Voltage Sags Evaluating Methods, Power Quality and Voltage Sags Assessment regarding Voltage Dip Immunity of Equipment

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Abstract: - A large number of electrical equipment or devices installed in industrial field are equipped with electronic control circuits. These devices are an important part of the production technology and their failure can result in production restriction for a long time and cause significant financial losses. Regarding of consumer protection, there was passed standard EN 50 160 “Voltage characteristics of electricity supplied by public electricity networks”, which defines the power quality requirements. The constant value of voltage cannot be fulfilled permanently in the distribution system, and therefore sensitive equipment must withstand a certain voltage changes in the defined limits. Voltage dip immunity testing of sensitive equipment is realised according to standard IEC 61000-4-11 "Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current less than 16 A per phase" and standard IEC 61000-4-34 "Testing and measurement techniques - voltage dips, short interruptions and voltage variations immunity tests for equipment with input current more than 16 a per phase." Power quality according to standard EN 50160 and voltage dip immunity equipment against voltage deviation are different aspects. Although the distribution system operator comply with the power quality requirements, sensitive equipment installed in industrial do not have to work properly or can come to the failure. In such cases, it is necessary to evaluate the power quality and immunity to voltage swells or sags. This contribution describes voltage sags evaluating methods and the measurement results evaluated by ITIC curves.

Key-Words: - Failure, Voltage Sag, Interruption, Voltage Dip Immunity, ITIC Curve

1 Introduction
In the past, the interest of electricity customer was focused mainly on permanency of power supply, i.e. reliability of power supply, but its quality has not been adequately monitored. At present, it is paid more attention to the issue of power quality, because this issue is increasingly associated with economic impact on electricity suppliers and customers. It is important to differentiate between power supply reliability and its quality.

Power supply reliability is determined by the number of interruptions and duration of these interruptions. Reliability assessment considers the type of interruption (scheduled or unscheduled), interruption duration (transient, short-term or long-term interruption), voltage level, type of permanency indicator of power supply and the number or duration of interruptions.

The quality of power supply from the customer's perspective is determined by voltage quality, which is assessed by deviations from the ideal voltage waveform representing a simple sinusoidal waveform with a constant frequency and RMS value.

2 Power Quality of Power Supply
The power quality of supply by public networks are usually assessed according to standard EN 50160 "Voltage characteristics of electricity supplied by public electricity networks".

By equity of standard, there are distinctions between:
- Continuous phenomenon, i.e. deviations from the nominal values that occur consistently in time; such a phenomenon occurs mainly due to the loading sample, loading changes or due to non-linear loads;
Voltage events, i.e. sudden and significant deviations from normal and required waveform; voltage events typically occur due to contingencies (e.g. faults) or external causes (such as weather conditions, actions by third side).

2.1 Interruptions and Voltage Sags

Interruptions are very unpredictable and variable depending on occurrence of location and time. Currently, there is not indicated any representative statistical results of density interruption measurement in all European networks. According to standard EN 50 160, a voltage interruption is a side case of voltage sag when the RMS voltage value in some node in the power system sags to zero value. Due to the problematic measurement of very small voltage values, there is determined by an agreement the threshold voltage value of interruption, which based on the power grid type is approximately in ones of percents of nominal voltage. Interruption of power supply is considered the voltage sag to a lower level than the agreed threshold voltage value of interruption.

In case of three phase systems, the interruption of power supply is considered only the voltage sag to a lower level than the threshold level simultaneously in all three phases. Threshold value of voltage sag is usually defined as the minimum voltage value which can occur in the power system permanently. This value is set at 90% of nominal voltage Un. The main factors that describe the voltage events are the voltage sag depth $\Delta U$ and event duration $\Delta t$.

Voltage sags and short-term interruptions belong to the low-frequency electromagnetic interference phenomena. This type of electromagnetic interference affects the sinusoidal voltage curve, mainly its amplitude. Generally, the voltage events are decisive characteristics such as the voltage amplitude and voltage deviations. In Fig. 1 are shown voltage events with defined limit values of the nominal voltage.

