Effect of size on electrical performance

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Abstract
The electrical breakdown performance, either unaged or after ageing (laboratory or service), is often used as the basis for qualification of a device, design or material. Many of the features that affect these performance levels have been discussed in other documents; contaminants, propensity for water treeing, insulating and semiconducting materials. However the size of cable tested is rarely discussed. This is somewhat surprising as it has been long recognized that electrical failure is an Extreme Value (the Weibull distribution is a member of this family) or weakest link process. In Extreme Value processes the performance of the whole device is determined by the single "weakest link". Thus when more "weak links" are present the chance of failure is consequently higher: the measured performance depends on weak link concentration or size of the device. Additionally at some dimensions the thickness of the dielectric can influence the breakdown mechanism itself; especially if the thermal influences are present

This paper will attempt to discuss a number of these size related issues for both AC & Impulse conditions; these will include:

- The effect of the dielectric volume actual mechanism of failure
- Prediction of performance on service length cables from short length laboratory tests. This has practical relevance on the selection of appropriate qualification levels which will have direct relevance to service performance.
- The requirements for cable quality when increasing the size (thickness or length) installed.

1,0 Introduction

Recent predictions show that the world will require 60% more energy by the year 2030. This presents electric power distributors with a very real challenge: "How to maintain the necessary pace of network development and ensure consistently high system performance and reliability". Reliability will become increasingly more important as regulatory frameworks raise expectations in respect of 'supply quality'.

The transmission and distribution of electrical energy requires efficient and reliable networks with low losses. Traditionally this role has been fulfilled by overhead networks, which have been considered as a lower cost alternative to underground cable solutions [1, 2]. However, with progressive advances in technology, calculations show that the costs of overhead lines and cables are much closer when compared on the basis of 'Total Cost'. This comparison goes beyond installation costs only and takes into account a broader range of criteria, including fault rates and dielectric losses.

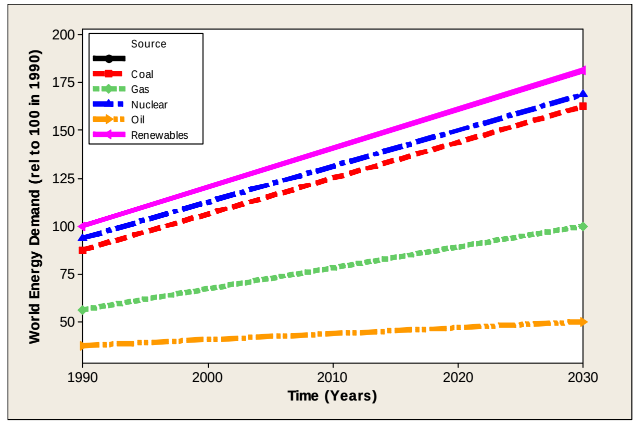

Figure 1 Estimated world energy demand (International Energy Agency)

It is now understood that cables are valuable because they are both invisible and reliable. If the cables were not reliable then the necessary repairs would make them visible, as well as costly. The conclusion to be drawn is that reliability equals value and anything that compromises reliability is a "false economy". This is of vital importance to customers and a commercial imperative for grid owners as transmission reliability gives maximum earnings through volume of transmitted energy.

2.0 Theoretical Basis

Failure data can be analysed using a wide variety of techniques; Gaussian, Non Parametric to Extreme Value. The most common approach is to use the Weibull distribution (Equation 1) [3]. Equation 1 shows the most general or 3 Parameter form; however it is quite usual to see the 2 Parameter form where S_L =0.

$$P(S) = 1 - \exp(\frac{S - S_L}{\alpha})^{-\beta} \qquad \textbf{Equation 1}$$

Where **P** is the probability of failure at the applied stress **S**; **S** is the stress (voltage, electrical stress, number of cycles) applied to the system; S_L is the location or threshold parameter, the probability of failure is vanishingly small below this value; α is the magnitude estimator and is referred to as the scale parameter; β is the mechanism estimator and is referred to as the shape parameter.

