Operating Extruded Distribution Cable Systems at Elevating Temperatures

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ABSTRACT

ICEA, UL, and AEIC cable standards and specifications for EPR and TRXLPE insulated cables allow for operating cable conductors at highly elevated temperatures. The associated industry cable and accessory qualification test program requirements, however, do not evaluate the performance of the system components at these elevated temperatures. Therefore, the consequences of operating an extruded cable system at highly elevated temperatures are not fully understood by operators of these systems.

This paper describes the studies undertaken to review and summarize current industry requirements for evaluating the performance of cable systems operating at and above the generally accepted normal operating conductor temperature of 90 Deg. C. It identifies gaps between industry evaluation requirements and actual operating temperature conditions. Furthermore, it provides guidance so that users could determine the appropriate level of testing required for the accessories, cables, connectors; should users wish to operate at elevated temperatures.

KEYWORDS

Reliability, MV, Extruded Cable Systems, Elevated Temperature

INTRODUCTION

Operating temperatures for underground extruded power cables commonly installed across North America are specified in standards prepared by the Insulated Cable Engineers Association (ICEA) or Underwriters Laboratories (UL). These standards rate medium voltage cables made with polymeric insulations i.e. water tree retardant cross-linked polyethylene (WTRXLPE) or ethylene propylene rubber (EPR) at conductor temperatures up to 140 °C under emergency operating conditions. The implication is that complete cable systems have the same ratings and that the relevant standards require test programs that verify reliable operation at these temperatures.

It is instructive to note that utilities are not reporting significant failures due to elevated temperature operation and there is a good reason for this. While utilities purchase cables rated at a conductor temperature of 90/130 °C or 105/140 °C, survey responses clearly show that the most common maximum conductor operating temperature is between 45 °C and 60 °C for URD cable systems and between 75 °C and 90 °C for feeder cable systems. The design principles for Utilities is based on the premise that their cable systems will operate reliably at the rated emergency temperature even though they rarely operate them at these temperatures. The concern is that if they ever chose to operate them at their rated temperature, there is evidence that such operation will degrade the cable system, with a subsequent reduction in reliability that is impossible to predict. Additionally recent service experience above 70 C has resulted in service failures leading a number of utilities to question the ability of a complete cable system to operate at elevated temperatures. A number of laboratory studies supports this concern.

To better understand the topic, a project was undertaken to provide an overview of high temperature operation issues for extruded underground distribution cable systems.

APPROACH

To prepare the overview, a number of sources of information were consulted, including:

a) Operating temperatures specified in relevant cable and cable accessory standards
b) Utility and manufacturer expectations of the cable system operating temperature
c) Tests outlined in relevant standards to verify elevated temperature operation
d) Extruded cable material properties as a function of temperature
e) Risks associated with elevated temperature operation
f) Potential options for mitigating the risk of high temperature operation.

Permitted temperatures and the temperatures experienced by devices during testing were extracted from the relevant standards / specifications - detailed at the end of the paper.

RESULTS

Operating Temperatures – what is allowed and what is tested

Performance requirements for extruded distribution cable systems are not covered by one standard; cable conductor operating temperature ratings are specified in ICEA and UL standards, with ratings for cable accessories (splices, terminations and separable connectors) being covered in separate component standards published by IEEE. The IEEE standard for cable joints (splices) also references an ANSI standard for evaluating the connectors used to join cable conductors inside joint housings. Cable specifications prepared by AEIC were reviewed because they provide supplemental test requirements to the ICEA documents. A summary of the temperature ratings outlined in relevant extruded distribution cable standards appears in Table 1.

