Embracing 'State of the Art' in MV Cable Testing

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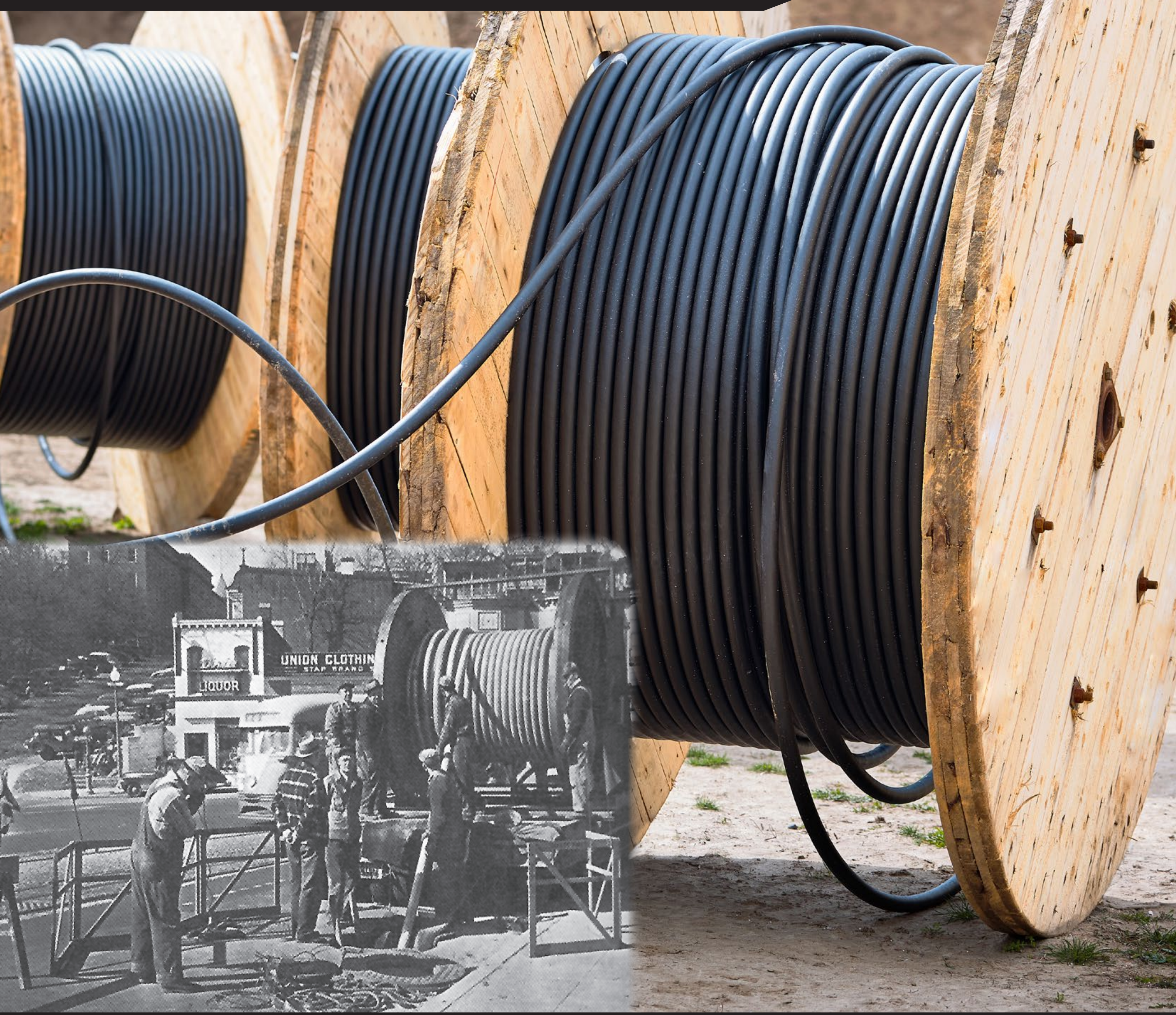

Preamble:

When assessing what might at first appear to be a "new technology" to our industry, it is reasonable to seek a degree of evidence of its established provenance offshore and in the application to which it is intended to be applied in the 'local' context.

