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Voltage Stability Contingency Screening and Ranking for Voltage Control Areas

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SUMMARY

Fast and accurate contingency screening and ranking has become a requirement for secure operation of power systems. This is due to market activities, complex controls, and power supply intermittency caused by the integration of renewable energy sources. The objective of contingency screening and ranking is to identify the most critical contingencies from a large list of credible contingencies and rank them according to their severity. Several techniques could be used. However, their computation complexity and accuracy should be considered. This paper investigates different voltage stability indices to identify the most critical contingency for voltage control areas (VCA). VCA is a concept proposed to subdivide a network into multiple sub regions within which reactive power resources are effective. For each contingency, a critical bus is identified for each VCA and then various voltage stability indices are computed at these critical buses of the system. VQ analysis is used to identify a reference set of critical contingencies, which is used to assess the performance of the various voltage stability indices. A comparison is made between five different voltage stability indices: sensitivity factor index (SFI), tangent vector index (TVI), fast voltage stability index ($FVSI$), voltage reactive power index (VQI), and voltage collapse prediction index ($VCPI$). The definitions of these indices are adjusted to be associated with a single VCA as opposed to the entire system. The performance of the voltage stability indices is evaluated on three different networks: IEEE 300-bus, synthetic 2000-bus, and Polish 2746-bus networks. Three criteria are used to compare the performance of the voltage stability indices: profile under stressed conditions, computation complexity, and ability to identify the most critical contingency for each VCA. The results obtained indicate that the sensitivity factor index performs best with different networks under a range of stressing conditions.

KEYWORDS

Sensitivity Factors, Tangent Vector, Voltage Control Area, Voltage Stability, Voltage Stability Index, VQ Analysis.

1. Introduction

Reactive power resources are important for maintaining adequate voltage levels and system voltage stability. However, transferring reactive power over long distances in power grids can incur losses that make it costly and ineffective. Identifying zones of the network within which available reactive resources are effective for voltage control is important for monitoring and, maintaining adequate voltage control capability, and for improving system reliability. EPRI has developed and implemented a methodology and software to identify voltage control areas (VCA) in transmission networks [1]. The concept of electrical distance paired with clustering techniques are used to identify VCA partitions for a given set of network topologies and system operating conditions. The VCA approach is useful in assessing reactive reserve adequacy throughout the system, finding regions with deficient reactive power support or prone to voltage instability, and identifying effective mitigation or control actions to move the system back to secure operation condition and increase reactive power margin.

Various metrics are used in the VCA approach to evaluate reactive power reserve adequacy in each VCA for maintaining voltage stability and security. The voltage security method measures reactive reserve adequacy by its ability to restore voltage to an acceptable level after a branch or generator contingency. This is contrasted with the voltage stability method, which measures reactive reserve adequacy to ensure voltage stability even during the most severe contingency. Clearly, it is necessary to identify the most critical contingency from a list of given contingencies in order to properly evaluate voltage stability metrics. Practically, the methodology to rank contingencies based on their severity and identify the most critical one needs to also be accurate and computationally efficient. Several methods and indices have been proposed in the literature for this purpose [2], [3], [4].

This paper investigates various voltage stability indices (VSI) that can be used to identify the most critical contingency for a VCA. The performance of the VSIs is tested based on their ability to recognize the most critical contingency under a variety of system conditions. VQ analysis is used as a benchmark for measuring the accuracy, in terms of contingency ranking and identification, of the other techniques. Execution time for computing VSIs is another factor considered to compare the indices and select the best option for VCA reactive reserve analysis. Five VSIs are analyzed in this paper: sensitivity factor index (SFI), tangent vector index (TVI), fast voltage stability index ($FVSI$), voltage reactive power index (VQI), and voltage collapse prediction index ($VCPI$). The definitions of these indices are adjusted in this work to be associated with a single VCA as opposed to the entire system. The performance of the voltage stability indices is evaluated on three different networks: IEEE 300-bus, synthetic 2000-bus, and Polish 2746-bus networks.

