INSULATION COORDINATION BEST PRACTICES LEADING TO IMPROVING CONTINUITY OF SUPPLY

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ABSTRACT
This paper describes a project carried out at EDP Distribuição, in collaboration with Labelec and KEMA, aiming to establish insulation coordination best practices leading to improving continuity of supply. The different phases of the project are described, including the adopted methodologies, deliverables and related main achievements. The innovative overall methodology and the value of cooperation between EDP Distribuição, Labelec and KEMA are highlighted.

INTRODUCTION
EDP Distribuição is the Portuguese electricity distribution company, delivering energy nationwide to more than 5 million customers, with a total annual consumption of around 40 TWh. Further to the low voltage grid, EDP Distribuição operates at 60, 30, 15 and 10 kV. Aiming at being among the best performing network operators in Europe, EDP Distribuição carried out extensive and consistent actions for improving the quality of service, following a comprehensive program started in the year 2000, with special focus in reducing outage duration and frequency. Results achieved in reducing outage duration (specified by TIEPI) are remarkable and the company pursues further reduction in the coming years (figures 1 and 2).

Initial analysis by EDP have indicated that performance improvements could be obtained by implementing more adequate operating and maintenance practices, as well as by enhancing the quality and reliability of the infrastructures. In 2003 EDP Distribuição invited KEMA to conduct an independent review and assessment [1] to identify most important causes of failures and incidents, which result in outages that have a substantial impact on TIEPI. Initial analysis by EDP have indicated that performance improvements could be obtained by implementing more adequate operating and maintenance practices, as well as by enhancing the quality and reliability of the infrastructures. In 2003 EDP Distribuição invited KEMA to conduct an independent review and assessment [1] to identify most important causes of failures and incidents, which result in outages that have a substantial impact on TIEPI.

Following the Quantitative Risk Assessment (QRA) performed by KEMA, an Improvement Program was established, encompassing several Projects, which cover a diversity of areas, among which Insulation Coordination. A multidisciplinary team was set-up at EDP Distribuição, involving people from different Departments and background, thus ensuring a complete insight of the Insulation Coordination practices and field experience.

METHODOLOGIES
The Insulation Coordination project developed in a 1st phase (2004-2005), covered by the assessment conducted by KEMA [2] which allowed to establish root causes for reviewing insulation coordination practices. A 2nd phase followed, the ultimate goal of the project being to identify Insulation Coordination best practices leading to improve continuity of supply.

In the 2nd phase (2006-2007), which is reported in the present paper, studies have been performed to set up the fundamental technical grounds for establishing revised Insulation Coordination Guidelines for EDP Distribuição. Those included a number of studies carried out by Labelec for evaluating system behavior under transient conditions, as well as a study by EDP Distribuição to classify and rationalize the distribution line structures.

Results were thoughtfully discussed by the EDP Group project partners (EDP Distribuição and Labelec) together...
with KEMA, considering theoretical, practical, installation and regulatory aspects.

A challenge in establishing the revised Insulation Coordination Guidelines for EDP Distribuição was applying a uniform insulation coordination philosophy throughout the whole system. Indeed, there is a large existing system, encompassing regions where different methodologies were previously applied, as a result of the historical pre-existence of several distribution companies operating in the different regions of the country.

The 2nd phase of the project was completed by a training program targeting key people that can act as insulation coordination “innovation agents”, horizontally incorporating best practices in the company. The training program included field inspections and laboratory demonstrations. The Insulation Coordination project is currently in the roll out phase, including disseminated training actions, and further internal communication media.

**LINE INSULATION COORDINATION (IC)**

In the 1st phase of the project, MV overhead lines were identified as the equipment mostly involved in the technical causes of outages. As a matter of fact, the top-8 outage causes that create 67.2 % of the outage time were identified, and MV overhead lines were found as the number one cause, with 17.2 % of the total top-8 TIEPI causes [1]. Therefore the different line insulation coordination practices have been carefully reviewed, and standardized practices established.