When that 'new technology' is well established offshore but new to our region or industry, we must consider the question what information is required to address and allay any uncertainties or questions as to the suitability of the *technology* per se for the intended application and the *quality of its said provenance*.

This discourse, in part philosophy and in part technical update, illustrates but one such current scenario of significant consequence presently before us in the Australasian Power Industry. In this case, however, the gravitas of the situation is magnified…there is a major and pressing job to be done but it appears presently that there is little interest from our Industry in embracing either the task at hand or the pathway to that end. This discussion document is, then, timely in its theme and discourse in laying the matter before us as an Industry.

What is the Problem to be Solved? A Perspective and Observations:

The purposes of this discussion are:

- To draw attention to the disturbing fact that extremely little detailed and systematic condition profiling is currently being deployed or contemplated for the MV (11-33 kV) cable population across the Australasian region (with a few notable exceptions in NZ and Australia). This effectively means that our MV cable asset base, which constitute some 50+ % on average of the capital value of most urban electricity distribution networks, is essentially of unknown condition! Right at a time when our aging MV cable infrastructure is being asked to step up to take even more load from renewable generation, this should be a most concerning observation to us all and of far-reaching potential interest also to our shareholders, stakeholders, and Regulator.
- To make the point that 'cable fault history' is neither a valid measure of cable condition nor any indication of near term or *future cable condition*. The two are often read as one but the corroboration is slim.
- To observe that our Industry has simply not kept up with the widespread use of suitable technology to carry out such work and it is the role of such a perspective as this to assist the matter constructively, admittedly an interesting role for the consultant to take but one that is nonetheless delivered sincerely and genuinely.
- To recognise that much of our MV power cable assets across Australia and New Zealand, if not the whole world, are not only of unknown condition but also now have concerning age profiles. Not only is the issue one of age profile exclusively…the true picture is far more complex. Such profiles are unavoidably overlaid with a long history of present and pending issues with not only the technology and application of jointing and termination practice, but also legacy issues with cable design, manufacturing, QA shortcomings, all combined with many and varied aging mechanisms and third-party damage.
- To make the point that all the above factors should now collectively and rightfully be top of our minds as in Industry when: contemplating both near- and longer-term reliability of these vital assets; planning for what investments are required in the near term to address legacy issues; and to at least maintain an adequate level of serviceability if total replacement can be avoided *via informed assessment based only on a detailed knowledge of the cable condition*.
- To convey constructively the background, deployment level, international uptake, and technical evidence enough to allow us to move closer to embracing with confidence what a reasonable assessment would determine to be the most appropriate such

technology identified presently to address the above observations effectively, one also meeting the vital ancillary consideration of being capable of being deployed practicably by our field technicians familiar with cable testing. To that end, the so named **'near 50Hz' partial discharge cable diagnostic testing technology**, applied to both new and in-service condition assessment of our 11-33 kV cable population, is presented and reasoned *generically* below to offer a potential lifeline to our Industry at a critical time in the effective asset management of the region's MV cable population. For the sake of clarity, 'near 50Hz PD measurements' are ones taken with a test voltage source having a 30-500Hz bandwidth. Such sources can be: 50Hz, Damped AC ['DAC'], and Cosine-Rectangular ['CR'] and are discussed further below.