The content of this paper is as follows: Section 2 briefly introduces the overall approach to identify the most critical contingency and critical bus in each VCA. Section 3 reviews the concept of VQ analysis while Section 4 describes the various of VSIs considered in this work. Section 5 discusses the results and the comparison of the VSIs, and some conclusions are drawn in Section 6.

2. Voltage Stability Contingency Screening and Ranking for VCA approach

Figure 1 shows a flow chart of the proposed approach to identify the most critical contingency in each VCA. For each contingency, the critical bus for each VCA is first identified. In this work, the bus with the highest $\partial V/\partial Q$ in each VCA is considered as the critical bus. This is a well-known characteristic of the power flow Jacobean at the nose point [5], [6], [7]. The next step is calculating the VSI at the critical bus for each VCA. Finally, the contingencies are sorted and the most critical one is identified for each VCA. Unsolved contingencies are flagged for further analysis.

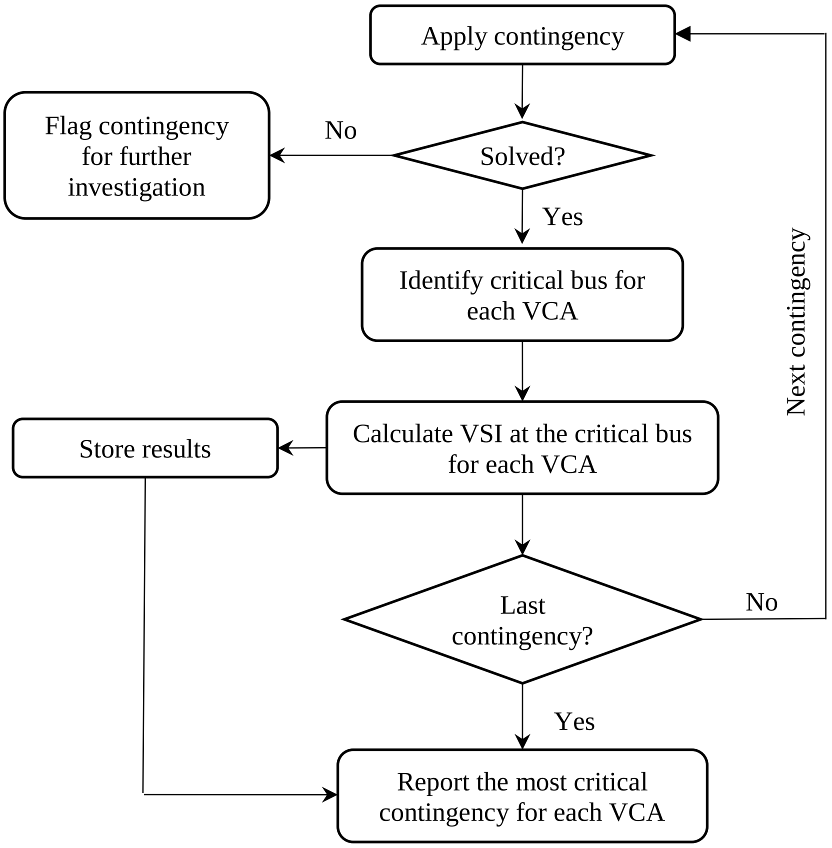

Figure 1: Flow chart of voltage stability contingency screening and ranking for VCA

3. VQ analysis

VQ analysis is used as a reference to compare between different voltage stability indices. VQ analysis can determine the reactive power margin (Qmin), which is the negative of the minimum reactive power value of the VQ curve [7] at all buses of the network. Under different contingencies, the reactive power margin of the buses affected by the contingencies changes. The critical contingency with the minimum margin can then be identified. To perform VQ analysis, a fictitious synchronous condenser is placed at the bus that is being studied. Power flow is used to solve the base case, where no reactive power is absorbed or injected by the synchronous condenser. Then, the scheduled voltage of the synchronous condenser is varied gradually, and the reactive power output of the synchronous condenser is recorded. Finally, the VQ curve is plotted such that the horizontal axis represents the bus voltage and the vertical axis depicts the reactive power output of the synchronous condenser. Negative margin indicates that a reactive power deficiency exists at this bus, and this amount of reactive power is needed to come out of voltage collapse. Positive margin refers to the maximum reactive power loading at this bus before voltage collapse. Figure 2 depicts VQ curves for stable (a) and unstable buses (b).