The Weibull distribution is particularly attractive because:

- It works for small sample sizes (5 – 20); much smaller than any of the other techniques (>40)
- The shape of the probability distribution can be estimated from the data itself
- Its very robust for missing or suspended data. In this case suspended data are samples that either have not failed or failed from a different mechanism to that under study
- It give both the magnitude (scale parameter, α) and information on the mechanism (shape parameter , β)
- Enables predictions for other conditions
- Comes from the branch of statistics which deals with extreme values and thus fits well to the physics of failure where breakage of one element leads to complete device failure

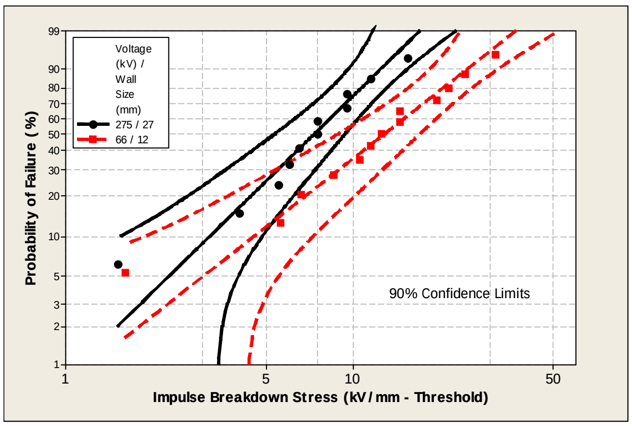

Figure 2 Effect of cable voltage and insulation thickness on the impulse breakdown strength of XLPE cables at 90°C

Parameter	66kV 12mm	275kV 27mm
3 Parameter		
Location / Threshold S_L (kV/mm)	71	70
Scale α (kV/mm)	16	9
Shape β	1.8	2.2
2 Parameter		
Scale α (kV/mm)	89	80
Shape β	11	21

Table 1 Weibull analysis for the data in Figure 1 using two different routes

The analysis is conveniently carried out by a computer; however the data presentation is primarily graphical in nature. The form of presentation uses a linearised set of axes employing double and single logarithmic scales [3] Figures 2 & 3 and Table 1 shows the case for impulse tests on XLPE cables [4] of differing voltages and size. It is clear that either graphically of via computation (Equation 1) the Probability of failure at any stress S can be estimated. In fact it is equally common to estimate the stress at which a particular level of probability.

It has been long recognized that electrical failure is an extreme value (Weibull) or weakest link process and that in Extreme Value processes the performance of the whole device is determined by the single "weakest link". Thus when more "weak links" are present the chance of failure is consequently higher: the measured performance depends on weak link concentration or size of the device.

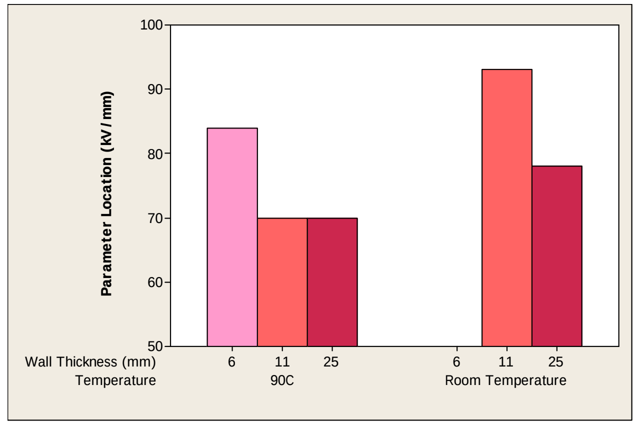

Figure 3 Effect of cable size (wall thickness) and temperature on the impulse breakdown strength of XLPE cables

Generally it would be expected that the Scale and Location Parameters will decrease (failure become more likely at stress **S**) when the volume of insulation tests is increased. In the case where $\mathbf{S_L}$ the Weibull equation reverts to the more normal two parameter form and in this case the effect of volume, either from increased length or increased conductor size can be estimated (Equation 2). Increasing the volume will modify (reduce) the actual strength as it is measured; in this case the Weibull Scale parameter (α). This approach covers the case where the same failure mechanisms operate in the volume range of interest ie the β values are constant.

$$\alpha_{actual} = \alpha_{ref}\left(\frac{V_{ref}}{V_{actual}}\right)^{1/\beta} \qquad \textbf{Equation 2}$$

Where **ref** and **actual** refer to the volumes (**V**) tested and the scale / shape parameters (α, β) from Weibull analysis

The discussion above could be regarded as a a statistical diversion coming from some arbitrary choice of distribution. Thus it is useful to examine the experimental data (Section 3) and then to look at the consequences in the "Real World" (Section 4).

