An Improved Method for Assessing Voltage Stability Based on Network Decomposition

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Abstract

In this paper we present an improved method for assessing the voltage stability based on network decomposition. It is an analytical approach to finding the radial paths that are transformed into two-bus equivalents combined with an analytically proven test for the voltage-collapse proximity measure that has a physical meaning. The first modification allows for power-flow tracing that obtains the generator active- and reactive-power shares on each section of a radial path. The shares make it possible to allocate the transmission losses among the generators, which are required to assess the voltage-collapse proximity. Based on the reactive-power tracing, the improved approach also makes it possible to assess the availability of reactive-power sources and their ability to supply load buses. The proposed solution is faster than the existing search algorithm and gives more accurate results. The method was tested on the IEEE 39-bus test system.

Keywords

Network decomposition, power-flow tracing, radial paths, voltage-collapse proximity, voltage stability.

Introduction

Changes in the energy market have introduced new requirements for the operation and control of power systems. The objectives in this new environment are a higher return on investment and a more efficient exploitation of the existing network infrastructure. A consequence of these changes is that transmission lines are reaching their voltage-stability margins.

Voltage instability can be caused either by the inability of reactive-power sources to produce enough reactive power to supply load buses, or by the inability of the power lines to transmit the required reactive power to the buses. Although the nature of the voltage instability is dynamic, many system-oriented approaches are based on static models [1]–[5] because of their simplicity. Dynamic methods [3]–[6] are a far better choice if a more comprehensive analysis is required. They are, however, more time consuming. Most of the available static methods are based on an analysis of the system's Jacobian matrix, either by exploiting its sensitivity [3], [7] or by determining its closeness to the singularity [5], [8], [9]. Since these solutions sometimes have no clear path to a physical interpretation of the process, two new methods with a physical meaning were recently proposed. The first method is based on network decomposition [10]–[13], which means it is more complex and time consuming; the second method is based on local phasors [14], [15], which means it is faster and more exact, and it provides results by considering two operating states with a slight difference in the total system loading. The main problem with this second method is the selection of these two states. However, another problem is that this method does not identify whether the voltage collapse is caused by a lack of reactive-power production or by an insufficient power-transfer capability.

In this study we looked at modifying the method based on network decomposition in the hope that it would provide us with a new, faster and more exact approach. A novelty of the proposed solution is the incorporation of reactive-power tracing, which is required to define the voltage phasors of each bus of a two-bus equivalent of the radial transmission path. On this basis, two voltage-collapse proximity indices can be formulated. These indices are related to the inability of the sources to produce enough reactive power to supply a critical load bus and the inability of the power lines to transmit the required reactive power to the bus.

Since the proposed approach is based on power-flow-tracing methods it is essential to point out that several solutions have already been proposed [16]–[20], of which the decoupled TGDF method [21] seems to be the most appropriate for coping with the voltage-stability assessment. Our proposed method allocates the transmission losses among the generators without any matrix expansion; it is also appropriate for reactive-power analyses. Our method is faster, especially when compared to the TGDF method [16], [17], which can also be applied to the area of voltage instability discussed in this paper.

The proposed modified method based on network decomposition was exhaustively tested on the IEEE 39-bus test power system. According to the results, which show the advantage of the new solution, it can be concluded that the method is suitable for a more appropriate contingency analysis.

Proposed improvement of the method

To understand the proposed modification, the original method needs to be briefly described. The most common static approach to voltage-stability assessment is an analysis of the Jacobian matrix. For a two-bus network with a constant voltage amplitude at the input bus 1, U_1 = const, the Jacobian matrix **J** indicates the voltage instability when its determinant takes the value:

$$\det \mathbf{J} = \frac{\partial P_2}{\partial \delta_2}\frac{\partial Q_2}{\partial U_2} - \frac{\partial P_2}{\partial U_2}\frac{\partial Q_2}{\partial \delta_2} = 0, \tag{1}$$