In the case of contingency screening, VQ analysis is computationally expensive; as for each VQ curve, multiple power flow solutions are required. In this work, screening and ranking of contingencies using different voltage stability indices is compared with the results of the VQ analysis to select the best voltage stability index.

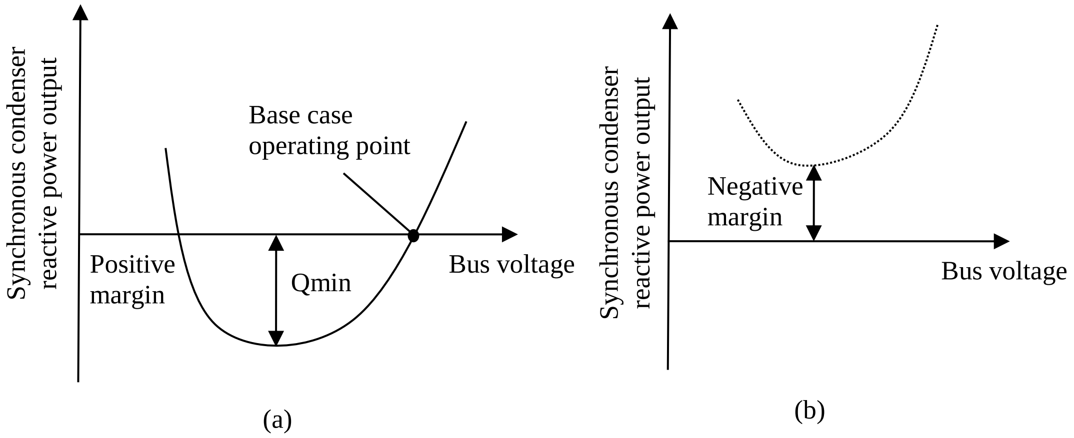

Figure 2: VQ curve, (a) stable case, (b) unstable case

4. Voltage Stability Indices

Several voltage stability indices have been proposed to quantify proximity to the voltage collapse point. The selection of voltage stability index to be used depends on its computational complexity and its ability to identify the same critical contingency identified by VQ analysis. The indices described below are selected from the literature based on their computation complexity.

4.1. Voltage Sensitivity Factor

Voltage sensitivity factor is a well-known index used by several utilities to detect voltage stability problems and to predict voltage control problems [6], [8], [9] . The sensitivity factor index (SFI) of a VCA is defined here as the reciprocal of the voltage sensitivity of the critical bus within the VCA [6]:

$$SFI := \left(\left|\frac{dv_i}{dQ_i}\right|\right)^{-1}, \tag{1}$$

where i denotes the critical bus of the VCA.

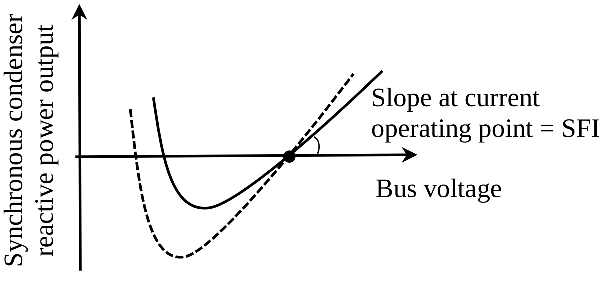

Figure 3: VQ curve and sensitivity factors index

As bus i in the VCA approaches the bottom of the VQ curve, the SFI becomes very small and approaches zero. Figure 3 illustrates the concept of the SFI, which is the slope of the VQ curve at the intersection with the x-axis. When the reactive power margin is reduced, the value of the SFI is also reduced. If the reactive power margin for all contingencies is large, the SFI may be unable to rank these contingencies. SFI works well when the bottom of the VQ curve is close to the x-axis. In other words, it works best when the critical contingencies have a small reactive power margin.

