ABSTRACT

This paper presents the results from the work of joint working group C4.110: a cooperation between CIGRE, CIRED and UIE. Its mandate period stretches from early 2006 through early 2009. The group has addressed several aspects of the immunity of, especially, industrial equipment against voltage dips. Quantifying or specifying equipment performance is part of the assessment or improvement of the voltage-dip ride-through of an industrial process.

INTRODUCTION

This paper gives an overview of the main contributions and the conclusions reached by joined CIGRE / CIRED /UIE working group C4.110, “voltage-dip immunity of equipment in installations”. More details can be found in the final report that will be available during 2009 [1]. This paper concentrates on the general methodology for considering voltage dips in the choice of electrical equipment for powering industrial processes. Earlier results from the working group have been presented, among others in [2]. It should be clearly noted that this paper contains the interpretations of the authors of the state of the discussions within the group as of early January 2009, which may deviate from the final conclusions of the group as will be presented in [1].

DESIGN WITH DIP IMMUNITY IN MIND

The working group has developed a method for including immunity against voltage dips in choice of equipment to power industrial processes. The overall design method is shown in Fig. 1.

The input parameters are the performance of the power supply (in terms of voltage dips), the performance of the industrial process against voltage dips (in terms of economic value and process immunity time). Combining the required process performance and the actual network performance gives the required immunity of the process. This is next used, together with the process immunity time, to put requirements on the equipment performance. Finally the equipment is selected or alternatively changes are made in one of the three input parameters.

Fig. 1. Design method considering voltage-dip immunity of equipment and of the process.

Step 1. Supply performance

The number of voltage dips varies significantly between different locations in the power system. The number of dips is an important parameter in the choice of equipment. It can be obtained by monitoring the supply voltage over a period of several years or by calculating the number of dips from the fault frequencies of the network components and the network structure. The latter requires information from the network operator.

The voltage-dip performance of the supply can be expressed in a number of ways. A voltage-dip table or a contour chart is the most appropriate way. It is further recommended to get information on the number of phase-to-phase or phase-to-neutral voltages involved in the dips. The distinction between balanced and unbalanced dips is especially
important. Within the working group the following classification of voltage dips has been used:

- Type I: a major drop in magnitude of one phase-to-neutral or two phase-to-phase voltages.
- Type II: a major drop in magnitude of two phase-to-neutral or one phase-to-phase voltage.
- Type III: a major and approximately equal drop in magnitude of all three phase-to-phase or phase-to-neutral voltages.

**Step 2. Process performance requirement**

A second important input to the design is the required process performance, i.e. what is the maximum number of times per year that the production process may be allowed to stop due to a voltage dip. This step should start with an assessment of the economic consequences of dip-initiated process stoppages. Only after this assessment is an end-user able to decide about the performance requirements in term of maximum number of process stoppages. This can be done for new installations as well as for existing ones.

**Step 3. Process immunity time**

The process immunity time (PIT) is the maximum time the process can continue without electricity. It is important to consider the immunity of the actual process, not the immunity of any electrical equipment driving the process. The PIT is illustrated in Fig. 2. A serious voltage dip or an interruption starts at time \( t_1 \); a piece of equipment keeping the process running stops functioning at time \( t_1 + \Delta t \). The process parameter remains within its acceptable performance up to time \( t_2 \). It is the latter time at which the process stops and which is an input to the design as discussed here.

![Fig. 2. Definition of process-immunity time (PIT).](image)

The PIT depends strongly on the types of industrial process. Even within the same installation, the PIT may be less than 100 ms for some part of the process and several minutes or even hours for another part.

**Step 4. Process immunity requirement**

The supply performance (step 1) is combined with the process performance requirement (step 2) to obtain an immunity requirement for the process. Knowing how many dips per year are expected and how many times per year the process is allowed to trip, makes it possible to calculate for which dips the process should not trip. The process immunity requirement can thus be expressed in the form of a voltage-tolerance curve for the process.

For the same supply and the same immunity requirement different voltage tolerance curves can be obtained, as three parameters (residual voltage, duration, three-phase dip type) can be freely chosen. This could make the design rather complicated. For voltage-dip durations up to about one second the equipment curves to be discussed below can be used as guidance. For longer voltage-dip durations, interruptions in all three phases can be used as the dominating voltage-tolerance requirement.

**Step 5. Equipment performance requirement**

The next step combines the process immunity requirement with the process immunity time. This results in immunity requirements for individual equipment. As mentioned before, different parts of the production process can have different immunity times and this will be reflected in different designs.

A decision on equipment requirements can be made based on equipment immunity class and on pass/fail criterion. For short process immunity times (below a few seconds), the full-operation criterion should be used. For immunity times from about one second to several minutes, self-recovery may be used instead. For immunity times longer than several minutes assisted-recovery can be used if personnel is available to assist with the equipment recovery or restart.

Different immunity classes and pass/fail criteria are discussed in the section “Voltage dip/fail criteria”.

