# A Novel Comparison on "Central Improvement" of Voltage Dips in 16 Bus Distribution System by D-STATCOM and DVR

Minh V. Nguyen and Khanh Q. Bach*

**Abstract—** *The paper introduces a new comparison on DVR's and D-Statcom's performance for voltage dip mitigation in distribution systems. From the viewpoint of "central improvement", DVR and D-Statcom are optimally located and sized by the Genetic Algorithm for systematically mitigating voltage dips of a distribution system of interest. The comparative assessment is made on the system bus voltage deviation which is the objective function of the above said problem of optimization for DVR's and D-Statcom's application. In this problem of optimization, the effectiveness of systematic voltage compensation by DVR and D-Statcom is modeled in the problem of short-circuit calculation by using Thevenin's superimposition and suitable models of DVR and D-Statcom. The paper uses a 16-buses test distribution system for voltage dip simulation and influential parameters in the problem of optimization are discussed for better comparisons.*

***Keywords*— Distribution System, Voltage Dip, Dynamic Voltage Restorer, Distribution Synchronous Compensation, Genetic Algorithm.**

## 1. INTRODUCTION

According to IEEE1159 [2], voltage dip/sag 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. The main cause of voltage dip is the short-circuit in the power systems. For distribution system, there are various solutions for voltage dip mitigation [3, 4], and they are basically divided into two groups [1]. The first group is namely "distributed improvement" where its solutions are applied for protecting a single sensitive load. This is the earliest solutions for voltage dip mitigation. The other group is named "central improvement" where its solutions 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 like the dynamic voltage restorer (DVR) and distribution static synchronous compensator (D-Statcom), have recently attracted more and more interest from utilities as the cost of solutions has gradually declined.

When custom power devices are used for totally improving PQ in distribution system, the problem of optimally selecting their location and size is always concerned and [1] summarizes various researches for modeling and solving the problem by using DVR or D-Statcom [5]-[11]. There have been researches on comparing between DVR or D-Statcom [12-14], but they focused only on their PQ mitigation performance at a single position in a system and only device's dynamic simulations were tested for local improvement. [15] considers DVR and D-Statcom support to photovoltaic system in a renewable energy sources system including PV and win turbine, but again, only device's dynamic simulations were tested. There's no comparison between corresponding mitigation solutions for voltage dip "central improvement", and this paper tries to compare the effectiveness between DVR and D-Statcom application for total voltage dip mitigation. To do so, the paper proposes methods for optimally sizing and placement of DVR and D-Statcom and compares them on the improved system voltage dip index. Furthermore, nowadays, the problem of optimally sizing and locating DVR or D-Statcom for total voltage dip mitigation still needs much further improvement on solving method, objective function definition, modeling of DVR and D-Statcom for short-circuit calculation and power-flow analysis of power systems… In comparing DVR and D-Statcom for voltage dip mitigation, the paper proposes the new application of DVR and D-Statcom modeling in the short-circuit calculation in distribution system. The research uses a 16-bus distribution feeder as the test system. The problem of optimization is solved by the Genetic Algorithm (GA). Short-circuit calculation for the test system as well as the modeling and solution of the problem of optimization using GA are all programmed in MatLab.

The paper includes the following parts: Part 2 presents the DVR and D-Statcom models for short-circuit calculation in distribution system. Part 3 introduces the modeling of the problem of optimization where objective function is defined and the DVR and D-Statcom models are individually included in the system modeling for short-circuit calculation and voltage dip quantification. Finally, the results for different scenarios are analysed and concluded in Part 4 and 5.

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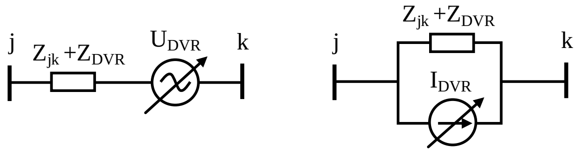
## 2. MODELLINGS OF DVR AND D-STATCOM FOR SHORT-CIRCUIT CALCULATION

### *2.1 Modelling of DVR*

DVR is also 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 [4] in series with the impedance of the branch where the DVR is connected as Figure 1.a [12]. In modeling the power system for short-circuit calculation, the method of bus impedance matrix is often used [18] and such DVR's model of series connected voltage source is difficult to applied. 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.