4.2. Fast Voltage Stability Index

In [10], the $FVSI$ is derived based on voltage collapse under contingency condition as given by the following equation:

$$FVSI := max\left\{ \frac{4Z_{ij}^2 Q_j}{V_i^2 x_{ij}} \;\middle|\; (i,j) \in \mathcal{L} \right\}, \tag{2}$$

where $\mathcal{L}$ is the set of lines connected to the critical bus of a VCA, Z_{ij} and x_{ij} are line impedance and reactance, respectively, Q_j is the reactive power at the receiving end, and V_i is the sending end voltage. For stable operation, the magnitude of the $FVSI$ should be less than 1 for each VCA. Reactive power loading of a line is an important factor for voltage stability. Therefore, a large amount of line reactive power transfer with low sending end voltage results in a larger $FVSI$ and indicates that voltage collapse is near.

4.3. Voltage Collapse Prediction Index

The $VCPI$ is proposed in [11] to predict voltage collapse in a power system. Computation of this index requires the system admittance matrix and the bus voltage magnitude and angle. $VCPI$ can be defined as follows:

$$VCIP := \left|1 - \frac{\sum_{k \neq i} V_k'}{V_i}\right|, \tag{3}$$

where i is the critical bus of a VCA,

$$V_k' := \frac{Y_{ik}}{\sum_{j \neq i} Y_{ij}} V_k, \tag{4}$$

and Y denotes the admittance matrix of the network. $VCPI$ varies from zero during normal operation to one at voltage collapse.

4.4. Voltage Reactive Power Index

The VQI is introduced in [12] to determine voltage stability at each line, and to predict system voltage collapse. The VQI for a VCA is defined here as follows:

$$VQI := max\left\{\frac{4Q_j}{|Y_{ij}| \sin(\theta_{ij}) V_i^2} \middle| (i,j) \in \mathcal{L}\right\}, \tag{5}$$

where $\mathcal{L}$ is the set of lines connected to the critical bus of the VCA. Once the VQI approaches unity, the voltage stability limit is reached.

4.5. Tangent Vector Index

The TVI is proposed in [13] and it is the reciprocal of the voltage sensitivity of the critical bus with respect to load variation. This index is computationally inexpensive, as it can be computed at a maximum cost of one additional Newton-Raphson iteration [6]. The TVI for a VCA can be defined from the power flow equations as follows [6]:

$$\begin{bmatrix} d\theta/d\lambda \\ dV/d\lambda \end{bmatrix} = [J]^{-1} \begin{bmatrix} P \\ Q \end{bmatrix}, \tag{6}$$

where λ represents the load increase factor at all buses except the slack bus, J denotes the power flow Jacobean matrix, P and Q are bus power injections, and then

$$TVI := \left|\frac{dV_i}{d\lambda}\right|^{-1}, \tag{7}$$

where i is the critical bus of the VCA. As the collapse point is approached, $dV_i/d\lambda \rightarrow \infty$ and hence, $TVI \rightarrow 0$.

5. Results

Three criteria are used to compare the performance of the different VSIs, in the following order:

1. Identification of the most critical contingency at each VCA
2. Profile of the VSI under stressed conditions
3. Computationally complexity

The performance of the VSIs is evaluated using different test networks and under different loading conditions. PFNET [14] was used to implement and test the VSIs. In this section, the results of the Polish 2746-bus, synthetic 2000-bus, and the IEEE 300-bus networks are presented. Table 1 shows the number of VCAs used in each network.

