CHAPTER 3

HV and EHV Cable System Aging and Testing Issues

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3.0 HV AND EHV CABLE SYSTEM AGING AND TESTING ISSUES

As with medium voltage cables, high voltage cables are defined as long, insulated, current carrying conductors with a grounded outer surface that operated at high voltage [2 - 4]. They are terminated and joined together by accessories to constitute a “cable system”. Cable systems form an important part of the electrical power transmission and distribution networks as they carry power to areas that are not accessible by overhead lines and generally are more reliable (lower fault rates) and have lower maintenance requirements than overhead lines. For information on the evolutionary history of underground cable systems, see Chapter 2.

Looking specifically at North America, HV & EHV cable constructions have evolved over the years with many major and minor improvements. This evolution includes a number of manufacturing developments. These changes are presented here in a tabular format as shown in Table 1 and Table 2 for cable and Table 3 for accessories.

Table 4 represents the major changes in cable construction, excluding changes in wall thickness. These are represented as generations. Generations A, B, and C are the genesis for this work as they embody the last developments in fluid impregnated paper taped cables. Installation of Generations 1 and 2 has ceased in US and Canada for all practical purposes. Generation 5 represents the majority of the cables installed at the present time.

Table 1: Major Developments in HV/ EHV Cable Construction
(Excludes Changes in Wall Thickness)

Generation	Insulation	Semiconducting Insulation Screen	Jacket	Barrier
A	*Paper* *Oil*	*Carbon Tape*	*Jacket*	*Self-Contained* *Lead*
B	*Paper* *Oil*	*Carbon Tape*	*Steel* *Pipe*	
C	*Paper* *Polypropylene* *Laminate* *Oil*	*Carbon &* *Aluminum Tapes*		
1	XLPE or EPR (up to 138kV only)	Extruded Thermoplastic	Jacket	Lead Or Wires
2		Extruded Thermoset (crosslinked)		Lead Or Copper Wires & Aluminum Foil
3				Copper Wires & Aluminum or Copper Foil Or Lead
4				Copper Wires & Aluminum or Copper Foil Or Lead Conductor Water Blocked
5				Copper Wires & Aluminum or Copper Foil Or Lead Conductor Water Blocked Core Water Blocked
6	?	?	?	?

Table 2: Major Developments in Cable Core Extrusion Correlated with Generations of Cable Construction (numbers refer to construction technologies defined in Table 1)

Material Handling	Extrusion Technology	Cure Technology	
		Steam	Dry (Nitrogen)
Open	1 + 2 2 + 1	2	2
Closed	True Triple	2	3 - 5

Table 3: Major developments in HV/ EHV accessory cable construction

Generation	Terminations	Joints
i	Porcelain Oil Filled Condenser Cone	Hand Taped
ii	Porcelain Oil Filled EPDM Stress Cone	Machine Taped
iii	Porcelain Oil Filled EPDM & Silicone Stress Cone	Pre-molded Multi Part EPDM
iv	Composite & Porcelain Oil Filled EPDM & Silicone Stress Cone	Pre-molded Single & Multi Part EPDM
v	Composite & Porcelain Oil Free EPDM & Silicone Stress Cone	Pre-molded Single & Multi Part Silicone & EPDM

The steps in the evolutionary path of design and manufacturing are described above in Table 1 and Table 2 as well as the current state of the art for both MV and HV cables is summarized in Table 4 and Figure 1. In this chapter the discussion is essentially confined to the issues associated with HV cable systems (grey column in Table 4 and green area in Figure 1). It is important to recognize that although they have many similarities, HV Cable Systems are distinctly different from MV cable systems, primarily with respect to the materials used for the insulation and insulation screens as well as the electrical stress. See the green area in Figure 1.

Table 4: Summary of the State of the Art for both MV and HV cables in North America

Attribute	Medium Voltage (MV)	High Voltage (HV)
Voltage Range (kV)	5 – 30 (5 – 46 in North America)	30 -150 (46 – 150 in North America)
Typical Conductor Size Range (mm^2)	34 - 500	240 - 2500
Mean Electrical Stress (kV/mm)	1.8	3.8
Conductor Screen Material	Thermoset Bonded Semi Conducting	Thermoset Bonded Semi Conducting
Insulation Material	Thermoset WTR XLPE Thermoset EPR	Thermoset XLPE Thermoset EPR
Insulation Screen Material	Thermoset Strippable Semi Conducting	Thermoset Bonded Semi Conducting
Metallic Screen	Wire Tape Foil	Wire & Foil Lead Aluminium
Protective Jacket	UV Resist LLDPE or HDPE	UV Resist LLDPE or HDPE
Accessories	Elbows Joints Terminations	Joints Terminations
Material Handling Systems	Closed Bulk Supply	Closed Box Supply
Extrusion Technology	True Triple CCV Dry N2 Cure	True Triple CCV & VCV Dry N2 Cure