Voltage waveforms can have different shapes during the voltage sag and interruption. In Fig. 2 is shown one possible shape of voltage events, where the voltage steeply sags at the beginning of the event to the new value and for the end of the event is also typical a steep voltage swell to the acceptable range. For voltage sags caused by short-circuit fault is characteristic a rectangular waveform of sag with a very short duration of rising edge and falling edge.

During the duration of voltage sag there is no significant voltage changes.

![Fig.1 Schematic Representation of Failures on Low Voltage Level](Image)

Voltage sags caused by switching of large loads mainly of inductive character have a serrated waveform where the voltage steeply decreases at a minimum value during the voltage sag after load switching caused by current impact and consecutively gradually increases until the voltage sag termination. The amplitude of the voltage sag is defined as the difference between the voltage during the voltage sag and nominal voltage in the grid. This difference is put as a percentage of the nominal voltage. In multiphase systems, the voltage sag begins at the moment of voltage sag of RMS value at least in one phase below the threshold value and ends when the voltage reaches in all phases, respectively exceeds the threshold values for the voltage sag termination.

![Fig.2 Voltage Waveform in Instant of Voltage Sag and Interruption](Image)

If we make a summarisation of statistics data, voltage sags/swells must be measured and evaluated according to standard EN 61000-4-30 using the nominal voltage of power supply as a reference value. This standard considers following characteristics of voltage sags/swells: the residual voltage (maximal RMS value of voltage swell) and time duration. In terms of voltage sag effects on
electrical equipment, it is necessary to know the voltage values at its terminals. In some situations, a distant failure in power system induces a significant voltage deviation. Electrical equipment is usually connected to a lower voltage level than the voltage level of failure occurrence. The voltage values at the terminals of this equipment do not depend only on the voltage values at PCC (node or point of company connection to the distribution system), but also on the transformer winding connections between PCC and equipment terminal, as well as the type of load connection.

Fig.3 Example of Voltage Sags and Interruption Evaluation

2.2 Voltage Sags Evaluation

Voltage sags evaluation must be realised according to standard EN 61000-4-30. The method of analysis voltage sags depends on the evaluation purpose.

In low-voltage grids apply:
- if a three-phase grid considering, there has to be used a multiphase aggregation; multiphase aggregation consists of defining an equivalent event duration characterised by one duration and one residual voltage;
- Time aggregation; time aggregation consists of defining the equivalent event in case of multiple subsequent events; the method used to aggregation of multiple events can be set depending on the final data using; some reference rules are specified in standard IEC/TR 61000-2-8.

Data relating to voltage sags/swells should be presented according to the following procedure.

The collected data should be homogeneous in terms of voltage level. At the same voltage level it is necessary to distinguish between prevailing cable line grids or overhead line grids. Observation should take one year at least in order to evaluate all season effects.

Data should be collected in tables and should record the following information:
- Average occurrence of voltage sags/swells on the busbar per year;
- 90% or 95% occurrence of voltage sags/swells on the busbar per year;
- Maximum occurrence of voltage sags/swells on the busbar per year.

Measured data about the voltage sags and interruptions is possible evaluate and draw by:
- Tables;
- Histograms;
- CBEMA, ITIC, ANSI curves;
- SAIDI, SAIFI, SARFI-X index.

CBEMA, ITIC and ANSI curves describe a tolerance (immunity) of electrical equipment to voltage faults.

Fig.4 CBEMA, ITIC, ANSI Curves

The curves represent the boundaries of the maximum and minimum allowable voltage depending on the duration of voltage fault. These curves define the area to a safe area (between curves) and dangerous area (outside curve) to help customers determine the rate of power quality of power supply. Point distance from the curve determines the probability that the device can withstand failure and will be able to operate without restriction or data loss.

The basic indicator of the power quality of power supply in terms of voltage sags is SARFIX (System Average RMS Variation Frequency Index), which defines the number of voltage sags below the voltage level during a certain period (30 days or one year), where X is the threshold voltage level (e.g. 90, 80, 70, 50, 10% of Un) with a duration usually between 10ms and 60s (180s).
3 Voltage Dip Immunity of Equipment

One of the effective methods to eliminate the negative effects of voltage sags for sensitive equipment is exceptional attention of ability of this equipment withstands voltage sags. Therefore, it is very useful before installation this kind of equipment to inform about its immunity to voltage sags.

