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MAINTENANCE FOR HV CABLES AND ACCESSORIES

Working Group
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1. INTRODUCTION

At the 2001 SC B1(former 21) meeting in Madrid it was decided to initiate a WG B1-04 on the maintenance of HV cables.

The terms of reference for this Working Group were as follows:

- To define different types of maintenance, in co-ordination with similar work already done within other CIGRE study committees
- To list technical problems (maintenance issues) in different types of cable and accessories, to specify related detection/repair methods, to compare different approaches and if possible to develop common criteria for decisions (condition assessment tools)
- To collect case studies about how maintenance has been accomplished in practice
- To indicate how certain maintenance actions can be improved from a technical and from an economical point of view
- To recommend guidelines for structured maintenance, tailored to the different type of cable/accessory and adjusted to system requirements and to customer needs

Previous work by the SC in this area had focussed on diagnostic methods for both paper cable and extruded cable, resulting in three publications:

1) "Consideration of ageing factors in extruded insulation cables and accessories", (WG 21-09), published in 1992 [1]
2) "Diagnostic methods for HV paper cable and accessories" (WG 21-05) published in 1998 [2]
3) "Partial discharge detection in installed extruded cable systems" (WG 21-16) published in 2001 [3]

Although these reports describe advanced technical tools for the condition assessment of cable systems, they do not inform the reader about when, where or how these tools are recommended to be used in the context of maintenance. This report considers these issues for the whole cable system, i.e. cable and accessories, for the following cable designs:

1) Low pressure or self contained fluid filled (SCFF) cables
2) High pressure fluid filled (HPFF) cables
3) Gas compression cables (GP)
4) Extruded cables (PE, XLPE and EPR)

The IEC definition of maintenance is: "the combination of all technical and administrative actions, including supervisory actions, intended to retain an item, or restore it to a state in which it can perform a required function". Reinterpreting this definition specifically for cable systems, this general IEC definition becomes:

- Performance of condition assessment on a cable or accessory, followed by adequate action to avoid failure in service, or

- Perform an action at predetermined intervals to avoid a failure in service, or
- To repair a fault on a cable or accessory after the failure has happened.

The first part of this definition is called “Condition Based Maintenance”, or “Predictive Maintenance”, the second part is called “Time Based Maintenance” or “Preventive Maintenance” and the third part is called “Corrective Maintenance”.

Given that following a cable system failure corrective maintenance is the most likely utility response, this WG has focussed on “predictive maintenance”. The application of this type of maintenance practice for cable systems varies considerably between utilities even though this type of maintenance may contribute to improved reliability and reduced maintenance cost. Recent technical advances mean that many more tools are now available to enable successful predictive maintenance than in the past. For example, bad workmanship during accessory installation can cause early failures during operation; however, such errors can be tested by using an after-laying voltage test. Moreover, for extruded cables, partial discharge detection at the accessories provides an additional tool to detect installation errors and can hence potentially avoid such incipient defects become real failures during service.

Many utilities consider the diagnostic tools and associated methodologies necessary for a predictive maintenance programme are neither sufficiently reliable nor cost effective [4]. Consequently these utilities prefer to perform corrective maintenance rather than predictive maintenance. The economics of a predictive maintenance programme within a utility’s overall maintenance strategy is not considered as part of this report. This is because of the wide variations in operating frameworks between different countries and/or companies, which necessarily impacts on the financial justification. This report is however focused on a more proactive approach to maintenance and is intended to assist cable users to identify diagnostic tools and methodologies that can be applied in the user’s particular operating environment.

The report considers the following four questions:

1) What maintenance practices are being applied at present?
2) What are the causes of failure for cables and accessories?
3) How can these potential failures be detected?
4) How can maintenance be improved?

Addressing these questions has resulted in the following four main chapters:

1) A survey of presently used utility maintenance programmes (section 4)
2) A list of common failure modes for cable systems and related diagnostic detection methods and maintenance actions (section 5)
3) A list of available diagnostic tools (section 6)
4) Recommendations for effective and efficient maintenance (section 9)

The report also provides a list of definitions of key terms (section 2 and Appendix A) and an outline of different maintenance strategies (section 3). Maintenance case studies from a range of countries are presented to illustrate practical applications of maintenance policies (section 7 and Appendix B). The subject of remaining life estimation is briefly considered (section 8) and future technological developments in the cable maintenance area are outlined (section 10).

2. DEFINITIONS

Listed below are definitions for some of the key terms used throughout this report. A fuller list of terms and associated definitions related to the topic of maintenance can be found in Appendix A. The vast majority of the definitions have been taken from IEC 60050 [5]. Where a definition does not exist in this IEC document the alternative source has been indicated.

- **Condition based maintenance[†]:** an equipment maintenance strategy based on measuring the condition of equipment in order to assess whether it will fail during some future period, and then taking appropriate action to avoid the consequences of that failure. The condition of equipment could be performed using Condition Assessment, Statistical Process Control techniques, by monitoring equipment performance, or through the use of the Human Senses. The terms Condition Based Maintenance, On-condition maintenance and Predictive Maintenance can be used interchangeably.
- **Corrective maintenance:** the maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function.
- **Failure:** the termination of the ability of an item to perform a required function.
    1. After failure the item has a fault.
    2. "Failure" is an event, as distinguished from "fault", which is a state.
    3. This concept as defined does not apply to items consisting of software only.
- **Fault:** the state of an item characterised by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources. - A fault is often the result of a failure of the item itself, but may exist without prior failure.
- **Maintenance:** the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function.
- **Predictive maintenance[†]:** an equipment maintenance strategy based on measuring the condition of equipment in order to assess whether it will fail during some future period, and then taking appropriate action to avoid the consequences of that failure.
- **Preventive maintenance:** the maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item
- **Time based maintenance[‡]:** an equipment maintenance strategy based on the fact that after a fixed period of time a component is serviced or overhauled, independent of the wear of the component at that time. Therefore, the strategy has just one parameter, the maintenance interval. The requirement of this strategy is to determine an adequate interval, as both a very rare and a very frequent execution of the preventive activities are both sub-optimal.

[†] http://www.plant-maintenance.com/terminology.shtml
[‡] http://www.ergonetz.de/maintenance/indu_p_e.html

3. MAINTENANCE STRATEGIES

3.1 Introduction

Maintenance is performed on high voltage equipment for a variety of reasons. The main reasons for carrying out maintenance are:

- To avoid failures
- To avoid environmental damage
- To avoid more expensive maintenance later
- To extend the life of the equipment
- To avoid unsafe situations
- To repair failed components
- To avoid legal and financial penalties

There are three fundamentally different ways to carry out maintenance:

- Corrective maintenance (CM), to repair or replace broken items
- Time-based maintenance (TBM), to perform preventive maintenance based on a specified predetermined schedule
- Condition based maintenance (CBM), to perform preventive maintenance based on the present condition of the component (condition assessment)

TBM and CBM both have the intention to avoid failures in service. CBM can also be called "Predictive Maintenance", meaning maintenance to be carried out to determine which maintenance actions will follow in order to avoid failures in service.

3.2 Previous CIGRE questionnaire

The CIGRE Report "Questionnaire on Maintenance Polices and Trends (JWG 23/39)", published in 2000 [6], examined maintenance practices and costs for different types of maintenance on a range of transmission system apparatus, including substations, transformers, switchgear, overhead lines, cables, protection and control. The questionnaire considered a variety of issues relating to five major parts of the world - Asia, Eastern Europe, Western Europe, North America and the Southern Hemisphere. Questions were asked about the type of maintenance program being used and, particularly of interest to utilities, the maintenance costs. The responses to the question: "Could you breakdown the direct maintenance cost in predictive maintenance, corrective maintenance, refurbishment and other", are of particular interest and they indicate the differences between maintenance on cables and maintenance on other components. This is illustrated in Table 3.1:

Table 3.1: Breakdown of direct maintenance cost by % for different transmission equipment								
	G	**S**	**Tr**	**L**	**T**	**Ca**	**P**	**Co**
Predictive Maintenance	54	57	50	36	35	24	57	40
Corrective Maintenance	18	17	23	29	26	45	18	32
Refurbishment	20	17	18	29	35	24	13	12
Others	9	9	8	6	4	7	11	19

G = general T = tower
S = switchgear Ca = cable
Tr = transformer P = protection
L = line Co = control

This table shows that cables, in contrast with other equipment, have the lowest expenditure on predictive maintenance, and the highest expenditure on corrective maintenance. The reasons for this difference are not clear. Due to the fact that cables are buried out of sight in the ground, they may receive less attention than other more prominently visible components. The absence of moving parts and the low risk of explosion, at least for the cable and joints, may also be a factor. The difference in maintenance attention may indicate that better criteria are needed to devise the available maintenance budget in the optimal manner. The available maintenance budget should be assigned according to the contribution to the overall system reliability [7]. Thus cables should have a higher maintenance priority, as, in common with other electric apparatus, cable and accessories are subject to failure and outage. A condition based maintenance approach appears to offer opportunities to detect potential failures before they happen and to reduce the probability of failures in service.

3.3 Summary

The above table, as well as the following section reviewing current practices, shows that compared to other plant types cables receive less predictive than corrective maintenance. This therefore offers the possibility of performing maintenance in a different manner in the future. Sections 5 and 6 review tools for performing predictive maintenance and the defects that these tools can detect. These new tools need to form part of a coherent maintenance strategy, which balances corrective and predictive maintenance according to the needs of the asset owner.

4. SURVEY OF PRESENTLY USED MAINTENANCE PROGRAMMES

4.1 Introduction

A brief survey of the current maintenance policies of ten different companies using high voltage cables was carried out as part of the work of CIGRE WG B1-04. This chapter contains a summary of the information gathered about their preventive maintenance actions. Rather than issuing a questionnaire, each utility was asked to provide details of their cable maintenance policy. Tables 4.1 to 4.4 were compiled based on the information received from the companies. However, not all companies provided information about all actions, so there are some blanks in the tables. Therefore a blank does not necessarily mean that such an action is not performed, but that it is not specifically detailed in the maintenance policy details provided.

The preventive parts of the maintenance programs can be divided in actions to avoid external damage and internal failures.

4.2 Maintenance to avoid external damage (dig-ins)

Maintenance to avoid external damage is the same for fluid filled and extruded cables. The actions done in different companies are shown in Table 4.1. The ten companies are referred to as no. 1 - 10 in the following tables (each number refers to the same company in all tables).

Preventive maintenance to avoid third party damage is done in almost all companies, but the way it is done differs. The two most common practices are

1. Routine inspection of cable routes
2. Administrative procedures to provide cable route information to third parties

For the routine inspection of cable routes, employees of the utility drive along the cable route looking for evidence of activities by civil contractors or other third parties which could cause damage to the cables. If there is evidence of digging activity near cables, the third party is alerted to the presence of live cables and appropriate precautions are taken. The frequency of the inspections varies from every week to every second month. The success of this maintenance practice is dependent on the frequency of the inspection. Often the frequency varies based on the importance of a cable circuit.

In some countries, the third party must gather knowledge about other buried services (water, electricity, gas, etc) in advance of digging. To help with this either nationally, or in the company itself, a central office issues the necessary information about the position of the cable system to the third party.

In some countries, if the work involves excavation within 1 metre of a live cable, the third party must contact the electric utility several days before digging begins to discuss if the cables can be in operation during the third party work.

4.3 Maintenance to avoid internal failure of the cable system

Although some tests are common to extruded and fluid filled cables, this type of maintenance differs with the type of cable system. Tables 4.2 and 4.3 show the maintenance practice for extruded and fluid filled cables, respectively.

Extruded cables

A comparison of Tables 4.2 and 4.3 shows fewer maintenance tasks are carried out on extruded cables compared to fluid filled cables. The most common maintenance tasks carried out for extruded cables are sheath testing (serving test) and visual inspection of terminations. In companies where tunnels are used also these and the alarm equipment is inspected.

The serving test indicates if the sheath is damaged. The damaged sheath is located and repaired when a suitable outage on the cable circuit is available. Sheath repair will stop further ingress of water, which has great influence on the lifetime of the cable. By locating the sheath fault it can also be possible to find the cause of failure (third party, stones, bad outer sheath). Another common used test is visual inspection of the terminations. This can indicate the early stages of leakage from terminations and other failures, which can eventually lead to breakdown.

Some companies carry out thermal monitoring of cable circuits, particularly on critical circuits. This can be in the form of thermocouples placed in hot spots or in new systems as continually measuring the temperature on an optical fibre placed in, on or near the cable.

Fluid filled cables

Table 4.3 shows that for fluid filled cables, as on extruded cable sheath test, visual inspection of the termination and temperature measurement is part of the maintenance in many companies.

A visual inspection of the terminations in substations and also other equipment as oil tank is carried out.

Most companies monitor the pressure in the cable and use an alarm system to indicate if the pressure is too low.

Periodic checking of the alarm equipment and control of pressure level is part of maintenance in most companies. By keeping track of the pressure and comparing with the load on the cable it is possible to identify oil leaks at an early stage and to minimise the environmental effects of an oil leak by carrying out a repair as early as possible. When the leakage rate reaches a certain level, it is necessary to locate the leak and repair the cable generally during a planned outage of the cable circuit.

Tests on specially bonded systems.

Table 4.4 shows the tests done on specially bonded cable systems - single point bonded and cross-bonded systems.

In nearly all companies, the special bonding system and link boxes are visually inspected to ensure that there is no corrosion or water ingress. This test is often done at the same time as the serving test. Only a few companies carry out a test on the surge arrestor.

In one company, the current running in the earth point is measured to give an indication of a sheath failure. This enables continuous monitoring of the cable sheath.

Test under consideration

Certain tests are under consideration in some companies.

Tests such as dielectric loss angle measurement (tan δ) and partial discharge measurement are used in some companies. These tests are being used more and more on medium voltage cable systems as the experience grows and the cost of the tests is falling. For high voltage cables, the size of the equipment is the greatest barrier against the use of these tests. This test may be used in the future as a tool to assess condition of the cables system.

Dissolved gas analysis (DGA) is being tried out in a few companies on paper (SCFF/HPFF) cable systems in order to assess the condition of the oil.

4.4 A statistical approach and failure analysis.

A statistical approach cannot be seen as maintenance where actions are undertaken on the cable system. It is based more on collecting data on the individual cable systems (i.e. fault statistics etc.) and for the different types of system. Based on the collected data it is decided whether or not a cable or accessory shall be exchanged. This statistical approach is used in most companies. In the sense that they have a fault statistic which can show the fault rate and point out the weak components which are nearing the end of life.

Many companies use a statistical approach as a method for developing a plan of action. A statistical approach allows the economic value of different maintenance approaches to be estimated. However, the low probability of faults in general and the limited experience with some failure modes can mean that there is limited availability of statistics concerning failure modes. Furthermore, there is a great diversity in cable designs, accessories and installations covering several decades of technological development. Therefore, the statistical approach needs to take such uncertainties into account.

When planning strategic maintenance actions, identification of the failure modes which are the most common and have the most serious consequences (e.g. safety, loss of reputation, financial penalties etc) is important. For each of these, the costs and benefits of using available diagnostic tools or other possible preventive actions should be considered. Benefits should include both direct (corrective maintenance) and indirect costs of faults (outage costs, loss of goodwill etc).

Analysis of failed components is important in collecting information for a fault database. Failures are often analysed to obtain information that can be used for the improvement of the maintenance plan.

Occasionally, opportunities arise to remove and analyse parts of the cable system (e.g. due to cable replacement, diversion or extension). Such opportunities are used by some companies to analyse the condition of the cable or to take these samples for possible further reference for future failure analyses. A procedure on how to analyse the cable system components removed from service and an example of a checklist for the evaluation of materials is given in Appendix C of this report.

4.5 Summary

This brief survey shows that the preventative maintenance practices vary widely between the utilities which participated. Nevertheless, it does indicate that preventative maintenance is being applied rather than a policy of only performing corrective maintenance. Moreover, these utilities also have maintenance policies that dictate the frequency and/or when certain actions need to be taken.

Many utilities take the opportunity to gain knowledge following cable system failures by undertaking detailed failure investigations. Furthermore, some utilities also collect samples from cable systems when the opportunity arises. Both these approaches lead to a better understanding of the condition of the cable system, which in turn can be used to develop and/or improve a cable owner's maintenance strategy and policy.

Table 4.1: Preventive maintenance to avoid external damage

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
Patrol of cable routes	Every 2 months	currently by special people		Check for civil work, cable markers are visible	Annually	Annually	6-monthly	Monthly for checking of environment activity (only for important circuits)		
Inspection of warning signs					Annually	Annually		Annually: knowledge of environment modification		Warning sign is not used
Administrative procedure, to provide information on cable routes to contractors					Yes, national	Yes, national				Yes

Table 4.2: Extruded cables, Preventive maintenance to avoid internal failure

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
Sheath test (serving test)	Every 3 years	Annually	Annually	Yes, frequency depending on local needs	Annually, for cross-bonded systems	Annually in city. Elsewhere every 2 years	Annually	Yes, before warranty limit or after a major repair, or if there is a doubt		Every 5 years, planned in future
Hot spot temperature measurement i.e. PT100				Yes				Yes		
Temperature measurement (optical fibre)								On some cables		On some cables
Visual inspections of terminations				To check for: external damage, dielectric fluid leakage, oil level, connections to overhead lines.		Annually		Every 3 or 6 months	Regularly, part of control in substation	50kV: every 6 months 132kV: every 3 months
Cleaning and treatment of outdoor termination				Yes						
Snaking control in tunnel								Every 1 or 6 years	Regularly	
Inspection of tunnel								Every 1 or 6 years	Regularly, to check for water ingress, corrosion of clamping, sleeves and sediments on cables. Also inspected is accessibility, safety and fire alarms and ventilation systems	
Test of earth resistance								every 6 years		

Table 4.3: Fluid filled Cables, Preventive maintenance to avoid internal damage

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
Pressure Monitoring, alarm	Yes	Yes					Yes	Yes	Yes	Yes
Pressure readings	Every 2 months	Monthly		Yes		Every 2 years	Monthly	Every 3 or 6 months	Every 2 months	50kV: every 6 month 132kV: every 3 months
Alarm gauge check SCFF + GC	Every 3 years	Every 3 months			Annually	Yearly		Every 1, 3, or 6 year	Annually	50kV: every 6 months 132kV: every 3 months
Inspection for corrosion	Every 3 years	Annually	Annually		Annually, only on gas pressure cables	Yearly on gas pressure cables on FF cables protection of tank is controlled	Every 6 months	Only on terminations every 3 or 6 month		
Sheath test (serving test)	Every 3 years	Annually	Annually	Yes		Annually in city, else every 2 years	Annually	Condition-based		
Check of thermocouple				Yes				Yes		
Visual inspections of terminations	Every 3 years			Check for external damage, dielectric fluid leakage, oil level and connections to overhead lines.		Annually		Every 3 or 6 months	Annually	50kV:every 6 months 132 kV every 3 months
Cleaning and treatment of outdoor termination				Yes						
Visual inspection of oil tank	Every 3 years							Every 3 or 6 months	Annually	
Analysis of cable oil	Every 3 years									
Test of earth resistance								Every 6 years		

Table 4.4: Tests on Specially Bonded Cable Systems

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
Visual inspection of cross bonding system		Annually		Yes	Annually	Annually	Annually	Every 6 years		Every 5 years
Test of surge arrestors				Yes			Monthly			
Sheath current alarm										Yes, continually

5. FAILURE MODES/RELATED DETECTION METHODS AND MAINTENANCE ACTIONS

5.1 Introduction

This section of the report is concerned with the identification of the main causes of failure for each type of high voltage cable and accessory.

