EXAMINATION OF VOLTAGE STABILITY BY CONSIDERING CPF ALGORITHM WITH STATCOM UNDER CONTINGENCY

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ABSTRACT

The use of Continuation power flow (CPF) analysis is introduced in this paper as a means of assessing and analyzing the voltage stability and controlling power flow in large scale -systems. This method initially starts with system base values and progresses to the critical point while continuous maintaining stability even with single precision computation. In the event of transmission line and failure of transformer, the other branches may become overloaded, and there exits the system voltage fluctuations. This paper mainly aims the specific case of line contingency (emergency) and examines the impact STATCOM on various parameters like system voltage, reactive power, and voltage stability using the CPF Algorithm.

Keywords – Continuation Power Flow; Contingency; STATCOM; Stability Index.

1. INTRODUCTION

With an increase and variations in load Voltage stability is becoming a more severe issue as power systems get increasingly complicated. Because to the substantial number of major washouts occurs due to this phenomena, voltage difficulties recovers a source of great concern during the development and power system operation and control. As a result, instruments for Voltage Stability Analysis (VSA) are required in today's Energy Management Systems (EMS).[1],[2].

Indeed, from a various literatures proposed indices of voltage stability that included a power flow analysis of some kind [3],[4],[5],[6],[7],[8]. A special issue addressed in the named analysis that at steady state limit (SL) load flow using Jacobian of Newton Rapson method becomes Divergent. In fact, the Critical point (CP) is defined and termed as steady state limit, and also viewed as power flow divergent of Jacobian flow.

Due to the above analysis the power flow solution nearer to critical parameters are pore to variations and inaccurate [9].

This article explains how to fight the Jacobian's divergence by sluggishly rewriting the equations related with load flow and employing a closely studied follow-up technique [10]. The improved mathematical model is well-conditioned during the consequence, continuous flow of electricity, thus the variation and perturbations in accuracy caused by the unique Jacobian are not encountered.

The uninterrupted flow of electricity is based on solving a set of load flow equations using a predictor-corrector algorithm, which predicts and corrects the values of voltage and power at each point in the power system until a
set of converged solutions is obtained. Load constraints are also incorporated into these equations to ensure the safe operation of the power system. Effective load flow calculations, optimization algorithms, and load constraints are all necessary for the reliable operation of the power system. [11],[12]. It starts with a well-known resolution similar to a modified load parameter value as shown in Fig. 1[13]. The outcomes of the similar Newton-Raphson approach employed for conventional power flow are then utilized to modify this calculation [14]. The limited parameterization discussed above provides a tool for characterizing specific points along the solution lane and demonstrates a crucial role in avoiding the Jacobian's divergence.

For consideration of each bus i of an n bus system, where the subscripts L indicates load bus, G generation bus and T bus injection respectively. And \(V_L, \delta_L, V_T, \delta_T\) are the bus voltages of i and j buses respectively and \(y_{ij}\) is the (i,j)th element of YBUS. And the real and reactive powers at respective buses at ith bus as PLi andQLi terms in the load flow equations must be modified. This can be achieved by splitting each term to two components. Original load at ith bus be \(P_{0_i}\) and \(Q_{0_i}\), which represents first component. The second component represents change in the load parameter \(\lambda\) denoted as \(P_{\lambda_i}\) and \(Q_{\lambda_i}\).

One simple way to add a load parameter to the equations is to use a constant power load model, where the load at each node is represented as a constant power, which is a function of the voltage at that node. The complex power of the load at node i can be expressed as a function of the voltage and the load parameter \(\lambda\). By introducing a load parameter \(\lambda\), the load flow equations become parameterized and can be solved using a continuation technique, which involves solving a sequence of closely related problems as the load parameter \(\lambda\) is varied. This allows for the analysis of the behavior of the power flow as the load changes, and can help to identify potential problems or instabilities in the power system.

