EVALUATING VOLTAGE STABILITY IN A SUBSTATION

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INTRODUCTION

The increasing loads, the great distances between the production and consumption centers as well as the state of the transport and distribution networks turns the Electrical Power System operating near its stability limit. When the system gets unstable a blackout situation may occur, which is critical to the system operator and consumers. We have recent examples in United States and Italy where the system was without power for several hours, causing serious problems in hospitals and public transportations.

One of the causes of a blackout may be the Voltage Instability, which turns this subject widely discussed and studied. The speed of evolution of the Voltage Stability phenomenon allows us to analyze the problem as a static problem rather than a transitory one [1].

It is well known how important the Power Quality Indexes are to an Electrical Distribution Company. So, the ability to “measure” inside a substation the system’s proximity to the Voltage Stability Limit becomes a very important tool.

This article will show one way to “measure” locally the proximity of the system to the Voltage Stability Limit.

VOLTAGE INSTABILITY

As shown in [1] and [2], it is possible to determine if a certain point of the network is in a Voltage Stability situation by calculating the ratio between the impedances viewed from the busbar \( Z_m/Z_j \) according to Fig. 1 and 2.

If the ratio is smaller than 1 it means that the system is stable. The system will become instable when this ratio is bigger than the unit, as shown in Fig. 3.

Considering the analysis in busbar \( j \), it is possible to measure its voltage and the current flowing to the load, and consequently easily determine the value of \( Z_j \) applying the Ohms Law, \( Z_j = V_j/I_j \). The difficulty is the calculation of \( Z_m \) based on the readings of the voltage and the current in busbar \( j \).

If a way to determine the value of \( Z_m \) is defined, it will be easy to analyze the system’s proximity to the voltage stability limit, calculating the ratio \( Z_m/Z_j \).

CALCULATING \( Z_m \)

Usually substations are equipped with voltage and current transformers (VT and CT). These transformers give information to protection relays and to measurement equipments. Most of the substations are equipped with Programmable Logic Controllers (PLC) and/or computers, which are able to communicate with the control center, to make some operations in the substation equipment and to perform calculations. The PLC/computer also knows, at all the time, the state of every equipment in the substation.

The calculation abilities of the PLC/computer will be used to determine the value of \( Z_m \) based on the readings of the current and voltage in the correct places of the substation.
The center of a substation is the power transformer, so this is a good place to measure the current flowing in or out the substation. If we have transformers in parallel we must sum the currents of each one. The best place to measure the voltage is the busbar, as shown in Fig. 4. It is also important to determine the angle between the voltage and the current.

The objective is to determine the Thévenin equivalent of the network viewed from the busbar (shown in Fig. 2). To determine the voltage and the impedance of the equivalent it will be needed to record the measurements of the voltage and current in the substation in 3 time instants. The Thévenin impedance will be \( Z_m \).

Assuming that the impedance viewed from the busbar (\( Z_m \)) and the voltage \( U_0 \) do not change during this 3 time instants we may write:

\[
\begin{align*}
U_0 \cdot e^{j\alpha_1} & = U_1 \cdot e^{j\theta} + (Z_m \cdot e^{j\phi_1} \times I_1 \cdot e^{j\varphi_1}) \\
U_0 \cdot e^{j\alpha_2} & = U_2 \cdot e^{j\theta} + (Z_m \cdot e^{j\phi_2} \times I_2 \cdot e^{j\varphi_2}) \\
U_0 \cdot e^{j\alpha_3} & = U_3 \cdot e^{j\theta} + (Z_m \cdot e^{j\phi_3} \times I_3 \cdot e^{j\varphi_3})
\end{align*}
\]

where:
- \( U_0 \) → Thévenin voltage;
- \( \alpha_1, \alpha_2, \alpha_3 \) → Phase difference (3 time instants) between Thévenin voltage and substation voltage;
- \( U_1, U_2, U_3 \) → Substation voltage in 3 time instants;
- \( \theta \) → Arc tang \( (X_m / R_m) \);
- \( I_1, I_2, I_3 \) → Current flowing through the substation in 3 time instants;
- \( \varphi_1, \varphi_2, \varphi_3 \) → Phase difference (3 time instants) between voltage and current and voltage.

