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Steady-State Power Flow Modeling for a Dynamic Voltage Restorer

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Abstract: - This paper presents analysis, modeling and simulation of power distribution network performance incorporating with an installed dynamic voltage restorer (DVR). DVR is one of series compensators used in power distribution systems in order to maintain load voltage at critical location or to compensate load voltage during fault. In this paper, a steady-state current injection model of DVR is proposed and used for power flow calculation. This model directly results in power flow equations, therefore the effect of current injection from the DVR on power flow equations needs to be included. The simple iterative Gauss-Seidel method is employed to solve a set of nonlinear power flow equations. To evaluate use of the proposed injection model for DVR, three test systems, which are 10 and 25 node distribution network, are simulated under a normal loading condition.

Key-Words: - Power flow, Dynamic voltage restorer, Gauss-Seidel method, Modeling, Simulation

1 Introduction

Electric power distribution network becomes more increasingly important and plays an essential role in power system planning. This type of power systems has a major function to serve distributed customer loads along feeder lines, therefore under competitive environment of electricity market eservice of electric energy transfer must not be interrupted and at the same time there must provide reliable, stable and high quality of electric power. To complete this challenge, it requires careful design for power network planning. There exist many different ways to do so. However, one might consider an additional device to be installed somewhere in the network. Such devices are one of capacitor bank, shunt reactor, series reactors, automatic voltage regulators and/or recently developed dynamic voltage restorers (our focus), or combination of them [1].

Problems of installing additional reactive power compensators in power distribution network are to answer these two questions, which are “where a compensator needs to be installed” and “what is its appropriate size”. With these questions, many consequences have been arisen. Over-rating design can cause unnecessarily expensive investment or availability of DC supply required by a control unit of the compensator can limit a place of installation. To solve this problem, a basic tool of power flow analysis in electric power distribution system is key. Although optimization can formulate mathematical expression to seek for an optimal operating point that inform system operators where to install a compensator and how large the compensator should be specified, a power flow solver is necessary. Most problems of reactive power planning define total power losses of the system as the objective function to be minimized. Therefore, expression of power losses must be obtained first. Although there are loss formulae in several forms, most of them require voltage solutions from the power flow solver. With this reason, power flow models of reactive power compensators must be the first priority to derive. This paper attempts to establish a steady-state power flow model for a novel series compensator, called dynamic voltage restorer (DVR) [2-3]. This model will be included into the power flow solver.

This paper gives four main sections consisting of i) A Current Injection Model of DVR, ii) Problem Formulation, iii) Simulation Results and iv) Conclusion.

2 A Current Injection Model of DVR

DVR is one of a series type compensator consisting of i) DC link capacitor, ii) separately phase-controlled switched-mode inverter, iii) LC filter, iv) series transformer, v) gate triggering circuit and vi) external DC power source [4] as shown in Fig. 1.

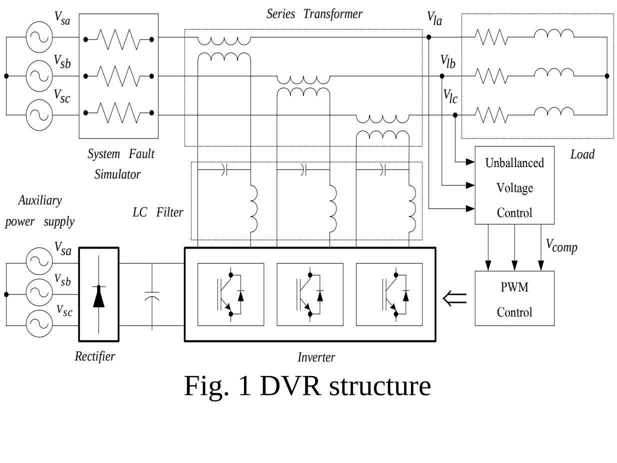

Fig. 1 DVR structure

In steady-state operation with heavy loading, DVR typically injects appropriate voltage in series with the incoming feeder, thus voltage at the outgoing terminal of the DVR will be lifted close to the nominal or other regulated value. This implies that voltage-controlled source in series with impedance [5] is sufficient to represent the DVR as shown in Fig. 2. In the figure, the DVR is assumed to installed between bus i and j. V_c and X_c represent phasor voltage and impedance of the DVR.