First let \(\lambda\) represent the load parameter such that \(0 \leq \lambda \leq \lambda_{critical}\). Where \(\lambda = 0\) corresponds to the base load and \(\lambda = \lambda_{critical}\) corresponds to the critical load. We desire to incorporate \(\lambda\) into

\[
0 = P_{\lambda_i} - P_{0_i} = \sum_{j=1}^{n} V_{ij} y_{ij} \cos(\delta_i - \delta_j - \delta_j) - V_{ij} y_{ij} \sin(\delta_i - \delta_j - \delta_j)
\]

\[
0 = Q_{\lambda_i} - Q_{0_i} = \sum_{j=1}^{n} V_{ij} y_{ij} \sin(\delta_i - \delta_j - \delta_j)
\]

(1)

For consideration of each bus i of an n bus system, where the subscripts L indicates load bus, G generation bus and T bus injection respectively. And \(V_L, \delta_L, V_T, \delta_T\) are the bus voltages of i and j buses respectively and \(y_{ij}\) is the (i,j)th element of YBUS. And the real and reactive powers at respective buses at ith bus as PLi andQLi terms in the load flow equations must be modified. This can be achieved by splitting each term to two components. Original load at ith bus be \(P_{0_i}\) and \(Q_{0_i}\), which represents first component. The second component represents change in the load parameter \(\lambda\) denoted as \(P_{\lambda_i}\) and \(Q_{\lambda_i}\).

Thus,

\[
P_{\lambda_i} = P_{0_i} + \lambda \left( K_{Li} S_{angle} \cos \psi_r \right)
\]

\[
Q_{\lambda_i} = Q_{0_i} + \lambda \left( K_{Li} S_{angle} \sin \psi_r \right)
\]

(2)

From above the terms are defined as Initial (original) values of load at bus i, active and reactive respectively be \(P_{0_i}, Q_{0_i}\), with change in load at ith bus be \(\lambda\), with multiplier to designate the rate of load change be \(K_{Li}\). \(\psi_r\)-power factor angle of load change at bus i. \(S_{angle}\)-a given quantity of apparent power which is chosen to provide appropriate scaling of \(\lambda\).

Along with known terms, the active power generation term can define as:

\[
P_{Gi} = P_{Gi,0} \left(1 + \lambda K_{Gi} \right)
\]

(3)

From above equation at ith bus KGi is a constant used to specify the rate of change in generation as \(\lambda\) varies and With base case consideration ith bus active generation is \(P_{Gi}\) and KGi is a
constant defined the rate of change in generation as \( \lambda \) variation. Now the modified equations with substitution the resultant power flow equations the result is defined as

\[
0 = P_{gb}(1 + \lambda K_{gb}) - P_{b0} - \lambda(K_t L_t S_{base} \sin \psi) - P_{f1}
\]

\[
0 = Q_{gb0} - Q_{b0} - \lambda(K_t L_t S_{base} \cos \psi) - Q_{f1}
\]

(4)

3. CONTINUATION ALGORITHM TECHNIQUE

The problem is defined with a set of equations denoted by \( F \) with consideration of set of variables as shown below:

\[
F(\delta, V, \lambda) = 0, \quad 0 \leq \lambda \leq \lambda_{critical}
\]

(5)

Where \( \delta \) represents the vector of bus voltage angles and \( V \) represents the vector of bus voltage magnitudes. And \( \delta_0, V_0, \lambda_0 \) defines as the base values of the solution within a range \( \lambda \), as the solution path for the conventional power flow.

The mathematical equations implemented in continuation algorithm are represented as give below.

\[
d[F(\delta, V, \lambda)] = F_\delta d\delta + F_V dV + F_\lambda d\lambda = 0
\]

(6)

\[
\begin{bmatrix}
F_\delta & F_V & F_\lambda
\end{bmatrix}
\begin{bmatrix}
d\delta \\
dV \\
d\lambda
\end{bmatrix} = 0
\]

(7)

\[
x_k : \|t_k\| = \max \|f_1, f_2, \ldots, f_m\|
\]

(13)

Where \( t \) is the tangent vector with an equivalent dimension \( m=2n_1+n_2+1 \) and the index \( k \) resembles to the element of the tangent vector that is utmost.

\[
x_k : \|t_k\| = \max \|f_1, f_2, \ldots, f_m\|
\]

(13)

Where \( * \) stands for the expected solution for a future value of (loading) and is a scalar that represents the step size.

\[
\begin{bmatrix}
\delta \\
V \\
\lambda
\end{bmatrix}
= \begin{bmatrix}
\delta \\
V \\
\lambda
\end{bmatrix} + \sigma \begin{bmatrix}
d\delta \\
dV \\
d\lambda
\end{bmatrix}
\]

