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Online Conditioning Monitoring of Electricity Assets – a Literature Review

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Abstract [369 words; limit 400]

This paper summarizes a literature review of current research and practice in the field of online condition monitoring for electricity grid assets. The purpose of the literature review was to identify potential for further research in the field of online condition monitoring, specifically on relating readily available information from or about the grid to asset failures to build prediction models of asset life failure. Information relevant to condition monitoring has been summarized from sources such as academic research papers, asset management plans (AMPs), innovation funding incentives (IFIs), network innovation allowances (NIAs), case studies and project reports. Academic papers were investigated, providing information on various condition monitoring techniques that have been developed, proposed or theorized. Such techniques include dissolved gas analysis (DGA), partial discharge (PD), frequency response analysis (FRA), ΔV – I locus and statistical modeling techniques that utilize available data such as survival and failure curves. Electricity distribution companies from New Zealand, Australia, the United Kingdom, the United States of America (U.S.A.) and Canada were searched for publicly available documentation related to condition monitoring. New Zealand companies publish AMPs annually and United Kingdom companies publish IFIs or NIAs annually that provide summaries of all innovation projects that are funded by the utilities. Unlike companies residing in New Zealand and the United Kingdom, power distribution companies in the U.S.A., Australia and Canada are not required by law to publish such information. However some of these companies have still published some documents relevant to condition monitoring. From analyzing these documents it was concluded that online condition monitoring is still a popular area of research. However, other than statistical analysis techniques based on survival and failure curves, no online condition monitoring technique has been developed that only utilizes readily available information from pre-existing sensors or data sources. Conversely, most successful techniques employ expensive sensors to collect unique information from individual assets, or methods have been proposed but not tested in the field. The paper concludes that researchers have attempted to develop regression methods that relate easily available data to failures with little success. The primary reason for little success is not enough failure information to build reliable prediction models, and little relationship between failure and easily available information, such as voltage and current.

Introduction

This paper investigates literature relating to condition monitoring of assets critical to the electricity grid. Relevant papers from researchers around the world and publications from distribution companies in New Zealand, Australia, the United Kingdom, the U.S.A. and Canada are summarised and used to determine what has been researched and what is being used in practice. The summarised information will be used to determine whether online condition monitoring, for the purpose of accurately predicting asset maintenance requirements and / or failure, can be achieved using readily available asset loading, supervisory control and data acquisition (SCADA), and other environmental parameters such as temperature. Online condition monitoring of transformers is specifically investigated in this paper due to their high cost, importance to, and large numbers in, the electrical power system.

Background

Power transformers are expensive assets, vital to the reliable functioning of power systems. While power transformers are built to be versatile, they are subject to aging. Traditionally transformers are taken offline after a set number of years in order to manually assess their condition and need for maintenance or replacement. While effective, this technique is expensive, time consuming and cannot account for early or unexpected asset failure.

Given these costs and risks, there is interest in research and development of automatic online condition monitoring technology. To date this research has involved improving sensors and existing techniques, along with developing new methods of determining transformer condition. Some existing methods of continuously monitoring asset health require the connection of specialist instrumentation. In addition to the expense of this, and need to deal with additional data, the majority of condition monitoring techniques can only provide useful information on one part of the asset. For example, dissolved gas analysis (DGA) only provides useful condition information on the oil of a transformer.

This paper defines online condition monitoring of electricity assets as:

A system which can automatically monitor the condition of an asset while it is in use, providing the asset owner information on the degradation, current condition, predictions for lifetime and a hazard function.

A challenge is that older transformers, for example, those that are near the end of their life and therefore most in need of online condition monitoring, were not designed to be monitored in such a way. To achieve a comprehensive online condition monitoring system for the transformer, multiple sensors and measuring instruments must be installed on the unit to monitor areas where aging and stress cause degradation and ultimately asset faults and failure.

Condition Monitoring Techniques

Dissolved Gas Analysis (DGA)

DGA, also known as gas in oil analysis, involves taking samples of transformer oil and analysing the concentration of all gasses present to determine its condition [1-3]. Like most other techniques used to obtain condition data for transformers, DGA has traditionally been used as a method of offline condition assessment. The analysis of multiple different types of gaseous compounds can provide more information on the type of fault(s) that are beginning to develop due to stress and aging [3, 4].

