Quantifying the Economic Benefits of Online Monitoring

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ABSTRACT

Online condition monitoring equipment with the capability to detect a wide range of failure mechanisms in power systems equipment is now widely available at affordable prices. Online monitoring with its near continuous sampling can dramatically improve the effectiveness of condition monitoring as a risk mitigation tool by reducing the possibility for a failure to develop undetected between inspection periods. This type of system however carries significant up-front implementation as well on-going operating costs associated with system maintenance and the management and interpretation of condition data. In this paper we discuss the economics of implementing on-line monitoring by comparing estimates of the reduction of risk against the cost to install and operate a typical on-line partial discharge condition monitoring system. Risk estimates are calculated in monetary terms using EA Technology's Condition Based Risk Management (CBRM) methodology taking into consideration network performance, safety, cost and environmental consequences. Through analysis of aggregated distribution company CBRM data we present examples where online monitoring is clearly justified as well as statistics indicating the proportion of typical circuit breaker populations where continuous monitoring is likely to be cost justified on a risk mitigation basis.

Index Terms—*Reliability, Distribution networks, Partial discharges, Online Condition Monitoring, Risk Management.*

1.0 PARTIAL DISCHARGE MEASUREMENT AND THE REDUCTION IN FAILURE

Partial discharge activity has long been accepted as a major cause of failure of HV/MV switchgear [1 & 2]. Reference [1] states that "PD measurements are an ideal method for evaluating switchgear apparatus with non-self-restoring insulation. During a temporary over-voltage, during a high-voltage test, or under transient voltage conditions during operation, partial discharges may occur on insulation of this type, which includes gas, liquid, and solid materials. If these partial discharges are sustained due to poor materials, design, and/or foreign inclusions in the insulation, degradation and possible failure of the insulation structure may occur."

Some of the results that utilities have achieved in terms of reduction in failure rate, just through widespread deployment of hand held instruments and a condition based maintenance approach have been impressive. Companies have demonstrably delivered a very short return on investment, year on year reduction in failure and significant improvement in network performance. For example, the large national distribution company in Reference [4] has reduced the total number of outages due to MV switchgear failure by 71% over a 5 year period and are now experiencing 473 fewer failures per year.

2.0 TECHNIQUES TO DETECT PARTIAL DISCHARGE IN SWITCHGEAR

In practice, partial discharge in HV/MV insulation can be considered to take two forms: i) surface partial discharge and ii) internal partial discharge. When surface partial discharge is present, tracking occurs across the surface of the insulation, which is exacerbated by airborne contamination and moisture leading to erosion of the insulation. Internal partial discharge occurs within the bulk of insulation materials and is caused by age, poor materials or poor quality manufacturing processes. If allowed to continue unchecked, either mechanism will lead to failure of the insulation system under normal working stress, potentially resulting in catastrophic failure of the equipment.

From extensive testing of switchgear with partial discharge tracking across the surface of insulation, it has been observed that surface discharge activity often has low amplitude but very high discharge rate. Due to the low amplitude of surface discharges, one of the most appropriate methods for detection is using ultrasonic techniques [2&3].

In contrast to surface discharges, internal void discharges as they develop will have consistently high amplitude levels but much lower discharge rates. The most commonly deployed techniques for detection of this type of internal discharge is through the detection of Transient Earth Voltages which are induced voltage spikes on the surface of the surrounding metalwork when partial discharge occurs. The TEV phenomenon was discovered by Dr John Reeves at EA Technology in the 1970s and has been in used for the non-intrusive detection of partial discharge since.

3.0 PERIODIC SURVEYS TO PERMANENT MONITORING

As soon as organisations start to achieve business benefit in terms of cost saving and network performance through the use of handheld partial discharge instruments, attention invariably moves towards the potential for the additional benefits provided by permanent 24/7 partial discharge monitoring systems [2, 5]. Utilising permanent monitoring systems enables assets to be monitored under a variety of different operating and environmental conditions, and of course can be less labour intensive in collection of condition data.

The level of relative humidity in a substation can have a direct effect on the occurrence of surface partial discharge activity. This is particularly so on modern air insulated switchgear with polymeric or cast resin insulation, and early stage problems in particular are often dictated by the presence of moisture in the atmosphere [6]. This is demonstrated by the graphs in Figure 2 from an UltraTEV monitoring system installed on an 11kV switchboard. The lower trace shows relative humidity within the substation and the upper traces show levels of ultrasonic partial discharge. Early warning in this manner gives asset owners the opportunity to slow down the degradation processes and effectively extend the life of the substation simply through management of substation conditions.