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.**

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 Figure 2 [19]. Note that the node k is the position of which the voltage is compensated by DVR. In the radial distribution system, node j is the node nearer to the source and node k is the node farer to the source (i.e. toward the load side).

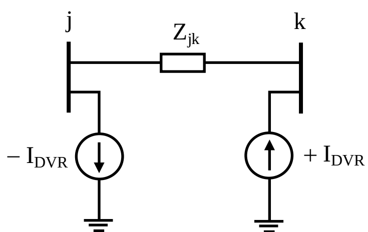



**Fig.2. Steady-state current injection model of the DVR.**

### *2.2 Modelling of D-Statcom*

D-Statcom is a FACTS device that is 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 [4] that injects the required current in the bus that is needed for voltage compensation. For voltage dip mitigation, the load voltage during the dip 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 (Fig. 3) [4].

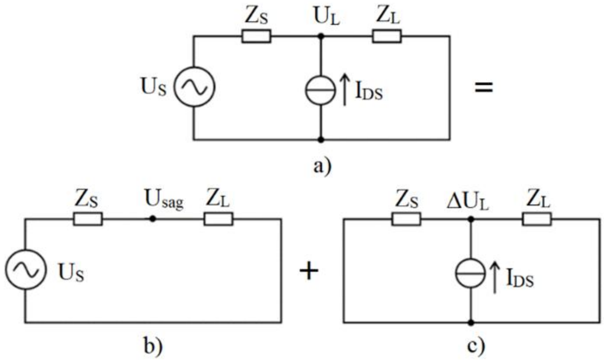



**Fig.3. Modeling D-Statcom for voltage dip mitigation.**

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 dip, the load voltage ($U_{dip}$) can be compensated $\Delta U_L$ 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.).

$$U_L = U_{dip} + \Delta U_L \tag{1}$$

From Fig. 1c, we have:

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

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

## 3. CALCULATING SYSTEM VOLTAGE DIP DUE TO FAULTS IN DISTRIBUTION SYSTEM WITH THE PRESENCE OF DVR OR D-STATCOM

### *3.1 16-Bus Test System*

This paper uses a 16-bus distribution feeder (Fig. 4) as the test system for the research. It is modeled basing on the IEEE 13-bus distribution test system, while it also takes account of the typical features of the Vietnamese power distribution network where loads and branches that are of three-phases balanced.

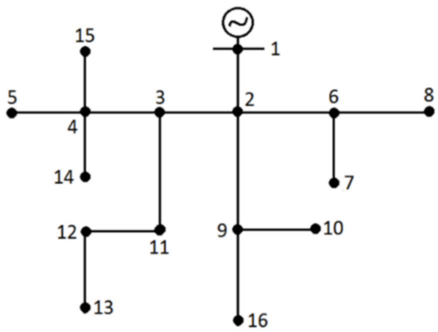



**Fig.4. 16-bus distribution feeder as the test system.**

In this research, base power is assumed 1p.u. = 100kVA. The system voltage is 1.05pu. Short-circuit power of the system is assumed to be 150MVA. The parameters are given in [20].

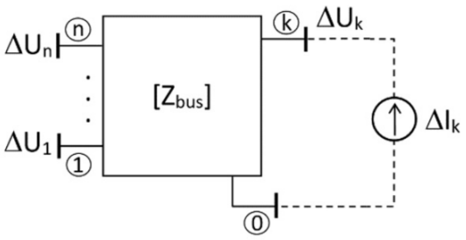
### 3.2 Short-circuit calculation

System voltage dips can be modeled by short-circuit calculation for the test system. The paper considers a three-phase short-circuit with the fault impedance $Z_f = R_f + jX_f$ (Ω). Short-circuit calculation is performed in Matlab using the method of bus impedance matrix. The resulting bus voltage dips can be calculated for different scenarios as analyzed in Part 4.