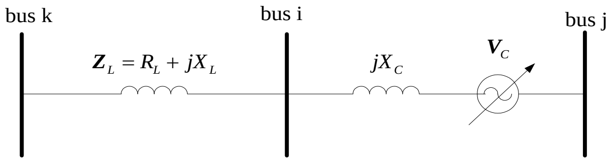

Fig. 2 Appearance of DVR in distribution feeders

In general, to insert a DVR needs temporary bus of connection. As shown in the figure, bus i is the temporary bus and increases dimension of the system matrix. Therefore, bus i must be eliminated. However, in this paper only rearrangement of equivalent network seen from terminals k and j is used without applying any matrix reduction formulae. This can be illustrated schematically in Figs 3 and 4. The Norton's equivalent circuit in Fig. 4 is ready to be used by a power flow solver.

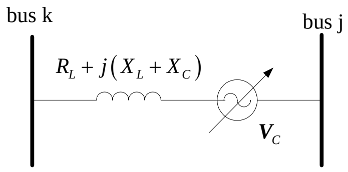

Fig. 3 Elimination of bus i

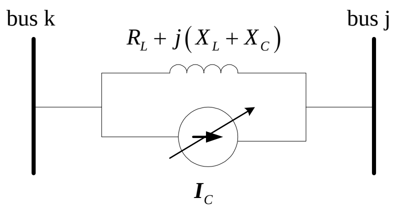

Fig. 4 Norton's equivalent circuit

where,

Z_L is the feeder impedance
I_C is the current injected by DVR
V_C is the DVR's series voltage
X_C is the internal reactance of DVR

A current injection model can replace the Norton's circuit in Fig. 4, consequently the DVR can be simplified and promptly to be included into power flow equations. Expression of the power flow equations after insertion of the DVR will be explained in the next section.

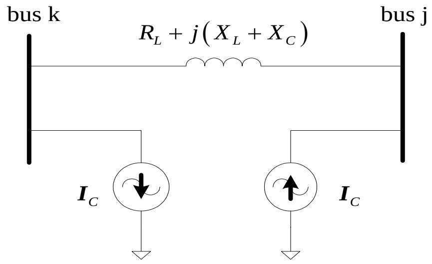

Fig. 5 Current injection model of the DVR

3 Problem Formulation

Consider n-bus power network. Assume that a DVR is assigned to be installed between bus k and j as shown in Fig. 6.

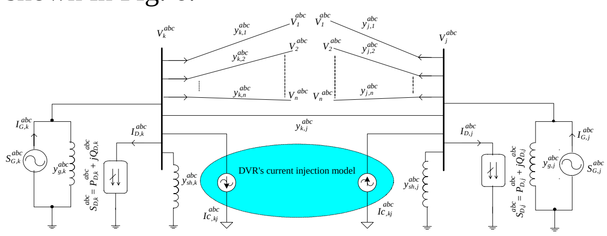

Fig. 6 Schematic diagram representing bus k and j

By power-balanced principle, the complex power mismatch equation at buses k and j can be expressed as shown in Equations 1 and 2, respectively.

$$\left[\frac{P^{abc}_{sch,k} - jQ^{abc}_{sch,k}}{V^{abc*}_{k}}\right] - I^{abc}_{C,kj} = \sum_{i=1}^{n} Y^{abc}_{ki} V^{abc}_{i} \qquad (1)$$

$$\left[\frac{P^{abc}_{sch,j} - jQ^{abc}_{sch,j}}{V^{abc*}_{j}}\right] + I^{abc}_{C,kj} = \sum_{i=1}^{n} Y^{abc}_{ji} V^{abc}_{i} \qquad (2)$$

where,

V^{abc}_{k} is a three – phase voltage at bus k
Y^{abc}_{ki} is the matrix admittance of bus k and j
$I^{abc}_{C,kj}$ is the current injected by the installed DVR
$P^{abc}_{sch,k}$ is real power schedule at bus k
$Q^{abc}_{sch,k}$ is reactive power schedule at bus k
* is complex conjugate