The four cable types [8] specifically considered in this report are namely:

SCFF		Self Contained Fluid filled
HPFF		High Pressure Fluid filled
GP		Gas Pressure
Extruded Cables:	**XLPE**	Cross-Linked Polyethylene
	EPR	Ethylene Propylene Rubber
	PE	HDPE, LDPE

Some failure modes are common to more than one cable type (e.g. third party damage). Other failure modes are unique to a particular cable type (e.g. loss of nitrogen pressure in gas pressure cables). In order to present the information more clearly, a separate table of failure modes has been produced for each cable type. Although this results in some repetition of failure modes that are common to different cable types, it facilitates ease of reference for the reader. For each failure mode, the associated diagnostic indicator, if indeed there is one, is listed.

A standardised list of failure modes was compiled into tables for each cable type under the following headings:

Item	'Item' identifies the component in the cable system to which the failure mode is related (e.g. the cable, joint, termination, etc.)
Event/cause	'Event/cause' describes the event that has occurred to cause the cable system failure, damage or degradation (e.g. metal sheath damaged by third party).
Consequence	'Consequence' describes the direct effects on the cable system of the 'event/cause' (e.g. loss of oil from cable).
Probability of occurrence	The 'probability of occurrence' of the 'event/cause' is categorised as high, medium or low. The categorisation determined in the tables has been based on overall utility experience of operating these cables. The prevalence of failure modes can vary from utility to utility.

Impact:	The ‘impact’ of each ‘consequence’ is categorised into one (or more) of the following areas: *Health & Safety* The ‘consequence’ of the ‘event/cause’ endangers the health and safety of utility personnel or the general public. (e.g. third party damage to cable resulting in a breakdown) *Environment* The ‘consequence’ of the ‘event/cause’ poses a risk of environmental damage. (e.g. oil leak from a fluid filled cable) *System* The ‘consequence’ of the ‘event/cause’ affects the normal operation of the power system. A distinction is drawn between a consequence that causes the circuit to trip and a consequence, which requires the cable to be switched out in a controlled manner by the operator.
Diagnostic indicator	The ‘diagnostic indicator’ for an ‘event/cause’ is the measurable or detectable property of the cable system that changes as a result of the ‘event/cause’. (e.g. loss of insulation resistance of the oversheath in the case of a sheath fault)
Maintenance/preventive action	The ‘maintenance/preventive action’ details the specific actions that can be taken in respect of each ‘event/cause’ to reduce the probability of its occurrence and to monitor the condition of the cable. (e.g. serving test)
Effectiveness	The ‘effectiveness’ of each ‘maintenance/preventive action’ is categorised as either well established or under development.
On-line monitoring or off-line measurements	Each ‘maintenance/preventive’ action is categorised as capable of being done either on-line (i.e. with the cable in normal service) or off-line (i.e. the cable must be switched out).

In the following paragraphs, the failure modes for each cable type are identified from the tables. This is based on the day to day operating experience of the utilities participating in the Working Group and wider discussions with other cable users.

5.2 Self contained fluid filled cables

The failure modes, related detection methods and maintenance actions for self-contained fluid filled cables are presented in Table 5.1.

The following events/causes were considered to have a higher probability of occurrence:

- Damaged cable by third party
- Damaged oversheath caused by third party, brittleness, external contamination of oils, solvents, bitumen etc.
- Damaged metal sheath caused by third party, corrosion or fatigue
- Ingress of water in the insulation
- External mechanical stress due to ground changes, thermal expansion-contraction (snaking) and improper clamping
- Assembly error causing local increase of electrical stress in joints and terminations
- Leakage of internal insulating oil from termination
- Failure of oil pressure gauges/transducers or gauge contacts
- Movement of cable due to thermal cycling or poor clamping
- Water ingress into link boxes
- Failure of forced cooling system (where fitted)

In Electra No. 176 February 1998, CIGRE WG21-05 published report entitled "Diagnostic Methods for HV Paper Cables and Accessories" [2]. This report details diagnostic methods for high voltage paper cable and, in particular, guidelines for using the tests.

5.3 High pressure fluid filled cables

The failure modes, related detection methods and maintenance actions for high-pressure fluid filled cables are presented in Table 5.2.

The following events/causes were considered to have a higher probability of occurrence:

- Damaged cable by third party
- Leaking or damaged steel pipe due to corrosion
- Assembly error causing local increase of electrical stress in joints and terminations
- Leakage of internal insulating oil from termination
- Failure of oil feeding and pressurisation system due to oil leaks in associated pipe-work, oil leak from reservoir tank, oil pump system failure, faulty gauges

5.4 Gas pressure cables

The failure modes, related detection methods and maintenance actions for gas pressure cables are presented in Table 5.3.

The following events/causes were considered to have a higher probability of occurrence:

- Damaged cable by third party
- Leaking or damaged steel pipe due to corrosion
- Assembly error causing local increase of electrical stress in joints and terminations
- Leakage of internal insulating oil from termination
- Failure of gas pressure system due to gas leaks in associated pipe-work, gas leak from canister and faulty gauges

5.5 Extruded cables

The failure modes, related detection methods and maintenance actions for extruded cables are presented in Table 5.4.

The following events/causes were considered to have a higher probability of occurrence:

- Damaged cable by third party
- Damaged over sheath caused by third party, brittleness, external contamination of solvents, oils, bitumen etc
- Damaged metal sheath caused by third party, corrosion or fatigue
- Ingress of water in the insulation
- External mechanical stress due to ground changes, thermal expansion-contraction (snaking) and improper clamping
- Assembly error causing local increase of electrical stress in joints and terminations
- Movement of cable due to thermal cycling or poor clamping
- Water ingress into link boxes
- Failure of forced cooling system (where fitted)

TABLE 5.1

FAILURE MODES, RELATED DETECTION METHODS AND MAINTENANCE ACTIONS FOR SELF CONTAINED FLUID FILLED CABLES

TABLE 5.1 - FAILURE MODE ANALYSIS OF SCFF CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
1) Cable	Damaged cable by third party	Instant failure (loss of electrical continuity and/or voltage withstand)	High	System Safety (to the third party) Environment	Lack of power transmission through the cable system (line tripping)	Cable route information. Procedures to exchange information (e.g. cable route records) between utilities and contractors.	Depending on local practices	Not applicable
						Periodic inspections along the cable route to check for evidence of third party activity.	Well established	Not applicable
		Loss of oil possibly leading to failure			Falling oil pressure	Continuous measurement of oil pressure and/or low pressure alarms	Well established	On-line
2) Cable	Damaged oversheath caused by third party, brittleness, external contamination of oils, solvents, bitumen etc	Corrosion of metal sheath Rise of standing voltage on sheath and/or loss of cross-bonding function (see further item 32)	High	System	Loss of insulation resistance of oversheath	Serving test (measurement of outer sheath resistance)	Well established	Off-line
3) Cable	Corrosion of reinforcing tapes on lead-sheathed cables[1]	Failure of reinforcing tapes leading to expansion and splitting of lead sheath and subsequent oil loss	Low	System Environment	Tape thickness	Sampling of the reinforcing tapes. Cable elevation surveys and analysis of route profile allows selective pressure reduction and/or cable replacement[2]	Under development	Off-line

[1] This problem has only been experienced (after many years in service) on cables with copper bronze reinforcing tapes and a particular grade of PVC oversheath
[2] Cables can be targeted for replacement based on the severity of the corrosion, the possible pressure reduction achievable (to reduce hoop stresses) and environmental risk assessment

TABLE 5.1 - FAILURE MODE ANALYSIS OF SCFF CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
4) Cable	Damaged metal sheath caused by third party, corrosion or fatigue	Loss of oil if sheath is breached	High	System Environment	Falling oil pressure	Continuous measurement of oil pressure and/or low pressure alarms	Well established	On-line
		Water ingress into the cable if positive oil pressure is lost	Low		Lack of oil pressure		Well established	On-line
					Loss of insulation resistance of oversheath	Serving test (measurement of outer sheath resistance)	Well established	Off-line
5) Cable	Thermal ageing of insulation due to overheating (e.g. soil dry out or current overload)	Decrease of insulation strength	Low	System	Increased cable temperature	Monitoring of thermal experience and hot-spots, by spot temperature measurements or along the entire cable route using distributed temperature sensing (DTS)[3] where fitted	Well established, but limited experience	On-line
					Visual evidence	Route survey, checking for building over cables etc.	Well established	On-line
					Material property changes in insulating oil	Chemical and physical analysis of insulating oil	Well established	Off-line
6) Cable	Defects not seen during acceptance tests and factory quality control, which with age lead to local increase of electrical stress	Local increase of electrical stress. Repeated failures on circuits with the same components/design i.e. type faults.	Low	System	Partial discharge	Partial discharge measurement	Under development	On-line
					Material property changes in insulating oil	Chemical and physical analysis of insulating oil	Well established	Off-line
7) Cable	External mechanical stress due to ground changes, thermal expansion-contraction (snaking) and improper clamping	Damage leading to local increase of electrical stress	Low[4]	System	Visual evidence (e.g. cable movements)	Inspection of cable route and verification of clamping design	Well established	Depending on safety policies
8) Joint	Assembly error causing local increase of electrical stresses	Local increase of electrical stresses	Low	System	Visual evidence High local temperature	Disassemble joint only if a problem is suspected.	Not applicable	Off-line

[3] The optical fibre for DTS measurements must be installed with the cable
[4] Although may vary depending on the amount of civil works

TABLE 5.1 - FAILURE MODE ANALYSIS OF SCFF CABLES AND DIAGNOSTIC INDICATORS

Item		Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
9)	Joint	Assembly error leading to incorrect assembly of joint connector	Local overheating and insulation damage	Low	System	Visual evidence High local temperature	X-ray image of joint DTS measurements depending on the sensitivity of the system (where fitted)	Well established Well established	Off-line On-line
10)	Joint	Movement of cable due to thermal cycling or poor clamping	Cracking of sheath plumbs	Medium	System Environment	Visual inspection Falling oil pressure	Reinforcement of sheath plumbs on opportunistic basis or targeted programme of work prioritised according to local drivers[5,6]. Continuous measurement of oil pressure and/or low pressure alarms	Well established Well established	Off-line On-line
11)	Joint	Movement of cable due to thermal cycling or poor clamping	Unplugging of ferrule and core movement within the joint	Low	System Safety	Infrared or x-ray images	When direct measurement is not possible the use of infrared or x-rays images may offer an alternative	Well established	Off-line
12)	Joint	Deposition of copper sulphide in joint papers	Dielectric breakdown in joint[7]	Low	System Environment	Occurrence of copper sulphide deposits	Opportunistic stripdown of joints removed from service[8]	Under development	Off-line
13)	Joint	Electrophoretic and dielectrophoretic effect on conducting and non-conducting particles respectively in cable oil	Gas evolution in regions of high electrical stress leading to joint breakdown	Low	System Environment	Material property changes in insulating oil	Chemical and physical analysis of insulating oil[9]	Well established	Off-line
14)	Termination	Leakage of internal insulating oil from termination	Gas: decrease in dielectric strength of insulating medium as pressure falls Oil: uneven voltage distribution	Medium	System Environment	Falling gas pressure Falling oil pressure	Continuous measurement of gas pressure and/or low pressure alarms, SF6 sniffers or cameras may aid leak location Continuous measurement of oil pressure and/or low pressure alarms.	Well established Well established	On-line On-line

[5] Drivers may include need for improved circuit availability or environmental considerations, such as proximity to water courses, aquifers etc
[6] Refurbished joint bays may also be fitted with oil proof liners and oil detecting sensors
[7] Copper sulphide deposits have been found in a number of joints removed from service, the location of these deposits correlates with at least two known failure paths in the UK
[8] Forensic inspection and strip down of items removed from system, which may or may not have failed, to elicit knowledge of ageing mechanisms prior to failure
[9] Respecification of cable oil to oil with better gas absorbing properties. Introduction of respecified oil into old cables to achieve a minimium 35% DDB content.

TABLE 5.1 - FAILURE MODE ANALYSIS OF SCFF CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
15) Termination	Degradation/decomposition of internal insulation oil at termination due to ageing and/or breakdown	Decrease of dielectric strength of insulating medium. Local increase of electrical stress	Low	System	Increased partial discharge Material property changes in insulating oil/gas	Partial discharge measurement[10] Chemical and physical analysis of insulating oil/gas	Well established Well established	On-line Off-line
16) Termination	Assembly error causing local increase of electrical stress	Local increase of electrical stresses	Medium	System Safety	Visual evidence Physical characteristics of dielectric	Disassemble only if a problem is suspected. Partial discharge	Under development	Off-line
17) Termination	Movement of cable due to thermal cycling or poor clamping	Unplugging of connector stalks and ferrules at terminations. Core movement within the termination.	Medium	System Safety	Change in the position of connector Infrared or x-ray images	Periodic inspection of outdoor termination. Modification if significant movement is detected When direct measurement is not possible the use of infrared or x-rays images may offer an alternative only if a problem is suspected.	Well established Well established	Off-line Off-line
18) Termination	External damage due to mechanical stresses	Local increase of electrical stress or local increase of environmental stress (surface insulation)	Low	System Environment	Visual evidence	Visual inspection	Well established	On-line
19) Termination	Surface pollution of outdoor insulators	Leakage current Tracking In extreme cases, flashover	Low, but depends on location	System	Visual evidence Leakage current	Visual inspection using IR, visible or UV light Measurement of leakage current Insulator washing	Well established Well established Well established	On-line On-line On-line/Off-line
20) Termination	Extrinsic surface pollution on outdoor polymeric insulators	Loss of hydrophobicity for polymeric type terminations	Low, but depends on location	System	Reduced surface free energy	Surface wetting characteristics (STRI method)[11] Contact angle of water droplets	Well established Well established	Off- line Off- line

[10] Conventional methods, acoustic methods, UHF methods etc.

[11] The STRI hydrophobicity classification guide provides a coarse value of the wetting status, analysing the wetting appearance and contact angle betwen water drops. The guide can be found in IEC Technical Specification TS 62073

TABLE 5.1 - FAILURE MODE ANALYSIS OF SCFF CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
21) Termination	Intrinsic surface pollution on outdoor polymeric insulators	Chalking on the insulator surface[12] leading to loss of hydrophobicity	Low	System	Visual evidence	Inspection of the surface of the insulator	Well established	On-line
22) Termination	Insulator tracking[13]	Increase of electrical stress	Low	System	Partial discharge	Partial discharge measurement[14]	Under development Well established	On- line Off-line
23) Termination	Mechanical damage to porcelain	Leakage of insulating medium leading to possible failure	Low	System Safety	Visual evidence Falling oil pressure	Visual inspection Continuous measurement of oil pressure and/or low pressure alarms	Well established Well established	On-line On-line
24) Ancillary	Failure of oil pressure gauges/transducers or gauge contacts	Undetected falling oil pressure leading to potential oil loss and failure	High	System Environment	Visual evidence Failure to issue alarm under test conditions	Periodic inspection of oil pressures Regular gauge maintenance and calibration. Regular testing of gauge/ transducer alarm functionality	Well established Well established	On-line On-line
25) Ancillary	Corrosion of oil tanks	Loss of oil to the environment	Low	Environment	Visual evidence	Periodic inspection of accessible tanks[15]	Well established	On-line
26) Ancillary	Corrosion or fatigue of oil pipes	Loss of oil to the environment	Low	Environment	Visual evidence	Periodic inspection of exposed pipework	Well established	On-line
27) Ancillary	Failure of cooling system (water or air)	Loss of cooling function and de-rating of cables. Loss of water pressure in the cooling system	Medium	System	Visual evidence and/or pump and fan monitors Falling water pressure Increased cable temperature	Periodic inspection of cooling system Continuous measurement of water pressure and/or low pressure alarms Cable temperature monitored using DTS (where fitted)	Well established Well established Well established	On-line On-line On-line

[12] Chalking (or flouring) is the appearance of some particles of the filler of the housing material forming a rough or powdery surface. The visual effect is a white powder (similar to flour)
[13] Tracking is an irreversible degradation by formation of paths starting and developing on the surface of an insulating material. These paths are conductive even under dry conditions. Tracking can occur on surfaces in contact with air and also on the interfaces between different insulating materials
[14] Conventional methods, acoustical methods, UHF methods etc.
[15] Manufacturing methods and installation conditions are known to contribute to the problem. Targeted replacement programme for those oil tanks most at risk based on an environmental risk assessment and/or system security.

TABLE 5.1 - FAILURE MODE ANALYSIS OF SCFF CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
28) Ancillary	Water ingress into the link boxes	Corrosion of link boxes, possible failure of SVLs. Reduction in cross-bonding function	High	System	Visual evidence	Periodic visual inspection of the link boxes [16]	Well established	Off-line
29) Ancillary	Failure of signalling (protection) equipment	Oil loss or electrical failure	Low	System Environment Safety	Periodic testing	Periodic testing of the signalling equipment	Well established	Off-line
30) Ancillary	Failure of SVL[17]	Damage to oversheath during switching and/or lightning surges	Low	Safety	Increased sheath standing voltage Visual evidence	Periodic voltage testing of SVLs Periodic visual inspection	Well established Under development Well established	Off-line On-line Off-line
31) Ancillary	Cross-bonding: incorrect laying geometry[18], non-uniform characteristics of ground (electrical) resistance[19]	Loss of cross-bonding function, i.e. risk for overload at normal operating	Low	System Safety	High circulating current in the sheath	Measurement of circulating current in the sheath	Well established	Off-line
32) Ancillary	Cross-bonding: Loss of insulation from earth of cross-bonding system due to damage on outer sheath, screen separation at joints or surge arresters in link boxes	Reduction or loss of cross-bonding function leading to possible overload of the cable. Increased sheath voltage	Low	System Safety	Loss of insulation resistance High circulating current in the screen	Measurement of insulation resistance Measurement of circulating current in the screen	Well established Well established	Off-line Off-line
33) All	Loss of integrity of the oil system	Oil entering watercourses. Possible failure	Low	Environment Safety	Visual evidence Falling oil pressure	Periodic inspection along the cable route for evidence of oil loss into nearby water courses Continuous measurement of oil pressure and/or low pressure alarms	Well established Well established	Off-line On-line

[16] During major refurbishments, the cross bonding system can be redesigned to reduce the number of link boxes.
[17] Silicon carbide SVLs have been known to fail explosively.
[18] Incorrect laying geometry occurs when the distances between the three phases (cables) change along the route. This generates a e.m.f. not perfectly balanced, yielding a circulating current in the screens of the cables
[19] For long cable routes, electrical characteristics of the ground can vary along the route

TABLE 5.1 - FAILURE MODE ANALYSIS OF SCFF CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
34) All	Removal by the utility of items, either failed or not, from the cable system	Loss of valuable asset condition knowledge	Low	System Environment Safety	Strip down with visual examination, electrical tests or chemical analysis	Forensic inspection and strip down of items removed from system to elicit knowledge of ageing mechanism prior to failure	Under development	Off-line