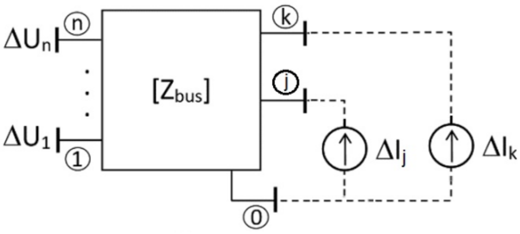
### 3.3 A new modeling for total voltage dip mitigation using DVR and D-Statcom

#### 3.3.1 Generality

The paper considers the placement of one DVR or one D-Statcom in the test distribution system for total voltage dip mitigation. To model the effectiveness of DVR and D-Statcom for voltage dip mitigation, the paper introduces the application of the superposition principle according to the Thevenin theorem for modeling the voltage dip mitigation with the presence of D-Statcom (Figure 5.a) or DVR (Figure 5.b) [18].




a) Test system modeling using $[Z_{bus}]$ with the presence of one D-Statcom




b) Test system modeling using $[Z_{bus}]$ with the presence of one DVR

**Fig.5. Modeling the DVR's and D-Statcom's effectiveness for voltage sag mitigation.**

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

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

where

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

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

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

$[Z_{bus}]$: 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 [18]:

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

where

$$[\Delta U] = [Z_{bus}] \times [\Delta I] \ (7) \text{ or } \begin{bmatrix} \Delta U_1 \\ \vdots \\ \Delta U_k \\ \vdots \\ \Delta U_n \end{bmatrix} = [Z_{bus}] \times \begin{bmatrix} \Delta I_1 \\ \vdots \\ \Delta I_k \\ \vdots \\ \Delta I_n \end{bmatrix} \ (8)$$

where

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

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

#### 3.3.2 Placing a DVR in the system

Assuming a DVR is placed on the branch j-k. Basing on the DVR modeling in Part 2.b as well as Fig. 5b, in the matrix of additional injected bus current, there're only two elements that do not equal zero. 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 above assumed values of $\Delta I_i$ into (8), we have

$$\Delta\dot{U}_k = Z_{kk} \times \Delta\dot{I}_k + Z_{kj} \times \Delta\dot{I}_j = (Z_{kk} - Z_{kj}) \times \dot{I}_{DVR} \quad (9)$$

According to the DVR modeling in Fig. 2, the voltage of bus k is compensated up to the desired value. It means the bus k voltage increases from $U_k^0 = U_{dip.k}$ up to $U_k = 1$. So, $\Delta\dot{U}_k = 1 - \dot{U}_{dip.k}$ (10)

Replace (10) into (9), we get $I_{DVR}$

$$\dot{I}_{DVR} = \Delta\dot{I}_k = \frac{\Delta\dot{U}_k}{Z_{kk} - Z_{kj}} = \frac{1 - \dot{U}_{dip.k}}{Z_{kk} - Z_{kj}} \quad (11)$$

and the power rating of DVR

$$\dot{S}_{DVR.k} = \Delta\dot{U}_k \times \hat{I}_{DVR} \quad (12)$$

Ultimately, we calculate the upgraded voltage for other bus i (i=1-n; i≠k) in the test system.

$$\Delta\dot{U}_i = Z_{ik} \times \Delta\dot{I}_k + Z_{ij} \times \Delta\dot{I}_j = (Z_{ik} - Z_{ij}) \times \dot{I}_{DVR}$$
$$= \frac{Z_{ik} - Z_{ij}}{Z_{kk} - Z_{kj}} \times (1 - \dot{U}_{dip.k}) \quad (13)$$

and system bus voltages with the presence of DVR:

$$\dot{U}_i = \Delta\dot{U}_i + \dot{U}_{dip.i} = \frac{Z_{ik}-Z_{ij}}{Z_{kk}-Z_{kj}} \times \left(1 - \dot{U}_{dip.k}\right) + \dot{U}_{dip.i} \quad (14)$$