where the voltage phasors are denoted as $U = U \cdot e^{j\delta}$ with indices 1 and 2 at the input bus and load bus, respectively. P_2 and Q_2 are the active and reactive powers at the load bus. The method based on network decoupling assumes that the voltage phasors contain enough information to detect the voltage instability [11]. For the simple two-bus power system with the generator bus 1, the load bus 2 and the corresponding phasor diagram in Fig. 1, a critical condition for stable operation is reached when the voltage drop ΔU_{12} is equal to the load voltage U_2:

$$\Delta U_{12} = |U_1 - U_2| = U_2, \tag{2}$$

Combining (1) and (2) leads to the following expression:

$$U_1 = 2U_2 \cos\delta_{12}, \tag{3}$$

which implies that the applied approach based on voltage phasors is suitable for the voltage-proximity assessment.

A. Two-bus equivalent of the radial network

The method is also able to apply this concept successfully to radial networks with several load buses, Fig. 2. The radial network fed by the generator contains a series of nodes feeding various loads $S_i = P_i + jQ_i$ that all match the generator's active P_1 and reactive Q_1 powers. The voltage phasors at the generator node and at the radial network end node are U_1 and U_n, respectively. Sections along the path are defined by the impedances and loads causing active and reactive transmission losses. They result in the voltage drops $\Delta U_{d\,1n}$ and ΔU_q 1n in the radial network as follows:

$$\Delta U_{d\,1n} = \frac{P_1 \sum_{ij\in\Gamma} L_{ij}^{P} + Q_1 \sum_{ij\in\Gamma} L_{ij}^{Q}}{P_1^2 + Q_1^2} U_1, \tag{4}$$

$$\Delta U_{q\,1n} = \frac{P_1 \sum_{ij\in\Gamma} L_{ij}^{Q} - Q_1 \sum_{ij\in\Gamma} L_{ij}^{P}}{P_1^2 + Q_1^2} U_1, \tag{5}$$

where L_{ij}^{P} and L_{ij}^{Q} denote the active- and reactive-power losses in the section i-j of the radial network, respectively. Γ is the set of sections (lines) of the observed radial network.

To apply the concept based on voltage phasors to radial networks the method constructs a two-bus equivalent of a radial network utilizing its operational parameters, as described in [11]. The equivalent should reflect the common properties of the original radial network and make possible a voltage-stability assessment. The input power, the load impedance at the end of the radial network as felt by the input bus, and the voltage drop along the path have to be retained. This set of conditions leads to the following expressions with the exact derivation in [11]:

$$U_1 I_1 = U_1^{'} I^{'} , \tag{6}$$

$$U_1 U_{\mathrm{n}} = U_1^{'} U_2^{'} , \tag{7}$$

$$\frac{U_1^{'}}{U_1} = \frac{I_1}{I^{'}} = \frac{U_{\mathrm{n}}}{\mathrm{U}_2^{'}} , \tag{8}$$

$$\Delta U_{\mathrm{d\ 1n}} = U_{\mathrm{d}}^{'} , \tag{9}$$

$$\Delta U_{\mathrm{q\ 1n}} = U_{\mathrm{q}}^{'} , \tag{10}$$

where $U_1^{'}$ and $I^{'}$ are the voltage and the injected current at the generator bus of the two-bus equivalent, respectively. $U_2^{'}$ is the voltage at the load bus, and $U_{\mathrm{d}}^{'}$ and $U_{\mathrm{q}}^{'}$ are the voltage drops of the equivalent. Fig. 3 presents the two-bus equivalent with the corresponding phasor diagram.

The following set of nonlinear equations:

$$U_{\mathrm{d}}^{'} = U_1^{'} - U_2^{'} \cos \delta^{'} , \tag{11}$$

$$U_{\mathrm{q}}^{'} = U_2^{'} \sin \delta^{'} , \tag{12}$$

can be solved by considering (6) to (10). The two-bus equivalent is thus completely determined, and its variables can be employed for the voltage-stability assessment, which is explained in the subsequent text.