All electrical equipment can be assessed according to rate of their immunity to voltage sag and interruption. Equipment immunity is generally characterized as the ability of a device or system fully performs its function during the electromagnetic interference. There are many devices and equipment, which behave during sags and short-term interruptions in different ways. The immunity rate of a particular device depends primarily on its construction and function.

Deterioration of voltage quality can cause to a destabilization of operation mode of device, what can lead to a non-standard device behavior and increased risk of device damage. Non-standard device behavior can be assessed by functional criteria of immunity, by which are classified the testing results of equipment in terms of function loss or operation interruption in testing mode. According to standard is recommended the following classification:

- Normal operation of the testing equipment within the limits set by the manufacturer, applicant for the equipment test or buyer;
- Temporary loss of function or restriction of operation, which stops after the disturbance, normal functional of testing equipment is renewed without operator intervention;
- Temporary loss of function or restriction of operation, where the correction requires an operator intervention;
- Loss of function or restriction of operation, which is not restorable, what is caused by damage of hardware, software or data loss.

Determination and verification of ability to withstand the voltage sag are defined for different tests, which are described in detail in the following standards:

- EN 61000-4-11 - Voltage dips, short interruptions and voltage variations immunity tests;
- EN 61000-4-34 - Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current more than 16 A per phase.

3.1 Voltage Dip Immunity Requirements

As mentioned above, equipment installed in industrial field is highly sensitive to voltage sags. Therefore, there were defined the CBEMA curve, which describes the required voltage dip immunity of sensitive equipment.

CBEMA curve was originally defined as a voltage tolerance curve for computers, but many experts use this curve today as a voltage tolerance curve for other sensitive equipment as well. Shape of CBEMA curve is shown in Fig. 5. If the intersection of voltage sag value and voltage sag duration lies under the curve CBEMA, there is a high probability of failure or malfunction of the equipment or process.

In the past, the CBEMA curve was revised and renamed the ITIC curve, which is shown in Fig. 6. These standards define the curves determining the depth and duration of voltage sags, i.e. the equipment must withstand during defined time period the voltage values over the curves of particular standards. Standards stated above are useful for manufacturers of electrical equipment, which must design their equipment with ability to withstand certain voltage sags during specified time duration of the voltage sag.
Among further globally recognized standards investigating the voltage dip immunity of electrical equipment include IEC 61000-4-34, MIL STD 704E and MIL-STD 1399.

Table 1 Required Voltage Dip Immunity of Equipment

<table>
<thead>
<tr>
<th>Percent of Voltage during Voltage Sag</th>
<th>Voltage Sag Length in 50Hz Grid</th>
<th>Voltage Sag Length in 60Hz Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>10 periods</td>
<td>12 periods</td>
</tr>
<tr>
<td>70%</td>
<td>25 periods</td>
<td>30 periods</td>
</tr>
<tr>
<td>80%</td>
<td>50 periods</td>
<td>60 periods</td>
</tr>
</tbody>
</table>

Table 2 Recommended Voltage Dip Immunity of Equipment

<table>
<thead>
<tr>
<th>Percent of Voltage during Voltage Sag</th>
<th>Voltage Sag Length in 50Hz Grid</th>
<th>Voltage Sag Length in 60Hz Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>1 period</td>
<td>1 period</td>
</tr>
<tr>
<td>80%</td>
<td>500 periods</td>
<td>600 periods</td>
</tr>
</tbody>
</table>

4 Assessment of the quality and the voltage dips measurements

To assess the quality and the voltage sags for electricity consumers in the low voltage grid, the measurements were done at two voltage levels. The first measurement was placed in the customer main 22kV transformer substation and the second measurement was located to the selected technological equipment. The power quality was measured and assessed according to the standard EN 50160 of 2 months duration. The power quality results of measurement are shown in Tab. 3.

Table 3 Quality Measurement Results in MV and LV System

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Medium Voltage Level</th>
<th>Low Voltage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Frequency</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Flicker</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Unsymetry</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>THD</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Harmonics</td>
<td>OK</td>
<td>OK</td>
</tr>
</tbody>
</table>

The measurement results demonstrate complying with the standard limits of EN 50160. All power quality parameters monitored reached the low level of the allowed ranges given by EN 50160.