Rearranging Equations 1 and 2 in order to update three-phase bus voltages by using the Gauss-Seidel iterative method, voltage vectors at buses k and j at iteration h + 1 are obtained in Equations 3 and 4. It notes that other bus voltage can be updated by using a regular voltage formula as appeared in most high-street power system textbooks [6].

$$V_k^{abc(h+1)} = \frac{1}{Y_{k,k}^{abc}} \left\{ \frac{P_{sch,k}^{abc} - jQ_{sch,k}^{abc}}{\left(V_k^{abc(h)}\right)^*} - \sum_{i=1}^{k-1} Y_{kj}^{abc} V_i^{abc(h+1)} - \sum_{i=k+1}^{n} Y_{kj}^{abc} V_i^{abc(h)} - I_{C,kj}^{abc} \right\} \quad (3)$$

$$V_j^{abc(h+1)} = \frac{1}{Y_{j,j}^{abc}} \left\{ \frac{P_{sch,j}^{abc} - jQ_{sch,j}^{abc}}{\left(V_j^{abc(h)}\right)^*} - \sum_{i=1}^{j-1} Y_{jj}^{abc} V_i^{abc(h+1)} - \sum_{i=j+1}^{n} Y_{jj}^{abc} V_i^{abc(h)} + I_{C,kj}^{abc} \right\} \quad (4)$$

To solve power equations by the Gauss-Seidel method, a set of n-bus voltage equations is updated successively, iteration-by-iteration, until one of termination criteria is met. The step-by-step Gauss-Seidel power flow solution is summarized as follows.

START:

Step 0
Load a test feeder
Initialize all bus voltages to be 1.0 p.u.
Reset all counters
Formulate the bus admittance matrix

Step 1
Find two bus indices in which DVR is installed in between and define them as bus k and j.

Step 2
For *bus_number* = 1 to n
If *bus number* = k
Update bus voltage with Equation (3)
Elseif *bus_number* = j
Update bus voltage with Equation (4)
Else
Update bus voltage with regular equations

Step 3
Check all termination criteria
If one of the criteria is met
Then, go to step 4
Otherwise, increase counters and go to Step 2

Step 4
Voltage solutions are successfully obtained.

STOP

4 Simulation Results

In this paper, two test systems, which are i) 8.66-kV, 10-bus test feeder [7] and ii) 4.16-kV, 25-bus test feeder [8] as shown in Figs 7 and 8 respectively, are used for evaluation.

