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Underground Cable Construction : A Survey

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***Abstract*—Power transmission and distribution can be done either by overhead lines or power cables. Although overhead lines have been most reliable for many years, the deregulation of the electricity supply markets and growing environmental awareness are creating exciting new markets for power transmission solutions based on underground cable technology. Although there are different constructions for high-voltage cable systems this paper only deals with the following essential parts: conductor, semi conductive shielding, insulation and sheathing. This information is provided as a tool which can be utilized by electric utility engineers to improve power system performance.**

Keywords- underground cables, conductor, shielding, XLPE, EPR,DCP sheathing.

I. INTRODUCTION

Today the world is facing a great challenge due to deregulation and growing demand of electrical power. Optimum power flow in proper environmental conditions and on commercial terms has increased the responsibilities of the power utilities. So its utilities work to provide most effective, environment-friendly, reliable and optimal power to consumer [1]. Electric power can be transported from generating stations to load areas either by overhead lines system or by underground cables. The growing demand of electric power has led utilities to analyze both overhead and underground power distribution system considering their reliability, liability, maintenance and installation cost. Many countries like United States, European Union, and Australia are considering revising protocol for new power distribution installations and/or converting existing infrastructure to underground mode [2].Overhead lines have been considered generally most reliable for transmission and distribution of power technically and economically for many years. But modern technology has made possible to fabricate and utilize the highly reliable high voltage cables with overhead lines to improve the overall power network performance. Deregulation of the electricity supply markets and growing environmental awareness are creating exciting new markets for power transmission solutions based on underground cable technology.

Underground cable network now has become an important element in the power delivery chain from sub-transmission to the doorstep of consumer. Importance of underground cable network and its efficient management in the modern day electric utility is of prime importance. Underground cable network has silent benefits of reliability and safety endowed with suitable technological developments. The underground cable has several advantages like less liable to damage through storms or lightning, low maintenance cost, less chances of faults, smaller voltage drop and better general appearance. However, their major drawback is that they have greater installation cost and introduce insulation problems at high voltages compared with the equivalent overhead system. For this reason, underground cables are employed where it is impracticable to use overhead lines. Such locations may be thickly populated areas where municipal authorities prohibit overhead lines for reasons of safety, or around plants and substations or where maintenance conditions do not permit the use of overhead construction. Other substantial benefits include: interconnection of renewable energy generation, improvement of amenity, reduction of bush fires risk and reduction in number of fatal car accidents [3]

Despite the lower cost of most overhead lines, it is likely that a decreasing proportion of power will be transmitted overhead because of ecological, practical and aesthetic considerations which are reflected in the difficulty of obtaining new rights-of-way. It may be difficult to make a meaningful comparison of fault frequency, fault duration, cost of fault repair, and operating costs between overhead and underground delivery because the comparison needs to be site specific [4].

II. UNDERGROUND CABLES

An underground cable essentially consists of one or more conductors for transmitting electrical power covered with suitable insulation which is needed to insulate the conductor from direct contact with earth or other objects, and surrounded by a protecting cover which protects cable against mechanical damage, chemical or electro-chemical attack, fire or any other dangerous effects external to the cable [5].

Although cable has many types, the type of cable to be used will depend upon the working voltage and service requirements. Generally a cable must fulfill the following necessary requirements:

1. A tinned stranded copper or aluminum of high conductivity should be used as conductor in cables. Stranding is done so that conductor may become flexible and carry more current.
2. The conductor should have appropriate size so that it carries the desired load current without overheating and caused voltage drop within permissible limits.
3. Insulation used in cables should have proper thickness in order to give high degree of safety and reliability at the voltage for which it is designed.
4. A suitable mechanical protection should be provided so that the cable may withstand the rough use in laying it.

The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

III. Cable Construction

Although high voltage underground cables has different construction but they all have the following essential pares: conductors, semiconducting shields and insulation.

A. *Conductors*

High voltage cable may have one or more than one conductors in the core depending upon the type of service for which it is intended. For instance, the 3-conductor cable is used for 3-phase service for which it is intended. The conductors are either circular, circular compacted or sector shaped and consists of [6]:

a) Plain annealed copper or aluminum-class 1or 2.
b) Plain or metal coated copper-class 5or 6 for flexible.

The IEC 60228 gives minimum number of wires minimum and maximum wire diameters and maximum D.C. resistance for each conductor cross sectional area according to its formation; if solid (class 1), stranded (class 2), or flexible (class 5 or 6) .