**Step 6. Equipment selection**

At this stage of the design process, immunity requirements are known for each piece of electrical equipment powering the industrial process. Based on these requirements, equipment manufacturers can be contacted to start the purchasing process. The voltage-dip immunity labels proposed by the working group (see next section) are a way of streamlining the communication between equipment manufacturers and designers of electrical installations powering industrial processes.

Instead of equipment with a very high immunity (i.e. that can tolerate long and deep dips) special mitigation equipment, for example using energy storage, can be used.

In some cases, the costs of equipment fulfilling the requirements are excessive or it is perceived that cheaper solutions exist. In those cases the input parameters of the design process can be changed.

- Improving the supply performance through investments
in the distribution or transmission network supplying the installation.
✓ Relaxing the process performance requirement by accepting more production stoppages. It can either be accepted that the chosen requirement is not the economical optimum, or the industrial process can be changed in such a way that the restart time after a production stoppage becomes less.
✓ Increasing the PTT by making changes in the industrial process.

VOLTAGE DIP IMMUNITY LABELS

The working group proposes to label electrical equipment for use in industrial installations, based on its immunity to voltage dips. The classification consists of two parts: a voltage-dip immunity requirement and a pass/fail criterion.

Immunity classes

Different immunity requirements are proposed for balanced and unbalanced voltage dips. The before-mentioned distinction between Type I, II and III dips is used, where Type III represents balanced dips. The immunity requirements for unbalanced dips are summarized in Fig. 3. The solid curves give the requirement for Class A and C1; the dotted curves for Class B and D.

Fig. 3. Proposed immunity classes against voltage dips of Type I and Type II (unbalanced dips).

The different classes have been chosen as follows:
✓ Class A provides the best immunity, even for sites with a high number of voltage dips.
✓ Class B provides good immunity at most locations.
✓ Class C1 for unbalance dips is based on the immunity tests prescribed by IEC 61000-4-11 and IEC 61000-4-34 for a Class 3 environment. Requirements for balanced dips have been added.
✓ Class C2 is similar to C1, but with a 50% lower limit instead of the 40% value under class C1. This is to make it easier to design equipment passing the test in countries with lower values of the nominal voltage.
✓ Class D for unbalanced dips is based on the tests prescribed by IEC 61000-4-11 and IEC 61000-4-34 for a Class 2 environment. Requirements for balanced dips have been added.
✓ Class F, not shown in the figures, refers to equipment that has failed the test or that has not been tested.

The immunity requirements against balanced dips are presented in Fig. 4. As balanced dips are less common and as it is more expensive to make equipment immune against balanced voltage dips, these requirements are less severe than the ones for unbalanced dips. The requirements are the same for Class C1, C2 and D. Especially this result of the project remains preliminary, as discussions are still ongoing. The immunity requirements in the figure and the statistics in the tables below should therefore be seen as examples. The reader is again referred to the final report [1] for the final recommendations.

Number of equipment trips

The choice of the immunity classes (especially Class A and Class B) is based on a global database with voltage-dip statistics that has been collected by the working group [2]. The database has been used to define a number of reference sites, referred to as CP50, CP75, CP90 and CP95. CP50 is the nominal site, half of the sites experience more dips than this one, half of the sites experience less. In the same way, 75% of all the sites in the database experience less dips than CP75, 25% experience more. CP95 is thus one of the worst sites for equipment sensitive to voltage dips. In fact three of the four reference sites are “worst than nominal”.

The number of dips exceeding the immunity curves in Fig. 3 and Fig. 4 has been calculated for these reference sites. The results are shown in Table 1 through Table 4. The tables should be interpreted as follows. Consider equipment that complies with Class B but not with Class A (this is typically called “Class B equipment”). Its performance will be between the Class A and Class B curves. Table 3 now states
that this equipment will trip at most 14 times per year at 90% of the sites.

Table 1. Dips per year that exceed the different immunity classes: 50% of sites are better than this, and 50% are worse.

<table>
<thead>
<tr>
<th>Immunity Class</th>
<th>A</th>
<th>B</th>
<th>C1</th>
<th>C2</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I dips</td>
<td>&lt;0.25</td>
<td>&lt;1</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>&lt;4</td>
</tr>
<tr>
<td>Type II dips</td>
<td>&lt;0.25</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;2</td>
<td>&lt;6</td>
</tr>
<tr>
<td>Type III dips</td>
<td>&lt;1</td>
<td>&lt;1.5</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Total</td>
<td>&lt;1.5</td>
<td>&lt;3.5</td>
<td>&lt;8</td>
<td>&lt;9</td>
<td>&lt;15</td>
</tr>
</tbody>
</table>

Table 2. Dips per year that exceed the different immunity classes: 75% of sites are better than this, and 25% are worse.

