Using Norton's Equivalent Circuit of DVR in Optimal Location of DVR for Voltage Sag Mitigation in Distribution Systems

Khanh Q. Bach* and Minh V. Nguyen

***Abstract*— The paper presents a novel application of Norton's equivalent circuit of dynamic voltage restorer (DVR) for mitigating voltage sags due to faults in distribution systems. DVR installation is assumed to be made by the utility for improving the power quality for not only a single load, but also for various neighboring load buses in the system of interest. Locating and sizing DVR is based on a problem of optimization with regard to minimizing the lost energy due to voltage sag for all load nodes in the system of interest. The optimization problem is solved by Genetic Algorithm for the case study of 16 bus test distribution system. The paper also discusses cases of study for different short-circuit fault impedances (voltage sag levels) and fault positions to analyze the influences on the DVR's placement and size.*

***Keywords*— About four key words or phrases in alphabetical order, separated by commas.**

1. INTRODUCTION

According to IEEE1159, voltage dip/sag [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. The main cause of voltage sag is the short-circuit in the power grid. Voltage sag is one of the most concerned and difficult-to-handle issues in Vietnam in recent years, especially in the industrial distribution systems where a lot of power electronics devices are used. There are many solutions for voltage sag mitigation, but they are mainly introduced for protecting a single sensitive load. The solutions for systematically enhancing PQ in the distribution system, especially the use of D-FACTS devices [2] have recently attracted more and more interest by utilities as the cost of solutions has gradually declined while the electricity market has widely expanded down to power distribution systems.

When using D-FACTS devices for improving PQ in distribution system by utility's viewpoint, the problem of optimally selecting the location and size of D-FACTS devices is always concerned and [3] summarizes various researches for modeling and solving the problem. The problem of optimization can take account of one or more PQ issues and the common approach for modeling this problem is often a multi-objective optimization [4, 5, 6, 7]. However, there're a number of difficulties needed to be solved in modeling the problem of optimization and this paper addresses two following issues. The first issue deals with the cost for PQ events. We know that this data is always hard to quantify and thus, we have to model the problem in the manner that avoids to use assumed costs of PQ. The second issue relates with the modelling of the PQ solution that depends on the characteristics of individual PQ phenomena. For the problem of voltage sag mitigation is distribution system, this difficulty is the modelling of the D-FACTS device for power system short-circuit calculation.

This paper also builds the model of the problem of optimizing the location and size of DVR for voltage sag mitigation in distribution system. For overcoming the two above mentioned difficulties, the paper introduces the DVR model for short-circuit calculation in the distribution system with the presence of DVR. Regarding the modelling of the problem of optimization, the paper introduces the objective function that minimizes the total system voltage deviation during the voltage sag event. Thus, no cost for PQ is included in the model. The research uses a 16-bus distribution feeder as the test system that takes account of typical three-phase medium voltage distribution system in Vietnam.

For solving the problem of optimization, the research uses the Genetic Algorithm (GA) that has been proven to be an effective search tool [8, 9, 10] for this type of the problem of optimization. Short-circuit calculation for the test system and the modeling and solution of the problem of optimization using GA are all programmed in MatLab. This research is also seen as the initial efforts in Vietnam for applying DVR in PQ enhancement in distribution system.

The paper includes the following parts: Part 2 presents the DVR modelling for short-circuit calculation in distribution system as well as the test system data. Part 3 introduces the model of the problem of optimization where objective function and constraints are defined and the DVR model is included in the system modeling for short-circuit calculation and voltage sag quantification. Problem solving using GA is also presented. Finally, the results for different scenarios are analysed and concluded in Part 4.

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2. RELATED ISSUES FOR PROBLEM DEFINITION

2.1 Dynamic Voltage Restorer Modeling

DVR is a D-FACTS device. This device 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. As a result, the DVR can mitigate different PQ issues such as voltage sag, voltage unbalancing, harmonics and reactive power compensation on the power grid [2, 11].

