Low voltage DC cable insulation challenges and opportunities

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Abstract - This paper addresses the challenges arising when considering the conversion of an existing low voltage cable infrastructure in distribution networks from AC to DC. It will explore the ageing mechanisms of low AC voltage cable insulation and how could they differ when operated at DC voltages. In a DC environment, the cables may experience lower voltages but higher currents; hence the thermal ageing could be the dominant stress component that may determine the lifetime of DC cables. A model based on a campus distribution network is used to identify possible constraints. Existing AC cables and their characteristics (based on a 6.6 kV distribution network), such as ampacity, temperature-current characteristics, power requirements of the system and simulation results for cables at different loads are investigated. Properties affected by ageing under AC conditions for the existing cables are considered along with constraint-points of the network.

I. Introduction

Government policies to reduce CO_2 emissions from electricity generation as well as the increasing financial cost of generating electricity create an immediate need for efficient generation, transmission, distribution and consumption of electricity. High Voltage DC transmission links are already planned and implemented around the world with China building an 1000 kV transmission line to reduce reactive power losses and increase efficiency [1]. Further to the increased use of DC as a transmission medium, it is also being used for links between offshore wind farms and the mainland [2]. Two key features of HVDC are: long distance lines have the benefit of lower power losses than the equivalent AC link, and HVDC links can be used between AC systems without the need for them to be synchronised.

At the other end of the supply chain, models of homes and offices created around the globe have shown that DC networks within buildings may be viable [3]. The majority of appliances in the office and home now convert AC to DC internally. Many are also voltage-tolerant allowing much larger voltage variations than regulations allow utilities at present.

Research groups and organisations around the world are trying to establish different DC voltage levels to be used in in-building DC systems. "Emerge Alliance", an industry association consisting of major manufacturers, recently published a standard for DC voltage levels. The DC standard produced covers an occupied space such as an office and provides for 24 VDC [4]. The IEC (International Electrotechnical Commission) is working on a global standard for 380 VDC [5]. ETSI (European Telecommunications Standards Institute) has approved a standard for 400 VDC [6] and NTT (Nippon Telegraph and Telephone) is already using 380 VDC in Japan [7]. Major car manufacturers have agreed on a new ultra-fast DC charging standard to be used across all their electric vehicles [8]. The move to electric vehicles will create very large increases in electricity demand in urban areas, particularly if there is a move to electricity for space heating. These changes will require a unique period of change in distribution networks, including the move to 'smart grids', in the distribution sector. One question which may sensibly be asked is *'if DC is prevalent in the transmission system, and omnipresent in the office and home, might it offer opportunities in the distribution network?'*

This paper focuses on Low Voltage (LV) AC cables used in a typical private distribution network. It will consider the basic limitations of their performance in situ. Buildings on served by the distribution network have live monitoring meters enabling their peak power requirements to be taken for consideration in this study.

II. Existing Cables

Existing cables used in distribution networks have either a copper or an aluminium conductor. In the network considered, these are rated at either 1 kV or 6 kV. The next layer is the electrical insulation which may be, for example, XLPE (Cross-linked Polyethylene). The 6.6 kV cable has a screen between the conductor and insulation. A typical 1 kV 300 mm^2 will have a capacity of 943 A when placed horizontally in free air. The electrical insulation for the two cables under investigation is 1.8 mm and 2.8 mm for the 1 kV and 6.6 kV cables respectively. These values are dictated by standards [9]. The armour used in these cables is either made of aluminium wire or steel wire which gives rigidity and strength to the cable. The last layer is the outside protection jacket which is made out of a LSZH (Low smoke zero halogen) polymer.

Around 90% of the underground cables in the campus considered are three core 300 mm^2 XLPE/SWA (Steel Wire Armoured) or PVC operating at 6.6 kV (Fig.2). The remaining 10% consists of oil impregnated paper cable. Inside the substations 1 kV XLPE/SWA/LSZH cables of various diameters are used operating at 230 Vrms. XLPE and PVC LV cables are the most commonly used cables and this study will mainly focus on those cables. The cables are operated at either 3.8 kVrms or 230 Vrms (phase to ground). XLPE insulation should not be operated above 90 °C. When these cables are assigned a current carrying capacity rating this thermal rating is the major consideration. After examination of the digital meters installed around the distribution network examined it was observed that the cables are never utilised above 50% of their capabilities, a situation typical in a distribution network.

III. FEA Simulations

Comsol Multiphysics was used to model the thermal characteristics of the 300 mm^2 cables. Reference values of material properties were used and soil resistivity was set at 0.5 W/mK. Differences in soil conductivity can greatly affect the cable temperature but in this study a reference value was chosen to aid the comparison of temperatures in different load scenarios.

