Condition based maintenance strategies for distribution networks

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Utilities in SA face demands for improved quality of supply with constraints on maintenance resources and an ageing distribution infrastructure. A condition-based maintenance strategy would permit efficient application of limited maintenance resources. Costs and the requirement for shutdowns limited the adoption of condition-based maintenance in the past.

Now a novel technique for cost effective non-intrusive on-line condition assessment of MV and HV cables and connected substation equipment offers a unique solution.

Utilities are expected to provide high levels of quality of supply, measured and compared to international norms. Maintaining quality of supply with an ageing power electrical infrastructure, combined with cutbacks in maintenance budgets and skills shortages, is an almost impossible challenge, exacerbated by the sharp rise in prices and extended lead times on new or replacement equipment.

To have any realistic chance of success, it is necessary to apply world-class maintenance strategies. It is recognised that most effective use is made of maintenance resources if they are deployed only when and where needed. For this reason reactive maintenance and preventative maintenance cannot be considered, as both place great reliance on availability of maintenance resources, and the only viable options are strategies which employ predictive or condition based maintenance as a core element.

The situation is compounded when the tools for determining condition require the equipment to be shut down. The practice of “sweating the assets” has come to mean that planned equipment shutdowns are rarely tolerated. Some utilities have an added problem where rapidly growing关电 needs have outstripped the pace of infrastructure growth, with consequential loss of the redundancy required for partial shut downs. Additional concerns are the effect on ageing of the insulation systems. Much or all of the benefit is lost if the act of measuring itself introduces premature failures.

It has not been possible to apply predictive or condition based maintenance in the proper sense, simply because it has not been possible to determine condition. The consequences can be seen in costly and embarrassing high profile failures, often of a catastrophic nature.

On-line distribution system condition assessment

The problems associated with shutting systems down for condition assessment tests are not new and have resulted in considerable research and development to find a practical solution. This article discusses one such solution: a passive on-line condition assessment technique which is non-intrusive and does not require shut downs or switching. It is equally effective on medium and high voltage systems and on all cable types, even with mixed cable networks. Although the method was originally devised to determine the condition of cables, the fact that assessments are done on-line means that information is simultaneously available on the condition of accessories and connected equipment. It should therefore more properly be thought of as a tool for distribution system condition assessment.

Objectives

The overall objective of diagnostic testing is to identify defects which lead to system failure and predict the time for these defects to progress to failure [1]. The test should be economically justified and should not cause additional degradation to the system.

Diagnostic testing to estimate future performance of cable systems represents an important option as it allows users to identify weakened cables, joints, terminations, switchgear or other system components for maintenance or replacement at a convenient time, rather than a critical time. It also allows users to separate weaknesses due to component defects or poor workmanship from end-of-life issues due to ageing of insulation systems. The remedial strategies are totally different and therefore it is important to have this knowledge. A planned diagnostic test program can therefore:

- Improve overall reliability
- Eliminate the crisis aspect of cable or component replacement
- Permit the prioritised replacement of weak sections of a system
- Reduce overall costs
- Reduce pressure on resources
- Identify the common type of weakness and permit an effective remedial strategy to be developed.

Ideally, such a test program should be performed while the cable system is energized and in normal operation without disrupting supply.

The on-line method of diagnostic testing

The ability to perform in-situ testing of installed cable systems while at operating voltage to estimate future performance represents a significant advance in diagnostic technology. This advance is possible due to novel technology developed by DTE Energy Technologies (CableWise) involving application of a totally passive technique that utilizes radio frequency (RF) pulses emitted by a cable system while it is energized in service. Examples of the measurements are shown in Fig. 1.

The radio frequency pulses are measured
and analysed using signal processing techniques. This is referred to as condition assessment diagnostic testing, and is most effective as it provides early identification of weakened components while the aged cable system remains energized. It can locate the degraded components of the system and determine the extent of the degradation; non-degraded components are also identified. A key point is that since cable systems age unevenly along their lengths, the weakened regions can be easily located and selectively removed.

An operating cable is continuously emitting signals during operation, many of which are difficult to detect [2]. Changes in the condition of the cable leads to changes in the nature of those signals, with identification becoming ‘easier’ as degradation proceeds. Special equipment is required to detect signals from defects such as water trees, [3]. When a cable exhibits partial discharge, (PD), signals are easier to detect. It is also possible to detect signals prior to partial discharge from energized and operating cables, giving valuable additional diagnostic information. Connected equipment and cable accessories such as joints and terminations are most likely to fail because of PD that causes degradation.

Moisture in PILC cables increases the dielectric losses resulting in localized heat generation that thermally degrades the paper insulation and normally leads to rapid cable failure. PD may only be present at advanced stages of such degradation; hence evaluation of pre-PD signals is of merit. The majority of cable failures in an extruded cable system are related to water treeing, which fail the cable when they convert to electrical trees. Once this happens, the time to failure is very short as the initiated electrical tree propagates rapidly through the already weakened dielectric. The only window for detection is during the conversion process. Under normal operating conditions, such conversion is caused by prolonged activity in cavities created in the water tree channel. Evaluation of RF pulses emitted while the system is in service is of value in estimating future performance.

