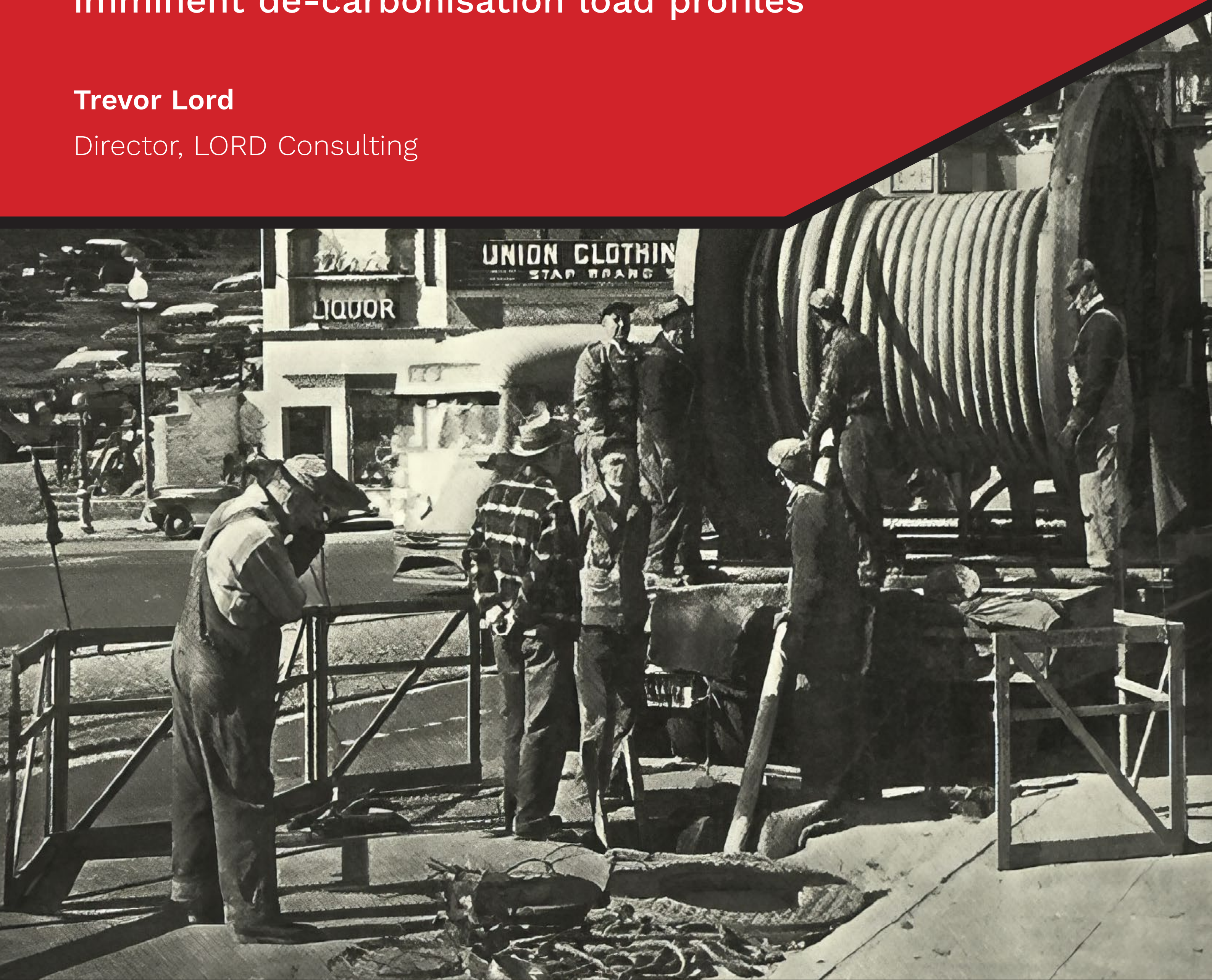
Commissioning & condition assessment of 11–33kV cable infrastructure

... ensuring it's capable of meeting the imminent de-carbonisation load profiles

Trevor Lord

Director, LORD Consulting



"Old cable management practices were fine in their day but they certainly will no longer achieve the desired reliability and service life outcomes with MV XLPE cable!!"

www.lordconsulting.com

Abstract:

Our industry, together with investors, stakeholders, regulators, and the government, has committed to transitioning to low-carbon electricity generation to meet growing demand, largely replacing current carbon-based options.

Whilst the work is proceeding apace, a significant challenge in the linking of generation and load, via present infrastructure working harder and likely the loss of an N-1 architecture through economic necessity, is apparent.

Several key points are made in the paper:

- ***Issue:*** *New Zealand's 60,000 km of MV cables may not handle the increased load needed for a low-carbon future due to management issues.*
- ***Action Needed:*** *More inspections, better techniques, and revised standards are required for both new and in-service MV cables.*
- ***Financial Risk:*** *Uncertainty about achievable cable capacity under new loading and load profiles could have significant financial consequences.*
- ***Solution:*** *The paper suggests methods to improve cable reliability and to ensure they can handle increased and rapidly changing loads.*
- ***New Approach:*** *A patented asset management method is introduced to extend cable life and reliability using a quality-focused strategy.*

1. What is the Problem? Perspectives and High-Level Observations:

New Zealand is committed to achieving ambitious decarbonization goals. According to an MBIE report of 7 February 2024, "New Zealand will likely reach 96-98% renewable energy in the next decade" [92].

To this end, not only is there a very significant present focus in our region on the planning and progressive installation of a large carbon-neutral generation, but there is also necessarily a parallel scale of investment, consumer incentives, and political effort focused on moving increasingly to an electrified transport, heating, and industrial infrastructure model designed to ensure low carbon generation effectively serves a low carbon load.

This is a smart and balanced approach to investing in infrastructure for both supply and demand. It's an investment opportunity that is now widely discussed in political, consumer, business, and technical circles, capturing the attention of both investors and users of clean, low-carbon electricity.

Illustrating the degree of penetration and consumer-side involvement in these projects, mention of terms like 'grid exit' and 'grid connection' points is now common in mainstream media. New investments and announcements of low-carbon generation schemes are announced routinely, transmission companies are working hard to adapt and interface to the geographically diverse, if not haphazard, low carbon generation and load sites emerging at an increasingly high rate of announcement, and things all *seem* on the surface to be proceeding as they should on this long and exciting journey.

Everyone is doing their best. Investors and stakeholders have predicated their investments on abundant low carbon energy 'at the door' being the reality which will be duly delivered.

In their Legal Update of 7 February 2024, MinterEllisonRuddWatts [92] also made the prophetic comment: *"The immediate challenge is maintaining security of supply".*

Unfortunately, in response to the above comment, when it comes to the backbone 11-33 kV distribution network (both private and EDB) where the 'heavy lifting' of final delivery of low carbon power takes place to the rapidly increasing electric load profile, a major problem is looming that has yet to be recognized, agreed, or effectively confronted. That problem is disruptive to the underpinning visions outlined and is, quite simply, but surprisingly at first mention, the largely unknown engineering integrity of our backbone 11-33 kV cable infrastructure.

Elaborating on this disturbing observation, New Zealand has an estimated 60,000km of such cable infrastructure in service, an increasing proportion of that total now notably within the low carbon generation sites themselves. Concerningly, with a few notable exceptions in NZ, little detailed and systematic condition profiling is currently being deployed, or contemplated, for the aging, in-service MV (11-33 kV) cable population. Further, present commissioning practices of MV cable are, either through deficiencies in institutional knowledge, training, or equipment selections, neither aligned in quality, nor generally delivered with enough 'forward visibility' of future operational reliability.

This effectively means that our MV cable asset base, which constitutes some 50+ % on average of the capital value of most urban electricity distribution networks and is totally integral to the low carbon transition vision, is essentially of unknown condition. That situation currently provides no demonstrable assurance to stakeholders of adequate future performance under the higher operational stress low carbon vision.

Financial Perspectives:

Conservatively estimated at an Industry accepted replacement cost of $1000 to $10,000 per metre for such cable, this effectively represents an asset value of a **minimum** of $60 billion in NZ whose condition and suitability for purpose as a heavily loaded backbone of the low carbon delivery architecture is unverified by any formal inspection methodologies.

The scale of this proposed expansion of our electricity distribution system to meet the low carbon future is staggering. Let us consider just the New Zealand picture for a moment. According to a NZ Ministry of Business and Innovation and Employment (MBIE) briefing to the incoming NZ Minister of Energy on November 27, 2023, projections are for a 70% rise in electricity demand by 2050 [91]. Aligned to this, in Q1 of 2023 the New Zealand Electricity Networks Association (ENA) spoke of having to supplement (but not replace) these cables and associated infrastructure by a minimum of factor of two, to as much as three over present levels, to meet near-future load demand [89]. The Boston Consulting report released in New Zealand in October 2023 [90] suggested that a $42 billion investment in generation, transmission, and storage was required, *of which $22 billion was for local distribution.*

Concerningly, the above investment predictions of course presumed that the present MV cable infrastructure, amongst other related system building blocks, was up to the task of carrying the nominal doubling of load implicit in the above predictions vs the present N-1 design ratings. After all, there seems to be no choice.

Given the projected 70% load growth by 2050 and given the market-constrained $22 billion estimated for local distribution (say, 60% of the for MV cable at $1000/m) that only allows an expansion of the MV network by 13,000km or 22% of present. If we use a model of increasing the present MV loadings by say 40% from an estimated present average of 44% (i.e. raising average loadings to say 62% and accepting a loss of N-1 on the wider network but still allowing a strategic redundancy on the say some 11 and 33kV backbone cable), and add on 22% more for the expanded cable investment, we get an increased load capability of around 70% over present. Just enough. That said, this calculation ignores retirement and replacement of some older cables pre-2050, and the need to overlay others (below), which adds more to the figure and is likely to force loadings higher unless Government (or others) invests in more MV cable (which is unlikely given the constrained commercial models around the appetite of the consumer around forward pricing). The likely loss of redundancy through the pressures of associated economic models in servicing the much-increased low-carbon load, challenges all present MV cable commissioning and in-service management and operational practices, also then likely to challenge service delivery performance statistics, to the angst of the consumer and Regulator.

Given the status of our MV cable condition being presently unknown, one must make an allowance to potentially replace some MV cable assets and perhaps 'strategically overlaying' others (likely at significantly more than $1000/m), after formal condition assessment. Even if a conservative estimate of replacement or overlaying 20% of the present MV cable population at $1000/m adds some $12 billion to the NZ estimate of $22 billion in the Boston Report above, a 50% increase over earlier estimates at time when the consumer billing side of this equation, felt by ENA not to be able to stand more than a doubling, is confronting. That further investment of $12 b is likely to fall even more heavily on the profitability of a constrained expansion by distribution, generation, and industrial cable stakeholders. The juggle is financing this or 'sweating the MV cable assets' further, a dilemma indeed.

Further problems to compound the MV cable owners:

Even more worryingly, multiple further factors converge unfavourably on this problem:

- MV Cable asset owners conflate and confuse *historic cable reliably* with *cable condition.* The correlation is tenuous at best. Thus, perceptions of *future* cable reliability, made without appropriate condition assessment technologies, are in the most part fraught.
- The aged cable profiles of most cable networks are not skewed favourably toward inherently high reliability, and many MV cables are now mixed compositions of XLPE and PILC cable (Fig 1).
- Further confounding cable reliability predictions, cables have a long history of present and pending issues with not only the technology and application of jointing and termination practices but also legacy issues with cable design, manufacturing, laying, sheath damage, QA shortcomings, all combined with many and varied aging mechanisms and third-party damage. (Fig 2).

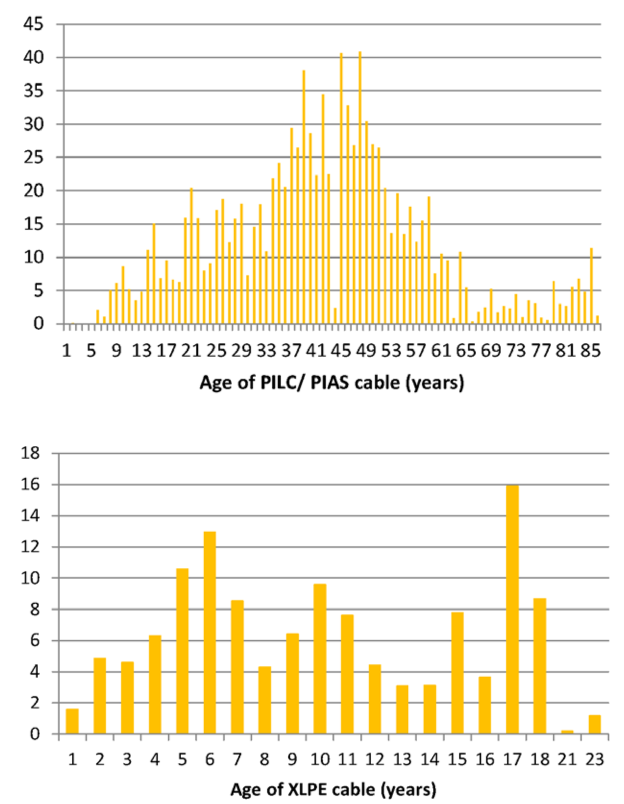


Fig 1a: Illustrative
Aged Profiles seen in NZ [after 87]

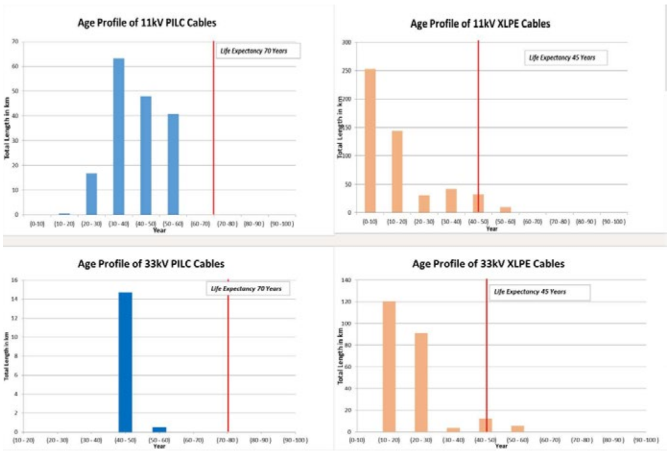


Fig 1b: Illustrative
Aged Profiles seen in NZ [after 86]

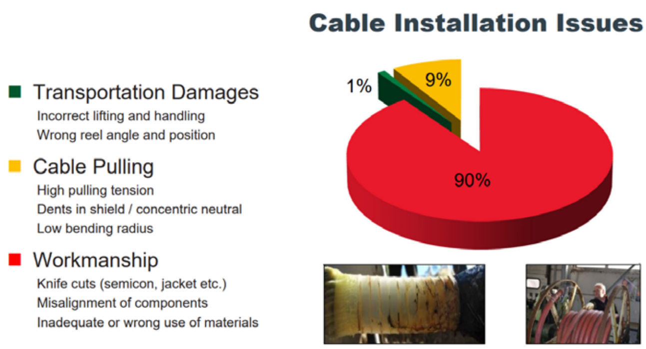


Fig 2: Cable installation issues
Source: METSCO Cable Assessment Workshop; Ali Naderian; "Basics of Underground Cable Testing & Condition Assessment"; 2017

- The changing load profiles for cables associated with low carbon generation are already adversely impacting cables, joints, and cable accessories. These are largely designed based on historical load performance and engineering experiences. This problem challenges traditional assumptions for trenching, joint design, duct design, thermal operating environments. Wind and solar farms cannot afford to have a mitigating loading margin buffer. This has been a factor in several cable failure investigations in that sector but will soon inevitably adversely impact the MV distribution sector also.
- XLPE cables have a known propensity to discharge (PD) more severely when running hot, risking ensuing cable failures at layered interfaces. Presently, most run at around 40% full load only. Thus, it may be anticipated that increased loading on aged cable will shorten its life if it is not suitably and regularly assessed and managed.
- Compounding the above problem increased loadings of MV XLPE cables of popular aluminium core construction (of high thermal expansion coefficient), result in enhanced mechanical stresses when moving between very heavy and lighter loads, damaging joints and terminations, and compromising reliability.
- A progressive loss of skills and understanding of optimum MV cable design & build standards, & field test & management practices, pervades and concerns. Training & upskilling in these areas is an immediate priority for our industry to ensure necessary future reliability of the entire MV cable population.