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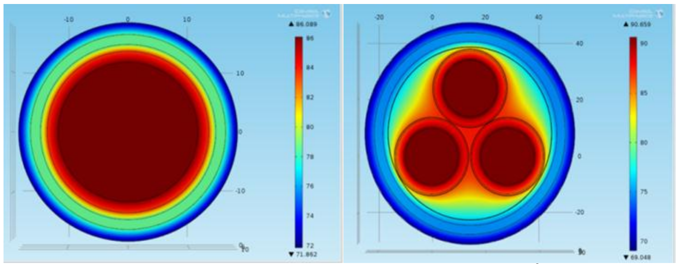

Fig. 1. Heat distribution in the different layers of the 300 mm^2 cables at the maximum current capacity.

The single core 1 kV cable was run at its full rated current capacity, under DC conditions, of 943 A in air as indicated by the standard [10]. Similarly the three core cable is rated at 670 A. The simulation showed that the insulation temperature did not pass its limit at full DC load. In Fig.1 the heat distribution is shown in the different layers of the cables. It can be clearly seen that the insulation reaches the temperature of the conductor since it is the immediate layer in contact with the conductor. Table 1 compares how the temperature changes according to the total load carried by the cable.

Fig.2 and Fig.3 show the maximum conductor temperatures when the cables are laid 80 cm directly in soil and in conduits buried in soil. Cables which touch each other greatly increase the conductor temperature. Cables in conduits have a higher temperature compared to cables buried directly in soil. Simulations showed that at full current capacity there is a minimum spacing of at least 1 metre between cables in order to drop the temperature to acceptable values.

IV. Operation Voltage Levels

A. 415 V 300mm^2 cables

The parameters in the simulation of the cable were altered in order to observe how the temperature changes as a result of lowering or increasing the operation voltage level of the cable. By changing the voltage of the cable the current will vary accordingly in order to meet the same load requirements. Electrical systems in old buildings were over-engineered a few decades ago with a very high current carrying capacity in order to be future proof. The peak steady state power a single 300 mm^2 cable can carry is 565.8 kW (943 A at 600 V).

These 300 mm^2 cables are usually connected on the low voltage side of the transformer which runs at 240 Vrms (415V phase to phase) and they are connected in pairs in order to minimize the load on each cable. The building under consideration has a peak power of 800 kW in an hour. At 415 V, the current required to meet the load of the building under study will be 3330 A. The peak power requirements of the building is carried through two transformers each having 6 cables (two for each phase). The peak power through each cable will be around 66.7 kW and the peak current 278 A. That is around 30% utilisation of the maximum current carrying capacity of each cable. These values are only correct if all three phases are perfectly balanced and that the two transformers share equal loads. Therefore in an unbalanced situation we could assume a 40% utilisation which equates to around 377 A per cable.

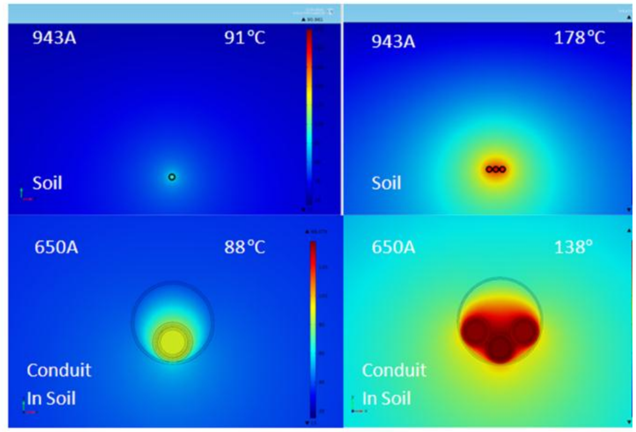

Fig. 2. Heat distribution of the single core cable buried 80cm in different scenarios and different current ratings. Maximum conductor temperature is shown.

Table 2 compares the different possible operating voltages that could be used in the existing 415 V AC cables. At 12 V the maximum power that can be carried without causing overheating is only 135 kW which is 17% of the total power required by the building. Similarly with voltage levels of 24 V and 48 V the maximum power carried is 34% and 68% respectively. At the voltage level of 72 V, the building's power requirements are marginally met when the cables are utilised at their maximum capacity. Above this voltage level the building power requirements are met without utilising the cables to their maximum capability thus reducing the thermal strain on the

Table 1
Maximum temperatures of the 300 mm^2 1 kV cable at different current values.

