Online Assessment of Voltage Stability in Power Systems with PMUs

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Abstract—For the assessment of voltage instability which comprises the detection of voltage instability and identification of critical buses, two indices namely, system wide $Q_{SV}$ and bus-specific $Q_{BV}$, are proposed. The $Q_{SV}$, based on the sensitivity of the reactive power injections to the loading in the system provides early detection of impending voltage instability. The computed $Q_{BV}$ indices identify the critical buses among the load buses in the system. The identified critical buses provide optimal locations for the corrective control actions for averting voltage instability. Additionally, for voltage stability monitoring, determining the point of exhaustion of the reactive reserves in the system is also crucial. This is addressed by proposed Q-Monitoring Index (QMI), which is the ratio of the reactive component of the source current to the sink current that flows through the adjacent transmission line. These proposed indices together can provide early indication to impending voltage instability. This has been illustrated on IEEE-39 bus system. The reactive support on identified critical buses results in maximum increase in the loadability of the system.

Keywords- PMU, synchrophasors, Voltage Stability, loadability, voltage collapse

I. INTRODUCTION

INCIDENCES of blackouts due to voltage collapse have demonstrated that only offline planning measures do not suffice in averting voltage instability. Ever increasing power demand and the market intensive restructured power systems call for online monitoring measures for voltage stability requirement. PMUs in a power system are the devices that synchronously measure voltage and current phasors across the wide-spread power system taking synchronizing signals from almost error free GPS clock signals, so that true phasor representation of the system is possible [3]. Optimal location of PMUs coupled with the system network model can lead to complete system observability [3]. Given that the state-of-the-art PMUs can offer reporting rates as high as 1 set of all voltage and current phasors for every cycle of the fundamental frequency, a true real-time wide area monitoring system based on PMUs has now become a reality. Real-time processed PMU data eliminate the gap between the lab based simulation analyses of the system and the actual operational power system. As such, techniques based on real-time synchrophasors to evaluate the system for voltage stability are going to be of immense importance from the operational perspective.

Several approaches have been reported to compute the proximity to loadability limit of the system. While the early approaches based on PV or QV curves are reliable, the large computational requirements render them ineffective in the real-time environment. The continuation power-flow techniques [4] minimize the computations as compared to load flow analysis, but their applications to large power system and for load rise at several buses increase the size and complexity involved making them cumbersome in real-time applications. Similarly, the techniques based on the singularity of the system Jacobian or its modal analysis [12], [5], [10] are time consuming and do not go with the real-time capabilities that the PMU technology offers. Several sensitivity based analyses have also been reported which require detailed modeling of the system components. The method suggested in [15] is an improvisation, since it does not rely on detailed dynamic model or load models. However, the indication of voltage instability with this approach occurs at a time not sooner than the actual arrival of the loadability limit. A continuous assessment of voltage stability or the proximity to the loadability limit as deduced from the technique proposed here is more desirable. Also from the point of view of computational requirements, the proposed approach is better than the aforementioned approaches. Several methods to identify the thevenin’s impedance of the network as seen from the load bus via multiple snapshots have been reported [20]-[22]. However, since loading at all the other buses is also likely to increase at more or less the same magnitude as the load bus in consideration, the thevenin impedance cannot be accurately determined by multiple consecutive measurements in practical power system. Other reported indices [25] show sudden and unpredictable variations as the system nears its loadability limit or when Q-resources of the system get exhausted which renders them ineffective in giving an early prediction to voltage instability. A need for a simple and
An elegant way to quantitatively assess the voltage security of the system in real-time environment and to give a clearly visible signature for impending voltage instability well ahead in time has been the motivation to develop the indicators discussed here.

The paper presents a solution based on monitoring of the reactive injections in the network at the active sources (generators, synchronous condensers, active compensators) with the help of synchrophasor measurements provided by PMUs. It is known that as the system gets loaded, the reactive losses in the system rise such that at the loadability limit maximum amount of losses are observed. At higher loading conditions, more losses occur and more reactive power needs to be injected into the system. This relationship has been used to define an indicator $Q_{tax}$ based on computation of the reactive injections. The calculation of reactive injections in the system requires the calculation of complex power injections at the generator and the load buses in the system obtained from the set of processed synchrophasor measurements stored in the Phasor Data Concentrator (PDC). The trend of the $Q_{tax}$ indicator is able to provide an identifiable signature to voltage instability. The same concept of monitoring of reactive injections has been extended to identify the critical buses in the network. The reactive compensation at the identified critical buses and lines will be more effective in avoiding voltage instability than at any other buses and lines.