The above being the case, probing questions might well be asked by lenders were distribution companies to consider leveraging capital borrowing for the said expansion program against their capital assets, of which MV cable assets of unknown condition comprise a major share. The burden of the required $32billion investment in the New Zealand context cited above, then, might well need to fall heavily on the NZ Government, given the inability of the consumer to bear the additional cost under a CPP.

'The Problem'.... a Summary:

Concluding the above perspective, it is clear that our problem is that, right at a time when our aging MV cable infrastructure in New Zealand is being asked to step up to take even more load from low carbon renewable generation, little is typically known about the 'diagnosed' condition status of this asset category and reassurances to that end are few.

The implications fall into both financial and performance camps. The collective implications of this issue should be a most concerning observation to the low carbon industry shareholders, stakeholders, asset owners, and Regulators, as well as provoking an immediate concerted response by the Distribution sector to face and address these matters by preventative and proactive interventions.

2. The True Worth of Testing and Condition Assessment in the Cable Context:

MV power cable assets represent a major investment in their own right, that investment being initially the sum of the cable itself, the planning investment underpinning its installation, the installation cost itself (comprising open trenching, thrust boring, and compliant reinstatement), jointing and termination of the connected whole, and finally the testing and commissioning costs.

Of the contributing costs, the latter segment is variously estimated to amount to no more than 5% of a typical MV cable project, even for the most comprehensive testing specification that industry best practice might call for. Notwithstanding, and very significantly, the testing and commissioning component of the project has a hugely disproportionate bearing on the longevity, reliability, and overall cost of ownership of the cable asset concerned.

Over the life of a cable asset, reliability and longevity are the main contributing issues governing the variable costs of ownership. SAIDI minutes, lost revenue, direct repair and reinstatement costs, and brand damage are all direct consequences with real economic value in the event of unreliability over life. Indeed, one network [5,11] attributes 70% of the cost of running and maintaining their distribution network cable systems.

On the other hand, unchecked cable failure mechanisms leading to premature aging and forced early replacement decisions as a result of reliability, or aging issues have a very significant real NPV cost. Again, in each matter, testing and condition assessment practices applied to the cable over its life play a disproportionate part in the mitigation of such issues.

Clearly, then, although testing, commissioning, and condition assessment practices are one of the lowest real costs levied against cable assets over their life, the contribution and financial return from an investment in best practice effort in this quarter is arguably one of the more significant determining factors as to the profitability (ROI) of such assets in real terms.

3.0 Identification of the Major Issues Determining Cable Life and Reliability:

Internationally, there is almost total unanimity in the literature [6,7,11] as to the fact that the major factors governing the longevity and service reliability of modern underground MV cabling lie not in the cable manufacturing quality itself but in the quality of the initial installation, construction, and cumulative life management techniques applied to each MV cable circuit [10,18,21]. There is also uniformity of opinion [4,6,7,12,22] toward the view that joints and terminations [5] remain the two single most areas of concern in this regard.

3.1: Cable Design and Manufacture

Certainly, the actual factory cable design and manufacture process will play a significant role in itself in terms of inherent cable life and reliability, with such issues as the presence or otherwise of water tree inhibiting chemicals (TR-XLPE) in the XLPE polymers, water blocking of outer layers and even the core material itself, quality and purity of raw materials used particularly in the extruded insulation, final factory testing rigour, and sealing quality for shipment all contributing [4,10,34,43].

Undeniably, mandated and delivered standards of cable design and manufacture internationally have greatly improved [4,9,10,34,43]. Notwithstanding, the buyer is never absolved of a significant duty of care to oversee and intervene in these issues but largely this matter remains outside the direct scope of this discussion.

In general, it has been noted that the Australasian market has been well served by good cable quality from local manufacture in recent years but issues like the legacy issue of lack of water tree retardant insulation in Australian-made MV cable product is of concern for its potential impact alone on present and future cable reliability, New Zealand-made product having had such provision for some 35+ years to date [10,34].

Further cable design issues such as the absence of water blocking tapes, and the use of aluminium sheaths which are not protected by adequate outer layers to provide continued protection against water ingress and subsequent corrosion are but some areas of latent concern to note in otherwise competent designs.

3.2: Design of Jointing and Termination Kits

Without question, the quality and design of jointing and termination kits, ferrules and ferrule compression techniques, and technology for jointing high expansion cable materials such as aluminium, remains as one of the more significant issues determining overall cable reliability and life [12,13,22]. Such cable accessories are well known to exhibit partial discharge activity [6,7,13,32,33,43] and contribute to cable failures [11,43] but for optimum life they should run discharge-free [32,33]. Given the proposed high loading of the MV cables intended as backbone distribution for the low carbon generation, the verification of joint connection integrity is of enhanced importance.

3.3: Workmanship in Cable Installation and Final Construction

Closely allied to the comments in (3.2), and arguably at the root of the present problems suffered by our Industry to a much greater degree than cable or jointing technology, is the matter of workmanship in the installation and construction process [7,24,43].

At the top of the list is without question the jointing and termination craftsmanship and training [4], this being identified as a critical matter to address as an Industry [10,11,12,22]. Perhaps motivated by an unfortunate perception of 11 kV cables being ‘forgiving’ in their tolerance to workmanship issues, and perhaps being

Modern cable insulation testing practises have, perhaps sadly, certainly moved on in sophistication

exacerbated in some organisations by the prevalent use of contracted services administered under a climate of inadequate levels of direct accountability and outcome performance-based results derived from suitable condition assessment techniques applied to 100% of the installations constructed, the matter continues to perplex and frustrate our Industry.

Given now that poor workmanship issues can indeed be identified upon commissioning by improved testing and condition assessment techniques [43], this approach is held out now to be pivotal in the proposed quality assurance-based concepts proposed herein. Indeed, a suitably measured quality of outcome at the commissioning phase is a recommended part of any applicable contractual relationship between the asset owner and contractor, forming part of the focus of this paper.

3.4: Testing and Condition Assessment

As commented above, the provision of cable testing and condition assessment technologies is not only very well developed [17,18,20,24] but also reasonably priced, readily applied, and implemented with minimal training burden.

Whilst most techniques are still necessarily applied to the cable in a de-energised state, on-going condition assessment is increasingly able to be conducted to good effect upon energised cable via partial discharge equipment.

A summary of the technologies employed is presented in **Table 1** below, whilst a fuller discussion on the underlying parameters and mechanisms being measured is provided in Appendix A.

TABLE 1: Summary of Technologies for Cable Testing and Condition Assessment

Technology Or Device	Testing Conducted	Mechanisms Or Effects Detected or Measured	Typical Equipment Cost (AUD +AGST)	Typical Operator Training Period (days)
Time Domain Reflectometer ("TDR")	Signature of Cable (Preferably also conducted in known good state) *	Localized deterioration of joints (water ingress etc.) or severe insulation failure	9k (for dual channel, downloadable TDR with software to compare present and stored signatures)	0.5 to 1
Sheat fault locator bridge, 10kV, with high resistance cable fault location mode also	Pre-location of sheath faults, high resistance cable faults, and ditto with flashing fault component <10kV	Sheath failure or high resistance cable fault to ground (or between phases), or flashing faults ,10kV	35k	1
Sheath fault pin-pointing device	Identifies locations of all sheath faults to ground on a cable. May be a stand-alone device or integrated into a cable fault location set or a cable fault pinpointing device or all of the above.	Failure of Cable Sheath	10k to 40k (if combined with cable fault location test set as an incremental feature)	1
Cable Fault Locator (with associated pin-pointing device)	Allows location of cable faults of a wide range or types, as well as their location on the ground.	Modern cable fault location devices are highly featured designs to pre-locate and ultimately pinpoint most fault types. Many now have powerful 'operator assist' modes to permit locations in the shortest possible time with a declining skill resource. Ideally all modern such sets have the ability, if used correctly, to minimise the number of HV impulses that the cable is exposed to, thus minimising cable insulation damage in the course of the fault but this is part of operator training	45-120k (depending on specifications, cable voltages they are designed to assist with, power/range of set, and operational features to enhance operator/device performance.	2-5
5 kV Automatic Insulation Tester	Polarization Index (PI)* And Step Voltage (SV) tests* And Sheath tests# And Screen Resistance tests#	PI: moisture ingress & surface contamination SV: Cracks and voids in Insulation Sheath: damage to outer Insulation layer over sheath Damage to screen insulation	8k (for rechargeable 0.5-5 kV fully automatic insulation tester with range to at least 10TeraOhms, configurable PI and SV testing, real-time download, and software)	0.5 to 1
Low Resistance Ohmmeter (1-10A)	Resistance across Joint Ferrules#	Poor crimping or ferrules	10k (for rechargeable 4 terminal ohmmeter with duplex handspikes, 1A min. output current, 0.1 micro-Ohm resolution, storage and download)	0.5

Low Resistance Ohmmeter (high Current)	Overall, Cable core Loop resistance#	Integrity of final built cable core integrity	16k (for switch-mode power supply design, 4 terminal, advanced connection options, selectable 200-600 A nominal current, storage and download)	0.5
Very Low Frequency (VLF) Pressure Test Set	Over voltage withstand test of cable insulation in band 0.1 to 0.02 Hz, usually at 2.3Uo rms only	Compromised insulation due to contamination or moisture ingress, severe water treeing, or electrical treeing	95 to 100K (for testing 11 & 33 kV cable). VLF Tan Delta often priced additionally (c20k) (for 0-60 kV peak sine wave field-portable VLF, with 0.1Hz nominal but also 0.02 and 0.05 Hz, cable capacitance meter, range to 5.5uF cable length)	1
VLF Tan Delta	VLF ramped voltage test of cable tan delta over range 0 to 2Uo rms*	Quantification of water tree damage in in-service cables only over 7 years old*	50k (but can be found now integrated as an optional feature, priced incrementally, in present generation VLF sinus test sets) (for real-time plotting and download of Tan delta vs. applied VLF test voltage, able to be interfaced to up to 60 kV sine wave VLF set)	1
On-Line Partial Discharge	PD level and profile, recorded via sheath conductor at time of commissioning and then optionally 3 months later for added reassurance. Localization of PD source in more severe cases*	Deterioration of cable bulk insulation, or insulation at joints and terminations. Not for detection of water treeing!	Up to 120k (For latest adaptive algorithm PD equipment for optimum signal to noise ratio and minimum possible PD level detection. Including PD location facility via external PD transponder technology, and all accessories to detect PD from cable sheath)	7+
Off-Line Partial Discharge using 'near 50Hz' test waveforms to IEEE400.4 (DAC or near square wave). Note: Now supersedes use of earlier 0.1 Hz VLF PD testing.	PD level, profile, and localization of site(s), with voltage ranges from 0.5Uo to 1.70Uo RMS (for in-service cable) and up 2.3 Uo RMS for Commissioning, with test voltages guided by IEEE400.2*.	Deterioration of cable bulk insulation, or insulation at joints and terminations. Assessment of voltage-dependency of PD. Not for detection of water treeing!	In range 420 to 450k, depending upon test voltages sought and whether additional capabilities required from same equipment (e.g.: water tree determination)	7+

* Test data & test result profile with time typically downloaded and profile kept for later condition comparison purposes.
# Test data typically kept for later condition comparison purposes

3.5: Stewardship of Cable Systems over Life

Following either satisfactorily commissioning new cable systems, or perhaps even more validity in the case of attending to existing and older cable system assets [3,13], the key determining factor to the achievement of 'maximum possible asset life' is the quality of on-going stewardship applied to the asset [3, 7, 11,14, 17, 18, 20, 21,24].

This observation has clear relevance in the NZ context, with XLPE cables having an optimistic 45-year asset life under our Industry's 'Optimised Deprival Valuation system (ODV) [66]' which is clearly unattainable without significant intervention over the life of the cable.

The key areas of stewardship are summarised in **Table 2.** Each of the categories are considered in fuller detail in appendix A2 and developed as to their combined effect in the proposals herein.

The issue of avoiding undue levels of consequential damage as a result of cable fault location procedures is an important one in which much work has been done [23]. Technology and procedures are readily implemented to assure that this matter contributes in no significant manner toward a reduction in on-going cable system integrity and life [27].

Much of the optimum stewardship techniques are only able to be delivered with the cable in a de-energised state. Clearly an issue, the most common approach taken is to ensure all relevant techniques are applied as an added part of the response to a cable fault or planned cable outage, the net costs and practicability to obtain outages otherwise generally being prohibitive.

Holding the greatest single promise in the area of on-going stewardship is on-line partial discharge surveys (Appendix A2), these now being possible through well-developed technology and in a very cost and time-effective manner.

TABLE 2: Summary of Key Aspects of On-Going Cable Management Stewardship

Technology Or Device	Testing Conducted	Mechanisms Or Effects Detected or Measured	Nominal Planned Interval of Inspection	Performed Online?
Time Domain Reflectometer ("TDR")	Signature of cable (Preferably compared to earlier-recorded profile)	Localized deterioration of joints (water Ingress etc.) or Severe insulation failure	At planned outages or during cable fault process	No, except on LV cable
5 kV Automatic Insulation Tester	Polarization Index (PI) And Step Voltage (SV) tests And Sheath tests	PI: moisture ingress & surface contamination SV: Cracks and voids in Insulation Sheath: damage to outer Insulation layer over sheath	Each of the three tests done at planned outages or during cable fault process Sheath tests not left more than annually if possible if cable has aluminium sheaths	No
Cable Fault Location via Arc Reflection or surge decay approach	Application of single HV DC impulses to Pre-locate cable faults, then pinpoint them (via radio-linked impulsing commands).	Cable fault of flashover type	Upon cable fault	No
Very Low Frequency (VLF) Pressure Test Set	Over voltage withstand test of cable insulation in band 0.1 to 0.02 Hz, usually at 2.3Uo rms only. Conducted to voltage levels outlined in IEEE400.2: 2013	Compromised insulation due to contamination or Moisture ingress, severe water treeing, or electrical treeing	At planned outages or during cable fault process	No
VLF Tan Delta	VLF ramped voltage test of cable tan delta over range 0 to 2Uo rms**	Quantification of water tree damage in in-service cables over 7 years old	At planned outages or during cable fault process if cable is purely XLPE, not water-tree inhibited & over 7 years old.	No
On-Line Partial Discharge	PD level and profile, recorded via sheath conductor. Localization of PD source(s) in more severe cases, as desirable.	Deterioration of cable bulk insulation, or insulation at joints and terminations. Not for detection of water treeing!!	12 monthly, or as condition or risk management policy of the asset owner dictates for the respective feeder (based on prior testing conducted). NB: Survey need only be 5 mins per feeder (excl. setup time), unless location directed.	YES
Off-Line Partial Discharge at 'Near 50 Hz', per Table 1	PD level and profile, recorded via coupling capacitor connected directly to conductor under test. Localization of PD source(s) in more severe cases, as desirable	Deterioration of cable bulk insulation, or insulation at joints and terminations. Assessment of voltage-dependency of PD Not for detection of water treeing!!	At commissioning, and/or as condition or risk management policy of the asset owner dictates for the respective feeder (based on prior testing conducted and risk profile so generated by the test report).	No

** Not suitable for application to hybrid connections of XLPE and paper cable, as paper cable likely to dominate results.