TABLE 5.2

FAILURE MODES, RELATED DETECTION METHODS AND MAINTENANCE ACTIONS FOR HIGH PRESSURE FLUID FILLED CABLES

TABLE 5.2 - FAILURE MODE ANALYSIS OF HIGH PRESSURE FLUID FILLED CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequences	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
1) Cable	Damaged cable by third party	If cable core is breached: cable failure, major oil leak at high pressure, risk of electrocution of third party and fire. If damage is to the pipe only: Major oil leak at high pressure, consequent formation of voids in insulation, decrease of insulation strength, water ingress	High	System Environment Safety	Lack of power transmission If core not breached: falling oil pressure, alarm activation, excessive pump operation.	Cable route information. Procedures to exchange information, eg cable route records, between utilities and contractors. Periodic inspections along the cable route to check for evidence of third party activity. Continuous measurement of oil pressure and pressure alarms	Depending on local practices Well established Well established	Not applicable Not applicable On-line
2) Cable	Leaking or damaged steel pipe due to corrosion	Oil leakage In extreme cases, formation of voids in insulation and decrease of insulation strength	High	System – switch out cable if alarm, Environment	Falling oil pressure – alarm activation, excessive pump operation, rise in impressed current of cathodic protection system (where fitted)	Monitor pipe oil pressure Periodic coating survey Monitoring of pipe to soil potential	Well established	On-line
3) Cable	Thermal ageing of insulation (caused by overload, short circuits, hot spots)	Decrease of insulation strength	Low but increases with cable age	System	Insulation temperature Paper degradation Increase in Tan δ	Do thermal survey of cable route. Chemical and physical analysis of papers[1] and impregnant[20]	Under development	Off-line
4) Cable	Mechanical ageing of insulation (caused by thermal expansion and contraction)	Local increase of electrical stresses	Low but increases with cable age	System	Changes in physical characteristics of dielectric	Do x-ray if mechanical movement of the cable is suspected.	Under development	Off-line
5) Cable	Degradation of dielectric impregnant (e.g. due to impurities in the pipe filling medium)	Decrease of insulation strength	Low	System	Changes in the chemical and physical characteristics of dielectric	Chemical and physical analysis of papers and impregnant	Under development	Off-line

[20] Chemical and physical analysis of impregnant include the following tests - measurement of dielectric breakdown strength of impregnated paper tapes, analysis of cable dielectric fluid (DGA, dissipation factor, dielectric breakdown strength, moisture content, acidity)

TABLE 5.2 - FAILURE MODE ANALYSIS OF HIGH PRESSURE FLUID FILLED CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequences	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
6) Cable	Defects not seen during acceptance tests and factory quality control, which with age lead to local increase of electrical stress	Local increase of electrical stresses	Low	System	Material property changes in the dielectric	Chemical and physical analysis of papers and impregnant	Under development	Off-line
7) Joint	Assembly error causing local increase of electrical stresses	Local increase of electrical stresses	Low	System	Visual evidence	Disassemble only if a problem is suspected.	Not applicable	Off-line
8) Joint	Assembly error leading to incorrect assembly of joint connector	Local overheating and insulation damage	Low	System	Visual evidence High local temperature	If problem suspected, do x-ray imaging and/or disassemble joint.	Well established	Off-line
9) Joint	Assembly error leading to imperfect sealing	Water penetration causing reduced material properties	Low	System Environment	Falling oil pressure – alarm activation	Monitor pipe oil pressure	Well established	On-line
10) Joint	Mechanical ageing of insulation (due to cable movement under thermal expansion)	Decrease of insulation strength	Low	System	Changes in physical characteristics of dielectric	Chemical and physical analysis of papers and impregnant	Under development	Off-line
11) Termination	Assembly error causing local increase of electrical stress	Local increase of electrical stresses	Medium	System Safety	Physical characteristics of dielectric	Disassemble only if a problem is suspected. Partial discharge	Under development	Off-line
12) Termination	Movement of cable due to thermal cycling or poor clamping	Unplugging of connector stalks and ferrules at terminations. Core movement within the termination.	Low	System Safety	Change in the position of connector Infrared or x-ray images	Periodic inspection. Modification to the termination if and when significant movement is detected When direct measurement is not possible the use of infrared or x-rays images may offer an alternative	Well established Well established	Off-line Off-line
13) Termination	Leakage of internal insulating oil from termination (due to corrosion or ageing of O-rings and gaskets)	Dielectric breakdown	Medium	System Safety	Falling oil pressure – alarm activation Visual evidence of leak.	Visual inspection and gauge check – periodic inspection programme.	Well established	On-line
14) Termination	Ingress of contaminants to internal insulating fluid	Decrease of dielectric strength of insulating medium. Local increase of electrical stress	Low	System	Changes in the chemical characteristics of the insulating fluid	Chemical and physical analysis of insulating fluid	Well established	On-line

TABLE 5.2 - FAILURE MODE ANALYSIS OF HIGH PRESSURE FLUID FILLED CABLES AND DIAGNOSTIC INDICATORS

Item		Event/cause	Consequences	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
15)	Termination	External damages due to mechanical shocks	Local increase of electrical stress or local increase of environmental stress (surface insulation)	Low	System Environment	Visual evidence	Visual inspection	Well established	On-line
16)	Termination	Surface pollution (of outdoor insulators)	Leakage current Tracking In extreme cases, flashover	Low, but depends on location	System	Visual evidence	Visual inspection using IR, visible or UV light Measurement of leakage current Insulator washing	Well established Well established Well established	Off-line On-line On-line/Off-line
17)	Termination	Insulator tracking[21]	Increase of electrical stress	Low	System	Partial discharge	Partial discharge measurement[22]	Under development Well established	On- line Off-line
18)	Termination	Mechanical damage to porcelain	Leakage of insulating compound leading to possible failure	Low	System Safety	Visual evidence	Visual inspection	Well established	On-line
19)	Ancillary	Failure of oil feeding and pressurisation system due to, oil leaks in associated pipe-work, oil leak from reservoir tank, oil pump system failure or faulty gauges	Loss of oil pressure Oil leakage Forced outage of circuit	High	System Environment	Falling oil pressure – alarm activation	Periodic inspection programme covering the entire oil feeding system, associated components and accessories.	Well established	On-line
20)	Ancillary	Failure of signalling (protection) equipment	Lack of alarms from diagnostic indicators (using the signalling system)	Low	System Environment Safety	-	Periodic testing of the signalling equipment	Well established	Off-line
21)	Ancillary	Corrosion of oil tanks	Loss of oil to the environment	Low	Environment	Visual evidence	Periodic inspection of accessible tanks[23]	Well established	On-line
22)	Ancillary	Corrosion or fatigue of oil pipes	Loss of oil to the environment	Low	Environment	Visual evidence	Periodic inspection of exposed pipe-work	Well established	On-line

[21] Tracking is an irreversible degradation by formation of paths starting and developing on the surface of an insulating material. These paths are conductive even under dry conditions. Tracking can occur on surfaces in contact with air and also on the interfaces between different insulating materials

[22] Conventional methods, acoustical methods, UHF methods etc.

[23] Manufacturing methods and installation conditions are known to contribute to the problem. Targetted replacement programme for those oil tanks most at risk based on an environmental risk assessment and/or system security.

TABLE 5.3

FAILURE MODES, RELATED DETECTION METHODS AND MAINTENANCE ACTIONS FOR GAS PRESSURE CABLES

TABLE 5.3 - FAILURE MODE ANALYSIS OF GAS PRESSURE CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequences	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
1) Cable	Damaged cable by third party	If cable core is breached, instant failure (loss of electrical continuity and/or voltage withstand), gas leak at high pressure. If damage is to the pipe only, gas leak at high pressure	High	System Safety (to the third party) Environment	Lack of power transmission If core not breached, falling gas pressure.	Cable route information. Procedures to exchange information, eg cable route records, between utilities and contractors. Periodic inspections along the cable route to check for evidence of third party activity. Continuous measurement of gas pressure and pressure alarms	Depending on local practices Well established Well established	Not applicable Not applicable On-line
2) Cable	Leaking or damaged steel pipe due to corrosion	Gas leak (slow) In extreme cases, formation of voids in insulation resulting decrease of insulation strength	High	System	Reduced gas pressure – alarm activation Rise in impressed current of cathodic protection system (where fitted)	Monitor pipe gas pressure Periodic coating survey Monitoring of pipe to soil potential	Well established	On-line
3) Cable	Thermal ageing of insulation (caused by overload, short circuits, hot spots)	Decrease of insulation strength	Low[24]	System	Insulation temperature Paper degradation Increase in Tan δ	Thermal survey of cable route. Chemical and physical analysis of papers[25] and impregnant[26]	Under development	Off-line
4) Cable	Mechanical ageing of insulation (caused by thermal expansion and contraction)	Local increase of electrical stresses leading to hot spots	Low	System	Changes in physical characteristics of dielectric	Physical analysis of papers and impregnant at specific locations.	Under development	Off-line
5) Cable	Degradation of dielectric impregnant (e.g. due to impurities in the pipe filling medium)	Decrease of insulation strength	Low	System	Changes in the chemical and physical characteristics of dielectric	Chemical and physical analysis of papers and impregnant	Under development	Off-line

[24] Low, but probability of occurrence may increase with cable age
[25] Chemical and physical analysis of papers include the following tests - folding strength, tear strength, burst strength, degree of polymerisation, extension to break, tensile strength
[26] Chemical and physical analysis of impregnant include the following tests - measurement of dielectric breakdown strength of impregnated paper tapes, analysis of cable dielectric fluid (DGA, dissipation factor, dielectric breakdown strength, moisture content, acidity)

TABLE 5.3 - FAILURE MODE ANALYSIS OF GAS PRESSURE CABLES AND DIAGNOSTIC INDICATORS

Item		Event/cause	Consequences	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
6)	Cable	Defects not seen during acceptance tests and factory quality control, which with age lead to local increase of electrical stress	Local increase of electrical stresses	Low	System	Material property changes in the dielectric	Chemical and physical analysis of papers and impregnant	Under development	Off-line
7)	Cable	Migration under gravity of dielectric impregnant in vertical installations	Decrease of insulation strength in the higher part of the system	Low	System	Changes in the chemical and physical characteristics of dielectric	Physical analysis of papers and impregnant	Under development	Off-line
8)	Cable	Expansion of lead sheath under its own weight in low-lying sections of cable	Displacement of insulating medium resulting in decrease of insulation strength	Low	System	Changes in the physical characteristics of dielectric	Physical analysis of cable section	Under development	Off-line
9)	Cable	Cable operation at reduced pressure or no pressure for long periods (e.g. 24/48hrs+)	In extreme cases, void formation in dielectric resulting in decrease of insulation strength	Low[27]	System	Electrical characteristics of dielectric	Ensure operations engineers are aware of operating limitations of gas pressure cables	Not applicable	Off-line
10)	Joint	Assembly error causing local increase of electrical stresses	Local increase of electrical stresses	Low	System	Visual evidence High local temperature	Disassemble joint if problem is suspected	Not applicable	Off-line
11)	Joint	Assembly error: Incorrect assembly of joint connector	Local overheating and insulation damage	Low	System	Visual evidence High local temperature	If problem suspected, do x-ray imaging and/or disassemble joint.	Well established	Off-line
12)	Joint	Assembly error leading to imperfect sealing	Water penetration causing reduced material properties	Low	System Environment	Falling oil pressure – alarm activation	Visual inspection		
13)	Joint	Mechanical ageing of insulation (due to cable movement under thermal expansion)	Decrease of insulation strength	Low	System	Changes in the physical characteristics of dielectric	Chemical and physical analysis of papers and impregnant	Under development	Off-line
14)	Termination	Assembly error causing local increase of electrical stress	Local increase of electrical stresses	Medium	System Safety	Physical characteristics of dielectric	Disassemble only if a problem is suspected. Partial discharge	Under development	Off-line

[27] depends on operating practice of utility

TABLE 5.3 - FAILURE MODE ANALYSIS OF GAS PRESSURE CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequences	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
15) Termination	Movement of cable due to thermal cycling or poor clamping	Unplugging of connector stalks and ferrules at terminations. Core movement within the termination.	Medium	System Safety	Change in the position of connector Infrared or x-ray images	Periodic inspection. Modification to the termination if and when significant movement is detected When direct measurement is not possible the use of infrared or x-rays images may offer an alternative	Well established Well established	Off-line Off-line
16) Termination	Loss of insulating compound from termination due to corrosion, ageing of O-rings and gaskets	Dielectric breakdown	Low	System Safety	Falling oil pressure – alarm activation Visual evidence of leak.	Visual inspection and gauge check – periodic inspection programme.	Well established	On-line
17) Termination	Contamination of internal insulation fluid	Decrease of dielectric strength of insulating medium. Local increase of electrical stress	Low	System	Changes in the chemical characteristics of the insulating fluid	Chemical and physical analysis of insulating fluid	Well established	On-line
18) Termination	Infiltration of nitrogen gas into core of cable which accumulates at top of sealing end	Dielectric breakdown in joint/termination	Low	System Safety		Disassemble and physically examine sealing end	Well established	Off-line
19) Termination	Leaks in pipe-work	Leakage of insulating compound leading to possible failure	Low	System Safety	Drop in pressure in equalising fluid reservoir and alarm activation.	Visual inspection Gauge check	Well established	On-line
20) Termination	External damages due to mechanical shocks	Local increase of electrical stress or local increase of environmental stress (surface insulation)	Low	System Environment	Visual evidence	Visual inspection	Well established	On-line

TABLE 5.3 - FAILURE MODE ANALYSIS OF GAS PRESSURE CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequences	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
21) Termination	Surface pollution (of outdoor insulators)	Leakage current Tracking In extreme cases, flashover	Low, but depends on location	System	Visual evidence	Visual inspection using IR, visible or UV light	Well established	On-line
					Leakage current	Measurement of leakage current	Well established	On-line
						Insulator washing	Well established	On-line/Off-line
22) Termination	Insulator tracking[28]	Increase of electrical stress	Low	System	Partial discharge	Partial discharge measurement[29]	Under development Well established	On- line Off-line
23) Termination	Mechanical damage to porcelain	Leakage of insulating compound leading to possible failure	Low	System Safety	Visual evidence	Visual inspection	Well established	On-line
24) Ancillary	Failure of gas pressure system due to gas leaks in associated pipe-work, gas leak from canister, faulty gauges	Loss of gas pressure Forced outage of circuit	High	System Environment	Falling gas pressure – alarm activation	Periodic inspection programme covering the entire gas system, associated components and accessories.	Well established	On-line
25) Ancillary	Failure of signalling (protection) equipment	Lack of alarms from diagnostic indicators (using the signalling system)	Low	System Environment Safety	-	Periodic testing of the signalling equipment	Well established	Off-line

Note: The 'Enfield' design of gas pressure cables requires particular consideration. This design has been widely used in the UK. These cables appear to suffer from the following ageing phenomena:

- Fatigue of scratched reinforcing tapes, particularly after installation damage or minor abrasion
- Possible work hardening of joint sleeves
- Fatigue/ageing of reinforced lead tubes
- Accumulation of 'copper dust' in sealing ends
- Loss/gain of oil into compensators

The future reliability of existing 'Enfield' GP circuits appears to be affected by how they are operated. They appear to have very little operational flexibility. Several failures in recent years in the UK have been preceded by increases in the loading of these cables.

[28] Tracking is an irreversible degradation by formation of paths starting and developing on the surface of an insulating material. These paths are conductive even under dry conditions. Tracking can occur on surfaces in contact with air and also on the interfaces between different insulating materials

[29] Conventional methods, acoustical methods, UHF methods etc.

TABLE 5.4

FAILURE MODES, RELATED DETECTION METHODS AND MAINTENANCE ACTIONS FOR EXTRUDED CABLES

TABLE 5.4 - FAILURE MODE ANALYSIS OF EXTRUDED CABLES AND DIAGNOSTIC INDICATORS

Item	Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
1) Cable	Damaged cable by third party	Instant failure (loss of electrical continuity and/or voltage withstand)	High	System Safety (to the third party)	Lack of power transmission	Cable route information. Procedures to exchange information (e.g. cable route records) between utilities and contractors. Periodic inspections along the cable route to check for evidence of third party activity.	Depending on local practice Well established	Not applicable Not applicable
2) Cable	Damaged oversheath caused by third party, brittleness, external contamination of solvents, oils, bitumen etc	Corrosion of metal sheath (if applicable), water ingress under the oversheath (leading to ageing water trees on cable without radial water barrier) Rise of standing voltage on sheath and/or loss of cross-bonding function (see further item 35)	High	System	Loss of insulation resistance of oversheath	Serving test (measurement of insulation resistance)	Well established	Off-line
3) Cable	Damaged metal sheath caused by third party, corrosion or fatigue	Water ingress under the oversheath (leading to ageing water trees on cable without radial water barrier) Rise of standing voltage on sheath and/or loss of cross-bonding function (see further item 35)	High	System	Loss of insulation resistance of oversheath	Serving test (measurement of insulation resistance)	Well established	Off-line
4) Cable	Ingress of water in insulation area [30]	Ageing, water trees	Low to high (cable without radial water barrier)	System	increased power factor	tg δ measurement methods (have only been developed for medium voltage cables, and are at the moment not possible to use on HV cables.)	Well established for MV Under development for HV	Off-line
5) Cable	Thermal ageing of insulation due to overheating (e.g. soil dry out or current overload)	Decrease of insulation strength	Low	System	Increased cable temperature	Monitoring of thermal experience and hot-spots, by spot temperature measurements or along the entire cable route using distributed temperature sensing (DTS) where fitted	Well established, but limited experience	On-line

[30] through damaged oversheath or through conductor on damaged cables without proper water barriers

TABLE 5.4 - FAILURE MODE ANALYSIS OF EXTRUDED CABLES AND DIAGNOSTIC INDICATORS

Item		Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
6)	Cable	Defects not seen during acceptance tests and factory quality control which with age lead to local increase of electrical stress[31]	Local increase of electrical stresses	Low	System	Increased partial discharge	Partial discharge measurement. Increased partial discharge is detectable only during a short time before failure.	Well established Under development	Off-line On-line
7)	Cable	Ageing : detachment of semiconductor	Local increase of electrical stress	Low, but depends on construction quality	System	increased partial discharge visual evidence	Partial discharge measurement. See item 6 X-ray examination	Well established Well established	Off-line Off-line
8)	Cable	External mechanical stress due to ground changes, thermal expansion-contraction (snaking) and improper clamping	Damages leading to local increase of electrical stress	Low[32]	System	Visual evidence (e.g. cable movements)	Inspection of cable route and verification of clamping design	Well established	Depending on safety policies
(9)	Joint	Assembly error causing local increase of electrical stresses[33]	Local increase of electrical stresses	Medium	System	Partial discharge Visual evidence High local temperature	Partial discharge measurement and or joint disassembly if faults are suspected. Partial discharge measurements as an after laying test may detect the fault before failure.	Well established	Off-line. On-line possibility would be of interest.
10)	Joint	Assembly error leading to incorrect assembly of joint connector	Local overheating and insulation damage	Low	System	Visual evidence High local temperature	x-ray image of joint DTS measurements depending on sensitivity of the system (where fitted)	Well established[34]	Off-line On-line
11)	Joint	Assembly error leading to imperfect sealing	Water penetration causing reduced material properties	Low	System	Increased partial discharge	Partial discharge measurement	Well established	On-line
12)	Joint	Movement of cable due to thermal cycling or poor clamping	Cracking of sheath plumbs	Medium	System Environment	Visual inspection	Reinforcement of sheath plumbs on opportunistic basis or targeted programme of work prioritised according to local drivers[35,36].	Well established	Off-line
13)	Joint	Movement of cable due to thermal cycling or poor clamping	Unplugging of ferrule and core movement within the joint	Low	System Safety	Infrared or x-ray images	When direct measurement is not possible the use of infrared or x-rays images may offer an alternative	Well established	Off-line

[31] roughness, inclusions, contaminants, cavities and irregularities in insulation, between or in conductive sheaths, cuts in screen and insulation, external mechanical stress due to bending at installation
[32] Although may vary depending on the amount of civil works
[33] incorrect position of the stress cone, incorrect finishing of the semiconductor, finishing or geometrical coupling not correct, contamination on interface or lack of materials compatibility
[34] Well established but difficult to implement in public areas
[35] Drivers may include need for improved circuit availability or environmental considerations, such as proximity to water courses, aquifers etc
[36] Refurbished joint bays may also be fitted with oil proof liners and oil detecting sensors

TABLE 5.4 - FAILURE MODE ANALYSIS OF EXTRUDED CABLES AND DIAGNOSTIC INDICATORS

Item		Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
14)	Joint	Ageing: Low contact pressure (loss of materials elasticity with time) due to bad/wrong material	Local increase of electrical stresses	Low	System	Increased partial discharge	Partial discharge measurement	Well established	On-line
15)	Joint	Shrink-back (of the cable insulation)	Local increase of electrical stresses	Low	System	Increased partial discharge	Partial discharge measurement	Well established	On-line
16)	Joint	Prefabricated joints: Defects not seen during acceptance tests and which with age leads to local increase of electrical stress	Local increase of electrical stresses	Low	System	Increased partial discharge	Partial discharge measurement	Well established	On-line
17)	Termination	Movement of cable due to thermal cycling or poor clamping	Unplugging of connector stalks and ferrules at terminations. Core movement within the termination.	Low	System Safety	Change in the position of connector Infrared or x-ray images	Periodic inspection. Modification to the termination if and when significant movement is detected When direct measurement is not possible the use of infrared or x-rays images may offer an alternative	Well established Well established	Off-line Off-line
18)	Termination	External damages due to mechanical shocks	Local increase of electrical stress or local increase of environmental stress (surface insulation)	Low	System Environment	Visual evidence	Visual inspection	Well established	On-line
19)	Termination	Assembly error causing local increase of electrical stress[37]	Local increase of electrical stresses	High	System	Increased partial discharge	Partial discharge measurement	Well established	On-line
20)	Termination	Assembly error: imperfect sealing	Water penetration causing reduced material properties	Low	System	Increased partial discharge Water content in insulating oil Visual evidence	Partial discharge measurement Water content measurement Visual inspection of sealings	Well established	On-line Off-line Off-line
21)	Termination /Interface	Ageing: Low contact pressure (loss of materials elasticity with time) due to bad/wrong material	Local increase of electrical stresses	Low	System	increased partial discharge	Partial discharge measurement	Well established	On-line
22)	Termination /Interface	Shrink-back (of the cable insulation)	Local increase of electrical stresses	Low	System	increased partial discharge	Partial discharge measurement	Well established	On-line

[37] incorrect position of the stress cone, incorrect finishing of the semiconductor, finishing not correct, geometrical coupling not correct (use of components bought from different suppliers), contamination on interface, lack of materials compatibility, improper cleaning of moulds etc.

