VOLTAGE STABILITY ASSESSMENT CONSIDERING THE POWER SYSTEM CONTINGENCIES USING CONTINUATION POWER FLOW METHOD WITH REGRESSION

VEERANJANEYULU PUPPALA¹, DR.T.PURNA CHANDRARAO²

¹Associate Professor, Electrical & Electronics Engineering, MRIET, Secendrabad, TS, India.
²Professor (Rtd), Electrical & Electronics Engineering, NIT, Warangal, TS, India.

ABSTRACT

The voltage instability is a serious issue in the modern power systems with rapid voltage droop due to stressed system with increased loading. Many techniques have been given to predict the voltage collapse and maintain the voltage stability of a power system. The Voltage stability index (VSI) is a feature for solving voltage stability problems. In this paper, a new index is proposed and the performance of the new index with other indices is discussed. The effectiveness of the proposed method is demonstrated through numerical studies on IEEE 37 bus system, using several scenarios of load increase. The process known as continuation load flow is used. This paper, by considering of power system contingencies based on the effects of them on Mega Watt Margin (MWM) and maximum loading point is focused in order to analyze the static voltage stability using continuation power flow method. The study has been carried out on IEEE 37-Bus Test System with regression analysis using Mat lab and Psat software’s and results are presented

Keywords: Voltage Stability, Linear Regression, Modal Analysis, Predictor –Corrector Step, Maximum Loading Point, Bus Sensitivity Factor.

I. INTRODUCTION

The change in the loading margin to voltage collapse when line outages occur is estimated. Firsta nose curve is computed by continuation to obtain a nominal loading margin. Then linear and quadratic sensitivities of the loading margin to each contingency are computed and used to estimate the resulting change in the loading margin. The method is tested on a critical area of a IEEE 37 bus system and all the line outages of system in PSAT MATLAB. The results show the effective ranking of contingencies and the very fast computation of the linear estimates using regressive analysis with continuous power flow method (CPF).

In general terms, voltage stability is defined as the ability of a power system to maintain steady voltages at all the buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Instability that may result appears in the form of a progressive fall or rise of voltages of some buses. Voltage stability problems mainly occur when the system is heavily stressed beyond its capability. While the disturbance leading to voltage collapse may be initiated by a variety of causes, the main problem is the inherent weakness in the power system. Many voltage stability indices are based
on the Eigen value analysis or singular value decomposition of the system power flow Jacobean matrix [3], [4].

The prominent methods in voltage stability analysis are those that find system load margin, especially when system contingency is considered p-v curve and q-v curve are most considerable method to find active power margin and reactive power margin. Network configurations and load distributions can also reflect using pv curve.

The linear approach between the generator reactive power reserves and voltage stability margin is related to the system PV curves versus nodal VQ curves. Using this relationship, a systematic and practical method for determining the online voltage stability margin is proposed in [5]. In most of the research work the voltage stability has been considered as static phenomenon. This is due to slow variation of voltage over a long time observed in most of the incident until it reaches to the maximum loading point and then it decreases rapidly to the voltage collapse. Static voltage stability can be analyzed by using bifurcation theory. There are different types of bifurcation theory, in which saddle node bifurcation is used for static voltage stability analysis. This paper is concentrated on the steady state aspects of voltage stability. Indeed, numerous authors have proposed voltage stability indexes based on repeated power flow analysis. In this generally conventional load flow is used. The main difficulty in this method is that Jacobian of NR power flow becomes singular at voltage stability limit (critical point). A power flow solution near the critical point prone to divergences and error. Singularity in the Jacobian can be avoided by slightly reformulating the power flow equations and applying a locally parameterized continuation technique. During the resulting continuation power flow, the reformulated set of equations remains well-conditioned so that divergence and error due to a singular Jacobian are not encountered. The continuation power flow has some disadvantage of creating the Jacobian matrix so linear regression analysis is done for voltage stability assessment.

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II. CONTINUATION POWER FLOW

The purpose of continuation load-flow is to find a continuum of load-flow solutions for a given load/generation change scenario, i.e. computation direction [Ibs96]. It is capable of solving the whole PV-curve. The singularity of continuation load-flow equations is not a problem; therefore the voltage collapse point can be solved. The continuation load-flow finds the solution path of a set of load-flow
equations that are reformulated to include a continuation parameter \([\text{Aj}} 92\). This scalar equation represents phase conditions that guarantee the non-singularity of the set of equations. The method is based on prediction-correction technique. The prediction-correction technique applied to the PV-curve solution is illustrated in Figure 1. The intermediate results of the continuation process also provide valuable insight into the voltage stability of the system and the areas prone to voltage collapse.

