

Assessing the condition and remaining life of
underground electrical cables



ASSESSING THE CONDITION AND REMAINING LIFE OF UNDERGROUND
ELECTRICAL CABLES

First edition

December 2016

Published by

ENERGY INSTITUTE, LONDON

The Energy Institute is a professional membership body incorporated by Royal Charter 2003

Registered charity number 1097899

The Energy Institute (EI) is the chartered professional membership body for the energy industry, supporting over 23 000 individuals working in or studying energy and 250 energy companies worldwide. The EI provides learning and networking opportunities to support professional development, as well as professional recognition and technical and scientific knowledge resources on energy in all its forms and applications.

The EI's purpose is to develop and disseminate knowledge, skills and good practice towards a safe, secure and sustainable energy system. In fulfilling this mission, the EI addresses the depth and breadth of the energy sector, from fuels and fuels distribution to health and safety, sustainability and the environment. It also informs policy by providing a platform for debate and scientifically-sound information on energy issues.

The EI is licensed by:

- the Engineering Council to award Chartered, Incorporated and Engineering Technician status;
- the Science Council to award Chartered Scientist status, and
- the Society for the Environment to award Chartered Environmentalist status.

It also offers its own Chartered Energy Engineer, Chartered Petroleum Engineer and Chartered Energy Manager titles.

A registered charity, the EI serves society with independence, professionalism and a wealth of expertise in all energy matters.

This publication has been produced as a result of work carried out within the Technical Team of the EI, funded by the EI's Technical Partners. The EI's Technical Work Programme provides industry with cost-effective, value-adding knowledge on key current and future issues affecting those operating in the energy sector, both in the UK and internationally.

For further information, please visit <http://www.energyinst.org>

The EI gratefully acknowledges the financial contributions towards the scientific and technical programme from the following companies

BP Exploration Operating Co Ltd	RWE npower
BP Oil UK Ltd	Saudi Aramco
Centrica	Scottish Power
Chevron	SGS
CLH	Shell UK Oil Products Limited
ConocoPhillips Ltd	Shell U.K. Exploration and Production Ltd
DCC Energy	SSE
DONG Energy	Statkraft
EDF Energy	Statoil
ENGIE	Talisman Sinopec Energy (UK) Ltd
ENI	Tesoro
E.ON UK	Total E&P UK Limited
ExxonMobil International Ltd	Total UK Limited
Kuwait Petroleum International Ltd	Tullow Oil
Maersk Oil North Sea UK Limited	Valero
Nexen	Vattenfall
Phillips 66	Vitol
Qatar Petroleum	World Fuel Services

However, it should be noted that the above organisations have not all been directly involved in the development of this publication, nor do they necessarily endorse its content.

Copyright © 2016 by the Energy Institute, London.

The Energy Institute is a professional membership body incorporated by Royal Charter 2003.

Registered charity number 1097899, England

All rights reserved

No part of this book may be reproduced by any means, or transmitted or translated into a machine language without the written permission of the publisher.

ISBN 978 0 85293 952 9

Published by the Energy Institute

The information contained in this publication is provided for general information purposes only. Whilst the Energy Institute and the contributors have applied reasonable care in developing this publication, no representations or warranties, express or implied, are made by the Energy Institute or any of the contributors concerning the applicability, suitability, accuracy or completeness of the information contained herein and the Energy Institute and the contributors accept no responsibility whatsoever for the use of this information. Neither the Energy Institute nor any of the contributors shall be liable in any way for any liability, loss, cost or damage incurred as a result of the receipt or use of the information contained herein.

Hard copy and electronic access to EI and IP publications is available via our website, <https://publishing.energyinst.org>.

Documents can be purchased online as downloadable pdfs or on an annual subscription for single users and companies.

