Comparative Study of the Voltage Stability of an High Voltage Power Grid: Case of the Power Grid of the Electric Community of Benin

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Abstract: The voltage profile at the buses of an high voltage power grid makes it possible to predict the voltage stability of said power grid in order to guarantee production-consumption adequacy. The study presented in this paper is initially restricted to the variation of the active power demand of a consumption bus (PQ) in order to obtain the voltage profile of the entire electricity transmission network. Then, it makes it possible to predict the limit of the maximum increase in power demand at a PQ bus with the corresponding voltage level of all the other buses in order to anticipate the instability of the voltages liable to cause the collapse of the network. Finally, to correct the voltage levels linked to the observed instability, the study proposes the comparison by voltage sensitivity factors of two types of compensation such as shunt compensation and compensation by adding reactance to the line transmission. The Newton-Raphson method coupled with Predictor-Corrector methods was used for the Continuation Power Flow (CPF) on the electricity transmission network of the Benin Electric Community (CEB). The results from the bus voltage profile curves for the case of the CEB power grid have shown that the two types of compensation make it possible to recover the lost voltage stability. However, shunt compensation is best due to its lower voltage stability sensitivity factor. This study has the advantage of allowing the power grid operator to anticipate the instability of the tensions in the power grid in order to avoid its collapse. It thus helps the manager to properly plan the voltage stability of his power grid.

Keywords: Continuation Power Flow, Newton-Raphson, Voltage Profile, Shunt Compensation, Transmission Line Reactance, Voltage Stability Sensitivity Factor

1. Introduction

High Voltage (HV) power grid serve as a link between production centers and large areas of electrical energy consumption; these networks are said to be electrical energy transport or even interconnection [1]. They are characterized by buses with which are associated production groups, loads (consumption), lines and electrical energy transformers. This leads to the electrical system consisting of the production, transport and consumption (loads) of electrical energy, the main objectives of which are the search for quality and the reduction of operating costs while respecting the security constraints of said system. The major safety constraints in an HV power grid are the stability limit and the voltage profile [2].

Stability is linked to the power transit capacity of the
transmission lines [3, 4]. The profile of the voltages at the
power grid buses makes it possible to evaluate the variation
in the voltage of each bus of the network in order to control
the stability of the said power grid within its limits to
guarantee a production - consumption adequacy [5]. Several
studies have been done on voltage stability based on repeated
analyzes of the power flow (PF) with the Newton-Raphson
method [6]. The major difficulty of this method is the
Jacobian matrix of Newton-Raphson which becomes
singular at the critical point of the limit of stability in tension;
which leads to an error and a divergence in the solution of the
power flow at the critical point, [6, 7, 8]. To remedy these
shortcomings, we reformulate the PF equations by applying a
local technique of continuous parameterization called
Continuation Power Flow (CPF) [6, 9]. The CPF method
makes it easy to study the voltage stability of electrical
systems as in several studies [6, 10, 12]. The stability of the
power grid using the CPF after insertion of a wind power
plant in said grid has been studied in [11]. CPF was used in
[12] to simulate the near-stable state of an electrical system.
In [13], it developed the simulation of dynamic load
restoration using CPF. (ZHAO & al. 2015) contributed in [10]
from CPF to the study of voltage stability according to the
evolution of the load at the border between the transmission
network and the energy distribution network electric. Sudden
drops in voltage at buses in an power grid have been
investigated in [14] using the CPF. These studies are aimed
at preventing voltage instability due to increased demand for
electrical energy, which could lead to the collapse of power
grid. Avoiding the collapse of power grid implies finding a
solution for restoring voltage stability, hence the
compensation measures or at worst the shedding of certain
loads. There are several compensation modes [9] among
which we can cite Generator AVRs, Under-Load Tap
Changers, Shunt Capacitors, Series Capacitors, Shunt
Reactors, Synchronous Condensers.