3.6: Avoidance of THIRD-PARTY damage

Third party damage to cable systems is widely acknowledged as being one of the significant causes of premature cable failure and Minutes lost [11,24,43,45], not to mention being increasingly seen as an unacceptable imposition to stakeholders and asset owners alike [25]. Perhaps less relevant to this discussion, but still of major significance is the matter of the health and safety outcomes that also arise from such incidents.

In essence, third party damage is almost totally preventable given a suitable will and 'buy-in' of the requisite preventative measures by all stakeholders and underground asset owners in a given region.

An innovative work [25] published in New Zealand in 2004 calls for New Zealand and Australia to embrace a proactive policy of a quality-of-outcome based approach to underground detection and excavation methodology common to all buried assets and set by statute. Based upon proven new technologies and field-tested methodologies, the concept is reported to hold significant promise of mitigating in the near term this concerning area of risk to cable longevity.

4. A Quality Assurance Outcome Approach for Commissioning of New MV XLPE Cable, and Condition Assessment of In-Service MV Cable:

A new, innovative, and patented concept by the Author will now be discussed which addresses the issue of maximising both MV cable asset life and reliability through the use of a quality assurance-based methodology. The concept collates the progressive cumulative effect of combining the individual tools of 'best practice' techniques and appropriate responses to underlying failure mechanisms, presenting them instead as delivering an integrated spectrum of outcome quality. Against this outcome, one may balance aspects of remaining strategic risk against policies established by the Corporate Governance level of management, the cost of performing the process to a given level of quality, and the time burden to do so.

4.1 A Quality Assurance Outcome Approach for Commissioning of MV XLPE Cable Systems.

The purpose of a sequence of after-laying testing of MV cable systems is to determine and verify the quality of installation [16,20,24,43].

A review of the cumulative impact of suitable testing and condition assessment practices applied to the context of the commissioning of new XLPE underground cable systems is proposed in Table 3.

TABLE 3: Chances Of Achieving an Initial 3 Year Trouble-Free XLPE MV Cable Life

Testing Sequence	Cumulative Outcome (% chance of getting a first 3 year trouble-free cable life)	Total Testing Time Burden (minutes), assuming a three phase MV cable (Including discharging after test. Excluding test set up times).	Notes
Install cable with NO testing as the cable is built up and just a 'basic' Megger test, suitably guarded (i.e.: no more than a 5-minute test, with NO temperature-corrected results) before livening	"Nominally 40%" *	<35 for 3ph cable	*With the rider that the range can be 30-70% (dependent upon training, quality of workmanship, and quality of jointing materials) but that it is weighted at the low AVERAGE of 40% in view of the overwhelming amount of the literature commenting on joints and terminations being the Achilles heel of the constructed cable, as well as the inability of such basic testing to expose these issues adequately. No figure is given for no testing prior to commissioning for obvious reasons.
Install and test as one goes per suggested practices of 5 kV SV & PI, suitably guarded, and 1 kV sheath test. All results temperature-corrected	55%	56-61 per completed section	.
Install and test as one goes per suggested practices of 5 kV SV & PI, suitably guarded, and 1 kV temperature-corrected sheath test. Plus, low current 4 terminal Ductor test across joint ferrules during jointing, as practicable, or at the very least a high current 'whole cable' Ductor test on all three phases after final build, prior to cable connections to final configuration being made off.	60%	58-63 per completed section Plus 2 minutes total for final Ductor test of over overall cable.	Tests should ideally be conducted after joining each cable section, at minimum finishing with the whole cable upon its completion. This ensures the integrity of each installed section is monitored and verified throughout the construction process, with any defects identified being addressed before joining the next section. Time is based upon 55-60 min for the total insulation testing plus 1 min for sheath test, 1 minute for Ductor testing of each joint as built up, (depending on extent), and 1minute total for final high current test of built cable
Install and test as one goes per suggested practices of 5 kV SV & PI, suitably guarded, and 1 kV temperature-corrected sheath. Plus, Ductor testing of cable sections as above. Plus, VLF to 2.3 Uo rms (values per IEEE400.2: 2013 Acceptance levels) for 30 min per phase	65%	93-98 min total	Based upon 55-60 min for the total insulation testing, plus 1 minute for the sheath test, plus 3 minutes for the Ductor tests plus, 31min for the combined-core VLF test (allowing 1 min discharge following the test). Also based upon premise that cable may be VLF tested with all three phases paralleled. Notwithstanding, if time permits it is preferable to test all cores individually for relative comparison purposes. Figures opposite are for the total final commissioning testing and exclude testing time per completed section during construction. Note: Contribution at 30 minutes would be a minimum acceptable figure below which VLF testing has been shown to be of minor value.
Install and test as one goes per suggested practices of 5 kV SV & PI, suitably guarded, and 1 kV temperature-corrected sheath. Plus, Ductor testing of cable sections as above. Plus, VLF to 2.3 Uo rms (values per IEEE400.2: 2013 for Acceptance Testing) for **60** min per phase	75%	123-128 min total	Based upon 55-60 min for the total insulation testing, plus 1 minute for the sheath test, plus 61min for the combined-core VLF test (allowing 1 min discharge following the test). Also based upon premise that cable may be VLF tested with all three phases paralleled. Notwithstanding, if time permits it is preferable to test all cores individually for relative comparison purposes. Figures opposite are for the total final commissioning testing and exclude testing time per completed section during construction. 60 minutes is the accepted norm. Being a 'blind test', the overall contribution of VLF testing conducted to IEEE400.2:2013 for 60 minutes has a forward visibility of around 2 years [59]. Thus, the contribution to total confidence over a 3-year period is restricted.
Install and test as one goes per suggested practices of 5 kV SV & PI, suitably guarded, and 1 kV temperature-corrected sheath. Plus, Ductor testing of cable sections as above. Plus, 'near 50Hz' Cosine-rectangular VLF pressure test, monitoring and recording ***calibrated*** PD throughout, to voltage levels of IEEE 400.2: 2013 at Acceptance levels, but for 15 minutes. Test each phase to sheath.	95%	108-113 min total, including 5 min. for calibration process for PD measurement	Result is a PD plot of pulse count, plus discharge level in pC, and distribution down cable, with each joint flagged on the test sheet. Process is predicated on: the noise floor being lower than in-service testing Any sites of PD are well below 300pC, and ideally near-zero, and of low site activity Action being taken by asset owner from the report to address any sites of concern prior to commissioning and putting cable into service. **This step is critical!**

Install and test as one goes per suggested practices of 5 kV SV & PI, suitably guarded, and 1 kV temperature-corrected sheath. Plus, Ductor testing of cable sections as above. Plus, 'near 50Hz' Cosine-rectangular VLF pressure test, monitoring and recording ***calibrated*** PD throughout, to voltage levels of IEEE 400.2: 2013 at Acceptance levels but for 15 minutes. Test each phase to sheath. Plus, **having implemented the above process prior to cable commissioning,** conducting an on-line *calibrated* PD survey (via HFCT on sheath earthing conductor) after 6-12 months from commissioning date to confirm that cable load cycling has not established any new or deteriorated PD locations. This would be especially wise for cables with Aluminium cores.	98%	108-113 min total, including 5 min. process for PD measurement Plus 5 mins for on-line survey	Result is a PD plot of pulse count, plus discharge level in pC, and distribution down cable, with each joint for calibration flagged on the test sheet. Process is predicated on: d) the noise floor being lower than in-service testing e) Any sites of PD are well below 300pC, and ideally near-zero, and of low site activity Action being taken by asset owner from the report to address any sites of concern prior to commissioning and putting cable into service. **This step is critical!** On-line PD Survey should be compared to the U0 figures taken from the prior off-line survey, noise floor permitting.

NOTES:

a) The figures above assume that the cable is correctly specified, is manufactured, tested during manufacture to IEC 60502.2 or equivalent for insulation and PD levels, transported to site with no damage, has end caps secured until jointing, is handled and laid to best practice methods, is jointed to best practice with best practice methods, is backfilled with correct thermal backfill for intended loading, and is operated subsequently to designed loading levels. Failure to attend to any of these details, or to accept lesser levels of quality in these areas, may reduce the levels of quality outcome above (the testing practices suggested assisting markedly, to within their quality bands nominated, to identify many of the likely such issues prior to their impinging upon outcome quality or reliability).

b) The "Cumulative Outcome %" figures given are determined from both empirical field observations and published material. They are intended as guidelines and serve to illustrate the proposed concepts from a standpoint of their relative weights of contribution to the expected outcomes from each combination of interventions. Some range of variation in the absolute values would be the case but their relative weightings would not vary. Except for the lower levels of intervention (where unexposed gross initial workmanship issues may still linger and inject less certainty accordingly), this is not expected to widen the bands by more than +/- 5% for a given set of tests and, arguably, even less so between the hierarchy of the various levels of intervention.

c) Joint ferrule compression and overall joint resistance integrity tests are also important to the outcome quality and to on-going reliability. The quality levels quoted above assume the satisfactory completion (as practicable) of a 10 second 4 terminal 10A micro-ohmmeter test across each compression joint ferrule during each joint construction. An optional high current micro-ohmmeter test of the completed cable core resistance 'loop' is also suggested, this taking 20 seconds per 'loop' measured, adding up to 1 minute of testing time maximum.

d) Old 24-hour soak testing concept has been dismissed as of no worthwhile validity for MV cable commissioning.

e) Following the VLF testing, an optional 60 second Dielectric Absorption Ratio (DAR) test [i.e.: (60 sec reading) / (15 - 30 second reading, depending upon cable parameters)] is suggested per phase to verify cable insulation integrity after the pressure test. As earths are then placed on the cable following the testing and prior to livening, no discharging time per test need be allowed for in the testing time.

f) VLF Tan Delta testing at commissioning is NOT recommended. More recent evidence suggests that water tree retardant chemicals have a settling in period for up to the first 7 years of cable energised life and can give misleading or confusing results if carried out prior.

Cable condition assessment is a bit more complex than it used to be!!

5 QUALITY ASSURANCE OUTCOME APPROACH FOR ACHIEVEMENT OF “THEORETICAL MAXIMUM PRACTICAL LIFE SPAN OF OPTIMAL RELIABILITY” OF MV XLPE CABLE SYSTEMS

A review of the cumulative impact of suitable cable management, testing, and condition assessment practices applied to the context of the achievement of theoretical maximum lifespan of XLPE underground cable systems is proposed in Table 4.

TABLE 4: Chances Of Achieving a Theoretical Maximum Practical Lifespan AND Optimal Reliability for XLPE MV Cable

Process(s)	**Cumulative Outcome (% chance of getting to maximum theoretical cable life)**	**Total Additional Testing Time (minutes) per testing event. Burden of technique(s) proposed (minutes), assuming a three phase MV cable (Including discharging after test. Excluding test set up times).**	**Notes**
Do nothing in the nature of a pro-active / targeted condition assessment or life-prolonging initiatives	40%	Nil	
Perform a calibrated on-line PD survey on bi-annual basis but take no other initiatives.	55%	10	
Perform a calibrated on-line PD surveys on a bi-annual basis , PLUS do controlled DC impulse testing during occasions of fault location (i.e.: limiting the total number of impulses via state of the art cable fault pre location equipment and radio-linked impulse generation / pin pointing surveys), PLUS do temperature corrected SV / PI <u>and</u> 1kV sheath testing on <u>all</u> occasions of planned outage*	65%	a) Normal annually: 10 min b) At the time of a cable fault or outage (including insulation and sheath testing): 66-71 min total	Based upon 10 minutes for the annual PD survey, plus 55-60 minutes total for the PI and SV testing, and 1 minute for the sheath testing. Also assumes that the controlled DC impulse testing cable fault location procedures adds NO testing burden (whereas in fact it generally reduces testing time burden in reality).
Perform a calibrated on-line PD surveys on bi-annual basis, PLUS do controlled DC impulse testing during fault location (i.e.: limiting the total number of impulses via state of the art cable fault pre location equipment and radio-linked impulse generation / pin pointing surveys), PLUS do temperature corrected PI / SV and 1kV sheath testing on such occasions of outage, PLUS perform VLF testing (using IEEE400.2:2013 for Maintenance testing) for 60 minutes **after all repairs or occasions of planned outage*.**	75%	a) Normal annually: 10 min. b) At the time of a cable fault: 127-132 min.	Based upon 10 minutes for the annual or post-repair PD survey, plus 55-60 minutes total for the PI and SV testing, plus 1 minute for the sheath testing, Also assumes that the controlled DC impulse testing cable fault location procedures adds NO testing burden (whereas in fact it generally reduces testing time burden in reality).
ALTERNATIVE METHOD TO ABOVE: Substitute an off-line ‘Near 50 Hz calibrated Damped AC [‘DAC’] to IEEE400.4 PD test, (carried out at 0.5Uo, 0.7Uo, Uo, 1.3 Uo, 1.5Uo and 1.7 Uo) for the 60 min VLF sinus test#. (note: results of ‘near 50 Hz PD’ test will inform optimal next inspection interval).	85%	a) Normal annually: 10 min. b) At the time of a cable fault: 46 min	#The DAC PD test takes about 15 minutes per phase … total of 45 mins, PLUS avoids the need for the SV and PI tests, AND (not being a blind test and with all PD data captured per phase) has a higher confidence level that single voltage on-line PD.
Do controlled DC impulse testing during fault location, **PLUS arrange a planned shutdown at no wider than <u>4-year</u> intervals** (note: results of PD test will inform optimal next interval, but it should not be more than 4 years, assuming no fault repairs in that period) and do: Temperature corrected sheath testing, PLUS an off-line ‘Near 50 Hz calibrated DAC’ PD test, (carried out at 0.5Uo, 0.7Uo, Uo, 1.3 Uo, 1.5Uo and 1.7 Uo) for 15 mins per p, PLUS do VLF tan Delta testing to IEEE400.2: 2013 at the same time if appropriate**	93%	59 min total	Based upon 1 minute for the sheath testing, plus 45 min for the ‘near 50Hz PD’ test (allowing 1 min discharge following each of the 3 tests), plus 10 minutes for the VLF Tan Delta testing. Also assumes that the controlled DC impulse testing cable fault location procedures adds NO testing burden (whereas in fact it generally reduces testing time burden in reality).

Perform continuous PD monitoring of the cable via sheath earth connection, PLUS do controlled DC impulse testing during fault location, PLUS arrange a shutdown at no wider than 4-year intervals (note: results of PD test will inform optimal next interval but it should not be more than 4 years, assuming no fault repairs in that period) and do: Temperature corrected sheath testing, PLUS an off-line 'Near 50 Hz calibrated DAC' PD test, (carried out at 0.5Uo, 0.7Uo, Uo, 1.3 Uo, 1.5Uo and 1.7 Uo) for 15 mins per phase, PLUS do VLF tan Delta testing to IEEE400.2: 2013 at the same time, if appropriate**	96%	59 min total	The addition of a continuous PD option offers a small degree of additional risk management to the good forward visibility offered by the more rigorous analysis of the DAC offline tool. Specifying a nominally 4-year retest interval for the DAC, plus other relevant attributes of the cable, may be viewed as the ultimate presently practicable MV cable stewardship effort.