(10)

This result in

\[
\begin{bmatrix}
F_\delta \\
F_V \\
F_\lambda
\end{bmatrix}
\begin{bmatrix}
\delta \\
V \\
\lambda
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\]

(9)

A new set of equations with considering \( x_k = \eta, \eta \) defined as an \( k \)th elements approximate value, then

\[
\begin{bmatrix}
F(x_k) \\
x_k - \eta
\end{bmatrix} = [0]
\]

(12)

The set of equations can now be solved using a slightly modified Newton-Raphson power flow method once an appropriate index \( k \) and value of \( \eta \) are selected.
4. VOLTAGE STABILITY

In order to analyze the voltage stability, a voltage collapse proximity indication index must be determined. This index provides an approximation of the system's vulnerability to voltage collapse. The voltage collapse proximity indicator can be found using a variety of techniques. The L-index method suggested by Kessel and Glavitsch is one such approach. It is founded on analysis of load flow. Its value is between 0 and 1 (no load condition) (voltage collapse). The bus in the system that has the highest L-index value will be the most at risk.

\[
I_{bus} = Y_{bus}.V_{bus}
\]

By segregating the load buses (PQ) from generator buses (PV), above Equation can write as

\[
\begin{bmatrix}
I_G \\
I_L \\
V_G \\
V_L
\end{bmatrix} = \begin{bmatrix}
Y_{GG} & Y_{GL} \\
Y_{LG} & Y_{LL}
\end{bmatrix} \begin{bmatrix}
V_G \\
V_L
\end{bmatrix}
\]

(15)

where \(I_G, I_L\) and \(V_G, V_L\) represent currents and voltages at the generator buses and load buses.

Rearranging the above equation we get:

\[
\begin{bmatrix}
V_L \\
I_L \\
V_G
\end{bmatrix} = \begin{bmatrix}
Z_{LL} & F_{LG} \\
K_{LG} & Y_{GG}
\end{bmatrix} \begin{bmatrix}
I_L \\
V_G
\end{bmatrix}
\]

(16)

\[
F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}]
\]

(17)

The L-index of the \(j^{th}\) node is given by the expression

\[
L_j = \left| \sum_{i=1}^{m} F_{ij} \left( \frac{V_i}{V_j} \cos \delta_i - \sin \delta_i \right) \right|
\]

(18)

The stability index is given by minimum singular value of jacobian.

5. MODELLING EQUATIONS OF STATCOM

STATCOM's inclusion raises the order of the Jacobian and tangent vectors as well as the power equations for the continuous power flow. STATCOM Jacobian is used in place of conventional Jacobian [21]. The following voltage source representation is assumed as the basis for the power flow equations for the STATCOM.

\[
E_{SR} = V_{SR} (\cos \delta_{SR} + j \sin \delta_{SR})
\]

(19)

After carrying out some composite operations, the subsequent active and reactive power equations are found for the converter and bus k, correspondingly.
\( P_{st} = V_{st}^2 G_{st} + V_{st} V_{s} [G_{st} \cos(\delta_{st} - \theta_s) + B_{st} \sin(\delta_{st} - \theta_s)] \)

\( Q_{st} = -V_{st}^2 B_{st} + V_{st} V_{s} [G_{st} \sin(\delta_{st} - \theta_s) - B_{st} \cos(\delta_{st} - \theta_s)] \)

\( P_{s} = V_{s}^2 G_{s} + V_{s} V_{s} [G_{s} \cos(\delta_{s} - \delta_{st}) + B_{s} \sin(\delta_{s} - \delta_{st})] \)

\( Q_{s} = -V_{s}^2 B_{s} + V_{s} V_{s} [G_{s} \sin(\delta_{s} - \delta_{st}) - B_{s} \cos(\delta_{s} - \delta_{st})] \)

(20)