Table 1: Number of VCAs in each network

Network	Number of VCAs
Polish 2746-bus	13
Synthetic 2000-bus	13
IEEE 300-bus	3

5.1. Critical Contingency Identification

To find the most critical contingency in each VCA, randomly selected N-3 contingencies are generated and applied to the networks. The performance of the VSIs is evaluated to find the critical contingency in each VCA. N-3 contingencies are selected to significantly stress the network and produce meaningful results. As previously mentioned, voltage instability starts locally and then spreads throughout the network. Therefore, some additional weight is given to the VSI that most often succeeded in identifying the critical contingency in the critical VCA. The identification accuracy of a VSI can be defined as the percentage of VCAs for which the most critical contingency is correctly identified. As described earlier, the correct critical contingency is identified by QV analysis. Figure 4 shows a comparison of the identification accuracy of the VSIs. Clearly, the sensitivity factor was the most accurate of the VSIs. $FVSI$ and VQI have similar profiles and accuracies.

For some cases, the Q margins for critical contingencies are approximately the same. Therefore, the ability of VSIs to correctly identify the top three most critical contingencies is also considered. The identification accuracy is measured as the average percentage of number of top-3 most critical contingencies identified for each VCA. Figure 5 shows the accuracy of the VSIs when identifying the top three contingencies for each VCA.

Execution time of each VSI for all VCAs and all contingencies is reported in Table 2. All VSIs had low computation time compared to VQ analysis. The time reported in Table 2 is the total time required to execute the flow chart of Figure 1.

Table 2: The execution time (in minutes) of calculating the VSIs

Network	VQ	$FVSI$	VQI	$VCPI$	SFI	TVI
Polish 2746-bus	113.2	12.10	12.15	12.9	12.0	33.6
Synthetic 2000-bus	1826.1	19.18	19.34	21.5	18.5	42.4
IEEE 300-bus	3.95	0.277	0.286	0.290	0.257	0.34

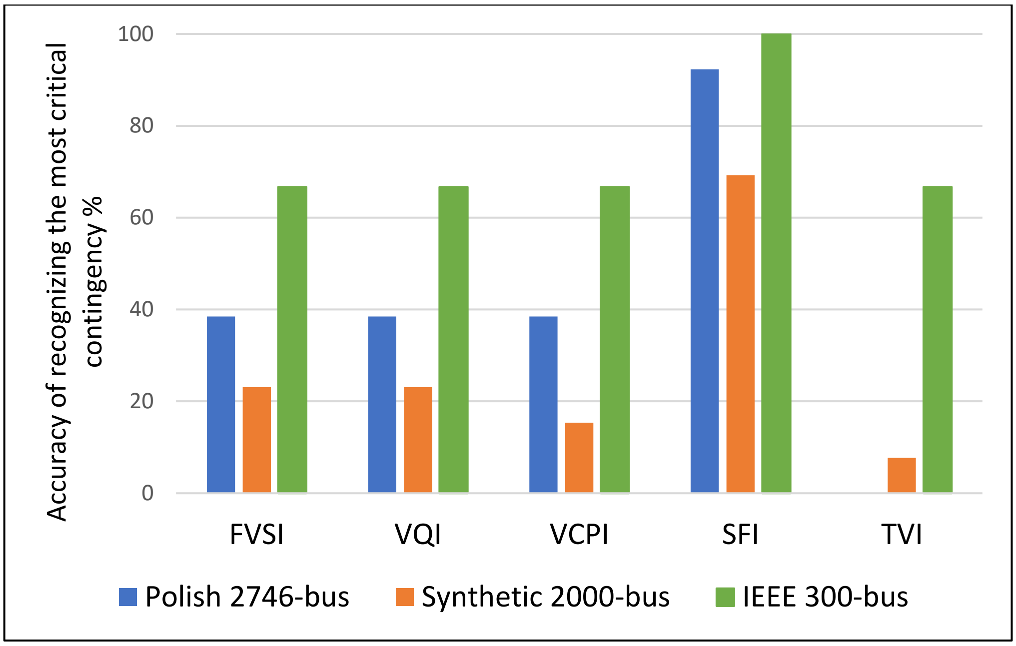

Figure 4: Accuracy of VSIs for identifying the most critical contingency for each VCA

