Return to Session

DEVELOPMENT OF HIGH VOLTAGE EXTRUDED CABLES: THE ITALIAN EXPERIENCE

Antonio FARA, ENEL SpA, (Italy), antonio.fara@enel.it
Ernesto ZACCONE, Prysmian SpA, (Italy), ernesto.zaccone@prysmian.com

---

ABSTRACT

High voltage extruded cables have been massively employed in the Italian distribution and transmission grid for more than 20 years. Approx 900 km circuit length of extruded insulated cables at rated voltages of 132-150 kV, have been placed in service, with an excellent record of service.

The development of a new cable system design together with the optimization of the installation procedures have permitted the reduction of the global cost of ownership and allows the realization of a number of new projects, both in urban and suburban area.

As well as a new category of accessories permitted the undergrounding of part of existing overhead lines crossing difficult areas as the penetration in the cities.

KEYWORDS

Underground Cable (UGC)
High Voltage (HV)
Extra High Voltage (EHV)
Overhead line (OHL)

INTRODUCTION

This paper illustrates the impressive development of the High Voltage (HV) cables in Italy.

For more than 50 years oil-filled cables were the only underground cables in Italy with an excellent track record in terms of reliability and performances.

During the last 25-30 years extruded cables practically totally replaced oil filled cables, up to t150 kV voltage and were used in a extensive amount for new connections both in urban and suburban areas in place of / or as a replacement for existing overhead lines.

After this period, the extruded cable systems demonstrated excellent reliability, similar or better than that of other electric apparatus. This experience confirmed the expected reliability level theoretically evaluated during the development process. Today we can affirm, with certainty and on the basis of practical experience, that the recommended methods for the prediction of the life and the evaluation of the quality of the new products, defined by institutions like CIGRE and Standards like IEC, are very effective.

THE HV AND EHV SYSTEM

The conformation of Italy and the localization of high density populated and industrialized areas require a very well meshed transmission and distribution network, in order to sustain the load demand.

Voltage systems

The Italian system voltages for HV distribution and EHV transmission are the following:

- 132 kV North
- 150 kV central, South, and islands
- 220 kV
- 380 kV

This paper takes into consideration mainly the 132 kV and 150 kV voltages (HV) that are used both for distribution and transmission, while 220 and 380 kV (EHV) are used only for transmission.

Concerning the selection of the cable system (cable and accessories) for the voltage range 132 -150 kV it was decided to adopt an unified voltage of 150 kV.

Composition of the grid

The Italian transmission and distribution grid is constituted mainly of overhead lines (OHL) but the adoption of underground cables (UGC) is rapidly growing especially for the HV up to 150 kV. The composition of the Italian grid and the length of the circuits in service at 2005 is given in table 1.

Table 1: Composition of the Italian grid at 2005

Voltage kV	Overhead lines km of circuit	Underground cables km of circuit
132-150	38280	910
220	10920	200
380	10650	34

CABLE TYPES

The transition from oil filled cables to extruded cables passed first trough the adoption of EPR (Ethylene Propylene Rubber) insulated cables that are still used for some applications and in a second time, by the adoption of a compact design of XLPE (Cross Linked Polyethylene) insulated cables.

EPR insulated cables

The first 150 kV EPR insulated cable was put in service in 1973, originally the cable was composed of a copper conductor with an insulation thickness corresponding to a maximum electric stress at conductor screen of 6 kV/mm, an extruded lead metallic sheath, and an extruded outer PVC or polyethylene sheath. In a second time a lighter cable having a copper or aluminium conductor, and a copper wires metallic screen (in place of the lead sheath) was employed. This latest cable was named wet design due to the fact that no impervious water barrier was applied Figure 1. The design of this cable was made possible thanks to the outstanding and well proven resistance of the EPR insulation to the water treeing phenomena.

Return to Session

Figure 1: 150 kV EPR insulated cable with tinned copper wires conductor, and copper wires metallic screen wet design

Some cables projects with small conductor cross sectional area were also realized with a reduced wall insulation, corresponding to a max electric stress at the conductor of 7 kV/mm. It should be noted that still today important submarine AC connections are realized with the adoption of EPR insulated cables.