While DGA requires additional equipment, it is the most widely used method of condition monitoring and is becoming more reliable and cost effective over time. Unison is trialing online DGA to monitor nine of their transformers that are at more prone to failure, as part of their smart network initiative [5].

Partial Discharge (PD)
PD is a major cause of damage to the insulation of power transformers; analysis involves measuring the PD signal and identifying the patterns and amplitude characteristics of the signal. The magnitude of the PD signal monitored is comparable to noise, which makes this method difficult to use for online monitoring [1-3]. PD analysis is considered an offline technique, however, studies have shown that the method could be carried out on an online transformer with the added drawback of up to 30% error in measurements compared to the offline method [6]. While the error in this monitoring technique is comparatively large at present, it may be an opportunity for further research to improve monitoring equipment to provide greater immunity to noise.

At present PD analysis requires additional equipment to perform and is often used in New Zealand while routine inspections are carried out on transformers. However, this analysis is performed offline at discrete intervals during a four to five year inspection cycle.

Frequency Response Analysis (FRA)
FRA involves generating the broad-spectrum frequency response of a transformer, up to frequencies of about 2 MHz [7, 8]. Once generated, the frequency response must be manually interpreted by a specialist, due to its complexity. FRA is considered an offline means of condition assessment. The feasibility of online FRA monitoring has been researched, with findings showing that there is little potential for this method to be implemented online [7, 8]. To further complicate making FRA online, the on-load tap changer (OLTC) position must be the same for FRA measurements to be compared, since altering OLTC changes the frequency response of the system [8].

FRA is not currently being used by any major New Zealand distribution company for either online or offline condition monitoring of transformers. This is likely due to the cost and complexity of the equipment required to perform FRA, as well as the highly specialised expertise in interpreting the data.

Transformer fingerprint (ΔV-I Locus)
This technique requires accurate waveform monitoring of the low-voltage (LV) side voltage, high-voltage (HV) side voltage and HV side current. The voltage differential, ΔV ($V_{HV} - V_{LV}$), is calculated and plotted against I_{HV}, producing a transformer "fingerprint". The shape of the resulting graph is used to determine whether mechanical faults have occurred. Comparisons with lifetime data can determine the severity of fault(s). Different types of mechanical faults have been found to yield different fingerprint shapes, with short circuit faults having the most obvious and drastic effects [9-12]. Simulations suggest that the shape of the resulting locus is not significantly affected by load power factor [11, 12]. The effects of the 3rd, 5th and 7th harmonics on the $\Delta V - I$ locus for five different types of mechanical fault have been investigated, and found that the shape of the footprint changes with the higher frequency components. This therefore means that the sampling rate has to be higher to resolve these harmonics [12].

This particular technique has only been tested on single phase, bench-top sized transformers, and would require the installation of new high frequency sampling equipment for voltage and current waveforms. Up to a 2 MHz sampling rate was used in these experiments, however, the sampling rate could likely be 100 orders of magnitude slower and still prove sufficient for modelling the ΔV-I locus [12].

Statistical Modelling

A transformer will experience a phenomenon called an accelerated aging event (AAE) when put under an excessive load. This excessive load is usually the result of either extreme weather conditions, or parallel transformer(s) in the same area being taken offline temporarily [13]. Researchers at IBM investigated the relationship between weather and the occurrence of AAEs, along with the severity of the AAE. A predictive model was developed and tested, yielding results with a normalised root mean square error of 0.9%. However, no information on datasets, predictive model or simulation process was provided [13]. Moreover, the predictive model only relates weather to the occurrence of AAEs, not the desired information on transformer ageing. Nevertheless, AAE information itself could be of use, as a case study conducted in Australia suggests that to maximise asset life, transformers that have experienced AAEs should be switched with similar transformers in areas that do not commonly experience AAEs and are less critical to the grid [14].

More common statistical analysis involves utilising lifetime, survival and failure data to estimate a hazard function life expectancy for transformers. Research has looked into: improving statistical modelling using both survival and failure data [15]; applying a Bayesian updating procedure to improve lifetime models [16]; and the effect lifetime data censoring has on the accuracy of lifetime models [17]. Data censoring is when a lifetime dataset is incomplete due to data not being recorded or lost, this is common with lifetime datasets of older transformer units where data predates digital systems used for storing such information. Since these techniques are purely statistical, they aren't necessarily considered condition monitoring techniques, because they do not have any way of detecting or sensing unexpected developing problems. Building regression models between readily available SCADA and weather data and asset failure is another method that has been attempted. Such models could be used to predict asset failure. However failure data is so sparse that the regression models have little underlying data to build them, and are therefore not particularly reliable.

