THE STATE OF THE ART OF CONDITION MONITORING: WHERE DO WE GO FROM HERE?

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AN OVERVIEW OF CONDITION MONITORING

The energy programme of the Research Councils UK is funding a programme of work (EPSRC HubNet grant number EP/I013636/1) to coordinate research in energy networks. Among its range of activities is the requirement to develop the future research agenda in subject areas that are of significance to energy networks. This is achieved through the development of 'position papers' that identify future research needs and attempt to 'roadmap' the subsequent development of any emergent technology to the point where it can be demonstrated on networks. One area under consideration is on-line condition monitoring and this paper represents a short summary of progress in the preparation of a position paper that reflects the best practice in both academia and industry. In doing so, the paper identifies where there is clear need for additional research. At the time of writing the authors have completed an extensive review of current practice within electricity networks worldwide and based on subsequent analysis are in the process of preparing to gather the opinions of asset managers from within the power industry.

Although there is already a lot of existing research activity in the area of on-line condition monitoring, there is evidence of a disconnect between cutting edge research and industrial practice, for example, some reported approaches do not scale for use in the field. There are significant differences between data created under laboratory conditions and field data, consequently, methodologies that are reliable under ideal laboratory conditions are not applicable in a real-world setting where assets experience multi-factor stressing. It is a central aim of the team working on this position paper to ensure that in setting a future roadmap for research that the resulting activity and related outputs will ultimately have significant impact on our transmission and distribution networks.

Existing (ageing) network infrastructure faces a highly challenging future, which in terms of its history is unprecedented. It is not just a question of the influence of external factors such as the possibility of more extreme or changeable weather conditions due to climate change or that there will be changes in customer requirements and demand, e.g. from future widespread adoption of electric vehicles. Also changes due to increased HVDC interconnection with the potential development of pan-European supergrids, changes in generation mix, the development of smart-grid technologies and environmental considerations will have impact on operation of the networks which in turn may lead to accelerated aging/degradation of assets approaching (or past) their original design life.

Thus there is a clear need to develop tools that will provide more than just a diagnostic capability once a developing problem has been identified. Ideally, we need to consider the future development of prognostic capabilities with the aim of providing enough information for the network operator to make timely and cost effective decisions whilst ensuring operational security of supply. This in turn implies that future on-line technologies need to be researched and developed and in all respects this represents a significant challenge.

However, before setting the future agenda it is important to assess the current state of the art and this paper summarises the initial findings of the authors in terms of specific transmission and distribution assets, before briefly discussing some of the areas that have been identified for future research and development.

Transmission Assets

This brief overview covers significant transmission assets. In all transmission systems, the nature of accessibility impacts the practical approach to condition assessment. Increased loading in general, and in particular increased loading in the summer months, due to demand for air conditioning, has meant that maintenance outages are harder to come by and so on-line assessment methods are becoming more valuable.

Transformers. The transmission transformer is viewed as a key asset and consequently is subject to extensive condition monitoring. This approach is sensible as large autotransformers are expensive to replace, are not available off the shelf and any failure could seriously impact on operational security of supply. Regular monitoring of condition through dissolved gas analysis (DGA) of transformer oil samples can provide indication of an incipient fault and indicate the need for further investigation. If necessary, between regular manual sampling of the oil, on-line monitoring of hydrogen, carbon dioxide and moisture levels can be realised using the Hydran™ [1]. These can be installed at a single valve and alarms raised should dissolved gas reach unacceptable levels. More detailed information about the transformer's health can be obtained using a nursing unit [2], which can monitor seven different dissolved gases and moisture content as well as recording data from external voltage, current, oil pressure and temperature sensors.

Either a symptom or the cause of degradation can be partial discharge (PD) activity and there has been significant research into methods for detecting, locating and quantifying PD activity within transformers. Partial discharge activity within a transformer can be detected using radiometric condition monitoring [3]. Location methods, using either acoustic sensors on the tank wall or measurements of current at bushing tap and neutral points, or use of UHF sensors placed in oil ports or dielectric windows in the tank have yet to mature into widely accepted reliable approaches for on-line PD monitoring. With all forms of non-conventional PD detection and measurement the estimation of the severity of any activity within the transformer is still an open question. Some specific on-line tools are available, for example on-line condition monitoring of tap-changers is achieved through the use of infrared temperature probes and differential analysis to identify hot spots.

