CALCULATION OF VOLTAGE SAGS ORIGINATED IN TRANSMISSION SYSTEMS USING SYMMETRIC COMPONENTS

Carlos CASAROTTO  
Comahue National University, Argentina  
cfcasarotto@yahoo.com

Juan Carlos GÓMEZ  
Rio Cuarto National University, Argentina  
jcgomez@ing.unrc.edu.ar

ABSTRACT
The objective of this work is the study of voltage sags presented at a particular point of an electric network, when a short circuit fault takes place in some point of the transmission system. Different types of short circuits were analyzed, so much balanced as not balanced, applied to a bar of a typical power system, and the resulting voltages were obtained in the terminals of the sensitive equipment that are connected at the point of common coupling (PCC) on another bar. The habitual techniques of symmetrical components for short-circuit analysis were used. The sensitive equipment were considered three-phase, star connected with neutral. To contrast the results the power system was implemented in the program DigSilent, and the same events were simulated. Starting from the obtained results, and carrying out the appropriate simplifications, the voltage sags were classified according to the approaches mentioned by Bollen.

INTRODUCTION
The voltage sag (Sag) can be defined as short duration reduction of effective value (rms) of voltage, caused by short circuits, overloads and motor starts. The interest in its study has been lately extended to be approached as a Power Quality Problem of global reach, and whose consequences can affect to different types of sensitive equipment as Adjustable Speed Drives (ASD), process control devices (for instance PLCs), and computers.

The equipment of “end use” that is affected by the existence of voltage sags, and in general for events of power quality, is denominated sensitive equipment (SE). They are affected, specifications, up to the upsetting of their operation. [2].

A very important statistical aspect it is constituted by the fact that the faults that take place in transmission systems have an occurrence percentage of approximately 45% for single phase, 21% for two-phase and 31% for three phase faults [2, 3].

The presence of transformers between the high voltage networks and the sensitive equipment introduces changes in the way in that the voltages are presented in the terminals of the low voltage equipment. These changes imply that the mentioned percentages will change according to the number and group connection of the involved transformers [4, 5].

Besides the magnitude and duration, most of the bibliography indicates that the equipment behavior depends on other variables, as the unbalance and the phase jump. For that reason, the work was centered in the characterization of voltage sags taken place by symmetrical and asymmetric faults, using the symmetrical components methodology, since it facilitates to extend the analysis per-phase to unbalanced systems. This method has demonstrated to be superior to the direct one to solve unbalanced problems [6, 7].

TYPES OF BASIC VOLTAGE SAGS
Were denominated basics the voltage sags that take place by the four elementary types of short circuit that are usually required in fault studies that are the three-phase short circuit, single-phase short circuit, two-phase short circuit and two-phase to ground short circuit.

As it is habitual in the studies of power systems, load starting from the impossibility of fulfilling their design current were considered negligible, when the fault takes
place, and the possible contribution from the motors connected to the industrial circuits was underrated. The representative loads of the sensitive equipment are considered, as first approach, three-phase and connected in star with neutral. The rest of the power system was replaced by an equivalent one static with three-phase and single-phase short circuit power of 1500 MVA and 1400 MVA respectively. The modeling of the high voltage lines for the manual calculations was based on the equations of short line, rejecting the resistive losses and the influence of parallel admittances. The short circuit voltages of the three winding transformer were considered only inductive, their losses neither the presence of tap changers were taken into account. All the values were referred to the high voltage system, with a common power base of 100 MVA and a voltage base of 132 kV.

1- Three-phase short circuit: Type A

The simplest case of being analyzed presents when a three-phase fault takes place in the bar 132 C of the transmission system. To quantify the voltage sag magnitude in radial networks, the simple circuit that is illustrated in Figure 2 can be used. In the circuit, the equivalent of the system or source it is represented by means of impedances Zt1 and Zt2. The impedance between the PCC and the fault connected to the point of common coupling (PCC), and by source it is represented by means of an impedance Zs.

In the present case

\[ Z_s = Z_{eq} + Z_{t1} \]  and \[ Z_F = Z_{t2} \] .

Figure 3 shows the connection of the sequence nets for this fault type. For being a symmetrical type of fault only direct sequence values are involved.