Statistical modelling methods are often used in conjunction with data obtained from other condition monitoring techniques such as DGA, in order to produce more accurate lifetime models.

Other Practice

Some distribution companies in New Zealand use alternative means of condition monitoring to the aforementioned methods. Orion has been using continuous online monitoring of transformer hotspot temperature as an indicator for imminent transformer failure [18]. Since transformers have specified operating temperatures, if the hotspot temperature sensors indicate that the transformer is exceeding a particular temperature threshold, then the asset will be taken out of service and inspected. A similar technique employed by Unison, uses continuous online monitoring of transformer oil temperature as an early indicator of failure [5]. Both of these companies have these condition monitoring systems installed on a select few of their assets [5, 18].

The majority of distribution companies in New Zealand also use a statistical modelling method. This involves assigning each transformer a health index rating and then ranking assets to determine which assets require treatment or replacement soonest. This technique involves a mix of lifetime modelling and use of data obtained through routine four or five yearly transformer condition assessments [5, 18-23].

Industry Research
Distribution companies in the United Kingdom publicise their prospective research projects through innovation funding incentives (IFIs) and network innovation allowances (NIAs), detailing the costs and benefits of each project. A significant portion of these research projects, revolve, around condition monitoring of some sort of asset, usually transformers. Some notable projects include the development of handheld condition monitoring tools, online PD monitoring, UAVs performing online condition analysis and other aspects of condition monitoring. Each of these projects will be looking into a new, innovative method for condition monitoring, however, none are investigating condition monitoring without installing new equipment [24-37].

Discussion
Table 1 presents a summary of the main condition monitoring methods reviewed, and their suitability for online condition monitoring and potential for further research. From the condition monitoring techniques discussed, DGA, PD and statistical methods (lifetime model analysis methods) have been used by industry to obtain useful condition information for transformer units. DGA has primarily been used for offline analysis in New Zealand, with limited trial use in online applications [5, 18-22]. Survival/failure models to classify the condition of transformers have been used in conjunction with DGA. ΔV-I locus requires high frequency sampling voltage and current waveforms to produce an accurate analysis. This information may be readily available at some facilities, however, in most cases it is not likely to be available. While this method looks promising, it is still under development. As yet, it does not have a set of specifications or requirements and it has not been tested on industrial rated transformers.

Table 1: A summary of condition monitoring techniques.

	Current practice	**Current use**	**Online feasibility**	**Scope for further research**	**Equipment needed for online**
DGA	Offline	Majority	Medium	Some	Yes
PD	Offline	Majority (4-5 year cycle)	Low	Little	Yes
FRA	Offline	Rare	Low	No	Yes
ΔV-I locus	Online	Laboratory only	Medium	Some	Yes
Statistical	Online	Few	High	Some	No

There is much research interest in the field of condition monitoring in the United Kingdom. However, the focus is primarily on new condition monitoring systems or installations, as opposed to working with existing data and sensors for online condition monitoring. The reasons for this are unclear.

It is clear that online condition monitoring is a popular area for research and development. This research suggests that existing techniques are becoming more cost effective and undergoing improvement over time. Statistical lifetime modeling of grid assets with the use of lifetime data obtained from discrete testing continues to be used in industry in order to determine transformer health. However, online condition monitoring using only SCADA and consumer data has not proven successful to date, with few signs of promise for the future. Moreover, online condition monitoring has not been accomplished without additional monitoring and measurement equipment.

Conclusion

Research suggests that additional equipment and sensors are required for online condition monitoring of distribution and power transformers. The majority New Zealand distribution companies statistically model the life expectancy of transformers, using results from offline methods such as DGA and PD. However, few transformers are being monitored using a form of continuous online condition monitoring, with the majority of transformers being inspected at discrete intervals on a four to five year cycle. DGA, hotspot temperature and oil temperature monitoring are the only known online condition monitoring techniques currently in practice in New Zealand. Current research trends indicate that new condition monitoring techniques are constantly under development, with new approaches to the challenge of online condition monitoring emerging.

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