Table 1: Operating Temperatures Allowed, by standards, for Extruded Power Cable System Components – limiting temperatures highlighted

Device	Relevant Standard	Insulation Material	Normal Operation	Emergency Operation	Short Circuit
Cable	ICEA S-94-649, AEIC CS8	XLPE, TRXLPE, EPR	90 °C	130 °C	250 °C
		XLPE, TRXLPE, EPR (Class III)	105 °C	140 °C	250 °C
Joint Housing	IEEE 404	All	Rating not specified. Testing is based on Cable Emergency Operating Temperature		Not Addressed
Joint Connector	ANSI C119.4	Tested on bare wire	≤ 93°C for Al-Cu or Al-Al, ≤ 100°C for Cu-Cu		Not Addressed
Terminations	IEEE 48	All	Rating not specified. Testing is based on Cable Emergency Operating Temperature		Not Addressed
Separable Connectors	IEEE 386	All	Temperature rating not specified. Devices have current ratings of 200 A, 600 A, 900 A		3,500 to 10,000 A

Whilst North American 'cable only' standards clearly specify emergency operating temperature ratings as high as 140 °C, accessory standards are somewhat less specific. Termination and joint standards specify that the rating shall be equal to or greater than the cable for which they are designed. The separable connector standard only specifies current ratings, though various test requirements used to evaluate the performance of these devices are conducted at a variety of temperatures. It is particularly notable that joint connectors are required to pass ANSI C119.4, which has a maximum connector operating temperature of 93 °C for aluminum-to-aluminium / aluminium-to-cooper conductors or 100 °C for copper-to-copper conductors. This implies that all cable systems with joints are limited to a maximum operating temperature of 93 °C or 100 °C depending on the conductor type, though this fact is not generally recognized.

The test procedures outlined in these documents are quite detailed and far too extensive to discuss in their entirety in this paper. Therefore, basic design/qualification test parameters relevant for qualifying cable systems are summarised.

A review of all relevant ICEA, UL, IEEE, AEIC and ANSI standards/specifications shows that no test or set of tests outlined in these cable and accessory standards and specifications adequately evaluates elevated temperature performance in a manner that accurately reflects service in the field. The gaps between what the standards allow and what they test for are provided for cables rated 90/130 °C in [4]. Similar gaps exist for cables rated 105 °C /140 °C.

PERFORMANCE RISK

Temperature characteristics of insulation materials

As mentioned in the introduction, the polymers that make up the extruded cable structure have physical and electrical characteristics that change as a function of temperature.

Detailed physical and electrical characteristics of polymeric cable insulation materials appear in [1]. Figure 1 and Figure 2 summarize the range of data encompassing common extruded cable insulation materials. Note that each material property characteristic has reduced performance (frowny face) characteristics as the material temperature increases, particularly at temperatures above 90 °C. The vertical dashed lines shown in each figure represent three cable conductor operating temperature zones (Figure 1 & Figure 2) that will be discussed later in this paper.