3,0 Experimental Evidence

3,1 Effect of thickness and electrode area

Figure 4 shows breakdown data for Aramid films of different thicknesses reported by Ul Haq and Raju. The tests have been carried out for a number of electrode sizes, expressed as insulation volume. The data shows that he breakdown strengths (Weibull Scale parameters) reduce as the volume increases. However there is a clear and separate effect of the different thicknesses; even at the same volumes. The full Weibull parameters are shown in Figure 5. Here we see that the Shape Parameter, and thus the mechanism of failure, changes with volume. Thus for these dimensions there is an effect of volume, **but** the transform of Equation 2 cannot be used as the mechanism of failure changes with size. In the case of thin films mechanical damage and thermal effects can have an additional influence above those of the increased concentration of defects.

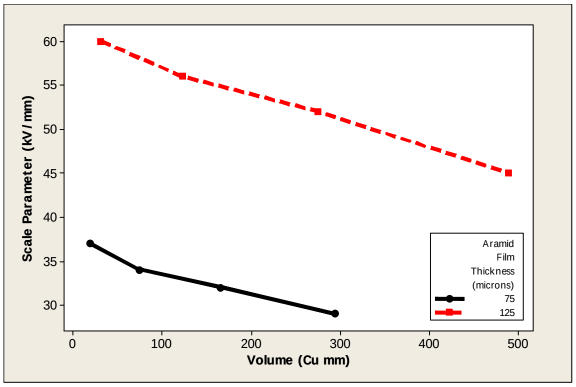

Figure 4 Effect of volume (mm^3)on the breakdown stress of Aramid films.

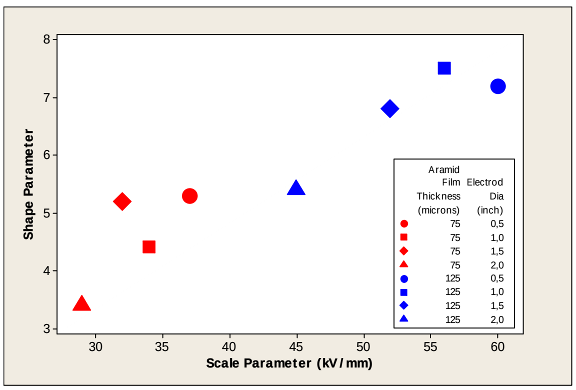

Figure 5 Full Weibull Parameter for selected thickness and electrode size

3,2 Effect of Test Length

The wet ageing is an important attribute for MV cable systems [4, 5]. Qualification of full sized cables requires ageing out to 1 and 2 years; however it has been found that testing of model cables out to 1000hours is an effective (faster) way to gain understanding of ageing [6].

Figure 6 shows the breakdown strength after ageing for selected sizes. Figure 7 shows how the breakdown strength decreases with increasing length. The transform works rather well in this case as the failure mechanisms (the gradients of the curves) are the same for all lengths.

Thus it is clear that the length of test specimen and the and its volume will have a significant influence on the results achieved in any ageing test.

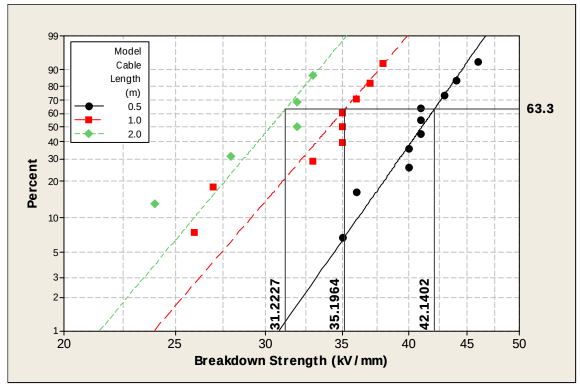

Figure 6 Breakdown strength of model cables (1.5mm wall) of different lengths after wet ageing for 1000hours

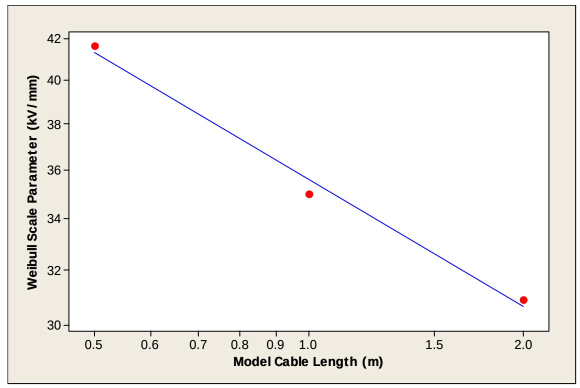

Figure 7 Reduction of breakdown strength (Figure 5) with increasing cable length

4 Practical Consequences

4.1 Length / Size of Test / Qualification Objects

MV cable tests in Europe use two years ageing at 50Hz to qualify materials and production machinery [4]. Figure 8 shows the typical results (aged and unaged) that are obtained for a qualification. The Weibull Scale and Shape parameters are 18Uo and 4.5 respectively.