B. Decomposition of the meshed network

The existing method proposes that the meshed network is decomposed into several radial networks, which are subsequently transformed into two-bus equivalents, making possible the appropriate voltage-stability assessment. This transformation assumes that only one generator at the beginning of the radial network covers all the transmission losses along the radial path, (4) and (5). This means that the presented idea cannot be directly applied to meshed networks, since the transmission losses need to be allocated among several generators in a system.

The method does, however, identify paths of active and reactive power from the generators to the loads. The active- and reactive-power flows are strongly correlated with the variation in the angle and the decrease in the voltage, respectively. Thus, each reactive-power transmission path is defined as a sequence of connected buses with decreasing voltage magnitudes, and each active-power transmission path is defined as a sequence of connected buses with decreasing phasor angles. Each reactive-power transmission path is interpreted as a radial network that can be transformed into a two-bus equivalent with the possibility to assess the voltage stability. Since the transmission losses are covered by numerous generators, a suitable approach for allocating the losses should be applied to calculate the actual voltage drops $\Delta U_{\mathrm{d\,1n}}$ and ΔU_{q} 1n in the observed radial network as follows:

$$\Delta U_{\mathrm{d\,1n}} = \frac{P_1 \sum_{\mathrm{ij}\in\Gamma} a_{\mathrm{ij},1} L_{\mathrm{ij}}^{\mathrm{P}} + Q_1 \sum_{\mathrm{ij}\in\Gamma} b_{\mathrm{ij},1} L_{\mathrm{ij}}^{\mathrm{Q}}}{P_1^2 + Q_1^2} U_1 , \tag{13}$$

$$\Delta U_{\mathrm{q\,1n}} = \frac{P_1 \sum_{\mathrm{ij}\in\Gamma} b_{\mathrm{ij},1} L_{\mathrm{ij}}^{\mathrm{Q}} - Q_1 \sum_{\mathrm{ij}\in\Gamma} a_{\mathrm{ij},1} L_{\mathrm{ij}}^{\mathrm{P}}}{P_1^2 + Q_1^2} U_1 , \tag{14}$$

where $a_{\mathrm{ij},1}$ and $b_{\mathrm{ij},1}$ are the shares of the generator at bus 1 in the active and reactive transmission losses on the line i-j, respectively. The active-power transmission paths do not affect the radial networks, they just enable a fair allocation of the active transmission losses, i.e., the calculation of the shares $b_{\mathrm{ij},1}$ is needed in (13) and (14).

C. Allocation of the transmission losses

The method based on the decomposition of a meshed network introduces a search algorithm for allocating the transmission losses among the generators. It treats the active and the reactive losses in the same way, but separately. Fig. 4 presents a part of the radial network. $M_{\mathrm{i-1,i}}^{+}$ is the active- or reactive-power flow on the section connecting the nodes i-1 and i directed in the node i, which is denoted by "+". All the flows from the node i are marked by "-".

The share k_{i1} of the power flow on the section i-1, i on the section i, i+1 can be calculated as follows:

$$k_{\mathrm{i1}} = \frac{M_{\mathrm{i-1,i}}^{+}}{M_{\mathrm{i,i+1}}^{-}} \left(1 - \frac{\sum_{\mathrm{j}\in\Xi_{\mathrm{i}}} M_{\mathrm{ij}}^{-} - M_{\mathrm{i,i+1}}^{-}}{\sum_{\mathrm{j}\in\Xi_{\mathrm{i}}} M_{\mathrm{ji}}^{+}} \right), \tag{15}$$

where Ξ_{i} is the set of nodes that are connected to the node i. Since the sum of all the shares is equal to 1, the share k_{i2} of the rest of the sections that supply the observed section i, i+1 can be calculated as follows:

$$k_{\mathrm{i2}} = 1 - k_{\mathrm{i1}} . \tag{16}$$

A recursive procedure makes it possible to calculate the generator shares on the sections as follows:

$$k_{\mathrm{gen}}^{\mathrm{i}} = k_{\mathrm{gen}}^{\mathrm{i-1}} k_{\mathrm{i1}} , \tag{17}$$

where $k_{\mathrm{gen}}^{\mathrm{i}}$ is the share of the generator at the source bus of the radial network on the section i-1, i. The first section of the radial network is supplied by only one generator, thus $k_{\mathrm{gen}}^{0} = 1$. The coefficient $k_{\mathrm{gen}}^{\mathrm{i}}$ represents the active or reactive share, i.e., $a_{\mathrm{ij},1}$ and $b_{\mathrm{ij},1}$, of the generator at bus 1 of the radial network in Fig. 1 on a certain section, e.g., line i-j. The shares make possible a voltage-stability assessment in meshed networks.

