Estimating MV Cable Endurance From Laboratory Qualification Data

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ABSTRACT

Feedback from utility cable engineers consistently shows that the anticipated longevity of the cable system is the number one priority when deciding on which cable design to employ at their utility. It is often very difficult to access data with which to guide such assessments. This work describes a way in which end users and cable designers can use existing qualification test data to establish the relative endurance that they might expect from different cable materials. Moreover, it provides a means by which the minimum performance criteria can be compared to actual cable test performance at utility scale.

KEYWORDS

Reliability, Extruded Cable Systems, Endurance, Accelerated Water Tree Test

INTRODUCTION

New cables with extruded insulations are being installed in greater amounts to improve network reliability. [1] End users would like to understand the longevity they might expect from these assets when they are installed at utility scales. This need can be understood when recognising that failures adversely impact system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI) data, and represent considerable operations and maintenance costs. [2] Thus, anticipated life is a key factor in determining a cable system's total cost rather than its first cost. Obviously, the most convincing data would come from large, long-term accelerated ageing tests. [3] However, such tests are likely to be prohibitively expensive in terms of both time and space. Moreover, they would need to include joint and termination performance.

To date, end users and standardisation bodies have used small samples in either time to failure (IEEE) [3] or fixed time breakdown (CENELEC, ICEA) tests [4][5] to develop an understanding of the sensitivity of materials and designs to typical multifactor ageing stresses. Generally, fixed time tests are preferred, as they do not involve open-ended test programs and it is reasonably straightforward to define simple success criteria. A range of success criteria are applied to the fixed-time breakdown tests in an attempt to define a suitable level of acceptability. Often, these criteria have the goal of defining performance that is comparatively better than that of a previous generation of technology. Unfortunately, the results of such studies cannot be directly related to service endurance; the tests provide a breakdown strength when users wish to judge longevity in the field.

Early-generation extruded cable system service performance is well-documented with problems associated with water trees. These led to many improvements in design, manufacturing, materials, specification and testing. [1] The benefits of these developments are easily recognised through the elimination of early poor performance, with useful service lives extending past 20 years. [6] - [16] In principle, such lives could be determined from utility records. However, the volume and fidelity of records are not sufficient, in most cases, to support such analyses. Thus, the only recourse to garner these estimates is to return to laboratory test data of the qualifications [4][5] and model the impact of design elements on the life in service.

This paper discusses one practical solution to this problem as using data from already well-established test protocols that use breakdown tests for samples that are removed at selected ageing times (CENELEC — 50 Hz option, and AEIC / ICEA). [3] In this approach, these data are collated, and utility length and utility scale reliability are adjusted to provide suitable breakdown strengths at the fixed ageing times. These data are then used to establish suitable life curves. The outcomes will be described in the context of a "life statement," which covers the model assumptions, the probabilistic nature and the associated life.

ACCELERATED WATER TREE TEST (AWTT)

Since moisture ingress into the cable is almost inevitable in most practical installations, manufacturers of cables and compounds continually work to prevent and/or minimize contaminants and imperfections that can serve as water tree initiation sites. To evaluate the effectiveness of these efforts, various cable testing protocols have been designed to rapidly screen new compounds, manufacturing methods and cable constructions. AEIC and CENELEC standards for MV cables require power frequency ageing for one- or two-year long-term (shorter at 500 Hz) periods in water. The AEIC protocol qualifies the cable design / materials / CV line and provides important information on cable performance. Table 1 contains a summary of the AEIC tests.

Ageing test protocols are designed to accelerate water tree ageing and attempt to quantify its effect. Although these protocols are not designed to investigate degradation mechanisms, they can, if considered appropriately, provide significant useful information about cable performance. MV cable test protocols generally specify the use of short test lengths placed in water-filled tanks or tubes. An AC ramp or step breakdown test at selected times is typically used to assess the extent of ageing after the prolonged ageing program. The minimum criteria for AECI CS8 / ICEA 649 testing are set out in Table 2.

It is useful to note that due to cyclic conductor current heating in AEIC CS8 / ICEA S-94-649, the conductor temperature is considerably higher than the controlled insulation shield temperature in water (45°C). Furthermore, the "in-air" portions outside the water tubes will have a different and generally hotter temperature profile. Thus, care needs to be taken if directly comparing performances obtained in different test protocols.

