Abstract - The present paper reports an experimental investigation on the thermal behavior of medium voltage underground cables laid in different types of soils and under different conditions of the ambient temperatures. The same paper shows as thermal degradation of the insulating system of the cables and their joints can become more consistent and faster due to the effect of the continuously overheating due to the ambient temperatures and to the thermal resistivity of the soil of higher values. An other source of thermal degradation of the cables and their joints may be indicated in the fault currents affecting the metallic shields in systems operating with a compensated neutral connection to ground. In particular, in these systems the fault current is lasted for a time of some tens of seconds to allow a faster localization of the failure, through the automatic sectioning switches. During this time, currents flow through the metallic shields of the cables, overheating the same shields especially in correspondence of poor connections which may be present inside the joints. In case that the single-fault-to-ground evolves in a double-fault-to-ground the same shield will be interested by much higher current (short-circuit) which will create a deeper degradation of the semiconductive compounds and the insulation located nearby the metallic shields. The paper also presents the results of visual inspections of failed cable joints, due to thermal causes. Based on these considerations, important solutions may be indicated to reduce the failure rate of the MV electrical system allowing improvements in the overall power quality of the entire electrical systems.

Keywords – power quality; failure rates; underground medium voltage cables; ampacity.

I. INTRODUCTION

Medium voltage (1-30 kV) underground cables represent an important part of the entire electrical network. In Italy the total extension of the medium voltage system is of about 350,000 km and more than half of this system is made through underground cables.

For this reason, it is important to investigate causes and mechanisms of faults of the medium voltage underground cables system to gain useful information to reduce the failure rate through the most appropriate possible actions. Reduction of the annual failure rates will allow important improvements in the overall power quality of the entire electrical systems.
This insulation screen is a layer of black cross linked semiconductive compound of approximately 1 mm thickness and is either fully bonded to the insulation layer, or can be “cold strippable” by hand.

One important requirement for any medium and high voltage cable is to maintain the maximum electrical field as low as possible to prevent long-term electrical aging and partial discharges activity in “void” which may be present at the interface between insulation and inner and outer materials [1].

The current capacity of the MV cables having different types of insulation are normally evaluated through the application of the IEC Standard 60287-x “Electric cables - Calculation of the current rating”. This series of IEC Standard is formed of three parts as in the following:

- Part 1: Formulae of ratings and power losses
- Part 2: Formulae for thermal resistance
- Part 3: Sections on operating conditions

In Italy the current capacity of the same MV cables are established by the Italian Standard CEI-UNEL 35027 (2009) “Power cables with rated voltages from 1 kV to 30 kV – Steady state current ratings: cables laid in air and in ground”, which are based on the above mentioned IEC Standard.

Sometimes, the effective ampacities are given by the Cable’s Producers deriving this information by the IEC Standard, which covers the typical operative conditions. It is normally assumed that the MV underground cables are laid at a nominal depth of 0.8 m, at an ambient temperature of 25 °C and in soils having thermal resistivity of 1.2 K·m/W. For all the others conditions, due to, for example, exceptional climate variations, corrective factors are suggested as reported in Tables I – III.

### TABLE I. CORRECTIVE FACTORS FOR MEDIUM VOLTAGE UNDERGROUND CABLES FOR DEPTH OF INSTALLATION DIFFERENT FROM 0.8 M

Note: If the underground cables is laid in tubes, the ampacity, under the same condition of temperature, is reduced of about 15%.

<table>
<thead>
<tr>
<th>Depth of Installation (m)</th>
<th>Underground three-phases cables (directly laid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.05</td>
</tr>
<tr>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>1.0</td>
<td>0.97</td>
</tr>
<tr>
<td>1.5</td>
<td>0.93</td>
</tr>
<tr>
<td>2.0</td>
<td>0.89</td>
</tr>
</tbody>
</table>

### TABLE II. CORRECTIVE FACTORS FOR MEDIUM VOLTAGE UNDERGROUND CABLES FOR AMBIENT TEMPERATURE DIFFERENT FROM 25 °C

<table>
<thead>
<tr>
<th>Maximum temperature for cables (°C)</th>
<th>Ambient temperatures of the ground (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

### TABLE III. CORRECTIVE FACTORS (Kr) FOR MV UNDERGROUND CABLES FOR GROUND THERMAL RESISTIVITY DIFFERENT FROM 1.2 K·m/W

<table>
<thead>
<tr>
<th>Ground Thermal Resistivity (K·m/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.07</td>
</tr>
<tr>
<td>1.02</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>0.93</td>
</tr>
<tr>
<td>0.89</td>
</tr>
<tr>
<td>0.86</td>
</tr>
</tbody>
</table>