D. A new method for power-flow tracing

The presented search algorithm for allocating the transmission losses is time consuming due to the additional recursive procedure for calculating the generator shares and the additional algorithm for the loop power-flow analyses. However, it can be effectively replaced by the decoupled TGDF method [21], based on a matrix calculation. The analytical solution is appropriate for active- and reactive-power-flow analyses and it does not introduce any additional algorithms in the case of loop power flows. This method also improves the identification of the active- and reactive-power transmission paths needed for presenting the decomposition of the meshed network. The generator shares obtained with the decoupled TGDF method reduce the size of the set of the buses that have to be accounted for when the angle variations and the voltage decreases are observed.

E. Voltage-collapse proximity indices

Since the voltage instability can be caused either by the inability of the power lines to transmit the required reactive power to the loads or by an insufficient production of reactive power, two voltage-collapse proximity indices are introduced. The decomposition of the meshed network and the analytical reduction of the radial network to a two-bus equivalent make it possible to determine the voltage proximity in a straightforward manner. For the two-bus equivalent in Fig. 3 with the generator voltage $U_1^{'}$, the line impedance $\underline{Z}_{\mathrm{v}}^{'}$, the load impedance $\underline{Z}_{\mathrm{b}}^{'}$ and the load bus voltage $U_2^{'}$, the maximum power-transmission capabilities are reached when the equality:

$$U_1^{'} = 2U_2^{'} \cos\delta^{'} , \tag{18}$$

is fulfilled. This defines the singularity point of the Jacobian matrix in (1) when the magnitudes of $\underline{Z}_{\mathrm{v}}^{'}$ and $\underline{Z}_{\mathrm{b}}^{'}$ are also equal. The transmission-path stability index (TPSI) can be formed as follows:

$$TPSI = 0.5U_1^{'} - U_{\mathrm{d}}^{'} , \tag{19}$$

which reaches the value 0 when the power transfer of the radial network becomes unstable.

A load-bus voltage is stable if this load is supplied with the required power through at least one stable path among the several paths in a meshed network. The transmission losses along a particular path grow very quickly with the increased load, and the power supply through the other paths must be additionally increased in order to balance the additional power-loss requirements. Additional loading of the rest of the supply paths results in a successive decrease in their TPSIs toward 0, and finally leads to the voltage collapse at the load bus. The most critical load bus j and its voltage-collapse proximity index (VCPI) are defined by the identification of the minimum value of the TPSIs:

$$VCPI_{\mathrm{j}} = \min\left\{TPSI\right\}. \tag{20}$$

Once the $VCPI_{\mathrm{j}}$ reaches the value 0, the load bus j becomes voltage unstable for the load increase within a few percent.

Although the maximum power-transmission capabilities are not yet reached, voltage instability can occur as a consequence of insufficient reactive-power production. Thus, the additional reactive-power index (RPI) concerns the maximum and the remaining production capabilities of the reactive power. For the load bus j, the RPI can be formed as follows:

$$RPI_{\mathrm{j}} = \frac{\sum_{\mathrm{i}\in\Psi_{\mathrm{j}}} Q_{\mathrm{i}}^{\max} - Q_{\mathrm{i}}}{\sum_{\mathrm{i}\in\Psi_{\mathrm{j}}} Q_{\mathrm{i}}^{\max} - Q_{\mathrm{i}}^{\min}}, \tag{21}$$

where Q_{i}, $Q_{\mathrm{i}}^{\max}$ and $Q_{\mathrm{i}}^{\min}$ represent the current, the maximum and the minimum reactive-power production at the generator bus i, respectively. Ψ_{j} is the set of generators that supply the load bus i with reactive power. An insufficient production of reactive power results in a progressive decrease of the RPI toward 0, and finally leads to the voltage collapse at the load bus.

