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A Review on the Need for Investigating Space Charge Behavior in Multi-Layered Polymeric Dielectrics

M.H. Wani
School of Electronics and Computer Science, University of Southampton, SO17 1BJ UK

Abstract: *The benefit of using HVDC system is partially reduced due to space charge accumulation in the insulation as the space charge has capability of enhancing the local electric field in the dielectric. Research indicates that the space charge effect is more pronounced at interfaces – precisely the dielectric-dielectric interface because of their specific properties compared to those of the bulk material. Since, multiple dielectric interfaces are encountered in cable joints, they (joints) have been identified as the weakest components of polymeric DC cable system. The local field enhancement means that the dielectric experiences electric fields above its design value at some points which can result in its breakdown eventually. A 5 year survey conducted by Cigre shows that more than 50% of the failures in extruded DC cable joints (land) were due to internal causes which makes them worthy of greater attention and calls for optimizing the compatibility of properties like permittivity and conductivity of the cable and its joint insulation by careful investigation of space charge behaviour at multi-layered dielectric interfaces. This paper aims at emphasizing the importance of improving the dielectric performance of multi-layered dielectrics by briefly reviewing the DC cable joints and the effect space charge accumulation has at its interfaces.*

Keywords - *DC joints, interface, polymeric cables, pulsed electro acoustic method, space charge.*

I. Introduction

Attributed to its several advantages like lower ohmic losses, asynchronous interconnections between two different alternating current (AC) networks, controllability etc. high-voltage direct current (HVDC) system is preferred over AC system for transmission of bulk power over longer distances [1]. However the benefit of using DC transmission is partially reduced due to the damage caused by space charge accumulation in the cable insulation. It is a well-known fact that every charge is a source of electric field, the accumulation of space charge within the insulation results in the enhancement of electric field in it which may sometimes be high enough to accelerate the electrical ageing eventually resulting in early insulation breakdown [2]. Interfaces are often encountered in dc insulation systems especially in dc cable accessories (like joints and terminations) and have received a lot of attention because the failure probability at the interfaces – precisely in cable joints is much higher than in the cable itself [3,4]. Therefore, it becomes increasingly important to gain a better understanding of charge dynamics within multi-layered dielectrics by carrying out careful investigations at interfaces. This paper provides a brief review of materials used in dc polymeric cables with special attention to cable joints, followed by a concise summary of space charge phenomenon in polymeric materials and its behavior at multi-dielectric interfaces. The paper ends up providing a brief description of the method that is used for testing of the dielectric samples for space charge density distribution in order to evaluate their dielectric performance.

II. DC Polymeric Cables and Accessories

A typical HVDC polymeric cable system comprises of a stranded copper or aluminium conductor surrounded by insulation which is sandwiched between two semiconducting layers in addition to outer protective layers and related accessories. The performance capabilities (both electrical and mechanical) of the dc polymeric cable are largely dependent upon the characteristics of the dielectric materials used in them [5]. Some of these materials have been briefly introduced in the following sections.

A. Dielectric Materialsused in Polymeric Cables

Most of the insulation in DC polymeric cables is based on polyethylene (PE) compounds [6]. The most preferred ones for HVDC are LDPE and particularly cross-linked PE (XLPE) - obtained by cross linking of LDPE with an organic peroxide such as dicumyl peroxide [5, 6]. Furthermore, ethylene propylene rubber (EPR) – a copolymer of ethylene and propylene – like XLPE offers good electrical properties, ease of processing at an acceptable cost and if properly compounded, can prove to be far more superior to the latter. Both XLPE and EPR have been used for more than 30 years and their performance advantages are well known [5].

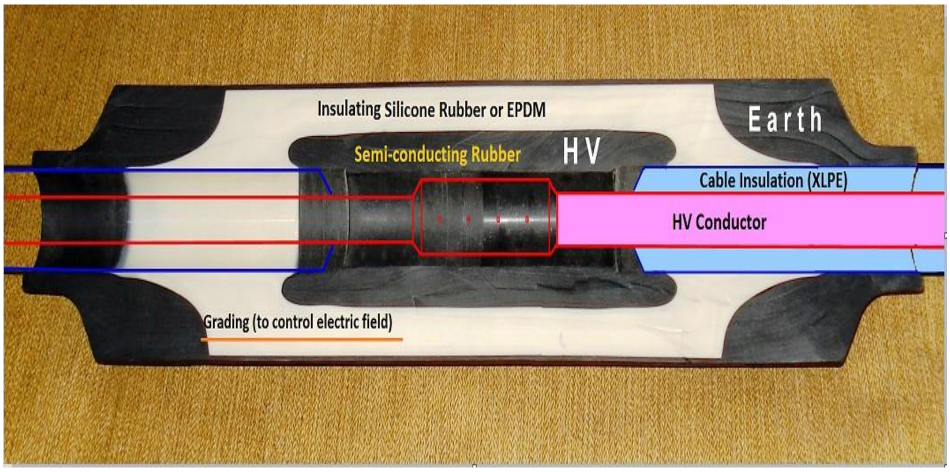

Fig. 1. Cross-section of cable joint [8]