XLPE insulated cables

One of the major advantage of the XLPE insulation in respect of EPR is the higher dielectric strength and the minor dielectric losses. All these properties reduce the insulation wall thickness and make possible the realization of more compact HV cable systems.

A typical design of a 150 kV XLPE cable is given in figure 2.

A major constructive aspect of the XLPE cable is the complete water tightness both in radial and longitudinal direction. The standard cable was planned to be longitudinally water tight both in the conductor and in the metallic screen, in such a way that the cable remains fully protected against water ingress that may happen during the cable laying, the installation of accessories or in case of external damages during service. If, for any reasons, the cable should be exposed to water ingress, only a short length (few meters) needs to be replaced avoiding possible expensive replacement of long cable lengths in very difficult conditions.

Losses

From IEC standards the dielectric losses of cables are given in the following equation:

$$W_d = 2\pi f \cdot C \cdot U_0^2 \cdot \tan\delta \text{ (W/m)}$$ where:

f = power frequency, Hz.
tan δ = insulation loss factor.
U_0 = phase to earth rated voltage, V.
C=Capacitance, F/m.

The following table indicates the impact of the dielectric losses in function of the selected cable

Table 2: Dielectric losses of 150 kV cables

Conductor size mm²	Conductor material	Insulation material	Tan δ at rated temp	Wd W/m
1000	CU	EPR	0.003	1.7
1600	AL	XLPE compact	0.001	0.6

Since the dielectric losses are voltage dependent their relative impact on service cost may be more relevant than the impact on the current rating. On the other hand the high amount of the dielectric losses is the limiting factor for the adoption of EPR insulation for the application to the EHV cables.

Choice of the conductor

For the 132-150 kV underground cable systems the conductor size was often based on the need to match the rating of the equivalent overhead line to which the cable may be connected. Typically the conductor used in the 132-150 kV OHL Italian system is a 31.5 diameter ACSR cable having a maximum continuous thermal current rating of 870 A as specified in the applicable standards [1]. After the initial adoption of a compact round copper conductor having a cross sectional area of 1000 mm², subsequently an equivalent compact round aluminium conductor of 1600 mm² has been chosen; in some circuits also the compact round aluminium conductor of 1000 mm² was considered sufficient. Table 3 shows the characteristics of the most used cables and the current rating capabilities for cables laid directly buried in a trench in trefoil formation at a depth of 1.4 m, with soil temperature of 20 ° C, soil thermal resistivity of 1 K.m/W and cross bonded metallic screens. The 1600 mm² compact round aluminium conductor has the same performance in terms of AC resistance and current carrying capacity as the 1000 mm² copper conductor, but offers a number of advantages in term of general characteristics and final cable cost. Independently on the nature of the metal it is usual practice to design the conductors having cross sectional areas higher than 1000 mm² in a segmental configuration (Milliken). The main two reasons for the adoption of the segmental conductor design is to make possible the construction of large conductors and the needs to reduce the skin effect that increases exponentially for large conductors with the consequence to minimize the benefits in terms of current carrying capacity of larger sections.

Table 3: Characteristics and ratings of the most common used compact round conductor for 150 kV XLPE cables

Conductor size mm²	DC resistance at 20 °C (Ω/km)	AC resistance at 90 °C (Ω/km)	Current rating (A)
1000 AL	0.0291	0.0409	850
1000 CU	0.0176	0.0272	1030
1600 AL	0.0186	0.0292	1025

For the 1600 mm² compact round aluminium conductor the skin effect and the current rating are approximately the same as the 1000 mm² compact round copper conductor, and from this point of view the adoption of the Milliken conductor design is not necessary. By doing a calculation according to IEC 60287,the 1600 mm² Milliken type

Return to Session

aluminium conductor has a current carrying capacity only 5% higher than the same compact round conductor: this does not justify the adoption of the more complicated Milliken design and is not requested by the ENEL grid load conditions.

When suitable facilities are available the compact round conductor design also offers some benefits in terms of manufacturing process and of general performances of the cable as the minor conductor diameter and the more accurate and regular external surface, thus allowing the adoption of higher electrical stresses at the conductor screen both in AC and at the basic impulse level (BIL) that for the 150 kV cables is of primary importance.