It is assumed that the RPI considers all the generators that supply the observing load bus equally and does not allow the generators to support that load bus. This means that the proximity of the voltage collapse is not properly assessed in some cases. The improved method therefore proposes a new form of the RPI, which is written as follows:

$$RPI_{\mathrm{j}} = \frac{\sum_{\mathrm{i}} \left(Q_{\mathrm{i}}^{\max} - Q_{\mathrm{i}}\right) c_{\mathrm{j,i}}}{\sum_{\mathrm{i}} \left(Q_{\mathrm{i}}^{\max} - Q_{\mathrm{i}}^{\min}\right) c_{\mathrm{j,i}}}, \tag{22}$$

where $c_{\mathrm{j,i}}$ is the reactive-power share of the generator i in the load at the bus j. This factor represents the ability of generator i to support the load bus j, and it is obtained by the decoupled TGDF method for the power-flow tracing. Generators with smaller shares do not ensure effective voltage support, even though they have sufficient reactive-power production capacities.

For the proper voltage-stability assessment, the VCPIs and the RPIs have to be merged as follows:

$$\left(VCPI_{\mathrm{j}} < \varepsilon_{\mathrm{U}}\right) \vee \left(\left(RPI_{\mathrm{j}} < \varepsilon_{\mathrm{Q}}\right) \wedge \left(VCPI_{\mathrm{j}} > \varepsilon_{\mathrm{U}}\right)\right), \tag{23}$$

where ε_U and ε_Q are predefined critical values of the $VCPI_j$ and RPI_j, respectively. This criterion first allows for the power transmission capabilities, and if the critical value ε_U is not reached, it assesses the remaining reactive-power production capacities of the generators that supply the observed load bus.

Fig. 5 presents a comparison of the method based on network decomposition and its improvement. The proposed modification obtains the improved proximity indices by incorporating the power-flow-tracing method.

Results

Our improved method based on network decomposition was tested on the meshed IEEE 39-bus test system. The loads were progressively increased until the load-flow program failed to converge. The increased generation was distributed evenly among the generators in the system according to their base case production. It is well recognized that a purely static load, e.g., a constant impedance or a constant current load, cannot cause voltage instability, so at least a part of the load must be dynamic, i.e., the load must exhibit some sort of self-restoring characteristic. Thus in this paper we assumed the loads were primarily constant MVA.

For a desired power-system voltage profile during operation, both a sufficient amount and an appropriate allocation of reactive power are needed in a power system. Voltage instability can thus be caused either by the inability of the reactive-power sources to produce enough reactive power to supply the load bus or the inability of the power lines to transmit the required reactive power to the bus. To show the advantages of the proposed improvement of the method, two scenarios were simulated. In the first scenario the voltage collapse was reached at critical bus 7 with $VCPI_7 \cong 0.3285$ in the last stable power flow solution with a 1.86-times increased total system load S compared to the base-case total system load S_b, Fig. 6. Due to the relatively high value of $VCPI_7$ we can assume that the voltage collapse was caused by insufficient reactive-power production and not by the lack of transfer capabilities. The decrease of RPI_7 obtained with (21) is shown with the dashed line in Fig. 7. This index does not take into account the ability of generators to support the load buses, thus it reached a relatively high value 0.344, despite the voltage collapse. To identify the voltage instability correctly, the improved RPI_7 in (22) is required. In the simulated operating state it reached the critical value of 0.091, as shown with the solid line in Fig. 7.

To avoid a lack of produced reactive power during the increase of the total system's loading, the generators' production capabilities in the second scenario were 5-times larger than in the first scenario. Figs. 8 and 9 show the last stable operating state, which has a 2.335-times higher increased total system load S than the base-case total system load S_b. Increased production margins result in relatively high values of the RPIs in the critical bus 7, Fig. 8. Despite the available reactive-power production we can assume that the voltage instability occurred as a result of the lack of power transfer that caused the decrease of the $VCPI_7$ to the critical value of 0.034.