To analyze the immunity of the technological equipments that is installed at the consumer premises, relevant measurements were done. Voltage variation of sensitive equipments, such production lines, regulators, frequency converters, etc. should withstand the voltage sags defined by standard EN 61000-4-30. One of the most sensitive equipments used in industrial factories are the convertors, which restrict an operation even during very short non-voltage state. According to the ITIC curve, these equipments should withstand the voltage sags with the residual voltage value of 70% with time duration of 500ms. Voltage sags by ITIC curve measured at the medium and the low voltage level are shown in Fig. 7 and Fig. 8.

Fig.7 ITIC Curve with Voltage Sags Recorded in MV System

Fig.8 ITIC Curve with Voltage Sags Recorded in LV System

The following Tab.4 shows the voltage sags recorded in medium voltage power system and their impact on the low voltage grid. The aim of this part is to investigate the voltage sags impact in the
production process and feedback of the sensitive equipments to these voltage sags. Some of the voltage sags recorded by the measurement caused the outage of the technological equipments and consequently the production restriction.

From the measurement results the voltage sags in the medium voltage system with residual voltage of 0.9Un did not transfer into the low voltage grid. It is due to ratio of the main transformers feeding the industrial customer. The ratio of these transformers is 22/0.42kV and that is the reason of voltage sags in medium voltage power system with the residual voltage value of 90% being transferred to low voltage grid as voltage sags of 94.5% residual value.

As well, the voltage sags with similar value and time duration did not have the same impact on the production process. In case of the voltage sag of 76.6% with time duration of 249ms there was the production restricted. In another case of the voltage sag of 76.8% and the time duration of 251ms there no restriction occurred. Despite the fact that the equipments according to the ITIC curve should withstand in normal operation, in many cases the outage of sensitive equipments was recorded. (See the voltage sag numbers 16, 17, 19, 20, 23 in Tab. 4).

Based on the measurements, the ability of sensitive equipments to sustain the operation in case of voltage sags cannot be uniquely determined. It is necessary to make a test of sensitivity of equipments using the voltage sags generator in order to select the problematic equipments.

Table 4 Voltage Sags Measurement Results in MV and LV System

<table>
<thead>
<tr>
<th>Event num.</th>
<th>Medium Voltage Sags</th>
<th>Low Voltage Sags</th>
<th>PR*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time Duration [s]</td>
<td>Minimum Voltage [%]</td>
<td>Time Duration [s]</td>
</tr>
<tr>
<td>1</td>
<td>0.06</td>
<td>82.8</td>
<td>0.06</td>
</tr>
<tr>
<td>2</td>
<td>0.07</td>
<td>79.7</td>
<td>0.06</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>75.4</td>
<td>0.24</td>
</tr>
<tr>
<td>4</td>
<td>0.22</td>
<td>89.4</td>
<td>no sag</td>
</tr>
<tr>
<td>5</td>
<td>0.05</td>
<td>85.1</td>
<td>no sag</td>
</tr>
<tr>
<td>6</td>
<td>0.04</td>
<td>87.5</td>
<td>no sag</td>
</tr>
<tr>
<td>7</td>
<td>0.05</td>
<td>84.6</td>
<td>no sag</td>
</tr>
<tr>
<td>8</td>
<td>0.04</td>
<td>86.8</td>
<td>no sag</td>
</tr>
<tr>
<td>9</td>
<td>0.02</td>
<td>90.0</td>
<td>no sag</td>
</tr>
<tr>
<td>10</td>
<td>0.05</td>
<td>86.5</td>
<td>no sag</td>
</tr>
<tr>
<td>11</td>
<td>0.04</td>
<td>88.5</td>
<td>no sag</td>
</tr>
<tr>
<td>12</td>
<td>0.05</td>
<td>86.3</td>
<td>no sag</td>
</tr>
<tr>
<td>13</td>
<td>0.03</td>
<td>89.4</td>
<td>no sag</td>
</tr>
<tr>
<td>14</td>
<td>0.07</td>
<td>59.9</td>
<td>0.06</td>
</tr>
<tr>
<td>15</td>
<td>0.07</td>
<td>55.1</td>
<td>0.06</td>
</tr>
<tr>
<td>16</td>
<td>0.04</td>
<td>81.2</td>
<td>0.04</td>
</tr>
<tr>
<td>17</td>
<td>0.04</td>
<td>77.7</td>
<td>0.04</td>
</tr>
<tr>
<td>18</td>
<td>0.25</td>
<td>70.1</td>
<td>0.25</td>
</tr>
<tr>
<td>19</td>
<td>0.249</td>
<td>76.6</td>
<td>0.25</td>
</tr>
<tr>
<td>20</td>
<td>0.219</td>
<td>89.5</td>
<td>0.18</td>
</tr>
<tr>
<td>21</td>
<td>0.14</td>
<td>53.4</td>
<td>0.14</td>
</tr>
<tr>
<td>22</td>
<td>0.07</td>
<td>86.2</td>
<td>0.07</td>
</tr>
<tr>
<td>23</td>
<td>0.25</td>
<td>75.6</td>
<td>0.24</td>
</tr>
<tr>
<td>24</td>
<td>0.16</td>
<td>58.2</td>
<td>0.15</td>
</tr>
<tr>
<td>25</td>
<td>0.15</td>
<td>59.1</td>
<td>0.16</td>
</tr>
<tr>
<td>26</td>
<td>0.251</td>
<td>76.8</td>
<td>0.24</td>
</tr>
<tr>
<td>27</td>
<td>0.01</td>
<td>89.9</td>
<td>no sag</td>
</tr>
</tbody>
</table>