Load	Current (A)	Temp(^{o}C)
25%	235.75	28.80
50%	471.50	40.27
100%	943.00	86.09
125%	1178.75	120.45
150%	1414.50	162.45

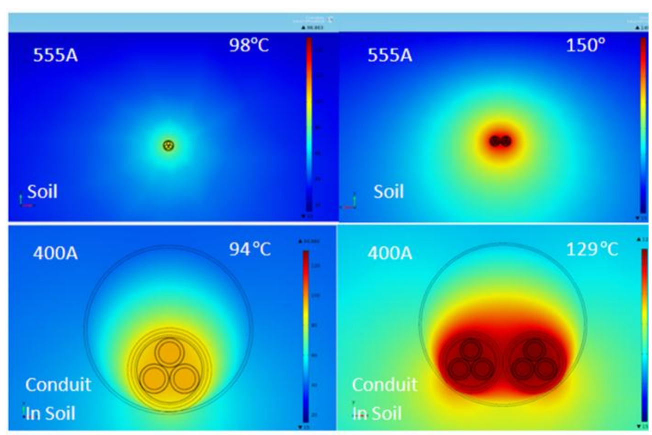

Fig. 3. Heat distribution of the three core cable buried 80cm in different scenarios and different current ratings. Maximum conductor temperature is shown.

cables.

B. 6.6 kV cables

When power is calculated in AC circuits the RMS (1/√2 of the amplitude) voltage is multiplied by the current to give the average power. In a DC circuit on the contrary the voltage is always at its 'peak' and power is calculated using that value. The insulation in an AC cable is rated for the peak voltage of operation: if the same cable is operated at DC and the insulation is be able to withstand the electric field , a clear advantage of around 40% (=(√2-1)*100) is gained in average power transfer. Respecting the cable insulation limitations in a 6.6 kV DC distribution network, it will be required to increase the operating voltage from 3.8 kVAC rms to 5.37 VDC. This allows the power capacity of the cable to increase from 1.52 kW to 2.15 kW while keeping the same current rating. For a given load demand, if the voltage is raised then the current will drop. In this case the Joule losses can be minimised as well.

By switching to DC there will be a clear advantage in power savings from the lack of a power factor, although additional losses may occur in power converters. Another benefit when using DC voltage is that voltage drops may be lower in the cable. The drop is due only to the resistance of the cable and not to the impedance as in AC voltage. For a single 300 mm^2 core cable operated at 240 Vrms the voltage drop under DC is 0.17 mV/A/m compared to 0.25 mV/A/m in AC. In long distances this will prove significant.

V. Ageing Under Ac And Dc Conditions

A major challenge is to predict the aged state of each underground cable used in the distribution network. It is not possible to know service history (loading, faults etc). Under AC voltages these cables will degrade due to several ageing mechanisms [11]. Thermal ageing occurs when excessive current is used or when there are environmental and/or extenal factors acting on the cables as shown in Table 3. Table 4 compares the diferent dielectric phenomena associated with

Table 2.
Comparison of voltage levels using existing 415 V 300mm^2 Cables

Voltage RMS(V)	Current through each cable (A)	Max. Power per cable (kW)	Max. Power available for the building* (kW)	Building Power reqs. (%)
12	235(25%)	2.82	33.84	4
	470(50%)	5.64	67.68	8
	940(100%)	11.28	135.36	17
24	235(25%)	5.64	67.68	8
	470(50%)	11.28	135.36	17
	940(100%)	22.560	270.72	34
48	235(25%)	11.280	135.36	17
	470(50%)	22.560	270.72	34
	940(100%)	45.120	541.44	68
72	235(25%)	16.92	203.04	25
	470(50%)	33.840	406.08	51
	940(100%)	**67.68**	**812.12**	**102**
96	235(25%)	22.56	270.72	34
	470(50%)	45.12	541.44	68
	940(100%)	**90.24**	**1082.88**	**135**
128	235(25%)	30.08	360.96	45
	470(50%)	60.160	721.92	90
	940(100%)	**120.32**	**1443.84**	**180**
196	235(25%)	46.06	559.2	70
	470(50%)	**92.12**	**1118.4**	**140**
	940(100%)	**184.24**	**2236.8**	**280**

*Maximum power is delivered through a total of twelve cables, six from each transformer.