Last but not least, the compact round conductor design facilitates longitudinal water-blocking adopting different methods.

Design of the insulation structure

The regularity of the surface of the compact round conductors permits the increase of electric stresses at the conductor screens, with the logical possibility of reducing insulation thickness .

The lesson we learnt from the prequalification of EHV cables according to the IEC 62067 standards and the CIGRE studies [2] was that for the extruded HV and EHV cables the stress at insulation screen is the predominant factor. Once the XLPE extruded insulation manufacturing process is properly developed the only weak point of the cable systems remains the outer surface of the insulation that represent the interface with the accessories and is subjected to human handling.

The philosophy followed was to design HV extruded cables in accordance with the maximum allowable electric stress of 5.0 kV/mm at the insulation screen interfaces, while a maximum stress at conductor screen of 8.0 kV/mm is acceptable. This decision was made possible thanks to the availability of suitable cable accessories that will be described later. Table 4 shows the impact of this new design method in respect to the one adopted originally, when the dominant insulation design factor was the maximum electric stress at conductor screen.

Table 4: Characteristics of 150 kV XLPE cables

Conductor size mm²	Designed for max 6.0 kV/mm at conductor screen		Designed for max 5.0 kV/mm at insulation screen	
	Overall diameter mm	Weight kg/m	Overall diameter mm	Weight kg/m
1000 AL	100	9.4	88	7.7
1000 CU	100	16	88	14
1600 AL	107	12	96	10

Due to the reduced cable diameter and weight, a longer length can be contained on the reel, so that a reduced number of joints is possible, improving the system reliability and reducing the total cost of ownership.

Metallic screen

All the cables we are considering in this paper are installed in the ground or in the presence of ambient moisture. All the existing standards recommend that the HV and EHV extruded cables shall be protected by a radial water impervious barrier. Since this protection is considered of particular importance for the XLPE insulation operated at elevated electric stress, the preferred solution was the adoption of a smooth welded aluminium sheath that represented an impervious barrier against water ingress or diffusion. Compared to the well known traditional corrugated aluminium sheaths, the welded aluminium sheath is tight to the cable and does not increase significantly the overall diameter of the cable. Moreover the thickness may be thinner and is selected in order to guarantee a suitable cross sectional area of the metallic screen that shall be capable of carrying the fault current to ground of the system in which the cable will be installed. A very important aspect of the smooth aluminium sheath is the risk of collapse at bending and the risk of corrosion. Both these two problems have been resolved by the adoption of a suitable polymeric oversheath that is firmly bonded to the aluminium sheath. Exhaustive bending test programs have demonstrated that the performances at bending of this configuration is better than that of the known metallic screen or sheath design thus allowing the adoption of reduced bending radius during the installation.

Over sheath

As said above the over sheath is of fundamental importance to obtain the necessary good performances of the cable during the installation and during the service life. Very good performances have been obtained with the Polyethylene over sheath material of the type ST7 according to the applicable IEC standards designation. Other materials may be also used for specific applications as for cables installed in air in tunnels or shafts where non flame propagation and/or low smoke and zero halogen performances are requested.

In order to guarantee a perfect bonding of the thermoplastic over sheath with the under laid smooth Aluminium metallic sheath an additional layer of suitable primer or glue shall be applied.

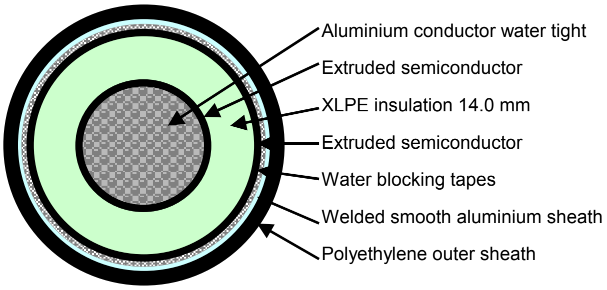

Figure 2: XLPE insulated 150 kV cable with 1600 mm² compact round aluminium conductor, and welded smooth aluminium metallic sheath.