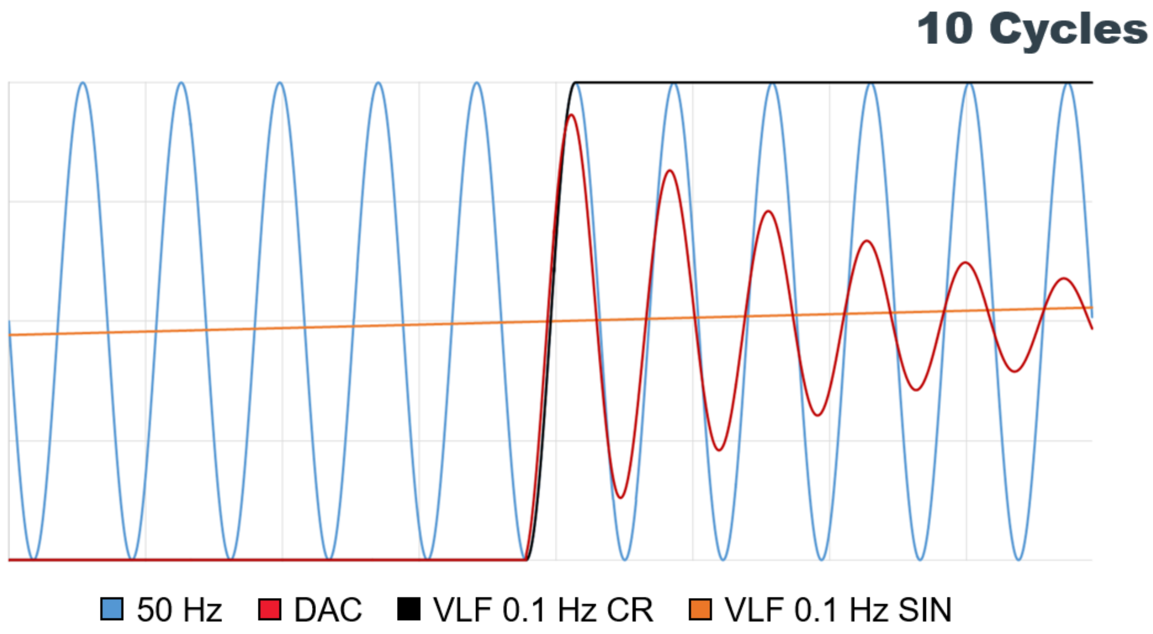

Image of 10 cycles of different waveforms potentially used for PD testing...Damped AC, VLF 0.1 Hz Cosine Rectangular, VLF 0.1 Hz sinus, compared to a 50Hz waveform

Background to the Technology Presented for Consideration:

The 'near 50Hz' cable diagnostic technology which is assessed in this document has its origins back in 1980s in Germany with the first patented commercial such equipment offered in 2004.

The 'near 50 Hz PD' cable diagnostic technology was first announced to the Australasian power distribution industry in New Zealand in October 2017 and demonstrated first in January 2018, with one exception of a single deployment in Victoria of a version of the technology since nominally 2011. Since that time the technology has attracted interest from all sectors, including the NZ Regulator, and has enjoyed a maturing of the practical devices and Industry 'knowledge rules' to apply it suitably to the wider task.

Its appeal to our Industry is its the ability of the technology to conduct formal, planned, and comprehensive surveys and risk management of 11-33 kV cable populations, an endeavour that has not previously been either practicable or as comprehensive in its diagnostic reporting in earlier efforts at such technologies (essentially explaining a dearth of interest in such process, to date).

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

International Uptake Status of 'Near 50Hz PD' Cable Diagnostic Technology:

The ease of use and its cost-effective application to the task has commended its market acceptance internationally. Over 1000 pcs are understood to be in service of various related versions, the figure being less important than its clear indication of a maturity of uptake and confidence in the technology.

As indicated above, Industry user groups have determined via practice and experience a range of sound 'knowledge rules' (see Figure). One manifestation of the 'near 50Hz PD testing' technology, known as Damped AC, now has its own standard in IEEE400.4 and a wider formal encompassing of the process is set to be published by Cigre B1.58 later in 2021, somewhat after the fact of a wide and successful deployment to do a job that was required of it.