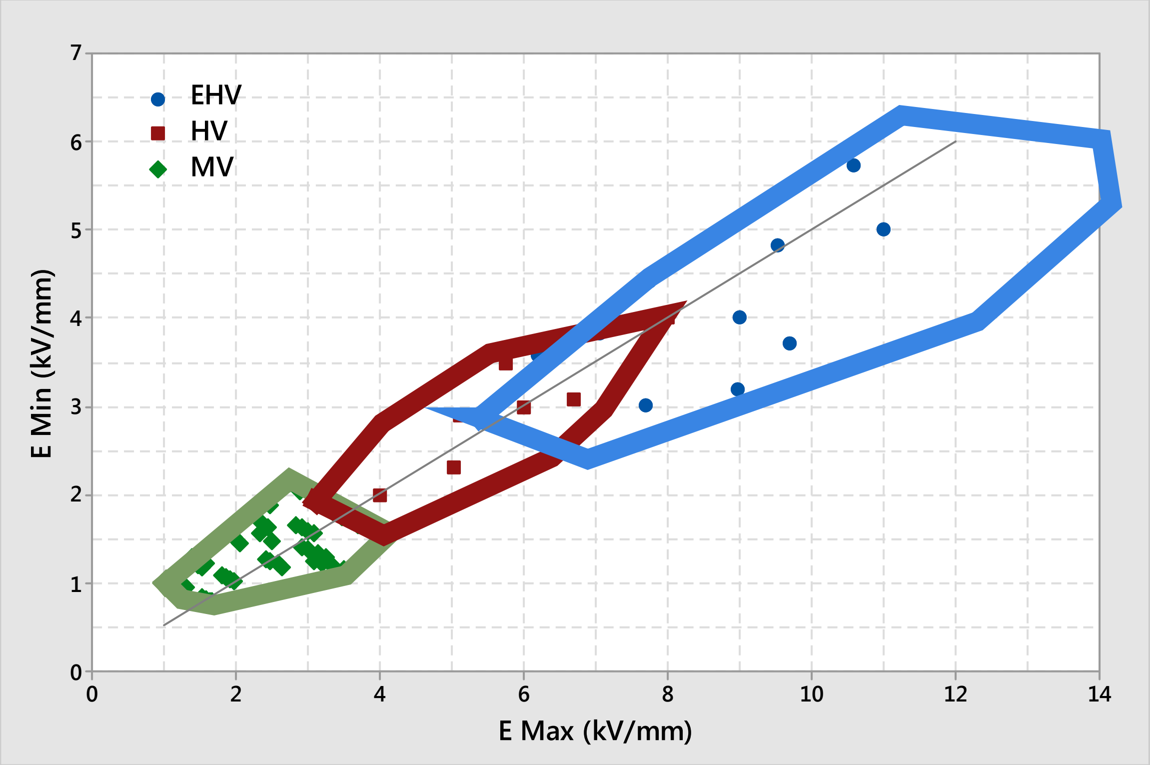


Figure 1: Range of Typical Electrical Stresses Employed in Cable Systems (E_{max} = electrical stress in the insulation adjacent to the conductor screen, E_{min} = electrical stress in the insulation adjacent to the insulation screen; note that the straight line represents the condition where $E_{max} = 2\ E_{min}$)

3.1 The Industry Problem

While the evolution in cable construction, materials and manufacturing processes was intended to produce continual increases in reliability with associated reductions in total cost of ownership, the process did not always yield the expected benefits. This observation is important because it drives much of need for and development of cable system diagnostics.

3.1.1 History

HV and EHV cable systems have been installed in North America for a number of years. On the whole, they have provided very reliable performance in recent years. A research study conducted by NEETRAC for extruded cable systems installed since 2000 led to estimates of the reliability (hazard plot or bath tub curve) of these systems as shown in Figure 2.