Cable additional protection

For some applications the underground cables cannot be protected from external damages or injuries by adopting concrete slabs, or ducts or troughs: for these applications an additional polymeric shock absorber layer has been developed. Figure 3 shows the same 150 kV XLPE cable of Figure 2 but with the additional shock absorber layer.

Return to Session

Figure 3: XLPE insulated 150 kV cable as for the Figure 3 with the additional polymeric shock absorber layer.

The advantage of the polymeric shock absorber layer in respect to traditional mechanical armours (i.e. metallic tapes or wires) is that the cable weight is not dramatically increased, no additional joule losses are introduced and the protective behaviour is the same or better. Figure 4 compares the response to a shock test (see Figure 5) of a metallic tape armour and of the polymeric shock absorber layer. The permanent deformation of the metallic armour Is clearly visible. This deformation is transmitted to the under laid layers and may carry to the cable failure. In the case of the polymeric protection the impact is fully neutralized by the shock absorber layer and no deformation is transmitted to the under laid layers, preserving the integrity of the core insulation structure.

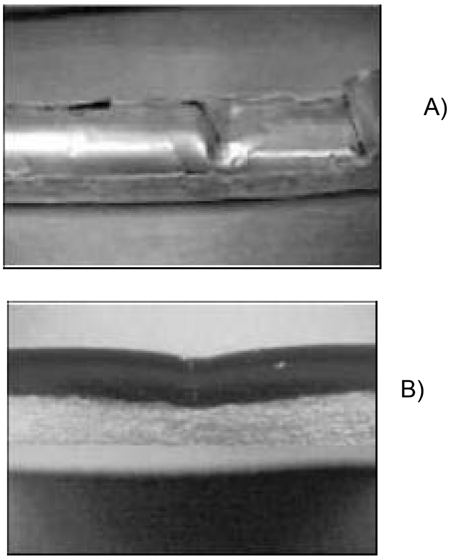

Figure 4: Results from the impact test:

A) traditional steel tapes armoured cable: the permanent damage is transferred to the under laid layers

B) polymeric shock absorber: no deformation of the under laid layers.

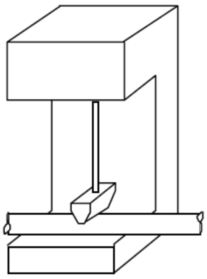

Figure 5: Apparatus for the impact test

HV CABLE ACCESSORIES

A full range of accessories types is today available for the HV and EHV extruded cables. When talking about the High Voltage and Extra High Voltage power cable systems, we have to take into consideration the fact that the availability of suitable accessories is of primary importance to guarantee the reliability of the cable system. As mentioned before the EV and EHV cable systems are operating at elevated electric stresses and, the appropriate design, qualification, and right selection of the most suitable type of cable accessory is of fundamental importance. The availability of prefabricated accessories, that reduce the workmanship and that are subjected to routine tests in the factory as well as the test on site, have strongly reduced the criticism and the risk of failures of the accessories.

Terminations

Terminations are of two main types, for external installation and for installation inside the switchgear or transformer connection.

Particular progress has been made for the development of composite outdoor terminations that are lighter and less susceptible to mechanical injuries than the traditional porcelain insulators. Composite insulator terminations are particularly suitable for the transition from OHL to UGC directly from the last pole. Figure 6 shows the transition of a 150 kV double circuit line.

Figure 6: 150 kV terminations with composite insulator installed on an OHL- UGC transition pole.

The terminations for the entrance into the switchgear and transformer oil box are of dry type and do not necessitate of maintenance or verification during service (see Figure 7).

The pre moulded stress cone of all types of terminations is routine factory tested, according to the requirements of the applicable standards.

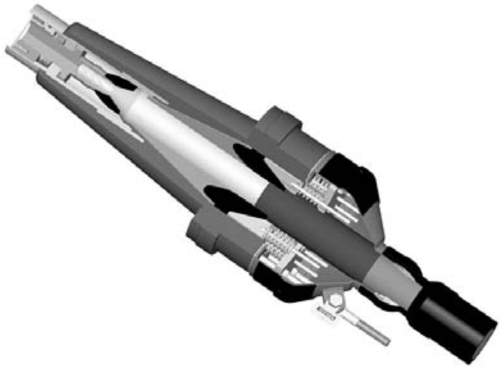

Figure 7: 150 kV GIS dry type termination.