Table 1. AEIC / ICEA MV cable qualification protocols

		AEIC CS8 / ICEA S-94-649
Ageing	Voltage	$3U_0$
	Time	0, 14, 120, 180, 360 Days
	Water	Inside conductor & outside in tubes
Thermal	Level	45 C
	Cycling	86, 129, 257 thermal cycles
Breakdown	Number	5 groups of 3 samples
	Length	6.4 m

Table 2 Minimum breakdown requirement for AEIC CS8 & ICEA S-94-649 tests

Number of thermal cycles	Number of daily voltage cycles	Ins^n	Min breakdown for 3 samples	
			(kV/mm)	(U_0)
0	0	WTRXLPE	26	13.3
14	0		27.5	14.1
86	120		27.5	14.1
129	180		24.4	12.5
257	360		16.5	8.5
0	0	XLPE	26	13.3
14	0		26	13.3
86	120		13.4	6.8

SOURCES OF DATA

The following discussion will focus on the results for AWTT testing to AEIC CS8. This protocol was developed in the early 1970s by the Cable Engineering Committee of the AEIC. Thus, there are sufficient AWTT data available for the following analysis. It is worth noting that the methodology described here can be used with CENELEC HD620 data or any data where the electric breakdown strength is evaluated after specific ageing periods.

The key feature of the AWTT data is that the breakdown strength is evaluated after specified ageing times. This work collated AWTT cable qualification data from a range of sources (tables and figures). [6] - [17] The collation mainly focuses on the performance of water tree-retardant polyethylene (WTRXLPE) cable. Where the data are available, information has been gathered on earlier-generation MV cables with XLPE insulation as well. Both conventional (furnace black-based) and superclean / smooth (acetylene black-based) conductor screens are included. In some cases, the screen type has been identified. All the cables have strippable core screens in common with the standard practice in North America. [1] The data range from the early 1990s to the mid 2010s. The cables covered by these data represent the backbone of present URD systems [2] and vintages of the most interest to utilities from an asset management perspective.

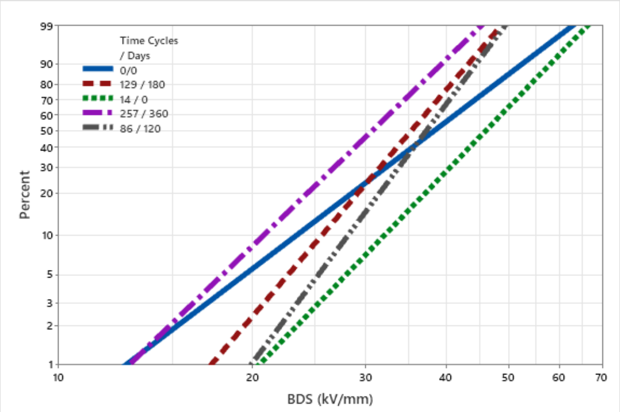

Figure 1. Weibull analysis of WTRXLPE for the mean electrical stress segregated by the ageing conditions

Figures 1 and 2 show the Weibull curves from the meta analysis for WTRXLPE with the breakdown strength displayed in terms of the mean electrical stress (kV/mm) and the operating voltage (U_0). These analyses are based on approximately 1,000 collated breakdown tests. Inspection of the WTRXLPE data in Figures 1 and 2 reveals a number of instructive features:

- Figure 1 shows the impact of the 14-day preconditioning where the reduced concentration of the gaseous (likely removed) and polar decomposition byproducts results in an increase in the magnitude of the breakdown strength (the curve moves to the right) as well as a reduction in the scatter of the data (the curve becomes steeper with an increase in the "Weibull Shape Parameter").
- Figures 1 and 2 show that as the accelerated ageing progresses, in terms of both thermal cycles and time on voltage, the breakdown strengths (Figure 3):
  - o Reduce in magnitude – Lower Scale Parameter
  - o Increase in scatter / change the mechanism of failure – lower Lower Shape Parameter
- The actual breakdown performance level is considerably above the minimum breakdown strength (one step above the withstand for the three samples) as observed from the black symbols of Figures 2 and 4. In the case of 257 cycles / 360 days of voltage application, the minimum required breakdown strength is 8 U_0, whereas the actual strength at the appropriate percentage is 12.4 U_0 — a 4 U_0 or 56% margin above the minimum.
- The rate of strength reduction (see the Scale Parameter) with time (both cycles and voltage) reduction is a reasonable fit to the common Inverse Power Law (IPL) model [20] (Figure 4).
- The minimum requirements are consistent with underlying ageing assumptions of a much more rapid degradation (shallower line) than observed in the experimental data. The experimental data have an ageing exponent from the Inverse Power Law of approximately 6.
- Extrapolating the fitted lines of Figure 4 to near operating voltage (U_0) may provide a sense of how long these samples (short lengths of a single design aged at elevated voltages) might last under this laboratory ageing regime.