The curves of the VCPIs and the RPIs experience sharp turns when the reactive-power production limit of one or more generators is reached and the total loading continues to increase. The limited generating bus may lose its role as a supporting point and a new critical path is formed.

Fig. 10 presents the comparison of the computational times of the existing and improved methods for several different sizes of power systems. It is clear that the improvements result in a faster calculation, especially when the loop power flows are presented, as in the case of the 30-bus and 57-bus IEEE test systems. These improvements will be beneficial when realistic power systems with numerous nodes are analyzed.

Conclusions

The existing method based on the decomposition of a meshed network into several radial paths is appropriate for a voltage-stability assessment. The method involves the construction of the exact two-bus equivalents for which the analytically proven test for voltage-collapse proximity measures with a physical meaning can be applied.

The applied identification of the reduced transmission losses can be successfully improved by the recently developed decoupled TGDF method for active- and reactive-power-flow tracing. This new approach to loss allocating makes possible a faster calculation of the collapse-proximity indices, which can be additionally improved by allowing for the electrical distance of the reactive power sources from the affected load buses in the calculation of the RPI indicators.

The proposed improved method can be used for a more appropriate contingency analysis.

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Vitae

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Gregor Verbič was born in 1971 in Slovenia. After graduating from the University of Ljubljana in 1995 he joined Korona Power Engineering, where he worked for three years. In 1998 he accepted a teaching-assistant position at the Faculty of Electrical Engineering, where he obtained an M. Sc. in 2000 and a Ph.D. in 2003. He is now a full-time assistant. His research activities are power-system operation, dynamics and control.

Ferdinand Gubina was born in 1939 in Slovenia. He received Diploma Engineer, M. Sc. and Dr. Sc. degrees from the University of Ljubljana, Slovenia, in 1963, 1969, and 1972, respectively. From 1963 he has been with the "Milan Vidmar" Electroinstitute, Ljubljana, where he was Head of the Power System Operation and Control Department. In 1970 he joined Ohio State University, Columbus, Ohio, for a year, as a teaching associate. Since 1988 he has been a full professor at the University of Ljubljana. His main interests lie in the area of electric-power system operation and control. Dr. F. Gubina served in the CIGRE SC-39, SC-38, C4 Study Committees, and in CIGRE AC and TC. He is a distinguished member of CIGRE Paris.

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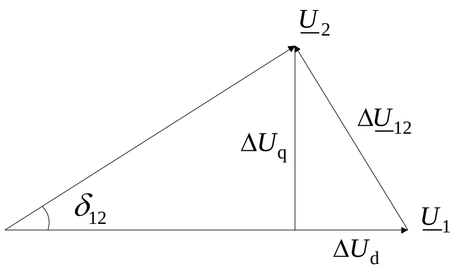

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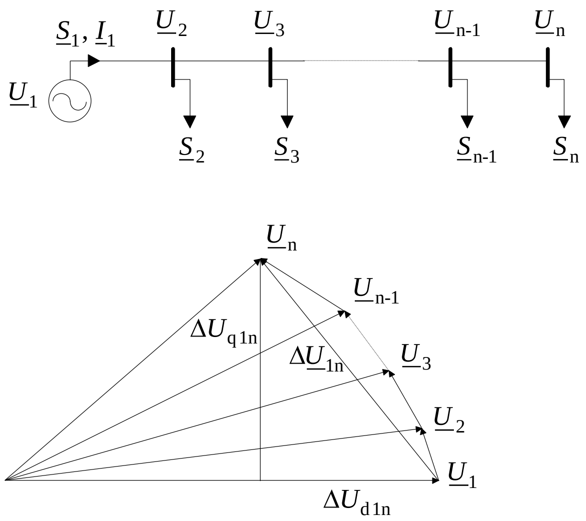