**Figure 1.** PV-curve solution using prediction-correction technique.

The prediction step estimates the next PV-curve solution based on a known solution. Taking an appropriately sized step in a chosen direction to the solution path can make the prediction of the next PV-curve solution. However, the prediction is not necessary, especially at the flat part of the PV-curve. The simplest prediction is the secant of last two PV-curve solutions. The computation of the secant is fast and simple. The tangent of last PV-curve solution is more accurate than the secant, but also requires more computation. The advantage of tangent direction is most valuable around the PV-curve nose. The step size should be chosen so that the predicted solution is within the radius of convergence of the corrector. The determination of step size can be based on the slope of tangent or the difference between previous predicted and exact solutions.

### III. CONTINGENCY ANALYSIS

The result of the contingency analysis is the classification of the power system into secure and insecure states. This is an essential part of security analysis. The contingency analysis programs are based on a model of the power system and are used to study outages and notify the operators of any potential overloads or out-of-limit voltages. Contingency analysis is a time-consuming process when the number of contingencies is large. The contingency analysis of one thousand outages would take about 16 min, if one outage case were studied in 1 second. This would be useful if the power system conditions did not change over that period of time. Most of the time spent running contingency analysis would go for solutions of the load-flow model that discovers that there are no problems. The on-line contingency analysis is usually performed with a short contingency list using simplified computation methods. The contingency list is selected according to contingency ranking.

#### A. Contingency selection

The selection of contingencies is needed to reduce the computation time of contingency analysis. Operators know from experience which potential outages will cause trouble. The danger is that the past experience may not be sufficient under changing network conditions. There is possibility that one of the cases they have assumed to be safe may in fact present a problem because some of the operators’ assumptions used in making the list are no longer correct.

The contingency list is dependent on the power system operation point; thus it must be periodically updated. Another way to reduce the list to be studied is to calculate the list as often as the contingency analysis itself is done. To do this
requires a fast approximate evaluation to discover those outage cases which might present a problem and require further detailed evaluation. Many methods have been proposed to solve this problem. The selection of contingencies is based on contingency ranking methods, and contingency ranking is used to estimate the criticality of studied outages. Contingency ranking methods assemble the appropriate severity indices using the individual monitored quantities such as voltages, branch flows and reactive generation.

As discussed in previous section, contingencies ranking are considered as major aspects in surveying contingencies in power system. Processing to contingencies ranking, first we calculate the variables of power system using an analytical method for each event and then the severity of effect in each event are calculated based on a performance indicator that is a function of these variables. Figure 2 shows the flowchart of ranking for contingencies. Attention to figure, appearing each contingency (like line outages and/or generation unit outages), the MLP and its corresponding MWM decrease percent would be calculated by continuation power flow method. Arranging MLP as ascending and its corresponding MWM decrease percent as descending, contingencies with lower MLP and higher MWM decrease percent set in higher ranks. MMWM and MWM calculate for system as:

**Fig. 2 The flowchart for contingencies ranking of first level.**

B. Evaluation of the contingency list

One way of building the contingency list is based on the fast load-flow solution (usually an approximate one) and ranking the contingencies according to its results. The DC load-flow is commonly used for contingency ranking which is a completely linear, non-iterative, load-flow algorithm. This method is used to eliminate most of the cases and run AC load-flow analysis on the critical cases. The DC load-flow solution may be further speeded up by bounding methods. These methods determine the parts of the network in which active power flow limit violations may occur and a linear incremental solution (by using linear sensitivity factors, i.e. generation shift and line outage distribution factors) is performed only for the selected areas. The solution of AC load-flow may be speeded up by attempts to localize the outage effects and to speed up the load-flow solution. The efficiency of the load-flow solution has been improved by means of approximate/partial solutions (such as following the below described 1P1Q method) or using network equivalents. The bounding method may also be applied to the AC load-flow solution. Another localized method for AC load-flow solution is the zero mismatch method.
C. Regression model

Regression analysis [Job92] is the statistical methodology for predicting values of outputs from a collection of input values. The output of regression model is

\[ y = Xw + \epsilon \]  

(1)

Where \( y \) is the output vector, \( X \) is the data matrix, \( w \) is the parameter vector and \( \epsilon \) is the error vector. The output is a linear function of the parameters. The data matrix describes the function to be modeled. A full quadratic polynomial can be expressed as \( X = \{1, x_i, x_j, x_i^2\} \), \( i, j = 1 \ldots p \), where \( p \) is the number of input variables. The error distribution is normal distribution \( N_n(0, s^2I) \), where \( n \) is the number of experiments, \( s \) is the error variance and \( I \) is the identity matrix.