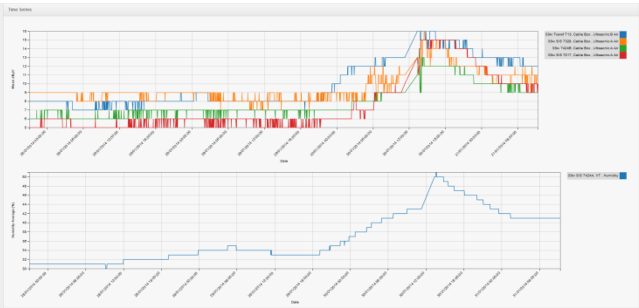

Figure 1
UltraTEV Monitor Trace correlation of Relative humidity and Ultrasonic PD activity

Network conditions can also play a part in whether partial discharge activity is present or not during substation surveys, particularly on industrial networks where switching is more common. An example is shown in Figure 2 where no partial discharge was detected during an initial survey but two TEV sources were detected by the subsequently installed PD monitoring system. The first and most severe source became active due to a switching operation, the second was at an early stage of development and intermittent in nature.

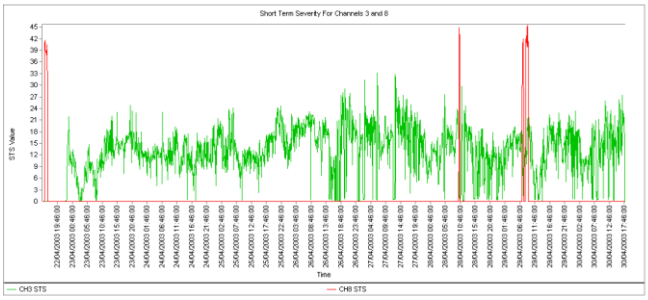

Figure 2
UltraTEV Monitor Trace of 2 TEV PD Activity Sources

So the benefits of incorporating non-intrusive partial discharge testing as part of a condition based approach to management of assets are quantifiably shown to help companies diminish failure rates, improve performance and reduce costs. The additional benefits of installing permanent monitoring solutions are again tangible in being able to assess the condition of switchgear 24/7 under different environmental and network conditions.
The question therefore turns to whether installation of on-line monitoring solutions on HV switchboards can be justified in economic terms.

4.0 QUANTIFYING THE ECONOMIC BENEFITS OF ONLINE CONDITION MONITORING

Online condition monitoring provides benefit by warning of developing failure modes. Early warning can provide an opportunity to minimise the negative effects of failure and therefore reduce the potential for negative consequences such as injury, loss of supply or production or costs such as damage to equipment and secondary damage.

Because the benefits of online condition monitoring are related to mitigating the impact of failures, quantifying the benefits of failure reduction requires a mature understanding of equipment failure related risk. The most popular definition of risk is that risk is the product of the probability and consequences of an event as shown in Figure 3 below.

Figure 3
Risk as the product of probability and consequences of failure

Individual but similar assets operated by an organisation can vary significantly in both their physical condition and in their operating context, factors that both influence risk. This may mean that in practice similar assets may present very different levels of risk and therefore levels of benefit for online monitoring.

4.1 QUANTIFYING RISK – CONDITION BASED RISK MANAGEMENT

EA Technology's Condition Based Risk Management (CBRM) provides a methodology to calculate the risk associated with large numbers of assets by developing calibrated estimates of each assets probability and consequences of failure. A quantitative probability of failure (failures /year) is derived from an asset 'Health Index' which combines known information relating to the assets age, design, operating environment, operating duty and physical observations of condition [7 & 8]. Construction of a typical health index is illustrated in Figure 4 below.

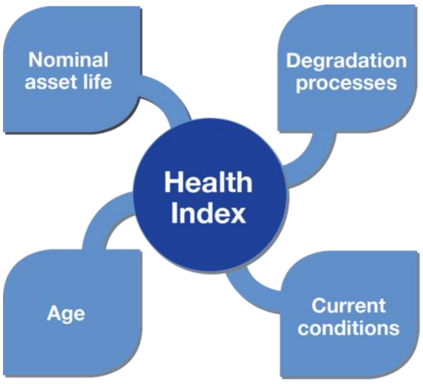

Figure 4.
The asset health index combines asset related data from a range of sources.

Consequences of failure are evaluated at the individual asset level in financial terms. This is achieved by firstly developing quantified estimates of the average consequences of failure in the dimensions of Network Performance (or production impacts), Safety, Financial, and Environmental impact. These average consequences are then individualised by scaling up or down to reflect an individual assets operating context through the application of appropriate criticality factors.