![Figure 2. Simple circuit model.](image)

![Figure 3. Sequence nets connection for three-phase faults.](image)

The direct sequence impedance of the external equivalent circuit can be obtained by:

\[ |Z_{eq}| = \frac{1}{S_{cc} \times pu} = \frac{1}{15} = 0.0667 \text{ pu} \]

For transmission lines, the impedance is given by:

\[ Z_{t1} = j \times 3.880 \Omega \Rightarrow Z_{t1} = j \times 0.02226 \text{ pu} \]

\[ Z_{t2} = j \times 13.58 \Omega \Rightarrow Z_{t2} = j \times 0.07793 \text{ pu} \]

The direct sequence short circuit impedance value results:

\[ Z_{ce1} = j \times 0.1669 \text{ pu} \]

The sequence currents are calculated as:

\[ I_0 = 0; \quad I_1 = \frac{E}{Z_{s1} + Z_{j1}}; \quad I_2 = 0 \]

As the load currents are neglected, the EMF value of the Thevenin equivalent on the faulted point is:

\[ E = 1 \angle 0^\circ \text{ (phase A reference) } \]

\[ I_1 = \frac{1 \angle 0^\circ}{0.1669 \angle 90^\circ} = 6 \angle -90^\circ \text{ pu} \]

The sequence voltages at the PCC are obtained by:

\[ V_1 = I_1 \times Z_{t2} = 0.4676 \angle 0^\circ \text{ pu} \]

\[ V_2 = V_0 = 0 \]

The phase values can be obtained from the Fortescue transformation matrix.

\[ \begin{bmatrix} v_{abc} \end{bmatrix} = \begin{bmatrix} t \end{bmatrix} \begin{bmatrix} \bar{v}_{012} \end{bmatrix} \]

\[ \begin{bmatrix} \bar{v}_a \\ \bar{v}_b \\ \bar{v}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \pi & \pi \\ 1 & \pi & \pi \end{bmatrix} \begin{bmatrix} v_0 \\ v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 0.467 \angle 0^\circ \\ 0.467 \angle -120^\circ \end{bmatrix} \text{ pu} \]

With \[ \bar{\sigma} = 1 \angle 120^\circ \]

These results were compared with those obtained by simulations. The obtained voltages at bar 132B are given:

\[ \begin{bmatrix} \bar{v}_a \\ \bar{v}_b \\ \bar{v}_c \end{bmatrix} = \begin{bmatrix} 0.475 \angle -5.37^\circ \\ 0.475 \angle -125.37^\circ \end{bmatrix} \text{ pu} \]

\[ \bar{v}_c = 0.475 \angle 114.63^\circ \text{ pu} \]

It is observed that besides a change in the magnitude, a phase jump appears. In the simplified method this change doesn’t appear because all the resistive losses were rejected. For short circuits in sub-transmission or distribution systems, this simplification can give important errors, due to the high resistance values for small cross section conductors. Also, the difference of impedance of the high and low voltage conductors can introduce phase jumps higher than those studied up to now. The cited errors are acceptable, for what the simplified method can provide very good results with minimum calculations. This is important in cases where the study is done without specialized programs. This sag was classified by Bollen as Type A [1].
2- Single Phase short circuit: Type B
For this fault type the sequence nets are connected in series. The three windings transformer will be studied for the connection group more commonly used in power systems. The presence of the delta winding allows the circulation of the necessary harmonic component for the magnetic circuit, excitation without important voltage distortions. The high voltage windings are connected in star to ground, which allows lower insulation level. It was decided to include in the circuit the zero sequence, adding a transformer primary neutral. In consequence this path doesn’t participate in the calculations. For the analysis of the circulation of the zero sequence components, it should be kept in mind that the delta coil allows the current negative sequence components to circulate in the zero sequence, allowing to consider the delta winding as a path for the zero sequence and for the second harmonic. It should be noted that the second harmonic component allows the current to circulate in the line L1 and L2. The zero sequence component allows the current to circulate in the line L1 and L3.

The presence of the delta winding allows the circulation of the necessary harmonic component for the magnetic circuit, excitation without important voltage distortions. The high voltage windings are connected in star to ground, which allows lower insulation level. It was decided to include in the circuit the zero sequence, adding a transformer primary neutral. In consequence this path doesn’t participate in the calculations. For the analysis of the circulation of the zero sequence components, it should be kept in mind that the delta coil allows the current negative sequence components to circulate in the zero sequence, allowing to consider the delta winding as a path for the zero sequence and for the second harmonic. It should be noted that the second harmonic component allows the current to circulate in the line L1 and L2. The zero sequence component allows the current to circulate in the line L1 and L3.

This event type has been defined as voltage sag Type B. In fact in the classification proposed by Bollen the presence of the voltage sag only affects the failed phase, rejecting for the healthy phases so much the voltage elevation like the phase change (although small) that is evidenced in the calculated values and also in the results of the simulation that are given next.