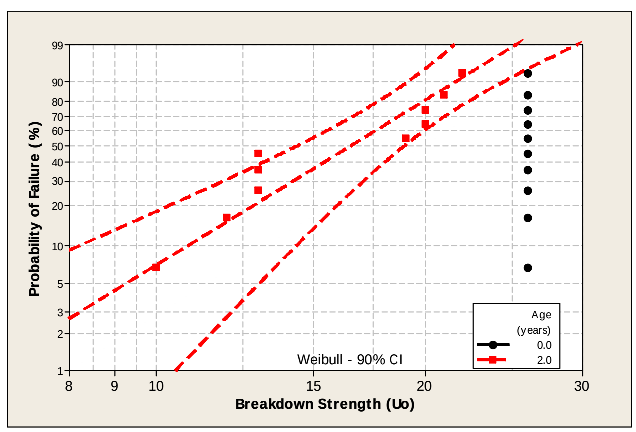

Figure 8 Breakdown strength of MV cables (20kV) after 2 years ageing

The data in Figure 8 are in agreement with very many studies show that good performance can be obtained in accelerated aging tests when using compounds designed to have enhanced performance. Yet it is important to recognize that these data do not directly relate to predictions of performance at:

- Longer Times (a service life of 30 – 40 years)
- Longer Lengths – only short lengths (5 - 10m) are tested in accelerated tests

True cable life estimates are difficult to achieve as various allowances need to be made to the test data, perhaps the so called Accelerated Cable Life Tests (ACLT) come closest. The two main issues are

- How much service ageing is represented by the accelerated laboratory tests? In service the cables will experience transients generally drier conditions and lower voltage stresses
- How do the much longer lengths installed in service relate to the much shorter lengths tested in the laboratory?

We do not discuss the first point further in this paper; however it is worthwhile to undertake some calculations to estimate breakdown stress at longer lengths. This is because it enables use to look at some of the fundamentals of the success levels. Figure 9 shows estimates of performance at lengths based on the CENELEC HD620 data from Figure 8 and the transform in Equation 1. This graph should be interpreted as the situation for cables between joints. This is because joints are known to have different and higher failure rates to cables; that said they are generally located in more accessible places such that repairs are less onerous.

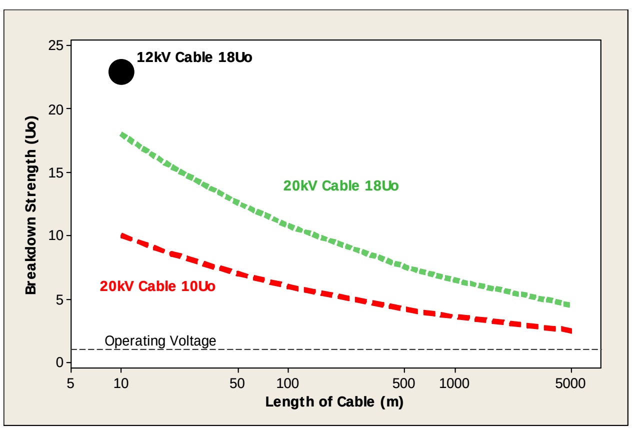

Figure 9 Effect of cable length (between joints) on the breakdown strength

The green curve represents the data in Figure 8 and shows that even at long lengths a breakdown voltage of >4Uo would be expected. The red curve shows the case for a cable that just passes the minimum requirement; in this situation the breakdown strength at between 500 and 5000m is between 4 and 2.5Uo: considerably lower. Thus such an approach is useful to utility engineers as it provides a tool whereby they can ensure that the success requirements on short lengths reflect what there wish to have in service. Of equal importance it enables them to check that they are not requiring levels that are too high for service requirements. Practically this means that utility engineers should consider very carefully data that only just pass the minimum requirements; a reasonable margin should be required.