TABLE 5.4 - FAILURE MODE ANALYSIS OF EXTRUDED CABLES AND DIAGNOSTIC INDICATORS

Item		Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
23)	Termination	Leakage of internal insulating fluid/gas from termination	Gas: decrease in dielectric strength of insulating medium as pressure falls Oil: uneven voltage distribution	Medium	System Environment	Falling gas pressure Falling oil pressure Occurrence of oil outside of termination	Continuous measurement of gas pressure and/or low pressure alarms, SF6 sniffers or cameras may aid leak location Continuous measurement of oil pressure and/or low pressure alarms Visual inspection of oil gauges and surrounding ground.	Well established Well established Well established	On-line On-line On-line
24)	Termination	Contamination of internal insulation fluid/gas at termination due to ageing	Decrease of dielectric strength of insulating medium. Local increase of electrical stress	Low	System	Increased partial discharge Material property changes in insulating oil/gas	Partial discharge measurement [38] Chemical and physical analysis of insulating fluid	Well established	On-line On-line
25)	Termination	Surface pollution (of outdoor insulators)	External leakage current	Low, but depends on location	System	Visual evidence Leakage current	Visual inspection using IR, visible or UV light Measurement of leakage current Insulator washing	Well established Well established Well established	On-line On-line On-line/Off-line
26)	Termination	Extrinsic surface pollution on outdoor polymeric insulators	Loss of hydrophobicity for polymeric type terminations	Low, but depends on location	System	Reduced surface free energy	Surface wetting characteristics (STRI method)[39] Contact angle of water droplets	Well established Well established	Off- line Off- line
27)	Termination	Intrinsic surface pollution on outdoor polymeric insulators	Chalking on the insulator surface[40] leading to loss of hydrophobicity	Low	System	Visual evidence	Inspection of the surface of the insulator	Well established	On-line
28)	Termination	Insulator tracking [41]	Increase of electrical stress	Low	System	Partial discharge	Partial discharge measurement	Well established Under development	Off-line On- line

[38] Conventional methods, acoustic methods, UHF methods etc.
[39] The STRI hydrophobicity classification guide provides a coarse value of the wetting status, analysing the wetting appearance and contact angle betwen water drops. The guide can be found in IEC Technical Specification TS 62073
[40] Chalking (or flouring) is the appearance of some particles of the filler of the housing material forming a rough or powdery surface. The visual effect is a white powder (similar to flour)
[41] Tracking is an irreversible degradation by formation of paths starting and developing on the surface of an insulating material. These paths are conductive even under dry conditions. Tracking can occur on surfaces in contact with air and also on the interfaces between different insulating materials.

TABLE 5.4 - FAILURE MODE ANALYSIS OF EXTRUDED CABLES AND DIAGNOSTIC INDICATORS

Item		Event/cause	Consequence	Probability of occurrence	Impact	Diagnostic indicator	Maintenance/preventive action	Effectiveness	On-line monitoring or off-line measurements
29)	Termination	Mechanical damage to porcelain	Leakage of insulating compound leading to possible failure	Low	System Safety	Visual evidence	Visual inspection	Well established	On-line
30)	Ancillary	Failure of cooling system (water or air)	Loss of cooling and de-rating of cables Loss of water in the cooling system	Medium	System	Visual inspection and/or pump and fan monitors Falling water pressure Increased cable temperature	Periodic inspection of cooling system Continuous measurement of water pressure and low pressure alarms Cable temperature monitored using DTS (where fitted)	Well established Well established Well established	On-line On-line On-line
31)	Ancillary	Failure of signalling (protection) equipment	Lack of alarms from diagnostic indicators (using the signalling system)	Low	System Environment Safety	-	Periodic testing of the signalling equipment	Well established	Off-line
32)	Ancillary	Water ingress into the link boxes	Corrosion of link boxes, possible failure of SVLs. Reduction in cross-bonding functions	High	System	Visual evidence	Periodic visual inspection of the link boxes	Well established	Off-line
33)	Ancillary	Failure of SVL[42]	Damage to oversheath during switching and/or lightning surges	Low	Safety	Increased sheath standing voltage Visual evidence	Voltage test on SVL Visual inspection	Well established Under development Well established	Off-line On-line Off-line
34)	Ancillary	Cross-bonding: incorrect laying geometry[43], non uniform characteristics of ground (electrical) resistance[44]	Loss of cross-bonding function, i.e. risk for overload at normal operating	Low	System Safety	High circulating current in the screen	Measurement of circulating current in the screen	Well established	Off-line
35)	Ancillary	Cross-bonding: Loss of insulation from earth of cross-bonding system due to damage on outer sheath, screen separation at joints or surge arresters in link boxes	Reduction or loss of cross-bonding function leading to possible overload of the cable. Increased sheath voltage	Low	System Safety	Loss of insulation resistance High circulating current in the screen	Measurement of insulation resistance Measurement of circulating current in the screen	Well established Well established	Off-line Off-line

[42] Silicon carbide SVLs have been known to fail explosively
[43] Incorrect laying geometry occur when the distances between the three phases (cables) change along the route. This generates a e.m.f. not perfectly balanced, yielding a circulating current in the screens of the cables
[44] For long cable links, the electrical characteristic of the ground can vary along the link.

6. AVAILABLE DIAGNOSTIC TOOLS

6.1 Introduction

This section of the report is concerned with the identification of the main diagnostic tools available for the maintenance of high voltage cables and accessories.

In general the diagnostic tools are common to all types of cables, however some are specific to a particular type. In order to present the information clearly a separate table of diagnostic tools has been produced for each cable type in common with the principle presented in section 4.0.

The list of available diagnostic tools has been compiled into tables for each cable type under the following headings:

Tool	"Tool" briefly identifies the available diagnostic tool.
Description of Method	"Description of Method" summarises the basic principles of the diagnostic tool.
Events/cause detected	Description of the events/causes that has occurred to cause the cables system failure which are detectable with the diagnostic tool.
Comment	Comments regarding the tool.
On line/Off Line	Each tool is categorized as either being capable of being done on-line (i.e. with the cable in normal service) or being done off-line (i.e. the cable must be switched off)

In the following paragraphs the available diagnostic tools for each cable type are identified from the tables.

This information is based on the day to day operating experience of the utilities and contractors participating in the Working Group.

6.2 Self contained fluid filled cables

The available diagnostic tools for self contained fluid filled cable systems are presented in Table 6.1.

The available tools identified are:

- Cable route inspection (for third party activities)
- Indication of falling oil pressure
- Serving test
- Temperature measurement.
- Partial discharge measurement
- Chemical and physical analysis of insulating oil
- X-ray of accessories
- Inspection of the cable system
- Inspection of termination for ferrule retraction
- Regular gauge maintenance and calibration
- Regular testing of gauge/transducer alarm functionality
- Sheath Voltage limiter test
- Bonding System test

6.3 High pressure fluid filled cables

The available diagnostic tools for high pressure fluid filled cable systems are presented in Table 6.2.

The available tools identified are:

- Cable route inspection (for third party activities)
- Indication of falling fluid pressure
- Electrical test on pipe coating
- Inspection of the cathodic protection system
- Temperature measurement
- Thermal backfill survey
- Chemical and physical analysis of paper and impregnant
- X-ray of accessories
- Inspection of the cable system
- Inspection of termination for ferrule retraction
- Inspection of pumping system
- Regular gauge maintenance and calibration
- Regular testing of gauge/transducer alarm functionality

6.4 Gas pressure cables

The available diagnostic tools for gas pressure cable systems are presented in Table 6.3.

The available tools identified are:

- Cable route inspection (for third party activities)
- Indication of falling gas pressure
- Electrical test on pipe coating
- Inspection of the cathodic protection system
- Temperature measurement
- Thermal backfill survey
- Chemical and physical analysis of paper and impregnant
- X-ray of accessories
- Inspection of the cable system
- Inspection of termination for ferrule retraction
- Regular gauge maintenance and calibration
- Regular testing of gauge/transducer alarm functionality

6.5 Extruded cables

The available diagnostic tools for extruded cable systems are presented in Table 6.4.

The available tools identified are:

- Cable route inspection
- Serving tests
- tg δ measurement
- Temperature measurement
- Partial discharge (PD) measurement
- Chemical and physical analysis of insulating fluid in termination
- X-ray of accessories
- Inspection of the cable system
- Inspection of termination for ferrule retraction
- Sheath Voltage limiter test
- Bonding System test

TABLE 6.1 - DIAGNOSTIC INDICATORS FOR LOW PRESSURE FLUID FILLED CABLES

	Tool	Description of method	Events/cause detected	Comments	On-line/Off-line
1)	Cable route inspection (for third party activities)	Visual inspection of the cable route to observe any third party activities near the cable route	Prevention of damage by third party	Well established	On-line
2)	Indication of falling oil pressure	Continuous measurement of oil pressure and/or low pressure alarms	Damaged metal sheath leakage from termination	Well established	On-line
3)	Serving Test	Measurement of the oversheath insulation resistance by HV testing. Location of any defects and repair	Damaged outer sheath	Well established	Off-line
4)	Temperature measurement	Measurement of temperature along the route by optical fibre (DTS)	Increased temperature causing thermal ageing Failure of cooling system	Well established technique, but requires fibre to be installed on the system	On-Line
5)	Partial Discharge measurement	Measurement of discharges within the cable system	Defects and degradation of insulation	Under development. Effectiveness dependant upon system design	On –Line/Off-line
6)	Chemical and physical analysis of insulating oil	Fluid samples taken from the cable system and tested for: - DGA - Tan delta - Water content - Particles - etc	Thermal ageing of insulation (caused by different events)	Well established technique, relies on regular testing regime since interpretation of individual DGA results not clearly understood	Off-Line
7)	X-ray of accessories	Use of X-ray on accessories	Movement of cable causing ferrule unplugging. Incorrect assembly of joint connector	Well established but significant Health & Safety issues and practical application limitations	Off-line
8)	Inspection of cable system	Visual inspection of all components of the cable system for damage, leaks, corrosion etc.	Visual damage, leaks, corrosion etc.	Well established	On-line
9)	Inspection of termination for ferrule retraction	Internal inspection and measurement of ferrule movement	Movement of cable causing ferrule unplugging	Well established	Off-line
10)	Regular gauge maintenance and calibration. Regular testing of gauge/transducer alarm functionality	Hydraulically initiate the gauge/sensor alarm contacts Pressure alarm tests from device to control room	Prevention of failure in alarm system Prevention of false alarm	Well established	Off-line
11)	Sheath voltage limiter test	Measurement of increased sheath standing voltage	Failure of SVL	Basic test on integrity only	Off-Line
12)	Bonding systems test	Checking the integrity of specially bonded systems by measurement of insulation resistance and/or circulating current in the screen	Loss of cross-bonding function	Well established	Off-line

TABLE 6.2 - DIAGNOSTIC INDICATORS FOR HIGH PRESSURE FLUID FILLED CABLES

	Tool	Description of method	Events/cause detected	Comments	On-line/Off-line
1)	Cable route inspection (for third party activities)	Visual inspection of the cable route to observe any third party activities near the cable route	Prevention of damage by third party	Well established	On-line
2)	Indication of falling fluid pressure	Continuous measurement of fluid pressure and/or low pressure alarms	Damaged steel pipe leakage from termination	Well established	On-line
3)	Electrical test on pipe coatings	Insulation resistance of jacket	Damaged steel pipe	Under development	Off-line
4)	Inspection of cathodic protection system	Measurement of pipe to soil potential	Damaged steel pipe	Requires cathodic protection to be installed and operating properly. More effective when trends are analysed	On-line
5)	Temperature measurement	Measurement of temperature along the route by optical fibre (DTS)	Increased temperature causing thermal ageing Failure of cooling system	Well established technique, but requires fibre to be installed on the system	On-Line
6)	Thermal backfill survey	Measure thermal resistivity of backfill in vicinity of cable	Thermal ageing of insulation caused by overload, short-circuit, hot spots	Effective where a problem is suspected	On-line
7)	Chemical and physical analysis of papers and impregnant	Measure the following: - folding strength - tear strength - burst strength - degree of polymerisation - extension to break - tensile strength	degradation of insulation (caused by different events)	Well established, but the interpretation of the results of these tests is not yet clearly understood in terms of deciding the end of life of the cable	Off-Line
8)	X-ray of accessories	Use of X-ray on accessories	Movement of cable causing ferrule unplugging. Incorrect assembly of joint connector	Well established but significant H&S issues and practical application limitations	Off-line
9)	Inspection of cable system	Visual inspection of all components of the cable system for damage, leaks, corrosion etc.	Visual damage, leaks, corrosion etc.	Well established	On-line
10)	Inspection of termination for ferrule retraction	Internal inspection and measurement of ferrule movement	Movement of cable causing ferrule unplugging	Well established	Off-line
11)	Inspection of pumping system	Visual and mechanical check of pump, pipework, etc. when oil pressure alarm is activated	Oil pump system failure	Very effective	Off-line
12)	Regular gauge maintenance and calibration Regular testing of gauge/transducer alarm functionality	Hydraulically initiate the gauge/sensor alarm contacts Pressure alarm tests from device to control room	Prevention of failure in alarm system. Prevention of false alarm	Well established	Off-line

TABLE 6.3 - DIAGNOSTIC INDICATORS FOR GAS PRESSURE CABLES

	Tool	Description of method	Events/cause detected	Comments	On-line/Off-line
1)	Cable route inspection (for third party activities)	Visual inspection of the cable route to observe any third party activities near the cable route	Prevention of damage by third party	Well established	On-line
2)	Indication of falling gas pressure	Continuous measurement of gas pressure and/or low pressure alarms	Damaged steel pipe leakage from termination	Well established	On-line
3)	Electrical test on pipe coatings	Insulation resistance of jacket	Damaged steel pipe	Under development	Off-line
4)	Inspection of cathodic protection system	Measurement of pipe to soil potential	Damaged steel pipe	Requires cathodic protection to be installed and operating properly. More effective when trends are analysed	On-line
5)	Temperature measurement	Measurement of temperature along the route by optical fibre (DTS)	Increased temperature causing thermal ageing Failure of cooling system	Well established technique, but requires fibre to be installed on the system	On-Line
6)	Thermal backfill survey	Measure thermal resisitivity of backfill in vicinity of cable	Thermal ageing of insulation caused by overload, short-circuit, hot spots	Effective where a problem is suspected	On-line
7)	Chemical and physical analysis of papers and impregnant	Measure the following: - folding strength - tear strength - burst strength - degree of polymerisation - extension to break - tensile strength	Insulation (caused by different events)	Well established, but the interpretation of the results of these tests is not yet clearly understood in terms of deciding the end of life of the cable	Off-Line
8)	X-ray of accessories	Use of X-ray on accessories	Movement of cable causing ferrule unplugging Incorrect assembly of joint connector	Well established but significant H&S issues and practical application limitations	Off-line
9)	Inspection of cable system	Visual inspection of all components of the cable system for damage, leaks, corrosion etc.	Visual damage, leaks, corrosion etc.	Well established	On-line
10)	Inspection of termination for ferrule retraction	Internal inspection and measurement of ferrule movement	Movement of cable causing ferrule unplugging	Well established	Off-line
11)	Regular gauge maintenance and calibration Regular testing of gauge/transducer alarm functionality	Hydraulically initiate the gauge/sensor alarm contacts Pressure alarm tests from device to control room	Prevention of failure in alarm system. Prevention of false alarm	Well established	Off-line

TABLE 6.4 - DIAGNOSTIC INDICATORS FOR EXTRUDED CABLES

	Tool	Description of method	Events/cause detected	Comments	On-line/Off-line
1)	Cable route inspection (for third party activities)	Visual inspection of the cable route to observe any third party activities near the cable route	Prevention of damage by third party	Well established	On-line
2)	Serving Test	Measurement of the oversheath insulation resistance by HV testing. Location of any defects and repair	Damaged outer sheath	Well established	Off-line
3)	Tan δ measurement	Measurements of increased power factor	Ingress of water in insulation area	Under development. The methods have only been developed for medium voltage cables, and are at the moment not possible to use on HV cables	Off-line
4)	Temperature measurement	Measurement of temperature along the route by optical fibre (DTS)	Increased temperature causing thermal ageing Failure of cooling system	Well established technique, but requires fibre to be installed on the system	On-Line
5)	Partial discharge measurement	Measurement of discharges within the cable system	Defects and degradation of insulation. Assembly errors in accessories	Well established for accessories. Increased partial discharges are only detectable in cables during a short time before failure	On –Line/Off-line
6)	Chemical and physical analysis of insulating fluid of terminations	Fluid samples taken from the cable system and tested for:- - DGA - Tan delta - Water content - Particles - etc	Thermal ageing of insulation (caused by different events)	Well established technique, relies on regular testing regime since interpretation of individual DGA results not clearly understood	Off-Line
7)	X-ray of accessories	Use of X-ray on accessories	Movement of cable causing ferrule unplugging. Incorrect assembly of joint connector	Well established but significant H&S issues and practical application limitations	Off-line
8)	Inspection of cable system	Visual inspection of all components of the cable system for damage, leaks, corrosion etc.	Visual damage, leaks, corrosion etc.	Well established	On-line
9)	Inspection of termination for ferrule retraction	Internal inspection and measurement of ferrule movement	Movement of cable causing ferrule unplugging	Well established	Off-line
10)	Sheath voltage limiter test	Measurement of increased sheath standing voltage	Failure of SVL	Basic test on integrity only	Off-Line
11)	Bonding systems test	Checking the integrity of specially bonded systems by measurement of insulation resistance and/or circulating current in the screen	Loss of cross-bonding function	Well established	Off-line

7. MAINTENANCE CASE STUDIES

7.1 Introduction

In this section, maintenance case studies from different countries are presented. These studies are practical examples presented by various companies on some of the preventive actions discussed in this report. They are reproduced as submitted to the working group. These studies show the benefits that preventive maintenance can bring as part of an overall maintenance strategy. Two of the cases are on MV systems. However, it is considered that such actions will be of interest also for HV systems in time.