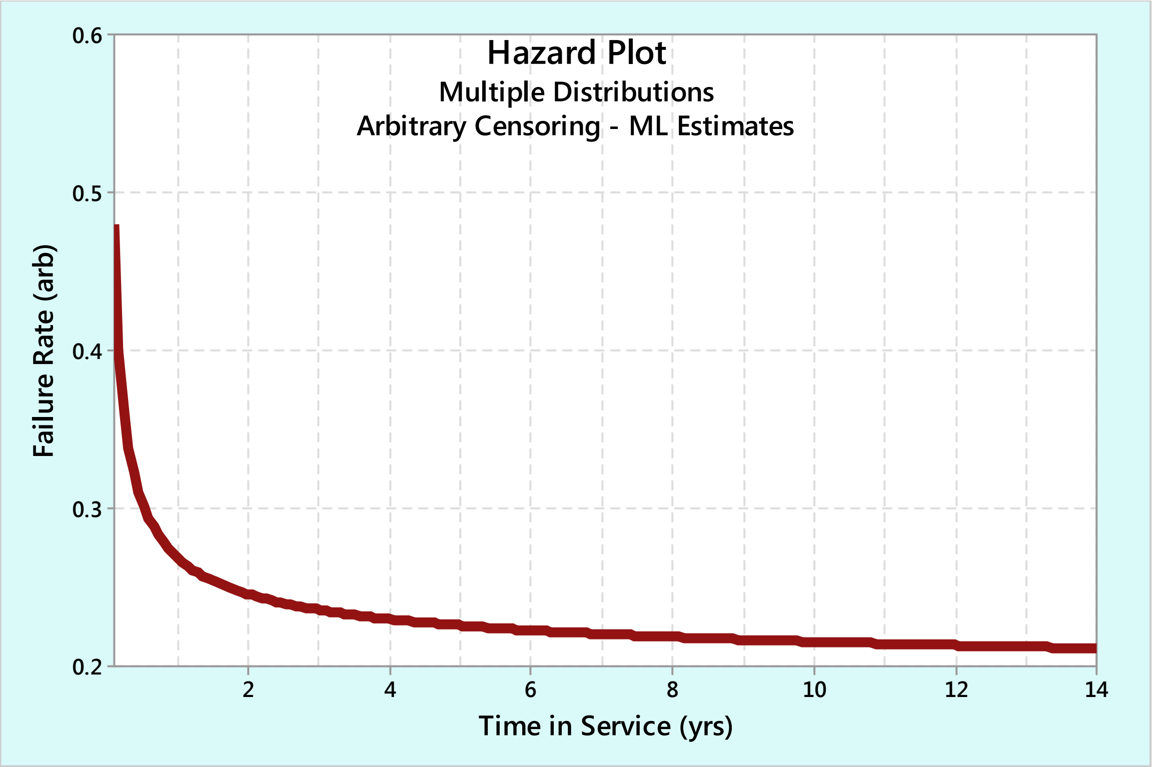


Figure 2: Cable System (HV and EHV combined) Hazard Plot (Derived from the Weibull Analysis for Installations Since 2000)

Figure 2 shows that the failure rate in the first three years of life is slightly higher than the failure rate after three years. As would be expected the right hand edge of the bathtub curve is not visible because the cable systems studied have not yet reached the wear out stage of life. Only the left hand (infant mortality) and the central (normal operation) portions of the curve can be seen for this data set.

Except for some very early 69 and 115kV designs that did not utilize metallic water barriers, water treeing has not been shown to be a significant issue in the aging/failure of HV & EHV cable systems.

It is equally interesting to see how failures are distributed among the components of the cable system as shown in the Figure 3 pie chart. In this graph, the termination category includes both outdoor sealing ends (ODSE) and gas insulated structures (GIS).

The experience captured in Figure 2 and Figure 3 indicates why the current interest in diagnostics for the HV and EHV cable systems is focused on the infant mortality failures that are occurring, for the most part, in the cable accessories.