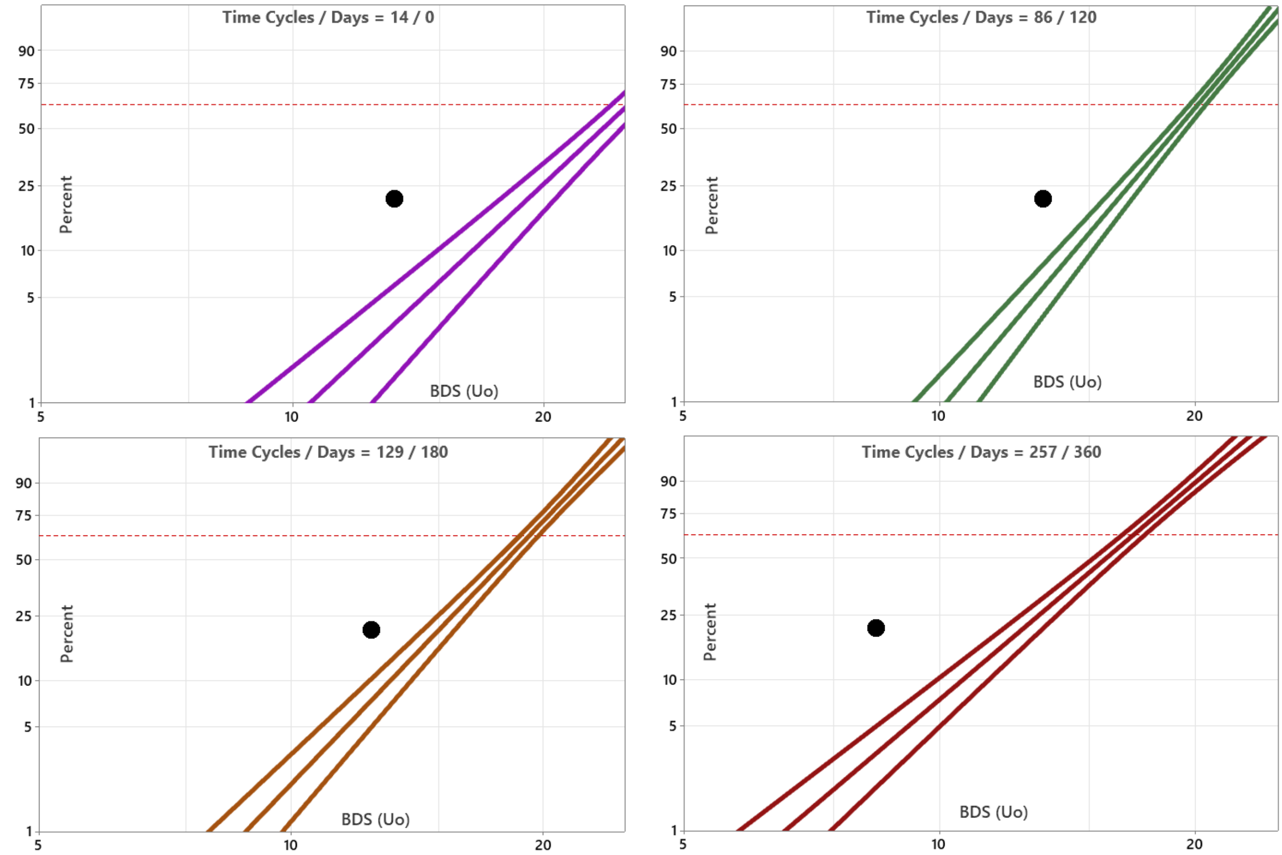

Figure 2. Weibull analysis of WTRXLPE in terms of the operating voltage segregated by the ageing conditions; the black symbol represents the minimum breakdown strength permitted by current industry acceptance criteria