In this paper, the objective is to predict not only the limit of
the maximum increase in power demand at a PQ bus but also
the voltage instability in order to provide an acceptable
compensation. Two compensation modes such as Shunt
Capacitors and Series Capacitors are presented and compared
for the case of the CEB's HV power grid. For the choice of the
appropriate compensation mode, it was first carried out to vary
the active power demand of a PQ consumption bus in order to
obtain the voltage profile of the entire electricity transmission
network. Then, the limit of the maximum increase in power
demand at the PQ bus with the corresponding voltage level of
all other buses was predicted in order to anticipate the
instability of the voltages that could cause the grid to collapse.
Finally, the correction of the voltage levels linked to the
observed instability, is obtained through compensations such
as shunt compensation and compensation by adding reactance
to the transmission line with the determination of their voltage
sensitivity factors. The study presented in this paper is based
on the Newton-Raphson method coupled with the
Predictor-Corrector methods used for Continuation Power
Flow (CPF). So this paper is structured as follows. After the
introduction, we first explain the CPF method used, followed
by the presentation of the CEB's HV power grid. Then the data
processing with the results is carried out and finally the
analyzes and discussions are presented followed by the
conclusion.

2. The Continuation Power Flow Method: CPF

The CPF method begins with the basic conditions using
conventional solutions of load distribution (Load Flow: LF)
from the Newton-Raphson algorithm to calculate the basic
parameter denoted λ. To do this, we reformulate the Load
Flow equation to introduce a load parameter λ. We rewrite the
Load Flow equation in a matrix form known as the Jacobian
matrix J.

Consider the conventional Load Flow equation defined in
relation (1), [14].

\[ \begin{bmatrix} P_i - P_{gi} + P_{Li} \\ Q_i - Q_{gi} + Q_{Li} \end{bmatrix} = 0 \]  

avec:

\[ P_i = \sum_{k=1}^{n} V_i V_k Y_{ik} \cos(\delta_i - \delta_k - \theta_{ik}) \]  

\[ Q_i = \sum_{k=1}^{n} V_i V_k Y_{ik} \sin(\delta_i - \delta_k - \theta_{ik}) \]

where: \( P_i \) and \( Q_i \) are respectively the active and reactive
powers at node \( i \); \( P_{gi} \) and \( Q_{gi} \) the active and reactive
power consumed at the bus \( i \); \( V_i \), \( \delta_i \) and \( \theta_{ik} \) the voltages at buses
\( i \) and \( k \); \( Y_{ik} \) the admittance \((i, k)\) element of the Ybus
admittance matrix; \( n \) is the total number of buses in the power
grid.

By asking \( P_i^{PQ} = P_{gi} + P_{Li} \) and \( Q_i^{PQ} = Q_{gi} + Q_{Li} \), we
rewrite relation (1) in relation (4).

\[ g(\delta, V) = \begin{bmatrix} P(\delta, V) - P^{PQ} \\ Q(\delta, V) - Q^{PQ} \end{bmatrix} = 0 \]

where: \( P(\delta, V) \) and \( Q(\delta, V) \) are the vectors of the active and
reactive power of the power grid; \( \delta \) variable vector
composed of the angle and the magnitude of the voltage of
each bus of the power grid; \( P^{PQ} \) and \( Q^{PQ} \) are the vectors of the
active and reactive power injected from each bus of the
network.

In order to know the state of the electrical system for
different load factors, we must add a state variable \( \lambda \)
to equation (4); we can obtain the plot of \( \delta \) and \( V \) by varying \( \lambda \)
[7]. The system of equation (4) then becomes that of relation
(5).

\[ f(\delta, V, \lambda) = \begin{bmatrix} P(\delta, V) - \lambda P^{PQ} \\ Q(\delta, V) - \lambda Q^{PQ} \end{bmatrix} = 0 \]

where: \( \lambda \) is the continuous parameter such that \( 0 \leq \lambda \leq \lambda_{\text{max}} \).
In the Newton-Raphson method (method not developed in this paper) for Load Flow, the reformulated Jacobian matrix of the system of equations (5) is written at relation (6), [7].