The assumptions related to the model are

- the expected value of errors is zero
- the error variance \( s \) is constant
- errors do not correlate with each other.

The model parameters are solved by least squares estimation. The estimate minimizes the sum-square error (SSE = \( r^TR \)) of the residual vector \( rYw^\dagger \), where \( w^\dagger \) is the estimate of the parameter vector. The minimum of sum-squares error is achieved by solving the normal equations of the least squares estimation problem [Job92]. The solution of the problem is a maximum likelihood estimate for the parameter vector. If the columns of the data matrix are independent, there is an explicit solution for the problem. The output and the parameter estimates are given in Equation 4.2, where \( X^T \) is a pseudo inverse of the data matrix [Net96]. The range of square matrix \( X^TX \) is full and thus it has an inverse.

The developed CPF has been tested on the standard 37-bus system, with its single line diagram shown in Fig. 3. Bus 3 was taken as the test bus for the implementation of CPF. The base condition reactive power at bus 3 was varied gradually until a sharp point of the P-V curve is obtained. The variation of \( p \) at bus 3 along with observation of the bus voltage is illustrated in Fig. 5

IV. RESULTS AND DISCUSSIONS

A. IEEE 37-bus Test System

Buses: 37
Lines: 53
Generators: 15
Loads: 29

Our test system is a IEEE 37-bus system. Stimulated diagram of System with 37 bus is drawn in Psat software in figure 3. This system has 15 generation units that bus 1 is slackbus. Also it has 53 transmission lines, 2 transformers and 29 load buses.

In this system generation unit are modeled as standard PV buses and loads are represented as constant PQ loads. The \( P \) and \( Q \) load powers are not voltage dependent and are assumed to change as follows:

\[
\begin{align*}
P_L &= P_{L0}(1 + \lambda) \\
Q_L &= Q_{L0}(1 + \lambda)
\end{align*}
\]

(2)

Where \( P_{L0} \) and \( Q_{L0} \) are the active and reactive base loads, whereas \( P_L \) and \( Q_L \) are the active and reactive loads at bus \( L \) for the current operating point as defined by \( \lambda \).

To analyze of static voltage stability to survey contingencies of power system (like the line outages and/or generation unit outages) with Psat software [13]. The continuation power flow for normal system manner is done that all generation units and lines are in the network and in fact no contingencies has occurred in system. Maximum Loading Point is \( \lambda_{max} = 3.97 \) p.u.
Also load active powers are in base and maximum cases are\( P_{\text{base}} = 3.626 \text{ p.u.} \) and \( P_{\text{max}} = 10.29 \text{ p.u.} \) respectively. The weakest bus also is identified bus14 with voltage 0.688 p.u.

### A. The results of simulation for single generation unit outages with CPF method and regression analysis

Table I shows the results of single generation units outages applying continuation power flow. As is shown in generation unit outages connected to bus, voltage magnitude in MLP in bus 37 that is known as the weakest bus is 0.68298 p.u. Note that in simulations, the generation unit connected to bus 1 that is known as slack bus does not exit from network.

![Real power profile generator outages](image1)

![Reactive power profile generator outages](image2)

**Fig 4. Real power profile generator outages**

**Fig 3. Reactive power profile generator outages**

### B. The Simulation results of single line outages with CPF method

Results of single line outages applying continuation powerflow are shown in table

It is observed that the position of the weakest bus in nocontingency (bus 05) has changed in 50 % of outages. The outage of line 11 connected to bus 1 to 2 has lowest MLP that in this manner bus 5 is identified as the weakest bus. The results of calculated MWM for contingencies of line outages in zero and first levels are shown in table V. Attention to (6),