Note: PR* - Production Restriction

The voltage sags recorded in the low voltage grid could be also a result of different faults in the transmission or distribution system. In general, the operation of AR is associated with operation of protections e.g. distance protection. In case of fault detection on the power line, the protection activates the AR operation. The AR sends tripping commands to circuit breaker and after auto-reclose time (the non-voltage operation of faulted power line required to extinguish the arc) sends the AR reconnection commands to circuit breakers of selected power line. In case of fault redetection, the AR sends commands to the definitive tripping of faulted power line.

Almost 75%-95% failures recorded in transmission or distribution overhead lines have temporary character and therefore it is appropriate to install the automatic reclosing systems.

The outage of sensitive equipments used to occur also in cases, when the time duration of the voltage sags was 100-200ms. This time range corresponds with the time to trip the fault in the transmission or distribution system.
This time comprises
- Time of protection reaction (time to evaluate the failure and generate the signal for circuit breaker); plus
- Time of circuit breaker reaction;

Considering the time period of 100-200ms to switch the failure with temporary character and the recorded outages of sensitive equipments, it results, that the outages occurred during the time period needed to switch the failure in power system. The failures with temporary character in transmission and distribution system is not possible to completely remove because is not possible to eliminate all the events, which are the reason of temporary failures. The events could be:
- Lightening;
- Strong wind;
- Icing cover;
- Birds on the pilons;
- Operation overvoltages;
- The condition of transformers, isolations, lines, etc.).

5 Conclusion
Many of electrical equipments operating in industrial companies comprise high precision control units. These units are sensitive to the voltage variations and thus the producers and customers are forced to this problem. The presented measurements demonstrate that the frequency converters get out of the operation despite the fact, that the converters should withstand the voltage sags.

Particular measurements and recorded production outages and restrictions prove the presence of voltage sags in the low voltage grid where the consumer’s equipments are connected into. These voltage sags can be explained as the consequences of the unpredictable transmission and distribution power system faults. It is also necessary to understand, that is not possible to eliminate the voltage sags caused by the factors such meteorological factor, (lightening, ice cover, strong wind), age of equipments, operation over voltages etc. There are many of the sensitive equipments installed in the production factory, on the other side is not possible to eliminate all the voltage sags. It results to the following precautions:
- Selecting the most sensitive equipments and increase the ability to withstand the voltage sags;
- Installation of special fast and precise sources between the distribution system and the internal customer electrical grid;
- Increase of the maintenance service in the transmission and distribution systems.

References:
[2] Standard IEC 61000-4-11: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current less than 16 A per phase.
[3] Standard IEC 61000-4-34: Testing and measurement techniques - voltage dips, short interruptions and voltage variations immunity tests for equipment with input current more than 16 a per phase.

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