THE ROLE OF DIAGNOSTIC TESTING AND MONITORING IN TRANSMISSION CABLE MAINTENANCE PROGRAMS.

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Abstract:

The structure of a traditional transmission cable maintenance program is reviewed together with a discussion of the business perspective that now makes these practices unattractive. Included is consideration of changing expectations in the maintenance environment, including the heightened expectation that the maintenance engineer can accurately predict the probability of reliable cable operation.

A review of the eventual consequences of unfocused maintenance is presented, illustrated by several examples from past experience. Also included are the effects of changes in the cable system operational environment and a discussion of the measures necessary to protect system integrity from external adverse effect.

The application of the "predictive maintenance" philosophy to cable maintenance programs is discussed, together with the impact this philosophy has had on cable maintenance in the past two decades.

A broad overview of the results of a 22 year cable oil sampling program is presented with a discussion of the insights this program has provided into cable condition.

A Variety of diagnostic tools, both intrusive and non-intrusive, which have been used in the past is reviewed. The role of some of these techniques in complementing the modern transmission maintenance program is discussed.

Based on the severity of the consequences of component failures, a priority list of diagnostic needs is developed. A discussion of the likelihood of the successful incorporation of diagnostic tools to satisfy these needs is provided. The potential for successful incorporation of partial discharge testing into the maintenance program is discussed.

1.0 Background

There have been many different approaches to HV cable maintenance evident within the electrical utility industry. Many of these were driven by a belief that if anything went wrong with a HV cable, it was necessary to have crews available to immediately carry out repairs. (In part this thinking is a reflection of a strategy that had proven itself to be very effective for overhead transmission lines. However, HV transmission cable repair has little in common with an emergency repair for overhead lines.)

Where cable crews have been established as an insurance against extended repair times, there has been a need to keep those crews occupied during non-emergency times. Many of the maintenance programs that have emerged from this type of work environment have a unique "flavour". This has a lot to do with the recurring problem of what tasks to assign to crews of cable jointers on days when there is no jointing to be done. As a result, a lot of maintenance programs have elements such as "clean and polish cable termination insulators" and carry out annual overhauls repeated at regular intervals.

This is not a criticism of the desire to maintain H V cable termination insulators free of contamination or to have confidence in the reliable operation of a pumping plant. Rather, it is recognition there is a basic incompatibility between maintaining an "in house" emergency repair capability and performing planned maintenance programs. The "clean polish and check" school of HV cable system maintenance had as it's major benefit a comfort zone that if anything went wrong, the resources were available to fix it while in the meantime something was always being done to "keep the system running".

A "pesky" outsider with a business background might suggest that a proper test of the value of this approach would be the degree to which a trend toward a reduced frequency of emergencies in the HV cable system has resulted!

I'm open to debate on this, but I believe that experience has not been supportive of the effectiveness of such maintenance practices.

2.0 Practical Considerations

There are a number of drawbacks to the traditional approach of combining planned maintenance and emergency response within a dedicated cable crew. These include:

- Difficulty in training and maintaining a suitable level of HV cable trade skills;
- Cost of acquiring and maintaining the work equipment and strategic spare parts necessary to support major cable repair work;
- Demands of staffing a cable crew at a level which allows effective response to cable failures at all times;
- Scheduling conflicts resulting from competition between completion of the planned maintenance program while also responding to emergencies;
- Ensuring the quality of work performance when emergencies aren't happening, [lets face it planned maintenance activities generally aren't very exciting while emergencies can induce adrenalin rushes;]
- equipment outages for planned maintenance increasingly require long lead times to establish but this planning may be derailed if a HV cable system alarm is received, (even minor alarms can be quite disruptive until the details are understood;)
- crew supervisors are constantly faced by the task of balancing resources and workload in a pattern of "feast or famine";
- crew supervisors tend to concentrate more energy on dealing with emergencies than planned maintenance as the consequences may be more dramatic;
- there is a tendency by traditional cable crews to view planned maintenance as "work we do when we're not busy with emergencies";
- diligent recording of detail is necessary to obtain a maximum benefit from maintenance activities as subtle changes may be early indicators of significant changes in the condition of the cable system;