NOTES:

a) The figures above assume that the cable is correctly operated to design loading levels and is jointed after repair to best practice with best practice methods. Failure to attend to these details, may reduce the levels of quality outcome above (the testing practices suggested assisting markedly, to within their quality bands nominated, to identify many of the likely such issues prior to their impinging upon outcome quality or reliability).

b) The "Cumulative Outcome %" figures given are determined from both empirical field observations and published material. They are intended as guidelines and serve to illustrate the proposed concepts from a standpoint of their relative weights of contribution to the expected outcomes from each combination of interventions. Some range of variation in the absolute values would be the case but their relative weightings would not vary. Except for the lower levels of intervention (where unexposed gross initial workmanship issues may still linger and inject less certainty accordingly), this is not expected to widen the bands by more than +/- 5% for a given set of tests and, arguably, even less so between the hierarchy of the various levels of intervention.

c) *Joint ferrule compression tests are essential also to reliability. The quality levels quoted above assume the satisfactory completion (as practicable) of a 10 second 4 terminal 10A micro-ohmmeter test across each compression joint ferrule during each joint done during cable repair. An optional high current micro-ohmmeter test of the completed cable core resistance 'loop' is also suggested, this taking 20 seconds per 'loop' measured, adding up to 1 minute of testing time maximum.

d) **In respect to VLF tan delta testing, this assumes cables being tested are not manufactured with TR-XLPE dielectric (i.e.: very old NZ XLPE cables of some 35-40 years of age, or ones made in Australia, or ones made offshore with no clear TR-XLPE component added), although such tests would remain good practice were there to be mixed XLPE and PILC, or sheath tests have not been done <2 years prior. There is less requirement to conduct this test if using modern TR-XLPE cable AND sheath testing has been kept current and is in good health.

e) In respect to the 'Near 50 Hz calibrated off-line PD test' being applied to 'in-service' MV cables, this is carried out typically in the 'Damped AC' ['DAC'] mode (to IEEE400.4). Tests are conducted at 0.5Uo, 0.7Uo, Uo, 1.3Uo, 1.5Uo, and 1.7Uo. The test report will contain a clear map of the cable, all known joints, the level of PD per phase and test point (PD level in pC and PD pulse count over the test voltages) and allow the asset engineer to plan any appropriate interventions, or even partial cable overlays, in an efficient and economic manner.

f) Given the impact of matters beyond the scope of testing and condition assessment equipment, such as third-party damage and operational/loading history, it is not a simple matter, and indeed quite beyond the scope of this paper, to speculate on the potential ***actual*** lifespan (in years) of any given cable system. Nor is it similarly possible to comment upon the specific quantum of the actual cable lifetime contributions of the "Cumulative Outcome Percentage" figures to the maximum possible life that might be achieved by the employment, or otherwise, of the methods proposed. For this reason, plus the realities of not being able to obtain unlimited time or unlimited opportunity to inspect a cable optimally, cumulative outcome percentages are only ever asymptotic guides toward the achievement of an idealised 100% figure, which of course can never be obtained.

In speaking to this point on general terms, however, it would be fair to say that for the lower levels of intervention presented a 'significant' effect on the reliability and general condition of the cable might be expected in the first quartile of its anticipated reliable lifespan.

For newer cable designs employing the likes of TR-XLPE, water blocking etc, the major issues will lie in joints and terminations and the higher order interventions will have a dramatic improvement on life extension toward as much as a 50-year figure and will be a totally essential contributor to that life being achieved.

6 WHERE TO BEGIN TO ASSESS CONDITION OF 'IN-SERVICE' MV 11-33V CABLE WHEN FIRST ENCOUNTERING IT:

When encountering an MV 11-33 kV feeder for the first time for the purposes of assessing its condition and determining 'next steps', the following essential steps are recommended:

a) De-energise and earth the cable

b) Remove Sheaths from ground

c) Conduct a temperature-corrected 1kV sheath test for 1 minute and determine if it requires a response (if so, advise asset engineer that a location and repair of all noted defects will be required until the tests show acceptable condition). *Ideally, the sheath should be of good integrity prior to conducting the PD tests below.*

d) Reconnect sheath.

e) Conduct an off-line 'Near 50 Hz calibrated DAC' PD test. To do this effectively, prepare each phase in turn, and prepare the heading page of the test report (cable details, type, name, length, position of all joints known on the cable, and composition of each section of cable (if mixed XLPE and PILC). Prepare a PD-free connection (such kits are typically supplied with the devices) for the first phase to be tested, calibrate the equipment, and prepare the cable plan for the test report. Conduct several successive 'shots' of DAC impulses, beginning at 0.5Uo and ranging through 0.7Uo, Uo, 1.3 Uo, 1.5Uo and 1.7 Uo) for about 2 mins per phase. Discharge after the test and repeat for next phases in turn. Finalise report and add any pertinent observations to allow asset engineer to determine condition and whether there is any requirement for action (such as addressing a single joint issue, or planning a partial cable overlay to address areas of issue), or whether the condition is such as to instruct a re-test at a later date of their calling, or to take no further action until the nominally 4 year next test period falls due.

f) If merited, conduct a VLF sinus 0.1 Hz Tan Delta test to IEEE400.2 and assess results. Note: this test is a global condition assessment, and no locations of issue are possible. It may corroborate moisture ingress from a sheath issue, but indications of poor tests from water-treeing would be rare in New Zealand. If there are sections of PILC cable in the cable circuit, these sections will dominate the readings, so an experienced eye is important in making such an assessment. As mentioned in the earlier notes, this test should NOT be routinely conducted if the cable is XLPE and under 7 years old.

g) After any mitigations that follow the actioning of the report by the asset owner, re-test as above to determine the efficacy of the actions taken, and that the cable has no appreciable issues remaining prior to recommissioning it.

Note: These are very 'high confidence' tests and, if conducted suitably, will provide a very suitable base to profile the cable condition and begin a condition-based management regime.

7. Observations and Conclusions:

Power system assets have traditionally been managed by an essentially ad-hoc application of various 'industry-accepted practices.

In the case of MV cables, our Industry has observed over the past 20 years both a flowering of excellence in the subject, then more recently a declining degree of effort and awareness in the commissioning of such cables, in particular. MV cable condition assessment has long been and remains (with few exceptions presently in New Zealand) very weak, too often confused with historic MV cable reliability.

Until comparatively recently, few companies guided their Asset Managers with a clear set of risk management policies and objectives drawn up at the corporate governance level [1]. As a corollary, the declining absence of such policies has effectively prevented the implementation of a suitably co-ordinated approach to MV cable asset life management derived from a more appropriate deployment of such practices.

In response subsequently to a wider perception at the governance level of not only the risks posed by older assets to the security and viability of the power industry but also their obligation to shareholders and stakeholders alike for an adequate level of asset stewardship, such directives are progressively being formulated.

New and emerging drivers, in particular the relatively sudden imposition of a substantial and unavoidable rise in MV cable loading to meet the 2050 low carbon load demand forecasts, coupled with very constrained network growth budgets and constrained market pricing barriers, have shaken our Industry. Consideration is now being given as to how best to achieve with confidence both a reliable and feasible very significant upgrading of 11-33 kV loadings by 2050.

A majority of MV cables is (currently) of unassessed condition. With time being of the essence to determine same, and thence to make good any defects and then pivot to embark on a programme to ensure these cables remain reliable under imminent loadings at a level neither seen prior nor forecast when constructed, the need for a practical and feasible condition assessment and formal cable management regime is paramount.

The concept of applying a quality-of-outcome methodology to the management power system assets, presented herein, is a timely one. Coupled with the recent availability of a comprehensive and practically applied suite of diagnostic tools, the concept offers an appropriate response to meeting emerging commercially constrained, but ambitious, corporate risk management directives.

APPENDIX A: A REVIEW OF THE MECHANISMS AND TECHNOLOGIES OF CABLE MANAGEMENT

The basic insulation quality of MV cable is essentially determined by the net response of the cable dielectric to a single polarity (negative to earth) pressure of nominally 5 kV DC. In the presence of such an imposed condition, the cable dielectric will produce a time-based response in the manner of the current drawn from the DC source. This response is a net effect of three main component signatures acting in their own right [26]:

- capacitive, (or charging) current as a direct result of the capacitive nature of the cable. In general, this is a short-duration effect dictated solely by cable design parameters. It is of little diagnostic value.

- leakage current of constant level arising from a steady-state leakage path across or through the bulk insulation, primarily as a result of contamination or steady-state insulation deterioration.

- absorption current as a result of the net effect of the alignment of the insulation dipole molecules in the presence of the electric field. This current is primarily influenced by the degree of water molecules ingress within the bulk insulation, taking longer to decline as more water molecules are present.

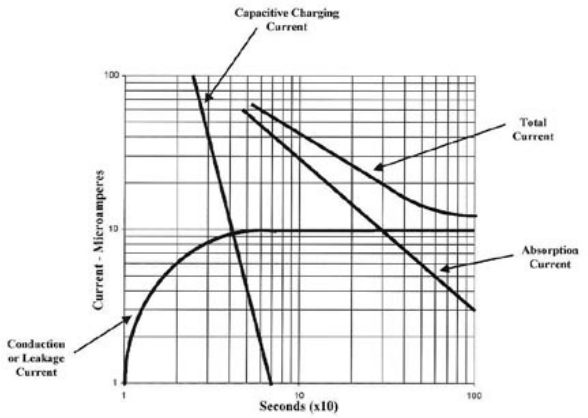


Figure 1: Component and composite effects of cable Insulation

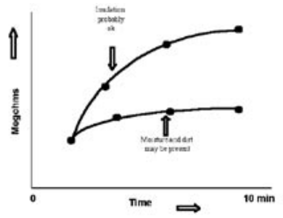


Fig 2: Good Insulation Shows Increasing Resistance Over Time

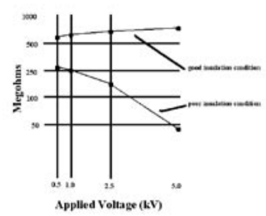


Fig 3: Good insulation stands increasing voltage


Figure 4: Use of an Automated 5 kV insulation tester to commission MV XLPE cable

Figure 1 depicts this net effect, the inverse of which is an insulation profile against time. Good dry insulation has the effect of an increasing level of insulation resistance with time (Figure 2), typical times to judge this over being 10 minutes for older insulation or as little as sub 1 minute for modern XLPE in shorter lengths. The ratio of the insulation resistance at 10 minutes divided by the insulation resistance after 1 minute, is known as the Polarisation Index of the cable and is generally in the range 1.5 to 2.5 for XLPE cable. Modern XLPE testing focusses increasingly on such ratios taken at between 15, 30, or 60 seconds (known then as Dielectric Absorption Ratios, 'DAR') and favours a shorter overall PI test as it tends to stabilise quicker in XLPE (more typically <1 minute for shorter lengths), due to its greatly superior insulation properties over older PILC. The ingress of moisture and conductive ions in 'generic' insulation lowers this level to nearer, or below, unity, particularly in 'generic' insulation.

Insulation figures for XLPE are extremely high and may reach over several Tera Ohms for shorter lengths of MV cable. It is imperative that one uses a tester with adequate specification to cover this measurement range, and also that one ensures that suitable guarding is in place at both ends of such cable (and that both ends are prepared correctly for test) to avoid misinformation as a result of surface leakage effects.

Bulk insulation of cables also exhibits a voltage dependence, exposed by way of the response of the insulation to a single polarity DC signal of between 1 and 5 kV, generally applied in equal voltage steps of 20% of the end level over 5 equal time periods, typically one minute each in duration. This so-called Step Voltage response (Figure 3) exposes insulation deterioration through cracks and voids, good insulation showing an increasing insulation figure with applied voltage in this band, and defective insulation an ultimate decline as the voltage is raised [28].

Being important condition indicators in their own right with validity for later comparison in characteristic to determine changed cable condition, both Polarisation and Step Voltage characteristic 'curves' should be recorded in full [22,29].

Temperature [30,31] plays a major part bulk in actual dielectric insulation levels observed, the effect decreasing the insulation as temperature is raised. Whilst the precise effect is a property of the insulation type involved and should be obtained for each cable type used if practicable, a rule of thumb is that for every 10 degrees above 20C, the insulation resistance will halve. Importantly, the signature of each of PI and SV will not generally change in profile with temperature although the actual SV values will and must thus be corrected to a standard temperature of 15.6 C nominally. PI being a ratio, the Index itself is generally unchanged with temperature.

Popular opinion might suggest that diagnostic cable insulation tests as described above will show more valid detail at elevated levels of around 10 kV DC, but this has not been shown to be the case and should not be practiced.

A2 PARTIAL DISCHARGE

A2.1 INTRODUCTION

Partial discharge ('PD') in any part of an XLPE cable or in resin-style joint and terminal kits used in the construction of the overall cable system is a destructive mechanism that will ultimately and inevitably cause the failure of that portion of the cable system. The magnitude and pulse count of the PD activity serves effectively to determine the severity of the destructive process [8,11]. Although the magnitude of the PD pulse may be modulated by the nature of the underlying PD site and nature of the materials at the PD site itself (often correlating to cable loading patterns) [8,36], the PD mechanism once started rarely ceases [38] and may thus be used as a reliable indicator of both severity of the problem and, when trended and qualified, an indicator of the time to failure [5,6,8,11,13,36,37].

Given that the voltage gradient in a solid dielectric decreases exponentially with distance from the cable core [4,39], it is more probable in the cable itself that PD would initiate near the core and proceed to progressively degrade the insulation locally via carbon tracking in the immediate area of the initial site. Once such a process begins, these carbon tracks progress toward the sheath on an increasingly wide front, exacerbated in scale as the remaining thickness of dielectric in that area is reduced and as the localised voltage gradient is consequentially increased. The resulting network of carbon tracking is aptly termed an 'electrical tree', and this finally compromises the remaining insulation to the point that it flashes over, causing complete failure of the cable itself [8].

Whereas in older XLPE cable the manufacturing processes, materials used, and purity levels employed often provided the catalyst for PD activity in the dielectric itself, modern practices and testing during manufacture limit the PD level below any level of concern. The cable dielectric from reputable makers may now be considered as a highly unlikely cause of PD activity [9,10,34]. Where the trouble lies more particularly currently is in the control of the voltage gradient between the various insulation layers (known currently more as the 'layered interfaces') between core and sheath of the resin-type joints and terminations used to compete the cable system itself. Any insulation discontinuities that are such as to flash over under the voltage gradients that exist at that point will initiate PD [4] and, as we have noted earlier (Section 3.2), this is a common problem in such accessories.