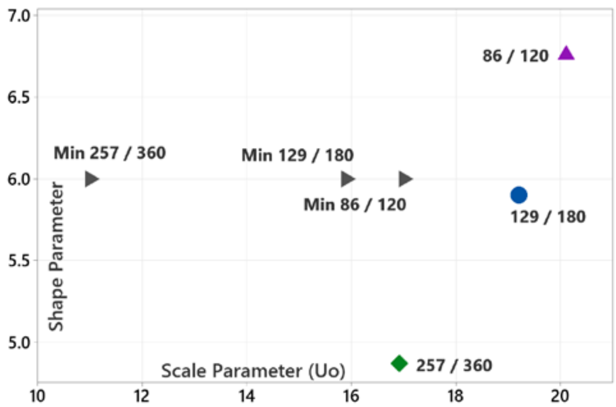

Figure 3. Weibull Parameters for collated WTRXLPE breakdown and minimum requirements at test times

TEST DATA VS. SERVICE LIFE

As noted previously, the fall-off in performance (Figure 4) can then be used to establish the rate of degradation. [1][3][6] - [17] Extrapolating this falloff appropriately out to operational stresses enables the time or endurance to be established. If the results of the laboratory tests were used directly to make this extrapolation, the outcome would contain all the accelerating factors that were included to allow the test to provide results in a reasonable time. The adjustments that are required include:

Cable length: Cable length is an important factor; the cables used in these accelerated ageing test protocols are, of necessity, much shorter than those used in service. Thus, it is necessary to adjust for the longer length when interpreting the relationship of the data and success criteria to service performance. This is because it is well established that the measured breakdown strength falls as the length increases. The reason for this is that there is a much higher probability that critical tree-initiating defects will occur in a long sample than a short one. A typical testing length for AWTT is 6 m, which is convenient for the laboratory. The typical length of a cable section, however, is 30 m to 100 m for a URD system and can reach 400 m to 2,000 m for a feeder or offshore application.

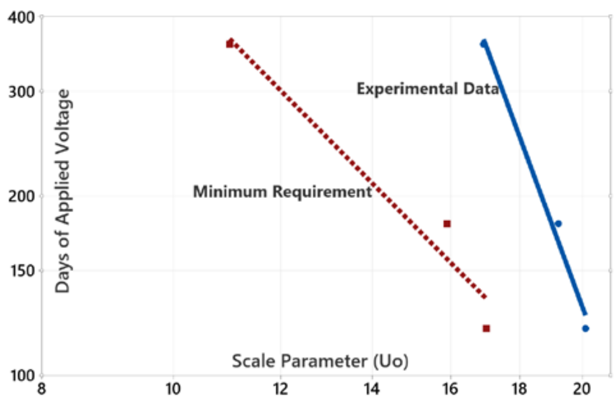

Figure 4. Reduction of test sample (WTRXLPE) breakdown strength with ageing for experimental data and minimum requirements

Cable size: The insulation volume of a cable, which is an enlargement / reduction factor of the cable life, is dependent on the conductor size and the wall thickness. The AWTT protocol requires that the test be conducted on a 53 mm^2 4.5 mm wall cable. However, the conductor size used in the field could vary from 33.6 mm^2 to 760 mm^2, depending on its application.

Performance requirement: AWTT testing ages samples to a specific number of cycles and a minimum number of days on voltage. Then, all the samples are step-tested to failure. In terms of qualification, the criteria are based on a failure percentage of 20% (Figure 2) — i.e., the y-axis plotting position of the minimum of the three breakdowns. [17] When analysed as a population, the breakdown results are most often described by the mean / average stress at failure or the stress for 63% of the samples to fail (Weibull Scale Parameter) [18] - [21] The consequence is that the metrics that engineers are used to handling are based on percentages, or B values (B20 or B50 or B63), when a large fraction of the samples have failed (Figure 3). These are typically much higher than utilities can live with in service.

In the course of utility interactions, it becomes clear that utilities generally become concerned before 10% of the field cable population first fails — i.e., much lower than occur in the qualification tests — and thus, the B10 life (time at which 10% fails) or even B5 is a more relevant breakdown strength for utilities. Therefore, when conducting analyses trying to establish endurances that are useful to the end user, it is important to use the strengths at the more appropriate probability.