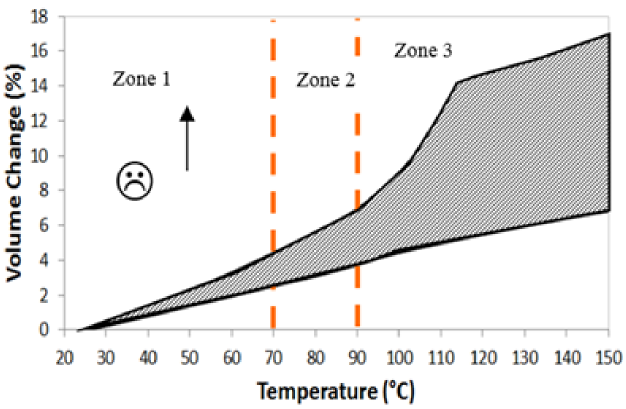

Figure 1: Polymeric Insulation Volume

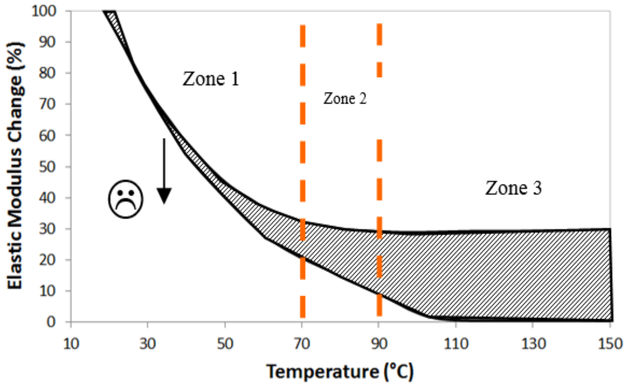

Figure 2: Polymeric Insulation Elastic Modulus

Consequences

The implications of the physical changes shown in Figure 1 & Figure 2 are demonstrated by laboratory tests conducted on samples of XLPE insulated cables. Figure 3 shows a cable with a concentric wire neutral operated at 130 °C in a conduit. The "scalloped" deformation occurred as the cable insulation expanded and pressed into the surrounding concentric neutral wires, which were removed before taking the photo.

In both of the cases, the cables did not fail electrically. However, it is obvious that the deformation changed the cable geometry thereby increasing local voltage stresses that over time accelerate aging. The hoop stress on a cable from an accessory such as a splice, termination or elbow could cause even greater deformation, which would further compromise the integrity of the cable/accessory interface.

Figure 3: Cable Deformation Due to Elevated Temperature Operation

Temperature Calculation Uncertainty

The foregoing discussions have focused on the implications for cable system reliability of the temperature at the conductor. This is a very common approach, however in real applications it is the current in the conductor that is measured and known, not the conductor temperature. Establishing the operating temperature of a cable system requires performing a heat transfer calculation often referred to as a Neher-McGrath ampacity calculation using a "ladder network" (Figure 4). The heat generated (W) by I^2R losses in the conductor and metallic shield (and to a lesser degree the heat generated from dielectric losses) must flow from the cable into its surroundings, typically the earth.

The thermal properties of the cable components ($T_{1,2,3}$, $W_{c,d,s}$) and the earth (T_4) must be known with reasonable accuracy to achieve an acceptable estimate of the cable conductor temperature at a given conductor current. The thermal properties of the cable components ($T_{1,2,3}$, $W_{c,d,s}$) are stable over the life of the installation and are fairly well established. However, the same is not the case for the soil thermal properties (T_4). These properties are difficult to establish accurately; unless specialised backfills are used. Moreover, they vary as a function of burial depth, soil type, soil moisture content and soil density, which is rarely constant along the cable system route. An example of this variability appears in [5], which shows that the thermal resistivity for the soil tested is strongly dependent on moisture content and soil density. A greater concern is the impact of changes, during the life of the cable system, in T_4 due to adjacent activities, for example installation of other cables, additional landscaping works that increase the soil depth, construction of roads / buildings etc.

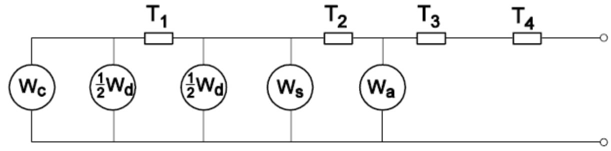

Figure 4: Ladder Network for Steady State Current or Temperature calculations (IEC60287-1-1)

In practical terms, this makes it not possible to operate a typical distribution cable close to a particular conductor temperature with any precision. Thus if the temperature contains considerable uncertainty, then so does any associated estimate of operational risk. This is recognized in some cable system installation guides which contain recommendation of reducing the operating temperature. As an example, AEIC CS8-13 [6] states: "In the absence of [adequate information], the permissible conductor temperatures should be reduced by 10 °C or in accordance with available data."

Accessory Connector Performance at Elevated Temperatures

Laboratory testing has shown that the performance of connectors (compression) in joints installed on medium voltage cables with 1/0 AWG and 750 kcmil aluminum conductors and subjected to a test patterned after the IEEE 404 test protocol can be problematic. The test was conducted at a cable conductor temperature of 40 °C, 70 °C, 90 °C, 105 °C and 120 °C for the 1/0 AWG samples and at a cable conductor temperature of 90 °C, 105 °C and 120 °C for the 750 kcmil samples. When joints are tested on 1/0 AWG cables, the joint connectors operate at a temperature that is close to the conductor temperature when the conductor is at 40 °C or 70 °C. This reasonable condition should not cause harm to the joint housings or the adjacent cable.