\[
J(\delta, V, \lambda) = \begin{bmatrix}
\frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_n} & \cdots & \frac{\partial P_1}{\partial \delta_m} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
\frac{\partial P_n}{\partial \delta_1} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \cdots & \frac{\partial P_n}{\partial \delta_m} \\
\frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_n} & \cdots & \frac{\partial Q_1}{\partial \delta_m} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
\frac{\partial Q_m}{\partial \delta_1} & \cdots & \frac{\partial Q_m}{\partial \delta_n} & \cdots & \frac{\partial Q_m}{\partial \delta_m}
\end{bmatrix}
\]  

(6)

This Jacobian matrix makes it possible to find the point of bifurcation of the system by systematic gradual increase of the load factor \( \lambda \) of the system thanks to the CPF. CPF techniques are a very robust tool for the calculation of trajectories of one or more parameters [7]. The considered system is summarized by relation (5).

Continuation Power Flow (CPF) is an iterative process which from an initial solution defined by \( (\delta^0, V^0, \lambda^0) \), consists to calculate a new situation \( (\delta^{j+1}, V^{j+1}, \lambda^{j+1}) \) with \( \lambda^j > \lambda^{j+1} \). This process thus converges towards \( \lambda_{\text{max}} \).

The CPF is then carried out in three steps, namely parametrization, prediction and correction.

### 2.1. Parametrization

Parametrization is mathematically a means of identifying each solution so that the next or previous solution can be evaluated. In this paper, the natural parametrization which takes directly \( \lambda \) as a parameter has been used according to relation (7).

\[
p^j(\delta, V, \lambda) = \lambda - \lambda^j - \sigma = 0
\]  

(7)

where: \( \lambda^j \) is the initial parameter; \( \lambda \) the new parameter and \( \sigma \) continuous measurement of the step.

### 2.2. Prediction

Prediction is the process of producing an estimate

\[
\begin{bmatrix}
\delta^j & V^j & \lambda^j
\end{bmatrix} = \begin{bmatrix}
\delta^j & V^j & \lambda^j
\end{bmatrix} + \sigma \bar{Z}_j
\]  

(8)

with:

\[
\bar{Z}_j = \frac{z_j}{||z_j||_2}
\]  

(9)

where: \( z_j = [d\delta \ dV \ d\lambda] \) is the tangent vector; \( \bar{Z}_j \) is the normalized tangent vector; \( e_k = \begin{bmatrix} p_\delta^j & p_v^j & p_\lambda^j \end{bmatrix} \) is the appropriate and dimensioned row vector such that all its elements are zero except the \( k^{\text{ème}} \) element that is worth \( \pm 1 \) he sign of the variation; \( k \) is the index of the maximum component of the tangent vector respecting the relation (11), [14].

\[
(\delta_k, V_k, \lambda_k): [z_k] = \max \{ |z_1|, |z_2|, \cdots |z_N| \}
\]  

(11)

where: \( N=2n_1 + n_2 + 1 \) with \( n_1 \) the number of buses PQ and \( n_2 \) the one of generation buses PV.

### Table 1. The data of the CEB’s HV power grid buses.

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Figure 1. Principle of Continuation power flow.

Figure 2. CEB's HV power grid.
2.3. Correction

The correction step provides the new solution \((\delta^{i+1}, V^{i+1}, \lambda^{i+1})\) by correcting the predicted solution \((\delta^i, V^i, \lambda^i)\). The Newton-Raphson method is used to find this new solution by solving the equation system of relation (12).

\[
\begin{bmatrix}
\frac{\partial f(\delta, V, \lambda)}{\partial \delta} \\
\frac{\partial f(\delta, V, \lambda)}{\partial V} \\
\frac{\partial f(\delta, V, \lambda)}{\partial \lambda}
\end{bmatrix}
= 0 \quad (12)
\]

The principle of continuation power flow is shown in Figure 1.