Voltage (electrical stress) and operating temperature: A single standard set of thermal cycle / voltage / environment conditions are employed when testing to the AWTT protocol. These conditions were established to provide a consistent acceleration of water tree growth / degradation. Although the load cycling (8 hours on and 16 hours off) seems to replicate a well-loaded cable quite reasonably, the ageing voltage is three times higher than operational conditions. In the case of the endurance estimates in Accelerated Cable Life Tests (ACLT), tests are conducted at selected voltage multipliers. Consequently, for AWTT, it is not possible to adjust the test results back to operating voltage. [3] Thus, the endurance estimate will be in terms of ageing at 3 U_0.

Moreover, the water environment (water constantly both on the inside and the outside) is very onerous, such that it is likely applicable to only the most egregious locations and workmanship problems, assuming that most water ingress is due to poor accessory installation or third-party damage.

In summary, it is possible to adjust the AWTT strength results to allow for longer lengths of cables installed in service, the differing designs (conductor / voltage) and utility concern (lower B value). However, no adjustment can be made for the elevated ageing voltage. Consequently, useful information can be derived concerning service performance from AWTT data. However, the analyses can only provide a relative perspective among different technologies / quality perspectives and construction / manufacturing.

APPROACH

This work uses AWTT and attempts to model the impact of these performances in a utility context. Algorithms were then constructed to scale test data collected on short cable cores to long cables in service using strength adjustment factors. The reduction factors for strength are:

- Longer lengths installed in service compared to those employed in laboratory tests
- Higher insulation volume used in service cables from large conductors and higher system voltages
- Lower critical risk levels (B1 or B5) for cable failures considered by utilities compared to the mean strength (B50) considered by tests

The implications for endurance (in terms of relative performance) were established using the Inverse Power Law approximation for the wet ageing performance.

Utility reliability / life requirement

The Weibull Scale Parameter gives the B63 life ie the strength by which 63 % of the tested samples will fail. Equation 1, derived from Weibull distribution, can be used to obtain the B life at the reliability level of the user's interest.

$$B(P)\,Voltage = \alpha_{adj}\left(-\ln(1-P)^{1/\beta}\right) \qquad [1]$$

- α_{adj} and β_T are the Weibull parameters derived from the length / size adjustments.
- P is tolerance of the utility to failure or the acceptable unreliability level.
- B(P) life is the voltage at which P% of the cables will experience their first failure.

Length adjustment

The AWTT test length is 6.4 m. A significant portion of the test length is submerged under and the rest above the water for termination purposes. The Enlargement Law [1][3][7][20][21] expressed in Equation 2 is thus applied to include cable length effect on cable service.

$$\alpha_2 = \alpha_1 \cdot R(L)\;\; R(L) = \left[\frac{l}{L}\right]^{\frac{1}{\beta_T}} \qquad [2]$$

- A_2 the characteristic life at the cable service length *L*.
- α_1 is the characteristic life at the tested cable length *l*.
- *R(L)* is the cable length enlargement coefficient.
- β_T is the shape parameter of the tested cable core.

As an example, the cable length enlargement coefficient for a 100 m cable when based on a 6.4 m test length is between 0.67, 0.63 and 0.57 for the conditions 86 / 120, 129 / 180 & 257 / 360, respectively. As the Shape Parameter changes with ageing, i.e., the mechanism of electrical breakdown changes, so does the value of R(L).

Insulation volume adjustment

The enlargement law (Equation 4) is also applicable to adjust for insulation volume effect. This allows users to estimate service life of cables that have a conductor size and/or insulation thickness and hence volume *V* different from that of a standard test cable (*v*).

$$\alpha_3 = \alpha_2 \cdot R(V)\; R(V) = \left[\frac{v}{V}\right]^{\frac{1}{\beta_T}} \qquad [3]$$

- α_3 is characteristic life with insulation volume of *V*.
- α_2 is tested cable characteristic life with volume of *v*.
- *R(V)* is the insulation volume adjustment coefficient.

CASE STUDIES

Case studies (Table 3) have been conducted at a critical utility performance level of 5% to show how modeling of test data and criteria may be used for different cable designs and insulations.