Fig. 2 depicts the important role played by the soil thermal resistivity in the evaluation of the maximum temperature which can be reached by the insulating system of the underground cables. In fact, the IEC Standard establishes a derating corrective factor of about 15% when the thermal resistivity of the ground change from the nominal value of 1.5 K·m/W to 2.5 K·m/W. Taking into account that along the route of an underground cable values of thermal resistivity of the ground of 2.0 – 2.5 K·m/W are possible, at least for local reasons, this means that the cable may well reach temperatures significantly much higher. For instance, with a current of 200 A, the temperature of the insulation of the underground cable may be estimated of about 35 °C when the thermal resistivity of the ground is equal at 1.0 K·m/W but increases to roughly 60 °C when the thermal resistivity reaches 2.5 K·m/W. Furthermore, the thermal resistivity does not change only with the intrinsic characteristic of the ground but it is also function of the temperature, increasing with it.

Fig. 3 shows for a medium voltage underground cable as the maximum temperatures of its insulation system increase with the ambient temperature (from 0 to 55 °C). For instance, for a typical MV underground cable (240 mm² Al, three-phases system laid at the depth of 1.2 m, soil thermal resistivity of 1.5 K·m/W) when the ambient temperature change from 20 °C to 50 °C the maximum thermal rating (90 °C) roughly decreases from 350 A to 260 A. For the ambient temperature, the existing international Standards indicate the value registered just in correspondence of the soil surface; in consequence the ambient temperature may be very high (≤ 60 °C) as in the case of the asphalt surfaces exposed to direct sunlight during the summer period.
These considerations introduce an important requirement for the cables, and in particular for their insulation: to maintain the operating temperatures as low as possible to slow down the unavoidable thermal aging (Arrhenius’s law) [2-4]. Of course, the operating temperature is also function of the ambient temperature as shown in the next section

III. INFLUENCE OF AMBIENT TEMPERATURE ON THE CABLE TEMPERATURES

With the aim to better evaluate the real maximum temperatures which may be reached during the summer period by the underground medium voltage cables experimental measurement have been performed. Different temperature probes have been installed inside the soil adjacent and in proximity of the cables. The correspondent signals of the cable transmitted current and of the registered temperatures by an appropriate datalogger have been acquired and processed. The measurements have been made during the period August 2014 – January 2015. The detailed experimental setup is reported in [5].

Fig. 4 shows the experimental results along three days period acquisition time in different periods of the year, representing typical summer and winter conditions. Being the transmitted currents practically unchanged (approximately 70 A), it was found in good agreement with the thermal applicable model that the cable temperature during the summer period is higher of about 15-20 °C, as the average of the ambient temperatures. It is interesting to note that even if the ambient temperatures present continuous daily variation the simultaneous temperature values of the cable remain practically unchanged.

The experimental work concerning the measurement of both ambient and underground cable temperatures have been repeated for cables located in different sites, as in the following:

- Cable 1 (localized nearby the town of Terracina): 20 kV underground 3x95 Cu mm² having an oil-paper insulation. In the period of the investigation, this cable was interested by a very low daily load with repetitive current variations from 50 to 100 A (typical values). This cable was directly laid in the soil at a depth of 100 cm, under an asphalt road. This dry loamy/sand terrain was found to have a thermal resistivity (\(\rho\)) equal to 2.1 K·m/W;

- Cable 2 (localized nearby the city of Tivoli): 20 kV underground 3x95 Cu mm² having an oil-paper insulation. In the period of the investigation, this cable was interested by a very low daily load with repetitive current variations from 30 to 90 A (typical values). This cable was directly laid in the soil at a depth of about 80 cm, under farmland uncultivated terrain (no asphalt). This dry silt/loam terrain was found to have a thermal resistivity (\(\rho\)) equal to 1.1 K·m/W;

Fig. 5 shows during a six months period the temperature variations of the external part of the underground MV insulation cable (Cable 1) in function of the ambient temperatures. Being this cable loaded with very low currents, the trend of the cable temperatures during the different period of the year was found to follow the contextual variations of the ambient temperatures; this behavior obviously tends to change much as the transmitted currents increase: in particular, underground MV cables loaded with not negligible or high currents present thermal profiles which follow both the load and the ambient temperature variations.