To ensure reliable operation of a cable system, an integral method that provides condition assessment based on the detection and location of both PD and water content is needed. The technique described here is capable of detecting both PD and moisture content while the system is energized and in normal service.

Due to defects, all cable components emit signals during operation, but the nature of those signals changes depending upon the cause; for example, loose shields yield different signals than do internal defects. This diagnostic technique does not depend on measuring PD magnitude alone, and other signals are also measured. Measuring PD magnitude involves many variables that render this information of limited value, as the severity of the PD condition depends on many factors, such as the nature of the insulation material in which PD occurs, the environment in which the cable system is operating, the type of defect producing the PD, the location of the defect leading to PD within the insulation wall, and the nature of the insulation-shield interface. Any specific reported PD value diminishes in significance as the PD activity is further removed from the conductor shield. The passive measurement technique described in this article avoids these issues.

When cables and accessories age, the changes that occur do not take place uniformly along the system length, and one must be able to assess the cable system as a function of cable length. Non-uniform aging may be due to many factors: manufacturing issues, localized contamination leading to weak boundary layers at an insulation-contaminant interface, water migration to high stress sites, loose shields at discrete locations, micro-cracks produced by mechanical fatigue, and so forth. Of great significance is the exact location of the defect within the cable and accessories.

Signal detection including PD measurements in the field is significantly different from partial discharge testing of extruded cables shortly after manufacture. The objective of the latter is to detect manufacturing defects (voids, shield-interface imperfections) as a result of the extrusion process and is intentionally performed at an over-voltage. In contrast, testing at operating voltage in the field requires suitable sensors, a noise filtration system and signal detection and processing capability. The on-line approach provides all this at operating voltage.

**Measurement method**

The PD pulses and other signals developed during aging induce a current flow in the cable shield and conductor. The frequency spectrum extends over a wide band including substantial high frequency components. The magnetic field resulting from the current flow is used to obtain measurements. The test method couples energy from the magnetic field of the signal pulse into the measurement system, and the sensors designed to pick up the magnetic field are capable of detecting signals across a wide frequency range. They are simply placed over an exposed section of cable at a convenient measuring point. See Fig. 3 and Fig. 4.

The readings are normally taken at intervals of up to 300 m. This is preferred since, cables age unevenly and knowledge of the aging condition over discrete sections is desired. Since this testing is performed while the system remains energized the cable and connected components are at their normal (elevated) operating temperature, and the method provides information at service temperature. Noise reduction is accomplished through signal processing in the frequency domain. Analysis involves both the frequency and time domain. The method is not limited by cable length,
operating voltage, insulation type, cable construction, or branching of the system. One measurement on one cable takes 10 - 15 min.

The development of fast, digital oscilloscopes and waveform digitisers, and recent advances in signal processing and computer technologies, have led to more information and better understanding of the role and significance of individual partial discharges and related signals in the degradation processes of insulation systems.

**Condition rating**

After measurements are taken they are processed and sent to a central laboratory for analysis and interpretation. It has been found that a reliable condition assessment and estimation of future performance requires a combination of knowledge, experience, expertise and skill which only resides in specialists allowed to focus on this task. The lab compiles and submits an objective report for the customer in which condition levels are assigned to each section of assessed cable and connected equipment. An example of the typical rating for each level in the case of a PILC cable is provided in Table 1.

Phase resolved studies of signals from several hundred thousand meters of cables (PILC, XLPE, EPR) over the past nine years enables characteristic patterns from the data to be extracted and analysed, which, in turn, facilitates estimation of future performance. This knowledge has been applied to a great many utility and industrial plants around the world of which the following are a few recent examples.

### Case studies

**Customer 1: Licht- und Kraftwerke Sonneberg (A Municipality in South-Eastern Germany)**

Eight medium voltage circuits which were expected to have problems were selected by this utility for an online condition assessment test. The test results showed two Level 4 circuits which will be replaced during 2008. The utility reported that the test results confirmed expectations regarding the condition of the selected circuits and online condition assessment testing will continue to be used in the future. Following is a description of the two Level 4 circuits:

- **Circuit 1:** Substation “Roednerweg” to Substation “Friedrich-Engels-Strasse”
  - Total Circuit Length: 1010 circuit m
  - Number of Test Points: two

- **Circuit 2:** Substation “Roednerweg” to Substation “UTS”
  - Total Circuit Length: 456 circuit m
  - Number of Test Points: two

- **Segment 1:** Three single core XLPE-cables, 3 x 1 x 150 mm², Aluminium, five circuit m, manufactured in 2004
- **Segment 2:** One 3-core PILC-cable, 1 x 3 x 185 mm², Aluminium, 70 m, manufactured in 2005
- **Segment 3:** One 3-core PILC-cable, 1 x 3 x 185 mm², Aluminium, 297 circuit m, manufactured in 2008
- **Segment 4:** Three single core PE-cables, 3 x 1 x 240 mm², Aluminium, 80 m, manufactured in 1974
- **Segment 5:** Three single core XLPE-cables, 3 x 1 x 150 mm², Aluminium, five circuit m, manufactured in 2005

**Additional Information:** The circuit length is longer than the total length. For data collection the sensor of the testing device has been placed close to the transition joint in the cell of substation “Roednerweg” as well as close to the termination in substation “Friedrich-Engels-Strasse”.