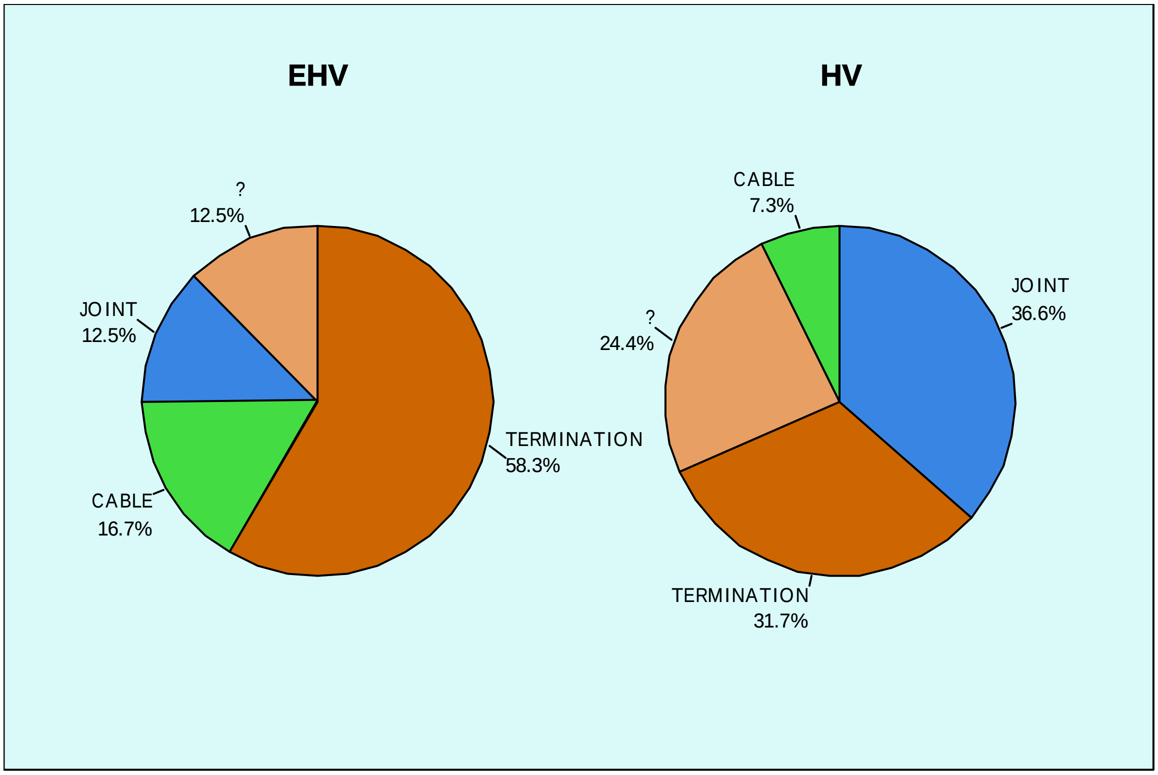


Figure 3: Distribution of Cable System Failures by Failing Component Segregated for HV and EHV Classes

3.2 Aging in HV Cable Systems

All cable systems, regardless of the dielectric type, age and fail. Thus it is useful to understand the aging failure mechanism(s) and therefore the cause of failure. A cable system fails when *local* electrical stresses (E) are greater than the *local* dielectric strength (α) of the involved dielectric material(s). The reliability and the rate of failure of the whole system depend on the difference between the *local* stress and the *local* strength. Failure of the dielectric results in an electrical puncture or flashover. The flashover can occur across the cable dielectric, across the accessory dielectric or along the interface between two dielectric surfaces such as the cable insulation and joint insulation. It can also occur as an external flashover at cable terminations. The failure can occur as a result of the normally applied 60 Hz voltage or during a transient voltage such as lightning or switching surges.

$$P_f = 1 - e^{\frac{E}{\alpha}^{\beta}} \qquad \textbf{Equation 1}$$

Where

P_f is the probability of failure

α is the characteristic breakdown strength (Weibull Scale) associated with the dielectric material

β is the Weibull shape parameter for the dielectric material. It is determined from a breakdown test in the laboratory
E is the relevant stress (determined in a laboratory breakdown test) that is considered to drive the system to failure;

- in a ramp or step test, this is the stress at which the system breaks down
- in a constant electrical stress test, it is the time at which failure occurs

In HV systems, failure is generally treated as a decreasing strength (a decreasing α) problem due to a change in isolated defects rather than an *increasing local stress (an increasing E) problem*. As time progresses, artifacts that raise the local stress (loss of bond between the defect/contaminant and the surrounding dielectric and/or the development of voids) can develop with time. The net effect is considered an aging process.

3.3 Causes of Increased Local Stress

The specific mechanisms by which the dielectric strength is reduced by electrical stress induced aging can occur as a result of:

- Manufacturing Imperfections: These tend to increase the local stress, leading to either early failures or increased rates of aging. Examples include:
    - voids
    - protrusions extending into the dialectic from the semiconducting screens
    - contaminants in the dielectric

- Poor Workmanship: These issues tend to increase the local stress, which also leads to either early failures or increased rates of aging. Examples include:
    - cuts
    - interfacial contamination in accessories
    - missing components or connections
    - misalignment of accessories

- Wet Environment: Tends to reduce increase the local stress after ingress of water (either through normal migration through polymeric materials for cables without a metallic moisture barrier or beaks in seals or metallic sheaths): The result is:
    - bowtie trees
    - vented water trees

If the HV cable system does not have a metallic moisture barrier, it is likely useful to consider a diagnostic approach that is similar to that deployed for MV cable systems, though very little work was performed on this type of cable system in the *CDFI*.