### 3.3.3 Placing a D-Statcom in the system

Assuming a D-Statcom is placed at bus k, according to D-Statcom modeling in Part 2.2 as well as Fig. 5a, that means the matrix of additional injected bus current only have one element at bus k that does not equal zero ($\Delta I_k \neq 0$). Other elements equal zero ($\Delta I_i = 0$ for i=1,n; i≠k). Thank to the injected current to bus k, the bus k voltage can be compensated from $U_k = U_k^0 = U_{dip.k}$ up to desired value, say $U_k = 1$pu. Replace these values into (8), we have the D-Statcom's injected current as follows

$$\dot{I}_{DS} = \Delta\dot{I}_k = \frac{\Delta\dot{U}_k}{Z_{kk}} = \frac{1}{Z_{kk}} \times \left(1 - \dot{U}_{dip.k}\right) \quad (15)$$

D-Statcom's required power rating if D-Statcom is placed at bus k: $\dot{S}_{DS.k} = \Delta\dot{U}_k \times \hat{I}_{DS}$ (16)

Other bus voltages ($\dot{U}_i$, i=1,n; i≠k) after placing the D-Statcom at bus k:

$$\dot{U}_i = \Delta\dot{U}_i + \dot{U}_i^0 = Z_{ik} \times \dot{I}_{DS} + \dot{U}_{dip.i} \quad (17)$$

With the calculation of system bus voltage in the short-circuit event with the presence of DVR and D-Statcom, we can define the problem of optimization for locating and sizing DVR and D-Statcom for total voltage dip mitigation in Part 4.

## 4. OPTIMIZATION PROBLEM FOR DVR'S AND D-STATCOM'S APPLICATION

### *4.1 The problem of optimization*

In this research, the comparison on DVR's and D-Statcom's effectiveness for total voltage dip mitigation is based on the problem of applying these devices for voltage dip mitigation in a same test system with the same voltage dip performance. The application of DVR and D-Statcom for this purpose is made by locating and sizing these devices under a problem of optimization where the objective function is to minimize the total system voltage deviation. This quantity can be seen as the index of system voltage dip energy [21].

$$\Delta U = \sqrt{\sum_{i=1}^{n}(U_{ref} - U_i)^2} \Rightarrow \text{Min} \quad (18)$$

where

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

$U_i$: Bus i voltage calculated in (14) for D-Statcom's application or (17) for DVR's application.

The variables of the problem are the DVR's or D-Statcom's location. DVR's and D-Statcom's power ratings (size) are calculated respectively depending on their locations and short-circuit position as per (10) for D-Statcom and (15) for DVR. The solution of the problem is the optimal location for DVR or D-Statcom installation that minimizes the objective function (18).

For this problem of optimization, we just consider the constraints for device's size and locations. For DVR, actually, it can be activated (the bypass disconnector in parallel with DVR is opened) when voltage at the compensation location drops lower than a required value. However, because of its in-series connection, to avoid DVR overloading, DVR's location is not selected at nodes on the fault current carrying path from the source to the fault position in the radial network. For D-Statcom, because of its shunt connection, it never carries fault current and there's no need to limit its possible placement. However, its size is still limited to a certain maximum value. In this research D-Statcom's size is not greater than 3p.u.

The problem of optimization is solved by GA used in MatLab as follows.

### *4.2 Application of Genetic Algorithm*

The genetic algorithm (GA) searches for an optimal solution using the principles of evolution based on a certain string which is judged and propagated to form the next generation. The major advantage of the GA is that the solution is globally optimal. Moreover, a GA is capable of obtaining the global solution to a wide variety of functions, such as differentiable or non-differentiable, linear or nonlinear, continuous or discrete, and analytical or procedural functions [16, 17]. The problem of optimally locating and sizing DVR or D-Statcom for voltage dip mitigation is also a suitable case for GA application. Main steps of GA for solving this problem are plotted in Fig.6.