**Customer 2: Stadtwerke Haiger (A Municipality in Mid-Western Germany)**

Eighteen medium voltage circuits were selected by the utility for an online condition assessment test. The test results showed...
two level 5 circuits/joints and one set of level 5 terminations (elbows) on a third circuit. Corresponding to the test results the utility decided for the two level 5 circuits to replace the two sets of transition joints from PILC to XLPE as well as the level 5 terminations on the third circuit. Following is a description of the two level 5 circuits and level termination:

- **Circuit 1**: Substation “Geisenbach” to Substation “Ritto”
  
  Total Circuit Length: 121 circuit m
  
  Number of Test Points: one
  
  The circuit consists out of two segments and has one set of transition joints.
  
  Segment 1: Three single core XLPE-cables, 3x1x95 mm², Copper, five circuit m, manufactured in 1995
  
  Segment 2: One 3-core PILC-cable, 1 x 3 x 35 mm², Copper, 116 circuit m, manufactured in 1965
  
  **Additional Information**: The sensor of the testing device has been placed close to the transition joint in the cellar of Substation “Geisenbach”

- **Circuit 2**: Substation “Geisenbach” to Substation “Cloos”
  
  Total Circuit Length: 194 circuit m
  
  Number of Test Points: one
  
  The circuit consists out of three segments and has two sets of joints.
  
  Segment 1: Three single core XLPE-cables, 3 x 1 x 95 mm², Copper, five circuit m, manufactured in 1995
  
  Segment 2: One 3-core PILC-cable, 1 x 3 x 35 mm², Copper, 116 circuit m, manufactured in 1965
  
  Segment 3: Three single core XLPE-cables, 3 x 1 x 95 mm², Copper, five circuit m, manufactured in 1995
  
  **Additional Information**: The sensor of the testing device has been placed close to the termination in Substation “Geisenbach”

- **Circuit 3**: Substation “Wacht” to Substation “Ritto”
  
  Total Circuit Length: 280 circuit meter
  
  Number of Test Points: one
  
  The circuit consists out of two segments and has one set of joints.
  
  Segment 1: Three single core XLPE-cables, 3 x 1 x 95 mm², Aluminium, 210 circuit m, manufactured 2006
  
  Segment 2: Three single core XLPE-cables, 3 x 1 x 70 mm², Copper, 70 circuit m, manufactured in 1989
  
  **Additional Information**: The sensor of the testing device has been placed close to the termination in substation “Wacht”. Strong discharge signals from the termination have been detected and lead to the conclusion (since the termination was fitted in 2006) that bad workmanship has been performed while fitting the terminations.

### Maintenance strategy

The on-line condition assessment technique is only a tool and whilst it offers unique and great advantages over previous technologies, it must be utilised in an appropriate way. Even the best tool will deliver disappointing results if not used correctly. In order to add greatest value to a utility or industry, and to be properly effective, on-line condition assessment must be integrated into a well-thought out overall strategy. What does this mean in practical terms?

The majority of utilities and large industrial users have aged networks which are too extensive in relation to their resources to permit whole scale replacement or even rolling out a condition assessment programme for the entire network. It is therefore necessary to prioritise based on a combination of criticality and failure risk factors. By analysing the network in this way and plotting on a chart as in Fig. 5, the number of risk elements begins to reduce to manageable proportions. It also clearly shows the high failure risk and high importance key risk elements where focus and attention is required.

Ideally the condition of all of the identified key risk elements should be known and it becomes possible to prioritise corrective maintenance action or replacement programmes. It may be found that even within this area there is too much for a complete condition assessment programme. The key risk elements should then be grouped into categories which are expected to be similar in respect of age, manufacture, operating environment, etc. At this point a condition based maintenance programme can be implemented by assessing the condition of a representative sample from each of the categories. If the results show relatively good condition the category can be assigned a low priority, if the condition is poor this will indicate the need for more extensive condition assessment tests on more samples in the category.

In order to fully benefit from the condition assessments, it is also important that maintenance management carefully analyse the assessments in order to distinguish between:

- poor condition due to irreversible and unavoidable ageing (calls for capital expenditure for replacement)
- weaknesses introduced by bad workmanship or use of substandard components (calls for investigation and elimination of the origin of these weaknesses)
- poor condition due to unavoidable but reversible ageing effects (calls for timely maintenance intervention).

### Conclusion

Maintenance of ageing distribution systems with limited resources and demands for improved quality of supply is a challenging task. Condition based maintenance strategies offer excellent options for achieving these goals, but until recently were not feasible for distribution systems. Now a cost effective, passive, non-intrusive, on-line technique is available for condition assessment of cables, cable accessories and connected equipment in the distribution system. Based on measurement and analysis of RF signals, it provides assessment of condition and an estimation of future performance. With this tool, maintenance engineers have the knowledge with which to manage efficient condition based maintenance programmes and so meet the target of increased reliability with limited resources.

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### References


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