The following elements are often considered in the degradation of MV cable systems. However, due to the differences in design and construction practices employed at HV, they are generally not considered:

- changes in the electrical environment (system voltage changes or lightning protection changes)
- overheating
- aggressive environment (contact with petrochemicals, fertilizer, etc.)

Defects in cables with extruded insulation that can lead to failure are shown schematically in Figure 4. These defects include screen protrusions, voids, cracks, contamination, delamination and semiconducting screen interruptions.

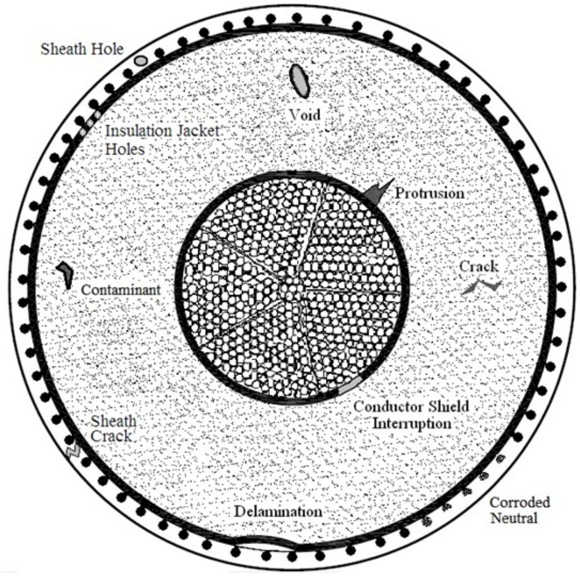


Figure 4: Typical Power Cable Defects

In addition, typical defects that can evolve into failures in a molded or extruded cable joint are shown in Figure 5. These defects can cause interface discharge (tracking at the interface of the cable insulation and the joint insulation) and/or partial discharge. It is instructive to note that the same types of defects that can occur in joint constructions, both taped and prefabricated, can also occur in terminations.

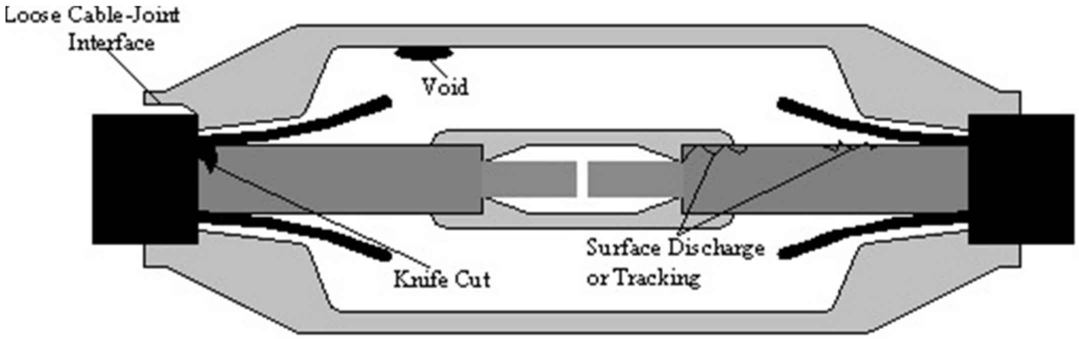


Figure 5: Typical Cable Joint Defects

As the aging mechanism depends on factors that involve the cable characteristics, accessory characteristics and operating conditions, different power cable systems will age in different ways at different rates. As the system ages, the dielectric strength of various components tend to reduce. In fact, aging, degradation, and failure mechanisms are statistical in nature. Therefore, there may be substantial variations in how the mechanisms develop and evolve over time with respect to cable length and accessories. This can lead to significant differences in the performance of different power cable systems even though they may be operating under the same conditions and exposed to similar environments. Moreover, due to the statistical behavior of these mechanisms, the power cable system properties measured through diagnostic testing will also show statistical differences. As a result, when utility engineers try to estimate the statistical time to failure for a given cable segment, the data should be interpreted correctly, (e.g. with a sufficient number of data points to provide a reasonable level of confidence for the assessment of trends and predictions.

Table 5 through Table 7 list typical deterioration or aging mechanisms along with the associated causes of these mechanisms for various accessory and cable types. Mechanisms that lead to rapid failure (thermal runaway and extremely high local stresses from contaminants) are omitted as they can occur so rapidly that they typically bypass the degradation step and thus do not permit intervention or prevention that might be possible from performing a diagnostic test.

It is useful to recall that the dielectric loss within a system is a function of the electrical stress (E), the applied voltage frequency (ω), dielectric permittivity (ε), and Tan δ:

$$\text{Dielectric Loss} \propto \omega E^2 \varepsilon \,\text{Tan}\,\delta \qquad \textbf{Equation 2}$$

In the case of HV and EHV cables, E, the electrical stress, is so much higher than in MV systems that dielectric heating can be very important. In fact, only ¼ of the Tan δ is required at HV stress to have the same heating effect as at MV stress.