Cables. The increased use of cable systems in transmission networks has led to significant interest in the development of condition monitoring tools. Transmission cables represent the most expensive asset in the network, in terms of both the cost of the cable and accessories and the capital costs associated with installation. In many cases access to retrofit monitoring systems is severely limited but new circuits will often contain distributed temperature sensing (using optical fibres) that measure an average temperature with a resolution of a few metres along the cable length; analysis of data can identify potential faults that cause a rise in local temperature. In reality these systems are also used to determine the real-time thermal rating of the circuit or as a warning system for fire [4]. Given that transmission cable circuits are extensively tested off-line after laying and before energisation, and that many transmission networks normally operate under an N-2 condition, most cable circuits are less than 50% loaded. However, switching operations, lightning surges and emergency operations can all lead to conditions that accelerate dielectric ageing and may initiate a degradation process. It is generally assumed that any fault is most likely to occur within accessories such as cable joints or terminations and that the fault will lead to detectable PD. The one exception to this rule is Sheath Voltage Limiters (SVL), which have an explosive failure mode and this can be detected through the use of a sacrificial optical fibre. Loss of an SVL is unlikely to cause an interruption in service, but in the short-term requires installation of a replacement unit.

In general, electrical detection of PD activity uses either capacitive couplers or High Frequency Current Transducers (HFCT). Capacitive couplers can be included in the joint design [5] or installed at interruptions in the sheath (such as near to joints or terminations). Pairs of capacitive couplers used to form directional couplers have also been employed for factory and commissioning tests. Results obtained using an optically-based PD detection system based on measurement directly across a sheath interruption on a factory joint have been reported [6] but this has yet to be applied in the field. Far more common is the use of HFCTs (or something similar) to detect partial discharge currents at the earthing points of the circuit. This technology has been widely applied on MV cable circuits and there are commercial systems available [7]. Clamp-like HFCTs are easy to install and remove; however, unlike the capacitive coupler that is effectively screened, the HFCT also detects external pulse-like disturbance and noise and this means that care has to be taken when processing obtained data. Acoustic detection of PD activity is possible, but the acoustic signal attenuation from source to measurement point does act to limit detection sensitivity. Acoustic detection of PD activity uses either hand-held "hot sticks" or fixed microphones. In fact, in terms of current research it is clear that the main concerns with condition monitoring of transmission cables are centred on the development of improved analytical tools for the interpretation of PD measurement data [8, 9].

Overhead Lines. There are three main elements: towers, conductors and insulators. In the UK, towers are principally lattice steel structures, and insulators are ceramic. Historically transmission overhead lines have proved reliable; experience which verifies design criteria laid down in the mid twentieth century. Transmission overhead lines have the same propensity to impact large numbers of customers as cables if poor reliability becomes an issue. However, because the primary insulation is air, and is self-restoring, and because they are relatively easily accessed, their reliability is not designed to be as high as buried cables. Indeed unsatisfactory reliability on overhead lines tends to mean having flashovers too frequently, rather than any absolute system failure [10]. In addition to the three main components of overhead lines, it is important to appreciate the fittings, such as clamps, conductor spacers, and vibration dampers are critical to the whole system reliability, and towers should be considered with their foundations.

Time-based inspection regimes, and time-based maintenance such as tower painting, have proved to be successful in providing a reliable system. Moreover despite its geographical dispersion and the fact that it is high voltage equipment, much of the system is readily inspected by eye or air-drone cameras [11, 12, 13]. Inspection by camera can relate to changes to the surface condition of any item. For conductors this might be associated with general ageing (which in early life reduces corona discharge as the cable becomes more hydrophilic), wear of suspension shackles, erosion of the surfaces of insulators, or corrosion of elements of lattice towers. Complementary to visual inspection are infrared and ultraviolet camera techniques. Infrared cameras allow areas of heat generation to be identified while UV emissions are indicative of corona discharge.