3. Materials

The CEB's HV power grid shown in Figure 2 and made up of 13 buses and 14 power transmission lines is used in this paper. Matpower 6.0 [15] software in a Matlab R2016a environment was used.

The data from the HV power grid were processed and modeled according to the format of Matpower, [15, 16]. The data of the CEB's HV power grid buses are presented in table 1.

Legend of table 1. ATA: Atakpamé; AVA: Avakpa; BOH: Bohicon; CVE: Cotonou-Vedogou; KAR: Kara; LAF: Lomé-Aflao; LPO: Lomé-Port; MOM: Mome-hagou; ONI: Onigbo, SAK: Sakete; a: Design; b: Bus type (1=PQ, 2=PV, 3=Slack, 4=isolated); c: bus number (positive integer); d: real power demand Pd [MW]; e: voltage magnitude Vm (p.u.); f: reactive power demand Qd [MVAr]; g: shunt conductance Gs (MW demanded at V=1.0 p.u.); h: shunt susceptance Bs (MVAr injected at V=1.0 p.u.); i: number area (positive integer); j: voltage magnitude Vmax (p.u.); k: base voltage (kV); l: loss zone (positive integer); m: maximum voltage magnitude Vmin (p.u.); n: minimum voltage magnitude Vmin (p.u.).

The buses are distributed as follows: 03 PV bus, 01 slack bus and 09 PQ bus.

Table 2 contains the formatted data of the electrical energy transmission lines of the CEB's HV network.

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</tbody>
</table>

Legend of table 2. 1. F_BUS " from" bus number; 2: T_BUS " to" bus number; 3: BR_R resistance (p.u.); 4: BR_X reactance (p.u.); 5: BR_B total line charging susceptance (p.u.); 6: RATE_A MVA rating A (long term rating), set to 0 for unlimited; 7: RATE_B MVA rating B (short term rating), set to 0 for unlimited; 8: RATE_C MVA rating C (emergency rating), set to 0 for unlimited; 9: TAP transformer off nominal turns ratio, (taps at " from" bus, impedance at " to" bus, i.e. if r=x=b=0, tap=|Vf /Vt|); 10: SHIFT transformer phase shift angle (degrees), positive) delay; 11: BR_STATUS initial branch status, 1=in-service, 0=out-of-service; 12: ANGMIN minimum angle difference, 0f - 0t (degrees); 13: ANGMAX maximum angle difference, 0f - 0t (degrees).

4. Methodology

The adopted compensation comparison methodology is presented in Figure 3. In this methodology, we define at each load bus i PQ the sensitivity factor \(S_{V_i}\) of the voltage stability by equation (13).

\[
S_{V_i} = \frac{dV_i}{dP_{Total}} \quad (13)
\]

where \(dV_i\) is the variation of the voltage in per unit (pu) at the bus i and \(dP_{Total}\) the lower this sensitivity factor to a bus i compared to another bus j, the more stable the bus i. The voltages of the buses of the power grid are subjected to a constraint of magnitude margin V according to equation 14 to guarantee the stability of the network.
5. Results

By varying the active power demand on bus 6 of the CEB’s power grid via the load factor lambda \( \lambda \), the voltage magnitude of the nine (09) PQ buses is obtained through the network voltage profile. Figure 4 shows the voltage profile.

The critical voltage at bus 6 is 0.5616 pu for a maximum load factor \( \lambda_{\text{max}} \) equal to 0.2705. This led to making the two types of compensation, namely the shunt compensation to bus 6 and the compensation by reactance of the transmission line on line (2-6) of the CEB’s power grid. Figures 5 and 6 show the voltage profile curves of the two types of compensation at bus 6.

While respecting the constraints related to the minimum and maximum magnitudes on bus 6, the results retained for the two types of compensation are summarized in Table 3.