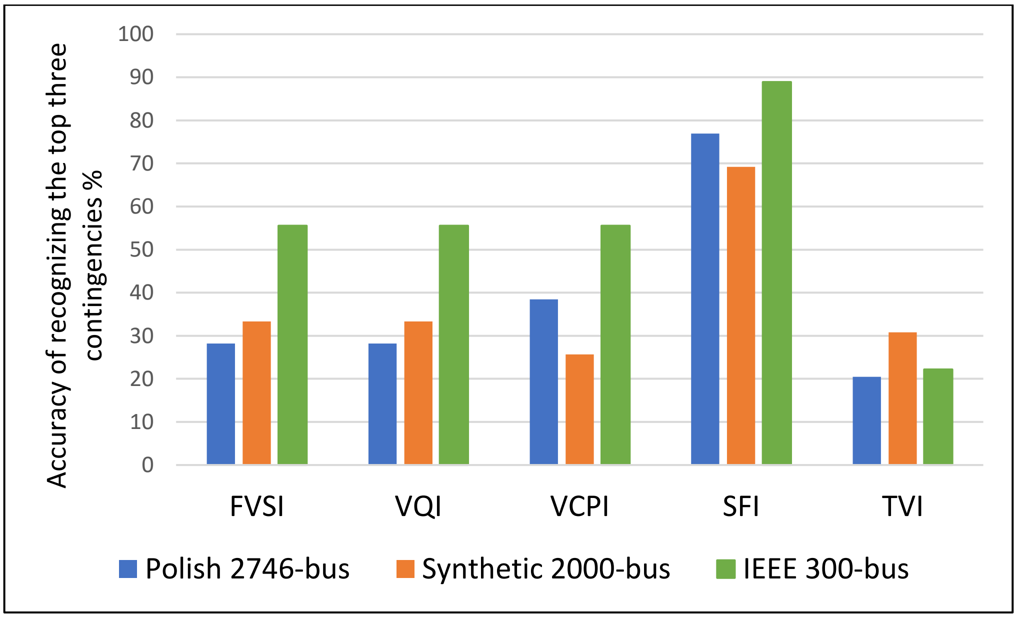

Figure 5: Accuracy of VSIs for identifying the top three critical contingencies for each VCA

5.2. Profile of the VSI under Stressed Conditions

It is important to test the robustness and performance of the voltage stability indices under stressed conditions. The profile of some VSIs near the collapse point becomes highly nonlinear and, in this case, may become less useless for identifying critical contingencies when the system is near the voltage collapse point. To evaluate this, the loading at selected critical buses is increased, and the value of the VSIs are recorded. Figure 6-7 show the VSIs as a function of system loading. *VQI* and *FVSI* have the same profiles. As shown in equations 2 and 5, both indices are the same if $X >> R$ of the line impedance. This is typically true for high voltage transmission networks.

As shown in Figures 6-7, with increased loading, the reactive power margin is reduced until it reaches zero and the system becomes unstable. The profile of the VSIs vary with the system loading. Theoretically, *VQI*, *FVSI*, and *VCIP* change from zero during stable system to one at voltage collapse. In Figure 6, the value of VQI and $FVSI$ exceed one near collapse point, and are small near the collapse point in case of IEEE 300-bus network, as shown in Figure 7. $VCPI$ increases gradually and its value near the collapse point is small. In this case, the value of these VSIs is meaningless as the voltage collapse can occur before these VSIs reach one or after. SFI approaches zero as the loading is increased and the system is closer to the voltage collapse point. TVI changes gradually and then the value starts to drop near the collapse point.