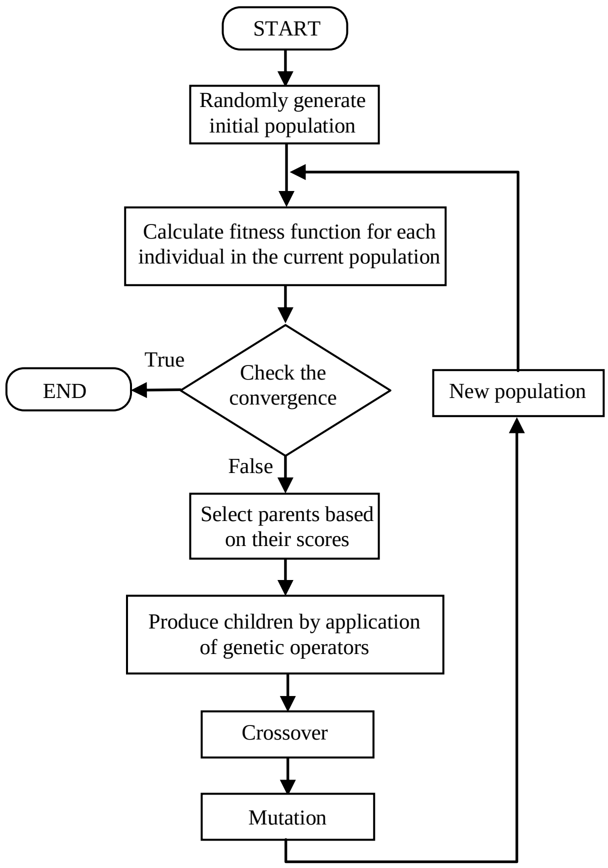



**Fig. 6. Flowchart of Genetic Algorithm.**

If the D-Statcom's location (similarly for DVR) selected from the set of 16 nodes of the test system is seen as a chromosome, then each chromosome will be defined as a string of 16-bit binary format, for example "0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0", where "0" means no D-Statcom nor DVR placement and "1" is with D-Statcom or DVR placement. So, the GA will start the search process to find the best chromosome in the total of chromosomes. GA procedure of calculation is performed by the function GA.m of Matlab. The parameters set in advance include the initial population, probability of crossover: 0.95, probability of mutation: 0.05. Call the function GA in MatLab to run the flowchart in Fig.6.

## 5. COMPARATIVE ESTIMATION OF RESULTS

### *5.1 Research Scienarios*

The comparative estimation of the effectiveness of DVR and D-Statcom will be better when various scenarios are considered. The research considers the following assumptions:

Location assumption: For DVR, the research only considers DVR placement at nodes out of the short-circuit current flowing path of the test system (in reality, a bypass switch will be used for deactivating DVR if its location is on this path). For D-Statcom, all nodes can be applicable.

Short-circuit type and fault impedance: Three-phase short-circuit through different values of fault impedances $Z_f$ will result in different magnitudes of bus voltage dip for the test system and different values of the objective function. The paper considers two alternatives of fault impedances for analysing its influences in the problem solutions. $Z_f = 0.25 + j0.16$(pu) and $Z_f = 0.1 + j0.08$ (pu).

Short-circuit positions: Fault position also have significant influence on the device's size and objective function. The paper considers three fault positions (8, 10 and 13) for estimating this influence.

### *5.2 Result analysis*

Solving the problem of optimization for assumed cases of short-circuit position, with regard to two assumed fault impedances, the corresponding optimal locations and sizes of DVR and D-Statcom are determined respectively. Besides, the resulting objective functions by DVR's and D-Statcom's applications accordingly are calculated. The main results are mentioned in the Table 1.

Improved system voltage dip performances, when DVR or D-Statcom is individually applied, are plotted in Figure 7 for different short-circuit positions accordingly. The system bus voltages are marked in blue sticks (without CPD), red line (with DVR) and brown line (with D-Statcom) for two cases of fault impedance.