It is possible to re-write the equations as follows:

\[
\begin{align*}
U_{01x} & = U_1 + R_m \cdot I_{1x} - X_m \cdot I_{1y} \quad (1) \\
U_{01y} & = R_m \cdot I_{1y} + X_m \cdot I_{1x} \quad (2) \\
U_{02x} & = U_2 + R_m \cdot I_{2x} - X_m \cdot I_{2y} \quad (3) \\
U_{02y} & = R_m \cdot I_{2y} + X_m \cdot I_{2x} \quad (4) \\
U_{03x} & = U_3 + R_m \cdot I_{3x} - X_m \cdot I_{3y} \quad (5) \\
U_{03y} & = R_m \cdot I_{3y} + X_m \cdot I_{3x} \quad (6)
\end{align*}
\]

considering that:

\[
\begin{align*}
U_{01x} \cdot \cos \alpha_1 & = I_{01x} \cdot \cos \phi_1 \\
U_{01y} \cdot \sin \alpha_1 & = I_{01y} \cdot \sin \phi_1 \\
U_{02x} \cdot \cos \alpha_2 & = I_{02x} \cdot \cos \phi_2 \\
U_{02y} \cdot \sin \alpha_2 & = I_{02y} \cdot \sin \phi_2 \\
U_{03x} \cdot \cos \alpha_3 & = I_{03x} \cdot \cos \phi_3 \\
U_{03y} \cdot \sin \alpha_3 & = I_{03y} \cdot \sin \phi_3
\end{align*}
\]

There are now 8 unknown variables \( U_{01x}, U_{01y}, U_{02x}, U_{02y}, U_{03x}, U_{03y}, R_m \) and \( X_m \) but only 6 equations. As assumed previously, the Thévenin voltage \( U_0 \) will not change during the 3 time instants, allowing us to write the following 2 missing equations:

\[
[U_{01x}] = [U_{02x}] = [U_{03x}] \iff \\
\begin{align*}
U_{01x} & = U_{02x} \quad (7) \\
U_{02x} & = U_{03x} \quad (8)
\end{align*}
\]

To solve this equation system, an iterative method based on the Newton-Raphson methodology may be used.

\[
X^{(i+1)} = X^{(i)} - \left[J^{(i)}\right]^{-1} \cdot F(X^{(i)})
\]

where \( i \) is the iteration number and:

\[
X^T = [U_{01x} \ U_{01y} \ U_{02x} \ U_{02y} \ U_{03x} \ U_{03y} \ R_m \ X_m]
\]

\[
F(X) = \\
\begin{bmatrix}
U_1 + R_m \cdot I_{1x} - X_m \cdot I_{1y} - U_{01x} \\
R_m \cdot I_{1y} + X_m \cdot I_{1x} - U_{01y} \\
U_2 + R_m \cdot I_{2x} - X_m \cdot I_{2y} - U_{02x} \\
R_m \cdot I_{2y} + X_m \cdot I_{2x} - U_{02y} \\
U_3 + R_m \cdot I_{3x} - X_m \cdot I_{3y} - U_{03x} \\
R_m \cdot I_{3y} + X_m \cdot I_{3x} - U_{03y} \\
U_{01x}^2 + U_{01y}^2 - U_{02x}^2 - U_{02y}^2 \\
U_{02x}^2 + U_{02y}^2 - U_{03x}^2 - U_{03y}^2
\end{bmatrix}
\]
All these calculations are based on the hypothesis that the values of $Z_m$ and $U_0$ are constant during the 3 time instants, as shown in Fig. 5. Let's call this Calculation Process 1.

Using similar deductions it is now possible to analyze the network assuming that there are variations on $U_0$ and/or on $Z_m$.

Considering 4 time instants and the possibility of changing $U_0$ in the third time instant (Fig. 6) it is possible deduce Calculation Process 2.

The matrices involved in the iterative process are as follows:

$$J = \begin{bmatrix}
-1 & 0 & 0 & 0 & 0 & 0 & I_{1x} - I_{1y} \\
0 & -1 & 0 & 0 & 0 & 0 & I_{1x} - I_{1y} \\
0 & 0 & -1 & 0 & 0 & I_{2x} - I_{2y} \\
0 & 0 & 0 & -1 & 0 & I_{3x} - I_{3y} \\
0 & 0 & 0 & 0 & -1 & I_{4x} - I_{4y} \\
2 - U_{0x} & 2 - U_{0y} & -2 - U_{0z} & -2 - U_{0y} & 0 & 0 & 0 \\
0 & 2 - U_{0z} & 2 - U_{0y} & -2 - U_{0y} & 0 & 0 & 0 \\
0 & 0 & 2 - U_{0z} & 2 - U_{0y} & -2 - U_{0y} & 0 & 0 \\
\end{bmatrix}
$$