The following case studies are presented:

- An administrative method to avoid 3rd party damage in the Netherlands
- The serving test performed in the Netherlands on 150 kV cables
- Using a probabilistic model to optimise different maintenance methods for one failure mode (to avoid faults due to external damage to the cable) in France
- Oil pressure monitoring in Belgium
- Early Leak Detection (ELD) in High Pressure Cable Systems in Canada , using Artificial Neural Networks
- Locating Leaks In Self-Contained Fluid filled Cables in Canada, using Atmospheric Tracer Technology
- Experiences with Condition Based Maintenance on MV power cable systems using PD diagnostics for REMU, Netherlands
- Condition assessment with PD measurements on MV cable circuits in Italy

7.2 An administrative method to avoid 3rd party damage in the Netherlands

One of the main causes of damage to underground cable systems is 3rd party damage. In the Netherlands a national organisation, KLIC (Kabels en Leidingen Informatie Centrum), tries to prevent this form of damage to buried underground services.

KLIC facilitates the flow of information between all interested parties, i.e. those with buried underground services and those who wish to dig near those services. When digging or drilling activities are planned the following administrative procedure has to be followed:

- The planned work has to be reported to KLIC between 3 and 20 days in advance of the planned activities. Requests can be made by telephone, fax, E-mail or via the internet. KLIC registers all such requests. KLIC also sends the proposed work location back to the requestor for confirmation.
- The request is sent to all underground service owners (electricity, gas, water, sewage and telecoms) who possess systems in the area surrounding the proposed activity site. KLIC makes available all the names and addresses of relevant parties (local owners of infrastructure buried in the ground).
- The service owners are asked to provide detailed maps of the relevant area and to give permission for digging or drilling activities to take place.

- The service owner makes a staff member available to attend and to guide the digging or drilling activity.
- For each particular digging or drilling activity specific instructions are given to the contractor.

Liaison meetings are held on a regular basis between the service owners of the different infrastructure companies (electricity, gas, water) to exchange experience and to further improve procedures. There are about 1000 companies that participate to make KLIC work and together they cover the costs of the organisation. KLIC handles around 130,000 questions per annum and sends about 1,000,000 messages to participating companies.

7.3 The serving test performed in the Netherlands on 150 kV cables

The outer protection of a cable nowadays generally consists of a plastic sheath. The main functions of the sheath are:

- To protect the cable against mechanical forces during and after installation
- To protect the metallic sheath against corrosion
- To isolate the metallic sheath from earth for special bonding
- To protect the primary insulation against water ingress

Furthermore, it allows additional functions as:

- To allow checking for mechanical damage.
- To mark the identification of the cable.
- To identify the buried service as an electrical cable.

After installation of a new cable circuit, the integrity of the outer sheath may be checked. The after-laying test on the outer sheath is a DC test of 4kV/mm of sheath diameter with a maximum of 10kV for 5 minutes. The voltage is applied between the metal sheath and earth. If there is a defect, the sheath will not support the test voltage and a high DC leakage current (>10mA) will flow. The fault is pinpointed using fault localisation techniques and a repair is carried out. This procedure is repeated until all faults are cleared. After commissioning of the new circuit, a maintenance test 5 kV DC for 1 minute is done periodically.

The fault location procedure uses a bridge measurement for the approximate positioning, followed by pinpointing with a voltage measuring system in the field with metal electrodes put in the ground. Depending on the length of the circuit and the difficulty of pin pointing, the fault location procedure can take several days.

Besides after installation, many utilities also perform the serving test periodically. The test interval depends on the situation of the surrounding and on the importance of the circuit. For example, important circuits and circuits in cities are tested every year. Circuits with cross-bonding are tested every 2 years, and other circuits are tested every 3 years.

7.4 A case study of probabilistic maintenance optimisation for external cable damage in France (see also Appendix B)

This case study relates to HV extruded cable systems owned by RTE in France. One failure event/cause is analysed in this study - external damage caused by third parties, and two preventive methods; inspection by car along the cable route, and serving tests.

This study uses an original quantitative probabilistic model to optimize economically an example of a typical maintenance policy, in this case, the use of serving tests and cable route inspection to detect external damage to the cable. In particular, this model makes it possible to quantify the interaction and effectiveness of two maintenance tasks which both act to prevent the same mode of failure. The originality of this method lies in the combination of deterministic analysis (where possible) with macroscopic analysis. This model objectively structures the knowledge held within a company for such complex systems, in contrast to keeping only a partial or subjective analysis (e.g. only retaining the failure rates) for determining the frequency of particular maintenance activities.

Definition of detectability period

The detectability period is defined as the duration between the beginning of a failure mode (e.g. leakage of oil from a termination) and the fault. Often this parameter does not have a single value but lies within a range determined by the experience of the utility and/or experts. The detectability period is an essential input parameter to determine the frequencies of the maintenance tasks.

Effectiveness of a maintenance task

The effectiveness of a maintenance task in detecting a particular mode of failure can be expressed as a probability as follows:

$Eff = E_{tech} \times E_o$.

Eff:	the effectiveness of the maintenance task
E_{tech}:	the probability of the maintenance task detecting the failure mode
E_o:	the probability of the maintenance task being carried out during this detectability period

This, of course, assumes that the probabilities E_{tech} and E_o are independent.

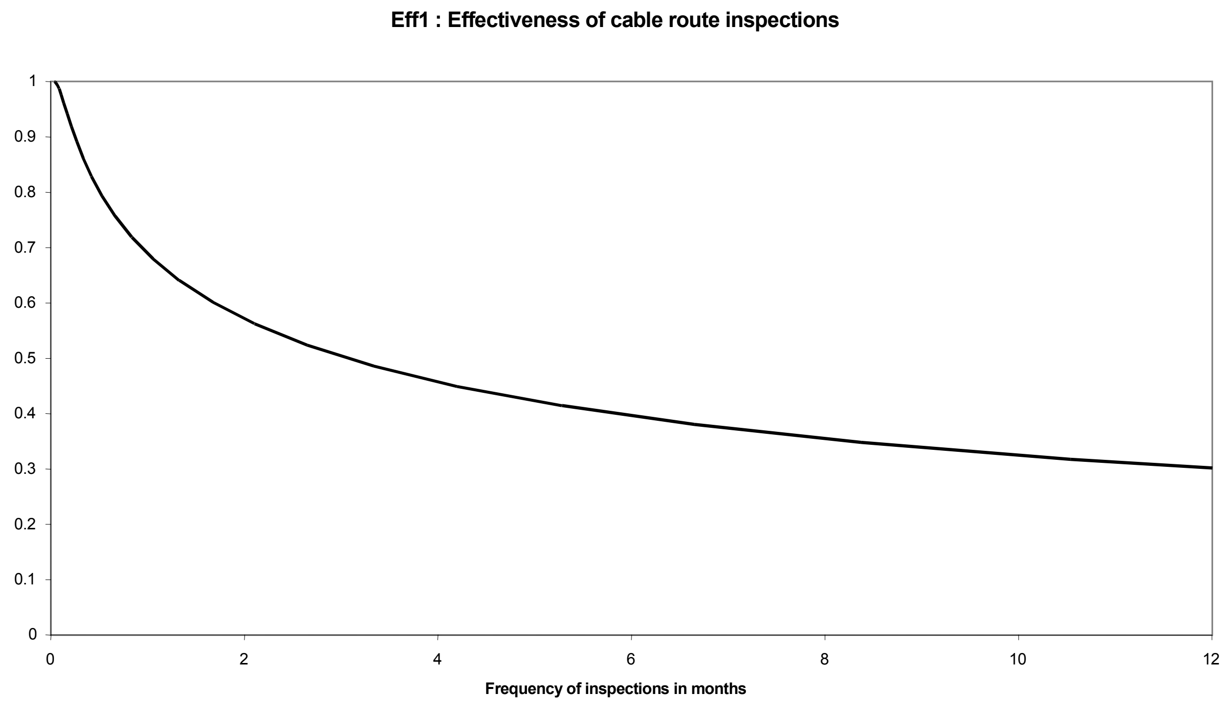
After calculating the effectiveness of the different maintenance tasks and the failure modes, a calculation of the total effectiveness compared to the failure modes will be carried out and will cumulate these two maintenance tasks.

The computation results relating to the effectiveness of the maintenance tasks are as follows:

		Maintenance tasks ↓		
		A1: Cable route inspection	A2: Serving tests	TOTAL Effectiveness
	Frequency→	T1	T2	
Failure modes →	C1 Detection of works before the third-party damage	Eff1	0	Eff1
	C2: detection of a damaged sheath, due to a third-party works	Eff2	Eff3	Effg

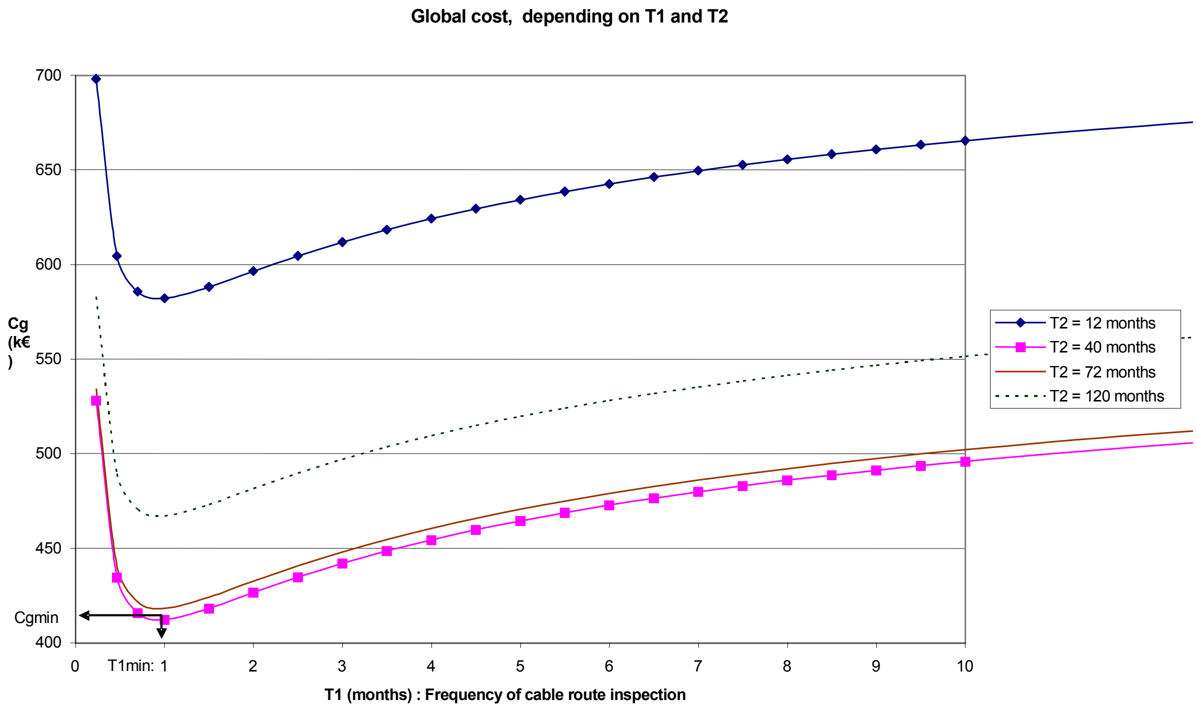
Eff1 represents the effectiveness of detecting the presence of a third-party before any damage has taken place, by a cable route inspection.
Eff2 represents the effectiveness of detecting damage to the sheath, by a cable route inspection (caused previously by a third-party).
Eff3 represents the effectiveness of detecting damage to the sheath, with a serving test.
Effg represents the total effectiveness (for C2) of detecting sheath damage through the combination of the maintenance tasks A1 and A2.

In France, a sample study was carried out in an area of Paris over 5 years. A distribution function has subsequently been deduced. Thus knowing f(D), E_{o1} was calculated according to T1, the frequency of cable route inspections. The curve below represents the effectiveness Eff1.



Eff2, Eff3, and Effg have been calculated (see Appendix B).

For different serving test frequencies, the total effectiveness Eff was calculated in regard to T1 and T2 on a 225 kVnetwork of 1000km.



The following conclusion can be drawn from the results:

- The economically optimal frequency for cable route inspections is 1 month, i.e. T1 = 1 month.
- The optimum frequency for serving test is between 3 and 6 years.
- For this network, the global maintenance cost is between €400,000 and €900,000 per annum.
- The optimal global maintenance cost C_g corresponds to the following proportions:
    - 32 % preventive maintenance cost, cable route inspection and serving tests
    - 68% corrective maintenance cost

<u>Summary</u>

This case study shows the application of economic modeling to a maintenance policy concerning HV cable networks. The method expresses the links between the failure modes and the maintenance tasks. These expressions are represented in the form of a matrix, which allows the calculation of the total maintenance cost (corrective and preventive). This method makes it possible to estimate, by the means of the model, the relevance of a new task in an existing maintenance program, or the relevance of a new maintenance policy.

This study shows that it is possible to combine the knowledge of experts with historic statistical data relating to faults and estimates of other parameters, to determine the optimal maintenance solution.

This study could be further expanded to include a thorough sensitivity analysis of the results, thereby ensuring that a robust economical solution is found. Furthermore, the option of continuous monitoring could be studied in the same way.

7.5 Oil pressure monitoring in Belgium

The pressure in a Self Contained Fluid filled (SCFF) cable must be continuously monitored (with gauge or other system). The paper insulation of this cable type is fully impregnated at all times by a low viscosity hydrocarbon fluid under pressure. The pressurisation is achieved by means of oil tanks connected to the cable termination or stop joint.

It is very important to continuously monitor the oil pressure for the following reasons:

- The pressure in the cable system must be maintained between maximum and minimum values under any operating conditions. The maximum value is generally 5.25 bar for sustained pressures and 8 bar for transient pressure. The minimum pressure is generally 0.2 bar. This pressure ensures full impregnation of the insulation and avoids vacuum formation.
- Pressure loss can indicate a crack or fracture of the metallic sheath and the anticorrosion protection and possible moisture ingress into the cable insulation, which must be avoided. Water ingress in the cable insulation will lead to degradation of the insulation and oil.
- Oil loss from cables due to leaks can have a negative environmental impact. Loss of pressure in the cable system can indicate the presence of an oil leak.

It is desirable to detect a loss of oil pressure prior to alarm activation indicating that the oil pressure in the cable system is outside safe limits.

Such pressure monitoring is in Belgium carried out as follows:

- A periodical visual inspection is carried out on cable terminations and tank installations. If an oil leakage is detected in this inspection, corrective maintenance is scheduled.
- Pressure gauge readings are taken at each injection point and they are compared with previous measurements. The comparison can indicate oil leakage in the cable or joints. To explain this point we use the two following examples:

  Example 1

Date	Load [A]	Pressure (Joint 1) [bar]	Pressure (Joint 2) [bar]
01/01/1999	260	0.66	0.76
01/02/1999	300	0.75	0.85
01/03/1999	280	0.69	0.80

Example 2

Date	Load [A]	Pressure (Joint 1) [bar]	Pressure (Joint 2) [bar]
01/01/1999	260	0.66	0.76
01/02/1999	260	0.64	0.74
01/03/1999	270	0.64	0.70

In example 1, the pressure varies with the current in a normal manner – when the current increases, the pressure increases.
In example 2, there is an oil leak in the cable – in this case the pressure decreases when the current increases.

Observation: the urgency with which the oil leak location is carried out can be influenced by several factors not all of which are technical. Such factors include circuit criticality, leakage rate, proximity to water, environmental legislation, and public perception.

A cost comparison between preventive maintenance and corrective maintenance depends on several factors, which varies for different networks/companies. However the following factors should be considered:

- For preventive maintenance with no oil loss, the cost includes
  - hours of the operator for the control.

- For corrective maintenance with loss of oil, the cost includes
  - hours of the operator for the control.
  - localisation (material, operators, …).
  - repair (joints, cable, excavation, …).
  - decontamination of the ground.

- For corrective maintenance with electrical damage, the cost includes
  - localisation (material, operators, …).
  - greater replacement of cable joined at the breakdown, greater water ingress, greater excavation, …
  - a bigger decontamination attributed to greater oil loss in the ground.
  - other damages on the other installations.
  - power interruption costs (claims and compensations for customers).

7.6 Early leak detection (ELD) in high pressure cable systems in Canada, using artificial neural networks

Two North American utilities are implementing a methodology based on the application of artificial neural networks to monitor the status of high pressure fluid filled cable systems (HPFF) and detect leaks as small as 5 litres per hour. HPFF cables are held in a steel pipe and maintained under a pressure of about 250 psi (17 bar); one or several large tanks are connected to the cable pipe, via pumps and relief valves, to maintain pressure and allow for oil movement between tanks and cable pipe as a result of electrical load fluctuations (i.e., oil expansion and contraction resulting from oil temperature fluctuations). Total oil volume can be upwards of 1,000,000 l depending on cable design and length. For such systems, monitoring of the oil level in the tank is of limited value to indicate the presence of leaks because of the large daily (load changes) and seasonal (ground temperature changes) oil movements. Large leaks can be detected by alarming on “excessive” pump operations but small leaks can go undetected for months with cumulative oil losses of several thousand litres.

Artificial neural networks (ANN) are systems constructed to make use of some of the organisational principles felt to be used by the human brain. An ANN has three main components: the neurons, the network topology and the learning algorithm. The neuron is the basic processor in neural networks. Each neuron has one output, which is generally related to the state of the neuron -- its activation -- and which may fan out to several other neurons. Each neuron receives several inputs over these connections, called synapses. The inputs are the activations of the incoming neurons multiplied by the weights of the synapses. The activation of the neuron is computed by applying a transfer function in this product. All the knowledge represented by the neural network is stored in the synapses, the weights of the connections between neurons. Before training begins, these interconnection weights are assigned random values. During the training process, these weights are modified in a manner that causes the desired input/output relationships to be learned. In the process of learning, the influence of certain interconnections is strengthened. The training process involves six steps: (1) gathering of training data, (2) normalisation of data, (3) selection of ANN's architecture, (4) training of the network, (5) testing of the network, and (6) selection of an alternative network architecture and additional training. Because of their highly parallel nature, ANNs are very fault-tolerant, and can learn to ignore noise with little impact on the network output. Once the data are gathered, the next step in training is to normalise all the data so that each value falls within the range of -1 to +1. This is done to prevent the simulated neurons from being driven too far into saturation. Once the saturation is reached, changes in the input value result in little or no change in the output.

The typical input parameters for an early leak detection system (ELD) such as described here include circuit load current, cable oil pressure, cable oil temperature (or jacket temperature as a proxy for oil temperature) and soil ambient temperature (at a similar depth to the cable). Additionally a maintenance interface is required to alert the ELD system to changes in operating conditions, particularly in the pumping plant (maintenance of the relief valve, etc.), to avoid unnecessary false alarms.

Output from the ELD system include the instantaneous leak rate (in l/h, this being normally zero in the absence of a leak), cumulative oil loss and start time and end time of the leak.