Joints

For the HV and EHV system, pre moulded joints are now available Figure 8. As requested by the applicable standards, these kind of accessories are routine factory tested, as for the terminations stress cones. The availability of these pre moulded accessories strongly reduced the time of installation and increased significantly the reliability of the cable system. Moreover, these kind of accessories facilitates the repair of the possibly damaged cables (ie. by third parts activities) thus reducing the unavailability time of the whole system.

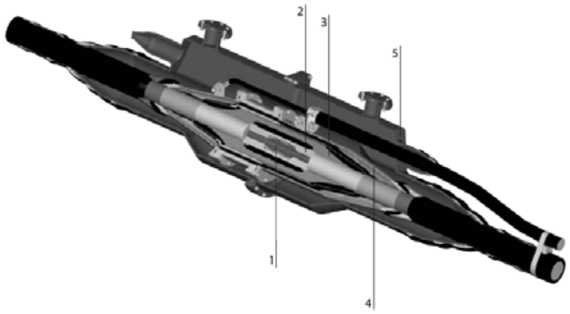

Figure 8: 150 kV pre moulded joint, 1-conductor connection, 2-corona shield, 3-EPR pre moulded sleeve, 4-copper casing with insulating ring, 5-outer protection.

Italian grid has a large number of fluid filled cables installed in service: modification, extension or rearrangement of existing circuits require the adoption of transition joints as indicated in Figure 9.

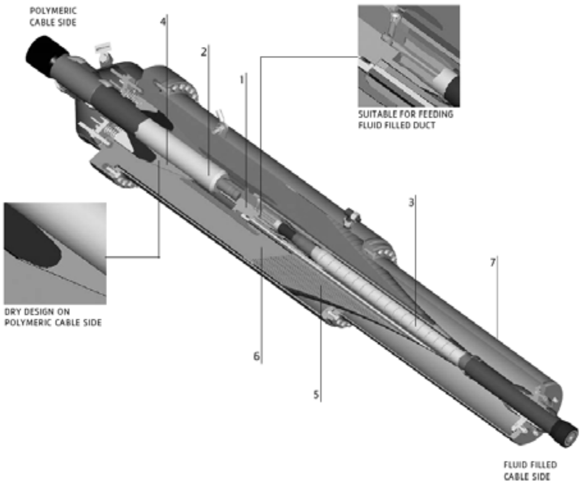

Figure 9: 150 kV transition joint, 1-conductor connection, 2-extruded cable, 3-fluid filled cable, 4-rubber stress cone, 5-paper stress cone, 6-epoxy resin bushing, 7-steel outer casing.

TESTS

The extruded HV cable systems has taken experience from the development of the extruded EHV cables systems, up to 400 kV as recommended by the CIGRE studies [3] and subsequently endorsed by the IEC standards.

In particular, a development test for the evaluation of the Weibull parameters and long term tests have been carried out on the cable systems; additional tests on the aluminium welded sheath have been carried out in accordance with the Electra 141 [3] with particular reference to the bonding of the aluminium sheath to the polyethylene outer sheath and to the resistance to the mechanical stresses and to the corrosion ,due to environmental laying conditions.

The complete cable system has been then subject to the type test in accordance with the IEC 60840 standards.

UNDEGROUND HV CABLES LAYING

One of the major aspects that influence the cost of HV cable systems is represented by civil works: during recent years a number of actions and new technologies have been considered with the scope of reducing this part of the total cost.

The cables have been laid in trefoil formation, in order to reduce the trench dimension and the impact of civil work.

New technologies for the crossing of existing structures, like directional drilling and pipe jacking, have permitted the realization of cable systems in very difficult conditions.