The HV cable trade is unique among the family of occupations that make up the utility work environment. Some insight into why this is so may be explained by the following:

- there are few formal training programs;
- the range of skills required for HV cable pulling, jointing and terminating is a unique mix of elements of several trades;
- career progression within the occupation is generally limited;
- the specialized needs for cable trade training tends to fit poorly within established utility training programs;
- it is difficult to bridge the gap between the work of the HV cable

trade and that of other trades within the utility family;

- it is virtually impossible for anyone other than the cable tradesperson performing the tasks to verify the quality of a HV cable installation;
- the consequences of installation deficiencies do not generally become evident for many years;
- a large stock of components, many with subtle dimensional differences, is essential to allow a prompt repair to a faulted HV cable;
- major cable repairs are labour intensive and are very impactive on the personal lives of the cable crew members;

The single most important activity in any HV cable program is maintaining the thermal integrity of the cable route. The contribution of this work to maintaining the integrity of the original system specification (and hence system reliability) is invaluable.

However, in major urban areas providing stakeouts for HV cable routes is a demanding activity which requires the provision of a 7/24 emergency response capability, the economics of doing this are distorted if cable tradespersons, who are overqualified for the duty, are used to provide the service. However, in the traditional cable crew stake outs has often been seen as a part of the crew workload because of it's apparent fit. A judicious mix of personnel knowledgable in the requirements for a thermally suitable cable environment together with personnel skilled in cable route print interpretation and cable locating would be more effective.

3.0 Current Utility Business Environment.

The emergence of competition in the electric utility business and the advent of regulators who expect full transparency for all expenditure and service reliability issues is a very new development for most of us. One consequence is that the electrical utility industry has now moved away from its reliance on service reliability as the only yardstick for measuring operational performance and for basing expenditure decisions.

It is now no longer enough to be able to make the right technical decision when faced with a system crisis. It is now necessary, (and this can be much more difficult), to be able to convince people unencumbered by a knowledge of past cable system repair and maintenance practices, of the value of proposed maintenance and capital expenditures and to be accountable for their effectiveness

We have seen some spectacular examples in the past few years of the consequences of deteriorations in HV cable system reliability. These events, allied with the regulatory climate changes, have forced utility executives to take an increased interest in HV cable system condition. Given the high capital cost of new HV cable installations and the impact of cable faults, it does not require a crystal ball to see that this will continue. It is also clear that cable maintenance engineers will be expected to be able to accurately describe system condition and predict the remaining reliable life of the system.

These developments have stimulated new interest in diagnostic procedures capable of describing the existing condition of the HV cable system and suggesting the future reliability of the system.

At the risk of being over simplistic, it does not appear unreasonable that one of the outputs of an effective HV cable maintenance program should be an objective assessment of the system condition supported by substantial data and capable of use for prediction purposes.

Whether these needs can be met using variations on the traditional cable maintenance / repair crew approach is an open question.

The cost of providing a dedicated cable crew is high in labour and equipment costs. A broad range of specialized skills is required for a program, which is geared to provide a diagnostic assessment of cable system condition. Typically, these are not the skills found in a HV cable crew whose principal skill base is cable repair and jointing.

Increasingly, it will be difficult to justify such expenditures to a cost sensitive regulator and support them by invoking a need to be totally self sufficient in HV cable maintenance and repair.

It is also becoming apparent that there are cost effective alternatives to "in house" emergency HV cable repair services. These can be effectively provided by specialized

external service providers working within properly structured emergency service contracts.
The economies of scale possible for such service providers working with several utilities are quite apparent. These result from better equipment utilization, better access to personnel with appropriate trade skills and a strong business incentive for advancing the techniques for HV cable repair and diagnostic maintenance.
The use of such service providers in conjunction with a utility rapid response capability to provide initial stabilization of an emergency situation may be the most cost effective and technically satisfactory method of providing cable system repairs.