<table>
<thead>
<tr>
<th>Immunity Class</th>
<th>A</th>
<th>B</th>
<th>C1</th>
<th>C2</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I dips</td>
<td>&lt;0.5</td>
<td>&lt;1</td>
<td>&lt;5</td>
<td>&lt;6</td>
<td>&lt;9</td>
</tr>
<tr>
<td>Type II dips</td>
<td>&lt;0.5</td>
<td>&lt;1</td>
<td>&lt;6</td>
<td>&lt;7</td>
<td>&lt;13</td>
</tr>
<tr>
<td>Type III dips</td>
<td>&lt;1</td>
<td>&lt;4</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Total</td>
<td>&lt;2</td>
<td>&lt;6</td>
<td>&lt;21</td>
<td>&lt;23</td>
<td>&lt;32</td>
</tr>
</tbody>
</table>

Table 3. Dips per year that exceed the different immunity classes: 90% of sites are better than this, and 10% are worse.

<table>
<thead>
<tr>
<th>Immunity Class</th>
<th>A</th>
<th>B</th>
<th>C1</th>
<th>C2</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I dips</td>
<td>&lt;1</td>
<td>&lt;3</td>
<td>&lt;10</td>
<td>&lt;12</td>
<td>&lt;19</td>
</tr>
<tr>
<td>Type II dips</td>
<td>&lt;1</td>
<td>&lt;4</td>
<td>&lt;15</td>
<td>&lt;17</td>
<td>&lt;25</td>
</tr>
<tr>
<td>Type III dips</td>
<td>&lt;3</td>
<td>&lt;7</td>
<td>&lt;19</td>
<td>&lt;19</td>
<td>&lt;19</td>
</tr>
<tr>
<td>Total</td>
<td>&lt;5</td>
<td>&lt;14</td>
<td>&lt;44</td>
<td>&lt;48</td>
<td>&lt;63</td>
</tr>
</tbody>
</table>

Table 4. Dips per year that exceed the different immunity classes: 95% of sites are better than this, and 5% are worse.

<table>
<thead>
<tr>
<th>Immunity Class</th>
<th>A</th>
<th>B</th>
<th>C1</th>
<th>C2</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I dips</td>
<td>&lt;1.5</td>
<td>&lt;7</td>
<td>&lt;16</td>
<td>&lt;20</td>
<td>&lt;28</td>
</tr>
<tr>
<td>Type II dips</td>
<td>&lt;1.5</td>
<td>&lt;9</td>
<td>&lt;23</td>
<td>&lt;26</td>
<td>&lt;41</td>
</tr>
<tr>
<td>Type III dips</td>
<td>&lt;5</td>
<td>&lt;17</td>
<td>&lt;30</td>
<td>&lt;36</td>
<td>&lt;48</td>
</tr>
<tr>
<td>Total</td>
<td>&lt;8</td>
<td>&lt;33</td>
<td>&lt;69</td>
<td>&lt;82</td>
<td>&lt;117</td>
</tr>
</tbody>
</table>

These tables clearly show the huge spread among performance between different sites and between different classes of equipment. The aim of these tables is to assist in the selection of the immunity classes presented in the previous section. The tables are not intended as an aid in selecting equipment for individual sites.

Pass/fail criteria

The voltage-dip immunity label not only indicates the immunity of the equipment against voltage dips. It also indicates which pass/fail criterion has been used during the tests. A distinction is made between three pass/fail criteria:

- **Full operation**: the equipment performs at full rated operation within technical specifications.
- **Self-recovery**: the equipment performance comes temporarily outside of its specifications; the equipment recovers automatically without operator intervention.
- **Assisted-recovery**: the equipment performance comes outside of its specifications; operator intervention is needed for the equipment to continue its normal operation.

CONTRIBUTIONS

The main contributions of the working group can be summarized as follows (where this paper only addresses a small part of the groups contributions):

- A detailed description of the different properties and characteristics of voltage dips. Special emphasis has been placed on the three-phase character and the occasional non-rectangular character of voltage dips.
- A summary of voltage-dip characteristics that may be used as a checklist during the early design and development of new equipment.
- An overview of the immunity of different types of equipment against voltage dips.
- A methodology for analysing in detail an entire process and finding for each part a process immunity time.
- A methodology for making industrial processes immune to voltage dips. The methodology is based on separating "equipment immunity" from "process immunity".
- Guidelines for characterization testing of equipment resulting in a "voltage tolerance curve". These guidelines define a way of communication between equipment manufacturers and users of their equipment.
- A global database with voltage-dip statistics. This database has, among others, resulted in new insights in the ratio between balanced and unbalances dips and in the appropriateness of different equipment immunity requirements.
- Recommendations to standard-setting organizations: test levels (combinations of duration, voltage magnitude and phase angle; for each of the three test voltages with three-phase equipment) and performance objectives.

ACKNOWLEDGEMENTS

Next to the authors, the following persons have actively contributed to the working group: Alastair Ferguson, Andreia Lopes Leiria, Bengt-Arne Walldén, Dan Sabin, Daniel Carnovale, Doug Powel, Filipe Corcoles, Francisc Zavoda, Gregory Rieder, Ian McMichaels, Jan Meyer, Koen van Reusel, Koji Sakamoto, Mark McGranaghan, Michel Trottier, Patrick Marteyn, Per Norberg, Philippe Goossens, Pierre Ligot, Tim Green, Ulrich Minnaar, Vesa Tiiponen.

REFERENCES