Rensselaer Polytechnic Institute

Report 1
State-of-the-art Voltage Stability Analysis Survey

Submitted to

Lawrence Berkeley National Laboratory
RFP No. DY-2012-1

Voltage Stability Applications using Synchrophasor Data

Submitted by

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March 2013

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1. Introduction

Ever since the voltage-collapse incidents in France [1] and Tokyo, Japan [2], there is a tremendous effort to understand the voltage instability phenomena and develop methods that can be used to assess voltage stability margin of an operating condition.

In order to provide a structure to the discussion in this report, we categorize our voltage stability survey into three classes:

a. Radial system analysis for a single load center
b. Detailed system model analysis
c. Hybrid model analysis

The relationships between these approaches are shown in Figure 1.

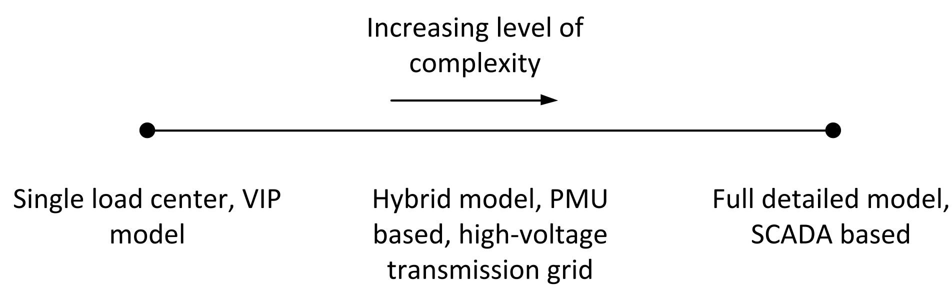
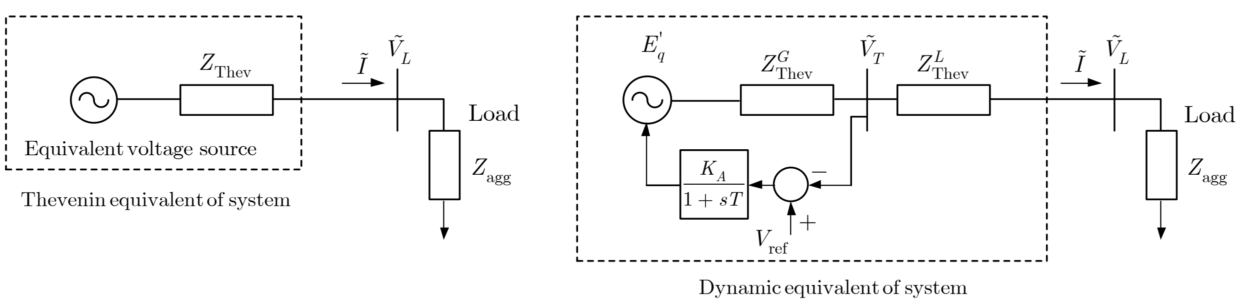


Figure 1: Approaches for investigating voltage stability

Voltage stability techniques using PMU data will be discussed as a fourth category.

2. Radial System Analysis for a Single Load Center

Early understanding of voltage instability has focused on radial load centers connected to a generator bus with a fixed voltage magnitude, as shown in Figure 2(a). This situation has been extensively analyzed in [3,4,5].



(a) (b)

Figure 2: Voltage stability models: (a) VIP model, and (b) dynamic VIP model

The radial power system is modeled by an equivalent Thevenin impedance $|Z_{\text{Thev}}|$ connected to an equivalent voltage source with a fixed voltage $|V_{\text{Thev}}|$. The main idea of this approach is that the load bus voltage is at the critical value when the load impedance $|Z_{\text{agg}}|$ is equal to the Thevenin impedance

$|Z_{\text{Thev}}|$. This is also equal to the maximum power transfer $P_{\max}$. Suppose that the current power transfer is P. Then the voltage-stability margin is $(P_{\max} - P)$. In case if contingencies are considered, then $P_{\max}$ is the maximum power transfer under the worst contingency.

In this technique, beside the radial system requirement, it is important that $|V_{\text{Thev}}|$ and $|Z_{\text{Thev}}|$ are computed properly. This computation can be achieved by using system data or measured data. Analytically, one only needs two sufficiently different sets of load voltage and current to compute the Thevenin voltage and impedance. If more data is available, such as in the case of a PMU continuously monitoring the power system data, a least-squares approach for computing and real-time updating the Thevenin equivalent can be taken. In fact, ABB has a product that supports this approach [6].