Perhaps the best illustration of the argument for the near-term uptake of the technology in Australasia is utilisation for 11-33 kV cable diagnostic work in the vast a majority of mature first world countries, including: Netherlands; Germany; Spain; Italy; Belgium; Sweden; Czech Republic; Slovak Republic; Romania; Hungary; Russia; Finland; Poland; Singapore; Malaysia; Indonesia. The latter 3 countries have reportedly integrated near 50 Hz PD testing into their cable testing standards.

Emerging markets taking up the technology include Kenya; Tanzania; China; UAE; Cambodia; USA; UK; New Zealand; Australia.

Selected Papers to illustrate the Advantages of 'Near 50Hz PD' Cable Diagnostic Technology over VLF 0.1 Hz sinus PD Testing (whence it derived):

Early perspectives:

In his thesis published in 2003, Professor Dr Gunter Voigt of The Hochschule Konstanz, (a German university located in Konstanz, Baden-Württemberg, Germany) published a study of findings of other authors. Page 13 Section 2.3.8 compiles the findings of some 7 authors on the observation that the PD inception voltage at 50Hz has always been lower than the figure obtained by using VLF sinus equipment. The ranges of that difference are as much as 0.5 times the PDIV at 0.1 Hz. In other words, the sinus 0.1 Hz approach used extensively to date was found to **under-represent the severity of the PD problem in each case**. The authors cited in the table are also well known for their strong research in this matter: Ref 13: Pepper and Kalkner; Ref 14: Muhe, Sumereder; Ref 15: Pepper and Kalkner; Ref 18: Colloca et al; Ref 19: Gockenbach Hauschild; Ref 20: Voigt, Mohaupt; Ref 21: Voigt (ref: reference list below).

Indeed, in one of his papers from the same year (May 2003): **"Partial Discharge Measurements on service aged Medium Voltage cables at different frequencies"** by Gunter Voigt (Germany) and Peter Mohaupt (Austria), Voigt concluded: *"Experimental results on service-aged cable show that the inception voltage at VLF is slightly higher [in fact 33%!] compared with 50 Hz tests and the number of discharges may be significantly less."*

A pivotal early paper to show the advantage (over 0.1 Hz sinus VLF) of conducting **field-based HV cable diagnostics** at the IEC 'Power Frequency' range of 30-500Hz, was published in 2004 (VWEW Info day seminar, 2004…see **'Difference PDIV between 50hz and 0.1 Hz'**, a paper also available on request) by **E-On** [a very large European utility company with approximately €120 billion annual revenue at that time and 35 million customers in EU]. E-On commissioned a comparative test of sinus 0.1 Hz PD testing, and 50 Hz testing. The results showed a marked dependence on the rate of change of test voltage (dU/dt) on the PC inception voltage (PDIV) and PD parameters in general. The results of this test showed that PD behaviour was **highly dependent** on **voltage gradient** over time…the **lower** the **rate of change of voltage**, the lower the **PD activity**. The matter was **particularly sensitive** in **layered interfaces** (accessories…joints and terminations) because of **surface discharges/ tracking/inter-facial discharges**.

The above findings were supported by various scientific publications that followed, a significant one being **N. Jäverberg, H. Edin** (Sweden): "Applied Voltage Frequency Dependence of Partial Discharges in Electrical Trees", 2009.

This again determined that **PD extinguishes** at very slow dU/dt and that waveforms in the IEC power frequency range (30-500 Hz) were strongly preferred for PD field testing.

More Recent Perspectives:

Many papers now exist to echo the above findings. By way of illustrating a consistent impression of the advantages of 'near 50 Hz PD' only, we refer to the following papers:

a) In June 2012 a paper: **"Condition Assessment of Wind Farm Medium Voltage Cable Joints"** was published by Halvorson (Norway). His findings included the important observation: "…At early stages of aging the PD signals totally disappeared at frequencies below 10 Hz… This means that signs of aging are not visible at lower frequencies unless sufficiently high voltage is used. This could lead to a wrong diagnosis of cable systems tested only with VLF methods…"

b) In their August 24, 2014 paper: **"PD and Dielectric. Response Measurements on Service Aged Cable Joints"** by Mauseth, Tollefsen, and Hvidsten (Norway), they also observed that the PD Inception voltage (PDIV) was dependent on the applied test frequency. They also noted that sinus 0.1 Hz VLF could indicate areas of issue that were not seen at 50Hz which further cast doubt on the ability of an asset owner to trust the information received from a 0.1 Hz sinus VLF 'PD' test.