In practice, the neural network system is initially allowed to train itself for a period of about one month to experience the normal swings in temperature and pressure resulting from the applied load current and ambient conditions. At the conclusion of the training period, the system is validated by performing a controlled leak which also serves to calibrate the neural network (l/h). Following successful completion of the calibration leak, the system is declared in service. The neural network approach for leak detection is particularly attractive in instances where full thermal and hydraulic modelling of a system is impractical and/or too costly.

The ELD system can be implemented in two basic configurations, networked with a User's own data acquisition systems or as a stand-alone system performing both on-line data acquisition and leak detection.

7.7 Locating leaks in self-contained fluid filled cables in Canada, using atmospheric tracer technology

Many high-voltage transmission cables experience leaks of insulating oil. Atmospheric tracers, added to the cable oil, have been used with success to locate leaks in high pressure fluid filled cables.

The tracer-based method for locating leaks involves the injection of a unique, harmless tracer chemical into the cable oil. When a leak occurs in the cable, some of the tracer leaks out along with the oil. The leaked tracer evaporates from the oil, moves up through the backfill and can be detected in the air above the cable route. The peak of the profile of the tracer concentration along the route is considered to be the location of the leak. The tracer employed in this application is one of a family of inert perfluorinated chemicals which are essentially not present in normal background air but which can be detected in infinitesimal quantity by advanced equipment. Although proven for high pressure cables, the atmospheric tracer technology has seen little use for low pressure cables.

Self-contained fluid filled (SCFF) cables, which typically exhibit much lower leakage rates, present additional challenges for tracer-based leak location techniques.

Dissolved gases must be excluded more stringently from SCFF compared to high pressure cables to prevent the formation of bubbles, which can lead to ionisation and ultimately failure of the cable. The tracer chemicals must be compatible with the oil and other materials in low pressure cables, both chemically and electrically. Nonetheless, the atmospheric tracer method offers the prospect of locating leaks in these cables without the inconveniences associated with the conventional approach and without removing the cables from service.

There are three major steps to apply tracer technology in self-contained fluid filled cables: (1) to mix the tracer in cable oil, (2) to inject the tracer into a cable reservoir, and (3) to measure the concentration of the tracer in the air.

An example of a recent successful use of tracer technology comes from Canada. Three self-contained fluid filled cables, each about 3 km long, were leaking recently. Two of the cables had been leaking for some time; the third cable had been leaking for a shorter period, coincidentally along the same route as one of the other cables. The cables were treated with different tracers and tracer concentrations measured after a suitable waiting period. An initial coarse search procedure provided peak tracer location for each cable with a 100m resolution. A second, fine search pinpointed the peak tracer location. The identified peak tracer location was found to be within about 3 m of the actual leak location for each cable (as found during excavation and repair).

7.8 Experiences with condition based maintenance on MV power cable systems using PD diagnostics for REMU, Netherlands

REMU is the former utility of the province of Utrecht, with a MV network consisting of about 5,000km of cable and about 28,000 joints. REMU covers an area of approximately 1,400km². The effectiveness of condition based maintenance [9] involving diagnostic measurements must be weighed against the effectiveness of time-based and corrective maintenance. Analysis of the faults on the REMU MV network shows that 59% of all faults relate to cable circuits, 17% relate to third party damage on cable circuits, other components 10% and other reasons and unknown 14%.

In order to review the maintenance strategy, a case study including cost analysis and practical CBM on selected cable circuits has been performed.
Cost analysis involves hard costs of diagnostics, personnel, early replacement and engineering. The 'hard' benefit is a reduction of outage costs for repair, fewer follow-up failures (a breakdown often causes subsequent failures), loss of income due to loss of non-supplied energy, and fewer claims and penalties. Furthermore, 'soft' benefits are recognised as failures that jeopardise the goodwill of customers and cause serious disruption and inconvenience. Though called 'soft' benefits, they still represent real money - they may mean loss of clients (thus income) and possible claims and penalties.

<u>Selection of cable circuits:</u>
The selection criteria for cable circuits to be diagnosed are based on the consequences of a breakdown of power supply and for the related costs for the utility. The selection criteria are:

- Expected outage time (number of switching operations required to restore power)
- Type of region (customer) for delivery
- Current loading
- Load pattern (dynamic or constant in combination with high or low current loading)
- Number of joints
- Type of soil (thermal aspects)
- Total number of failures in the area.

A circuit with many joints is more vulnerable to failure than one with no joints, as joints in general are less reliable than cable. Dynamic loading ages paper cables more than constant loading. The outage duration in a region supplied by a single circuit will be much longer than for a region supplied by a meshed network. The type and size of customer affected can determine the size of claims. In addition, the Regulator specifies a maximum allowable outage time before penalties will apply. Each selection criterion is given a value between 1 and 4 (4 is the most important). Each selection criterion has its own factor determining the weight (ranking) in comparison with the other criteria. Circuits will be excluded from diagnostic measurements if there are no joints and/or if they meet the (n-1) redundancy criterion.

Total selection: Each cable circuit in the network is analysed, resulting in a total selection value per circuit. The circuits with a total value of 26 and higher are at first selected for diagnosis (red alert). The circuits with a total value between 23 and 26 deliver the second choice (orange alert). Circuits with a total value below 21 are not selected (green alert).

Results for REMU: At the moment the hard benefits are in balance with the hard costs of CBM at REMU (and generally in the Netherlands). Taking the reduction of soft benefits into account, CBM becomes economically advantageous. Timely replacement of critical circuits increases the reliability of the system.

7.9 Condition assessment with PD measurements on MV cable circuits in Italy

Objective
To improve the quality of the electrical supply to customers and to comply with the increasing severity of the regulations imposed by National Authorities. There are stringent requirements regarding the number and duration of supply interruptions.

Background
Failures in MV cable circuits (representing over 34% of the total MV network) are responsible for a large proportion of the total number of voltage interruptions - second only to lightning induced overvoltages.

Approach
Perform a condition assessment of the cable circuits characterised by:
- a high failure rate (mainly located in southern Italy)
- important circuits supplying a large number of customers

Condition Assessment Method
The condition assessment method [10] comprised an off-line voltage test with measurement of partial discharge, location of the source of the discharge, and power loss factor evaluation.
Depending on the diagnostic parameters obtained, an indication is given of the maintenance action to be undertaken at the place of the discharges identified such as:
- immediate fixing of the defect (within days or a few months) with its location along the cable and precise indication of the place where to dig
- repetition of the check within 1 to 5 years depending on the criticality of the results

A secondary result of the checks is the mapping of the joint positions that are not always reported on the route record maps of the utility.

Results
The best way to assess the results of the effectiveness of the diagnostic campaign would be to compare the performances (in terms of failure numbers) of tested and non-tested cable circuits over many years after the measurements. However, this evaluation would require too much time. The accuracy of the diagnostic indication is verified through a systematic analysis of the components considered critical and that, as a consequence, were removed from service.

In order to deal with the very large number of tests (covering about 20,000km of underground cables), the management of the data was performed using a specifically developed database.

Statistical data on critical defects distribution is now available to enable the interpretation of such data by comparison with actual fault rates. Evaluation of the efficiency of the companies involved in the program in terms of number of tested sections per day and cost per section tested was also undertaken.

More information regarding the maintenance action above described can be found in [11] and [12].

8. REMAINING LIFE ESTIMATION

8.1 Introduction

Maintenance is performed for many purposes including improving reliability and remaining asset life. Nevertheless maintenance would probably not be performed on a component for which the remaining life was expected to be relatively short. Since remaining life is important within the context of any utility maintenance strategy it is discussed briefly in this report. Due to the size and complexity of this subject, a small task force within WG B1-04 has recommended that this topic be considered more comprehensively by a separate future WG.

8.2 Background

Remaining life estimation (RLE) is clearly a very important issue for network owners, because it is often the key information needed to execute an efficient replacement strategy. The challenge is translating diagnostic tests, which indicate the presence of an ageing/degradation mechanism into meaningful information, namely, how severe is the problem and what is the remaining life if no intervention is taken.

In general condition based maintenance is performed to extend a components remaining life. Nevertheless, maintenance may not be performed if the remaining life of the component is considered not extended significantly by the maintenance, i.e. the component is close to or already at the end of its life. However at present, a condition assessment only usually results in a “risk of failure” and not a time to failure. The accuracy of the determined risk is related to the following:

1. Reliable knowledge of the history of the given system (operation, failure statistics, changes in the environment, etc).
2. Knowledge of ageing of similar components under similar operation conditions. This knowledge could, for example, be gained from cable system components being investigated in the laboratory after being removed from service.
3. The accuracy of the diagnostic measuring technique.
4. The interpretation of the measured data.

Of these factors, the accuracy of the measuring technique is usually not the most significant factor. The limiting factor is most likely to be the interpretation of the measured data because there is no objective method of verification. The interpretation is often based on field experience (knowledge rules), i.e., relating known failures/past problems for a specific cable or accessory type to measured historic data and the severity of defect. Consequently, without this information linking past experience and measurements, any estimation of remaining life is subject to considerable uncertainty.

8.3 Criteria for end of life

The subject of remaining life is closely related to the question of what determines the end of life of a component of a cable system. The end of life for a particular component may be reached for numerous reasons, examples include:

- High risk of failure
- High cost of operation

- High cost of maintenance

Which of these applies in any particular situation will depend on a case by case basis, since numerous factors must be considered, e.g. circuit criticality, environmental impact, outage costs, repair versus replacement costs etc. A further consideration is the percentage of the cable system, which is deemed to have reached its end of life and whether the whole cable system or individual parts need to be replaced or maintained to extend the asset life.

8.4 Remaining Life Strategy

One approach to estimating remaining life is to separate the different concurrent ageing mechanisms and extrapolate appropriately the dominant ageing process (i.e. the ageing process that will first result in a failure) based on the condition assessment performed. This projection should be conducted in such a manner as not to over-estimate the remaining life.

The following steps can be envisaged to develop a feasible RLE process:

- To define properly the end of life
- To collect data from the designers and operators of the cable system
- To collect data concerning the ageing mechanisms of the related components (natural ageing, ageing due to improper installations, etc) and to select relevant ageing mechanisms
- To select appropriate diagnostic methods
- To improve condition assessment by preparing improved knowledge rules thereby aiding the interpretation of the measured diagnostic data
- To perform condition assessment on a cable system using appropriate diagnostic tools and to determine the different ageing processes and related ageing levels
- To establish the risk of failure of the different components due to the corresponding ageing mechanisms
- To propose corrective actions
- To convert failure risk into a remaining life estimation by extrapolating condition (at first linearly) based on the dominating ageing process from the moment of condition assessment till the end of life, and delivering the required RLE.
- To consider the effectiveness and efficiency of applied diagnostic techniques and methodology
- To continuously improve the RLE process by using feedback from practical experience (results of dissections, failure risk data, time to failure data)

9. RECOMMENDATIONS

The following section summarises the key finding of the report, in order to give guidance to cable owners regarding possible benefits of preventive maintenance. Section 9.1 gives general recommendations and 9.2 gives basic programmes to be considered for each type of cable.

9.1 General recommendations

Carry out cable maintenance with a clear strategy

Maintenance of cable systems should be carried out in accordance with a clear strategy. Maintenance strategies are needed to optimise the performance of the system. Poor system performance has a direct negative effect on customers as unscheduled power interruptions, poor quality of supply and associated additional customer costs are no longer tolerated. With more stringent requirements being imposed by regulators and higher customer expectations, the standard of system performance affects the overall business performance of the utility. Therefore, the asset management and maintenance policies chosen are very important.

Asset management should therefore start with an overall strategy, out of which a strategic plan of action follows. Effective maintenance must be the result of a strategic plan developed around the overall business requirements and the maintenance carried out should contribute to the overall business performance targets.

A statistical approach should be used in formulating maintenance policy

An effective method for developing a plan of action is to use a statistical approach that considers all failure modes and their respective occurrence. A statistical approach allows the economic value of different maintenance approaches to be estimated. However, the low probability of faults in general and the limited experience with some failure modes can mean that there is limited availability of statistics concerning failure modes. Furthermore, there is a great diversity in cable designs, accessories and installations covering several decades of technological development. Therefore, the statistical approach needs to take such uncertainties into account.

When planning strategic maintenance actions, it is recommended to identify which failure modes are the most common and have the most serious consequences (e.g. safety, loss of reputation, financial penalties etc). For each of these, the costs and benefits of using available diagnostic tools or other possible preventive actions should be considered. Benefits should include both direct (corrective maintenance) and indirect costs of faults (outage costs, loss of goodwill etc). When new technologies are evaluated and introduced, pilot projects to involve utilities actively in the application are recommended.

Keep maintenance strategy under review

The maintenance strategy and action plan should be kept under review taking into account new information gathered. Maintenance methods can also be developed and made more efficient. Although most failure modes of cable systems are well known, recent technology developments have resulted in an increase of preventive and condition-based maintenance activities despite the on-going trend towards "maintenance free" components. New and enhanced methodologies for diagnostics and interpretation of test results have increased the possibilities to assess the cable condition with a sufficient degree of confidence, although the costs of implementing these new technologies have to be permanently balanced with the costs of outages.

Develop and maintain a database of cable system failures
It is recommended that utilities set up a database to record and analyse the failure modes for the cables on their system. The database would provide a greater working knowledge of the cable system and it would allow failure patterns to be determined. The databases from different utilities could ultimately be shared for the benefit of all users. Such a database requires planning by the utility and it would be necessary to obtain the commitment of all the relevant staff involved (e.g. jointers, cable supervisors, cables engineers etc.) to contribute to the proper recording and documentation of cable faults when they occur. The database should also be maintained through changes in personnel and company re-organisations.

Fully investigate failures when they occur
Analysis of failed components is important in collecting information for a fault database. Failures should be analysed to obtain information that can be used for the improvement of the maintenance plan. Occasionally, opportunities arise to remove and analyse parts of the cable system (e.g. due to cable replacement, diversion or extension). Such opportunities should be used to analyse the condition of the cable or to take these samples for possible further reference for future failure analyses. A procedure on how to analyse the cable system components removed from service and an example of a checklist for the evaluation of materials is given in Appendix C of this report.

Pay particular attention to minimising third party damage
Third party damage of underground cables is a very serious issue for most companies. Although the activities of third parties are outside the direct control of a utility, there are some things that utilities can do to at least reduce the probability of third party damage occurring. Routine inspection of important cable routes is a simple tool that has been used by utilities for many years. Better administrative methods to avoid third party damage are recommended. Such methods require the involvement and co-operation of various parties, such as other utilities (water, gas, telecom etc), municipal authorities and civil works contractors. Careful consideration needs to be given to the implementation of such a system. The development of tools like Geographical Information Systems (GIS) has simplified the sharing of information such as route records between involved parties.

Implement preventive actions appropriate to the cable type
Maintenance recommendations to avoid the most common failure modes for each cable type are given below. These have been compiled with reference to the tables in Section 5 and 6 of this report. These recommendations have been divided into ‘basic maintenance’ and ‘additional recommended maintenance’. Basic maintenance is the minimum maintenance that a cable owner should consider carrying out. Basic maintenance carried out at regular intervals significantly reduces the probability of the most common failure modes occurring. Additional recommended maintenance will further reduce this probability. Many of the recommendations use the term ‘periodic’. It is up to each company to calculate/estimate and decide the periodic intervals appropriate to their own maintenance policy.

9.2 Recommendations for specific cable types

The previous section gave general recommendations for performing cable system maintenance. This section gives specific guidance for the different cable types considered in this report. The recommendations are divided into "basic" and "additional" maintenance. The Working Group recommends that the basic maintenance items listed represent the minimum level of maintenance that cable owners should consider, whereas the additional maintenance items could provide enhanced benefits if used as part of a clear maintenance strategy.

Self Contained Fluid filled Cables (SCFF)

Basic Maintenance

- Ensure that cable route information is available and procedures are in place to exchange information (e.g. cable route records) between utilities and contractors.
- Periodic inspections along the cable route to check for evidence of third party activity.
- Continuous measurement of oil pressure and/or low pressure alarms
- Periodic serving test
- Periodic inspection of outdoor terminations
- Regular gauge maintenance and calibration.
- Regular testing of gauge/ transducer alarm functionality
- Periodic visual inspection of link boxes
- Database including failure events and causes

Additional Recommended Maintenance

- Continuous measurement of gas pressure in terminations and/or low pressure alarms
- Periodic inspection of cooling system (where fitted)

High Pressure Fluid filled Cables (HPFF)

Basic Maintenance

- Ensure that cable route information is available and procedures are in place to exchange information (e.g. cable route records) between utilities and contractors.
- Periodic inspections along the cable route to check for evidence of third party activity.
- Continuous measurement of pipe oil pressure and pressure alarms
- Periodic inspection of outdoor terminations
- Periodic inspection programme covering the entire oil feeding system, associated components and accessories
- Database including failure events and causes

Additional Recommended Maintenance

- Periodic pipe coating survey
- Monitoring of pipe to soil potential (where cathodic protection is fitted)
- Continuous measurement of gas pressure in terminations and/or low pressure alarms.

Gas Pressure Cables

Basic Maintenance

- Ensure that cable route information is available and procedures are in place to exchange information (e.g. cable route records) between utilities and contractors.
- Periodic inspections along the cable route to check for evidence of third party activity.
- Continuous measurement of pipe gas pressure and pressure alarms
- Periodic inspection of outdoor terminations
- Periodic inspection programme covering the entire gas system, associated components and accessories
- Database including failure events and causes

Additional Recommended Maintenance

- Periodic pipe coating survey
- Monitoring of pipe to soil potential (where cathodic protection is fitted)
- Continuous measurement of gas pressure in terminations and/or low pressure alarms.

Extruded Cables

Basic Maintenance

- Ensure that cable route information is available and procedures are in place to exchange information (e.g. cable route records) between utilities and contractors.
- Periodic inspections along the cable route to check for evidence of third party activity.
- Periodic serving test
- Periodic inspection of outdoor terminations
- Periodic visual inspection of link boxes
- Database including failure events and causes

Additional Recommended Maintenance

- Continuous measurement of pressure in terminations (where used) and/or low pressure alarms

- Periodic inspection of cooling system (where fitted)

9.3 Summary

Different approaches to these methods from different companies often depend on different objective aspects. Replacement strategies and financial considerations affect the action plans, as well as network design, geography, geology, fault experience etc. Costs of different maintenance activities can vary in different countries or regions and therefore affect the choice of actions.

10. FUTURE DEVELOPMENTS

10.1 Introduction

The way in which maintenance is performed has seen dramatic changes in recent years, in many cases shifting from traditional time based activities to condition based maintenance with its potential for significant cost savings as previously discussed. The effectiveness of this change is obviously dependent on the ability to determine the condition of the cable system with a sufficient degree of confidence to postpone time based maintenance decisions. The challenges faced by operators in undertaking condition assessment of underground cables are particularly onerous, as most of the equipment is inaccessible. Nonetheless significant progress has been made to date and an emphasis on asset management by an increasing number of utilities will ensure that efforts are devoted to further develop diagnostic tools to support condition based maintenance.

10.2 Improved hardware and software

Increases in computer power have lead to faster more compact field hardware and software that only existed in laboratories a few years ago. These advances are particularly important where the acquisition of large data sets and/or noise cancellation is critical. The on-site measurement of partial discharge activity with enhanced sensitivity is a clear illustration of such progress. Continued progress in computer power will inevitably bring about the introduction of new methodologies for further enhancement of measurement capabilities and interpretation of test results.

New technologies will continue to be developed in the laboratory and gradually applied in the field. Current examples of such developments include low frequency dissipation factor measurements and variants thereof (e.g. dielectric spectroscopy and return voltage measurements) as well as early oil-leak detection technologies and oil-leak location technologies. More developments are still required for these technologies to evolve into mature diagnostic tools.

