequency improvement in the cases of optimal location of DVR is depicted in Fig. 14. For low value of X, the voltage sag improvement is small, but the $SARFI_X$ is also small. A higher value of X results in higher $SARFI_X$ but it also has a greater improvement of voltage sag.

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

We can see that the $SARFI_X$ improvement is generally not big for DVR because DVR can only compensate for the voltage of the buses from the DVR's location toward to load side.

5 CONCLUSION

This paper introduces a new method for system voltage sag mitigation by using DVR in the distribution system where the effectiveness of system voltage sag mitigation by DVR for the case of limited maximum current is modeled using Thevenin's superposition theorem in short-circuit calculation of power systems. This method allows us to consider the DVR's effectiveness of system voltage sag mitigation not only for event index but also for site and system indices. As the result, the optimal scenario of DVR placement is found by minimizing the resulting $SARFI_X$ for preset parameters including the voltage threshold X and the maximum injected current.

TABLE 1. RESULTS FOR USING ONE DVR

I_{DVRmax} (p.u.)	No DVR	0.1	0.2	0.3	0.5
		X=50%			
$minSARFI_X$	13.72	13.09	13.06	12.51	10.09
DVR branch	No DVR	5	7	16	8
		X=70%			
$minSARFI_X$	18.57	17.57	16.75	16.15	14.57
DVR branch	No DVR	7	8	8	12
		X=80%			
$minSARFI_X$	22.24	21.51	20.42	19.33	18.24
DVR branch	No DVR	12	6	6	6
		X=90%			
$minSARFI_X$	24.84	24.39	23.03	21.93	20.84
DVR branch	No DVR	22	6	6	6

For the purpose of introducing the method, some assumptions are accompanied like the type of short-circuit and the fault rate distribution. For real applications, the method can easily include the real fault rate distribution as well as all types of short-circuit. DVR's effectiveness of system voltage sag mitigation is relatively limited as DVR can only compensate the voltage of buses from the DVR's location toward load side and it's also disabled if it is coupled on the fault current carrying path.

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Cải thiện chỉ tiêu $SARFI_X$ cho lưới phân phối sử dụng thiết bị điều áp động có xét đến giới hạn dòng điện

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***Tóm tắt*—Bài báo giới thiệu một phương pháp mới tối ưu hóa vị trí đặt của một thiết bị điều áp động DVR nhằm cải thiện hiện tượng sụt giảm điện áp ngắn hạn trong lưới phân phối điện. Vị trí đặt của DVR sẽ được lựa chọn tối ưu dựa trên việc tối thiểu hóa chỉ tiêu tần suất sụt giảm điện áp ngắn hạn trung bình SARFIX của lưới điện đang xét. Bài toán tối ưu hóa được đề xuất trong đó việc mô phỏng DVR sử dụng mô hình mạch Norton tương đương để sử dụng trong tính toán ngắn mạch và xác định sụt giảm điện áp ngắn hạn theo nguyên lý xếp chồng Thevenin để từ đó xác định hàm mục tiêu là chỉ tiêu $SARFI_X$ của lưới điện khi có lắp đặt DVR trong lưới. Hiệu quả cải thiện sụt giảm điện áp ngắn hạn của DVR được xem xét trong trường hợp cho trước dòng điện lớn nhất mà DVR có thể bơm vào lưới. Bài báo sử dụng lưới phân phối mẫu 33 nút của IEEE để mô phỏng tính toán sụt giảm điện áp ngắn hạn và xem xét các tham số ảnh hưởng đến các kết quả của bài toán tối ưu.**

***Từ khóa*—Lưới phân phối điện, sụt giảm điện áp ngắn hạn, $SARFI_X$, thiết bị điều áp động-DVR**