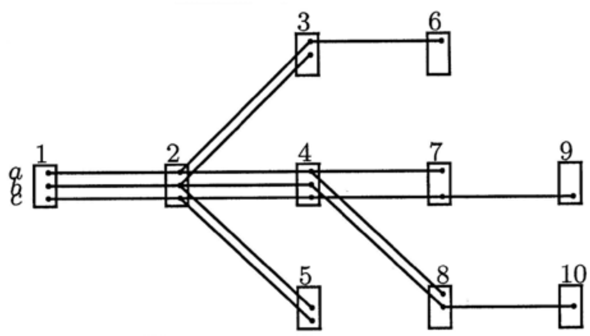

Fig. 7 10-bus test feeder

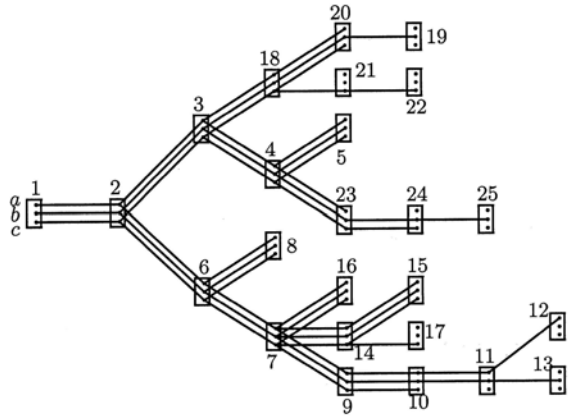

Fig. 8 25-bus test feeder

To perform the tests, DVR is assigned to be installed in series with a feeder line connected between bus 1 and bus 2. Maximum voltage tolerance used to stop the iterative process is set to 1×10^{-6} p.u. for all test cases. For the 10-bus test feeder, a three-phase DVR is added. The value of voltage magnitude and phase is set to 0.2 p.u and 0° degree to each phase equally, while the reactance is 2 Ω. Voltage solutions of the 10-bus test case with and without DVR are shown in Figs 9 – 11.

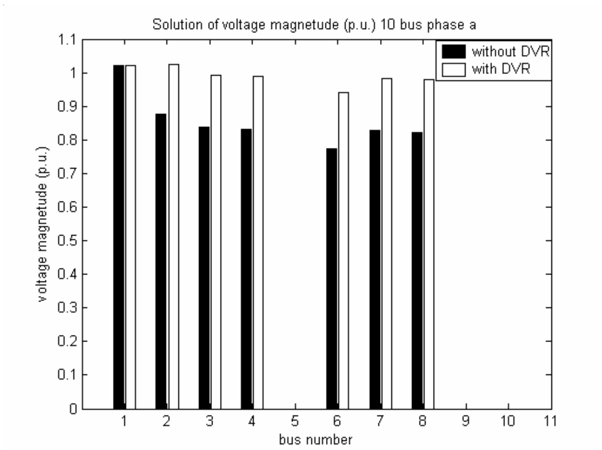

Fig. 9 Phase-a bus voltages of the 10-bus system

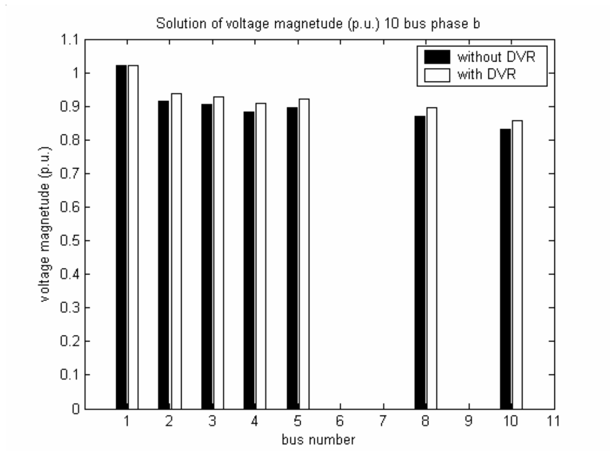

Fig. 10 Phase-b bus voltages of the 10-bus system

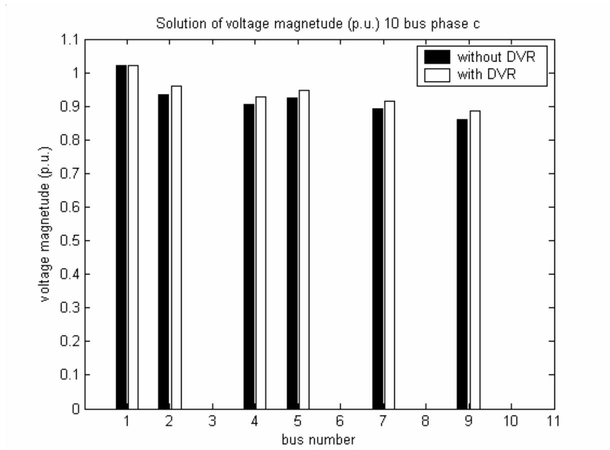

Fig. 11 Phase-c bus voltages of the 10-bus system

For the 25-bus test feeder, a three-phase DVR is added. The value of voltage magnitude and phase is set to 0.05 p.u and 0° degree to each phase equally, while the reactance is 2 Ω. Voltage solutions of the 25-bus test case with and without DVR are shown in Figs 12 – 14.