In order to provide flexibility to the cable generally stranded conductors are used. They also can increase the maximum electrical stress by 20%. These conductors have water penetration problem where water penetrate longitudinally in the interstices or spaces between the strands. This problem can be eliminated by filling the interstices with a plastic compound or entraining water absorbing (hygroscopic) materials within the strands. Solid conductors having no interstices can also be used to achieve this longitudinal water blocking, but they are not practically used for copper. The temper usually is full hard in drawn aluminum whereas when Al is extruded, it has a soft temper. Conductor forming involves process such as drawing, compressing, annealing, coating (tinning and plating), bunching and stranding [7], [8]. Comparison of Copper and Aluminum can be done as follow (AF. Nexans Group):

Properties	Unit	Copper	Aluminum
Density	g/Cm^3	8.89	2.703
Resistivity	$Ohm.mm^2/Km$	17.241	28.264
Constant mass temperature coefficient	$1/^0C$	0.00393	0.00403
Conductivity	Siemens m/mm^2	58	36
Temperature coefficient at ^0C	^0C	234.5	228
Specific heat per unit weight	$w/g/^0C$	0.389	0.8870
Coefficient of linear expansion	$1/^0C$	$17x10^{-6}$	$23x10^{-6}$
Ultimate tensile stress	Kg/mm^2	-	11.5-15.5
(annealed),approx.		25.0	-
(harddrawn),approx.		42.0	-

B. *Shielding*

Although the conductor is the more expensive element of the cable, and the insulator the second in weight, the semiconductor shield is a minor cable component (volume rise) and is critical to the cable’s operating life. Research on semiconducting shields has played an important role in the development of electric power cables. An electric power cable shield confines the dielectric field of a cable to the insulation of the conductor which is accomplished by a conductor stress control layer and an insulation shield.

The main function of shielding is to smooth out any edges on the conductor surface. This eliminates any electrical field stress by homogenizing the electrical field around the conductor. Shielding reduces electrical or water-tree growth at sharp nucleating point, which could lead to a catastrophic breakdown of the cable. Therefore in order to prevent partial discharge at interfaces between the insulation and conductor and between the insulation and external shielding layer semiconducting materials have been applied. They also provide protection against corona discharge at surface of the stranded conductors and the insulation by maintaining close contact between the inner and outer surface of the insulation.

Semiconducting shields are based on ethylene copolymers and contain high carbon black content. It consists in a polymer matrix of ethylene-ethyl-acrylate (EEA), ethylene-vinyl-acetate (EVA), and in some cases EPR. For EPR, carbon black has a loading from 25% up to 40% w/w, and provides the compound’s conductivity. The carbon black particles must be in very close proximity to each other as they are dispersed through the polymer matrix. Factors such as CB content, mixing quality and temperature that affects CB network development affect the properties of CB filled semiconductors. Increasing CB loading and process temperature decreases the volume resistivity, which usually vary between 10 and 100 Ω cm and should not exceed 10^4 Ω cm [9]-[12]. In order to provide screening in single or three core cables conductor and insulation screen is used with following exceptions:

a) At rated voltage 3.6/6 (7.2) Kv cables insulated with EPR and HEPR may be unscreened provided the larger insulation thickness.

b) At rated voltage 3.6/6 (7.2) Kv cables insulated with PVC shall be unscreened.

1) Conductor screen: The conductor screen used is generally non-metallic and consists of an extruded semi-conducting compound, which may be applied on top of a semi-conducting tape. The extruded semi-conducting compound shall be firmly bonded to the insulation.

2) Insulation screen: The insulation screen consists of a non-metallic, semi-conductive layer in combination with a metallic layer. The non-metallic layer should be extruded directly upon the insulation of each core and consists of either a bonded or strippable semi-conductive compound. A layer of semi-conductive tape or compound may then be applied over the individual cores or the core assembly. The metallic layer should be applied over either the individual cores or the core assembly collectively [13].

Comparison of EEA and EVA can be done as follows:

Properties	EEA	EVA	ASTM
Elastic modulus(Mpa)	28-52	48-200	D638
Tensile strength(Mpa)	11-14(at break)	15-28(at break) 8-41(at yield)	D638
Compressive strength at break or yield(MPa)	21-25		D695
Elongation at break(%)	700-750	200-750	D638
Hardness	27-38	17-45	D638
Izod impact(J/cm of notch) 1/8" thick specimen unless noted	No break	No break	D256A
Coeff. of Thermal Expansion ($10^{-6}/^0C$)	160-250	160-200	D696
Specific gravity	0.93	0.922-.943	D792
Water absorption(% weight increase)after 24 hrs	0.04	0.005-0.13	D570
Dielectric strength(V/mil);1/8" thick specimen unless noted	450-550	620-760	D149
Linear Mold Shrinkage(cm/cm)	0.015-0.035	0.007-0.035	D955
Melt flow(gm/10min)		1.4-2	D1238
Flexural Modulus(Mpa)at 23^0C		53	D790

C. *Insulating materials*

Insulating materials play a major role in the performance of power cables. Therefore for satisfactory operation of power cables the appropriate selection of insulating materials is essential. An insulating material should posses the properties like highly resistive, high dielectric strength, high mechanical strength, non-hygroscopic, non-inflammable, low cost and chemically unaffected. Since no one can have all these properties, therefore the use of insulating material depends upon the purpose for which the cable is required and the quality of insulation to be aimed at.