Monitoring of existing reactive resources is also necessary for early prediction of voltage instability. Exhaustion of reactive resources can adversely affect the system and bring down the loadability of the system. Another indicator called Q-Monitoring Index (QMI), proposed here, indicates the exhaustion of Q-reserve in relation to the reactive power demanded by the network. An integrated approach which accumulates all these ideas leads to a complete voltage security monitoring framework.

Section II gives an overall view of the voltage security framework. The indices and methodology introduced above are detailed in III and IV. Simulation studies on IEEE 39 bus system are provided in V, and section VI concludes the paper.

II. OUTLINE OF THE PROPOSED SCHEME

Interaction diagram of the various processes in the proposed scheme is shown in Fig. 1. The measurements obtained from PMUs are collected at a central Phasor Data Concentrator (PDC) located at the control centre of the power system. With optimal location of PMUs and processing of the measurements, full observability of the transmission network can be achieved. Hence, assuming complete observability of the transmission network, the processed measurements shall be used by applications grouped in four modules as shown in Fig.1. The different applications are implemented on cloud architecture for optimal allocation of computing resources. Module 1 applications give quantitative indices that are the measure of proximity of the system to voltage instability and also indicate the most vulnerable lines and buses in the system. Another indicator called
deals with applications in modules 1 and 2. Modules 3 and 4 and cloud implementation are beyond the scope of this paper.

III. PROPOSED INDICES FOR VOLTAGE STABILITY APPLICATION

A. Reactive injection based system wide voltage security index

With the system heading towards the voltage collapse point or the maximum loadability limit, the losses in the network are at maximum. Due to high X/R ratios of the transmission lines, the reactive losses outweigh the real losses. Hence, for practical purposes, it is sufficient to use reactive losses in the network and neglect the real losses. However, one cannot hold a definite threshold value for the reactive losses in the network to characterize uniquely the arrival of maximum loadability limit. It is still possible to use the system losses as an indicator to voltage instability using the following property.

“As the system is heading to voltage instability, the amount of reactive power required to push a definite amount of active power to the loads tends to infinity.”

The above property is due to the fact that all the reactive power pumped by the active sources in the power system is consumed in supplying the losses in the network at the voltage collapse point.

Consider the snapshots of the power-system at instants \( t_n \) and \( t_{n-k} \), such that the total net real-power demand at the present instant \( t_n \) is more than that in the selected past instant \( t_{n-k} \) by a definite amount \( D_{\text{diff}} \). Since the real losses in the network are minimal, one can also select the past instant to have real power generation \( D_{\text{diff}} \) less than the present generation. Indicator \( Q_{\text{tax}} \) is defined as below:

\[
Q_{\text{tax}} = \frac{\left[ \sum Q_G \right]_{n} - \left[ \sum Q_G \right]_{n-k}}{D_{\text{diff}}} \tag{1}
\]

where,

\[\left[ \sum Q_G \right]_{n} \rightarrow \text{the sum of reactive injections at all the active sources at instant } t_n\]

\[t_n \text{ is the present instant, and } t_{n-k} \text{ is the instant for which following is satisfied:}\]

\[
\left[ \sum P_D \right]_{n} - \left[ \sum P_D \right]_{n-k} = D_{\text{diff}} \tag{2}
\]

Where,

\[\left[ \sum P_D \right]_{n} \rightarrow \text{the sum of real power at all the load buses at instant } t_n\]

Both the real and reactive power used in (1) and (2) are calculated using the respective voltage and current phasors obtained by the synchrophasor measurements stored and archived in PDC.

As the power system is loaded, increase in \( Q_{\text{tax}} \) implies more stress on the system. As \( Q_{\text{tax}} \) tends to rise to infinite value, it can be inferred that system is heading towards voltage collapse.