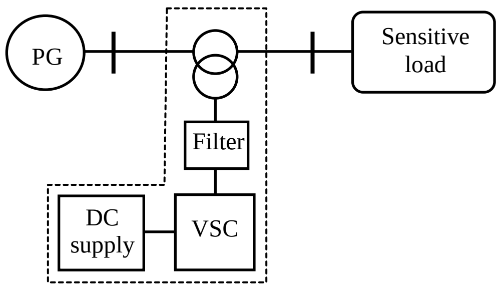
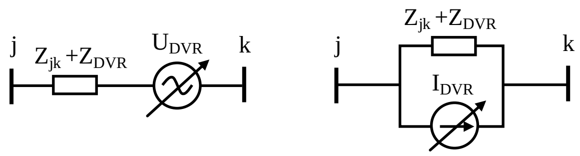


Fig. 1. A typical application of DVR for load protection.

The description of the DVR in the steady-state calculation is popularly given as a voltage source in series with the impedance of the branch where the DVR is connected as Figure 2.a [12]. In modeling the power system for short-circuit calculation, the method of bus impedance matrix is often used 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 2.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.2. Norton's equivalent current source model.

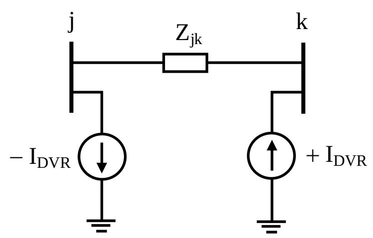


Fig.3. Steady-state current injection model of the DVR.

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 3 [13]. Note that the node k is the position of which the voltage is compensated by DVR.

2.2 16-Bus Distribution Test Feeder

This paper uses a 16-bus distribution feeder (Figure 4) as the test system for modeling the problem of voltage sag due to short-circuit in distribution system and analyse the scenarios for DVR placement for system voltage sag mitigation.

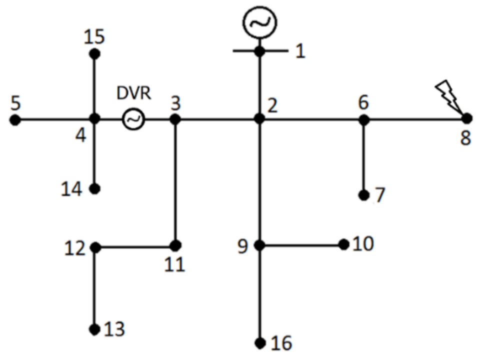


Fig.4. 16-bus distribution feeder as the test system

The 16-bus distribution feeder is modeled basing on the IEEE 13-bus distribution test system, but it also takes into account the typical features of the Vietnamese power distribution network where loads and branches that are of three-phases balanced. Voltage quality is assumed to follow the regulation of 39/2015/TT-BCT by the Minitry of Industry and Trade of Vietnam. The system voltage is 1.05pu. Short-circuit power of the system is assumed to be 150kVA. The parameters are given in [9].

3. PROBLEM DEFINITION

3.1 Test System Analysis in different operating conditions

3.1.1 Steady-state calculation

The steady-state calculation for the test system is made in Matlab and the resulted system bus voltages shown in Figure 3 are all greater than 0.95pu that are in compliance with the voltage tolerance defined by the regulation of 39/2015/TT-BCT in Vietnam.

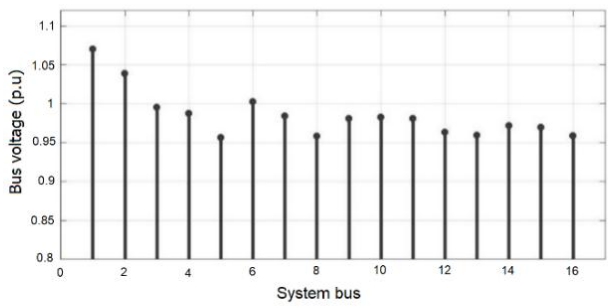


Fig. 5. System bus voltages in steady-state operation.