B. Dielectric Materials used in Cable Joints

Joints are used for connecting two cable ends and are frequently encountered in HVDC cable system for long distance power transmission. These may be prefabricated (land) or factory (sea) joints, depending upon the transport situation [1]. A conventional cable joint consists of an elastomeric body where all the stress control elements (both electrical and mechanical) are integrated. This elastomeric body may be made up of either silicone rubber or ethylene propylene diene monomer (EPDM) rubber. However, due to several outstanding properties like high thermal stability, long life, good electrical and mechanical properties, silicone rubber is much preferred [7]. Fig. 1 [8] shows a cross-sectional view of typical cable joint.

C. Interfaces

In addition to the interfaces between metal conductor and dielectric, the other physical interfaces generally encountered in extruded cable insulation system include semicon/dielectric and dielectric/dielectric interfaces [8]. Interfaces are the favorite place for the space charge accumulation and since their dielectric strength is much lower as compared to that of insulation bulk, electric field along interfaces is always a critical issue [7]. More so, due to the presence of all the above mentioned interfaces in the cable joints, they (joints) particularly have been identified as the weakest points in the cable system and are worthy of greater attention.

Cable Joint Failure Statistics

As per the previous survey undertaken by Cigre corporation [9] over a period of 5 years ending December 2005 for land cables and for 15 year period ending similarly for submarine cables, extruded (XLPE) cables have become the most widely used DC cable type. However, what is worrisome are the internal failure rates of accessories, particularly of joints. Almost 1003 extruded DC land accessories were in service at the end of 2005, among which 78% comprised of pre-moulded straight joints compared to 407 accessories installed in DC submarine cables of which joints comprised only 8.35%. More than 50% of the reported faults were due to internal failures in joints (especially in land cables) clearly indicating the significance of optimizing the dielectric strength of interfaces between multiple dielectric layers encountered in cable joints. Table I shows some of the data relevant to XLPE joints extracted from statistics published by Cigre in 2009 [9]. The reason for no faults reported due to cable joint failures in submarine cables during this period may be attributed to facts like: few replies received from utilities, unawareness of all failures by manufacturers and above all the small size of data population in case of DC submarine cables [9].

III. Space Charge Phenomenon

Space charge may be defined as excessive electric charge distributed over a region of continuum of space rather

TABLE I
DC CABLE JOINT FAULT STATISTICS [9]

DC Cable	Type	Total Fault Occasions	Total Faults at Joints	Total Faults at Joints (internal)
Land	XLPE	189	59	40
Submarine	XLPE	4	0	0

than at distinct points [4]. This distributed charge may include any form of charge carriers like, electrons, holes, charged particles or ions that can exist within the dielectric material. The physical processes behind space charge accumulation are quite complex and still not completely understood. However, there are few phenomenological models made mainly for polyethylene (PE) based materials that are used to study the phenomenon [2]. Investigations carried out by several authors using various techniques indicate that space charge formation in polymers is closely related to mechanisms like: charge injection/extraction, transportation, trapping/de-trapping and carrier generation in the material. A detailed account of all these mechanisms is given in [2]. Broadly speaking, the formation of space charge takes place due to [6]:

1) *Injected charge carriers* at the electrode-polymer interface. This involves the transfer of electrons (and holes) and is highly dependent on the conditions of interface, surface defects, impurities etc.
2) *Charge already present in the bulk polymer* due to the presence of ionic dissociable additives, impurities etc. which may be introduced during manufacturing of the material. For instance, the cross-linking by-products obtained in case of XLPE manufacturing process.

Accumulation of this space charge takes place when its flow into a region of space differs from the outflow from that region [2]. This as per [4] occurs when a gradient exists in conductivity (σ, S/cm) and permittivity (ϵ) of the dielectric material. According to the following equation space charge density (ρ, C/m^3) is given by[4]:

$$\rho = \sigma E.\nabla(\frac{\varepsilon}{\sigma}) \quad (1)$$

where E (V/m) is the electric field. The gradient (ϵ/ σ) may occur for several reasons, the most acceptable reasons include: firstly, the *material inhomogeneity* i.e. presence of crystalline and amorphous regions in dielectric having different conductivity (σ) and permittivity (ϵ); secondly, the *dependence of material conductivity* (σ) on temperature gradient and electric field (E). HVDC cable insulation is the typical case where this occurs [2, 4].

