INTRODUCTION

Power cables and accessories failures represent, on the ENEL power distribution network, the second cause of unavailability, after lightning induced overvoltages and their relative consequences. In fact power cables, after the effective controls undergone during the production processes must be laid down and, above all, jointed and terminated in the field. The structure and the conditions of the cable network is not uniform within the Country: although, at national level, 34.8% of the medium voltage network is underground, this ratio ranges widely from region to region: from a minimum of 20% central-southern regions, to a maximum of 45%-55% of northern regions and heavily urbanized southern locations. Voltage levels are also not uniform: northern regions are operated mainly at 15kV (even if the equipment is very often dimensioned for 20kV), while 20kV is mainly used in the south, with a mixed situation in the central part of the Country. This has a strong influence on the failure rates of the network. Figure 1 shows (data 2000) the failure rate of distribution underground cables in the different parts of Italy, in terms of number of failures per 100km per year. The left column (red) refers to the total failure rate, considering all failure reasons, while the right column (blue) reports the net failure rate, i.e. the rate of failure linked with internal reasons of cables and accessories (excluding therefore failures linked with excavation works or other external causes). It can be observed that central and southern regions suffer a higher failure rate (also linked with the higher margins allowed in the northern regions by the reduced distribution voltage level) and that external causes are responsible for nearly 50% of the failures.
analysis, specific procedures were set up for the inspection process and codes for an effective failure classification were determined. To ensure the widest dissemination of the failure analysis results an Intranet site was developed in which all failure reports were collected and a database was implemented to allow statistical evaluations.

FAILURE MODES AND DEFECTS

Failure modes of power cables can be subdivided into three main categories:

- External flashovers;
- Internal longitudinal discharges;
- Punctures

In our analysis external flashovers (such as surface pollution, surface flashovers linked with damages of the surface insulation linked with mechanical shocks, application of an inadequate type of accessory for the local pollution conditions) were excluded because they are responsible for short duration failures or are linked with external causes (shocks) and because the relevant remedial actions are to be searched locally and not at a national level. Internal longitudinal discharges, occurring on the interfaces inside the accessory and whose path mainly develops in the direction of the cable, are very often linked with assembly problems: i.e. non correct finishing, imperfect sealing, inclusion of contaminants, incorrect couplings etc. Punctures develop radially in the cable accessory; they may be linked with ageing phenomena (reduction of dielectric strength, trees etc.), to the presence of defects such as roughness, inclusions, protrusions in the assembling process or to the detachment of the semiconductive layer.

In terms of physical phenomena leading to the failure we have used the following classification:

- \( \alpha \): Presence of voids;
- \( \beta \): Presence of defects leading to the increase of the electrical stress;
- \( \gamma \): Presence of defects linked with the penetration of water or contaminants in the accessory.

More in detail, during the internal inspection of the failed components the expert classified the defects found in the categories shown in Table 1.

The results of our investigation will be referred to the type of defect and to the associated phenomena. Whenever deemed necessary, more sophisticated analysis were carried out to determine the primary cause of the failures considered: mechanical tests were carried out on plastic materials samples to point out degradations due to ageing, thermo-gravimetric and infrared tests were conducted to determine the conformity of the materials composition to the original declaration of the manufacturer, scanning electron microscope (SEM) analysis were made to verify the eventual presence of foreign materials in the failure path or close to it. Most of the complementary analysis were carried out comparing the characteristics of the analysed samples with those of similar samples taken from new cable accessories.