3.1.2 Short-circuit calculation

System voltage sags 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 sags can be calculated for different scenarios as analysed in Part 4.

For system voltage sag mitigation in distribution system, the paper considers the placement of one DVR as the service area of a distribution system is relatively small. The location and size of the DVR is the target of the calculation. The new idea proposed in this paper is that the paper introduces the application of superposition principle according to the Thevenin theorem for modeling the voltage sag mitigation with the presence of DVR as shown in Figure 6 [14]. Introduced DVR model as Figure 3 is added to the test system.

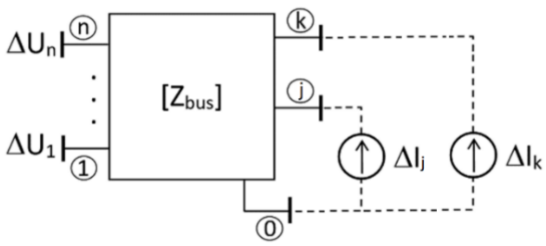


Fig.6. Test system modeling using [Z_{bus}] with the presence of DVR.

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

$$[U^0] = [Z_{bus}] \times [I^0] \tag{1}$$

where

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

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

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

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

$[Z_{bus}]$: System bus impedance matrix. $[Z_{bus}]$ is 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}].

Suppose that a DVR is inserted in a certain branch j-k, according to the proposed DVR model (Figure 3), its behavior during short-circuit state can be modeled as the injection of the current in the bus k $\Delta I_k = I_{DVR}$ and the outgoing current $\Delta I_j = -I_{DVR}$ from the bus j. Thus, according to the Thevenin thorem, the bus voltage equation should be as follows [14]:

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

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

or

$$\begin{bmatrix} \Delta U_1 \\ \cdots \\ \Delta U_k \\ \cdots \\ \Delta U_n \end{bmatrix} = [Z_{bus}] \times \begin{bmatrix} \Delta I_1 \\ \cdots \\ \Delta I_k \\ \cdots \\ \Delta I_n \end{bmatrix} \tag{6}$$

where

ΔU_i: Bus i voltage improvement (i=1,n) after adding the DVR in the branch j-k.

ΔI_i: Additional injected current to the bus i (i=1,n) after add the DVR to the system. Obviously, $\Delta I_i = 0$ for bus i (i=1,n, i≠j and i≠k).

$\Delta I_k = +I_{DVR}$ and $\Delta I_j = -I_{DVR}$

Replace the values of ΔI_i in (6), we have

$$\begin{aligned}\Delta U_k &= \Delta I_k \times Z_{kk} + \Delta I_j \times Z_{kj} \\ &= I_{DVR} \times (Z_{kk} - Z_{kj})\end{aligned} \tag{7}$$

According to the DVR model, the voltage of bus k is compensated up to the desired value. It means the bus k voltage increases from $U_k^0 = U_{sag.k}$ up to $U_k = 1$.

$$\text{So, } \Delta U_k = 1 - U_{sag.k} \tag{8}$$

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

$$I_{DVR} = \Delta I_k = \frac{\Delta U_k}{Z_{kk} - Z_{kj}} = \frac{1 - U_{sag.k}}{Z_{kk} - Z_{kj}} \tag{9}$$

and the power of DVR

$$S_{DVR.k} = \sqrt{3} \times I_{DVR} \times \Delta U_k \tag{10}$$

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

$$\begin{aligned}\Delta U_i &= \Delta I_k \times Z_{ik} + \Delta I_j \times Z_{ij} = I_{DVR} \times (Z_{ik} - Z_{ij}) \\ &= (1 - U_{sag.k}) \times \frac{Z_{ik} - Z_{ij}}{Z_{kk} - Z_{kj}}\end{aligned} \tag{11}$$

and system bus voltages with the presence of DVR:

$U_i = \Delta U_i + U_{sag.i}$

$$= \left(1 - U_{sag.k}\right) \times \frac{Z_{ik}-Z_{ij}}{Z_{kk}-Z_{kj}} + U_{sag.i} \qquad (12)$$

From the resulting values U_i, we can calculate the objective function which is the total system voltage deviation after placing DVR (13).