Partial discharges (PD) in voids and cavities will produce very similar pulse shapes with very fast pulse widths of a few tens or hundreds of picoseconds being typical. In the special case of PD in cables, the cavity responsible

Figure 5: HF CTs installed on sheath earths of 33 kV cable

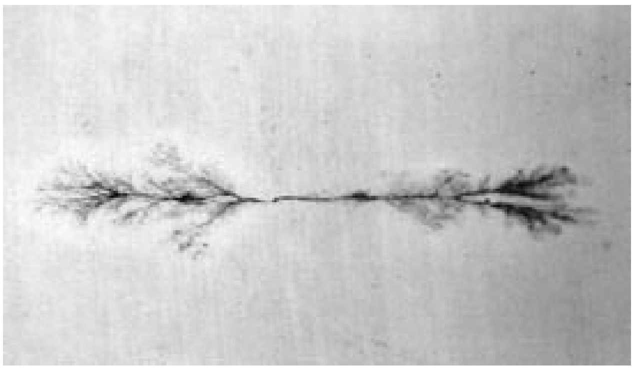


Figure 6: An electrical tree in XLPE

for the PD discharges into a real impedance (the 'surge impedance' of the cable) which is purely resistive at the point of launch. The resulting PD pulse is virtually monopolar with a fast pulse rise time and very short pulse width [7,21]. This pulse travels outward in both directions from the originating site, arriving at the detection point (generally at a switchgear termination) both wider and smaller, due to dispersion and attenuation respectively, during its travel along the cable to the measurement point. Detection of the pulses is simply achieved via high bandwidth (approx. 100 MHz for XLPE cable) split core CTs attached to the XLPE cable sheath earthing conductor (Figure 5), or via a suitable coupling capacitor in off-line PD test systems.

As the PD pulses travelling down the cable to the termination have an equal and opposite polarity on the conductor and screen respectively it does not matter whether (in the on-line PD measurement scenario) the HFCT's are placed in the earth strap, or the conductor. The important criterion is that only one of the earth or conductor currents is intercepted (if they are both intercepted then they effectively 'cancel each other out') [21].

At a simplistic level, cables with high PD activity can be classified as having a greater risk of failure than cables in which no PD activity can be detected [8,11,13]. Were PD activity to be identified in XLPE cable systems, the next process is to prioritise the defect severity by magnitude and pulse count, whereupon the defects which are causing the PD may need to then either be monitored further if the levels are presently not yet sufficient to concern, or be located (via on-line or off-line PD Mapping) and an action plan drawn up for what to do next (repair, replace, PD monitoring etc) [7,14,21,35,37,38].

In tandem with an increased level of performance quality of field partial discharge survey equipment [21], both on and off-line, PD testing is becoming increasingly viewed as the best diagnostic methodology for cable insulation [6,7,8,11,13,14,21,24,33,35,36,37,38,43], both at commissioning and when the cable has seen operational service. Clearly this applies primarily to insulation which both may exhibit and be degraded by PD activity. For insulation systems, such as XLPE cable installations, which is designed to be PD-free the knowledge gained through testing that the system actually is PD free is still a vital part of the diagnostic process [32,33].

On-line PD testing can also be used as part of the commissioning process for new cable installations to ensure cable accessories have been made-up correctly [33]. The advice that all MV XLPE cable distribution systems should be discharge-free is not debated [32,33].

The latest generation PD detectors are capable of reading on-line PD discharges in pC. UK research with such equipment [67] proposes the following key levels in pC 11kV XLPE cable: 0-250 pC ('discharge within acceptable limits'), 250-500 pC ('some concerns, monitoring recommended'), and > 500 pC ('major concern'). Mixed XLPE / PILC runs are viewed as more complex to quantify, as a result of the known propensity of PILC cables to exhibit PD in normal operation or especially if papers are gaining and drying, and cable mapping PD techniques are recommended in this situation [67].

Most polymer-based insulation now has stringent manufacturing standards [9,10,42,43] which set (at least in the type test) a PD level of better than 10pC [20,33] and more typically under 5 pC [9,10]. Mackinlay [33] proffers that it is difficult to see that properly installed plant which is discharging less than this level is going to fail by insulation failure. As earlier commented, all other failure modes can be addressed with on-going maintenance and stewardship programs.

A 2.2: Factors Influencing the Weighting of PD Measurements (After [33])

Operating Voltage

As the voltage increases, the same size PD becomes more serious. This is partly because the stresses tend to increase in larger voltage plant, partly because there are simply more volts available, and partly due to the geometry. Probably a rough rule would be to weight the voltage level linearly. Hence a discharge of 50pC in a 33kV system would be three times more damaging than the same size discharge in an 11kV system. Again, these depend on geometry, type of PD event, location etc, but the rough scaling is there.

Type of discharge

Internal PD events in dielectric cavities tend to be the most damaging. The 'daughter' products from the PD events remain within the cavity (these can be acids, corrosive chemicals, or simply active elements from the gases in the discharge). No ventilation is possible, and cavities like this almost always end up in failure. The timescale is the only variable. The important aspect here is the damage the PD events due to the surrounding insulation.

Insulation materials

The materials of the insulation are critical to cable longevity. Unlike PD between the likes of porcelain and metal parts which has almost no effect on the materials, with polymers this is not the case. The rate and route of deterioration will depend on the nature of the degradation of the insulation material.

Thermo-mechanical variations

The effect of load (i.e. temperature) is vital in the development of discharges. The variation with temperature can occur simply because the insulation is hotter. Polymers (both thermosetting and thermoplastic) will become softer and less resistant to PD as they heat up. Temperature variations can also produce a large change in the mechanical movements of the equipment as the components expand, particularly in cable accessories. Movement at terminations and joints are a good example of this, particularly in the case of aluminium cored cable with

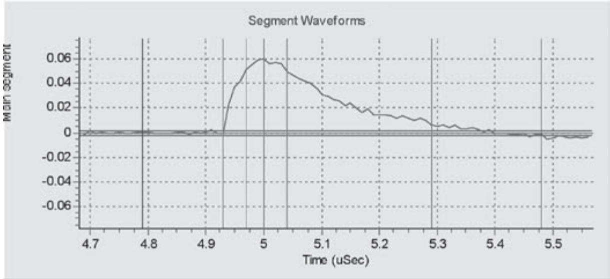


Figure 7: Pulse from a PD site in a cable... after 21)

its very high coefficient of thermal expansion. These movements can give rise to a large change in the PD activity due to stresses in the layered interfaces, depending on which parts of the high voltage region they move or distort.

Mechanical movement

Clearly the movement of parts in the high voltage system can cause PD to appear, increase or (rarely) decrease. More typically it tends to modulate measured on-line PD amplitude.

Environmental conditions

The effect of temperature and humidity is a vital component of damage due to PD activity and is manifested more commonly at the resin-type cable terminations.

A 2.3: Measurement Technologies for Surveying PD On-Line and Off-Line.

Recent innovation in the use of software algorithms and supporting PD pulse recognition techniques, first released commercially as early 2005 [21,41], have served to revolutionise the consistent applicability of on-line PD surveys in the presence of the range of background noise sources in the typical measurement environment.

A typical, monopolar cable PD pulse is shown below in Figure 7 with computer-generated cursors to measure the rise time, fall time, and other pulse properties. Such cursors are reported to provide key fiducial markers to permit reliable PD pulse recognition even after the loss of original amplitude and frequency content following transmission to the measurement point.

Work conducted in a co-operative fashion by various UK-based companies [6,14,21,41] resulted in the first commercially available field survey PD equipment over 20 years ago (Figure 8), but in very recent times most larger test equipment makers have presented viable on-line PD measurement devices. Conversely, a very small number of makers have, in parallel, now commanded the well-established off-line PD survey industry.

Such outcomes have collectively contributed four main advancements in on-line MV cable PD management:

-the availability at fair prices of a means to ensure MV cable PD can be competently assessed at commissioning and in service by readily trained field technicians

-major improvements in signal to noise measurement than earlier-generation conventional gating and background subtraction methods

-ability to 'see' significantly further down the cable when investigating PD

-the ability to detect smaller levels of PD than previously possible, giving an advance warning of the early initiation of PD or, conversely, the ability to apply the technology to HV cables where signal to noise constraints have previously prohibited the technique.

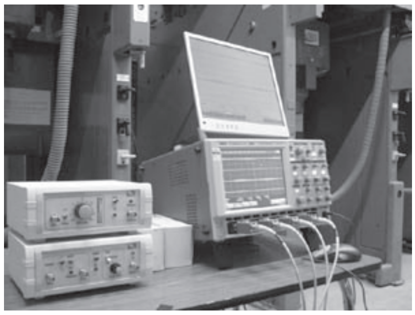


Figure 8a: An example of c2005 era, but highly, capable PD field survey instruments incorporating PD pulse recognition technology.

Figure 8b: An illustration of a current generation on-line cable PD measurement device

Having quantified the level of PD on a given cable via portable PD survey equipment, one may further qualify and trend PD in cases where the initial survey suggested such efforts might be merited. On-line PD monitoring, generally conducted in an episodic on-line fashion, provided access to sheath earths is practicable, is increasingly practiced in some networks as a policy [7,14,21,45] with the attraction that it may be simply deployed on critical cables in a proactive fashion.

A2.4: A Discussion on Off-line PD Technology Methodologies and Advancements:

Whilst continuous on-line PD trend recording units are also now employed to good effect [40 et al], off-line PD surveys are viewed by the international MV cable market as offering major advantages, due not only to the attributes of the concept per se but also to several key technology attributes brought to the market in scale during the past 10 years.

The key technical advantages of off-line PD testing of

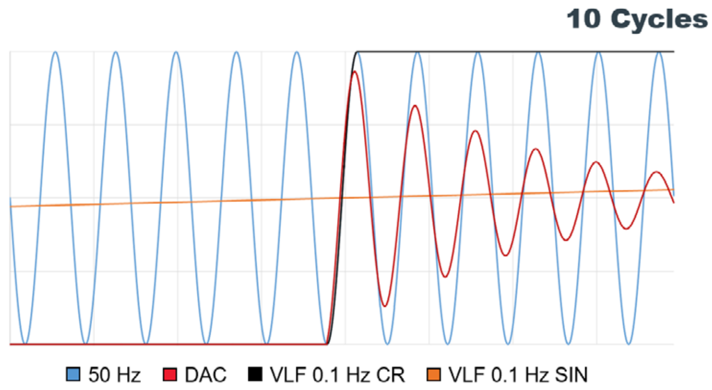


Image of 10 cycles of different waveforms potentially used for PD testing...Damped AC, VLF 0.1 Hz Cosine Rectangular, VLF 0.1 Hz sinus, compared to a 50Hz waveform

One example of a practical 'near 50Hz PD' offline diagnostic test set

MV cable over on-line PD testing are:

-The unique ability to carry out *calibrated* PD testing to the internationally adopted IEC PD testing standard IEC60270

-The ability to reduce the noise floor considerably over on-line methods, and thus the resolution of the PD results obtained (i.e.: seeing earlier manifestations of pending PD issues)

-The ability to vary applied test voltages and measure PD inception voltages ('PDIV') and PD extinction voltages to better qualify the nature of PD issues on the cable. Test voltages for cables in operational service run to typically 1.7Uo (the highest voltage likely to be seen on the cable if a phase is earthed on a Delta-Star transformer). In commissioning the equipment can offer both an initial stress test to IEEE400.2:2013 whilst also monitoring PD.

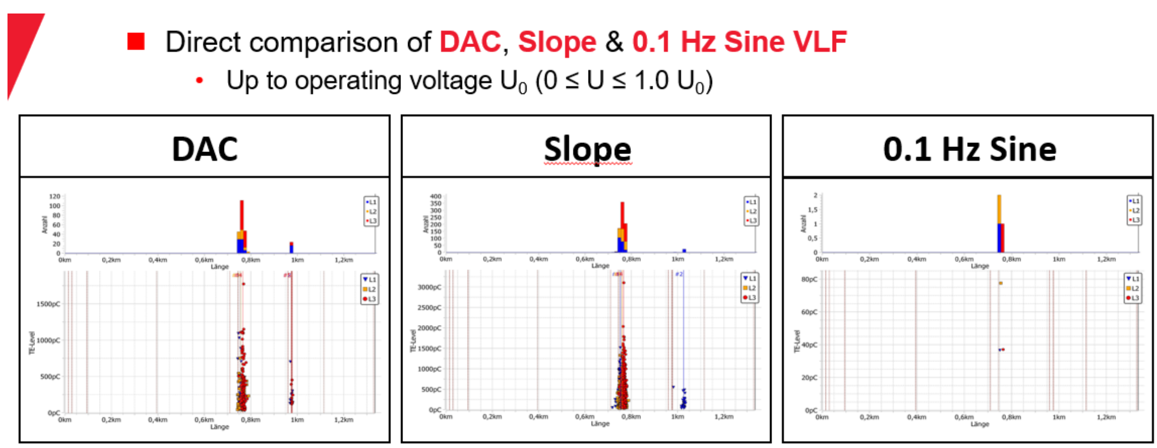
Two manifestations of the off-line technologies have dominated and competed in the market for the past 15-20 years. These are, respectively, those using VLF 0.1 Hz sinus excitation voltage, and those using an excitation voltage at or 'near' 50 Hz. Other than that, both use an IEC60270 test configuration of coupling capacitor, PD measurement device, and calibrator.

As opposed to the impracticalities of employing purely 50Hz waveforms (requiring a test set of vast size and power) technology in has now allowed the development of test waveforms that are within a small multiple of 50Hz (namely a bandwidth of 20-500Hz), these being called 'near 50Hz' waveforms, confirming to **IEEE 400.4-2015 – 'Guide for Field Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current (DAC) Voltage'.**

Suitable designs have been developed to produce two waveform options, generally being selectable from the one very compact and portable 'Very Low Frequency' hardware device. One such waveform is known as 'Cosine Rectangular' ('CR') which has a 'square wave' appearance but exhibits a near 50Hz rate of change at each polarity reversal. The other is known as a 'Damped AC' waveform and is a decaying sinus waveform from a charged DC impulse being passed into the cable capacitance via a series inductor.

Together the application of the CR and DAC waveforms has dominated the field of off-line PD testing, by comparison with the use of VLF sinus 0.1Hz waveform from a similar sized device, and greatly stimulated the uptake of that technology. Why is this?

Referring to the figure above, one sees graphically a



comparison on the same time base of waveforms of 50Hz, DAC, VLF 0.1 Hz, and VLC CR.

By way of summarizing the body of ***representative literature going back to the late 1990s [68-77]*** to the present day, one may confidently conclude:

- PD assessments at a given voltage on an 11-33kV cable are highly dependent on the rate of change of voltage, dU/dt, at working voltages likely to be encountered in normal operation (to 1.7Uo).
- PD measurements on an 11-33 kV cable are very comparable in both pulse count and pC level between 'near 50 Hz' equipment (working in the 30-500Hz range) and 50 Hz test frequency.
- Published evidence exits to illustrate that diagnostic PD testing done on 11-33 kV cable by VLF 0.1 Hz sinus test sources, largely because of the complex dU/dt phenomenon, is ***potentially unreliable*** in representing the true PD risk (both in pC levels measured and pulse count) that one would encounter in real terms at the operating frequency of the cable at the same voltage. Whilst on some occasions VLF 0.1 Hz test sources has been found to deliver similar results to Near 50Hz test sources, researchers noted that there is a more general risk of under-reading of PDIV by as much as 50%, potentially understating the PD risk. One illustrative test using all three waveforms below makes the point clearly [81]:
- The unreliability issue has been noted routinely. The literature [78-83] is clear on this point.

Test sources employing a CR or DAC waveform to IEEE400.4 are now strongly represented in the international market for both commissioning and diagnostic testing of MV cable. They have showed outstanding contribution in New Zealand also over the past 5 years [86, 87].