The progression of a new diagnostic tool from laboratory development to field application is often a dynamic process, as described in the body of the present report. A typical enhancement to an off-line diagnostic tool would be to allow the measurements to be performed on-line, thereby alleviating the need for costly outages and increasing the attractiveness of this method; partial discharge measurements on extruded cables could be such a technology with significant potential as an on-line tool.

10.3 Characterisation of extruded insulation

A notable shortcoming of current condition assessment methods is the determination of the state of thermal ageing in extruded insulation. While laboratory techniques exist which can provide an insight into this ageing, for example the determination of oxygen induction time by differential scanning calorimetry, these techniques are destructive albeit only a few milligrams of materials are required for an analysis.

10.4 Better non-destructive tests

Techniques need to be developed which could be applied in the field as a non-destructive test. Other developments which would be highly desirable include technologies to facilitate the rapid location of cable faults with greater accuracy, applied in conjunction with up to date cable maps, to enable a single excavation to be used to complete the cable repair. Enhancements on the near-universally applied serving test to accommodate cables in ducts would also be welcome by cable operators.

10.5 Linking field tests to laboratory tests

The improvements achieved in performing sensitive measurements in the field in recent years have not always been matched by a corresponding ability to interpret the raw test data. Researchers are, by necessity, limited to the investigations of "aged" samples which do not exhibit the richness of conditions found in real-life cable samples; for instance many investigations have depended on samples which were aged by an accelerated procedure which can obviously depart significantly from real samples. As experience with the diagnostic testing of real-life cables grows, it is likely that so will the ability to link raw test results with true cable condition. Well-established techniques have, generally, been in use for considerable time and good databases are available to perform more reliable condition assessments.

10.6 Summary

Enhancements in diagnostic technologies will, beyond maintenance, provide the asset manager with a more quantitative evaluation for orderly retirement of aged cable assets. As most components of cable systems are eminently repairable, remaining life is determined mostly from a financial perspective, namely the point at which repair and maintenance costs, and possible penalties for unexpected failures, exceeds current cable value. The continuing emphasis on asset management will be instrumental in driving the necessary new developments in cable condition assessment.

11. CONCLUSIONS

In this report, the Working Group has considered the subject of maintenance of HV cables and accessories. Two types of maintenance are addressed:

- Corrective maintenance - to repair a failure
- Predictive maintenance - to avoid a failure

The four cable types specifically considered in this report are:

SCFF		Self Contained Fluid filled
HPFF		High Pressure Fluid filled
GP		Gas Pressure
Extruded Cables:	**XLPE**	Cross-Linked Polyethylene
	EPR	Ethylene Propylene Rubber
	PE	HDPE, LDPE

A previous CIGRE report has shown that on average utilities spend less on predictive maintenance than corrective maintenance for cable systems than other plant types. The reasons for this may be many; nevertheless, this Working Group has examined the opportunities for redressing this imbalance.

A key finding of this Working Group is that cable owners should decide on a clear maintenance strategy, which balances both predictive and corrective maintenance. Because the operating environment for individual utilities varies considerably and is driven by many factors, financial, environmental, political etc, deciding on this balance must be the decision of the cable owner. For predictive maintenance, the investment and operating costs and the savings have to be estimated, whereas for corrective maintenance, only the full costs of the repair (i.e. materials, labour, lost income, financial penalties, loss of reputation etc.) have to be considered. Since these costs vary enormously between utilities, due to their different operating environments, this Working Group has decided not to consider this issue, as it is too difficult to estimate these costs in a general and objective way. Nevertheless, this report should allow utilities to consider the benefits offered by including predictive maintenance within their maintenance programme.

Within this report many tables have been compiled to assist cable owners choose appropriate maintenance methods to detect particular defects. These tables show that many effective diagnostic tools are currently available for carrying out predictive maintenance. Moreover, new or improved tools are becoming available all the time. For example, continued progress in computer power is enabling the introduction of enhanced measurement capabilities and the interpretation of test results. The measurement of partial discharge activity with enhanced sensitivity is a clear illustration of such progress. Other techniques to provide an insight into the ageing of extruded insulation need to be developed which could be applied in the field as a non-destructive test.

The Working Group has made recommendations regarding the possible benefits of preventive maintenance. The general recommendations are:

1. Carry out cable maintenance with a clear strategy

2. A statistical approach should be used in formulating maintenance policies
3. Keep maintenance strategy under review
4. Develop and maintain a database of cable system failures
5. Fully investigate failures when they occur
6. Pay particular attention to minimising third party damage
7. Implement preventative actions appropriate to the cable type

The Working Group has also recommended a basic minimum level of maintenance for each type of cable considered in this report. These maintenance activities should be considered by all cable owners in the context of their particular key drivers.

Due to the number of new diagnostic techniques becoming available and the potential for utilities to perform more predictive maintenance, this Working Group suggests that the subject of the maintenance of HV cables and accessories should be reviewed again by CIGRE in approximately 10 years.

The Working Group is of the opinion that a good cable maintenance policy should include both types of maintenance. It is too expensive to do only corrective maintenance. On the other hand, it is also too expensive to avoid all failures by predictive maintenance. There are indications that the balance decided upon by utilities between corrective and predictive maintenance is not necessarily the result of a deliberate choice, possibly because the utility has not adopted a clear maintenance strategy yet.

A major conclusion of the present work of this Working Group is that utilities should decide on a clear “maintenance balance” between predictive and corrective maintenance. Which part will be covered by predictive maintenance, which diagnostic tools are needed, how they will be applied etc. The other part will not get any attention in advance but only after the failure has happened. For predictive maintenance, the investment costs and the savings have to be estimated. For corrective maintenance, only the ”full costs”, thereby including all the extra costs associated with a failure have to be considered. The WG has decided not to consider costs in this report, as it is difficult to estimate these costs in a general and objective way. However, per utility costs play a major role in the decision to select the right maintenance balance.

For extruded cables only a few maintenance tasks are frequently done by several utilities such as serving tests and visual inspection of terminations. For fluid filled cables these tests are generally more common and complemented with insulation system diagnosis by fluid pressure monitoring.

Maintenance trends are moving from corrective maintenance in the direction of preventive maintenance and in some cases a predictive maintenance regime. In that context the Working Group believes that more co-operation between utilities will be needed to share experience and knowledge and to provide effective and efficient maintenance tools for the future. The effectiveness of this trend is obviously dependent on our ability to determine cable condition with a sufficient degree of confidence to postpone time based maintenance decisions. Significant progress has been made to date and the new emphasis on asset management will ensure that more efforts are devoted to further develop diagnostic technologies to support condition based maintenance.

APPENDIX A: DEFINITIONS

APPENDIX A DEFINITIONS

All definitions taken from IEC 60050 unless otherwise indicated.

- **Active corrective maintenance time:** that part of the active maintenance time during which actions of corrective maintenance are performed on an item.
- **Active maintenance time:** that part of the maintenance time during which a maintenance action is performed on an item, either automatically or manually, excluding logistic delays. A maintenance action may be carried out while the item is performing a required function.
- **Active preventive maintenance time:** that part of the active maintenance time, during which actions of preventive maintenance are performed on an item.
- **Ageing:** the irreversible changes in one or more properties of an insulating solid, liquid or gas as a result of its normal use.
- **Availability (performance):** the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.
    1. This ability depends on the combined aspects of the reliability performance, the maintainability performance and the maintenance support performance.
    2. Required external resources, other than maintenance resources do not affect the availability performance of the item.
- **Condition assessment (of a cable)[§]:** methodology performed to evaluate the condition of a cable by means of one or more tests. The assessment can be performed in Laboratory on cable samples or on-site using one or more electrical or non-electrical tests.
- **Condition based maintenance[†]:** an equipment maintenance strategy based on measuring the condition of equipment in order to assess whether it will fail during some future period, and then taking appropriate action to avoid the consequences of that failure. The condition of equipment could be performed using Condition Assessment, Statistical Process Control techniques, by monitoring equipment performance, or through the use of the Human Senses. The terms Condition Based Maintenance, On-condition maintenance and Predictive Maintenance can be used interchangeably.
- **Controlled maintenance:** a method to sustain a desired quality of service by the systematic application of analysis techniques using centralised supervisory facilities and/or sampling to minimise preventive maintenance and to reduce corrective maintenance.
- **Corrective maintenance:** the maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function.
- **Corrective maintenance time:** that part of the maintenance time, during which corrective maintenance is performed on an item, including technical delays and logistic delays inherent in corrective maintenance.

[§] Definition proposed by WG B1-04
[†] http://www.plant-maintenance.com/terminology.shtml

- **Degradation (of performance):** an undesired departure in the operational performance of any device, equipment or system from its intended performance. ***Note*** - the term "degradation" can apply to temporary or permanent failure.
- **Dependability:** the collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance.
- **Design failure:** a failure due to inadequate design of an item.
- **Equipment maintenance strategies[†]:** the choice of routine maintenance tasks and the timing of those tasks designed to ensure that an item of equipment continues to fulfil its intended functions.
- **Diagnostic method[§]:** test procedure carried out by means of specialist equipment used to identify the presence, nature and/or cause of a problem in equipment or a component.
- **Failure:** the termination of the ability of an item to perform a required function.
    1. After failure the item has a fault.
    2. "Failure" is an event, as distinguished from "fault", which is a state.
    3. This concept as defined does not apply to items consisting of software only.
- **Failure analysis:** the logical, systematic examination of a faulted item to identify and analyse the failure mechanism, the failure cause and the consequences of failure.
- **Failure cause:** the circumstances during design manufacture or use which have led to a failure.
- **Failure mechanism**: the physical, chemical or other process which has led to a failure.
- **Fault:** the state of an item characterised by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources. A fault is often the result of a failure of the item itself, but may exist without prior failure.
- **Fault correction:** actions taken after fault localisation to restore the ability of the faulty item to perform a required function.
- **Fault diagnosis**: actions taken for fault recognition, fault localisation and cause identification.
- **Fault diagnosis time:** the time during which fault diagnosis is performed.
- **Fault localisation:** fault location (deprecated in this sense). Actions taken to identify the faulty sub-item or sub-items at the appropriate indenture level.
- **Fault localisation time:** fault location time (deprecated). That part of active corrective maintenance time during which fault localisation is performed.
- **Fault mode:** one of the possible states of a faulty item, for a given required function. The use of the term "failure mode" in this sense is now deprecated.
- **Fault recognition:** the event of a fault being recognised.
- **Field maintenance; in situ maintenance; on-site maintenance:** maintenance performed at the location where the item is used.

[†] http://www.plant-maintenance.com/terminology.shtml
[§] Definition proposed by WG B1-04

- **Inspection[†]:** any task undertaken to determine the condition of equipment, and/or to determine the tools, labour, materials, and equipment required to repair the item.
- **Level of maintenance:** the set of maintenance actions to be carried out at a specified indenture level. ***Note*** - examples of a maintenance action are replacing a component, a printed circuit board, a subsystem, etc.
- **Maintainability (performance):** the ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources. ***Note*** - the term "maintainability" is also used as a measure of maintainability performance.
- **Maintenance:** the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function.
- **Maintenance policy:** description of the interrelationship between the maintenance echelons, the indenture levels and the levels of maintenance to be applied for the maintenance of an item.
- **Maintenance time:** the time interval during which a maintenance action is performed on an item either manually or automatically, including technical delays and logistic delays. Maintenance may be carried out while the item is performing a required function.
- **Maintenance tree:** a logic diagram showing the pertinent alternative sequences of elementary maintenance activities to be performed on an item and the conditions for their choice.
- **Manufacturing failure:** a failure due to non-conformity during manufacture to the design of an item or to specified manufacturing processes.
- **Mean maintenance man-hours:** the expectation of the maintenance man-hours.
- **Mishandling failure:** a failure caused by incorrect handling or lack of care of the item.
- **Misuse failure:** a failure due to the application of stresses during use which exceed the stated capabilities of the item.
- **Monitoring; supervision:** activity performed either manually or automatically, intended to observe the state of an item. Automatic supervision may be performed internally or externally to the item.
- **Off-site maintenance:** maintenance performed at a location different from where the item is used. An example of off-site maintenance is the repair of a sub-item at a maintenance center.
- **Operating time between failures:** total time duration of operating time between two consecutive failures of a repaired item.
- **Predictive maintenance[†]:** an equipment maintenance strategy based on measuring the condition of equipment in order to assess whether it will fail during some future period, and then taking appropriate action to avoid the consequences of that failure.
- **Preventive maintenance:** the maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.

[†] http://www.plant-maintenance.com/terminology.shtml

- **Preventive maintenance time:** that part of the maintenance time during which preventive maintenance is performed on an item, including technical delays and logistic delays inherent in preventive maintenance.
- **Redundancy:** in an item, the existence of more than one means for performing a required function.
- **Reliability (performance):** the ability of an item to perform a required function under given conditions for a given time interval.
    1. It is generally assumed that the item is in a state to perform this required function at the beginning of the time interval.
    2. Generally, reliability performance is quantified using appropriate measures. In some applications, these measures include an expression of reliability performance as a probability, which is also called reliability.
- **Reliability centred maintenance[†]:** a structured process, originally developed in the airline industry, but now commonly used in all industries to determine the equipment maintenance strategies required for any physical asset to ensure that it continues to fulfil its intended functions in its present operating context.
- **Repair:** that part of corrective maintenance in which manual actions are performed on the item.
- **Repair time:** that part of active corrective maintenance time during which repair actions are performed on an item.
- **Routine maintenance task[†]:** any maintenance task that is performed at a regular, predefined interval.
- **Scheduled maintenance:** the preventive maintenance carried out in accordance with an established time schedule.
- **Time based maintenance[‡]:** an equipment maintenance strategy based on the fact that after a fixed period of time a component is serviced or overhauled, independent of the wear of the component at that time. Therefore, the strategy has just one parameter, the maintenance interval. The requirement of this strategy is to determine an adequate interval, as both a very rare and a very frequent execution of the preventive activities are both sub-optimal.
- **Time between failures:** the time duration between two consecutive failures of a repaired item.
- **Time to failure:** total time duration of operating time of an item, from the instant it is first put in an up state, until failure or, from the instant of restoration until next failure.
- **Time to first failure:** total time duration of operating time of an item, from the instant it is first put in an up state, until failure.
- **Unscheduled maintenance:** the maintenance carried out, not in accordance with an established time schedule, but after reception of an indication regarding the state of an item.
- **Useful Life:** under given conditions, the time interval beginning at a given instant of time, and ending when the failure intensity becomes unacceptable or when the item is considered unrepairable as a result of a fault.
- **Weakness failure:** a failure due to a weakness in the item itself when subjected to stresses within the stated capabilities of the item. - A weakness may be either inherent or induced.

[†] http://www.plant-maintenance.com/terminology.shtml
[‡] http://www.ergonetz.de/maintenance/indu_p_e.html

- **Wearout failure:** a failure whose probability of occurrence increases with the passage of time, as a result of processes inherent in the item.

APPENDIX B: CASE STUDY DETAIL ON SERVING TEST/CABLE ROUTE INSPECTION

APPENDIX B CASE STUDY DETAIL ON SERVING TEST/CABLE ROUTE INSPECTION

B1 Introduction

Most of the HV cable technologies used by RTE have been designed with minimal maintenance as a key consideration. In spite of this design requirement, certain maintenance activities are necessary in order to ensure the continuing operation of these cables. HV cables have low breakdown rates and a variety of failure modes. They are therefore suited to the application of methods such as Life Cycle Costs or Reliability Centered Maintenance in order to estimate the relevance of particular maintenance actions.

This study uses an original quantitative probabilistic model to optimise economically an example of a typical maintenance policy, in this case, the use of serving tests and cable route inspection to detect external damage to the cable. In particular, this model makes it possible to quantify the interaction and effectiveness of two maintenance tasks which both act to prevent the same mode of failure. The originality of this method lies in the combination of deterministic analysis (where possible) with macroscopic analysis. This model objectively structures the knowledge held within a company for such complex systems, in contrast to keeping only a partial or subjective analysis (e.g. only retaining the failure rates) for determining the frequency of particular maintenance activities.

B2 Glossary

Detectability period	The detectability period is defined as the duration between the beginning of a failure mode (e.g. leakage of oil from a termination) and the fault. This parameter does not generally lies within a range. The range is estimated based on the experience of the utility and experts. The detectability period is an important parameter in determining the frequencies of the maintenance tasks.
Effectiveness	The effectiveness of a maintenance task is equal to the probability of detecting a particular failure mode. This definition of effectiveness comprises two factors: 1. the probability of detecting the incipient failure mode when the maintenance task is performed during the detectability period 2. the probability that the maintenance task will be carried out during this detectability period.

B3 Calculation of effectiveness

E_o corresponds to the organisational effectiveness, i.e. the probability that the maintenance activity occurs during the detectability period.

E_{tech} corresponds to the technical effectiveness, i.e. the probability of detecting the failure mode when the maintenance task is carried out during the detectability period for that failure mode.

Assuming that E_o and E_{tech} are independent, the total effectiveness of a maintenance task is given by:

$$Eff = E_o \cdot E_{tech}$$

Note :

- When the failure mode under consideration is detectable very easily by a simple visual inspection then $E_{tech}=1$.
- In the case of continuous monitoring then $E_o=1$. In contrast, $E_o = 0$ corresponds to the situation where all inspections are made outside the detectability period range.
- In certain cases, E_o and E_{tech} can be interdependent.

Calculation of E_o

If T_v is the frequency of the maintenance task and T_r is the detectability period then two situations can be considered.

(1) The detectability period of the mode is known statistically and considered as constant.
If it is supposed that $T_v \neq 0$, i.e. the failure mode is not continuously monitored and T_r is assumed to be a constant, then the probability that the maintenance task is carried out during the detectability period is:

$$E_o = \min(\frac{T_r}{T_v}, 1)$$

(2) Detectability period considered as variable.
If p(T) represents the probability density function of the detectability period, then the effectiveness becomes:

$$E_o = \int_0^{\infty} \min(1, \frac{T}{T_v}) \cdot p(T) \cdot dT$$

Calculation of E_{tech}

E_{tech} can be estimated by:

- data from the supplier of a diagnostic test or,
- by an analysis of the utility's maintenance records.

B4 Case study – third-party damage

This case study relates to high voltage extruded cable systems. Only one principal failure mode has been considered, namely, third party damage. In this example only the following consequences are considered as outcomes to this damage:

1. Immediate electrical breakdown
2. External damage to the sheath

Two maintenance activities can be used to detect this damage:

1. Cable route inspection, e.g. by car or on foot
2. Serving tests

The method described here makes it possible to calculate the optimal frequencies for these maintenance tasks subject to certain assumptions. Initially, for each failure mode and maintenance task the effectiveness is calculated. This then allows the effectiveness of the combined maintenance tasks to be calculated for each failure mode. The results of this analysis can be represented as:

<table>
<tr><td></td><td></td><td colspan="2">Maintenance tasks ↓</td><td></td></tr>
<tr><td></td><td></td><td>A1: Cable route inspection</td><td>A2: Serving tests</td><td>TOTAL Effectiveness</td></tr>
<tr><td></td><td>Frequency →</td><td>T1</td><td>T2</td><td></td></tr>
<tr><td rowspan="2">Failure modes →</td><td>C1: Detection of works before the third-party damage</td><td>Eff1</td><td>0</td><td>Eff1</td></tr>
<tr><td>C2: detection of a damaged sheath, due to a third-party works</td><td>Eff2</td><td>Eff3</td><td>Effg</td></tr>
</table>

Eff1 is the effectiveness of detecting the presence of a third party before any damage has taken place, by a cable route inspection.
Eff2 is the effectiveness of detecting damage to the sheath, by a cable route inspection (caused previously by a third party).
Eff3 is the effectiveness of detecting damage to the sheath, with a serving test.
Effg is the total effectiveness (for C2) of detecting sheath damage through the combination of the maintenance tasks A1 and A2.