All calculation relating with $[Z_{bus}]$, DVR's power S_{DVR} and (13) are programmed in Matlab.

3.2 Modeling the problem of optimization

In this research, DVR's location and size is optimally selected in 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 sag energy [16].

$$\Delta U = \sqrt{\sum_{i=1}^{n}(U_{ref} - U_i)^2} \Rightarrow \text{Min} \qquad (13)$$

where

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

U_i: Bus i voltage after placing DVR in the test system, that is calculated in (12).

In this research, base power of DVR is assumed that 1p.u. = 100kVA.

The variables of the problem are the DVR's location. DVR's power (size) is calculated depending on DVR location and short-circuit position as per (8). The solution of the problem is the optimal location for DVR installation that minimizes the objective function (13).

There're actually several methods for solving the problem of optimization. In this paper, the research uses GA. All calculations in the flowchart in Figure 7 is programmed in MatLab.

3.3 Application of Genetic Algorithm [12, 14]

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 algorithm is designed such that the "fitter" strings survive and propagate into later generations. 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 [7, 8]. The problem of optimally locating and sizing DVR for voltage sag mitigation is also a suitable case for GA application. Main steps of GA for solving this problem is plotted in Figure 7.

If the DVR location 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 DVR placement and "1" is with DVR placement. So the GA [8] 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 Figure 7.

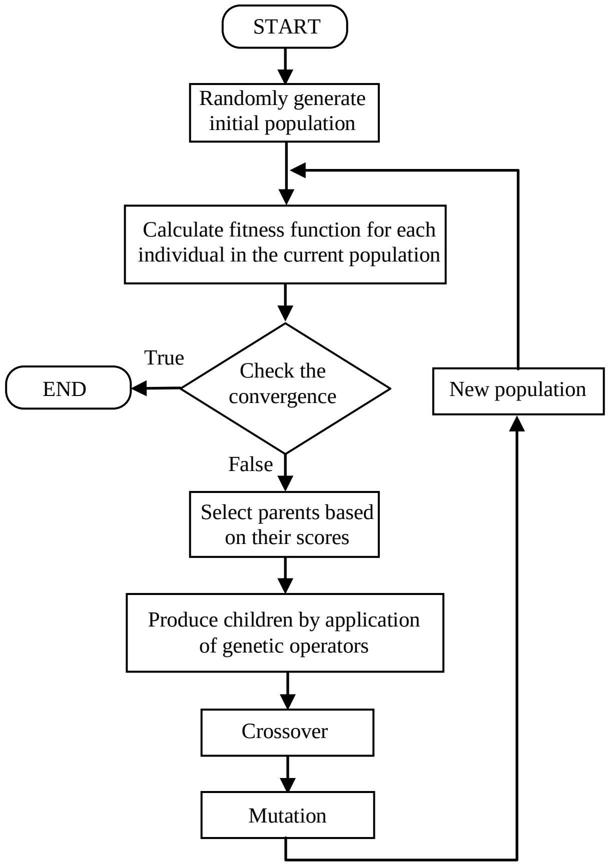


Fig. 7. Flowchart of Genetic Algorithm.

4 RESULT ANALYSIS

4.1 Research Scienarios and Results

The research considers the following assumptions:

- The assumption of DVR placement: Only considers DVR placement at nodes out of the short-circuit current flowing path of the test system.

- Three-phase short-circuit through different values of fault impedances Z_f will result in different magnitudes of bus voltage sag for the test system and different values of the objective function. In this research, the Z_f is in-advance selected so that the voltage sags throughout system buses are almost above 0.5p.u. The paper considers two alternatives of fault impedances for analysing its influences in the problem solution.