The recently published comments by Leufkens, via INMR [88], also repeated in Section A3.1 of this paper, serve to firmly secure the future of this cable assessment technology over purely binary VLF sinus 0.1 Hz HV devices that have served us well to date.

Associated PD interpretation guides are many but the simplest are often the best. Some are now emerging from client companies after successful findings, and one such is illustrated below, pragmatically blending cable PD around a 1nC decision point, feeder importance, and priorities for respective actions [after 85]

	PDIV	Q	important feeder cable	Take Action
Category 1	≤ U_0	≥ 1 nC	Yes	Immediately, as soon as possible
Category 2	≤ U_0	≥ 1 nC	No	Within 3 months
Category 3	≤ U_0	≤ 1 nC	Yes	Within 6 months
Category 4	≤ U_0	≤ 1 nC	No	Within 1 year

One illustration of an Industry-Sourced 'Near 50 Hz PD' Analysis Rule

A3 OVERVOLTAGE WITHSTAND

The ability of a completed MV XLPE cable to withstand an over voltage pressure is a key factor in the delivery of a suitable level of confidence in the outcome quality.

Following severe XLPE reliability problems particularly in the USA in the mid 1980's to mid 1990's, the industry was concerned as to the most appropriate electrical testing and management techniques for the longevity of such cable. It was quickly reasoned that the early choice made by the industry simply to commute techniques previously used for paper lead cable was partly to blame for the reliability issues, in concert with contributory matters of a cable manufacturing nature. Of these, the practice of DC over pressure testing was correlated to consequential damage to the cable dielectric [19,52,54,55,58,61,63,64 et al].

In the USA where this issue was noted acutely, the Insulated Conductor Cable Committee of the IEEE inaugurated in 1992 their Project 12-50: "Alternatives to DC Testing", ultimately to lead to a new IEEE 400.2 standard some 13 years later. This was followed by other such industry initiatives over the 1990 period, with a view to examining the issue more fully and to work on suitable alternative methods for satisfying the essential outcomes sought from over pressure testing of XLPE cable [64]. Over a period of about 8 years to the late 1990's DC over-pressure testing of MV XLPE fell from favour internationally in a cautionary reaction to the situation.

The industry quickly moved to adopt an AC test waveform in order to avoid the feared space charge accumulation issues of the former DC approach. Germany issued DIN VDE0276-1001 as a proposal in 1995 for the VLF testing of cable insulation [60]. In the USA the IEEE Insulated Conductor Committee began work toward the late 1990's on a new draft testing guideline for overpressure testing of MV XLPE cables. In the interim, Australian Standard AS/NZS 1429 'Electric Cables-Polymeric Insulated' included in a year 2000 release a simple provision for the mains pressure AC testing of XLPE cable systems for 24 hours prior to commissioning.

VLF Testing of an MV XLPE Cable Prior to Commissioning.

With AC over-pressure testing being viewed as an important ultimate contributor to MV cable insulation integrity, the industry first had to overcome the significant technical challenge of sourcing field-portable AC test sets with enough power to charge the cable. In tandem with the release of a patent by one USA maker in the late 1990's of a field-portable VLF set with an AC waveform and of sufficient power to test up to 50,000 feet of cable [55], and the offering about the same period of AC VLF sets with cos-squared and square wave AC voltages from three European makers [54,60], a move was made from late 1999 by IEEE's 400.2 committee to embrace formally the use of 0.1 Hz VLF testing technology for this purpose, the final Guide being released in March 2005 [52]. For the purposes of the Guide, VLF is defined as 0.1 to 0.01 Hz.

Subsequent to the wide-spread introduction of VLF testing of MV cables in more recent times, there is no shortage of reports in the literature confirming its effectiveness in commissioning and condition-assessment testing of MV XLPE cable [16,48,52,54,56,57,58, 61 et al].

The first version of this standard, IEEE 400.2: 2004, allowed up to 3Uo rms for a period of 60 minutes, qualified to cable status ('installation', 'acceptance', 'maintenance' and 'proof'). Following extensive international VLF cable testing experience on over 15,000 cable tests using VLF [58] which reported a significantly higher confidence factor in on-going cable reliability as one increased testing times from 15 to 60 minutes, the standard was ultimately issued citing a *minimum* recommended testing time of 30 minutes.

A similar correlation of a very high assurance (97%) of a 2+ year service life without failure followed a 15-year research programme [59] into the application of 3Uo VLF test voltage for 60 minutes. Together with this work, a further report [57] based upon 299 cable tests with VLF on 15 kV class cables investigating the in service failures following VLF testing at 2.2 and 3 Uo and test times of 15 and 30 minutes also provides concurrence to the position adopted by IEEE 400.2 in regard to the increased outcome quality offered by use of a test voltage of at least 2.20 Uo RMS and testing times between 15 and 60 minutes. Further anecdotal supporting evidence [63] continues to be reported in the literature.

VDE suggests simply 3Uo rms for 60 minutes and makes no distinction of cable status.

Industry opinion in New Zealand in the early to mid-2000 period generally considered the risk to cable too great for a blanket 3Uo level, particularly in view of the 'cable status' not always being known for existing systems and adopted a nominal 2.3Uo RMS level for 0.1 Hz sinus cable commissioning testing sources of 30 minutes minimum [61], drawn from the later IEEE400.2:2013, with a very effective testing outcome [62]. This version of the standard settled on three classes of test only: Installation, Acceptance, and Maintenance and again favours testing being for 60 minutes for "...important cables, such as feeders". IEEE 400.2: 2013 also caters for CR (cosine-rectangular) waveforms. Europe, however, prefers the CR waveforms as opposed to the sinus 0.1 Hz approach [81], and tends to embrace the VDE/CENELEC/IEC test standard IEC 60502 (up to 35 kV). New Zealand has softened its stance on the European approach in more recent times and has certainly embraced this methodology for cable diagnostic testing, as we have earlier noted.

Noting the widespread deployment of resin accessory systems on PLA cable, the hybrid assembly of cable systems combining PLA and XLPE cable lengths, and the frequent lack of accurate records of cable and joint types, NZ has generally deployed the use of VLF over pressure testing at the unified test voltage levels and testing times across all MV cable systems.

Advances over the past 10 years have seen the emergence of VLF test sets with solid state operation, and some even having integrated VLF Tan Delta capability.

A3.1 PERSPECTIVE ON THE FUTURE OF VLF TESTING IN NEW ZEALAND FOR MV CABLE COMMISSIONING OR CONDITION ASSESSMENT TESTING

What the VLF test sets do, in effect, is to apply a high voltage AC waveform (sinus 0.1 Hz or Cosine Rectangular) for a period of up to 60 minutes to force PD and Water Treeing mechanisms, in particular, to propagate in an accelerated manner and to 'show themselves up' if there are weaknesses. It also exposes any weak points in the insulation, even down to ingress of impurities or moisture. Any issues either fail or not, as the case may be.

Typical VLF test devices are a 'blind test', or sometimes called a 'binary' approach and produce nothing in the way of an informative test report. They either 'pass' the cable, or the cable fails and the set trips out. Whilst a basic and 'blunt' approach, it is simply used and deployed, does its job as intended, and has stood our industry in good stead for the past 25 years or so.

However, it is well known, and accepted to date, that this tool has a limited 'forward visibility confidence level and that is around 2 years [57] and that fact is now being seen as a significant shortcoming given the increasingly little redundancy of MV cables to allow such testing, even if there were a will to do so, unless one seeks to repeat the VLF testing on all commissioned cables of significance every 2 years.

If one seeks to have confidence beyond that point, the optimum approach now being taken is to apply the 'near 50Hz' waveforms with a PD measurement capability, as discussed in Chapter A2.2 herein and offering a significantly clearer forward visibility for a shorter test time, and that is the place this new technology is increasingly filling in the formerly exclusive VLF test set domain. One recent and well-researched paper by Leufkens of DNV Energy [88] makes the statement clearly: "...Traditionally recommended over-voltage testing with a binary test outcome, i.e. 'breakdown' or 'no breakdown', may reveal major defects. But PD detection should *always be added where possible and a check should always be made of the risk to ignite faults that would not have occurred under operating voltages"*

A4 WATER TREEING

One of the most concerning and insidious failure mechanisms of service-aged extruded dielectric cable (XLPE, EPR, and polyethylene) is that of water treeing. Whilst undetectable by any on-line methods currently, the use of off-line VLF tan delta technology offers an excellent means to quantify and trend the problem and to plan remedial action if practicable.

A 4.1: Nature and Mechanism of Water Treeing

In cable is not manufactured with water tree inhibiting chemicals (so-called "TR-XLPE") the mechanism is believed to be as quick as 5-6 [46] years after water ingress into taped screens or after 10-15 years exposure of extruded PVC jackets to water. Figures of significant numbers of water tree-damaged cable in the West Coast of the USA have been noted for service lives of just 1-10 years [20,47]. Propagation rates for water trees have been reported [48] to be roughly 200 um/year for MV XLPE cables surveyed.

As mentioned earlier, New Zealand would appear to have been an international leader in manufacturing TR-XLPE MV XLPE cables from around 1990 [10,34], whereas the same was generally not the case in Australia for many years.

In non XLPE material "water trees" begin to form when a cable is exposed to a combination of water, conductive ions from either the semiconductor layer itself or the groundwater [49] or other cable materials, and normal operating voltage over an extended period of time [20]. Electrical forces acting on the water molecules (electrophoresis [20]) at a microscopic point within the insulation drives a localised chemical reaction which changes the polymer from hydrophobic to hydrophilic [49]. Water and ions then travel along and condense into these hydrophilic paths (usually less than 0.025 mm diameter [47]) from cavity to cavity in the dielectric, ultimately propagating via a myriad of radiating micrometre-sized channels where at the tip of each the same reaction is occurring (Fig 10).

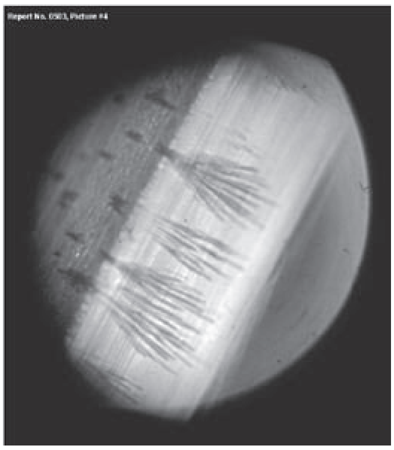


Figure 10: 1972-vintage 11kV XLPE cable insulation showing extensive water treeing; Rothmans Feeder, Napier, NZ 2004 (courtesy Unison, NZ).

Propagating radially from the original point of origin in a direction nominally parallel to the electric field [47], the result is a tree-like structure, in effect acting as a sharp electrode producing highly localised stresses. As long as the propagating conditions remain, the tree ultimately compromises the insulation properties of the dielectric.

With the insulation voltage gradient in solid dielectric being essentially an exponential decay profile from the core (Section A2), the compromise in insulation wall thickness from the outside soon introduces excessive voltage stresses on the remaining insulation as the

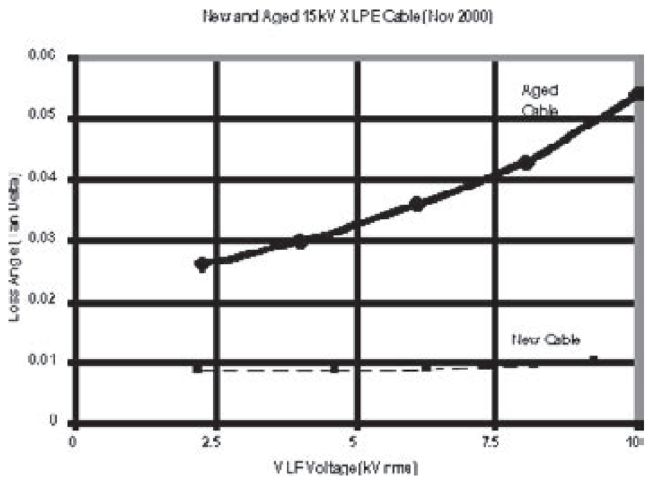


Figure 11: Tan Delta vs. Voltage for new and aged XLPE cable.

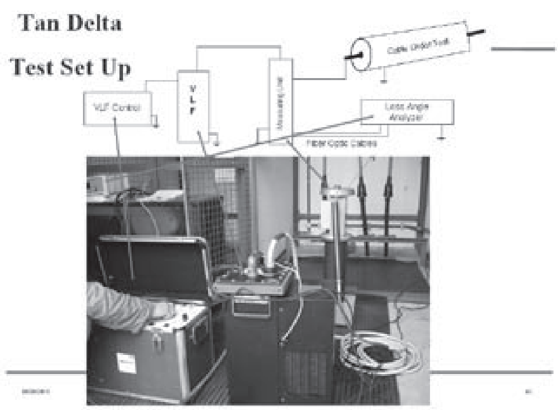


Figure 12a: Earlier generation VLF tan Delta system with external TD coupler.

Figure 12b: A modern solid-state Sinus 0.1 Hz VLF Tester with in-built VLF Tan Delta measurement capability

water tree grows. Voltage-induced partial discharge and electrical trees may ultimately result, quickly followed by complete flashover of the dielectric and associated cable failure.

Two types of water tree exist. ‘Vented’ water trees [49,50] originate from the conductor shield or insulation shield and remain in contact with the source of the water and conductive ions fuelling the process [4]. “Bowtie” trees [50] are caused by a trapped impurity or void and propagate both toward the conductor and outward to the shield [47,49], giving the characteristic shape.

It is important to note TR-XLPE material significantly retards the growth of water trees but does not prevent the mechanism totally.

A 4.2: Detection and Measurement of Water Treeing

So, water trees are a major concern but how do we detect and quantify the risk they pose to insulation integrity? Essentially, the methodology of detection lies with the mechanism. As the electro-oxidized water trees start to bridge the insulation, the once purely capacitive insulation dielectric begins to be shunted by a resistive pathway which in turn progressively shifts the capacitive leakage current phase angle from 90 degrees leading against the applied voltage. The losses dissipated through the insulation begin to increase accordingly and this effect is clearly discernible via measurement of the insulation ‘dissipation factor’ or ‘tan delta’ [20,54].

As far back as 1981 Bahder et al [50] in the USA published material to support the use of loss factor tan delta testing to monitor the aging and deterioration of extruded dielectric cable. Bach et al [51] published work in Germany in 1993 that observed a correlation between an increasing 0.1 Hz dissipation factor and insulation breakdown voltage level at power frequency. Uchida et al [48] in 1998 demonstrated that water treeing could be effectively exposed by means of VLF testing with minimal adverse impact on the cable’s existing water trees (unless of course insulation had been compromised to the point that insulation flashover was inevitable). Lelak et al [5] in the Slovak Republic also demonstrated in 2000 the suitability of VLF tan delta as a means of determining the condition of aged PVC cable

Drawing on the work above, IEEE 400.2:2013 “Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency VLF” [52] describes in Table 4 of Section a three-step assessment methodology for VLF tan Delta (Figure 13). The testing process employs a test of VLF tan delta at between 0.5Uo and 1.5Uo, the difference between them being a figure of merit used to rank and trend cable water tree condition.