The principal area of research in transmission overhead lines since the 1980s has been the application of composite insulators. This has resulted in a move from well-established and exceedingly reliable glass and porcelain insulation to pultruded glass with either Ethylene Propylene Diene Monomer (EPDM) or more often silicone-based polymer shed systems. This transition adds new requirements for condition assessment [10, 14].

In addition to visible inspection of insulators, non-destructive assessment of surface ageing can be carried out by measuring online leakage current, including magnitude and third harmonic analysis. This is a relatively expensive process however and is usually confined to research activity. The Electric Power Research Institute (EPRI), however, are developing a leakage current device which is in a series of trials [15]. Laser induced fluorescence has been shown to be capable of identifying organic growth on insulators from the ground. Detailed surface analysis still requires destructive sampling, however, enabling techniques such as Fourier Transform Infrared Spectroscopy (FTIR) and Energy-dispersive X-ray spectroscopy (EDX) can be used to identify compounds and elemental composition [16]. Hand-held devices have recently become available to measure FTIR in situ.

The principle issue here for condition assessment is the use of new materials, but in particular the need to drive all assets 'harder'. In general no asset is run close to its limit, but the demand is to enable this to happen in extremis (such as when other lines are out of service). Two important developments have arisen from this need. Firstly, more spatially refined and real-time measurement of the conductor's working environment (referred to as 'circumstance monitoring' [17]) and secondly, a need to understand ageing of the new conductor alloys, constructions, and associated fittings. A method known as 'overhead line corrosion detection' (OHLCD) is well established, and enables corrosion to be detected in situ using a remotely controlled device which passes along a conductor. Robotic inspection is an area of continuing improvement and will certainly improve efficiency in the future [18]. Perhaps the most pressing issue is management of the lattice towers around the UK. In additional to regular painting, elements which are corroded can and are replaced or reinforced. Clear gains can thus be made by optimising the timing of such work. However, detailed inspection by maintenance teams climbing towers is slow and costly [12]. Paint and galvanising thickness measurement can now be carried out by magnetic induction measurement [19].

AC Substations. In addition to the high value assets considered in other sections, substations contain secondary and auxiliary systems which may benefit from monitoring. These include circuit breakers, fault current limiters, surge arrestors, protection, control including communications systems, and earthing. Historically these may be tested on a periodic basis or simply run to failure, but the impact of failure on the resilience of the grid coupled with decreasing costs of data capture and storage leads to some interest in online monitoring.

With this in mind, one of the influences against adoption of online monitoring is the cost and effort of installing and maintaining a monitoring system itself. For this reason, some research considers ways of making sensors more self-sufficient, such as energy harvesting [20]. Using inductive or capacitive energy harvesting, sensors with low power requirements can be deployed for long term monitoring without requiring maintenance for battery changes every three to five years. This also drives research into novel, low-powered sensors.

Monitoring of switchgear and circuit breakers is widely undertaken using time-based off-line tests, although the criticality of some transmission circuit breakers does merit on-line monitoring. In 2002, the IEEE Switchgear Committee published a methodology for selecting appropriate SF_6 breaker monitoring [21], which lists all subcomponents and key failure modes, and highlights the importance of parameters relating to SF_6 density, open timings, and contact wear.

An increase in the time taken for a breaker to open may indicate a variety of problems, from poor lubrication to high contact resistance causing decreased current in the trip coil. In contrast to SF_6 density and the opening time, which is indicative of breaker faults, contact wear is a measure of breaker ageing, and is generally calculated based on currents broken and arc duration.

However, the breadth of possible circuit breaker failure modes and required sensors means it can be hard to justify the cost of monitoring given the low probability of failure. One approach is to quantify the effectiveness of past maintenance in order to target specific future fault modes [22]. Other approaches include novel sensors such as vibration monitoring [23]. Data can be collected through Supervisory Control and Data Acquisition (SCADA), or more recently through Digital Fault Recorders (DFR), which are used by Scottish Power Ltd [24].