4.2 Case-study 1

This case-study assumes Z_f = 0.25 + j0.16 (Ω) and the short-circuit position is at node 8. Figure 8 shows the results of system bus voltages without placing DVR (blue bar) and with placing DVR (red curve).

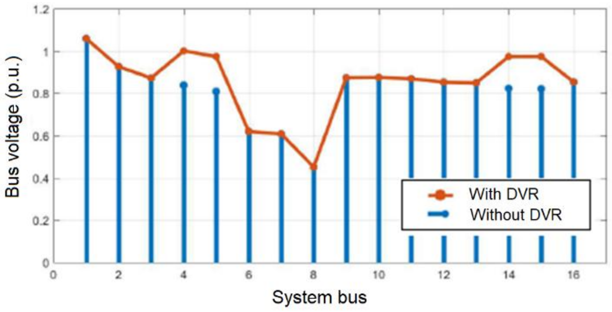


Fig. 8. System bus voltage before and after placing DVR for the case-study.

Optimal location of DVR, the resulted DVR size and the value of objective function are mentioned in Table 1. DVR is placed on the branch 3-4 where the node 4 is the position for voltage compensation. So, U_4 = 1 and the corresponding results about I_{DVR} and S_{DVR} are achieved as (8)-(10).

Table 1. Optimal parameters of DVR for the case-study 1

Optimal location of DVR	Branch 3-4
DVR power (p.u.)	0.2310
Min ΔU (p.u.)	1.6727

4.3 Case-study 2

The case-study 2 considers a smaller fault impedance, Z_f = 0.1 + j0.08 (Ω) while the short-circuit position remains at the node 8. Deep sags at nodes near the short-circuit position are resulted. The system bus voltages are also plotted in the Figure 9.

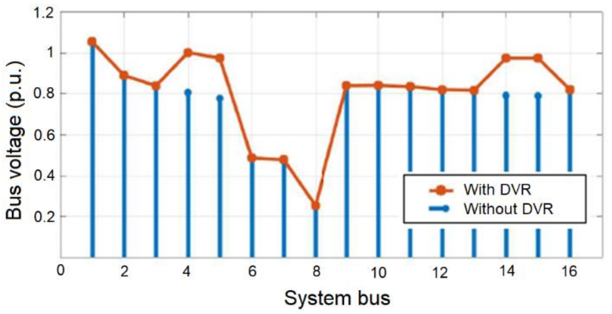


Fig. 9. System bus voltage before and after placing DVR for the case-study 2.

And the optimal location, the size of DVR and the value of objective function are given in Table 2.

Table 2. Optimal parameters of DVR for the case-study 2

Optimal location of DVR	Branch 3-4
DVR power (p.u.)	0.3255
Min ΔU (p.u.)	2.4549

From the Figure 8 and 9, the voltages at buses behind the DVR location are significantly upgraded. For both two scenarios, voltages at nodes 4, 5, 14 and 15 increase up to the safe level in comparison with the required voltage tolerance for short-time voltage variation. Therefore, the effect of voltage compensation by DVR is totally suitable with the typical response of DVR against voltage sag. That also proves the proposed DVR model is correct.

The case-study 2 implies deep sags that require a bigger size of the DVR. However, the DVR size is generally small. That's because the research already assumes the DVR placement that is not on the short-circuit current carrying path.

5 CONCLUSION

The paper newly proposes the application of Norton's equivalent current circuit of DVR in combination with using the superposition principle by Thevenin theorem for modeling the voltage compensation by DVR for voltage sag mitigation in the event of short-circuit in distribution system. Therefore, this DVR's effect is successfully built in the modeling the problem of optimizing the DVR location. The paper also uses GA for solving the problem of optimization and the results show the effectiveness of GA application. The research considers the test system that includes typical structure of balanced three-phase medium voltage system for the case of Vietnam. Two scenarios for fault impedance are considered for estimating the influences to the outcomes such as DVR size. The results show that the solution of using DVR for system voltage sag mitigation is suitable and it's also practical for utilities to apply this solution.

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APPENDIX

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