Case 1

The first case considered is that of the modelled endurance of a cable that met the requirements, but only at the minimum requirements of the standard. [4] In this case, it has been assumed that at least one of the three samples fails at the voltage step above the withstand level. The estimated "Weibull Scale Parameters" are detailed in Figure 3. Following the process outlined previously, with adjustments for increased length, larger conductor and the utility critical failure percentage of 5%, the reduction in the breakdown strength is represented by the dotted green line of Figure 5. The Shape Parameters for WTRXLPE (Figure 3) have been used in this modelling where the Shape Parameter decreases; the breakdown strength becomes more scattered, with decreasing strength. Inspection shows that the Inverse Power Law (IPL) model intersects the U_0 condition at approximately 2,000 days. As noted earlier, this is an endurance estimate for the ageing employed in the test and thus is not a direct estimate of life.

However, it does serve as a useful reference case for other cases and provides a useful context or visualisation for the minimum requirements. Further inspection indicates that the IPL estimates for this conductor, length and 5% of the samples would fail within 260 days of ageing at 3 U_0.

Table 3. A summary of tested case studies

	Insulation	Voltage/ conductor	Installed length
1	WTRXLPE Min	15 kV / 185 mm^2	100
2	WTRXLPE	15 kV / 50 mm^2	100
		15 kV / 185 mm^2	
		15 kV / 500 mm^2	
3	WTRXLPE	15 kV / 185 mm^2	100
	WTRXLPE + Defects		
	XLPE		
4	WTRXLPE	15 kV / 500 mm^2	100
		15 kV / 500 mm^2	300
		25 kV / 500 mm^2	300
5	CoPolymer XLPE "Two-year test"	15 kV / 185 mm^2	100