<table>
<thead>
<tr>
<th>N.</th>
<th>Defect</th>
<th>Associated phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Production defect</td>
<td>((\alpha), (\beta), (\gamma))</td>
</tr>
<tr>
<td>1</td>
<td>Bending</td>
<td>((\alpha))</td>
</tr>
<tr>
<td>2</td>
<td>Damages on outer sheath</td>
<td>((\gamma))</td>
</tr>
<tr>
<td>3</td>
<td>Lack of adherence of outer sheath</td>
<td>((\alpha), (\gamma))</td>
</tr>
<tr>
<td>4</td>
<td>Presence of pollution on insulation</td>
<td>((\gamma))</td>
</tr>
<tr>
<td>5</td>
<td>Incorrect assembling of outer sheath control</td>
<td>((\beta))</td>
</tr>
<tr>
<td>6</td>
<td>Incorrect sealing</td>
<td>((\gamma))</td>
</tr>
<tr>
<td>7</td>
<td>Incorrect metallic screen assembly</td>
<td>((\beta))</td>
</tr>
<tr>
<td>8</td>
<td>Incorrect conductor connection preparation</td>
<td>((\beta))</td>
</tr>
<tr>
<td>9</td>
<td>Incorrect type of connection</td>
<td>((\beta))</td>
</tr>
<tr>
<td>10</td>
<td>Damages of cables insulation</td>
<td>((\alpha), (\beta))</td>
</tr>
<tr>
<td>11</td>
<td>Incorrect removal of insulation semiconducting screen</td>
<td>((\beta))</td>
</tr>
<tr>
<td>12</td>
<td>Incorrect ground connection assembly</td>
<td>((\beta))</td>
</tr>
<tr>
<td>13</td>
<td>Incorrect distances and dimensions</td>
<td>((\beta))</td>
</tr>
<tr>
<td>14</td>
<td>Presence of humidity</td>
<td>((\gamma))</td>
</tr>
<tr>
<td>15</td>
<td>Other defects</td>
<td>((\alpha), (\beta), (\gamma))</td>
</tr>
</tbody>
</table>

Examples of defects. Some examples of typical defects are shown in the following. Figure 3 shows a joint which has been heavily bent during the laydown operations: such bending has occurred when the cable accessory was still at a temperature higher than ambient and has generated the formation of voids. These voids were responsible for the ignition of partial discharges activity which resulted fatal for the accessory in the medium term.

Figure 4 shows the transversal section of a resin-type joint in which a heavy radial asymmetry was evidenced; such defect generated the formation of large voids; the partial discharges activity in this case was less critical because of the paper insulation type; however, inner spaces were available for the absorption of humidity and water.
Figure 4: Radial asymmetry in a joint with voids

Figure 5 shows the internal parts of joints in which the sealing compound was applied improperly, covering completely the contact zone between the electric field control and the insulation, thus inhibiting the functionality of the field control.

Figure 5: Incorrect application of sealing compound

Figure 6 shows the most common defects found during the internal inspections: i.e. the presence of cuts and damages to the insulation; these cuts are often produced during the cutting of the semiconductive screen in the process of assembly of the accessory. The manipulation in this phase is extremely delicate and whenever the semiconductive layer is very much adherent to the insulation or when the ambient temperature is very low the operator might have the tendency to increase the pressure of cutting to overcome the higher resistance, potentially causing such dangerous damages to the insulation.

Different types of defects in the shaping of the semiconductive screen are shown in Figure 7: the component in the middle is shaped correctly, while in the top one the shaping is not correct as the edge of the semiconductor is not cut straight and does not cover the insulation uniformly; in the bottom case the stress cone reaches directly the surface of the insulation because the semiconductive layer is too short: this situation damages the insulation which is subjected to high field stresses.

Figure 6: Deep cut in the cable insulation occurred during the shaping of the semiconductive screen

Lack of sealing, such as shown in Figure 8, where the sealing compound is nearly not present in the termination (both on the top and at the edge of the stress cone), may cause the penetration of humidity or water between the outer sheath and the insulation of the termination. If this situation persists for some time, the electrical stress may be enhanced locally and tracking can occur, like in the situations shown in Figure 9, seen with an optical microscope.

Figure 7: Different defects in the shaping of the semiconductive layer

Figure 8: Lack of sealing on a cable termination
SAMPLES ANALYSED

In the period 2001-2002 CESI carried out nearly 200 failure analysis in the frame of this project, out of which about 130 were on joints and about 60 on terminations. The representativity of the samples analysed in terms of fraction of samples subjected to inspection with respect to the total number of components failed in main Italian regions is reported in Figure 10: it can be seen that for what pertains to the northern and central regions the samples well represent the population of failed elements, while for the southern parts a higher number of samples would be necessary to increase the value of the information.

RESULTS

In terms of types of accessories sent for inspection, Figure 11 shows that most of the accessories are thermosetting: this is in fact also linked with the initial indications given to the maintenance operators which might have biased a little bit the collection towards more recent technologies.

Time to failure. In terms of time to failure, Figure 12 reports the number of samples inspected for different service life lengths.