<table>
<thead>
<tr>
<th>Generati on unit outage</th>
<th>Bus No with lowest voltage magnitude in MLP (p.u.)</th>
<th>( \lambda_{\text{max}} ) (p.u.)</th>
<th>Pload (p.u.)</th>
<th>Qload (p.u.)</th>
<th>Regressi on analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>0.704</td>
<td>0.8834</td>
<td>0.7067</td>
<td>0.5300</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0.729</td>
<td>1.0955</td>
<td>0.840</td>
<td>0.642</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>0.68298</td>
<td>1.1067</td>
<td>0.8853</td>
<td>0.6639</td>
</tr>
<tr>
<td>12</td>
<td>26</td>
<td>0.69943</td>
<td>1.1429</td>
<td>0.8241</td>
<td>0.6439</td>
</tr>
</tbody>
</table>

**TABLE I : THE RESULTS OF SINGLE GENERATION UNIT OUTAGES.**

The simulation was initially run by conventional P-Vcurve calculation to find the load margin for all possible firstlevel contingencies, and then was tested using the proposed screening method. The program was successfully able to categorize the same contingencies in comparatively shortertime with no error. The complete description of IEEE 37-Bus TestSystem can be found in reference [20]. In the base-case, the total system loading is 2355 MW, the swing bus (bus # 9) generates 24 MW, which is the largest unit following (bus # 12) with 87 MW at generation. The minimum voltage is at bus (bus # 8) with 0.943 p.u and it can observe the real and reactive power in fig.3, fig.4 when the generator outages.
there are ten contingencies in zero and first levels. We set the calculation of MWM with the line outages in first level. Exiting line 11, MWM and its percent calculate 2.0697 p.u. and 31.04 % respectively that decrease more than other line outages. Table II shows contingencies ranking of first level in line outages. Attention to table, outages of lines 05, 11, 22 and 26 are considered as critical lines and are in higher ranks in table. The outage of Line 11 with $\lambda_{max} = 1.527p.u.$ and MWM decrease percent 68.96% is identified as the most critical lines between other line outages. This line because of connection to slack bus (bus 1) and generation unit bus (bus 2) is under high loading, so its outage results in sudden voltage drop and more approximating the system to voltage collapse. Lines 1, 2, 6, 9, 15 and 13 with higher loading point and lower MWM decrease percent are in lower ranks in table and pv curves as shown on critical bus 5 and 6 as shown in fig.5, fig.6.

TABLE II RESULTS OF SINGLE LINE OUTAGES.

<table>
<thead>
<tr>
<th>LINE OUTAGE</th>
<th>BUS</th>
<th>VOLTAGE</th>
<th>LAMDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>Bus 11</td>
<td>0.532</td>
<td>1.1067</td>
</tr>
<tr>
<td>Line 2</td>
<td>Bus 27</td>
<td>0.55941</td>
<td>1.067</td>
</tr>
<tr>
<td>Line 3</td>
<td>Bus 15</td>
<td>0.24865</td>
<td>1.239</td>
</tr>
<tr>
<td>Line 4</td>
<td>Bus 4</td>
<td>0.34596</td>
<td>1.1067</td>
</tr>
<tr>
<td>Line 5</td>
<td>Bus 5</td>
<td>0.69277</td>
<td>1.2149</td>
</tr>
<tr>
<td>Line 6</td>
<td>Bus 5</td>
<td>0.69173</td>
<td>1.21740</td>
</tr>
<tr>
<td>Line 7</td>
<td>Bus 22</td>
<td>0.6241</td>
<td>0.8839</td>
</tr>
<tr>
<td>Line 8</td>
<td>Bus 6</td>
<td>0.6924</td>
<td>1.5427</td>
</tr>
<tr>
<td>Line 9</td>
<td>Bus 11</td>
<td>0.6729</td>
<td>1.2190</td>
</tr>
<tr>
<td>Line 10</td>
<td>Bus 26</td>
<td>0.6921</td>
<td>1.2231</td>
</tr>
</tbody>
</table>

V. CONCLUSION

In this paper to analyze static voltage stability, we set to surveying contingencies of power system (like line outages and generation unit outages) based on ranking these contingencies with continuation power flow method with regression technique based on MLP and MWM decrease percent. The results show that the occurrence of contingencies in power system result in increasing of voltage drop in some of buses, the possibility of change in the weakest bus position, decrease of MLP and so its corresponding decrease of MWM. The contingencies with lower loading point and higher MWM decrease percent dedicates itself higher ranks. So with
identifying these critical contingencies, we can do works to create preventive and reforming strategies to avoid system static voltage collapse.

VI. REFERENCES