Once Eff1 and Effg are estimated, an economic model is proposed which will ultimately determine the optimal maintenance frequencies ($T1_{opt}$ and $T2_{opt}$).

Calculation of Eff1

Cable route inspection makes it possible to detect third-party activity along the route (C1), which may prevent sheath damage from occurring. Cable route inspection also allows evidence of recent third party activity to be recorded and allows the detectability period to be determined (i.e. the time elapsed since the previous inspection). Assuming activity results in damage then this is C2.

If Ω represents the total number of third-party damage events on all cables systems belonging to a utility, and it is assumed that the arrival of a third party corresponds to the beginning of a failure mode, then the corresponding detectability period is equal to the duration between the commencement of third-party works and the damage. The detectability period is consequently shorter than the planned duration of the works.

Assumptions:

- The detectability period is uniformly distributed over the planned duration of the works. The detectability period is hence variable.
- The probabilities E_{o1} and E_{tech1}, corresponding to Eff1, are assumed to be independent. Thus Eff1 = $E_{tech1} \cdot E_{o1}$
- $E_{tech1} = 1$

1st case: the duration of the planned works is constant and is equal to D.
The probability density function of the detectability period is then:

$$p(Tr) = \frac{1}{D} \qquad \text{if } 0<Tr<D \text{ ; } p(Tr)=0 \text{ if } Tr>D$$

The organizational effectiveness can be calculated :

$$E_{o1} = \int_0^D \min(1, \frac{Tr}{T1}) \cdot \frac{1}{D} dTr$$

If D<T1, then

$$E_{o1} = \int_0^D \frac{Tr}{T1} \cdot \frac{1}{D} dTr = \frac{D}{2 \cdot T1}$$

If D>T1, then

$$E_{o1} = \int_0^{T1} \frac{Tr}{T1} \cdot \frac{1}{D} dTr + \int_{T1}^{D} \frac{1}{D} \cdot dTr = \frac{T1}{2 \cdot D} + \frac{D - T1}{D} = 1 - \frac{T1}{2 \cdot D}$$

2nd case: Ω is composed of works with a variable duration.
Let f(D) (for 0<D<Dmax) represent the planned works probability duration distribution function for all third-party works. Assuming that T1 < Dmax then the probability that the cable route inspection occurs during the detectability period, i.e. before the damage has occurred, is:

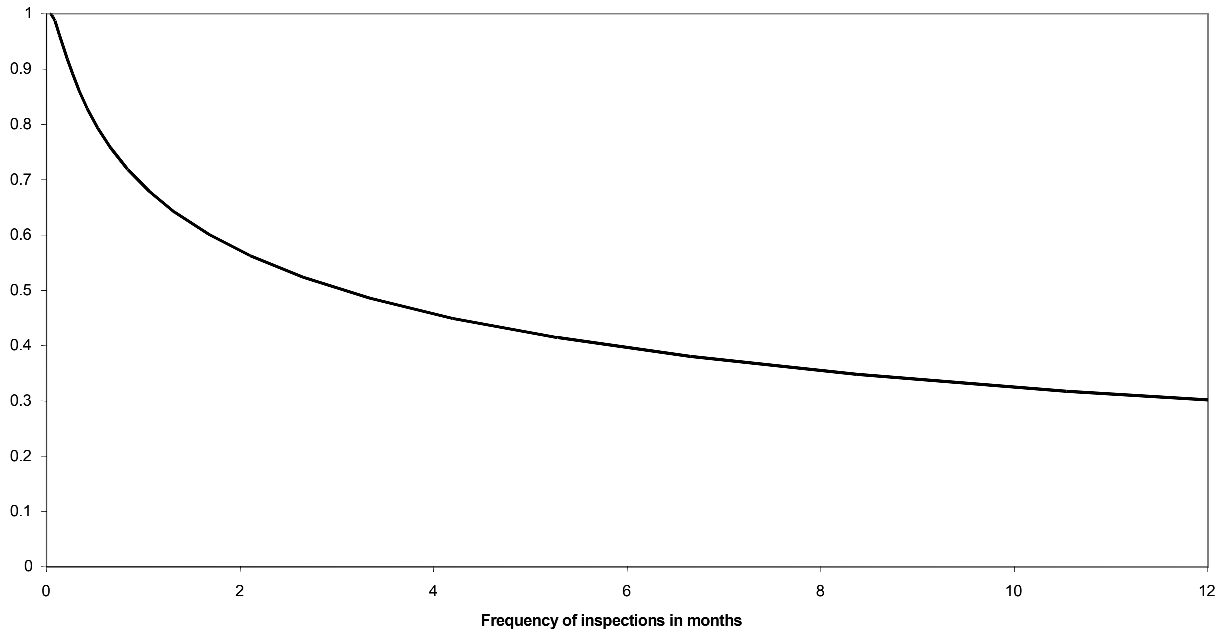
$$E_{o1} = \int_0^{T1} \frac{D}{2 \cdot T1} \cdot f(D) \cdot dD + \int_{T1}^{D\max} (1 - \frac{T1}{2 \cdot D}) \cdot f(D) \cdot dD$$

Thus if f(D) is known, the effectiveness E_{o1} can be deduced.

Estimation of f(D):

The planned works probability duration distribution function, f(D), can be estimated from statistics recorded for actual third-party works. In France, a sample study was carried out in an area of Paris over 5 years. A distribution function has subsequently been deduced. Thus knowing f(D), E_{o1} was calculated according to T1, the frequency of cable route inspections. The curve below represents the effectiveness Eff1.

Eff1 : Effectiveness of cable route inspections



Calculation of Eff2

Given Ω represents the total number of third-party sheath damaging events on all cables systems belonging to a utility, then Eff2 represents among all these events, the probability of detecting this damage by cable route inspection before the moment of breakdown. This is clearly influenced by the frequency of the inspection, T1. The corresponding detectability period is then equal to the duration between the damage and the breakdown.

Assumptions:

- This detectability period is, in this case study, represented by the distribution function g(Tr) defined in the detectability period $[0;Tr_{max}]$ (Tr_{max} is likely to be higher than T1, the frequency of the cable route inspection).
- In addition, it is assumed that E_{tech2} varies according to the duration between the third-party damage and the moment of the inspection.

$Eff2 = E_{o2} \cdot E_{tech2}$

Calculation of E_{o2}:

The function g(Tr) is defined as follows :

$$g(Tr) = \frac{1}{Tr_{max}} \text{ for } Tr<Tr_{max} \text{ ; 0 if not.}$$

$$E_{o2} = \int_0^{Tr_{max}} \min(\frac{Tr}{T1},1) \cdot g(Tr) \cdot dTr = \frac{1}{Tr_{max}} \cdot (\int_0^{T1} \frac{Tr}{T1} \cdot dTr + \int_{T1}^{Tr_{max}} dTr)$$

$$E_{o2} = 1 - \frac{T1}{2 \cdot Tr_{\max}}$$

Calculation of E_{tech2}

The probability that once on site the person in charge of maintenance detects former work activity is represented by E_{tech2}.

Two situations need to be considered:

1. Site works that leave a clear visible sign of changes e.g. a new building
2. Site works that do not leave any clear visible signs of changes e.g. work on underground services - gas, water, telecommunications etc.

It can be deduced that in the former case, $E_{tech2} = 1$, and in the latter case, $E_{tech2} = 0$.

From the sample study in Paris referred to previously, it is possible to estimate the relative proportions of these two cases, which were found to be 15% and 85% respectively. Consequently:

$$E_{tech2} = 1 \text{ x } 0.15 + 0 \text{ x } 0.85 = 0.15.$$

Hence,

$$Eff2 = E_{o2} \cdot E_{tech2} = 0.15 \cdot (1 - \frac{T1}{2 \cdot Tr_{\max}})$$

Calculation of Eff3

Eff3 represents the effectiveness of detecting a damaged sheath due to previous third-party activity by a preventative serving test. Like the other effectivenesses, Eff3 comprises of two components, E_{o3} and E_{tech3}. Since Eff3 acts on the same mode as Eff2:

$$E_{o3} = 1 - \frac{T2}{2 \cdot Tr_{\max}}$$

Concerning E_{tech3}, the experts estimate that the reliability of this diagnostic is excellent. It is proposed an average E_{tech3} of 0.9 is used.

$$Eff3 = E_{o3} \cdot E_{tech3} = 0.9 \cdot (1 - \frac{T2}{2 \cdot Tr_{\max}})$$

Calculation of Effg

Effg represents the over all effectiveness of the two maintenance tasks, A1 and A2, on the failure mode C2 (effectivenesses Eff2 and Eff3 respectively). Since the two effectivenesses (Eff2 and Eff3) have been calculated in this model using independent variables then it can be deduced that Effg depends on T1 and T2 and is expressed by:

$$Effg = Eff2 + Eff3 - Eff2 \cdot Eff3$$

B5 Economic optimization

Now that the effectivenesses Eff1, Eff2, Eff3 and Effg have been estimated, the following economic model makes it possible to find the optimum maintenance frequencies, namely, $T1_{opt}$ and $T2_{opt}$.

Estimate of the parameters relating to the modes of failure C1 and C2

For each failure mode, a triplet of parameters (C_b, C_r, δ_0) can be estimated representing respectively:

1. C_b - the cost of breakdown including unavailability costs,
2. C_r - the cost of repair of the cable if the failure mode is detected before breakdown, including unavailability costs,
3. δ_0 - the failure rate of this failure mode without any maintenance task.

Thus (C_{b1}, C_{r1}, δ_{01}) and (C_{b2}, C_{r2}, δ_{02}) are the two triplets corresponding to the two modes C1 and C2.

Estimate of the parameters relating to the maintenance tasks A1 and A2

To perform the optimisation it is also necessary to know the cost of undertaking the maintenance activities. Let C_{d1} and C_{d2} represent the unit costs of the maintenance actions A1 and A2, including unavailability costs.

Calculation of the total annual utility cost

In the following calculation the option of monitoring is not considered. The total annual cost, C_g, relating to predictive and corrective maintenance is the sum of:

1. Corrective maintenance of the detected modes
2. Corrective maintenance corresponding to the faults that have not been detected by any maintenance task
3. Scheduled preventive maintenance corresponding to the annual cost of all the maintenance tasks.

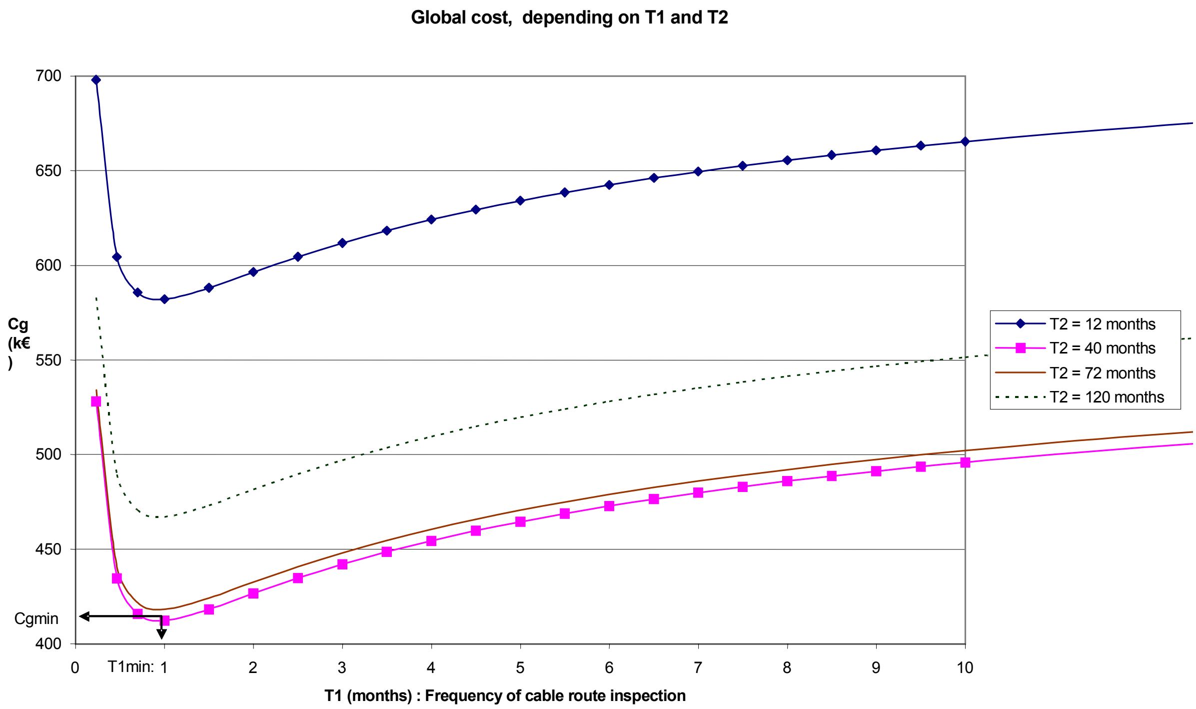
The total annual cost of to both corrective and preventive maintenance of this system is thus:

$$C_g(T1,T2) = \left(C_{r1}\cdot\delta_{01}\cdot Eff1 + C_{r2}\cdot\delta_{02}\cdot Effg\right) + \left(C_{b1}\delta_{01}\cdot(1-Eff1) + C_{b2}\delta_{02}\cdot(1-Effg)\right) + \left(\frac{C_{d1}}{T1} + \frac{C_{d2}}{T2}\right)$$

$T1_{opt}$ and $T2_{opt}$ are obtained by

$$C_g(T1_{opt}, T2_{opt}) = \min(T1,T2) \in]0;Tr\max[\left(C_g(T1,T2)\right)$$

The following figure shows the minimum total annual cost, C_g, applied on a 1000km 225 kV network:



<u>Interpretation of the numerical results</u>

The following conclusion can be drawn from the results:

- The economically optimal frequency for cable route inspections is 1 month, i.e. T1 = 1 month.
- The optimum frequency for serving test is between 3 and 6 years.
- For this network, the overall maintenance cost is between €400,000 and €900,000 per annum.
- The optimal overall maintenance cost C_g corresponds to the following proportions:
    - 32 % preventive maintenance cost, cable route inspection and serving tests
    - 68% corrective maintenance cost

B6 Conclusion

This case study shows the application of economic modeling to a maintenance policy concerning HV cable networks. The method expresses the links between the failure modes and the maintenance tasks. These expressions are represented in the form of a matrix, which allows the total maintenance cost (corrective and preventive) to be calculated. This method makes it possible to estimate, by the means of the model, the relevance of a new task in an existing maintenance program, or the relevance of a new maintenance policy.

This study shows that it is possible to combine the knowledge of experts with historic statistical data relating to faults and estimates of other parameters, to determine the optimal maintenance solution.

This study could be further expanded to include a thorough sensitivity analysis of the results, thereby ensuring that a robust economical solution is found. Furthermore, the option of continuous monitoring could be studied in the same way.

APPENDIX C: CHECK LIST FOR FAILURE ANALYSIS

APPENDIX C EXAMPLE OF CHECK LIST FOR FAILURE ANALYSIS

C1 Introduction

The proper investigation of failures in cable systems is very important, as understanding the failure can help to avoid recurrences of similar failures. This is particularly true for failures due to design faults and jointing errors.

In Section C.2 and C.3 below, guidelines are given for the correct removal and analysis of failed medium voltage cable accessories.

These procedures can also be applied to high voltage accessories, taking due consideration of the characteristics (in terms of materials and dimensions) of the components.

C2 Procedure for the removal of failed MV accessories

In this section guidelines [12] for the proper removal and storage of the failed accessory from the circuit is provided.

In order to identify the causes of failure on a cable accessory, it is usually necessary to perform a failure analysis in a specialised laboratory. Before the investigation, it is necessary to obtain all necessary information relating to the circumstances of the failure. These guidelines are based on the analysis of a joint, but they can be readily adapted for the analysis of terminations also.

Procedure

1. Locate the failed accessory and carry out a visual inspection of the site where the component is installed. The following details should be noted:
   - Presence of water around the joint
   - Unusual bending of the accessory
   - External damages
   - Any other significant evidence

2. When removing the accessory, leave a cable length of about 20cm at each side of the failed component. Make sure that the ends are not subjected to bending or mechanical forces.

3. With a label or a tape note the following information:
   - 'HIGH' side of the joint
   - Names of the substations connected at each end

4. Seal the ends of the component with a safety cap to avoid water ingress.

5. Place the failed accessory in a waterproof bag and seal. If all three joints are removed, insert the three components in the bag.

6. Enclose a report with the information regarding:
   <u>the installation site:</u>
   - City and contact people

- Name of the MV cable circuit (and substations)
- Distance of the fault from each substation
- Identification of the failed phase
- Occurrence of transient phenomenon
- Number of reclosures, and kind of fault location performed
- Number of previous faults on the same line

the cable circuit and the failed component:

- Rated voltage
- Installation (date, company etc.)
- Date of the failure
- Kind of circuit (underground, overhead, mixed)
- Presence of protection systems (surge arresters, spark gaps, other)
- Length of the circuit
- Installation details including depth and mechanical protection
- Number of joints on the same phase
- Kind of accessory (taped, cold-heat shrinkable, etc.)
- Cable characteristics (conductor size, insulation, etc.)

C3 Check list for evaluating materials

In this section guidelines for the systematic analysis of failed accessories are described.

The following checks mainly refer to shrinkable MV accessory designs. The dimensional checks are used to verify that the mounting of the accessory has been carried out in accordance with the approved mounting instructions of the accessory manufacturer. The visual inspection and checks are used to judge the adequacy of the mounting operation.

MAIN DIMENSIONAL CONTROLS AND VISUAL INSPECTION

Complete accessory
Overall length
Outer Diameter
Marking on the protective covering (Manufacturer Identification, Reference Number)
Other (abnormal bending, signs of damage, etc.)

Accessory insulation
Length of the shrinkable tube(s)
Length of cable insulation
Position of the insulation tube with respect the centre of the accessory
Regularity of the thickness of the tube
Marking

Metallic connector / Terminal Lug
Length
Diameter
Use of suitable tooling (hydraulic press, etc.)
Marking

CHECKS (presence of materials, correctness of operations)

Damage on the surfaces of the tubes
Pollution in the accessory body
Manufacturing defects (e.g. voids)
Abrasion on the cable oversheath (to ease sealing of the component)
Moisture under the protective covering
Condition and position of the metallic screen layer
Connection adequacy (use of proper connector)
Presence of irregularities on connector surface (needles, oxidation)
Presence/absence of mastics (between adjacent tubes)
Presence of grease on the surface of insulation
Shielding of the connector
Cuts or irregularities in the insulation surface
Other significant evidence (e.g. cable eccentricity)

In particular for PILC Cable accessories:
Drying/carbonisation of the paper tapes
Treating of lead surface (e.g. soldering, abrasion, smoothness of cut edge)

In particular for overhead cable accessories:
Positioning of the earthing connection plate
Presence of tightening bands
Indentation of cable outer semi conductive screen

In some cases dimensional checks and visual inspection are not accurate enough to explain the reason of the breakdown. For example in the case a chemical contamination of the insulating material, more powerful and dedicated analysis is required to explain the failure.

Examples of such analysis are:

- SEM (scanning electron microscope)
- TGA (thermogravimetric analysis)
- DSC (differential scanning calorimetry)
- Microthome/Microscope analysis (trees analysis)
- Semiconductor resistivity measurement
- Pervasive liquid test
- Mechanical test of insulating or sheathing materials

APPENDIX D: LITERATURE LIST

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APPENDIX E: CIGRE WG B1-04 MEMBERSHIP

APPENDIX E MEMBERSHIP OF CIGRE WG B1-04 "MAINTENANCE OF HV CABLES AND ACCESSORIES”

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