The data reported refer to the accessories mounted by local operators only. The typical bath-tub shape is evident, showing that after an initial period where “childhood” defects are brought to evidence, a long period with a reduced failure rate appears; the failure rate increases again when ageing phenomena start to prevail on defects. A generally similar trend could be observed for accessories mounted by ENEL Distribuzione SpA personnel, except for a peak of failures in the range 10-15 years (only for resin-type joints), linked with specific problems in one of the Italian regions.

Analysis by defect type. The inspection carried out on 200 cable accessories revealed the presence of more than 700 defects, out of which more than 400 were directly linked with the failure (called fatal defects in the following); other defects were put in evidence which would have potentially lead to a failure in the course of time but which were not linked with the failure considered during the inspection. The contribution of the different types of defects to the number total failures is reported in Figure 13 (see classification of defects in Table 1). It can be observed in the figure that, for what concerns joints, most of the defects occurred during the latest parts of the mounting sequences: i.e from the reconstruction of the insulation (defect 5) to the sealing and its consequences (defects 6, 3 and 4); several damages were linked with the manipulation of the joint and cable during assembly (defects 2 and 10) and during
laydown (defect 1). The most critical parts of termination assembly seem to be the inner ones, linked with the manipulations and preparation of the conductor and the connectors (defects 8, 9); the insulation is very often damaged during these manipulations (defect 10); it is interesting to observe that in more than 10% of the terminations showing fatal defects, the primary cause of failure was linked with a production defect in the materials used (defect type 0 in Table 1).

**Analysis by defect origin.** A further elaboration of these data was carried out in terms of physical phenomena associated with the different types of defects.

This gives the information on the possibility to detect the defect using diagnostic indicators and helps in the selection of the most appropriate mix of diagnostic indicators to be used.

The contribution to the fatal failures of the different phenomena driven by the defects pointed out during inspection is shown in Figure 14.

Most of the failures can be associated with phenomena which can be detected either by partial discharges and/or by tgδ measurements, confirming the validity of combined diagnostic assessments.

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**Figure 13: Contribution to the total failures of the different types of defects**

![Bar chart showing the contribution of different types of defects to total failures](image1.png)

**Figure 14: Contribution of the different types of failure origins to fatal failures**

![Bar chart showing the contribution of different types of failure origins to fatal failures](image2.png)
Analysis by manufacturer. The cables accessories analysed in the frame of this project covered the entire population of manufacturers active in the Italian market. During the failure analysis project each manufacturer was given a letter symbol (the letter Z means: “all other manufacturers together”). Figure 15 shows, for each of the manufacturers considered, the percentage of presence in the total failures considered. It can be observed that the data are quite uniform except for manufacturer “B” to which may be recalled more than half of the failures of terminations and one third of the failures of joints. The data from figure 15 must be considered in conjunction with the information about the failures liked with manufacturing defects.

Production defects are responsible for 10% of the fatal failures that were observed on terminations and for 5% of the failures of joints; in terms of contribution of manufacturers to the failures linked to production defects we observe the predominance of manufacturer B over all the others. Now, being the design of the components checked in the frame of type tests doubts are risen about the conformity of the installed components to the approved type: further investigation is considered in this respect. The link between failures and production defects for Manufacturer B appears evident, but is not sufficient to justify the higher failure rates of this type of equipment: mounting instructions and personnel training need to be reconsidered at the light of these results.

CORRECTIVE ACTIONS

The initial results obtained in the frame of the activity carried out have pointed out the necessity to increase the level of skill and experience of the personnel charged for jointing and terminating medium voltage cables: training courses for internal and external operators on accessory mounting and checks were organized. Diagnostic checks were set up to point out the presence of defects on cables and their accessories, as illustrated in a parent paper presented in this session. Complete checks about the conformity of the installed components to the approved type were also initiated.

CONCLUSIONS

The feed-back of medium voltage cables reliability obtained by the systematic analysis of failed components has evidenced that incorrect manipulations during the assembly of joints and terminations are responsible for the majority of defects leading to early failures. Production defects of subcomponents share the responsibility and need to be carefully monitored by means of conformity checks. The validity of diagnostics based on partial discharges measurements and location has also been confirmed, because most of the failures pointed out are linked with defects which generate partial discharges.