Before failure, there is either tracking or an electrical tree. Thus it should be noted in all of the flow diagrams in Table 5 that tracking and electrical treeing precede all failures. The only question is how long they can be observed before the failure.

Table 5: Aging and Degradation Mechanisms for Extruded MV Cable

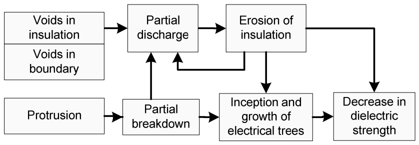
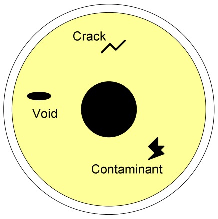
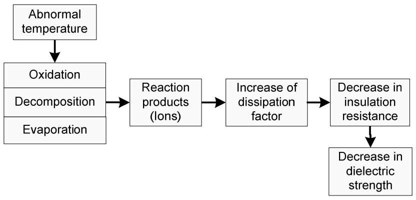
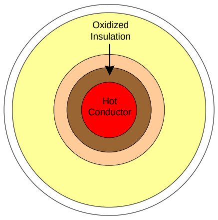
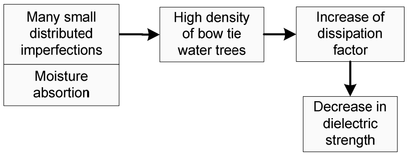
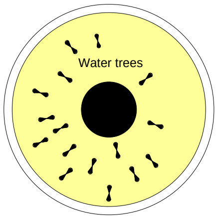
Type of Deterioration	Aging Process	Typical Causes	Example
Dry Electrical		Manufacturing imperfections (i.e. voids, contaminants)	
Thermal		Poor workmanship on accessories Incorrect choice of accessory Excessive conductor current	
High Density of Small Water Trees		Moisture ingress (external and via conductor)	

Table 6: Aging and Degradation Mechanisms for Paper Cable

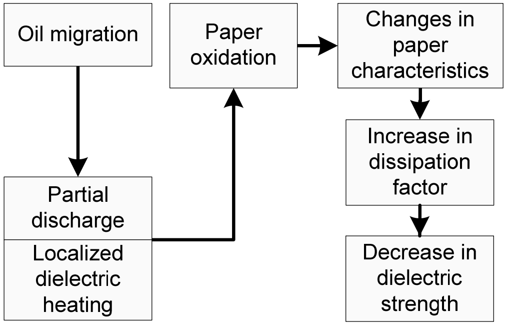
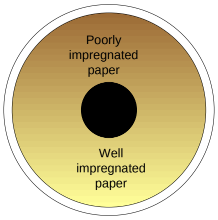
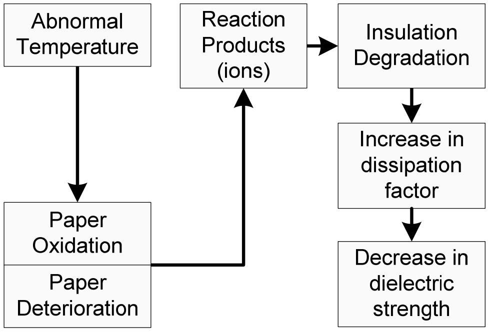
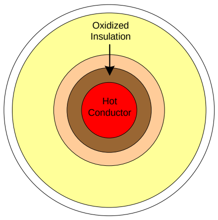
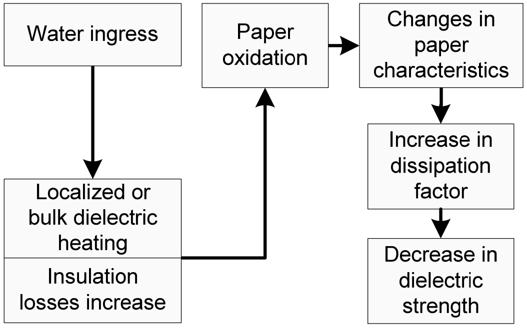
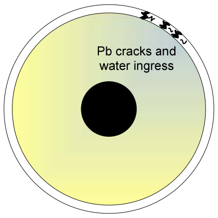
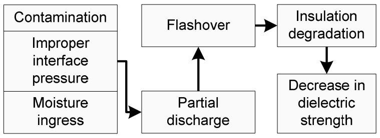
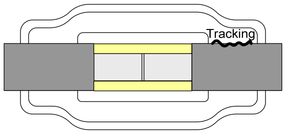
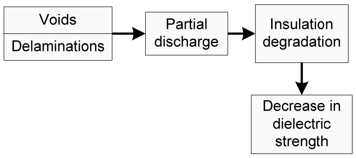
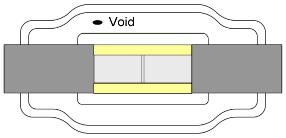
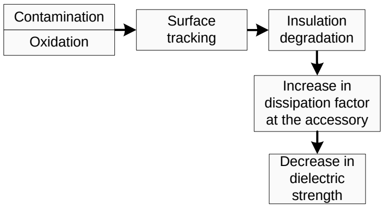
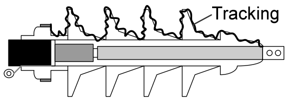
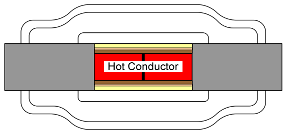
Type of Deterioration	Aging Process	Typical Causes	Example
Oil Starvation		Extreme elevation changes, Lead (Pb) breach: through cracks and corrosion	
Thermal		Excessive conductor current for a given environment and operating conditions	
Water Ingress		Lead (Pb) breach through : cracks and corrosion	