B. Identifying critical buses in the system:

![Figure 1. Illustration for cut-set selection for finding local Q\text{tax,30}](image)

Critical buses can be identified by monitoring the local reactive power requirement around the buses. This can be done by identifying a cut-set around the bus \( j \) comprising of the branches directly incident upon it. We define a local \( Q_{\text{tax},j} \), namely \( q_{\text{tax},j} \) as net rise in reactive power sent through the sending end of all the directly incident branches on the bus \( j \) under consideration. \( q_{\text{tax},j} \) indicates the vulnerability of the bus \( j \) from the point of view of voltage instability.

For the purpose of illustration bus 30 of IEEE-30 bus system is considered. Lines 28-30 and 29-30 are directly incident on bus 30. Hence, the cut-set for bus 30 is as shown in the following figure. The local Q-tax for bus 30 will be:

\[
q_{\text{tax},30} = \frac{Q_{29-30} + Q_{28-30}}{Q_{29-30} + Q_{28-30}} \tag{3}
\]

Note that local Q-tax as is the relative rise in the local reactive requirement of the bus under consideration. In this way it differs from the definition of \( Q_{\text{tax}} \) defined for system. At near the voltage instability point, the buses with high local Q-tax can be considered to be critical buses. The corrective actions to avert the voltage instability like reactive support, or load shedding, will be more effective at these buses. Following three criteria are also considered for verification of identified critical buses.

A1. Buses with highest reactive losses at incident lines
A2. Buses with highest rise of reactive losses at incident lines
A3. Buses with highest rise in reactive power at sending end of the incident lines per unit real power delivered at the load buses

The indices discussed in this section serve the purpose of early identification of voltage instability and critical buses.
which are more prone to voltage collapse. This has been illustrated by application on IEEE-39 bus system in section V. It is also important to monitor the available Q-reserves in the system. Section IV gives an approach to monitor the exhaustion of reactive sources in the system.

IV. Q-RESERVE MONITORING

Exhaustion of reactive reserves such as generators and STATCOMs has a detrimental effect on voltage stability of the system. One way of determining the exhaustion of the resources in the scenario when the resource is not capable of communicating its status is by examining the Q-V sensitivities. Sensitivity of the reactive power generated by reactive resource at bus $i$ to the load bus voltage at bus $k$ connected through bus $j$ can be computed by (4). The key is to express the sensitivity in terms of Jacobian sensitivity factors.

$$S(Q_i,V_k) = \frac{\Delta Q_i}{\Delta V_j} \frac{\Delta V_j}{\Delta Q_j} \frac{\Delta Q_j}{\Delta Q_k}$$ (4)

where $O(m,n)$ represents the Q-sensitivity of the reactive resource at bus $m$ to the voltage at bus $n$ which is the same as the Q-V sensitivity factors of the Jacobian matrix.

$$O(m,n) = \frac{\partial Q_m}{\partial V_n}$$ (5)

Alternatively, one can keep track of reactive currents to determine if a reactive source has exhausted. The reactive current supplied by a source bears a constant ratio with the reactive current on the adjacent line through which the reactive power being supplied by the source is being fed to the network. Thus following indicator Q-Margin Index (QMI), can be defined:

$$QMI = \frac{I_{Q(i,j)}}{I_{O(i,j)}}$$ (6)

Here, $j-k$ is the adjacent transmission line which carries the reactive power supplied by source $i$. When reactive requirements of the network increase, the reactive current $I_{Q(i,j)}$ will increase along with $I_{O(i,j)}$. If QMI decreases, it means the source is responding to the additional reactive requirements of the network. An increase in QMI means that the source has hit its maximum reactive limit and is unable to supply additional reactive power. If the source is capable of communicating the status of reactive power margin left until exhaustion, a pre-intimation of the hitting of the reactive limits can be obtained for early prediction of exhaustion of the reactive resource. For example, AVRs of generators can raise a flag when the field current exceeds limit. Thus before the time when over-excitation limiter of the AVR comes into action, corrective measures can be taken to bring the field current back in the normal operating range.