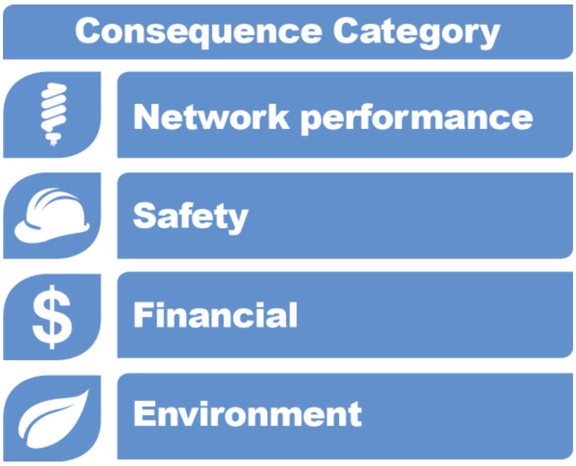

Figure 5.
Consequence categories for which consequences of failure are evaluated

The outcome of this process is a measure of asset failure related risk quantified in financial terms [9]. It should be noted that a significant part of risk quantification is evaluating the financial value of loss of electricity supply to customers. For distribution networks this is approached using a Value of Customer Reliability (VCR) methodology consistent with methods accepted by regulators in Australia and New Zealand. Calculating risk in financial terms makes it possible to use the derived risk values in cost benefit calculations to test the validity or otherwise of various risk management interventions.

4.2 QUANTIFYING THE BENEFITS OF ONLINE CONDITION MONITORING FOR METAL CLAD SWITCHGEAR

EA Technology has completed a large number of CBRM projects for clients worldwide. To explore the potential benefit for the application of online partial discharge condition monitoring we have pooled the estimates of failure related risk for a sample population of approximately 3,400 11 kV metal clad switchgear panels. The sample has been drawn from a range of operating environments consistent with those found in both Australia and New Zealand. By pooling data in this way we are provided with some insight into the spectrum of risk values presented by metal clad switchgear in the region.

Figure 6 shows a frequency plot of calculated annualised risk values. It should be noted that in all cases the quantum of risk is dominated by the effect of loss of supply or Network Performance Risk which can be highly variable depending on the network configuration and connected customers.

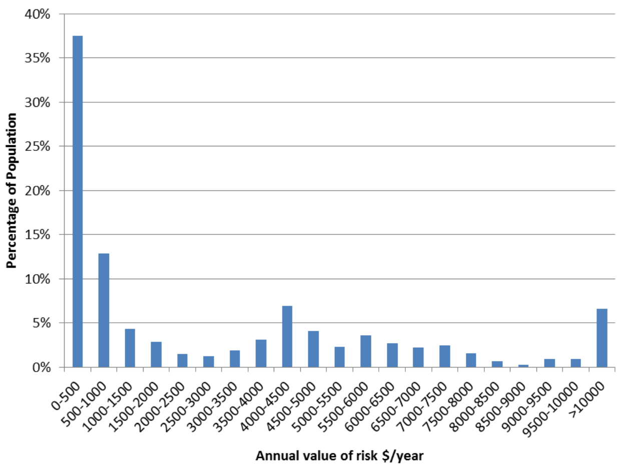

Figure 6.
Histogram of annual risk for a sample population of metal clad switchgear.

Considering Figure 6, it can be seen that the spectrum of risk varies significantly from relatively low values of less than $500 per year to some units with very high values of greater than $10,000 per year. Assets with high calculated risk values are typically ageing oil type switchgear in critical network locations. While the majority of assets present low risk values, as should be the case, a significant proportion of the population present risk levels that may warrant intervention by the addition of Online Condition Monitoring.

4.3 THE BUSINESS CASE FOR ONLINE PARTIAL DISCHARGE MONITORING

In this work we have estimated the financial benefits of online condition monitoring by conducting Net Present Value or NPV analysis. The parameters used in this analysis are shown and discussed in Table 1 below.