4.0 Maintenance Realities.

During the operational life of a HV cable system many situations occur requiring assessment and intervention. These range from events that turn out to be trivial, to cable faults, and major oil leaks.
The sub system most often involved in those events is the pressurization system. The cause of these alarms is often as straightforward as depleted nitrogen cylinders, out of calibration pressure switches or even alarm system malfunction. However, there are also potentially serious situations such as low or high reservoir levels and excessive pumping operations.
Despite the large number of "false alarms" such events can never be ignored, as the consequences of an unresponded worst-case alarm can be catastrophic.
It is evident that many of the older alarm systems still in operation are a throw back to the days when labour costs were loosely controlled and supervisory system technology was still in its infancy.
In the modern, cost sensitive, electrical utility environment, the use of PLC based alarm systems and computerized annunciation and communication technologies can provide prompt accurate information on the status of any element of the pressurization system and facilitate prompt, accurate, decision-making.
This is not only cost effective for the utility, it also provides assurance that serious cable system problems will be quickly identified and remedial measures implemented without delay.

The worst situation I faced was my first exposure to a major oil leak. Following an excessive pump operation alarm from a pumping plant, it took 28 hours in bitterly cold weather to find the source of an oil leak from the pipe type cable in an outdoor transformer station. It would have been much easier to locate if the leak was combined with an electrical fault, but such was not the case. The leak was finally discovered underground at a termination support structure where the riser pipe had been installed in contact with the structure. The cable had performed very satisfactorily for many years until the day when a transformer bushing flashed over at a transformer station two miles away! For a very brief moment, the potential difference between the metal of the riser pipe and the grounded structure was sufficiently large to break down the pipe covering and burn a hole the size of a quarter in the stainless steel pipe.
This was a very salutary lesson in HV cable maintenance for me. It suggested two fundamental properties of HV cable system maintenance.
Firstly, a record of many years of perfectly satisfactory cable system operation does not provide any assurance that the system is free of defects.
Secondly, unless the trade's people who perform the HV cable installation were also diligent as quality assurance inspectors, there are presently very few techniques for checking on the overall quality of a buried installation.
The significance of these observations were reaffirmed to me many more times during my career as "unique" sets of operational circumstances combined to produce cable system emergencies.
As a further observation, prompted by ongoing system emergencies, I believe that traditional maintenance practices are very unlikely to identify or prevent such occurrences.

5.0 Predictive Maintenance.

I believe that a sound cable diagnostic program should provide the ability to first identify and then monitor the effects of deviations from original specification due to installation deficiencies and changes in cable system condition which occur during the life of the cable.

The advent of predictive maintenance has occurred fairly rapidly in the maintenance of station equipment and protection systems. It has not been as straightforward to introduce it into HV cable maintenance programs. There are a number of reasons, which complicate its introduction.

This may be partly due to the generally satisfactory reliability record of cable systems and the impact of external interference as a leading cause of faults. Since HV cable system routes are largely outside station fences they are vulnerable to interference from other users of public areas. This is a factor well understood by transmission lines personnel, but is generally not present for the maintainers of station equipment.

One of the most significant changes, which can occur during the life of a HV cable system, is in its thermal environment. This is particularly true in rapidly developing urban centers where there is continuing pressure from new underground facilities threatening to encroach on the cable backfill. Constant vigilance is necessary, as there is a very poor understanding on the part of other underground users of the critical requirements of a transmission cable thermal environment. The addition of facilities which act as hot spots along the cable route may not have an obvious effect in the short term but in time, as loading increases, can lead to thermal degradation and eventual failure of the cable insulation.

Although it is labour intensive and therefore costly, it is important that the maintenance program recognizes this and includes frequent review of construction plans along the cable routes together with the ability to intervene if there is believed to be an adverse impact from any of the proposals.

By comparison with the predictive maintenance programs for station equipment, this may seem totally out of place. However, it is a vital part of maintaining the “as built” transmission capability of the cables in an otherwise uncontrolled environment.

A sound understanding of all aspects of HV cable operation is essential when designing program. One of the likely consequences of the application of predictive maintenance techniques will be a reduction in the frequency of inspections of some parts of the cable compared to a traditional maintenance program. It is important that the consequences of component failure are fully understood both from a personnel safety standpoint as well as system reliability. For instance the presence of cracks in the porcelain mounting insulators for terminations may appear operationally insignificant to some personnel. However, the combination of such cracks and contamination can cause these insulators to spread porcelain fragments over a wide area under system fault conditions. This is a serious hazard to any personnel who may be in the area at the time.