An illustration of the loadability limit determination on a 4-bus system is given below. The four bus system is the test system given in [2]. The dynamic data and all other relevant details are given in [2]. At 1.0 s one of the two circuits of line 1-4 gets tripped, which is hence forth referred to as contingency 1. Following this, generator 2 begins to supply reactive power greater than the rated value. On account of the inverse-time type over-excitation limiter (OXL) the generator inhibits the field current in the exciter to its rated value at around 71s. This is referred to as contingency 2. The three PV curves shown in Fig. 6 correspond to: 1) normal state with no contingency, 2) post-contingency-1, and 3) post-contingency-2. As can be seen from the latter two PV curves, the system is operating very close to the respective nose-points. The plot of QMI is in confirmation with the observed facts.

As can be seen from the plot, with every change in tap position, there is a fall in QMI until 71 s which indicates that the generator 2 is actively participating in supplying the reactive power required by the system. After 71 s QMI increases with change in tap position. This is because at 71 s, generator 2 over excitation limiter comes into action limiting generator field current to its rated value. Thus, even as the LTC increases the taps, the voltage at the load does not improve.


V. SIMULATION ON IEEE 39 BUS SYSTEM

The proposed indices are tested on a test case on IEEE 39 bus system. The loads at all the load (PQ) buses are increased as per the base case proportion. Correspondingly generations are also raised and distributed as per the base case. The loading is increased until the load-flow fails to converge.

A. Determining voltage instability

The plot of $Q_{tax}$ for the system is shown in the following figure. It can be seen that $Q_{tax}$ rises enormously as the loading at the load buses approaches to around 8900 MW. This is the signature to the impending voltage instability.

B. Determining critical buses

The critical buses for the system are determined by calculating local $Q_{tax}$ at near stability limit point for all the buses in the system. The first ten buses with highest $Q_{tax}$ values are listed below. The critical buses identified with other approaches are given in table 2. Buses 4, 7 and 8 are indicated by almost all the four approaches. These are the most critical buses.

<table>
<thead>
<tr>
<th>Critical Buses</th>
<th>$Q_{tax}$ Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.0174</td>
</tr>
<tr>
<td>3</td>
<td>0.0096</td>
</tr>
<tr>
<td>28</td>
<td>0.0095</td>
</tr>
<tr>
<td>16</td>
<td>0.0073</td>
</tr>
<tr>
<td>8</td>
<td>0.0039</td>
</tr>
</tbody>
</table>

TABLE I. CRITICAL BUSES BY LOCAL Q-TAX APPROACH

Further investigation reveals that bus 7 is the most critical bus in the system. A 100 MVar support applied on bus 7 leads to increase in system loadability by 308 MW. Application of the reactive support at all the other buses leads to lesser rise in the loadability.

C. Observations

Though the trend of $Q_{tax}$ shows a clear signature to indicate the voltage instability, the signature is not definite with fixed thresholds. It is subjective in nature. $Q_{tax}$ is a system-wide quantifier for the stress on the system due to loading of the system. But the quantification is relative in nature. One can decide by looking the trend of $Q_{tax}$ that the present state is more stressed or less stressed than the previous states for which the $Q_{tax}$ data is available. However, this cannot be done by looking at the isolated value of $Q_{tax}$ at given instant - the past trend is important. One can decide thresholds from security point of view by doing system studies.

The computations involved in calculation of indicators are very minimal. They include finding the active and reactive powers from voltage and current phasors obtained from the PDC and computation of the $Q_{tax}$ and QMI indicators.

VI. CONCLUSION

The proposed scheme discussed in the paper comprising of indices $Q_{tax}$, QMI, and local $q_{tax,j}$, assist in early determination of voltage instability. The critical buses in the system identified by different approaches are almost same as the buses indicated by local $q_{tax,j}$ values. One needs to resort to system studies in order to decide on the security thresholds for the value of $Q_{tax}$. Once the thresholds are set, the proposed scheme requires minimal computational efforts for voltage instability determination and for finding critical buses in the system.
VII. ACKNOWLEDGEMENT

The authors are thankful to Prof. D. Thukaram for sharing his valuable insights on the subject of voltage instability. The authors also thank M/S CG Ltd. Mumbai for their valuable financial support for this work.

References