Once the two types of compensation have been able to bring the maximum voltage of bus 6 to values greater than 0.9 pu, then we add a shunt of 0.6 pu to bus 6 and we bring back the reactance \( X_{2-6} \) of the line (2-6) to 0.1 \( X_{2-6} \). For each type of compensation with the optimal values in table 3, continuous power flow is carried out to obtain the profile of the voltage.

\[
V_{\text{min}} \leq V \leq V_{\text{max}}
\]
amplitudes of all the PQ buses in the network. Figures 7 and 8 show these profiles.

**Figure 4.** Voltage magnitude at all PQ buses by variation of load at bus 6.

**Figure 5.** Voltage magnitude for compensation by transmission lines reactance X2-6.

**Figure 6.** Voltage magnitude by adding shunt capacitor for compensation at bus 6.
Table 3. Results of two types of compensation at bus 6 in CEB’s power grid.

<table>
<thead>
<tr>
<th>Type of compensation</th>
<th>$V_{\text{max}}$ [pu]</th>
<th>$V_{\text{critical}}$ [pu]</th>
<th>Load parameter $\lambda_{\text{max}}$ [pu]</th>
<th>Voltage stability sensitivity factor $S_{V_6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shunt: 0.6 pu</td>
<td>1.25</td>
<td>0.97</td>
<td>0.45</td>
<td>0.010</td>
</tr>
<tr>
<td>Line transmission reactance 0.1X2-6</td>
<td>0.95</td>
<td>0.79</td>
<td>0.48</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Figure 7. Voltage magnitude at all PQ buses after transmission line reactance X2-6 compensation.

Figure 8. Voltage magnitude at all PQ buses after shunt compensation at bus 6.

Tables 4 and 5 contain the maximum value of the load parameter $\lambda_{\text{max}}$ with the amplitudes of the corresponding critical voltages $V_{\text{critical}}$ and of the sensitivity factor of the voltage stability for each PQ bus of the power grid respectively after the line transmission reactance compensation and the shunt compensation.

Table 4. New values of critical voltage magnitude and sensitivity factor for all PQ buses after line transmission reactance compensation at bus 6 in CEB’s power grid.

<table>
<thead>
<tr>
<th>PQ Bus N°</th>
<th>$V_{\text{critical}}$ [pu]</th>
<th>Voltage stability sensitivity factor $S_{V}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.93759</td>
<td>0.00273</td>
</tr>
<tr>
<td>3</td>
<td>1.05095</td>
<td>0.00982</td>
</tr>
<tr>
<td>4</td>
<td>0.97914</td>
<td>0.00018</td>
</tr>
<tr>
<td>5</td>
<td>0.996</td>
<td>2.98E-16</td>
</tr>
<tr>
<td>6</td>
<td>0.79134</td>
<td>0.01070</td>
</tr>
<tr>
<td>7</td>
<td>0.9984</td>
<td>0.00095</td>
</tr>
<tr>
<td>10</td>
<td>1.12264</td>
<td>0.00222</td>
</tr>
<tr>
<td>12</td>
<td>0.98356</td>
<td>0.00008</td>
</tr>
<tr>
<td>13</td>
<td>0.97716</td>
<td>0.00186</td>
</tr>
</tbody>
</table>
Table 5. New values of critical voltage magnitude and sensitivity factor for all PQ buses after shunt compensation at bus 6 in CEB’s power grid.

<table>
<thead>
<tr>
<th>PQ Bus N°</th>
<th>$V_{\text{critical}}$ [pu]</th>
<th>Voltage stability sensitivity factor $S_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.972</td>
<td>0.0014</td>
</tr>
<tr>
<td>3</td>
<td>1.05</td>
<td>0.00011</td>
</tr>
<tr>
<td>4</td>
<td>0.978</td>
<td>0.00013</td>
</tr>
<tr>
<td>5</td>
<td>0.996</td>
<td>1.47E-17</td>
</tr>
<tr>
<td>6</td>
<td>0.969</td>
<td>0.01018</td>
</tr>
<tr>
<td>7</td>
<td>0.998</td>
<td>0.00028</td>
</tr>
<tr>
<td>10</td>
<td>1.122</td>
<td>0.00025</td>
</tr>
<tr>
<td>12</td>
<td>0.983</td>
<td>0.00017</td>
</tr>
<tr>
<td>13</td>
<td>0.976</td>
<td>0.00041</td>
</tr>
</tbody>
</table>

The increase in the active power demand on bus 6 of the CEB power grid to the critical point reduced the voltage of this bus to 0.5616 pu for a maximum load factor $\lambda_{\text{max}}$ equal to 0.2705 as shown in Figure 4.