c) In their paper of July 2017: **"Effect of Applied Voltage Frequency of Partial Discharge in XLPE Cable Insulation"** by Alhamadi, Malik, Al-Arainy, and Wani (Saudi Arabia), they concluded also: "This paper presents an experimental investigation to determine the relation between the test voltage frequency and the behaviour of PD parameters using offline PD testing. The results show that there are some clear differences in the PD characteristics when tested using 60 Hz voltage and VLF voltage of 0.1 Hz". Again, this finding casts doubt and uncertainty on the reliability of sinus 0.1 Hz VLF PD data in making a condition assessment of cable.

d) In their Sept 2017 paper based on known reports and papers prior: **"Excitation Voltages for Partial Discharge Diagnostics on Medium Voltage Distribution Cables"**, by Probst, Putter, Petzold, Legler (Germany), outlined 3 case studies. Their conclusion included the following: "…sinusoidal VLF test sets are susceptible to incorrect measurements of PDIV and have repeatedly shown representations of PD rate, PD intensity and PD mapping not comparable to DAC or 50/60 Hz power frequency. This is due to the very slow voltage gradient / rate of change of voltage dU/dt in the region of the zero crossing. These limitations (…of VLF sinus PD test sets…) pose a significant problem for correct condition assessment and monitoring of the cable's accessories and therefore for precise and confident decision making". Their case studies include:

    - ENSO Energie Sachsen Ost–a German utility company in the federal state of Saxony servicing approximately 500,000 customers and earning a revenue of €1.1 billion per year. In this test sinus VLD PD indicated a weaker and lower PD count than near 50 Hz methods and gave the incorrect impression of being a non-critical situation.
    - ENRO Ludwigsfelde Energie–a small independent cooperative utility in the federal state of Brandenburg, Germany, servicing the local industrial parks including various factories of critical customers. In this test, whilst some VLF sinus test sites corroborated with DAC and CR near 50Hz methods, overall, the sinus VLF PD testing failed to see some defective areas of the cable at all to 1.7Uo. It was clear in this test that sinus VLF PD again demonstrated an unreliable guide to PD risk and severity in HV XLPE cables.

e) In the December 2017 paper: 'Investigating the Effect of Frequency and Wave Shape of Voltage Source on Partial Discharge Behaviour within Cavity in Medium Voltage Cable' by Gouda, El-Faraskopury, El-Sinary, and Farag (Egypt) their conclusions included the comments:

    - The PD activity in a power cable is dependent on the wave shape and frequency of the applied voltage as the PD level and the numbers of discharges vary with varying of them.
    - …. It is recommended using 'cosine-rectangular wave' at starting of MV cable diagnosis process as the most of PD's

events are ignited at the zone of change of its polarity(reversal); this is benefit in detecting of hidden defects…"

f) In the paper: 'Comparison of Partial Discharge Measurement Using Different Alternative Voltage Sources on Medium Voltage Cable' published in 2019 by Stanonik and Bonča (Slovenia), the authors concluded: "It turned out that the most sensitive is the Slope method, the OWTS [Damped AC] method gives comparable results, while the results obtained with the VLF sinus method deviate more."

Summary and Observations as to Comparative Advantages of 'Near 50 Hz' MV Cable Diagnostic Testing by Comparison to VLF sinus Diagnostic Testing:

By way of summarising the above body of *representative comment* ranging from 2003 to the present day, one may confidently conclude:

a) 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).

b) 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.

c) Published evidence exits to illustrate that diagnostic PD testing done on 11-33 kV cable by VLF 0.1 Hz sinus test sources is *potentially unreliable* in representing the true PD risk that one would encounter in real terms at the operating frequency of the cable at the same voltage.