Taking into account results from lightning performance studies (fig. 3), EDP has opted to insulate all MV overhead lines to a lightning impulse withstand voltage (LIWV) of 250 kV. In this process a range of standardized structures has been designed to meet this insulation level. Based on laboratory test results, a list of insulators has been identified which conforms to the required LIWV of 250 kV, and insulators with additional creepage distance are selected in areas close to the coast where the pollution level is very high. General practice adopted corresponds to allowing 48 cm-clearance distances and using 3-insulator strings in all 10, 15 and 30 kV voltage levels.

The equipment installed on a line which is upgraded to the 250 kV LIWV level needs additional overvoltage protection as the equipment insulation will have a LIWV below that of the line. Equipment will be exposed to a high level of lightning overvoltages, as line flashovers will not limit induced lightning overvoltages, and flashovers will be consequently concentrated at equipment locations. To avoid these additional stresses it is necessary to install surge arresters to protect vulnerable equipment. Priority is given to equipment containing non-self-restoring insulation and locations that experiences frequent flashovers.

**MV-LV TRANSFORMERS IC**

On EDP Distribuição MV overhead lines, there are three types of MV/LV transformer installations, hereafter designated by: (1) Pole-top transformers; (2) Cable fed indoor transformers; (3) Overhead-line-fed indoor transformers. EDP’s service experience shows that MV/LV transformers are vulnerable to overvoltages and over the years many of these transformers have failed. Especially, pole top transformers have shown high failure rates. An analysis of failure data has shown that approximately 23% of all transformer failures are assigned to lightning and 21% is assigned to an internal insulation fault.

Insulation coordination of all three types of installations was carefully revisited, and standardized practices established.

**Pole-top transformers**

Surge arresters are installed on the MV-side of the transformer to protect the transformer against overvoltages from the MV-line. Surge arresters are not installed on the LV side of the transformer, but the insulation is overdimensioned. A cabinet containing the LV-switchboard is installed at the base of the pole and directly connected to the protection earth. This is done to ensure that there is a low touch voltage to the switchboard and no voltage difference between the pole and the switchboard. Figure 4 shows the condition where the protection earth is separated from the neutral earth and the LV-cabinet is fitted with a spark gap.

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**Fig 3 – Estimation of the number of line outages caused by lightning (direct and induced) [3].**

**Fig 4 – General overview of a pole-top transformer installation, with separate protection and service earths.**
The decision process regarding combined versus separate protection and service earth is in accordance to the European countries harmonization document [4] and the proposed configuration is in line with international practices for lightning protection of pole-mounted transformers. The LV-cabinet spark gap ensures protection of the LV equipment, by providing a defined sparkover path, and it will also provide some protection to the transformer LV insulation. Selected low voltage insulation and protection levels are shown in table I.

<table>
<thead>
<tr>
<th>LV-insulation levels AC (50 Hz)</th>
<th>LV-protection level AC (50 Hz)</th>
<th>LV-insulation levels LIWV</th>
<th>LV-protection level LIWV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>10 kV</td>
<td>30 kV</td>
<td>--</td>
</tr>
<tr>
<td>QGBT Cabinet</td>
<td>10 kV</td>
<td>20 kV</td>
<td>--</td>
</tr>
<tr>
<td>Gap in QGBT</td>
<td>--</td>
<td>8 kV</td>
<td>18 kV</td>
</tr>
</tbody>
</table>

Arresters shall be installed on the MV-side of the transformer. Limit values for the length of surge arrester leads have been evaluated (see table II and figure 5). Details of the underlying calculations can be found in [5].

<table>
<thead>
<tr>
<th>Voltage level $U_a$ (kV)</th>
<th>$d_1 + d_2$ (m)</th>
<th>$d_1$ (m)</th>
<th>$d_2$ (m)</th>
<th>Total distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.7</td>
<td>0.3</td>
<td>0</td>
<td>&lt; 3 m</td>
</tr>
<tr>
<td>15</td>
<td>3.5</td>
<td>0.5</td>
<td>0</td>
<td>&lt; 4 m</td>
</tr>
<tr>
<td>30</td>
<td>6.3</td>
<td>0.7</td>
<td>0</td>
<td>&lt; 7 m</td>
</tr>
</tbody>
</table>

Cable-fed indoor transformers
A cable-fed indoor transformer set up is shown diagrammatically in figure 6. In this arrangement, an overhead line terminates into a cable that feeds into the power transformer located inside a building. The presence of the cable offers the transformer some overvoltage protection since only part of the incoming surge is transmitted through the cable due to its low surge impedance. For short cable lengths it is sufficient to only have surge arresters installed at the line to cable transition and not at the transformer terminals. However, for longer cable lengths, overvoltage reflections at the transformer imply the use of surge arresters at the transformer terminals also. A survey of cable length statistics was carried out (figure 7), as well as simulation studies to identify protection requirements (see table III).