Behavior at Multi-Dielectric Interface

The concept of energy band theory is also applicable to polymeric materials and can be a good means to understand the background of insulating properties of materials [6]. As already mentioned above, one of the mechanisms that influences space charge formation is trapping. *Trapping sites* or simply *traps* are potential wells where charge carriers can be captured [2] and their presence in insulating materials is ascribed to the material inhomogeneity. [2] and [6] refer to these sites as *localized energy states* present on either side of the forbidden gap. The sizes of these traps are of atomic level and electrons (or holes) crossing over from valence band to conduction band may enter these sites requiring considerable energy before they can leave thus, resulting in space charge formation. The reason for introducing this concept in the paper is to indicate its significance to interfaces. Whatever be their nature, interfaces play a fundamental role in space charge dynamics as they have specific properties compared to those of bulk material. This is because the energy distribution of trapping sites at interfaces (particularly the dielectric-dielectric interfaces) significantly differs from that of the bulk, due to physical and chemical disorders present at them [10]. Theory predicts that the space charge build up (ρ) at the interface of two dielectrics is controlled by Maxwell-Wagner-Sillars relationship given by equation (2) [10]:

$$\rho = [\varepsilon_2 - \varepsilon_1(\frac{\sigma_2}{\sigma_1})]E_2 = [\varepsilon_2(\frac{\sigma_1}{\sigma_2}) - \varepsilon_1]E_1 \quad (2)$$

where, subscripts 1 and 2 represent the components of permittivity, conductivity and electric field normal to interface between the two dielectrics respectively. During operation, there always exists a temperature gradient in the cable or its accessory and since, temperature influences conductivity there is a rise in the difference of ratios between permittivity and conductivity of both dielectrics. As per the Maxwell-Wagner theory greater this difference, greater is the space charge accumulation at interface which was also witnessed by [10] during investigations. This theory could be used to qualitatively analyze the space charge behavior at dielectric-dielectric interface. However, the actual quantitative deduction of space charge accumulation at dielectric-dielectric interface is not possible since, the theory has been put forth after assuming ideal conditions for two different dielectrics held together. In practice, a deviation from the hypothesis will be observed due to factors like existence of surface states, dependence of material conductivity and permittivity on electric stress (which is ignored in the Maxwell-Wagner theory) besides temperature, etc. [10]. For quantitative understanding/analysis of space charge build-up at layer interfaces, technical methods must be used.

IV. Overview of Methodology

A number of techniques have been in use since 1970s to investigate the space charge phenomenon. These include [1]: thermal pulse method (TPM), thermal step method (TSM), laser intensity modulation method (LIMM), pulse wave propagation (PWP), laser-induced pressure pulse (LIPP) and pulse electro acoustic (PEA) method. A detailed account of all these techniques can be found in [6]. Today, PEA is one of the most preferred methods for evaluating dielectric materials on space charge behavior [1, 4, 6]. The reasons for that include [6]: its simplicity in structure, low cost, ease of implementation, variable resolution – facilitating flexibility to be used over wide range of sample geometries (thick and thin) and above all electrical isolation provided between high-voltage circuit and signal detection circuitry, making it the safest method for studying samples subjected to high voltages.

The PEA method is based on the principle of Coulomb's force law [6]. External voltage pulses are applied to the sample placed between two electrodes which induce perturbing forces at the space charge location. These perturbing forces produce a sequence of pressure pulses setting up an acoustic wave which travels through the sample and is detected by a piezoelectric transducer mounted on the earth electrode [2, 4]. The information contained in the acoustic signal is extracted and calibrated through digital signal processing to fetch the space-charge profile information as a function of time [6].

The samples usually take the form of a thin sheet and have a specific thickness. At Southampton University samples of 100-200 μm thickness are generally tested. In order to study the space charge dynamics at multi-layered dielectric interfaces, a grade of LDPE and a couple of different brands of rubber (e.g. silicone rubber) each of 100μm thickness could be used to form various double-layered dielectric systems and to simulate a DC cable joint. The space charge profile of these double-layered dielectrics can then be compared with that of a single layer dielectric of same thickness (i.e. 200 μm) to estimate their dielectric performances at different DC voltages, applied across them.

V. Conclusion

The presence of space charge in a dielectric implies that the dielectric experiences electric fields above its design value at some regions. More quantitatively, Poisson's equation [6] indicates that space charge density of 1 $\mu C/cm^3$ in a planar XLPE sample will cause the field to change by 50 kV/mm over 1 mm distance. This additional stress can eventually result in insulation breakdown especially in cable joints which are identified to be the weakest points and where electric field distortion is witnessed more compared to rest of the dc cable system. This therefore calls for optimizing the compatibility of properties like permittivity and conductivity of cable and its accessory (joint) insulation, which could only be instigated by careful investigation of space charge behaviour at multi-layered dielectric interfaces.

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