The constraint linked to the voltage of each bus being $0.9 \leq V \leq 1.3$ and presented in Table 1 to make the line transmission reactance compensation on line $X_{2,6}$ (Figure 5) and the shunt compensation on bus 6 (Figure 6) in order to bring the bus voltage back within the above mentioned range. The results from these two types of compensation (Table 3) sufficiently show the advantage of shunt compensation on the line transmission reactance by their voltage variation interval which is respectively $0.79 \leq V \leq 0.95$ and $0.95 \leq V \leq 1.25$. The voltage stability sensitivity factor $S_v$ confirms this advantage at its value for the shunt compensation which is 0.010 against 0.011 for the line transmission reactance compensation. However, the maximum load factor $\lambda_{\text{max}}$ has increased in value in the two compensation cases with 0.45 pu for the shunt compensation against 0.48 pu for the line transmission reactance compensation and this increases the demand for active power.

The evaluation of the repercussions of each of the two types of compensation made separately in the entire CEB’s power grid and presented in Figures 7 and 8 with tables 4 and 5 clearly expresses the acceptable values of the critical voltage amplitude. $V_{\text{critical}}$ to all PQ buses except bus 6 (0.79134 pu) for line transmission reactance compensation. Figure 9 indicates for the critical voltages $V_{\text{critical}}$ that the values of the RMSE and of the correlation coefficient $R^2$ of the shunt compensation equal to 0.017661 and 0.93366 are clearly better than those of the line transmission reactance compensation respectively 0.069879 and 0.61291. The sensitivity factors of the voltage stability $S_v$ of the shunt compensation are lower than those of the line transmission reactance to all the PQ buses (Tables 4 and 5).

Thus in this CEB’s power grid where the increase in active power demand on bus 6 is noted, shunt compensation offers better voltage stability in view of the results obtained compared to the line transmission reactance.

7. Conclusion

The study proposed in this paper is the comparison of two types of compensation such as shunt compensation and line transmission reactance compensation. These two compensations follow the presence of voltage instability due
to increased demand for active power causing voltage drops to certain buses in the electrical network. The Newton-Raphson method coupled with Predictor-Corrector methods was used for Continuation Power Flow (CPF) on the electricity transmission network of the Benin Electric Community (CEB) to obtain voltage profiles. The results from the node voltage profile curves for the case of the CEB network showed that the two types of compensation make it possible to recover the lost voltage stability and to increase the demand for active power. The load factor $\lambda_{\text{max}}$ goes from 0.2705 pu to 0.45 pu for the shunt compensation and to 0.48 pu for the line transmission reactance.

For the magnitudes of the critical voltages $V_{\text{critical}}$ compared to those of the stresses, the values of the RMSE and of the correlation coefficient $R^2$ of the shunt compensation are respectively 0.017661 and 0.93366 and are clearly better than those of the line transmission reactance compensation respectively 0.069879 and 0.61291. In addition to this we note that the sensitivity factors of the voltage stability $S_v$ of the shunt compensation are lower than those of the line transmission reactance to all the PQ buses. In short, the stability of the voltages is much more guaranteed by the shunt compensation than the line transmission reactance compensation for the case of the CEB's electrical transmission network. This study will allow the grid operator to predict and anticipate the instability of the voltages in his power grid.

This study allows the manager to anticipate instability and to properly plan compensation for good voltage stability in its power grid.

References