Using these power equations, the linearized STATCOM model is given below, where the voltage magnitude \( V_{vr} \) and phase angle \( \delta_{vr} \) are taken to be the state variables

\[
\begin{bmatrix}
\Delta P_k \\
\Delta Q_k \\
\Delta P_{vr} \\
\Delta Q_{vr}
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial V_k} & \frac{\partial P_k}{\partial \delta_{vr}} & \frac{\partial P_k}{\partial V_{vr}} \\
\frac{\partial Q_k}{\partial \delta_k} & \frac{\partial Q_k}{\partial V_k} & \frac{\partial Q_k}{\partial \delta_{vr}} & \frac{\partial Q_k}{\partial V_{vr}} \\
\frac{\partial P_{vr}}{\partial \delta_k} & \frac{\partial P_{vr}}{\partial V_k} & \frac{\partial P_{vr}}{\partial \delta_{vr}} & \frac{\partial P_{vr}}{\partial V_{vr}} \\
\frac{\partial Q_{vr}}{\partial \delta_k} & \frac{\partial Q_{vr}}{\partial V_k} & \frac{\partial Q_{vr}}{\partial \delta_{vr}} & \frac{\partial Q_{vr}}{\partial V_{vr}}
\end{bmatrix} \begin{bmatrix}
\Delta \delta_k \\
\Delta V_k \\
\Delta \delta_{vr} \\
\Delta V_{vr}
\end{bmatrix}
\]

(21)

Due to the inclusion of STATCOM the local parameterization vector can be changed as

\[
\begin{bmatrix}
\delta \\
V \\
T_{vr} \\
V_{vr} \\
\lambda
\end{bmatrix}, \quad \begin{bmatrix}
x
\end{bmatrix} \in \mathbb{R}^{2n_1+n_2+1}
\]

(22)

The tangent vector can be changed as

\[
\begin{bmatrix}
F_{\delta} \\
F_{V} \\
F_{T_{vr}} \\
F_{V_{vr}} \\
e_k \\
F_{\lambda}
\end{bmatrix}, \quad \begin{bmatrix}
[1]
\end{bmatrix} = \begin{bmatrix}
0 \\
\pm 1
\end{bmatrix}
\]

(23)

The prediction step equation can be changed as

\[
\begin{bmatrix}
\delta^* \\
V^* \\
T_{vr}^* \\
V_{vr}^* \\
\lambda^*
\end{bmatrix} =
\begin{bmatrix}
\delta \\
V \\
T_{vr} \\
V_{vr} \\
\lambda
\end{bmatrix} + \sigma \begin{bmatrix}
d\delta \\
dV \\
dT_{vr} \\
dV_{vr} \\
d\lambda
\end{bmatrix}
\]

(24)

6.RESULTS AND DISCUSSIONS
Realistic Indian 75 bus test system is used as input in this paper. The uttarpradesh-75 bus system is represented by this real-world test system. At bus -75, the voltage magnitude and voltage angle are seen. With the change in load(λ), the voltage's magnitude and angle will change.

The value of λ depends on knee point, its value increases there after the knee decreases. Multiple contingencies are applied by detaching the lines connected between 39-31, 21-65, 18-71. The results are considered in the both the cases with and without STATCOM inclusion of STATCOM are discussed.

Table 1: With multiple contingency 39-31,21-65,18-71 with out STATCOM [1]