The reasons for the latter important observation, as reported in the papers, include:

- VLF sinus PD has been noted to understate PDIV by as much as 50% or more of tests done at the normal operating frequency (or 'near 50 Hz') and especially when testing layered interfaces such as
- joints and terminations. Adding a technical 'twist' to the observations, some papers have even reported that a *reverse* of this situation might even occasionally be possible, further complicating any ability to *second guess the reality* of the true PD situation without a comparable 50 Hz test done simultaneously.
- Such variations also apply to observed PD count and pC level for a given test voltage, exacerbating the above observation. Indeed, VLF sinus has been shown to generally significantly under-read on both these measures for a given test voltage below 1.7Uo (i.e.: over the full range of test voltages used to assess 'in-service' MV cable), in some cases reported either completely missing certain key sites known to be of issue when assessed at 50Hz, or incorrectly indicating there to be no significant issue when in fact the converse was found to be the case when assessed at 50 Hz.

Adding to the observations above (summarising earlier comments):

- For reasons of its consistent and trusted behaviour in representing the '50 Hz operating condition PD risk', the 'near 50 Hz PD' diagnostic test methods for 11-33 kV cable have largely been embraced and verified in service in much of the world over the past 16 years or so, and it is particularly the case through Europe, Middle East, and Asia.
- Over 1000 of the near 50 Hz PD testing sources have been taken up by the Industry internationally over that period.

By corollary of the above observations, an asset owner presented with data only from 0.1 Hz sinus PD testing would not reasonably, according to published such observations, be able to accept such readings with confidence in assessing cable condition and in planning mitigations based upon such evidence. Arguably, in view of there being a degree of uncertainty as to the time frame even a noted worrying PD issue may take to finally fail, it would be hard to prove this observation anecdotally, had evidence from prior work done not been presented in the likes of the representative material presented herein.

It is agreed that a cable tested at 0.1 Hz sinus VLF PD <u>*might appear sound*</u> *and might even go on working for an indeterminate period after the test* but eventually fail and there would potentially be no supporting historical evidence for this occurrence from the earlier 0.1 Hz sinus tests. In reality, the literature would suggest, had the testing been done at the outset with 'near 50Hz PD' technology, the true condition of the cable asset would have been evident at that time, an unplanned failure averted, and the asset manager been able to have made a judgement (assisted by the likes of any of the Industry Analysis Rules he may care to use) of any required actions *based purely on the reality and the facts of the matter*. Drawing from the anecdotes herein, there would be few of our cable asset managers that, given the choice and technology being realistically available, would deny themselves the best possible appraisal of a pending risk or the actual asset condition.

Recommendations and Concluding Observations for Deploying 'Near 50 Hz' HV Cable Diagnostic Testing:

Having illustrated above the outstanding merits of a 'near 50 Hz' approach to diagnostic HV cable testing, it is a fitting moment to speak briefly as to the practical application of this technology to the task…

Perspective of Off-Line Near 50Hz PD vs 50Hz PD testing:

We have spoken of two waveform types commonly used for the purpose, 'DAC' [damped AC, a decaying AC pulse of 5-7 cycles with a frequency component of 30-500 Hz nominally to IEEE400.4] and 'CR' [Cosine Rectangular VLF continuous waveform, having essentially an identical frequency composition as the DAC]. Both waveforms, when applied to an 'in service' HV cable, will result in comparable Partial Discharge patterns (amplitude in pC, and pulse count), also being reflective of the results that would be identified in a 50Hz operating environment but with the advantage that both DAC and CR can be generated from a much more compact and lower cost test set than an off-line 50Hz source.