Table 1
NPV Analysis Parameters

Parameter	Description	Value Used
WACC	Weighted Average Cost of Capital	8.5%
Equipment Capital Cost	Up front cost of online monitoring per switchgear bay	$5,400
Operating cost	Annual charges for data transfer and system maintenance (per bay)	$250
Equipment residual	Value of equipment at end of period	$0
Mitigatable Risk	The proportion of calculated risk that can be mitigated through early warning of failure	80%
Fault prediction efficiency	The effectiveness of the online monitoring approach in detecting potential failure.	Variable from 0.1 to 0.9
Forecast Period	Time over which the analysis was conducted	15 years

While most parameters were fixed in this analysis the fault prediction efficiency of the condition monitoring equipment was varied in order to explore the sensitivity of the cost benefit as a function of proportion of failures detected. Fault prediction efficiency refers to the effectiveness of the online monitoring device in predicting potential failure. Fault prediction efficiency can be influenced by the failure mode (i.e. is the potential failure mode related to partial discharge), the technical capability and sensitivity of the system, and the system availability. It is our experience that the combination of on-line TEV and ultrasonic monitoring provides prediction efficiency in excess of 80% for typical types of metal clad switchgear, however varying this parameter illustrates whether lower levels would still be cost beneficial and therefore worthwhile.

The NPV analysis was conducted so as to estimate the proportion of the sample population for which the NPV was positive over the 15 year analysis period for a range of fault prediction efficiencies. The results of this analysis are shown in Figure 7 below.

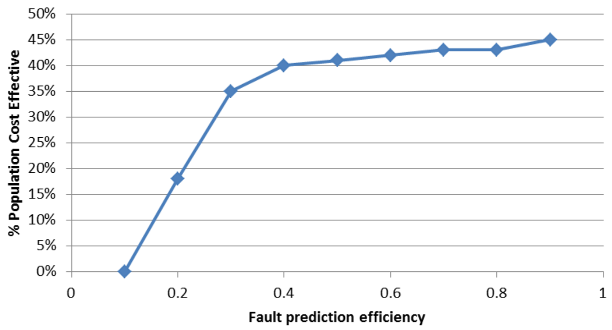

Figure 7
% Population with Positive NPV vs. Fault Prediction Efficiency

It can be seen that for reasonable fault prediction efficiencies of greater than for 40% that it is cost effective to install condition monitoring for a significant proportion of the population ranging from 40% to 45% in this analysis.

While NPV analysis provides a theoretical measure of the optimal application of condition monitoring, a more tangible and direct method is to consider the payback period. In this analysis the payback period is considered to be the time taken for the value of mitigated risk to be equal to the investment cost of the equipment plus the sum of the annual operating costs. Figure 8 below shows a chart of the payback period as a function of the asset population. The chart can be read by selecting a payback period from the Y axis and then reading off the proportion of the population that would provide an equal or shorter payback period on the X axis. As for NPV the analysis is conducted for a range of fault prediction efficiencies.

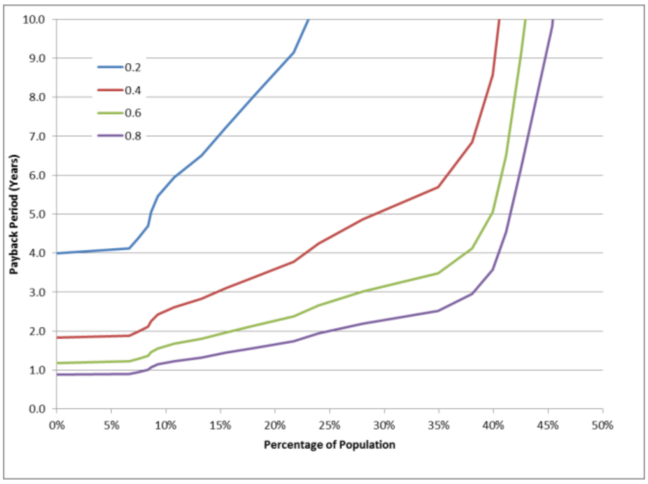

Figure 8
Payback periods vs % of Population for various efficiencies

Considering Figure 8 above we can see that for reasonable fault prediction efficiencies of greater than 40%, that a significant proportion of the asset population relatively short payback periods of less than 5 years.

5.0 CONCLUSIONS

The majority of asset lifecycle management decisions are centred around balancing the allocation of resources against avoiding negative outcomes, or in other words managing risk. In order to optimise these decisions some form of quantitative analysis is required. EA Technology's CBRM methodology provides a proven means to quantitatively evaluate risk and apply this knowledge to developing effective risk management interventions.

In this example we have shown how online partial discharge condition monitoring can be used to mitigate risk associated with disruptive failure of 11 kV metal clad switchgear. Our analysis shows that when considered on a risk basis that quantifies the impact of loss of supply, that online monitoring can be a cost effective strategy for a far more significant proportion of the asset population than is currently managed in this way.

5.0 REFERENCES

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