However, for both the 1/0 AWG and 750 kcmil samples, the connector temperature exceeds the conductor temperature when the conductor is operated at 90 °C and far exceeds the conductor temperature when the conductor is operated at 105 °C or 120 °C. Polymeric joint housings and cables in the locality will readily degrade and ultimately fail at these highly elevated connector temperatures.

Table 2 summarizes the test results, showing the median of the connector temperatures at each cable conductor temperature. These data will be included in the later discussion on operating temperature zones.

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Table 2: Median of Connector Temperatures at Each Cable Conductor Temperature (Aluminum Conductors)

Cable Temperature °C	Connectors for specified conductor size	
	1/0 53.5 mm^2	750 kcmil 380 mm^2
	Median Connector Temperature °C	
40	45	-
70	71	-
90	140	104
105	194	122
120	>400	141

Note:

- 10% of 1/0 samples were removed during 90 °C cycles as a result of severe overheating
- 30% of 1/0 samples were removed by the end of the 105 °C cycles as a result of severe overheating

Workmanship

It is important to recognise that the testing undertaken for qualification of components (cable, connectors, joints, terminations etc), and the results in Table 2, were developed following the manufacturer's instructions ie they are free from workmanship issues. Experience shows that this "best case' does not hold in the field, where workmanship is a significant occurrence. Furthermore, the typical workmanship issues found in MV joints elevate the temperatures by at least 10 °C [2, 3].

RISK ZONES

The information in the previous sections enables the cable system conductor operating temperatures to be classified into three temperature zones relating to the "risk" to reliability:

- **Zone 1: 40 to 70 °C**
  - Data (test and experience) are available to support operating in this zone
  - No known issues with field operations
- **Zone 2: 70 to 90 °C**
  - Some data are available to support operating in this zone, but they are not comprehensive and some problems have been observed in lab tests
  - Insulation properties begin to change significantly
- **Zone 3: 90 to 140 °C**
  (Elevated Temperature Operation)
  - Insulation properties experience large and significant changes
  - Laboratory data shows joint connectors (primarily on aluminum conductor) often overheat
  - Few data are available to support operating in this zone
  - Field issues are reported (wind farms, highly loaded circuits with a high load factor)

RISK MITIGATION

The preceding sections identified the potential risks of operating extruded distribution cable systems at elevated temperatures; it is now worthwhile to review how a utility might minimize these risks. The most obvious risk mitigation approach is to avoid operating cable systems at conductor temperatures approaching 90 °C. However, there can be times when, to avoid service outages, a utility needs to operate a cable system at 90 °C or higher. Furthermore, they would like to be assured that the elevated temperature operation would not cause a reduction in the life of the cable system over and above the natural reduction in life resulting from operating a system at elevated temperatures.

A number of test protocols can assess the performance of cable systems at elevated operating temperatures. The tests suggested in Table 4 do this by building on test programs outlined in current cable and accessory standards and specifications. As an example, operation in the temperature Zone 1 does not require testing over and above standard test programs. Zones 2 and 3, however, require progressively more comprehensive tests to help assure that a given cable system, made up of a specific set of cable and accessory designs, will perform with only the normal loss of life expected for elevated temperature operation.

Table 4: Enhanced Testing for Minimizing Risk of Operating at Elevated Temperatures

	Zone 2 (70 up to 90 °C)	**Zone 3 (90 – 140 °C)**
Connectors[1]	Determine connector temperature in IEEE 404 & 48 Style Test (or Proven Alternative) on <u>specific</u> Connectors Connector Temperature Must be ≤ Conductor + 5 °C	Determine connector temperature in IEEE 404 & 48 Style Test (or Proven Alternative) on <u>specific</u> Connectors Connector Temp. Must be ≤ Conductor
Housings	Existing IEEE 404 & 48 Tests Appear to be Adequate	Run Extended Duration[2] IEEE 404 & 48 Tests
Cable	Run Accelerated Cable Life Test (ACLT[4]) at 44 or 34 conditions Require no cable failures within a Year	Run Enhanced[3] Thermomechanical Test <u>and</u> Run Accelerated Cable Life Test (ACLT[4]) at 45[5] or 36[5] conditions

		Require no cable failures within a Year

When using the suggestions contained in Table 4 the notes below provide additional context:

1. To assess connector performance, the IEEE 404/48 test should be run in the usual manner with thermocouples (or other temperature sensing devices) applied to monitor the temperature of the accessory connector. No voltage is applied during this test.