Table 7: Aging and Degradation Mechanisms for Accessories of Extruded MV Cable

Type of Deterioration	Aging Process	Accessory Type	Typical Causes	Example
Contaminated Interface		Joint, termination, separable connector	Moisture ingress, poor workmanship	
Dry Electrical		Joint, termination, separable connector	Manufacture defects, natural aging, poor workmanship	
Electrical External		Termination	Pollution, Ultra Violet (UV) degradation	
Thermal	NEW	Joint, termination, separable connector	Poor workmanship Incorrect choice	

3.4 Diagnostic Testing at HV and EHV

As noted previously, the propensity of HV and EHV cable systems to fail in infancy (<1.5 yr) as well as the propensity of the failure to occur in the accessories (3 to 4 times more frequently than the cable), means that diagnostics in the HV and EHV arena has been focused on commissioning tests using either Simple Withstand tests using resonant ac test voltage systems or Monitored Withstand tests using resonant ac test voltage systems with partial discharge detection.

Figure 6 shows the PD inception voltage (PDIV) for a large number of tests carried out in different countries (as reported in the research study conducted within CIGRE B1.28). As shown in the figure, the occurrence of PD at U_0 is low. Thus online PD testing is rarely performed.

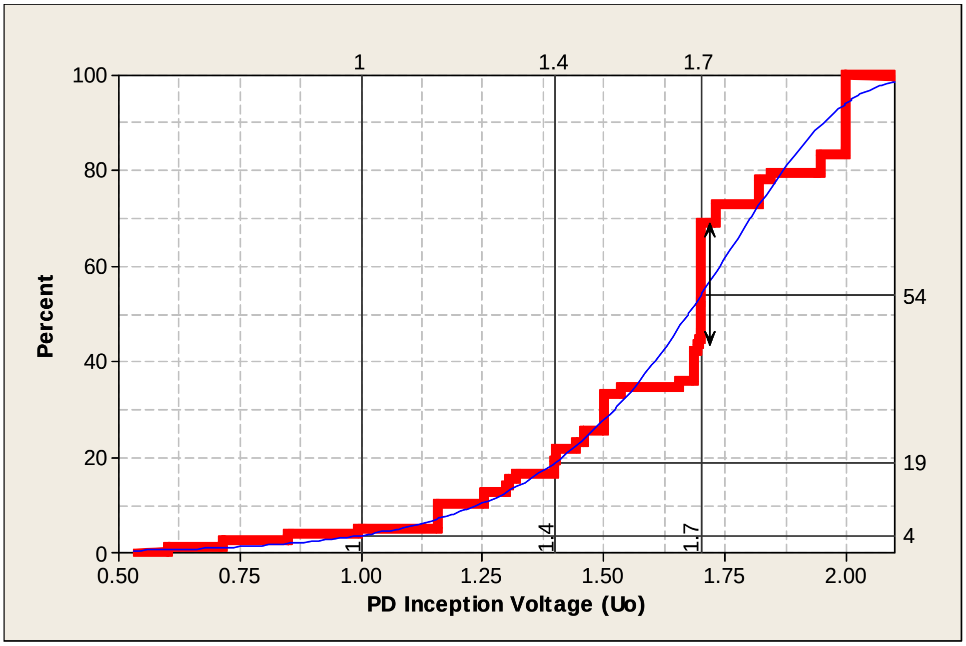


Figure 6: Distribution of PDIV (Based on Available Data from Service Providers)

An alternative approach that was postulated within the CIGRE working group was to test at $1.4U_0$. This will definitely have a greater chance of detecting defects that lead to partial discharge than tests performed at U_0, but it would miss the discharges that occur up to $2U_0$. The most technically solid voltage level is $1.7U_0$, which is the basic recommendation in IEC60840 and 62067. At this level, it is anticipated that between 44 and 70% of the discharges will be detected.