EMF mitigation

Italy is one of the first countries to have a proper national law on the electromagnetic fields EMF generated by power lines. This law fixes a limit of 3 microTesla on the magnetic field in proximity of residences, for all new projects [4]. The definition of residences, according to the interpretation of this law, is for all those buildings where people are present for an average time of 4 hours per day. By adopting the installation of the 150 kV cables in trefoil formation, the distance of the cable axis to the building is less than 3 m. Where this distance cannot be maintained and in proximities of the joints where the phases distance is increased, EMF mitigation measures are taken into account. These measures may consist of the installation of the cables in a ferromagnetic raceway (Figure 10) or, in proximity of the joints, by the adoption of passive cables loops.

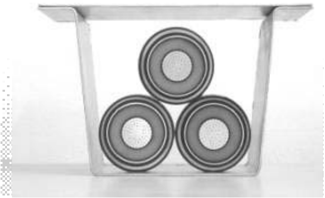

Figure 10: Cables 150 kV in ferromagnetic raceway.

AFTER LAYING TEST

A very important improvement of the most recent technologies and diagnostics method has been obtained by the possibility of carrying out the AC withstand voltage test on site. As for the CIGRE study reported in Electra 173 [5] the DC withstand test on extruded dielectric cables has been demonstrated to be ineffective and sometimes dangerous. Today the variable frequency systems, from 20 to 300 Hz, allows the matching of the resonance of the reactor and the capacitance of the cable. With this system is possible to AC test very long cable lines, involving it a reduced power and reasonable dimension and weight apparatus. Another recent improvement is the possibility of measuring the partial discharges on site test of the accessories. The scope of these tests on site is the verification of the right installation procedures and accessories assemblies; since all the cable system components are routine tested in the factory, this test has not the scope to ascertain the quality of components. Particularly important is also the test on site of the integrity of the outer sheath, this test is very important also as a maintenance test for the verification of damages to the outer sheath that may be a prelude to future cable failure.

RELIABILITY

As far as the cable life expectancy is concerned, the well known referred fault rate of 0,2 failures/year*100 km circuit - related to three phase line - is usually applied in designing electrical lines. Considering the availability of spare cables and joints and a repair time of one week, the unavailability of the system calculated with the following equation is in the order of 0.004 per 100 km circuit.

$$u = \frac{\lambda * T}{8760}$$ where:

u = Unavailability rate – 100 km circuit
λ = Failure rate – 0.2 failure/year*100 km circuit
T = Time to repair – hours

Although this value of unavailability should be fully acceptable by the operator, the effective calculated fault rate in service referred to the 150 kV Enel network (total length 910 km) is less than one tenth. This theoretical consideration and the practical feedback indicates that the impact on the unavailability of service of 150 kV underground cables is practically negligible.

On the other hand this demonstrates that the methods applied in the development, the testing and the cable system design regarding life prediction are very effective.

CONCLUSION

The 150 kV Enel underground network is constantly monitored. During the period 1996-2006 no fault in cables had been experienced, while one fault in a joint occurred in September 2005, just after installation. The joint was quickly replaced within 3 days and the examination of the faulty joint showed that the breakdown was due to a wrong assembling of a component and related neither to material nor wrong design.

Rationalization of cable design and above all, the optimization of civil works brought to a sensitive reduction of 150 kV lines total cost. Such saving allows an increase in investments in underground HV lines, that are expected to rise during future years. The installation of underground cable lines will also be possible in areas not properly urban or with an high density of population typical of some Italian regions and where the respect of areas of prestigious infrastructure development and outstanding environmental heritage is necessary.

Finally, regarding EMC and environment matters, underground lines represent today the most suitable technical/economical and possible solution, especially in relation to those areas of our towns that are becoming more and more populated.

REFERENCES

[1] CEI 11-60 (Italian standard) Carrying capacity at thermal limit of overhead lines exceeding 100 kV.

[2] Electra 151-1993 – Recommendations for electrical tests prequalification and development on extruded cables and accessories at voltages>150(170)kV and ≤400(420)kV.

[3] Electra 141-1992 – Guidelines for tests on high voltage cables with extruded insulation and laminated protective coverings.

[4] Decree of the president of the council of ministers of Italy: “Establishment of exposure limits, attention values, and quality goals to protect the population against power frequency (50 Hz) electric and magnetic fields generated by power lines”, July 8th 2003.

[5] Electra 173-1997- After laying tests on high voltage extruded insulation cable systems