3- Two phase short circuit: Type C
To maintain the phase A as symmetry reference, it is supposed that the fault takes place in the phases B and C. For this fault type the direct and inverse sequence nets are connected in parallel, while the zero sequence net is opened by not being included the contact to ground. The results of the manual calculations and simulations, applying the same methodology of the previous examples, are:

<table>
<thead>
<tr>
<th>Manual</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_A ) = 0.572 ( \angle 0^\circ )</td>
<td>( V_A ) = 0.579 ( \angle -3.74^\circ )</td>
</tr>
<tr>
<td>( V_B ) = 1.018 ( \angle -121.7^\circ )</td>
<td>( V_B ) = 1.019 ( \angle -121.69^\circ )</td>
</tr>
<tr>
<td>( V_C ) = 1.018 ( \angle -121.7^\circ )</td>
<td>( V_C ) = 1.017 ( \angle -121.78^\circ )</td>
</tr>
</tbody>
</table>

This event type has been classified by Bollen as voltage sag Type C. It can be observed that the not failed phase doesn’t modify, while the two phases that participate in the short circuit suffer a magnitude decrease and a phase change.

4- Two phase to ground short circuit: Type E
In this case, the direct, inverse and zero sequence nets are connected in parallel. The results of the manual calculations and simulations are the following ones:

<table>
<thead>
<tr>
<th>Manual</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_A ) = 1.028 ( \angle 0^\circ )</td>
<td>( V_A ) = 1.028 ( \angle 0.08^\circ )</td>
</tr>
<tr>
<td>( V_B ) = 0.547 ( \angle -125.4^\circ )</td>
<td>( V_B ) = 0.532 ( \angle -132.30^\circ )</td>
</tr>
<tr>
<td>( V_C ) = 0.547 ( \angle -125.4^\circ )</td>
<td>( V_C ) = 0.510 ( \angle 123.38^\circ )</td>
</tr>
</tbody>
</table>

This voltage sag type has been proposed as sag Type E. In this case the not failed phase it is not affected and a decrease of the remaining two phases magnitude is verified but the phase change can be disregarded with little calculation error, which notably simplifies the mathematical expressions. The following table is a summary of the types of PCC voltage sags, according to the faults that originated them.

<table>
<thead>
<tr>
<th>Type of fault</th>
<th>Star with neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three phase</td>
<td>A</td>
</tr>
<tr>
<td>Single phase</td>
<td>B</td>
</tr>
<tr>
<td>Two phase</td>
<td>C</td>
</tr>
<tr>
<td>Grounded two phase</td>
<td>E</td>
</tr>
</tbody>
</table>

TRANSFER AMONG DIFFERENT VOLTAGE LEVELS
To connect the transmission net with the rest of the system, the existence of a 132/33/13.2 kV transformer station has been supposed in the bar 132 B that provides the electric energy to the subtransmission and distribution nets. These nets extend the feeding to the low voltage systems where it is supposed that the sensitive equipment is connected. The transformers can have diverse connection forms, but in order to explain the voltage sags transfers is enough to classify them in three types.

**Type I**: Transformers that don’t change the voltages between primary and secondary. For this type the voltages in pu in both sides are the same, this means that the transformer type I don’t produce any change in the voltage sag type when transferring the voltages between levels. The transformation matrix is the identity. Example YNy

**Type II**: Transformers that remove the zero sequence. The voltages of both sides are the same except for the component of zero sequence. Example Yy Dd

**Type III**: Transformers that eliminate the zero sequence and that exchange line by phase voltages. For these transformers each secondary voltage is the difference between two primary voltages. YNd Yd Dyn Dy

In matrix form: \( V_{abc} = [T_{g2}] V_{ABC} \). Where \( T_{g2} \) indicate the transformation matrix.
In table 2 the types of sags that can be obtained by transfer from high to medium voltage and from medium to low voltage are summarized, with the consideration of the group obtained by means of the multiplication of transformation matrixes. As it is not very probable in the real world the presence of two type I transformers in cascade I, only equivalents of the group TR2 or TR3 are possible. In consequence the sags type B and E do not take place in low voltage nets, since zero sequence component is blocked.

Table 2. Summary of different voltage sags types

<table>
<thead>
<tr>
<th>Primary</th>
<th>Group TR1</th>
<th>Group TR2</th>
<th>Group TR3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>B</td>
<td>D*</td>
<td>C*</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>E</td>
<td>E</td>
<td>G</td>
<td>F</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

The method of the symmetrical components has demonstrated to be a powerful tool for the analysis of unbalanced systems. The application to the case of voltage sags originated by faults in transmission system, with the habitual simplifications, allows the classification of the events in a simple way and with a minimum calculation effort. Keeping in mind the habitual transformer connection groups, only will be presented in the low voltage loads symmetrical voltage sags type A, due to balanced faults, and the asymmetric forms type C and D due to single and two phase fault, and type F and G due to grounded two phase faults. In reference to the statistical indexes shown at the beginning, it can be affirmed that the most probable sag types for industrial systems are C and D. The types F and G are usually consider as distorted forms of the previous ones.

### REFERENCES