Assessing the Condition of 'in-service' Cables:

Typically, for this application one would apply a DAC waveform for diagnostic purposes, testing between 0.5Uo, Uo, and up to 1.7Uo in steps that also include Uo. Where one encounters wet joints, CR offers an advantage of 'drying out' the joints prior to PD testing. This technique typically allows (depending on both cable and test set parameters) diagnostic PD testing of **XLPE cable of up to 6-8km**, and **PILC cables of up to 3km**. Longer cables would be tested by measuring from each end.

For Commissioning New 11-33kV Cables:

For this application, the Industry still wisely calls for a continuous over pressure test for a period. These levels of test are determined by IEC 60502-2 and IEEE 400.2. One has the choice of applying a VLF pressure test for up to 60 mins then immediately following it with DAC testing or to combine the VLF test with a **'monitored PD withstand test'** using the CR waveform. The CR waveform is suited to this but DAC is less so, by virtue of DAC not being a continuous stress test. The Industry internationally has widely embraced the 'monitored PD withstand testing' of new cables using 'CR', finding it to also be very time efficient. Indeed, savings in time of well over 30 minutes per cable are enjoyed, allowing a significantly greater productivity of diagnostic testing in the day and a reduced per cable testing cost.

What to Specify from Your Contractor?

For an optimal cost-and-time-effective outcome in performing diagnostic 'near 50 Hz' testing for HV cables both in-service and under cable acceptance/commissioning, **one is advised to specify (or seek from your contractor) the use of a test set that offers <u>both</u> CR and DAC waveforms**. The Contractor should also be asked to prepare a comprehensive report illustrating (at minimum) the cable makeup and lengths; the calibration waveforms prior to testing; the PD levels mapped along the cable length of PD at each of the tested voltage levels; the PD inception and extinction voltages for each such graph; and a short commentary on the observations.

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

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

Next Steps by the Asset Owner After Receiving a Cable PD Test Report: *Typically, the asset owner, or an external consultant, would:*

- *provide fuller commentary for each report as to their level of concern as to any matters observed in the report. The use of Industry 'knowledge rules' might typically assist in this assessment.*
- *suggest such actions as any joints requiring replacement or cable overlay that might be required (at nominally $1000 per metre to replace cable, selective overlay can be a most economic outcome of such testing)*
- *determine relevant the time frames believed appropriate for any such actions.*

Associated decisions would be guided by a risk assessed matrix drawing from: age and composition of cable (newly commissioned cables would dictate immediate priority, particularly if contractual implications pertain); strategic value of each cable to the company; cable condition noted; other factors that may be known about the cable; number of customers served by it; potential cost for such work (determining whether shorter term or longer term investment is called for).

What about VLF Tan-Delta Testing?

By way of a final observation, a comprehensive diagnostic testing of in-service HV cables also requires a VLF Tan Delta test, the results ideally being presented along with the stated recommendations from IEEE400.2. For such cables, one should specify this test in conjunction with the near 50 Hz PD diagnostic testing. In applying this technique, please note that it has full validity on older in-service XLPE and PILC cables (or mixed such cables) but the use of VLF TD has been found to have **no useful diagnostic benefit (and is discouraged)** when testing TR-XLPE cables under nominally 7 years of age. Were smaller sections of such cable to be present on older circuits of predominantly PILC cables, the matter is less relevant as the Tan D values of the PILC cable would dominate the reading obtained.

Conclusion:

The above technical and philosophical perspective has been prepared to inform and assist the thought processes of our Cable Asset Managers in the Australasian region. Whilst an eclectic mix of inputs, it is believed that the reported collective observation of this study demonstrates that an opportunity to finally conduct an effective and proactive MV cable management regime is now to hand in both a practicable and long-proven format.

It is the intent of this technology assessment that enough material has been tabled to inform and stimulate a priority review from our Electricity Distribution and Commercial Industry colleagues to enhance our collective thinking about appropriate MV cable management practices. It is arguably appropriate that we confront pressing condition management matters presently at this timely point in the life of our increasingly strategic, but aging, MV cable population.

Fuller information from: www.lordconsulting.com

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