One final point with respect to success levels is worthy of note; commonly these levels are described simply in terms of the scale (how high the values are), yet it is clear that a lower value of Weibull Shape (β) will give a steeper slope to the length curve. Thus in terms of service predictions it is equally important to look at the mechanism of degradation / failure (Weibull Shape (β)) as the magnitudes of the streses. CENELEC addresses this issue in a non parametric manner by setting stress segregated success levels: 6 samples > 14kV/mm, 4 samples >18kV/mm and 2 samples >22kV/mm.

A second useful point can be drawn in terms of the dimensions of cables. The green line represents a standard 20kV cable, however approvals can also be carried out on smaller cables. These cables have lower volumes and thus if the same test length is used we would expect them to have a higher strength. The circle in Figure 9 shows the case is the performance of the 20kV system were impressed upon a 12kV cable. In this case there would be an apparent improvement from 18 to 23kV yet this is simply a volume effect. The contrary is also true; if a smaller cable has the same performance as a larger cable then the true strength of that system will be considerably lower. In the case here if the 12kV cable had the same strength as the 20kV then the system performance would not be 18Uo but 14Uo. Thus qualification data based on unusually small cables should be volume corrected or treated with respect.

The analysis above serves to show that searching long term tests when coupled with appropriate success levels really can increase the value of cable to reliable service operation.

4.2 Scaling of design principles

It is widely recognised that High Voltage cables are not just larger Medium Voltage cables, they operate at much higher electrical stresses and in more critical parts of the electrical grid. Consequently it is of vital importance to consider the requirements of size and electrical stress when designing HV cables. Table 2 looks at the design and physical parameters of a number of Power Cables (I to IV); it shows that both the volume per metre and the average electrical stress increases with system voltage.

These two attributes have a direct impact on reliability: higher stresses make failure more likely and as we have seen earlier larger volumes increase the difficulty of manufacture, as well as the chances of finding a defect. With this information it is possible to calculate how the electrical requirement might be effected. The approach is based upon the assumption that the Probability of Failure is sufficiently low in a reference case to ensure satisfactory performance in service; this is usually verified by reliability statistics. Then it is relatively straightforward to use equations 1 & 2 to calculate the likelihood for failure in a wide variety of cases. We have termed this relative likelihood of failure as the 'Electrical Requirement'. We see that the performance required from the insulation (a function of the volume and the stress) increases significantly with system voltage and less strongly with volume.

Case	I	II	III	IV
Voltage (kV)	132	132	132	230
Insulation Thickness (mm)	14	18	18	24
Conductor (mm^2)	1600	630	1600	1600
Electrical Stress (kV/mm)	5.5	4.2	4.2	5.5
Rel vol (%)	*50*	*50*	*70*	*100*
Rel stress (%)	*100*	*80*	*80*	*100*
Electrical Requirement (%)	***46***	***10***	***14***	***100***

Table 2 Insulation requirements for typical HV constructions – AC conditions – Case IV 230kV 1600mm² 24mm EHV cable is taken as the reference case

Table 2 demonstrates a number of interesting features:

- EHV cables (Case IV) have considerably higher requirements than HV cables
- Changing the size of the conductor (Case II & III) has an effect on the requirement, even if the electrical stresses are identical
- Changing the operating stress (Case I & III) has a profound effect on the requirements
- Cable volume has a large effect (Case I & IV) even when the same electrical stresses are used

The last two features have important implications for design and approval (recognised in the recent work of CIGRE Study Committee B1). In moving to designs (say Cases I & III from Case II) it is necessary to increase the performance level of the cable to ensure the same level of reliability. This is most often accomplished by using higher quality insulations and semicons: EHV techniques (Case IV) may be used to manufacture HV cables.

At first sight the stress/volume effect discussed in Table 2 and Figure 9 might appear to argue for shorter cable dispatch lengths, but this would in fact require more joints. Joints these are acknowledged as having lower performance than the cables. Thus the practical solution for long length transmission is to take advantage of fewer joints and to compensate the increased cable requirement by improving the quality of the cable. Equally this thinking demonstrates the precautions that need to be taken when considering using both long lengths and reduced sizes.

5.0 Conclusions

The size of objects subjected to electrical breakdown tests has a very profound effect on the values obtained. Although this effect has its basis in rather straightforward principles; the likelihood of occurrence of defects within a volume, its effect is considered rather infrequently.

This issue has practical consequences on:

- The definition from service requirements of success levels in electrical ageing tests.
- The requirements of the manufacturing, material systems and test protocols when changing the design (stress and size) of electrical devices.
- The stringency of approval tests when it is possible to choose advantageously small designs for test

6.0 References

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