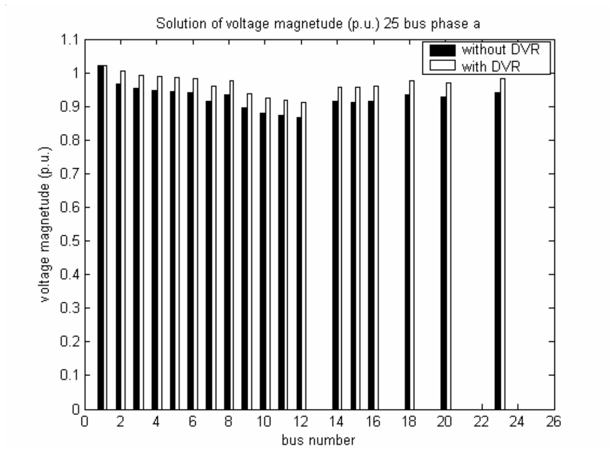

Fig. 12 Phase-a bus voltages of the 25-bus system

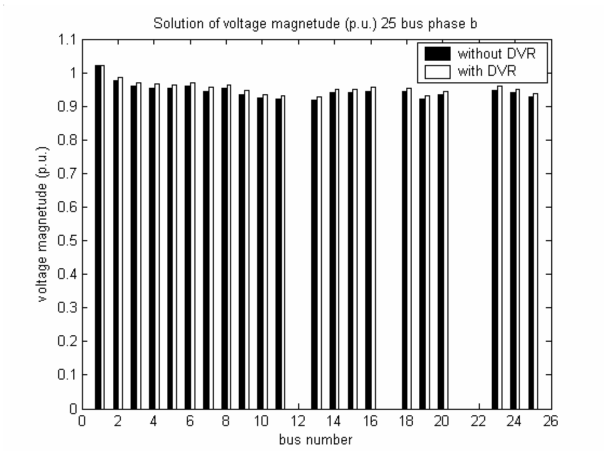

Fig. 13 Phase-b bus voltages of the 25-bus system

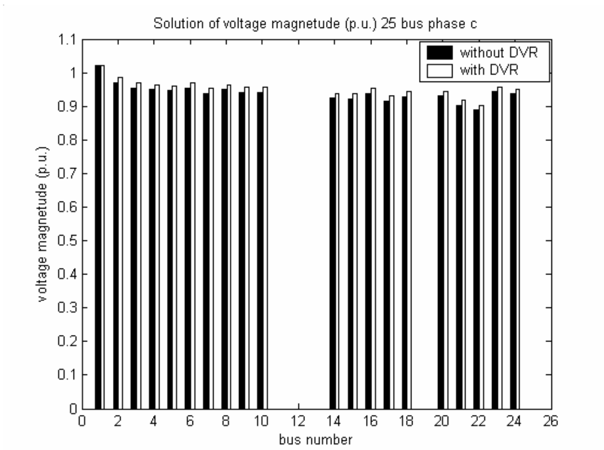

Fig. 14 Phase-c bus voltages of the 25-bus system

As a result, DVR can help improving bus voltages in radial distribution network. With an appropriate control of the voltage injection, load voltage can be regulated during a peak load condition or even faults.

For comparison, convergent properties and iteration number used by the Gauss-Seidel method for each test feeder with and without DVR are presented in Table 1 and Figs 15 – 18.