Insulating materials used in cables generally classified as thermoplastic and thermoset. Thermoplastic insulations melt, deform and flow at high temperatures whereas thermoset materials soften but do not flow. Within these two main groupings there are four main subsets: LDPE, HDPE, EPR and XLPE [14].

1) Cross-linked polyethylene (XLPE): Thermoplastic polyethylene is a semicrystaline polymer produced by polymerization of ethylene gas under pressure has good electrical properties; resistive to chemicals and moisture, low cost, easily processed and flexible in low temperature, but the main disadvantage of this material is that it cannot be used for high temperature application i.e. above 750C [15]. In order to enhance this property PE is cross linked with a cross linking agent, like organic peroxide. Cross linking increases maximum operation temperature to 900C, the emergency temperature to 1300C, and the short circuit maximum temperature to 2500C. Cross linking also increases impact strength, dimensional stability, tensile strength, thermal properties, chemical resistance, and it improves electrical properties aging and solvent resistance of polyethylene [16].

Generally three different technologies are used for the cross-linking of polyethylene i.e. irradiation, peroxide and silane cross linking. In the irradiation process radiation of accelerated electrons (β-radiation) or electromagnetic wave (γ-radiation) extract hydrogen atoms from the carbon chain and generate the free radicals which combine to form cross-linked material. This method enhance the mechanical, productivity, resistant to heat and chemical properties while non-uniform cross-linking distribution, thickness restrictions (needed for thick insulation for high voltages) are the drawbacks of this method. Irradiation cross linking commonly used for low voltage wire and cable because of lower thickness of insulation. Silane cross linking can be done using two step sioplas or the single step monosil technology where vinyl silane is grafted onto the polymer and during extrusion a small amount of catalyst like peroxide (commonly Dicumyl peroxide, DCP) is added which acts as initiator. This method is generally used for medium voltage cables. In peroxide curing decomposition of peroxide generates reactive free radicals which extract hydrogen from the polymer chain and like irradiation process cross-linking occurs. This method requires high pressure to avoid void formation. DCP is the most common peroxide used for PE which gives safe processing [17-24].

The design average voltage stress of power cable has limited of approximately to 4-8 Kv/mm while the short-time, intrinsic, dielectric strength of the base XLPE resin is in excess of 800Kv/mm. Defects in insulation is generally occurs due to high voltage stress in small, localized regions. Such defects as protrusions from a semiconducting shield into the insulation and conductive inclusions within the insulation [25-26].Generally the two well known vulcanization methods are used i.e. Catenary (CCV) and Vertical (VCV) continuous vulcanization in manufacturing of high voltage cables. VCV must be used in the thickest insulated cables for the proper concentricity [27-28].

Since it is generally agreed that many non-mechanical power cable failures result from degradation of the cable insulation through the mechanism of water treeing which result from the combined action of water and electrical stress [29-30]. Extensive studies have been made to improve the resistance of cables to water treeing. Water treeing problem can be solved by following ways:

a) Use of additives that are usually low molecular weight organic species and are in liquid form at room temperature. Incompatibility with XLPE caused diffusion of the additive out of the polymeric matrix and deteriorates the water retardancy. Dodecanol and silanes are commonly used additives [31].
b) Blending polar ethylene copolymers with XLPE make it hydrophilic due to which the electrical condensation of water in voids and contaminant sites reduces and thus water treeing. The disadvantage of this method is that it affects the electrical properties of XLPE [32].
c) It has been known that the resistance of polyolefin to water tree increases with decrease of crystallinity. VLDPE has low degree of crystallinity and therefore has a much lower density (0.89-0.91g/cm^3). So use of very low density polyethylene (VLDPE) is also a more effective method for enhancing the water tree retardancy capability of XLPE [32-33].

2) Etyelene propylene rubber (EPR) :

EPR has found a great application in high and medium voltage cables. Because of fully saturated and nonpolar nature of ethylene propylene copolymers (EPMs), they are highly resistive to ozone, oxidation, heat, weathering, water and polar solvents. Peroxide curing can only be possible for EPR because it has superior heat resistance, compression set resistance, and lower tension set than cures and preferred for cable industry while it has some disadvantages like high material cost, high cure temperature requirement and poorer tear strength than sulfur curing.