The deepest voltage dip is of course at fault position. Lower fault impedance results in deeper voltage dip and higher device's size. For DVR's effectiveness of voltage compensation, voltage is compensated to 1pu at the node of DVR's placement. DVR can only improve the voltages of the nodes toward load side from DVR's location (e.g. for short-circuit at node 5, DVR is placed on the branch 2-6, so node 6, 7 and 8 get voltage compensated). For D-Statcom's performance, the voltage is compensated to 1pu at D-Statcom's placement. However, D-Statcom can improve all nodal voltages in the system of interest. The number of nodes of which the voltage is compensated greater than 0.9pu is higher by D-Statcom. The objective function (system voltage deviation) is low for D-Statcom while high for DVR. That means, D-Statcom can improve system voltage dip better then DVR. However, D-Statcom's size is greater than DVR's.

**Table 1. Comparative results of DVR and D-Statcom for the 3 cases of short-circuit position**

| Fault impedance | $Z_f = 0.25 + j0.16$ (pu) | | $Z_f = 0.1 + j0.08$ (pu) | | Short-circuit position |
|---|---|---|---|---|---|
| CPD type | DVR | D-Statcom | DVR | D-Statcom | |
| Objective function (pu) | 1.3517 | 1.1945 | 1.6261 | 1.4521 | Node 5 |
| Optimal placement | Branch 2-6 | Node 10 | Branch 2-6 | Node 10 | |
| Size (pu) | 0.0708 | 0.6488 | 0.0994 | 0.7547 | |
| No. of node U > 0.9pu | 4 | 7 | 4 | 8 | |
| Objective function (pu) | 0.8668 | 0.6918 | 1.1824 | 0.9350 | Node 7 |
| Optimal placement | Branch 3-4 | Node 10 | Branch 3-4 | Node 10 | |
| Size (pu) | 0.2262 | 0.7776 | 0.3145 | 0.9818 | |
| No. of node U > 0.9pu | 5 | 8 | 3 | 7 | |
| Objective function (pu) | 0.8726 | 0.7119 | 1.1357 | 0.9480 | Node 16 |
| Optimal placement | Branch 2-9 | Node 7 | Branch 3-4 | Node 7 | |
| Size (pu) | 0.3440 | 1.0788 | 0.4585 | 1.3216 | |
| No. of node U > 0.9pu | 4 | 7 | 4 | 5 | |