IV. INFLUENCE OF SOIL THERMAL RESISTIVITY ON THE MV UNDERGROUND CABLE TEMPERATURES

Using the same experimental setup previously reported also the temperatures of two medium voltage cables (Cable 1 and Cable 2 of section III) laid in soils having different thermal
resistivity have been monitored. Fig. 6 depicts during a six
months period the temperature variations of the external part of
the insulation of these two cables in function of the type of the
soil under the realistic hypothesis of similar ambient
temperatures.

![Fig. 6. Temperature variations of the external part of two underground MV insulation cables (Cable 1 and Cable 2 as described in Section III) laid in soils having different thermal resistivities over a period of six months. Note: Cable 1 may be laid in a soil having a thermal resistivity higher of Cable 2 (2.1 K·m/W for Cable 1 and 1.1 K·m/W for Cable 2).](image)

The higher operating temperatures of the Cable 1 in comparison with the Cable 2 is clearly due to the higher thermal resistivity of the different soils where the two medium underground cables are laid down. This variation of the thermal resistivity of the soils get worse the thermal life of one of the cable which operates always at higher temperatures, being very similar both the ambient temperatures and the transmitted currents. Even if for the case of Fig. 6 the difference of the working temperatures of the two cables is limited at roughly 10 °C, the operational conditions of underground MV cables may reach temperatures much higher as the current increases (Fig. 2), the ambient temperature is still higher (asphalt case) and for local unpredictable reason which doesn’t allow a correct thermal dissipation [6]. According to the Arhenius’s law these worst working conditions, which may be estimated also in the order of 20-30 °C, will age the cable much more quickly. Under these conditions, the consequent degradation of the insulation of the underground cables will be much more remarkable in correspondence of joints and terminations, where unexpected failures could easily happen. This fact should be carefully considered when dealing with the challenge to reduce the failure rates of the underground cables to improve the power quality of the entire distribution system.

V. FAULT ANALYSIS IN CORRESPONDENCE OF CABLE JOINTS

With the purpose to better investigate the causes of the joint faults, direct inspections of some of these failed connections have been made. From these visual surveys, important degradation signs have been found in correspondence of the metallic screens and the surrounding semiconductive compounds as shown, as an example, in Fig. 7, regardless of joint age.

![Fig. 7. Typical damaged connection between the cable shield and the joint screen of a MV underground cable](image)

In fact, a discrete number of similar degradations of the semiconductive compounds, present in the proximity of the metallic shields of the cable joints, has been found. This observation allows to believe as possible that the metallic shields and surrounding compounds have been thermally overstressed and damaged during the life of the cables. In fact, in the case of the Italian medium voltage system operating with a compensated neutral connection to ground (Petersen coil) [7, 8], the single-fault-to-ground current (roughly 50 A) is lasted for a time of some seconds to allow a faster localization of the failure (Fig. 8). During this time, a current flows through the metallic shields, overheating the surrounding insulating compounds, especially in correspondence of some “bad contacts” which may be present into the joints. In a discrete number of cases, these events (single-faults-to-ground) have been found capable to evolve in double-faults-to-ground as result of insulation loss in correspondence of joints already thermally overstressed. Furthermore, as represented in Fig. 9, the double-faults-to-ground is a short circuit able to further degrade also the other joints present in the circuit creating the conditions for future failures. These phenomena of thermal degradations can be greatly diminished evaluating the possibility to disconnect the metallic screens to ground in correspondence of one of the terminal substations, also taking into account the limits for touch and step voltages in correspondence of the MV/LV substations.

![Fig. 8. Single-fault-to-ground scheme in a compensated neutral network](image)
VI. CONCLUSIONS

The concentration of the failures of the medium voltage underground cables has been found to increase during the summer period when ambient temperature is much higher and the thermal soil resistivity increases due to the scarcity of rains. An important number of these failures have been found to be triggered by the thermal overstressing due to the fault currents circulating in the metallic screens of the same MV underground cables; during the time, these phenomena induce faster degradations of the insulating compounds especially in correspondence of the joints, which are weak point and where the majority of these failures happen. Important improvements could be obtained implementing the following solutions:

- take into account of possible greater influence of temperature, humidity and thermal soil resistivity, in a general context of climate change in our areas
- possible disconnection of the metallic screens to ground in correspondence of some substations, taking into account the impact on both the protection system and the limits for touch and step voltages.

The adoption of these solutions will concur to a valuable reduction of the failure rates of the MV underground cables and will improve the power quality of the overall electrical distribution systems.

VII. ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support for this project by both the Italian Ministry of University, Scientific, Technological Research. Also a warm thank is expressed to Eng. Maurizio Della Corte of Enel Distribuzione for his precious contribution in overall the work presented in this paper.

VIII. REFERENCES