The base polymer i.e. EPM or EPDM are only 50% of the EPR insulation and has no direct effect on electrical properties, but it determines the minimum level filler for acceptable extrusion and mechanical properties. A rough extrudate surface and low mechanical strength are the results of extrusion of EPR alone which can be eliminated by filler addition that provides the smooth surface and mechanical strength required for electrical application, but addition of fillers like carbon black affects the electrical properties. Most common filler used in electrical industries are clay, talc, whiting, silica and alumina while treated clay and hydrated alumina are used for insulation purpose. The excellent electrical properties can be obtained by using compounds contains low filler levels and no processing oils (paraffinic or naphthenic).

EPR may be used up to 90^0 C continuously and it also retain its integrity as an insulation at the emergency overload temperature of 130^{0}C by maintaining acceptable physical strength. Attractive flexibility features of EPR insulation help to achieve reliable splices and terminations, especially in cold weather. Today EPR insulated cables can be used in wet environment without metal sheath because of improved technologies [34-36]. Comparison of XLPE and EPR can be done as follows [37-41]:

Properties	Unit	XLPE	EPR
Density	g/cm^3	.92	1.2-1.4
Modulus of elasticity	Mpa	121	5-14
Heat distortion	%	20	5-8
Tensile strength	Mpa	19	9-12
Thermal conductivity	W/m^{0}C	0.27	0.27-0.35
Dielectric constant		2.3	2.5-3.0
Dissipation factor at 20^{0}C	%	<0.03 <0.03	0.16-0.3

at 90^{0}C			0.3-1.0
Volume resistivity	Ohm-cm	10^{16}	10^{13}
Short–term AC breakdown on miniature cable	Kv/mm	48	30-40

D. Sheath (Jacket)

Jacket furnishes mechanical protection for cables during installation and heat cycling. Jackets retard the ingress of water and environmental chemicals into the underlying core. Jackets over metallic shields, sheaths and concentric neural wires also provide protection against corrosion. Jackets can be thermoplastic like polyvinyl chloride (PVC), low density black polyethylene (LDPE), medium density black polyethylene (MDPE), high density black polyethylene (HDPE) and chlorinated polyethylene (CPE) or thermoset like neoprene, nitrile butadiene rubber (NBR), chlorosulfonated polyethylene (CSPE). But the most commonly used jacket materials are reinforced neoprene, LDPE, PVC and CPE. In order to enhance particular physical characteristics like toughness, abrasion resistance, oil and flame resistance etc certain jackets can be modified by addition of fillers, plasticizers, activators and inhibitors. For example halogen-free, low fire-hazard compounds like polyethylene or ethylene vinyl acetate with 60-65% aluminum trihydrate and other additives have been used for many years. A semi conductive layer to be applied of extruded layer over the jacket layer for jacket field testing after installation. Armoring can also be used for better mechanical strength and protection. For protection against water penetration in the extruded dielectric a water barrier as a separate metallic laminated tape can be applied around the cable [42-46].

IV. SOME STANDARDS RELATED TO CABLES

Components	Materials Used	Standards
Conductor	Stranded class 2-Annealed Plain/Tinned Cu/Al as per	IS:8130/IEC 60228/BS 6360
Conductor Screen	Extruded semiconducting compound	IS:7098Part-2/IEC:60502 Part-2/BS:6622, BS:7835
Insulation	XLPE	IS:7098Part-2/IEC:60502 Part2/BS:6622, BS:7835
Insulation Non-metallic Screen	Extruded semi-conducting compound	IS:7098Part-2/IEC:60502 Part2/BS:6622, BS:7835
Insulation metallic Screen	Cu wire/Tape or Al wire/Strip	IS:7098 Part-2/IEC:60502 Part2/BS:6622, BS:7835
Fillers	Non-Hygroscopic PVC/ Polypropelene Fiber to maintain roundness of cable	
Inner sheath/Bed-ding	PVC ST2 as per	IS:7098Part-2/IEC:60502 Part-2/BS:6622, LSOH to BS:7835
Armour		IS:7098Part-2, IS:3975,IEC:60502Part-2/BS:6622, BS:7835
Outer sheath	PVC ST2, FR, FRLS as per	IS:7098Part2/IEC: 60502 Part2/BS:6622,LSOH to BS:7835

V. CONCLUSION

The construction for medium and high voltage cables may be different for different purpose. This paper has reviewed only the essential components of power cables. The different types of conductors, shielding and insulating materials have been discussed and compared. Each material has some merits or demerits; therefore each one has different applications.

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