<table>
<thead>
<tr>
<th>Change in load (λ)</th>
<th>Voltage magnitude at bus 75</th>
<th>Voltage angle at bus 75</th>
<th>L-index Value maximum</th>
<th>L-index at bus 75</th>
<th>Stability Indicator</th>
<th>Loss of Power-Active</th>
<th>Loss of Power-Reactive</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0015</td>
<td>0.9999</td>
<td>-0.6755</td>
<td>0.5283</td>
<td>0.2026</td>
<td>0.0603</td>
<td>2.1327</td>
<td>6.8401</td>
</tr>
<tr>
<td>0.0045</td>
<td>1.0016</td>
<td>-0.6819</td>
<td>0.5272</td>
<td>0.2024</td>
<td>0.0603</td>
<td>2.1399</td>
<td>6.8880</td>
</tr>
<tr>
<td>0.0090</td>
<td>1.0041</td>
<td>-0.6916</td>
<td>0.5249</td>
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<td>0.0603</td>
<td>2.1546</td>
<td>6.9871</td>
</tr>
<tr>
<td>0.0150</td>
<td>1.0074</td>
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<td>0.5216</td>
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<td>0.0603</td>
<td>2.1774</td>
<td>7.1442</td>
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<td>1.0116</td>
<td>-0.7205</td>
<td>0.5174</td>
<td>0.2011</td>
<td>0.0603</td>
<td>2.2091</td>
<td>7.3695</td>
</tr>
<tr>
<td>0.0285</td>
<td>1.0158</td>
<td>-0.7365</td>
<td>0.5126</td>
<td>0.2006</td>
<td>0.0602</td>
<td>2.2509</td>
<td>7.6768</td>
</tr>
<tr>
<td>0.0330</td>
<td>1.0199</td>
<td>-0.7526</td>
<td>0.5081</td>
<td>0.2003</td>
<td>0.0602</td>
<td>2.2952</td>
<td>8.0125</td>
</tr>
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<td>0.0360</td>
<td>1.024</td>
<td>-0.7687</td>
<td>0.5039</td>
<td>0.2002</td>
<td>0.0601</td>
<td>2.3419</td>
<td>8.3768</td>
</tr>
<tr>
<td>0.0375</td>
<td>1.0281</td>
<td>-0.7848</td>
<td>0.5001</td>
<td>0.2003</td>
<td>0.0601</td>
<td>2.3910</td>
<td>8.7696</td>
</tr>
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<td>0.2006</td>
<td>0.0600</td>
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<td>9.1910</td>
</tr>
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<td>0.4934</td>
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<td>9.6411</td>
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<td>0.0325</td>
<td>1.0360</td>
<td>-0.8330</td>
<td>0.4905</td>
<td>0.2017</td>
<td>0.0599</td>
<td>2.5533</td>
<td>10.1199</td>
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<tr>
<td>0.0285</td>
<td>1.0446</td>
<td>-0.8491</td>
<td>0.4879</td>
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<td>10.6274</td>
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<td>11.1638</td>
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<td>-0.8813</td>
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<td>0.2046</td>
<td>0.0596</td>
<td>2.7380</td>
<td>11.7291</td>
</tr>
<tr>
<td>0.0060</td>
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<td>-0.8974</td>
<td>0.4817</td>
<td>0.2059</td>
<td>0.0595</td>
<td>2.8045</td>
<td>12.3233</td>
</tr>
<tr>
<td>-0.0045</td>
<td>1.0608</td>
<td>-0.9134</td>
<td>0.4802</td>
<td>0.2073</td>
<td>0.0595</td>
<td>2.8736</td>
<td>12.9463</td>
</tr>
</tbody>
</table>
Figure 4. Angle at bus 75 with STATCOM under contingency

Figure 5. Maximum L index with STATCOM under contingency

Figure 6. Stability index with STATCOM under contingency

Figure 7. Value of active power loss with STATCOM under contingency
The obtained result of this analysis is compared with the results obtained for without inclusion of STATCOM [1].

From the result obtained several conclusions have been made. With step perturbation in load, the inclusion of STATCOM there is a vast change in watt-full and watt-less components of power losses with change in potential magnitude and phase angle under several multiple contingency by detaching the lines connected between 39-31, 21-65, 18-71 there is an improvement in stability index, improvement in voltage profile and reduction in the true power loss and apparent power losses.

This method of Continuation Power flow does not applicable for distribution systems as this method uses basics of Newton Raphson method.
Figure 9. Value of Voltage at bus 75 with and without STATCOM under contingency

Figure 10. Value of Voltage angle at bus 75 with and without STATCOM under contingency
Figure 11. Maximum value of L index with and without STATCOM under contingency

Figure 12. Value of L index at bus 75 with and without STATCOM under contingency
Figure 13. Value of Stability index with and without STATCOM under contingency

Figure 14. Value of Active Power loss with and without STATCOM under contingency
Figure 15. Reactive Power loss Value with and without STATCOM under contingency

6. CONCLUSION

The example provided in this paper demonstrates both the CPF's capacity and its effectiveness. For many outcomes of burden fluctuation, solutions tracks up to and beyond the CP have been established. Variance is never a problem in any of the situations, unlike with the traditional Newton-Raphson power flow. This paper discusses the voltage profile and power losses for multiple contingencies using a CPFA with and without inclusion of STATCOM. we can also conclude that by inclusion of STATCOM stability, voltage profile improved and losses reduced.

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