Table 3
Environmental stresses on cables

Environmental and external stresses	Close to the building (LV)	Far away from the building (MV)
Elevated temperatures (external environment plus internal joule heating)	●	
Wetting – High humidity	●	
Exposure to corrosive contaminants	●	●
Moisture intrusion; flooding	●	●
Voltage transients, harmonics		●
Handling, physical contact, maintenance, testing	●	●

diferent voltage levels and the minimum electric field strength required for their inception. Thermosetting plastics like XLPE loose elasticity and their oxidative stability degrades with age [12]. AC cable insulation can experience electrical breakdown in the form of electrical trees and water trees. Water trees require moisture [20] ingress, but are unlikely below 6.6 kV. Water trees may not lead to a complete insulation failure whereas electrical trees always lead to breakdown failure [13]. However direct moisture ingress in to a cable through a corroded sheath, is a major cause of failure in older distribution cables, particularly when thermal cycling is involved [14]. Electrical treeing is a phenomenon linked with partial discharge and it is caused by manufacturing imperfections such as voids and contaminants, or moisture penetration [13]. High electrical stress causes discharges in the voids leading to erosion and carbonisation in the insulation which results in a decrease of the dielectric strength and ultimately breakdown. One of the reasons moisture is a key issue is because it can lead to discharges at very low voltages [15].

Other types of deterioration in an AC cable are due to chemical processes such as spills, oil leaks or fertilizers in the ground. These chemicals often cause corrosion of the sheath, swelling, dissolving or cracking of the cable. Chemical trees (i.e. dentritic copper sulphate deposits) can also occur in a cable. These effects can directly impact the breakdown strength of a cable or can increase the dissipation factor leading to thermal runaway.

If the transition from AC to DC is to happen, some of the above ageing effects, associated with AC stresses may have already started to degrade the materials. Given the low electric stresses involved, some form of mechanical or chemical pollution such as corrosion and moisture penetration would

Table 4
Dielectric phenomena at different voltages

	HVAC	LVAC	HVDC	LVDC	Field Strength (kV/mm)
Corona	●	○	●	○	2.9 [17]
Partial Discharge	●	○	●	○	1.1 [18]
Electrical Tree	●	○	●	○	500 [19]
Water Tree	●	○	●	○	1.9 [20]
Space Charge	●	○	●	○	15[21]
Dielectic heat	●	●	○	○	-
Resistive Heat	●	●	●	●	-

normally be a pre-cursor. Changing the stress to DC may increase chemical tree growth, but would decrease AC thermal loss. However a major change might be accelerated moisture diffusion and perhaps thermal runaway as DC conductivity increases in the insulation. Thermal ageing may thus be the dominant factor affecting the cable under DC conditions [22]. The electric field distribution in the DC dielectric material is determined by the electrical conductivity which is dependent on temperature. At sufficiently high conductivity and electric field, the heat generation due to the current through the insulation could be significant.

Another major difference in moving to a DC system is the increased likelihood of sheath corrosion due to sheath leakage currents. Since moisture penetration is seen as a key processes this will be a key engineering issue in outdoor applications.

VI. Points Of Constraint In The Network

Estimates as to where most failures occur in an urban network vary by source but they all have in common three main components that cause more than 90% of the system failures [16]. These are cables, joints and terminations. Joints usually exist when the cable reaches the maximum length which is dictated by the reel size. In the case of the 6.6 kV cable it is every 250 m. Joints exist inside buildings where a cable is taken from the substation to another building that does not have a substation of its own. Terminations are present at the different busbars and ring main units (RMUs) as well as switching boards. Common failures in a joint are again caused by partial discharge and are usually due to manufacturing defects, poor workmanship and moisture ingress.

According to the FEA simulation in Section III, cable temperature depends on many factors. Soil conductivity plays a major role in the cable current carrying capacity. Changes in weather and soil moisture can contribute as well. Major constraint points in the network will be points that have the highest power flow (e.g. a cable carrying power to more buildings) and where joints with poor workmanship exist. If the whole distribution network switches from AC to DC then major parts of the system will have to be replaced, and some restriction can be mitigated at that stage.

VII. Summary and Conclusions

The thermal FEA simulation for existing 415 V AC cables showed that the minimum DC voltage to obtain equivalent power is 72 V. The existing 6.6 kV AC cable distribution infrastracture under study could be used for transition to DC power distribution. An imidiate advantage of a DC distribution network respecting the existing 6.6 kV current rating limitations will be the increase of the power transfer capacity.

However, a major ageing consideration of the insulation is the corrosion of sheath since it is a precursor to moisture penetration. DC voltage could accelerate this. A thorough understanding of low voltage ageing mechanisms is of paramount importance since they are distinct from well studied high voltage mechanisms.