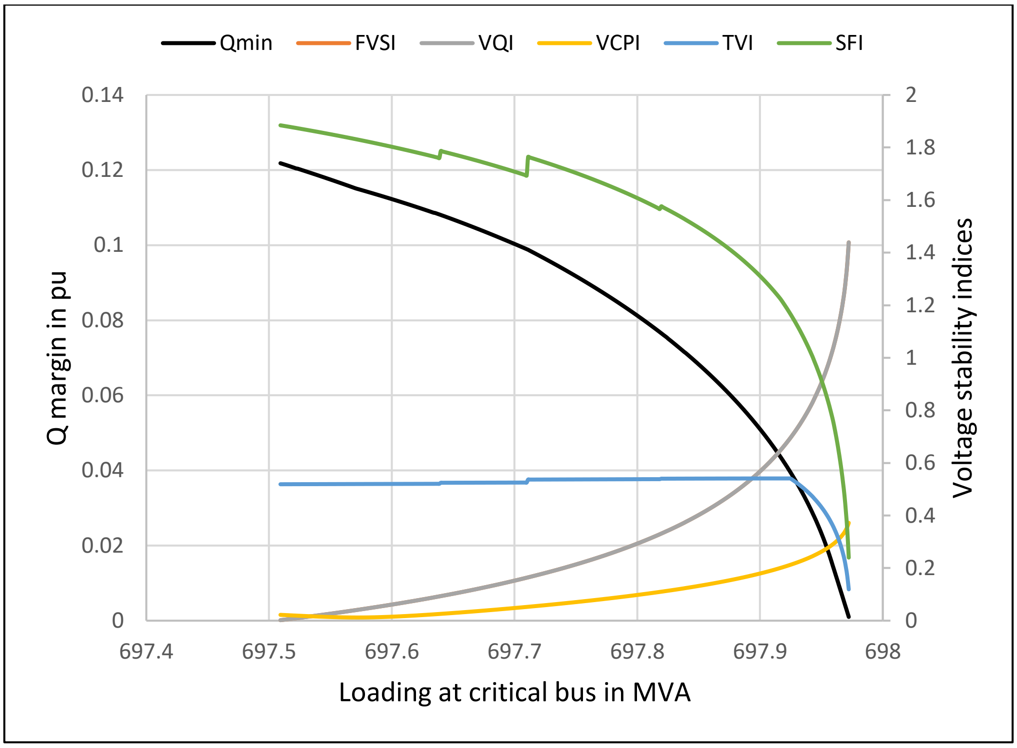

Figure 6: VSIs at bus number 1011, Synthetic 2000-bus network

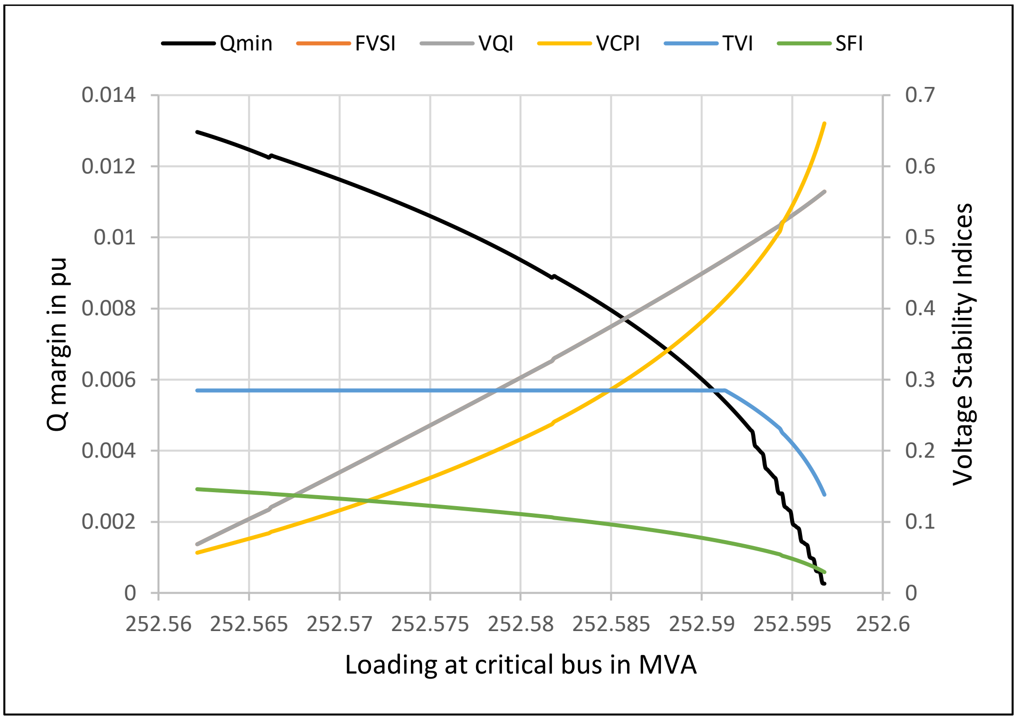

Figure 7: VSIs at bus number 9042, IEEE 300-bus network

6. Conclusions

This paper presents a comparative study of the performance of some voltage stability indices for identifying critical contingencies of VCAs. The results and application of these indices on IEEE 300-bus, synthetic 2000-bus, and the Polish 2746-bus networks are reported. For each contingency, the critical bus for each VCA is recognized and then the voltage stability indices are computed at these critical buses. VQ analysis is considered as a reference for comparison between different voltage stability indices for contingency ranking and selection. Three criteria are used to compare between the voltage stability indices: the performance under stressed conditions, the computational complexity, and the ability to recognize the most critical contingency for each VCA. The results obtained indicate that the sensitivity factor index performs better under different stress conditions and networks compared to other indices.

BIBLIOGRAPHY

[1] "Identification of Voltage Control Areas and Reactive Power Reserves," EPRI, Palo Alto, CA: 2018. 3002013861.

[2] E. Vaahedi, C. Fuchs, W. Xu, Y. Mansour, H. Hamadanizadeh and G. K. Morison, "Voltage Stability Contingency Screening and Ranking," *IEEE Transaction on Power Systems,* vol. 14, no. 1, 1999.

[3] T. V. Cutsem, C. Moisse and R. Mailhot, "Determination of Secure Operating Limits with Respect to Voltage Collapse," *IEEE Transactions on Power Systems,* vol. 14, no. 1, 1999.

[4] H. Chiang and R. Jean-Jumeau, "Toward a Practical Performance Index for Predicting Voltage Collapse in Electric Power Systems," in *IEEE/PES,* Vancouver, BC, 1993.