<table>
<thead>
<tr>
<th>Voltage level (kV)</th>
<th>Cable length at line to cable transition</th>
<th>Surge arresters at transformers</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 KV and 15 KV</td>
<td>Lc &lt; 50 m</td>
<td>Mandatory</td>
</tr>
<tr>
<td></td>
<td>Lc ≥ 50 m</td>
<td>Not mandatory</td>
</tr>
<tr>
<td>30 KV</td>
<td>Lc &lt; 70 m</td>
<td>Mandatory</td>
</tr>
<tr>
<td></td>
<td>Lc ≥ 70 m</td>
<td>Not mandatory</td>
</tr>
</tbody>
</table>

Overhead line-fed indoor transformers
This type of configuration is no longer built and service experience shows the need to redress problems experienced with the relatively old installations in operation. A number of solutions were defined. Further to the adequate installation of surge arresters, as in figure 8, an option is to modify the installation so to become similar to a cable-fed indoor installation. In such case the bushings and down leads are replaced by a cable, which runs from the overhead line termination to the indoor switchgear. The equipment in the installation is also modernized with the use of an indoor SF6 switchgear cabin.

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**HV-MV SUBSTATIONS IC**

Substations are the critical node points of the electrical system. Overvoltage protection concentrates normally on transformers, but line entrance equipment may also be vulnerable especially if line circuit breakers are open for substantial periods of time. Simulation studies of the transient behaviour of the overall system under lightning conditions were carried out. Special attention was given to HV side surge arrester protective distances and grounding of the MV cable sheaths.

Protective distances were evaluated, and maximum lengths defined for the connections leads to the arrester (see table IV and figure 9).

The sheaths of the MV-cables between the switchgear and the transformers are generally earthed on the switchgear side only. The cable sheath on the transformer side is protected by a cable sheath arrester. The sheaths of the MV-cables between the switchgear and the auxiliary transformers, reactors and capacitor banks are earthed on both sides. For these cables, only in exceptional cases, when there is a risk thermal overload due to sheath circulating currents, is it necessary to apply one-sided earthing, and then with the earth applied at the switchgear side. In such cases, sheath surge arresters are installed at the end that is not earthed.

**Table IV - Maximum protective distance for HV substation arresters placed near the transformer**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Maximum protective distance $d_1+d_2+d_3+d_4$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>One or more single circuit overhead lines</td>
<td>10</td>
</tr>
<tr>
<td>Double circuit overhead line entrance to one panel</td>
<td>7</td>
</tr>
<tr>
<td>Double circuit overhead line entrance to different panels</td>
<td>10</td>
</tr>
<tr>
<td>Cable entrance</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig 8 – General overview of an overhead-line-fed indoor transformer installation.

CONCLUSIONS

The 2nd phase of the Insulation Coordination project was successfully completed at EDP Distribuição. Best practices leading to improve continuity of supply have been identified, resulting into revised Insulation Coordination Guidelines to be applied throughout the HV (60 kV) and MV (30, 15 and 10 kV) networks. The challenge to overcome the differences in Insulation Coordination methodologies previously applied in different regions of the country was met, and the goal of applying a uniform insulation coordination philosophy throughout the whole system was achieved. This 2nd phase was completed by a training program targeting key people that can act as Insulation Coordination “innovation agents”, horizontally incorporating best practices in the company.

Key success factors of the Insulation Coordination project were the adopted methodology, the effective leadership and the fruitful collaboration of the EDP Group project partners (EDP Distribuição and Labelec) together with KEMA.

REFERENCES