For more information, contact the EI Publications Team.

e: pubs@energyinst.org

Contents

	Pages
Acknowledgements	7
Foreword	8
1 Introduction	9
1.1 Scope	9
1.2 Target audience	9
1.3 Historical perspective and changes in cable design	9
2 Deterioration and modes of failure	12
2.1 Detecting degradation prior to failure	12
2.2 Natural ageing	12
2.3 Thermal degradation	12
2.4 Water ingress	13
2.5 Partial discharge activity	13
2.5.1 Partial discharge overview	13
2.5.2 Partial discharge in PILC cables	14
2.5.3 Partial discharge in EI cables	15
2.6 Water trees and electrical trees	15
2.7 Fluid-filled cables	16
2.8 Jointing issues affecting modern cable joints and terminations	17
2.9 Further reading	19
3 Standards	21
3.1 Standards overview	21
3.2 After-installation (commissioning) tests	21
3.2.1 The purpose of after-installation tests	21
3.2.2 PILC and fluid-filled (pressurised) cables	21
3.2.3 EI cables	22
3.3 Test method standards	23
4 Safe methods of work	25
5 Condition assessment test methods	27
5.1 Online monitoring versus offline testing	27
5.1.1 Relative benefits of online and offline testing	27
5.1.2 Phased approach to non-intrusive/intrusive testing	28
5.2 DC insulation resistance and polarisation index	28
5.2.1 Issues with DC testing	28
5.2.2 DC testing procedures	28
5.2.3 Analysing DC test results	30
5.3 Very low frequency	32
5.4 Resonant frequency testing	34
5.5 Damped AC	36
5.6 Tan delta (loss angle) measurements	37
5.7 Partial discharge testing (online and offline)	40
5.7.1 Relative benefits of online and offline partial discharge testing	40
5.7.2 Online partial discharge monitoring	40
5.7.3 Ultrasonic partial discharge measurements	45

Contents continued		Page
5.7.4	Handheld partial discharge devices	46
5.7.5	Offline partial discharge testing	47
5.8	Swept frequency measurements	48
5.8.1	Dielectric spectroscopy	48
5.8.2	Line impedance resonance analysis	49
5.9	Return voltage and isothermal relaxation current methods.	50
5.10	Sheath testing	51
5.11	Thermal measurements	53
6	Installation conditions	55
6.1	Onshore and offshore	55
6.2	Direct buried and ducted	56
7	Condition assessment	57
7.1	Condition assessment matrix	57
7.2	Health indices	60
7.3	Remaining life predictions	64
8	Operational aspects	66
8.1	Safety	66
8.2	Management of ageing assets	66
8.3	Condition based maintenance	67
8.4	Fault detection and location	68
8.4.1	Stages in fault location process.	68
8.4.2	Fault diagnosis	69
8.4.3	Prelocation	69
8.4.4	Pinpointing	74
8.4.5	Subsea cable fault location.	77
8.4.6	Further reading	79
9	New and future technologies	80
9.1	Distributed acoustic sensing	80
9.2	Online tan delta.	80
9.3	Insulation resistance monitoring	80
9.4	Partial discharge foil sensing on accessories	80
9.5	Holistic systems	81
9.6	High voltage DC cable system monitoring	82
10	Conclusion.	83
Annexes		
Annex A	References.	84
Annex B	Glossary of abbreviations and acronyms	88
Annex C	Glossary of terms	90