6.0 Maintenance Testing.

A difficulty facing the designer of a predictive maintenance program for HV cables is the relatively small portion of the system that is visible or accessible. The program must therefore rely heavily on indirect means of assessing the condition of the system components. One of these techniques, which has been used by some utilities for many years, is the sampling and analysis of the cable oil. Analysis of these samples has often included measurement of gas in oil content or RGP measurement while circulating, water content and power factor at 100 degrees Celsius. Some other analyses have included measurement of interfacial tension and dielectric strength.

Other tests which have been in use include, dc hipot testing of direct buried cable jackets, pipe coating insulation resistance, pipe polarization potential surveys at closely spaced intervals and thermocouple readings.

These tests help to give some insight into the condition of the cable system but they have limitations. For instance, the use of thermocouple readings is only a reliable indicator of cable operating temperature if there is assurance that they are located at the most thermally sensitive parts of the cable route. In addition, some of these tests are better suited to identifying corrective repairs that need to be done. So it is very difficult on the basis of such results to provide any estimates of the remaining reliable service life of the cable system. However, in the current electric utility regulatory environment this is precisely what is required.

Although HV cable systems are inherently robust and will provide a long reliable service life, they are not indestructible and some will eventually need replacement at a high capital cost. In the current business and regulatory environment, it is important to be able to signal well in advance that this point is being reached and to be able to support the assessment with objective technical data.

In attempting to reach this point some utilities have undertaken some novel approaches. These have included x-ray inspection of pipe type joints, removal of termination porcelain insulators and inspection of the internal condition of the termination. In other cases samples of papers from the cable insulation have been removed for measurement of the degree of polymerization. The severe consequences of oil leaks have also been a catalyst for work such as the excavation of portions of cable trenches to examine the condition of pipe coatings.

One of the difficulties with such approaches is the absence of a reliable probability based methodology for identifying the highest risk parts of the system for such intervention. Equally importantly, the interpretation of the results is often problematic. In fact, for many analyses, the stability of the characteristic value over time maybe more indicative of the cable condition than the absolute value.

A review of the results of a gas in oil monitoring program extending back to the late 1970s demonstrates this quite clearly. Many of the results show few patterns of similarity between samples from cables of like age and construction. However, individual cables show a much greater consistency in their results. These tend toward a characteristic pattern for the presence of Hydrogen, Methane, Ethane and Ethylene that appears to be, for the most part, stable over time.

This is not to say that all older HV cables have detectible levels of Hydrogen, Methane, Ethane or Ethylene. Several cables, whether pipe type or low-pressure oil filled, show none of these gases even after several decades of operational service. However, for those cables that do display measurable concentrations of these gases, they are present at a wide range of levels. In some cases the presence of Hydrogen concentrations of 500 ppm or more, which would be considered alarming if found in a transformer, have been repeatedly found in results from certain cables over periods of several years. Furthermore, in tracking cables with detectable levels of Hydrogen, Methane, Ethane or Ethylene, it appears that there is often a general stability in the concentrations. Furthermore, over periods of several years, this stability appears to be independent of the concentration level in that particular cable.

Some may be tempted to view this lack of pattern as an obstacle to the adoption of a predictive maintenance program because of the inconsistency in interpretation of the results of diagnostic testing. However, I believe it can be seen as reaffirming the need for adoption of such a program at a sampling frequency which allows trends to be identified and plotted. Consistency in sampling is necessary to generate confidence in the understanding of the mechanisms which are progressing inside the cable system. No one type of testing will provide this level of confidence. Rather, the challenge is to develop and adopt additional test methods, which, in conjunction with methods like oil sampling, further the development of this understanding.

7.0 Diagnostic Programs.

Although the reputation for reliability of HV cable systems is very good, the direct and indirect consequences of failure of any part of the cable system are very serious. The system impact of the unavailability of a cable for an extended period can be severe as repairs are usually time consuming. In addition, the environmental impact of an oil leak can be even more serious as clean up costs, environmental liability and adverse publicity can be devastating.