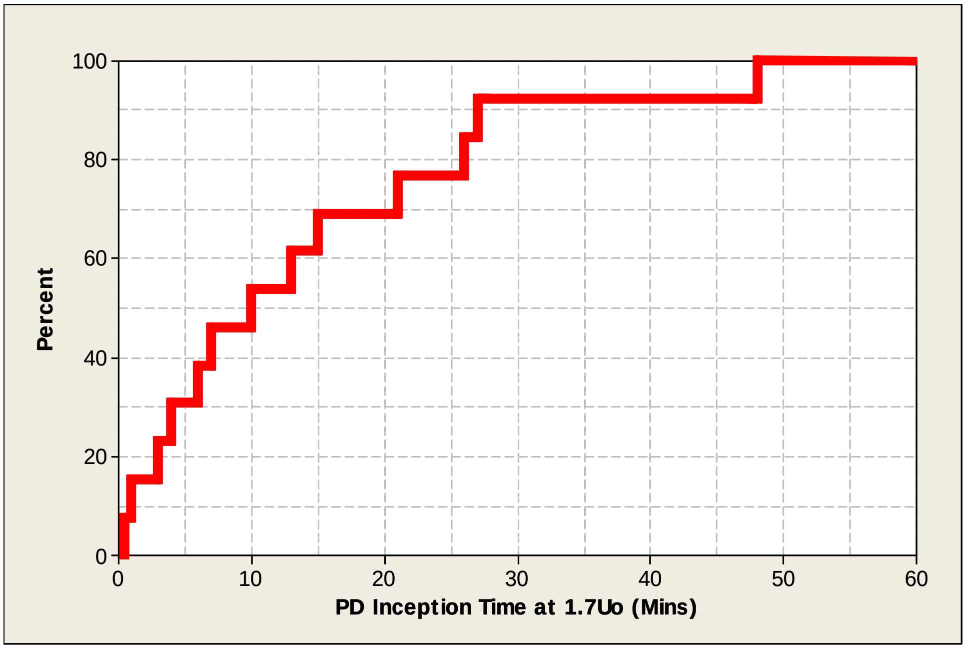


Figure 7: PD On-Set time at $1.7U_0$ (Based on Available Data from Service Providers)

As noted previously, $1.7U_0$ is the most preferred test voltage level. However, the other portion of a withstand test is the exposure time at the selected voltage level. The information in Figure 7 is for a

60 min time window. Although it is not known how many discharges would have been detected after 60 min, it is clear that the detection level was approaching an asymptote. The general feeling within the CIGRE working group is that the test time should be at least 30 min at $1.7U_0$ for both Simple and Monitored withstand tests. However, most practitioners take the view that most of the testing cost for HV cable systems is associated with the setup and thus the incremental cost to go on from 30 to 60 min is inconsequential and outweighed by the opportunity to identify the last 8% of the PD sites that may occur.

3.5 Summary

Only a limited amount of diagnostic testing or data analysis was performed on HV or EHV cable systems in the *CDFI*. However, this chapter points out the fact that there are demonstrable difference between MV and HV/EHV cable systems with respect to how they age and how diagnostics are deployed on these systems. As a result, the approach to diagnostic testing and deployment on HV/EHV cable systems is different. Simple Withstand tests and Monitored Withstand using partial discharge appear to be the most practical approaches. However, as discussed in Chapter 8, partial discharge testing is a complex process and many factors have to be taken into consideration when performing this test on HV/EHV cable systems.

3.6 References

1. RM Black; The History of Electric Wires and Cables; Peter Peregrinus 1983; ISBN 0 86341 001 4

2. R.A, Hartlein and H. Orton, Editors, *Long Life Insulated Power Cables*, Book published 2006 by Dow Chemical and Borealis LLC, translated into Russian and Chinese. 154 pages.

3. L.A. Dissado, and J.C. Fothergill, "Electrical degradation and breakdown in polymers," IEE Materials and devices series 9, Peter Peregrinus Ltd., London, 1992.

4. T. Toshikatsu and A. Greenwood, "Advanced power cable technology: present and future," CRC Press Inc., Boca Raton, vol. II, 1983, pp. 57-94.