LIST OF FIGURES AND TABLES

FIGURES

Figure 1	Traditional belted cable design	10
Figure 2	PILC cables – single core (left), screened (middle), S.L. type (right)	10
Figure 3	Evidence of PD activity on insulation papers.	14
Figure 4	Bow tie water trees in stained XLPE insulation	16
Figure 5	Thermomechanical buckling of cores in 3-core fluid-filled joint	17
Figure 6	Shear head bolt type connectors	18
Figure 7	Radial fault at screen termination	19
Figure 8	Example of earthing and signage placement	26
Figure 9	Heat shrink termination with visual evidence of partial discharge activity	27
Figure 10	Test circuit with third (guard) terminal (<i>source Megger</i>)	29
Figure 11	Example of valid connection for guard terminal (<i>source Megger</i>)	29
Figure 12	Change in DC insulation resistance with time	31
Figure 13	Step voltage results for good and suspect cables	32
Figure 14	Ultra Compact HVA28 VLF test set (<i>source Redskye Technology</i>)	33
Figure 15	200 kV VLF test set in substation (<i>source Redskye Technology</i>).	34
Figure 16	ACRF system with series connected reactors (<i>source High Volt</i>)	35
Figure 17	Supply set up with two resonant frequency units (<i>source High Volt</i>).	35
Figure 18	Damped oscillation test circuit	36
Figure 19	Damped oscillation test voltage and PD map of cable	37
Figure 20	Tan δ results for two cables (<i>source BAUR Test Equipment</i>).	38
Figure 21	Tip up in tan δ readings.	39
Figure 22	HFCT fitted to earth bond with insulated cable glands.	41
Figure 23	HFCT temporarily installed inside cable box with TEV probe.	41
Figure 24	Partial discharge pulse and reflections	42
Figure 25	Example of analysis window from partial discharge measurement software	43
Figure 26	Typical phase related signal due to partial discharge activity.	44
Figure 27	Three-phase partial discharge activity in PILC cable	44
Figure 28	AE sensor and TEV sensor in cable box (<i>source HVPD website</i>).	46
Figure 29	Hand held partial discharge detectors from EA Technology and HVPD	46
Figure 30	VLF cosine square wave (<i>source Megger</i>).	47
Figure 31	Dielectric spectroscopy measurements on HV cable	48
Figure 32	Cable diagnostic tester with RVM and IRC functions (<i>source Megger</i>)	51
Figure 33	Preparation of cable end for sheath test (<i>source Elmeridge Cable Services</i>).	52
Figure 34	Testing cable end prior to sheath test (<i>source Elmeridge Cable Services</i>).	52
Figure 35	Thermal image of 6,6 kV single core cable terminations.	53
Figure 36	Offshore wind export cable with optical fibre bundle.	54
Figure 37	Traditional bathtub representation of cable life	64
Figure 38	Nett P-F interval (Moubray, <i>RCM II, Reliability-centred maintenance</i>)	68
Figure 39	Basic TDR trace with series, open circuit, fault	70
Figure 40	TDR trace with shunt (phase to earth), fault.	70
Figure 41	'Straddling' the fault with TDR measurements from both ends.	71
Figure 42	Basic Murray loop fault location circuit	72
Figure 43	10 kV High-Voltage Bridge (<i>source Megger and Baur</i>)	73
Figure 44	Arc reflection pre-location measurement (<i>source Megger</i>)	73
Figure 45	LIRA finger print of new wind farm export cable (<i>source Wirescan</i>)	74
Figure 46	Cable fault pinpointing detector	75
Figure 47	MAGPIE HV DC transmitter unit	76

Contents continued		Page
Figure 48	DTS image of subsea cable fault (<i>source Omnisens</i>)	77
Figure 49	ROV fitted with subsea cable detection coil	78
Figure 50	Location screen showing signal detected by ROV	78
Figure 51	Foil electrode PD detection technique	81
Figure 52	Holistic cable monitoring system (<i>Source HVPD</i>)	81

TABLES

Table 1	After-installation tests on EI cables rated up to 33 kV.	22
Table 2	AC voltage tests on EI cables rated above 33 kV	23
Table 3	Selected maintenance test voltages, from IEEE Std. 400.1	30
Table 4	K values for different insulation materials based on ICEA values.	31
Table 5	Insulation condition indication from dielectric absorption ratio.	32
Table 6	Tan δ assessment levels from IEEE std. 400.2	39
Table 7	Indicative on-line partial discharge monitoring levels in XLPE cable circuits	45
Table 8	Baseline tests to be conducted during commissioning	57
Table 9	Applicable condition assessment tests	58
Table 10	Example of Condition Scoring for 3,3 kV to 22 kV XLPE Cables	61
Table 11	Condition assessment measures for polymeric cables.	62
Table 12	Health index scoring example	63
Table 13	Typical V_p values	71

ACKNOWLEDGEMENTS

Assessing the condition and remaining life of underground electrical cables was produced by the EI Power Utility Committee (PUC), and authored by Bob Dean (Edif ERA). During this project, PUC members included:

Graham Beale	Engie
Alan Dickson	Scottish Power (Chair)
Steve Gilmore	Uniper
Phillip Horner	Centrica
Edward Jamieson	RWE
Stuart King	EI (Secretary)
Ali Kuba	Saudi Aramco
Chris Martin	Engie
Daniel Rawdin	SSE
Doug Smart	EDF Energy
Konstantinos Vatopoulos	Aramco Overseas

The EI also acknowledges the following individuals for contributing to the stakeholder review of this publication:

Paul Donnellan	Shell
Zaur Sadikhov	Shell

The EI wishes to acknowledge the following organisations for their contributions to this project in providing information and images:

BAUR Test Equipment
Elmeridge Cable Services
High Volt
HVPD
Megger
Omnisens
Redskye Technology
Wirescan

Technical editing was carried out by Stuart King (EI).

Affiliations are correct at the time of contribution.

FOREWORD

Electrical power cable condition assessment has changed in recent years. In the past, normal practice was to leave a cable undisturbed until an unacceptable number of failures occurred and then to replace the cable. Today there are a confusing number of cable condition assessment techniques and systems available. Many technical papers have been written on the subject, but they tend to cover a particular test method, and are often written by specialists working for test equipment manufacturers, naturally favouring their own company's test methods and equipment.

Assessing the condition and remaining life of underground electrical cables was commissioned by the Energy Institute (EI) Power Utility Committee (PUC), with the intention of providing practical independent guidance on assessing the condition and remaining life of underground electrical power cables.

Efforts have been made to avoid duplicating existing publications, and where useful publications exist, these have been referenced in the text.

This publication is primarily for engineers working in the energy generation industry, but it also provides a useful source of information for engineers in other industries as well as students, engineering managers and consultants.

As well as being read in whole, this publication can be used as a reference document where relevant sections are referred to as and when required, for example when considering a particular test or assessment method.

The information contained in this document is provided for general information purposes only. Whilst the EI and the contributors have applied reasonable care in developing this publication, no representations or warranties, expressed or implied, are made by the EI or any of the contributors concerning the applicability, suitability, accuracy or completeness of the information contained herein and the EI and the contributors accept no responsibility whatsoever for the use of this information. Neither the EI nor any of the contributors shall be liable in any way for any liability, loss, cost or damage incurred as a result of the receipt or use of the information contained herein.

The EI welcomes feedback on its publications. Feedback or suggested revisions should be submitted to:

Technical Department
Energy Institute
61 New Cavendish Street
London
W1G 7AR

1 INTRODUCTION

1.1 SCOPE

This publication describes the onsite methods used to test underground electrical cables rated above 1 000 V phase to phase with paper insulated, lead covered (PILC), crosslinked polyethylene (XLPE) and ethylene propylene rubber (EPR) insulation. The test methods are applicable to generation, power distribution, high voltage (HV) motor and HV industrial cable types used in generation plants. A section is also included on subsea export and array cables for offshore wind farms.

1.2 TARGET AUDIENCE

This publication is for:

- engineers carrying out onsite testing of underground electrical cables, and
- asset managers who may be instructing others to carry out such testing.

It also provides useful information for anyone wishing to understand the results of electrical cable testing and condition assessment reports.

As well as being read in whole, this publication can be used as a reference document where relevant sections are read as and when required. The first section covers cable degradation and failure modes – the reader should ensure they understand how a cable can degrade and fail before they consider the various test and diagnostic methods described in later sections.

1.3 HISTORICAL PERSPECTIVE AND CHANGES IN CABLE DESIGN

Electrical cables were first developed at the end of the nineteenth century and for many years the prevailing policy was to test the cable when first installed but not to carry out any further testing. Cables were repaired (with a short length of cable and two joints) when a fault occurred. They were replaced when the incidence of faults on the circuit became too high. Where testing was carried out on electrical cables the test method was either a DC voltage withstand test or a direct current (DC) insulation resistance (IR) measurement.

The traditional cable design was PILC. This could be screened or belted. The belted cable design has paper insulation applied over the three laid up cores to achieve the phase to earth insulation thickness (see Figure 1).