[5] P. Kundur, Power System Stability and Control, New York: McGraw Hill Publishing Company, 1994.

[6] "Voltage Stability Assessment: Concept, Practices and Tools," Power System Stability Subcommittee, 2002.

[7] "Guide to WECC/NERC Planning Standards I.D: Voltage Support and Reactive Power," Reactive Reserve Working Group, 2006.

[8] P. A. Lof, T. Smed, G. Andersson and D. Hill, "Fast Calculation of a Voltage Stability index," *IEEE Transactions on Power Systems,* vol. 7, no. 1, pp. 54-64, 1992.

[9] C. A. Canizares, A. De Souza and V. Quintana, "Comparison of Performance Indices for Detection of Proximity of Voltage Collapse," *IEEE Transactions on Power Systems,* vol. 11, no. 3, pp. 1441-1450, 1996.

[10] I. Musirin and T. Rahman, "On-line voltage stability based contingency ranking using fast voltage stability index (FVSI)," in *Proceedings of the IEEE/PES Transmission and Distribution Conference and Exhibition*, Yokohama, Japan, 2002.

[11] B. Milosevic and M. Begovic, "Voltage-stability protection and control using a wide-area network of phasor measurments," *IEEE Transactions on Power Systems,* pp. 121-127, 2003.

[12] F. Althowibi and M. Mustafa, "Voltage stability calculations in power transmission lines: Indication and allocations," in *IEEE International Conference on Power and Energy*, 2010.

[13] V. C. M. Ana, G. C. Geraldo, J. C. de Oliveira and A. J. De Morais, "The Use of Tangent Vectors for Voltage Collapse Analysis," in *International Conference on Electric Utility Deregulation and Restructuring and Power Technologies,* London, UK, 2000.

[14] M. Baltzinger, T. T. De Rubira and A. Wigington, "A Modular and Efficient Modeling Library for Power Flow Network Steady-State Analysis and Optimization," in *2018 IEEE Power & Energy Society General Meeting (PESGM),* Portland, OR, USA, 2018.

[15] C. W. Taylor, Power System Voltage instability, McGraw Hill Education, 1994.