The impact of DC voltage on moisture penetration, and the impact of moisture and temperature on insulation conductivity needs to be established. This is likely to identify a significant difference in behaviour between oil/paper insulated systems and XLPE. Finally an understanding of cable joints and their vulnerability to defects and also corrosion of joint sheaths needs to be established.

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References

[1] R.M. Nayak, R.P. Sasmal, V.K. Sehgal, M. Rashwan, G. Flisberg “Technical feasibility and research and development needs for ± 1000 kV and above HVDC system” in CIGRE B4-105_2010, 2010

[2] Luckett, M.J. ,Jhutty, A.S. “Cost benefit analysis of redundancy levels of large, offshore windfarm equipment” in IET Conference on Reliability of Transmission and Distribution Networks (RTDN 2011), 2011

[3] PSMA 2012 EMerge Presentation - APEC/PSMA 2012, February 5, 2012

[4] http://www.emergealliance.org/standard/Overview.aspx

[5] IEC SG4, LVDC distribution systems up to 1500V DC, 2009

[6] ETSI EN 300 132-3, Published by ETSI, 2011

[7] K. Hirose, “DC powered data centres in the world”, in LVDC Workshop SMB Strategic Group 4 on LVDC distribution systems up to 1500 V, 29th & 30th of September 2011 (Dresden/Germany)

[8] CHADEMO standard, by CHADEMO Association

[9] BS 6724:1997+A3:2008, “Electric cables. Thermosetting insulated, armoured cables for voltages of 600/1000 v and 1900/3300 v, having low emission of smoke and corrosive gases when affected by fire” by British Standards, 1997
BS 6622:2007,“Electric cables. Armoured cables with thermosetting insulation for rated voltages from 3.8/6.6 kv to 19/33 kv. Requirements and test methods“by British Standards, 2007

[10] BS 7671:2008+A1:2011, “Requirements for electrical installations. Iet wiring regulations. Seventeenth edition”, by British Standards, 2011

[11] S. Bahadoorsingh, S. M. Rowland , “A Framework Linking Knowledge of Insulation Ageing to Asset Management” *IEEE Electrical Insulation Magazine* Vol. 24, Issue 3, pp. 38 - 46 (2008)

[12] J. Li , X. Tong, G. Yin, S. Li, J. Zhao, B. Ouyang, “The Effect of Accelerated Water Tree Ageing on the Properties of XLPE Cable Insulation” *in IEEE Trans. Dielectr. Electr. Insul*., pp 1562 – 1569, 2011

[13] W. A.Thue, “Electrical Power Cable Engineering” 2nd Edition, Chapter 19, CRC Press, 2012

[14] M Wang, S M Rowland and P E Clements, “Moisture Ingress into Low Voltage Oil-Impregnated-Paper Insulated Distribution Cables” IET Proc Sci., Meas. & Tech. 1 Issue 5 (2007) 276-283

[15] S M Rowland and M Wang, ‘Fault Development in Wet, Low Voltage, Oil-Impregnated Paper Insulated Cables’, *IEEE Trans. Dielectr. Electr. Insul.*Vol. 15, No. 2, (2008) pp. 484 – 491

[16]J. Altamirano, T. Andrews, M. Beovic, Y. del Valle, R. Harley, J.C. Hernandez Mejia, T. J. Parker, “Diagnostic Testing of Undeground Cable Systems” by Beetrac, December 2010

[17]X. Bian, L. Wang, J. M. K. MacAlpine, Z. Guan, J. Hui, Y. Chen, “Positive Corona Inception Voltages and Corona Currents for Air at Various Pressures and Humidities” in *IEEE Trans. Dielectr. Electr. Insul*. Vol. 17, No. 1; 2010

[18]Christou I., “Optimisation of High Voltage Electrical Systems for Aerospace Applications”, Ph.D thesis, The University of Manchester, 2011, pp. 246-247

[19]Noto F., Yoshimura N., Annual Report Confernce on Elecrical Insulation and Dielectric Phenomena, 1977, pp. 207-217

[20] Naybour, R.D. , “Annual report - Conference on Electrical Insulation and Dielectric Phenomena”, 1982, pp. 620-627

[21]G.C. Montanari, “The Electrical Degradation of Polyethylene Investigated by Space Charge and Conduction Current Measurments” *in IEEE Trans. Dielectr. Electr. Insul.,* Vol.7 No.3, 2000

[22]A. Tzimas, S. M. Rowland, L. A. Dissado, and U. H. Nilsson, “Effect of long-time electrical and thermal stresses upon the endurance capability of cable insulation material,” *IEEE Trans. Dielectr. Electr. Insul*., vol. 16, no. 5, p. 1436, 2009.