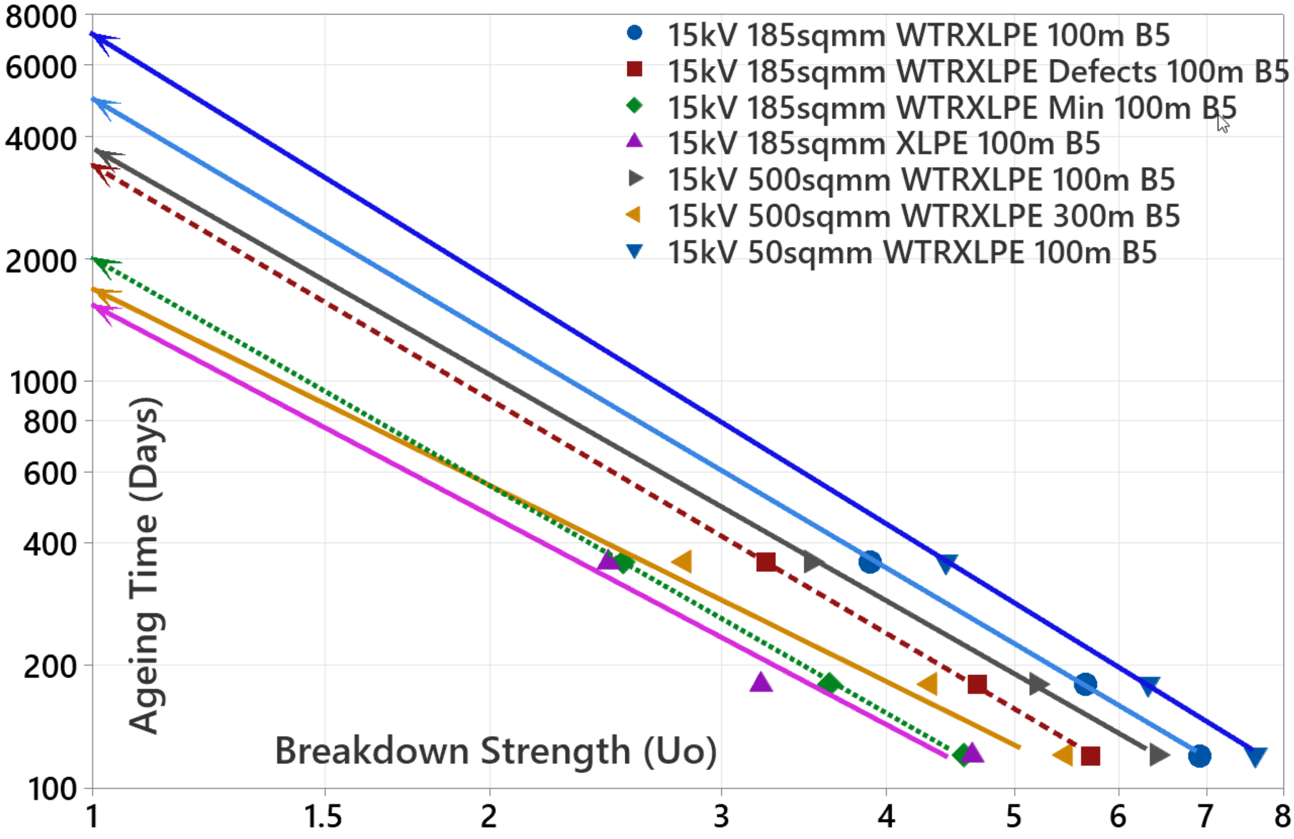

Figure 5. AWTT- based endurance curves for selected cable designs and insulations after adjustments for length, insulation volume and utility reliability

Case 2

Three conductor sizes (50, 185 and 500 mm²) are considered here, represented by the orange, light blue and grey lines of Figure 5. The AEIC / ICEA approaches use test data on a single cable size to qualify all conductor sizes and voltages within the MV range. Thus, these estimates show the spread in the endurances that might be anticipated when the single-size data are applied to more diverse sizes. The estimate for the 185 mm² core is just below 5,000 days, or 2.3 times longer than the endurance represented by the minimum specification performance in Case 1.

It is interesting to compare the 130% longer endurance [5] of WTRXLPE with the minimum to the 56% higher breakdown strength (Figure 3) determined from the test data themselves. The relationship between breakdown and endurance is nonlinear. Moreover, what may appear as small reductions in the strength margin are likely to result in much more significant reductions in the longevity.

The endurances for the 50 mm² and 500 mm² conductors bracket the 185 mm² estimate, with the larger cable having a shorter endurance. Using the central 185 mm² as a reference, the smaller conductor has a 62% longer endurance, whereas there is a 20% reduction for the larger conductor. Interestingly, relative to the spec minimums for the conductor sizes (it is important to recall that the minimum endurances depend on length and volume as well), the 50 mm² and 500 mm² conductors are 2.6 and 2.25. Thus, as the conductor size increases, the performance gets closer to the minimum. The increased volume of insulation / conductor screen has a significant impact on the longevity.

Case 3

The most significant advances in reliability have been ascribed to advances in material chemistry (XLPE to WTRXLPE) and improved methods to exclude defects from the insulation. Case 3 uses AWTT data to estimate what the magnitude of these improvement activities might be in terms of endurance at the utility scale and sensitivity (5% in this case).

The WTRXLPE exemplar has an endurance of 2.5 times the minimum (Case 1). As might be expected, the research study [14] where defects were intentionally added to the insulation shows, in a meta-analysis of this paper, that the breakdown strength is lowered at the test dimensions. At the same time, the endurance is reduced (assuming that it ages in the same way as WTRXLPE). The endurance with the defects is 1.7 times the specification minimum (Case 1) — i.e., 80% of the Case 1 performance is lost. This confirms the continued importance of maintaining a good focus on excluding defects and suggests that the presence of a number of defects may noticeably reduce the longevity.

Prior to the widespread use of WTRXLPE, [2] XLPE was the most commonly used insulation and still comprises a significant portion of the distribution grid in some locations. Thus, it is interesting to understand that the relationship between the performance of this insulation technology and the WTRXLPE of today and the minimum specification requirements. The XLPE performance is represented by the lowermost (purple) line of Figure 5. Cores with this insulation show an endurance that is 77% of the minimum WTRXLPE (Case 1).

The endurance estimate indicates that although the actual performance of WTRXLPE cables is well in excess of the specification minimums, the minimum performance level does guarantee longer endurance than XLPE. Moreover, even though the presence of defects in WTRXLPE reduces the endurance, the reduction does not take it to the levels achieved with XLPE. It is interesting that the AWTT protocol was developed towards the end of the period when XLPE was used as a MV insulation. Thus, the estimates here, based on later vintages of XLPE, are likely to overestimate the endurance of the earlier vintages that form the bulk of the installed population.