Table 4—Historical figures of merit for condition assessment of service-aged PE-based insulations (e.g., PE, XLPE, and TRXLPE) using 0.1 Hz

Condition assessment	VLF-TD Time Stability (VLF-TDTS) measured by standard deviation at U_0, [10^{-3}]		Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 [10^{-3}]		Mean VLF-TD at U_0 [10^{-3}]
No Action Required	< 0.1	and	< 5	and	< 4
Further Study Advised	0.1 to 0.5	or	5 to 80	or	4 to 50
Action Required	> 0.5	or	> 80	or	> 50

Figure 13: Practical Test Set Up for VLF Tan Delta testing using a HV Inc VLF test set and HV Inc VLF tan delta accessory unit

Contrary to popular belief, the loss of cable sheath material, which often precedes the inception of water treeing (especially if that sheath is aluminium), and water treeing itself DO NOT EXHIBIT PARTIAL DISCHARGE SYMPTOMS IN THEIR OWN RIGHT!! [20,33,46]. Whilst (as earlier observed) it is highly likely that the stresses caused by water tree damage will ultimately result in PD and associated electrical treeing, the mechanism usually occurs very soon before cable failure and at that time it is really too late to avoid major cable damage.

VLF Tan delta, then, is the only detection technology at present that is suitable for the task of quantifying and qualifying water tree damage to XLPE cable systems. It also has, of course, much validity in assessing aged PILC cable also.

Being a global test figure, it is not possible to determine from the VLF Tan Delta result itself where issues lie in the cable. Further if the cable is of mixed XLPE and PILC construction, the VLF Tan Delta readings will be dominated by those of the PILC, so results in such cases should be viewed with a measured eye.

Repair options for water tree damage are offered with a reported level of good effect [46]. Sheath damage or deterioration is a possible other issue to appraise on such occasions, particularly if aluminium sheaths are employed, and sheath testing is a vital preventative approach to ensuring the cable dielectric (and the cable screens) is in optimal condition.

A5 EFFECT OF CABLE FAULT LOCATION PROCESSES

In the case of the common MV flashing cable fault, Industry standard practice through to the mid 1990’s was simply to break the fault down on a continual basis by a capacitance-based cable impulsing (‘thumper’) unit, employing an acoustic (and possibly and electromagnetic) detection device at the suspected fault site. In order to improve the magnitude of the resulting discharge (‘thump’) at the fault site, it was also common practice to utilise the highest possible voltage from the impulse generator, thus increasing the joules applied as the square of the impulse voltage.

The practice caused severe damage to the XLPE dielectric, initially from the magnitude of the travelling wave/impulse which would change polarity when reflected from the far end of the cable and propagate back (with an opposite polarity) toward the test site and thus, after multiple such travelling waves served to charge the high Q XLPE dielectric, potentially introduce a very substantial charge level in the cable. The effect was exacerbated by both the level of impulse chosen and by the number of such impulses applied in the course of the fault location process, charging the cable and doing major secondary harm to the dielectric and to any weaker parts of the total insulation system unable to withstand the voltage gradient thus applied [23]. In a notable summary of the issue in 1996, Balaska [64] reported no less than 10 references to papers supporting the observation that cable fault location methods involving DC voltage testing, burning, and ‘thumping’ at high voltages in turn created further electrical faults in extruded XLPE cable. He also reported the release of the 7th draft of the IEEE’s Project 12-48 “Guide to Fault Location on Shielded Power Cable Systems” to address the matter constructively.

This concern remains as heightened today, were cable fault practices to not minimise the number of discharges to which the cable is exposed in the course of locating, and especially pinpointing, a fault.

The advent in the mid 1990 period of the differential arc reflection PC-based adjunct to the older impulse technology, meant for the first time that the location of a flashing fault could be undertaken precisely with just one impulse of just sufficient size to break over the fault [23]. A companion product released simultaneously at that time, integrating a hugely sensitive dual geophone acoustic detector, electromagnetic impulse detector, and a display of relative arrival times to direct the operator to reposition to the device correctly to confirm the exact fault site, not only reduced the need to apply excessively high voltage impulses of high energy to the cable but also meant that very few impulses needed to be applied to complete the pin pointing.

Combining the field deployment of both innovations via appropriate training and radio-linked communication, meant that for the first time MV cable faults in XLPE cable could be located and pin-pointed in nominally single digit numbers of impulses in total, whose level is unlikely to have any adverse secondary bearing on the cable. The practice, introduced first to New Zealand in 1997 accompanied by an extensive and on-going training and awareness campaign [27,44,65], is now an industry standard one in New Zealand and is applied equally to paper-lead, XLPE, and hybrid cable systems.

Subsequently to the above innovations first coming to market, over the past 30 years the technology has improved significantly in performance, versatility of hardware packaging for all fault location scenarios, and ease of use. The latter is perhaps one of the more significant areas of development, software now greatly assisting operators to provide an extremely competent result in most situations with ease.

Not only are impulse generator-based devices now very much more capable, allowing for scenarios where faults are either hard down or high resistance. Re-modelled bridge technologies, integrating their own HV DC sources, now also provide outstanding adjunct capabilities for the harder to find faults and also areas of former complexity such as sheath fault location.

In summary, MV cable reliability statistics, particularly under a declining redundancy scenario that we are now facing as an industry, are well served by the capabilities of the modern cable fault location devices, allowing efficient and capable fault location performance with minimal cable downtime. If required, a plethora of very sophisticated, customised, cable fault and test vans are now offered with were the capability and added response effectiveness to be required by the MV cable asset owner pressed over increasingly declining levels of redundancy in the low carbon transition.

Figure14a: Modern integrated differential arc reflection technology impulse generator platform.
Figure14b: Combination dual geophone, electromagnetic impulse detector, and relative time of arrival cable fault pinpointing unit
Figure14c: An example of a modern high voltage semi-automated cable fault location bridge.

Figure 15: An example of a modern, customisable specification, cable fault location test van.

Bibliography:

1 “On-Line Monitoring as a Strategic Tool to Enhance System Reliability”, Graham. Hodge and Trevor. Lord, LORD Consulting, June 2004, first presented at D2003 Adelaide Australia, November 2003.

2 “Reliability and Distribution Asset Management”, Richard E. Brown, KEMA, ‘Electric Energy T&D Magazine’, September/October 2004.

3 “Current Issues in Underground Transmission”, Mark Michailuk, Transmission Underground Cables Interest Group (TUCIG) of CEA Technologies Inc (CEATI), ‘Electric Energy T&D Magazine’, July/August 2005.

4 “Finding the Root Cause of Cable Failures”, Vern Buchholz, PowerTech Labs Inc, USA. ‘Electric Energy T&D Magazine’, Nov/Dec 2004.

5 “Diagnostics for MV Cables and Switchgear”, Dr Ross Mackinlay (HV Solutions UK) and Cliff Walton (London Power Networks), Australian Power Transmission and Distribution magazine, Dec/Jan 2003.

6 “High Voltage Cable Diagnostics”, Dr Ross Mackinlay (HV Solutions UK) and Matthieu Michel (London Power Networks UK), AVO New Zealand 3 International Technical Conference, Methven, NZ, 2002.

7 “Partial Discharge Testing of In-Situ Power Cable Accessories-An Overview”, Harry E. Orton, OCEI, USA. ‘Electric Energy T&D Magazine’, CUEE Special edition, 2002.

8 “Diagnostics for MV Cables and Switchgear as a Tool for Effective Asset Management”, Dr Ross Mackinlay (HV Solutions UK), Cliff Walton (London Power Network), AVO New Zealand International Technical Conference, Methven New Zealand, April 3-5th 2001.

9 “Design Manufacture, and Testing of MV XLPE Power Cables”, Stuart Castle, BICC General Cable NZ Ltd, AVO New Zealand International Technical Conference, Methven NZ, October 27-29, 1999.

10 “Maintaining Cable Quality Assurance from Manufacture to Commissioning”, Mr David Griffiths, Olex Cables NZ, AVO New Zealand International Technical Conference, Methven NZ, October 15-17, 2002…

11 “Incipient Failure Detection & Location for Underground Cables”, C.M. Walton, London Electricity, 1998.

12 “48+386+404+592=Cable Accessories???”, Ted Balaska, Insulated Power Cable Services Inc., USA, 1996 AVO International Technical Conference, July 14-17, Dallas, TX, USA.

13 “Online Partial Discharge Testing and Monitoring of HV and MV Polymeric Cables”, A. Cavallini, G.C. Montanari, M. Oliveri, F. Puletti, Electricity Engineers of NZ Conference, Auckland NZ, June 2005.

14 “Comparison of Off-Line and On-Line Partial Discharge MV Cable Mapping Techniques”, M. Michel, EDF Energy UK, CIRED 18th International Conference on Electricity Distribution, Turin, 6-9 June 2005.

15 “Diagnostics of Medium Voltage PVC Cables by Dissipation Factor Measurement at Very Low Frequency”, J. Lelak, V. Duman, J. Packa, O. Olach, Slovak University of Technology, 2000.

16 “Selectivity of Damped AC (DAC) and VLF voltages in After-Laying Tests of Extruded MV Cable Systems”, B. Oyegoke, P. Hyvonen, M. Aro, N. Gao, High Voltage Inst., Helsinki Univ. of Technology, Finland. IEEE Transactions, Oct 2003, Vol. 10, Issue 5, ISSN: 1070-9878.

17 “Middelen Vorr Kwaliteitsbepaling Van Oude En Nieuwe Midden-En Hoogspanningskabels”, E.R.S. Groot, C.G.N. De Jong, M. Van Riet, D.M. Harmsen, J. Pellis, H. Geene, E. Gulski, F.J. Wester, Nuon Prielli Cables and Systems N.V., TU Delft Hoogspanningslaboratorium, 2000.

18 “Maintenance Strategy with New Diagnostic Metrologies in Medium Voltage Underground Cable Networks”, Baur Pruf-und Messtechnik GmbH & Baur do Brasil, Belo Horizonte, Electro Paulo, Martin Baur 06-07-2004.

19 “Specifications and Standards Activity…NETA 2003 Conference-Cable Discussion”, R. Patterson SETS-AC Testing, Orlando NETA Conference, Summer 2003.

20 “Diagnostics Filed Testing of Medium-voltage Cables”, C. Goodwin, HV Diagnostics Inc, USA, NETA World magazine Fall 2003, official publication of the International Electrical Testing Association.

21 “MV Cable Diagnostics-Applying Online PD Testing and Monitoring”, Dr L. Renforth (IPEC Engineering UK), Dr R. Mackinlay (HV Solutions UK), M. Michel (EDF Energy UK), MNC-CIRED, Asia Pacific Conference on MV Power Cable Technologies, 6-8 September 2005.

22 “Integrating Cable Testing Data to a GIS Package”, B. Norris and D. Edwards, Mainpower NZ, presented at 3rd AVO New Zealand International Technical Conference, Oct 15-17th 2002, Methven, NZ.

23 “Underground Cable Fault Location Using the Arc Reflection Method”, Mike Scott, Megger USA, ‘Electric Energy T&D Magazine’, Jan/Feb 2004.

24 “Maintenance for HV Cables and Accessories”, CIGRE Technical Brochure No. 279, CIGRE Working Group B1.04, w. Boone (Convenor), CIGRE ‘Electra’ magazine no. 221, August 2005.

25 “Implementing a New Level of ‘Best Practice’ in Regard to Underground Service Detection”, T. Lord, LORD Civil, NZ, November 26th, 2004.

26 “A Guide to Diagnostic Insulation Testing Above 1 kV”, Balaska, Jones, Jowett, Thomson, and Danner, Megger Ltd Dover UK, Second Edition, 2002.

27 “Achieving Prompt and Minimal Impact Cable Fault Location”, Mike Scott, AVO International USA. Presented at the Second AVO New Zealand International Technical Conference, Methven, NZ, April 3-5, 2001.

28 “Diagnostic Insulation Testing”, Dave Jones, AVO International, Dover, UK, presented at Inaugural AVO New Zealand International Technical Conference, Methven, NZ, Oct 17-29th., 1999.

29 “Field Experiences with Diagnostic Testing of Power Cables”, Nick Chandler, Energex NZ, Second AVO New Zealand International Technical Conference, Methven, NZ, April 3-5, 2001.

30 “Diagnostic Insulation Testing”, Dave Jones, Megger UK, presented at the Third AVO New Zealand International Technical Conference, Methven, NZ, Oct 15-17th., 2002.

31 “Comprehensive Power System Plant Assessment Using Humble Insulation Testing Hardware”, Nick Chandler, presented at the Third AVO New Zealand International Technical Conference, Methven, NZ, Oct 15-17th., 2002.

32 “Partial Discharge Measurements in HV Joints: Brugg Solutions”, W. Weissenberg, Brugg Kabel AG, Switzerland. PD Workshop 2001, Alexandria, Virginia, Dec 3&4, 2001.

33 “Guide to PD Levels for Power System Measurements”,

Dr Ross Mackinlay, HV Solutions UK. Published by LORD Consulting, NZ, April 28., 2002.

34 "Cable Developments", Stuart Castle, General Cables, NZ. Presented at the Second AVO New Zealand International Technical Conference, Methven, NZ, April 3-5, 2001.

35 "Experiences in Partial Discharge Detection of Distribution Power Cable Systems", Working Group D1.33 'High Voltage Measuring Techniques', Task Force 05 'Measurement of Partial Discharges', "Electra" Magazine of CIGRE, No. 208, June 2003.

36 "Condition Monitoring of HV Cables", Dr R. R. Mackinlay, High Voltage Solutions UK. Presented at Inaugural AVO New Zealand International Technical Conference, Methven, NZ, Oct 17-29th., 1999.

37 "Some Developments in Diagnostics for High Voltage Cables", Ross Mackinlay (HV Solutions UK, Matthew Michel (London Power Networks UK). Presented at the Third AVO New Zealand International Technical Conference, Methven, NZ, Oct 15-17th., 2002.

38 "On-Line vs. Off-Line Partial Discharge Testing", Dr Ross Mackinlay (HV Solutions UK) and Trevor Lord (Lord Consulting, Aus & NZ), 'Australian Power Transmission and Distribution' magazine, Dec/Jan 2003.

39 "High Voltage Bushings", Young and Caruso (Lapp Insulation Company USA), and Gill (Gill Engineering USA), presented at the AVO International Technical Conference, Dallas Texas, 1996.

40 "Experiences with Continuous Partial Discharge Monitoring", Michael Webb and Mark Lomax (MW Test Equipment, UK), presented at the Third AVO New Zealand International Technical Conference, Methven, NZ, Oct 15-17th., 2002.

41 "New Methods in On-Line PD Detection for HV Plant", R.R. Mackinlay, High Voltage Solutions, UHV Net, Jan 2005.

42 'Cable Making Materials and Design Specifications", Stuart Castle, BICC General Cable Ltd, New Zealand, presented at the Electricity Engineers' Association Annual Conference, 16-17 June 2000, Auckland, NZ.

43 "Condition Monitoring of Power Cables", Ken Barber and Graeme Barnewell, Olex Cables, Australia. Presented at the TechCon 2002 Asia Pacific Conference, Melbourne, Australia, May 8-10, 2002.

44 "Underground Cable Fault Location", Barry Clegg, BCC Consultancy, UK. Presented at the Second AVO New Zealand International Technical Conference, Methven, NZ, April 3-5, 2001.

45 "Determination of the Most Suitable Mix of Maintenance Strategies for an Underground Power Distribution Network", Paul Dyer, 24Seven Utility Services Ltd, UK. Presented at the TechCon 2002 Asia Pacific Conference, Melbourne, Australia, May 8-10, 2002.