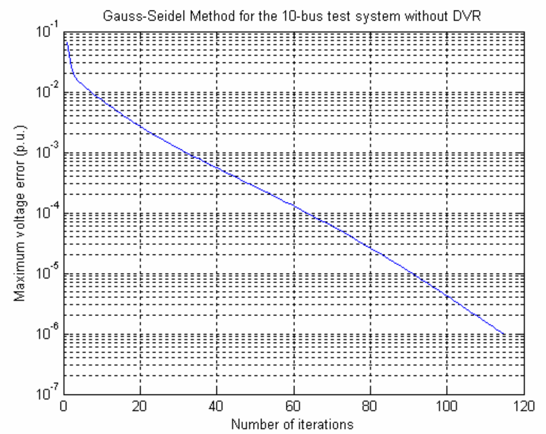

Fig. 15 Convergence of the 10-bus system without DVR

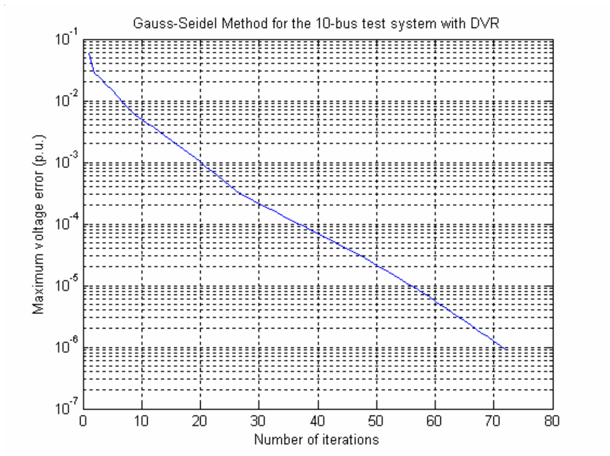

Fig. 16 Convergence of the 10-bus system with DVR

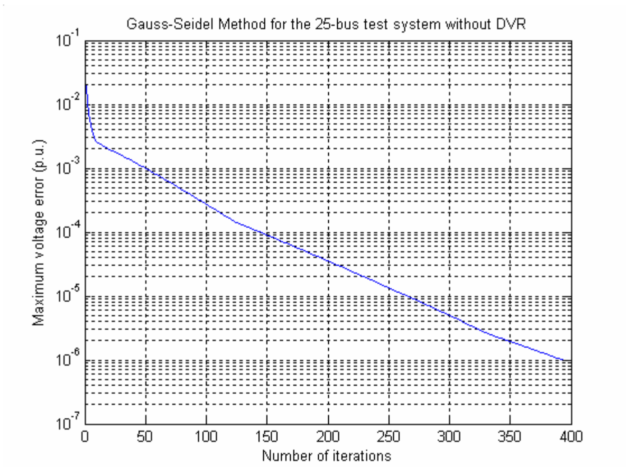

Fig. 17 Convergence of the 25-bus system without DVR

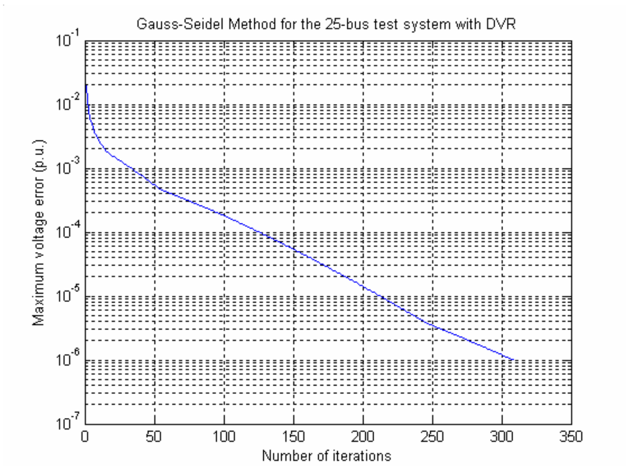

Fig. 18 Convergence of the 25-bus system with DVR

Table 1 Iteration used by the Gauss-Seidel method

Test system	**Without DVR**	**With DVR**
10 bus	116	73
25 bus	395	310

4 Conclusions and Further Work

This paper proposes a current injection model for a dynamic voltage restorer used in power distribution network. Power flow equations are modified due to the insertion of the DVR. To demonstrate the use of this model, the Gauss-Seidel power flow solution method is employed. The obtained voltage solutions from both test systems present essential information that the DVR can help improving far-end load voltages. The bus voltages with and without DVR confirm this.

For our further work, it is more useful if this current injection model is able to apply for Newton-Raphson power flow calculation. This method can be well embedded into a constrained optimization problem as equality constraints.

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