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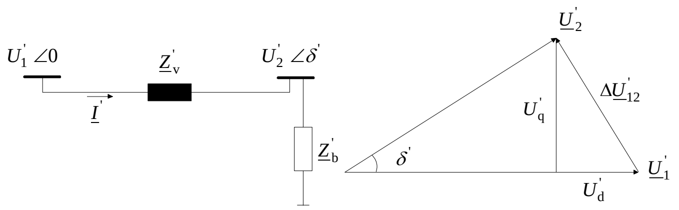

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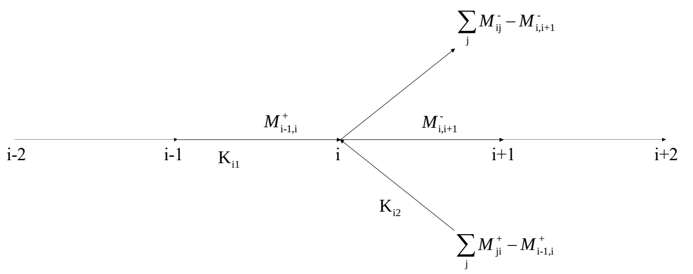

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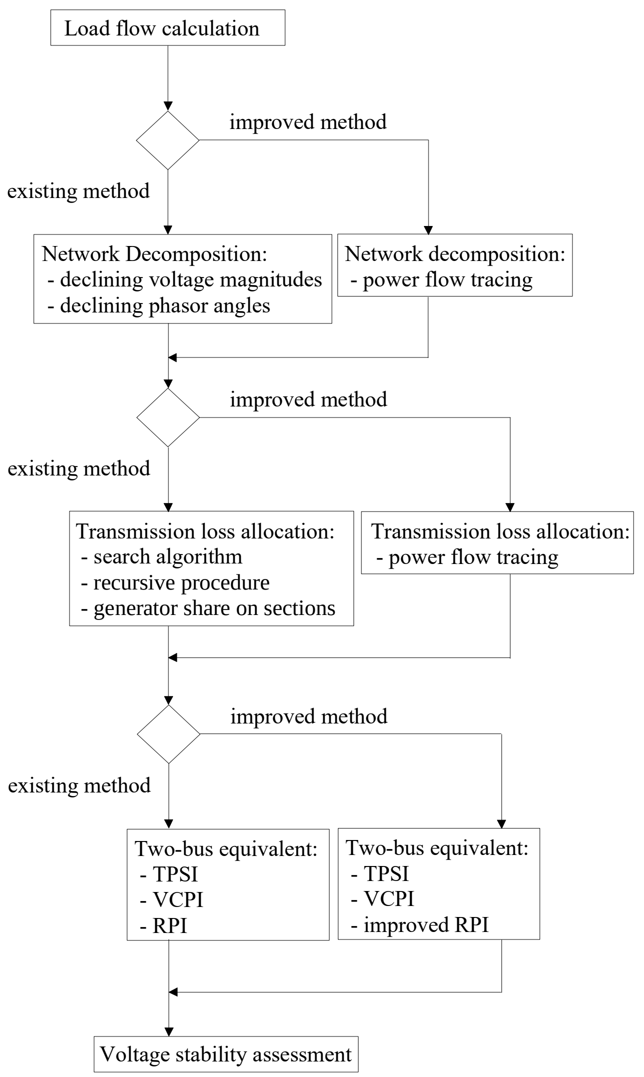

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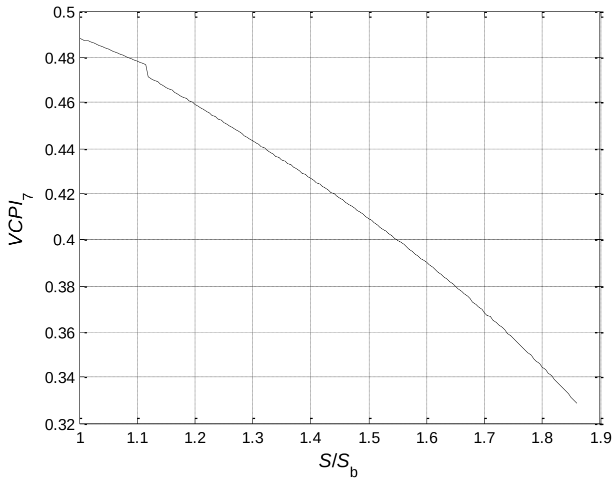