46 "Water Trees, Failure Mechanisms, and Management Strategies for Ageing Power Cables", Keith Lanan, Util-X, USA. Presented at E21C Conference, Brisbane, Australia, August 22., 2005.

47 "What are Water Trees?", Technical paper by USA Wire and Cable Inc, USA, accessed via web site www.usawire-cable.com from 2003.

48 "Life estimation of Water Tree Deteriorated XLPE Cables by VLF (Very Low Frequency) Voltage Withstand Test", K. Uchida (Chubu Electric Power), M. Nakade & D. Inoue (Tokyo Electric Power Co., Inc), H. Sakakibara & M. Yagi (The Furukawa Electric Co., Ltd)., 1998.

49 "Role of Semi conducting Compounds in Water Treeing of XLPE Cable Insulation", S.A. Boggs and M.S. Mashikian (Electrical Research Centre, University of Connecticut, USA), c 2003.

50 'Life Expectancy of Cross-Linked Polyethylene Insulated Cables Rated 15-35 kV", G. Bahder, C. Katz, G.S. Eager, E. Leber, S. M. Chalmers, W.H. Jones, W. H. Mangrum. 'IEEE Transactions PES', vol. 100, pp. 1581-1590, April 1981.

51 "Verlustfaktormessung bei 0.1 Hz an betriebsgealtern PE/VPE Kabelangen", R. Bach, W. Kalkner, D. Oldehoff. Elektrizitaswirtschaft, Jg 92, Heft 17/18, pp 1076-1080, 1993.

52 "IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)", IEEE Std. 400.2_2004, IEEE Power Engineering Society, 8 March 2005.

53 "MV Cable Testing with VLF at TVA-Nuclear", Kent Brown (TVAN), IEEE WG C18D-B, April 2005.

54 "Solid Dielectric Cable Testing: New Technologies-New Methods", M. Peschel (High Voltage Inc, USA), NETA, 2003.

55 "High Voltage VLF Test Equipment with Sinusoidal Waveform", Richard Reid, HV Inc, IEEE T&D Conference, 1999.

56 "AC Testing Without Cable Degradation", C.J. Doman, S.J. Heyer, PECO Energy Co, USA, 'Transmission and Distribution World' Magazine, July 1999.

57 "ComEd Test Data as of March 5, 2005", John Hans (Exelon-ComEd, USA) IEEE Working Group C18D.

58 "Very Low Frequency Testing-Its Effectiveness in Detecting Hidden Defects in Cables", Shew Chong MOH, TNB Distribution Sdn. Bhd-Malaysia, CIRED 17th International Conference on Electricity Distribution', Barcelona 12-15 May 2004.

59 "High Potential Testing...Voltage Withstand versus Voltage Step Test, 0.1 Hz AC VLF Effects of RMS vs. Peak Test Voltage", Frank Petzold and Henning Oetjen, ICC Meeting St Petersburg, April 20, 2005.

60 "High Voltage VLF Test Equipment", Michael Peschel, HV Inc, USA. Presented at Inaugural AVO New Zealand International Technical Conference, Methven, NZ, Oct 17-29th., 1999.

61 "Olex New Zealand Recommendations for Tests after Installation on XLPE Medium Voltage Cables", Olex New Zealand Technical Informative number 21-61-011, version 1.7 issued Sept 17, 2004. Accessed via www.olex.co.nz.

62 "Very Low Frequency (VLF) Testing Experience in New Zealand", Marc Meier, Alstom. Presented at the Third AVO New Zealand International Technical Conference, Methven, NZ, Oct 15-17th., 2002.

63 "Engineers Roll Out New Device for Testing Cables... New Instrument Detects Cable Weaknesses Without Destructive Side", Barry Henck, editor (Corporate Communications), Central Hudson (CH) Energy Group, Inc, News, Vol. 25, No. 37, Sept. 10th., 2004.

64 "Field Testing Insulation and Fault Location for Shielded Power Cable Systems, A Progress Report on Proposed IEEE Standards", T.A. Balaska (Insulated Power Cable Services Ltd, USA). Presented at the 9th AVO International Technical Conference, September 14-17, Dallas, TX, 1997.

65 "Underground Cable Fault Locating Methods", M. Scott, AVO International. Presented at Inaugural AVO New Zealand International Technical Conference, Methven, NZ, Oct 17-29th., 1999.

66 "Handbook for Optimised Deprival Valuation of System Fixed Assets of Electricity Lines Businesses" published 30th August 2004, NZ Commerce Commission.

67 "PD Threshold Levels for Diagnostics" IPEC Engineering and High Voltage Solutions UK, 2005

68 'VLF-TE Messungen an betriebsgealterten', Mittelspannungskabel-Abschlussbericht-Förderkennzeichen: 17 085 01 Projektleiter: Professor Dr. Gunter Voigt, Projektmitarbeiter: Dipl.-Ing. (FH) Dirk Blum Dipl.-Ing. (FH) Thekla Wolf Projektthema: VLF-TE Messungen an betreibsgealtern Mittlespannungskabel Foderzeitraum: 01,09,2001-30.09.2002 Durchfuhrende Institution: Fachhochschule Konstanz (PhD Thesis pub 2003)

69 'PD- measurements on typical defects on XLPE- insulated cables at variable frequencies', Pepper, Kalkner: 10th International Symposium on High Voltage Engineering (ISH), Montreal, CDN, 1997

70 'PD- pattern of defects in XLPE- Cable insulation at different test voltage shapes', Pepper, Kalkner: 11th International Symposium on High Voltage Engineering (ISH), London, GB, 1999

71 'The use of the 0.1 Hz cable testing method as substitution to 50 Hz measurement and the application for PD measuring and cable fault location', Muhr, Sumereder, Woschitz: 12th International Symposium on High Voltage Engineering (ISH), Bangalore, IND, 2001

72 'The selection of frequency range for high voltage on-site testing of extruded insulation cable systems', Gockenbach, Hauschild: IEEE Electrical Insulation Magazine, vol.16, no. 6 Nov. /Dec. 2000

73 'Comparison among different diagnostic systems for medium voltage cable lines', Colloca, Fara, de Nigris, Rizzi: 16th International Conference on Electricity Distribution (CIRED), Amsterdam, NL, 2001

74 'Partial discharge measurements on service aged medium voltage cables at different frequencies', Voigt, Mohaupt: JICABLE 2003, Versailles, F, 2003-05-15

75 'Partial Discharge Measurements on service aged Medium Voltage cables at different frequencies' Gunter Voigt, University of Applied Sciences, Konstanz, Germany Peter Mohaupt, C.8.1.10. BAUR Prüf- und Messtechnik, Sulz, Austria, Jicable, 2003

76 'Importance of Voltage Type Equivalence' E. ON: VWEW Info Day, 2004

77 'Applied Voltage Frequency Dependence of Partial Discharges in Electrical Trees', Nadja Javerberg, Hans Edin, KTH School of Electrical Engineering, Teknikringen 33, 10044, Stockholm, Sweden, Proc. IR-EE-ETK, Stockholm, Sweden, 2009

78 'Condition Assessment of Windfarm MV Cable Joints', by H.L. Halvorson, NTNU Norwegian University of Science and Technology, Trondheim, Norway, 2012.

79 'PD and Dielectric Response Measurements on Service Aged Cable Joints" by Frank Mauseth, Håkon Tollefsen, NTNU [Norwegian University of Science and Technology] and Sverre Hvidsten, SINTEF Energy Research, August 24, 2014

80 'Investigating the effect of frequency and wave shape of voltage source on partial discharge behaviour within cavity in medium voltage cable', by Osama Gouda; Adel El Faraskoury; AbdRabu ElSinary; Adel Farag, Published in: 2017 Nineteenth International Middle East Power Systems Conference (MEPCON), Cairo, Egypt.

81 'Excitation Voltages for Partial Discharge Diagnostics on Medium Voltage Distribution Cables Robert Probst', by Hein Putter, Frank Petzold, Philipp Legler, Megger Germany, 2017

82 "Effect of Applied Voltage Frequency of Partial Discharge in XLPE Cable Insulation" by Alhamadi, Malik, Al-Arainy, and Wani of King Saud University (KSU), College of Engineering, Department of Electrical Engineering, Riyadh, Kingdom of Saudi Arabia, July 2017

83 'Comparison of Partial Discharge Measurement Using Different Alternative Voltage Sources on Medium Voltage Cable' published in 2019 at the Cigre Study Committee B1-10/Cired at the 14th Conference of Slovenian Electrical Power Engineers, by Marko Stanonik, and Vili Bonča of Elektro Gorenjska d.d Slovenia.

84 'A Paradigm Shift in Underground Cable Asset Management, to Achieve Better Lifecycle Management and Reliability', by Mr Viram Sen (Maintenance Engineer, Strategy) and Mr Richard Kingsford (Asset Planning and Engineering Manager), WEL Networks, Hamilton. Presented at the EEA NZ Annual Conference 2021. Watch at: https://www.avo.co.nz/eea2021-cable-management-video

85 'Changing the New Zealand MV Cable Management Regime from Reactive to Proactive... A Review of the State-of-the-Art in Cable Diagnostics Technology', by Robert Probst August 15, 2019. Presented at the 2019 AVO International Technical Conference, Hamilton, 2019.

86 'Cable Maintenance Strategy: From reactive to proactive', by Vikram Sen – Maintenance Engineer (Strategy), WEL Networks, Hamilton.

87 'Asset Management Improvements for the WELL Cable Fleet', by Bradley Singh, Wellington Electricity, AVO New Zealand International Technical Conference, Hamilton NZ, August 2018.

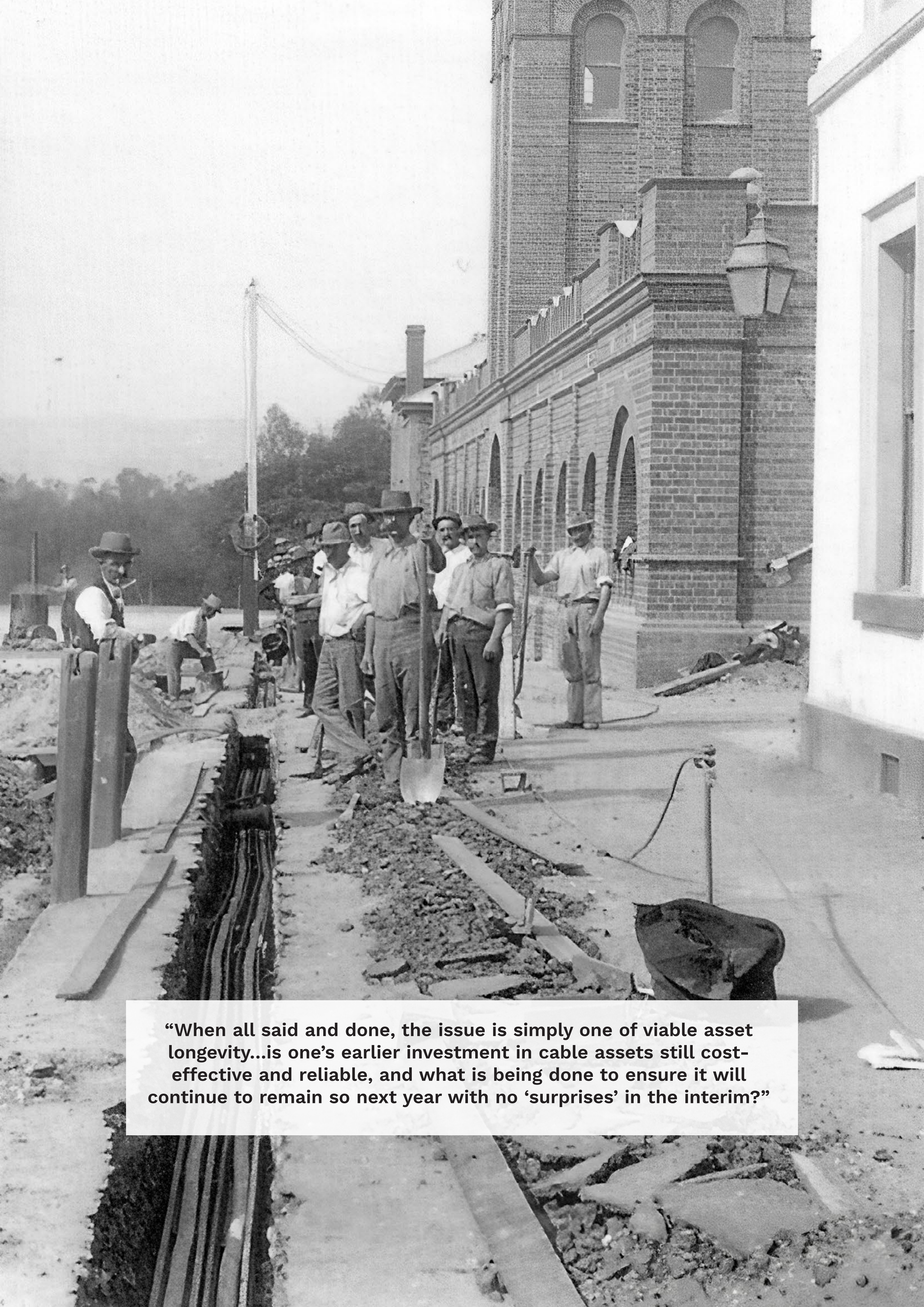
88 'Overview of Cable Testing: State-of-the-Art, Standards & Technologies', by Paul Leufkens of DNV Energy, USA, published by INMR, February 18th, 2023.

89 'Household electricity bills will double over 5 years, forecasts departing lines association boss', by Tom Pullar-Strecker, STUFF, May 12, 2023.

90 'THE FUTURE IS ELECTRIC A Decarbonization Roadmap for New Zealand's Electricity Sector', by Boston Consulting (François Tibi, Philip Hirschhorn, Rebecca Russell, Phillip Benedetti, Richard Hobbs, Daniel Sheridan, Ben Fulton, Emma Beal, and Alex Makarytchev), October 25th 2022.

91 'Briefing for the incoming Minister for Energy', by Ministry of Business, Innovation and Employment, 27 November 2023.

92 'MBIE releases briefing for the incoming Minister for Energy', Legal update by MinterEllisonRuddWatts, 07 February 2024.



"When all said and done, the issue is simply one of viable asset longevity...is one's earlier investment in cable assets still cost-effective and reliable, and what is being done to ensure it will continue to remain so next year with no 'surprises' in the interim?"

TREVOR LORD, LORD Consulting: Trevor Lord is Managing Director of LORD Consulting, a respected power systems asset management consulting company trading internationally. The third generation in his family to be involved in the industry, he holds a Master's degree in Electrical and Electronic Engineering from the University of Canterbury, NZ. He was a co-founder of Cigre New Zealand and has worked with the power and electrical Industries for 41 years in a wide variety of roles. As a passionate advocate for his work in both LV 'testing for safety', and in the wider field of power systems asset management, he has earned the respect of the industry internationally as a true 'mover and shaker'. He is known and respected for his efforts to support this vision via: engineering expertise; training and information programmes; and particularly his implementation of innovative and strategically-focused technical solutions to enhance the performance and reliability of power systems assets, and his regular industry Conferences and newsletters aimed at raising and unifying the level of best practice. He brings a wealth of practical knowledge and experience to the critically important emerging field of on-line and proactive monitoring of electrical network assets and holds two patents in asset management areas.

LORD CONSULTING

0800 485 990 (NZ), 1800 128 000 (Aus)
www.lordconsulting.com