$$J = \begin{bmatrix}
U_{0x} \\
U_{0y} \\
U_{0z} \\
U_{0x} \\
U_{0y} \\
R_m \\
X_m \\
\end{bmatrix}
$$

$$F(X) = \begin{bmatrix}
U_{1x} + R_m \cdot I_{1x} - X_m \cdot I_{1y} - U_{01x} \\
U_{1y} + X_m \cdot I_{1x} - U_{01y} \\
U_{2x} + R_m \cdot I_{2x} - X_m \cdot I_{2y} - U_{02x} \\
U_{2y} + X_m \cdot I_{2x} - U_{02y} \\
U_{3x} + R_m \cdot I_{3x} - X_m \cdot I_{3y} - U_{03x} \\
U_{3y} + X_m \cdot I_{3x} - U_{03y} \\
U_{4x} + R_m \cdot I_{4x} - X_m \cdot I_{4y} - U_{04x} \\
U_{4y} + X_m \cdot I_{4x} - U_{04y} \\
\end{bmatrix}
$$

Calculation Process 3 assumes that the values of $Z_m$ and $U_0$ are already known for time instant 1 (obtained from previous calculations). It also considers that $Z_m$ changes in $t_2$ and $U_0$ changes the next time instant, according to Fig. 7.

Using similar deductions it is possible to reach the following matrices used in the iterative process:

$$X = \begin{bmatrix}
U_{0x} \\
U_{0y} \\
U_{0z} \\
U_{0x} \\
U_{0y} \\
R_m \\
X_m \\
\end{bmatrix}
$$

$$F(X) = \begin{bmatrix}
U_{1x} + R_m \cdot I_{1x} - X_m \cdot I_{1y} - U_{01x} \\
U_{1y} + X_m \cdot I_{1x} - U_{01y} \\
U_{2x} + R_m \cdot I_{2x} - X_m \cdot I_{2y} - U_{02x} \\
U_{2y} + X_m \cdot I_{2x} - U_{02y} \\
U_{3x} + R_m \cdot I_{3x} - X_m \cdot I_{3y} - U_{03x} \\
U_{3y} + X_m \cdot I_{3x} - U_{03y} \\
U_{4x} + R_m \cdot I_{4x} - X_m \cdot I_{4y} - U_{04x} \\
U_{4y} + X_m \cdot I_{4x} - U_{04y} \\
\end{bmatrix}
$$
Finally, Calculation Process 4 also considers that the values of $Z_m$ and $U_0$ are known in $t_i$ and obtained by previous calculations, but only $Z_m$ changes in time instant 2, according to Fig. 8.

The PLC/computer should try to apply this calculation processes to the measurements obtained by this order (CP1 → CP2 → CP3 → CP4) until one of them gets a solution. The solution must be stored, because the results may be used in the next time instant.

Combining this 4 calculation processes, it is possible to cover most of the variations in the network, as shown in [2], although some times the method will need more than 1 new time instant readings to calculate new values.

The readings should not be taken in fixed periods of time, but whenever there are changes in the measurements. It is also important to adjust the minimum allowed variation between readings to consider it a new reading.

As seen, there are different calculation processes with different assumptions. The PLC/computer must be able to analyze the solutions obtained and decide if they are fiscally possible and compatible to the system.

One important thing about the method described is the independence of communications as well as information and data about the network. Some times there are failures in the communication system and it is common to have erroneous data and information about the network. This method is completely immune to those errors.

Another positive aspect concerning this method is that, usually, most of the substations are already equipped with measurement converters and PLC’s or computers, making this analysis easy and cheap to implement, because, in most situations, it won’t be necessary to buy new equipment.

When the PLC/computer detects that the network is close to an instability point, it should send an alarm to the control center and take corrective measures in the installation to prevent the system to reach a voltage instability situation. These corrective measures may be the blocking of automatic voltage regulation of power transformers and turning on capacitor banks in the substation. Even if there is a problem with communications and the alarm does not reach the control center, the system will try to prevent an instability situation by changing the network locally.

CONCLUSIONS

This is a methodology that allows the calculation of the value of $Z_m$, and consequently determines how close we are to an instability situation.

The accuracy of the values of $Z_m$ obtained by this methodology depends on the maximum allowed error in the iteration process. If the allowed error is too small, the iteration process may not converge to a solution, and the number of iterations will increase. One must have in mind that everything between the network and the PLC/Computer (measurement transformers and converters) will be a source of errors, turning the selection of maximum allowable error of iteration process very important.

REFERENCES