As an extension of this approach, because the load increment cannot be known for certain, the stability boundary needs to be determined for the worst power factor load increment, as illustrated in Figure 3.

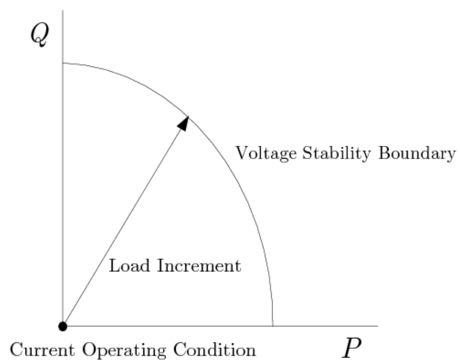


Figure 3: Voltage stability boundary for increments of active load *P* and reactive load *Q*

An enhancement to the Thevenin equivalent model is to include the impact of the voltage regulator, of which a schematic is shown in Figure 2(b). A discussion of such dynamic models can be found in [5].

3. Voltage Stability Analysis of Large Systems

In a large power system, voltage stability is determined by increasing the active and reactive power load until the critical voltage value is reached. Unfortunately the Newton-Raphson loadflow algorithm would diverge because the loadflow Jacobian matrix will become singular at the critical voltage value. This singularity can be measured by the gap between the largest and smallest singular value of the Jacobian matrix. To amend the ill-conditioning situation, the method of homotopy has been proposed [7,8]. In a homotopy method, a parameter λ is introduced and the method of derivative is used to continue the solution. At $\lambda = 0$, one has the initial problem which is readily solved. When $\lambda = 1$ or some other positive value, one obtains the solution to the difficult to solve problem.

When used for voltage stability analysis, given a number of interconnected PQ and PV buses, a loadflow formulation is given by the nonlinear equation

$$f(V, \theta, P, Q) = 0 \tag{1}$$

where V is the bus voltage magnitude, θ is the bus voltage angle, and P and Q are the bus active power and reactive power, respectively, of generators and loads. In the continuation method, a parameter λ is introduced to represent the increase in active and reactive at certain load buses. As a result, the new loadflow equation can be formulation as

$$\overline{f}(V,\theta,P,Q,\lambda)=0 \tag{2}$$

The solution of (2) for each new (increased) value of is obtained in two steps: first, a predictor step is taken to take the variables to be close to the new solution, and second, a corrector step is used to solve for the solution. This process is illustrated in Figure 4 by locating the loadflow solution on a PV curve. For example, at Point 1, the slope of the PV curve is computed and used to advance the system variables to be close to Point 2. This is the predictor step. Then the corrector step is used to iteratively obtain the solution at Point 2. The process would continue until the voltage collapse point is reached.

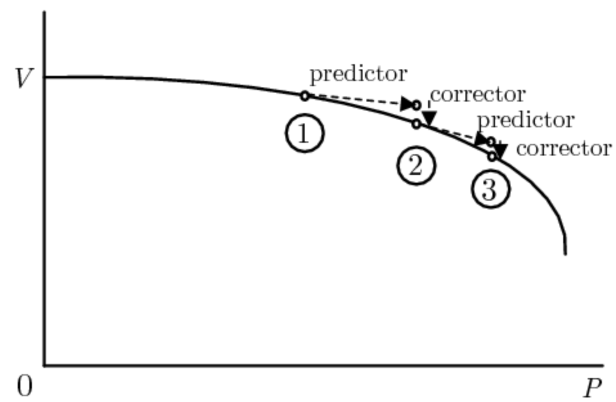


Figure 4: Predictor and corrector in the continuation power flow method

The CPFLOW program [9] demonstrated the application of the continuation method to large power systems, including a 3493-bus system. Currently, the continuation method is available in the Voltage Stability Assessment (VSA) program from Bigwood System, Inc., the IPFLOW program from EPRI (VSTAB), and the VSA program from Power Tech [10]. It should be noted that the Power Tech approach is based on an eigenvalue analysis of the loadflow Jacobian [10].

The ability to compute the critical voltage value and maximum power transfer level in a non-radial power system is important to the success of this project. The continuation method is one mechanism to circumvent the Jacobian singularity. Other mechanism to more directly circumvent the Jacobian singularity condition will be explored.

4. Hybrid Voltage Stability Analysis Approach

For performing real-time voltage stability analysis of a regional load center, the VIP approach may not be applicable and the full-model analysis with the continuation power flow technique may require excessive computational resources. Thus there is incentive to obtain a smaller power system relevant to the power stability analysis of a specific regional load center.