Case 4

The impact of installation length and voltage (thicker insulation) is an important effect to understand, especially as the trend towards undergrounding increases. These impacts have been calculated in the same manner. As the length and voltage (insulation thickness) increase, the likelihood of a weak spot occurring in an installed length increase, thereby reducing the B5 breakdown strength and hence the endurance at U_0.

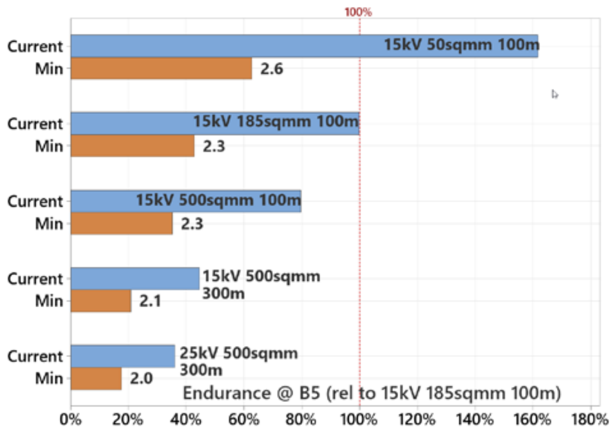

Figure 6. Endurance (relative to 15 kV, 185 mm², 100 m B5 case) for selected sizes and lengths for both actual test data and minimum performance; numbers represent the ratio of test performance to the minimum

Case 5

This case study represents an alternate ageing protocol (CENELEC 50 Hz) that uses breakdowns at selected ageing times (360 and 720 days). In this meta-analysis data [21][22] from the ongoing Production Monitoring test, which has the same ageing and test conditions as the qualification, is used. These data are interesting, as the cables that go into them are drawn from normal production cables over an extended period, thereby more closely representing what a utility would expect to receive.

The tests on 10 m cables to the CENELEC regime (water on the outside and 40°C constant) suggest Weibull Shape and Scale Parameters of 8 and 18.4 U_0, and 5.4 and 14.5 U_0 after 360 and 720 days, respectively. Unlike AEIC, the requirement is only specified for the final 720-day breakdown. There are generally two requirements considered by end users: [1][21] standard (6 > 14, 4 > 18, 2 > 22 kV/mm) or enhanced (6 > 23, 4 > 29, 2 > 35 kV/mm). The staged requirements make it straightforward to compute the minimum Weibull curve for these conditions.

The actual breakdown strength at 720 days is, like the case of AEIC, much larger than that defined by the minimums: 2.8 times for the standard and 2.1 times for the enhanced.

The same approach as used for the AEIC results in Figure 5 but, for the 360- and 720-day data, can be used to estimate the endurance for the actual test data at U_0. Using the case of a 20 kV, 185 mm^2 cable installed with 100 m lengths, the endurance at B5 was estimated at a little over 4,000 days.

As there is only one ageing period for which there are minimum requirements for the breakdown; the endurance at U_0 can only be estimated if an ageing rate is assumed. Thus, the same rate (gradient of the breakdown endurance log-log curve) as the test data was used. In this case, the endurance for the test data is 320% of the standard minimum and 137% of the enhanced. These cases show that moderate differences in the test success criteria (5.2 U_0 and 6.9 U_0 for standard and enhanced) correlate with much larger differences in endurances at utility scales and sensitivities (1,300 days and 3,000 days for standard and enhanced, respectively).

It is important not to directly compare the endurances for different protocols or materials, as the approach described here does not yet adjust for ageing voltages, environments and temperatures. Nevertheless, these case studies do show that the approach may be applied to different breakdown-based protocols.

CONCLUSIONS

The model developed in this project considers expansion and contraction factors, including cable length and design, plus the end user's need for reliability. Case studies using this model provide reasonable results.

The model and its process can be used to:

- Estimate cable endurance at a desired percentile, cable size and length
- Demonstrate that the actual endurance, from measured data, of a cable is 2 to 2.6 times that represented by data only meeting the minimum requirement
- Reaffirm that the quality of the cable manufacture, good dimensional control / eccentricity and absence of defects or protrusions remains an important attribute for the longevity of a cable.
- Relate the endurance and breakdown strength at qualification; however, the relationship is nonlinear: A 20% reduction in breakdown strength in AWTT relates to a 34% reduction in endurance.

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