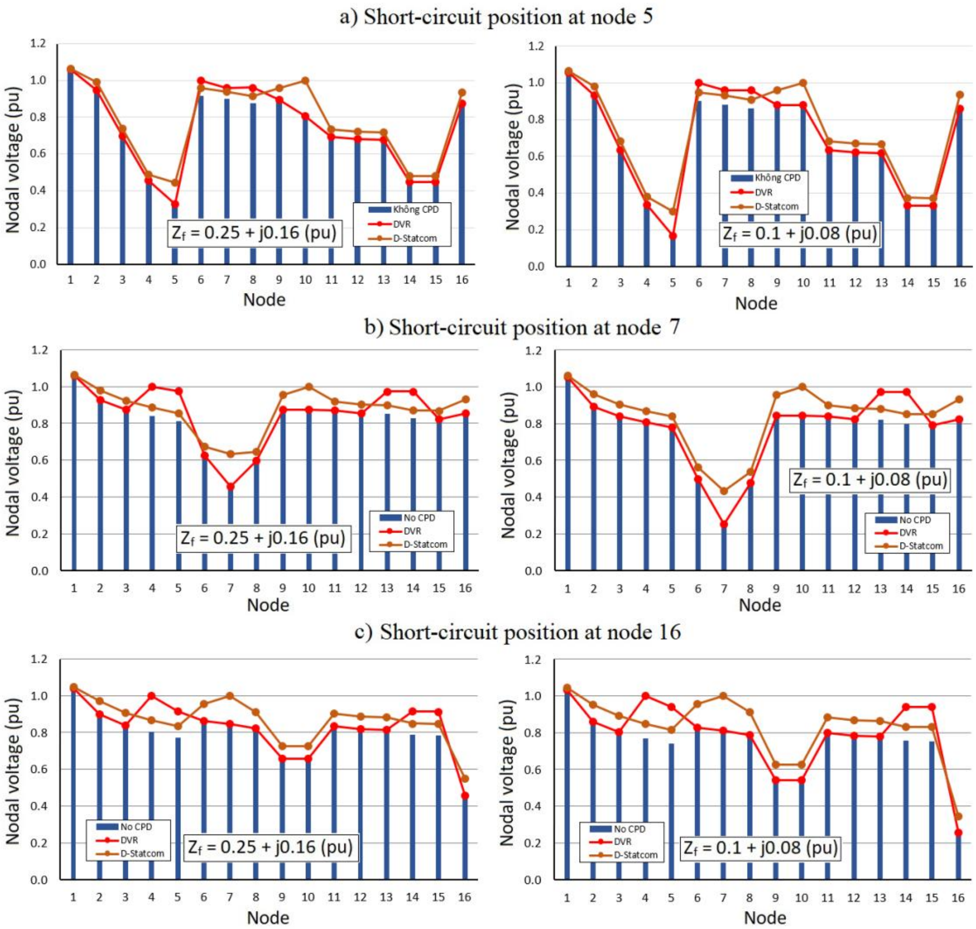



**Fig.7. System voltage improvement by DVR and D-Statcom placement.**

## 6. CONCLUSION

This paper performs a new comparative estimation for DVR's and D-Statcom's effectiveness on "central improvement" approached voltage dip mitigation in the distribution system. The comparison is based on the index of system bus voltage deviation which is the objective function of the problem of optimization for applying DVR and D-Statcom in a test distribution system of 16 bus for total voltage dip improvement. In solving the problem of optimizing the size and location of DVR and D-Statcom, the paper also introduces the application of Thevenin's superposition theorem modeling the DVR's and D-Statcom's function for system voltage dip mitigation following the "central improvement" approach. From the comparative results, we can conclude that D-Statcom's effectiveness on "central improvement" voltage dip mitigation is better than DVR's, but D-Statcom requires a larger power rating than DVR.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## APPENDIX

**Table A1. 16-bus distribution test system parameters**

| Node | Branch | | R (pu) | X (pu) | P (kW) | Q (kVar) |
|---|---|---|---|---|---|---|
| | From | To | | | | |
| 1 | - | - | - | - | - | - |
| 2 | 1 | 2 | 0.0192 | 0,0575 | 21.7 | 12.7 |
| 3 | 2 | 3 | 0.0452 | 0.1652 | 2.4 | 1.2 |
| 4 | 2 | 6 | 0.0570 | 0.1737 | 7.6 | 1.6 |
| 5 | 2 | 9 | 0.0132 | 0.1379 | 24.2 | 19.0 |
| 6 | 3 | 4 | 0.0472 | 0.1983 | 12.0 | 5.0 |
| 7 | 3 | 11 | 0.0581 | 0.1763 | 22.8 | 10.9 |
| 8 | 4 | 5 | 0.0119 | 0.1414 | 30.0 | 30.0 |
| 9 | 4 | 14 | 0.0460 | 0.1160 | 54.0 | 22.0 |
| 10 | 4 | 15 | 0.0267 | 0.0820 | 5.8 | 2.0 |
| 11 | 6 | 7 | 0.0120 | 0.1420 | 7.0 | 12 |
| 12 | 6 | 8 | 0.0123 | 0.1280 | 11.2 | 7.5 |
| 13 | 9 | 10 | 0.0334 | 0.1560 | 4.0 | 3.0 |
| 14 | 9 | 16 | 0.0232 | 0.1560 | 16.2 | 7.6 |
| 15 | 11 | 12 | 0.0312 | 0.1208 | 28.2 | 12.5 |
| 16 | 12 | 13 | 0.0124 | 0.1110 | 13.5 | 11.8 |