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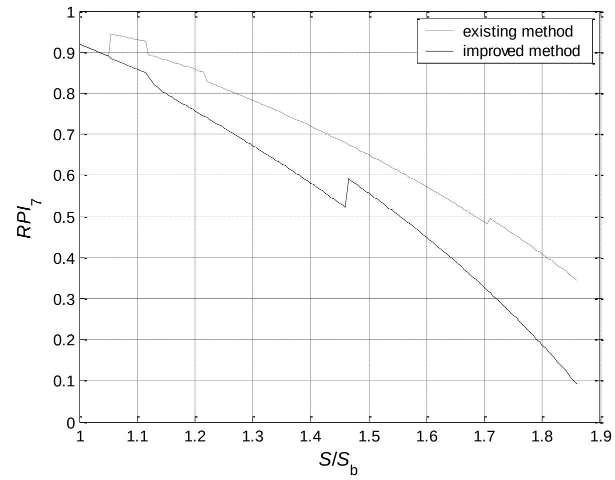

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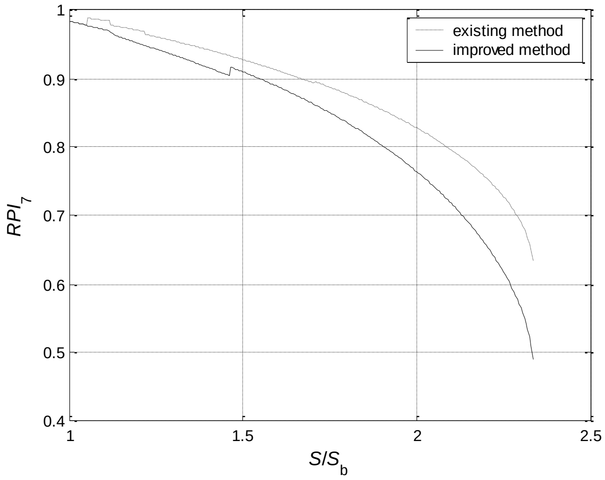

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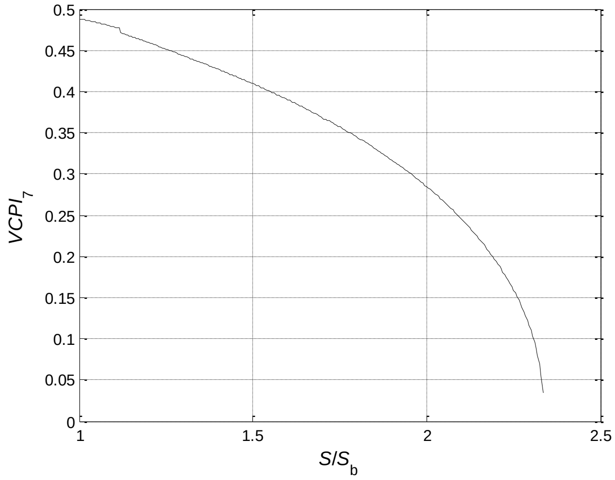

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Figure No. 9

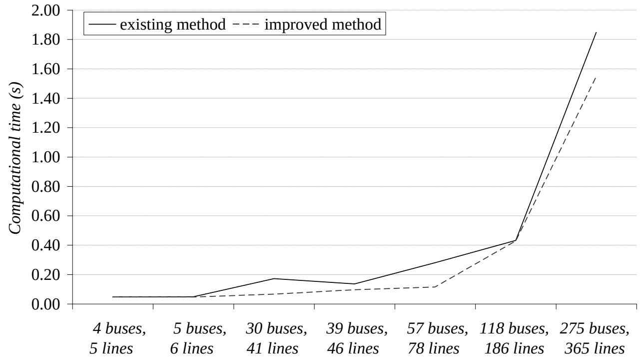

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Figure No. 10