   It should also be recognized that conductor design can also impact connector performance. There are many different stranding technologies used for power cable conductors. They can have a different number of strands, strand shapes and levels of compression and hardness. In addition, mastic, water swellable tapes, water swellable powders or combinations of these materials are often applied within the interstices of stranded conductors to prevent axial moisture migration. If low resistance strand-to-strand contact is required for a connector to perform reliably, these materials can impact connector performance, particularly under heavy loading (high current) conductions. Thus connectors should be tested on the specific conductor technology expected for use at elevated temperature operation.

2. Extended = a test duration of six months or longer

3. Enhanced = more rigorous performance requirements such as an ac breakdown strength test at the end of the load cycling period and elevated voltage applied during the test

4. In ACLT tests, the primary test conditions are described by a set of two numbers (41, 32, etc.) The first number represents a multiple of the cable operating voltage (1 - 4) and the second number represents the conductor test temperature (1 = 45 °C, 2 = 60 °C, 3 = 75°C, 4 = 90 °C). In Table 4, the suggested second number temperature aging conditions are:

   5 = 90 °C conductor temperature with periodic excursions to 130 °C
   6 = 105 °C conductor temperature with periodic excursions to 140 °C

It is anticipated that cable used for application that might be in Zones 2 & 3 would have a conductor that blocks moisture (solid or strandfilled). Otherwise, any moisture that might enter the conductor can turn to steam at temperatures above 100 °C, which can penetrate the cable structure and damage accessories.

The risk mitigation options suggested in Table 4 are applicable for new cable systems. Options for minimizing elevated temperature operation risks for existing cable systems are much more limited. However, a potential approach is to gather as much information as possible on the elevated temperature performance of the existing circuit components and use these to guide operational decisions.

CONCLUSIONS

Current extruded distribution cable and cable accessory standards allow for normal operation of cable systems at conductor temperatures as high as 105 °C with emergency operating temperatures as high as 140 °C. However, the test programs that are intended to verify reliable operation do not test at these elevated temperatures under typical field conditions. Thus, there are gaps between what cable and accessory standards allow and what they actually verify.

There are a number of reasons to be cautious about operating extruded distribution cable systems at elevated temperatures (Zone 2 & 3) including:

Problematic performance of accessory connectors

- Laboratory tests show that many joint connectors overheat significantly when the cable conductor temperature is operated at 90 °C and above.

Thermal environment uncertainty

- Soil thermal properties are often unknown and can vary along the cable system route, so the actual operating temperature of a cable system is extremely difficult to predict (calculate).

Material property changes

- Polymeric materials soften as their temperature increases, with a resulting loss in hardness and mechanical strength.
- Dielectric strength of polymeric insulations decreases as temperature increases.

As a result, operating an extruded distribution cable system at elevated conductor temperature (Zone 2 & 3) carries a risk of reduced system reliability (increase in the very low failure rate of modern cable systems) and it is difficult to predict the degree of risk for several reasons:

a) The consequences are likely not immediate as cable systems are very reliable.
b) The risk magnitude is impossible to predict.
c) Elevated temperature operation likely accelerates the degradation of localized “weak spots” in the system, which is virtually impossible to replicate in a standard laboratory test.
d) Higher temperature operation (and longer periods at elevated temperature) equals higher risk.
e) Actual temperature of operation is difficult to predict for a cable system.