As an illustration, consider the Pacific AC Intertie shown in Figure 5. It is one of the power transfer paths into the Los Angeles area. There are also power transfer paths coming into LA from the east (Nevada and Arizona). The voltage stability analysis of the LA area thus requires a model with several inflow paths. However, the VS analysis of the LA area clearly does not warrant using the complete WECC model. The hybrid approach is to develop a reduced model, possibly with multiple power in-feeds, that would be suitable for the voltage stability analysis of a regional load center. An impetus of the method is the availability of PMU data for model update and sensitivity models at the injection points.

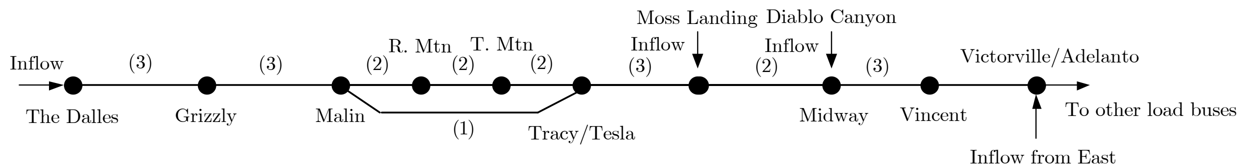


Figure 5: A simplified Pacific AC Intertie

There are some initial research activities in developing the hybrid model approach, notably the work of Dr. Kai Sun [11,12]. In this project, we will provide a systematic procedure to develop hybrid models for voltage stability analysis and investigate efficient methods for calculating voltage collapse points and hence voltage stability margins.

5. Use of PMU Data for Voltage Stability Analysis

If voltage and phasor measurements at a load bus are available, then the load active and reactive power consumption of the load can be measured. Given a disturbance affecting the power transfer to the load center, one can readily obtained a plot of the power versus voltage curve, such as the plot shown in Figure 6, which can be thought of as part of a PV curve [13]. A similar PV curve was obtained for the Southern California Edison System [14]. This technique has been adopted by EPG as a feature in its real-time phasor visualization program RTDMS.

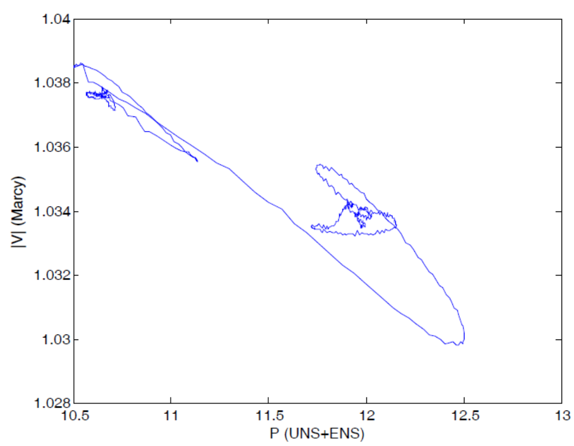


Figure 6: Dynamic PV curve at a Bus in Central New York

In using PMU data for voltage stability analysis, it is important that the measured phasor data are of high quality. For this purpose, we are developing a phasor state estimator to enhance the quality of the phasor data [15,16]. In this project, we will extend this technology to the hybrid VS analysis approach.

6. Voltage Stability Indices

For operation purposes, the outcome of a voltage stability analysis is typically an index or several indices, to allow for the development of some appropriate operator actions. The voltage stability indices include [5]:

1. Reactive power reserves – the amount of automatically activated reactive power reserve in effective locations.
2. Voltage drop – voltage drops as power transfer level increases.
3. MW/MVAR losses – power losses increase exponentially as a system approaches voltage collapse.
4. Incremental steady-state margin – an indicator based on the determinant of the power flow Jacobian.
5. Minimum singular value or eigenvalue – an index the closeness of the minimum singular value or eigenvalue of the power flow Jacobian to zero.

In the project, we propose to use a mix of voltage stability indices, namely reactive power reserves and additional power transfer till the voltage collapse point. We are developing a method that can bypass the singularity condition of the power flow Jacobian matrix and thus can compute robustly the maximum power transfer point.

7. Conclusions

In Report 1, we have provided a brief survey of voltage stability techniques and approaches. This is by no means an exhaustive examination of the voltage stability analysis development for the last 20 plus years. Its main purpose is to provide a background for the approach that we propose to use, and how our approach differs from the other approaches.

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