It is therefore important to ensure that the elements of the diagnostic maintenance program provide information on the condition of all parts of the cable system where the consequences of failure would be significant.

This requires that all critical subsystems be considered in the development of the maintenance program. Therefore, the program must be capable of providing insight into the dielectric properties of the cable insulation terminations and joints, the consistency of the thermal environment of the cable, the integrity of the cable pipe (or sheath) and corrosion protection systems, as well as an assessment of the systems for automatic pressurization, alarm annunciation and mechanical support and protection.

The use of partial discharge measurement equipment suitable for field measurements offers the prospect of getting direct insight into the condition of the cable insulation. The practical difficulties to be overcome in making these measurements are not insignificant. However, if successful, the availability of reliable partial discharge results would be an enormous asset in assessing the overall condition of a cable. Used in conjunction with a cable oil-sampling program, assessment of both sets of results can provide a real guide to the integrity of the insulation system of the cable and it's joints and terminations. Since electrical faults in cable systems often cause oil leaks as well, the adoption of any technique which reduces the likelihood of electrical insulation breakdowns offers a double benefit.

Many new cable installations are now taking advantage of distributed temperature sensing systems to monitor cable temperature in real time. This is not only a potent operating tool but also allows a comprehensive ongoing assessment of the actual thermal environment of the cable. However, for older cable systems this, unfortunately, is not a practical option. Monitoring the condition of the thermal environment can be a major undertaking if an ongoing program of route inspection and protection has not been followed. The value of the results of a backfill excavation and sampling program will be as good as the knowledge of conditions along the cable route which has been used in the site selection process. This is an expensive activity as excavation costs are high. The number of excavations required to generate confidence in the results as a model for the entire cable route can be large unless very good information has been gathered on the changes, which have occurred during the life of the cable. Nevertheless, such a program is advisable unless there is no likelihood of the cable operating at its design loading during its lifetime.

Unfortunately, there are no techniques that I am aware of which may, non-intrusively, provide information on the condition of a cable pipe. Information on any reduction in wall thickness or onset of localized corrosion would be extremely important if it were available. The closely spaced over the line polarization survey does provide information on the effectiveness of the protection provided by cathodic protection systems, but it is not an absolute assurance of corrosion control. In the past, satisfactory survey results have usually been taken as the best available indication that the pipe is protected from corrosion. This, however, does involve a leap of faith which, given the environmental consequences of a leak, utility managers would now prefer not to take.

There is a technique used by pipeline companies for an over the line coating survey where the attenuation of a high frequency signal injected into the pipe is measured along the route. This technique has been tested by some electrical utilities but it still needs refining for the cable operational environment because of the influence of ground grids and multiple ground return paths.

The combination of a refined over the line pipe coating survey together with the results of closely spaced polarization potential surveys can greatly improve the level of confidence in the condition of the pipe and it's protection systems.

Ideally, data on the operational condition of the remainder of the system can be gathered through planned inspections of the above ground elements of the cable and pressurization system. This inspection would normally include calibration checks of automatic operations of the pressurization and alarm annunciation systems, however, it should also include a review and analysis of the operating and defect history of the cable system.

8.0 Conclusion.

The role of the HV cable system maintenance engineer has changed dramatically during the lifetime of the cables which are the backbone of many electrical utilities. At one time the role was largely defined by the effectiveness of execution of repairs and the adequacy of the response to emergency conditions. Increasingly, there is an expectation that the cable engineer be the source of objective data to support an assessment of the overall condition of the system and it's operational limitations as well as provide a basis for accurately predicting the remaining useful life of the system. In addition, this data will be expected to be suitable for assessing the relative value of different options for extending that life expectancy.

Collection of the data to achieve this is still in its infancy in the field of HV cables, primarily due to a lack of suitable diagnostic techniques. Development of the tools which will make this more a science instead of an art is overdue. Application of many diverse principles is required to bring this about. The introduction of techniques such as partial discharge measurement in the field, improved techniques for assessing cable thermal environment and corrosion vulnerability will make this a very stimulating time for cable system maintenance engineers in the utility HV cable business.