Naturally, the easiest and most reliable method of minimizing risk is to avoid elevated temperature operation, that is, operate the cable system within the Zone 1 temperature range shown in Table 4. However, if elevated temperature operation (Zone 2 & 3) is required, the risk can be mitigated for new cable systems by doing the following:

a) Select cables and accessory designs known to perform well at elevated temperatures.
b) Verify high temperature operation performance for all components installed on a given cable system. This can be done by following the enhanced testing suggestions outlined for each temperature **Risk Zone**.

c) Establish the thermal conditions of the cable system environment (usually soil thermal properties) along the entire cable route.
d) Perform comprehensive ampacity calculations to maximize knowledge of the relationship between the cable current and the cable operating temperature. The calculations should include load factors that reflect expected variations in conductor current as a function of time.

When addressing existing cable systems, the best option is to follow the recommendations in (d) above and obtain any available information on the elevated temperature performance of the components used in the system.

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REFERENCES

[1] Research to Determine the Acceptable Emergency Operating Temperatures for Extruded Dielectric Cables, EPRI Project Report EL-938, 1978.
[2] T Parker, RN Hampton, Impact of filled-strand conductor on connector temperature for medium voltage joints, International Conference on Insulated Power Cables JICABLE11, Versailles France, June 2011, Paper C.1.5.
[3] B Fairley, T Parker, RN Hampton, The need to update / upgrade test procedures for connectors used in MV underground joints, International Conference on Insulated Power Cables JICABLE15, Versailles France, June 2015.
[4] High Temperature Operation of Extruded Distribution Cable Systems - White Paper, http://www.neetrac.gatech.edu/publications/16-062_7.7_High_Temperature_Cable_Operation-WhitePaper_FinalDistributedtoMembers.pdf
[5] Don't Guess, Measure, A Guide for Soil Thermal Resistivity, distributed by Decagon Thermal Devices.
[6] Specification for Extruded Dielectric, Shielded Power Cables Rated 5 through 46 kV, AEIC CS8, 2013.

REVIEWED STANDARDS

- Specifications for Extruded Insulation Power Cables and their Accessories Rated Above 46 kV through 345 kV ac, AEIC CS9, 2006.
- Guide for Establishing the Maximum Operating Temperatures of Extruded Dielectric Insulated Shielded Power Cables, AEIC CG6, 2014.
- Extruded Insulation Power Cables Rated Above 46 Through 345 kV, ICEA S-108-720, 2012.
- Test Methods for Extruded Dielectric Cables, ICEA T27-581, 2008.
- Concentric Neutral Cables Rated 5 Through 46 kV, ICEA S-94-649, 2013.
- Guide for Establishing Stability of Volume Resistivity for Conducting Polymeric Compounds of Power Cables, ICEA T-25-425, 2003.
- IEEE Guide for Accelerated Aging Tests for Medium-Voltage (5 kV-35 kV) Extruded Electric Power Cables Using Water-Filled Tanks, IEEE 1407, 2007.
- IEEE Standard for Test Procedures and Requirements for Alternating-Current Cable Terminations Used on Shielded Cables Having Laminated Insulation Rated 2.5 kV through 765 kV or Extruded Insulation Rated 2.5 kV through 500 kV, IEEE 48, 2009.
- IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2.5 kV -500 kV, IEEE 404, 2012.
- IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems above 600 V, IEEE 386, 2006.
- Power Cables with Extruded Insulation and their Accessories for rated voltages from 1 kV up to 30 kV, IEC 60502-2, 2014.
- American national standard for electric connectors, ANSI C119.4, 2011.
- Shielded and concentric neutral power cable for distribution utilities, CSA 68.5, 2013.
- Performance based Standard for Electric Utility Extruded Dielectric Shielded Power Cables rated 5 through 46 kV, ICEA S-113-684-2016.
- Standard for Medium-Voltage Power Cables, UL 1072, 2013.

GLOSSARY

ACLT: Accelerated Cable Life Test
AEIC: The Association of Edison Illuminating Companies
AWTT: Accelerated Water Treeing Test
ICEA: The Insulated Cable Engineers Association
IEC: International Electrotechnical Commission
IEEE: The Institute of Electrical and Electronics Engineers
UL: The Underwriters Laboratories