The state of the art for condition monitoring of surge arrestors includes measurement of leakage current, and in particular the 3rd harmonic component [25]. An alternative approach calculates the energy in a lightning strike, and the effects on the arrestor [26]. Finally, an online monitor measuring impulse and resistive current was found to also indicate pollution build-up on the insulator surface [27]. More novel techniques include passive Surface Acoustic Wave (SAW) [28], or even a rover tracking RF generated by arcing and pin pointing the fault position [29].

There is generally less concern about faults in control equipment, although the possibility of maloperation due to Electromagnetic Compatibility (EMC) has been considered [30]. However, the communication system represents another set of assets, with their own potential faults and failures. At the transmission level, the main concern seems to be network intrusion and other cyber threats [31, 32, 33]. These threats can be managed at a policy level, with methods such as virus scanners and adequate physical security. At the same time, improvements in data standards such as IEC 61850 can affect substation monitoring capabilities [34, 35]. As with monitoring of protection assets, there is currently little consensus about what data to gather or how to monitor control or communication equipment.

Earthing is largely monitored off-line, although it has been recognized that an online monitoring system would be beneficial to find the current state of earthing [36,37]. Measurements may include fall-of-potential, and one-box test sets are commercially available for voltage and resistance measurement. Standards exist for the types of earth required [38].

DC Substations. In addition to approaches covered in the AC substation section, it is important to monitor continuously the power electronic devices used in the valves. In the case of line commutated convertor thyristors their performance is monitored using voltage divider circuits that provide feedback to a centralised monitoring system [39]. The monitoring system is an integral element of the operator control system. In case of Voltage Source Convertor power devices, the Insulated-Gate Bipolar Transistors (IGBTs) are designed to failsafe as a short circuit, and an optical system is used to identify the location of any device that fails to respond to the control signal [40]. Although to date there are a limited number of HVDC substations in transmission networks, some components in the substation are known to age and degrade at greater rates than those found in AC substations, one example being convertor transformer bushings, where methods such as measurement of bushing capacitance from the tap point can be used to detect short circuits between grading foils.

Distribution Assets

This section covers specific details related to distribution assets that have not been covered in the transmission asset section.

Cables. Medium and low voltage cables presently in the distribution network may have been installed at any time in the last 100 hundred years: the majority having been installed within the last 60 years. Unlike transmission level cables, the range of designs is large and control of materials relatively relaxed because of the lower electric fields seen in service. Moreover failures are frequently attributed to joints and terminations which have a variability associated with installation practice.

Many faults in the distribution network are assumed to originate from some form of cable dig-up event, which has led to external jacket (or sheath) penetration. Resulting corrosion leads to moisture ingress and eventually cable failure [41]. These issues are substantially different from most models of transmission cable failure. However, as is often the case, methods used in the distribution network are derived from research targeted at high voltage networks.

The principle diagnostic methods available for cable insulation are standard dielectric methods such as partial discharge, Loss Angle (tanδ), and DC resistance [42]. They can be measured on cables in situ or on samples from cables. Destructive measurements can also be used to characterise cable insulation taken out of service, and these include moisture content, FTIR and Differential Scanning Calorimetry (DSC) measurements and dielectric breakdown. However these are rarely conducted on distribution cables taken from service, because the perceived value is low. That value is reduced because of the wide range of cable designs employed and the limited knowledge of their service history does not make knowledge gained from one installation readily applied to another. A key challenge in the distribution network is to extend the extensive knowledge developed for polymeric systems to paper-based insulation (PILC) [43].

Measurements of partial discharge are principally carried out on the higher voltage distribution networks. Commercial systems have been deployed [44], but the challenge of interpretation of data is still preventing clear prognostics. At present changes to PD patterns are being identified, but the impact of changing working environment such as temperature, load and power quality are not yet filtered from this. Time of flight techniques are used for PD source location, and Time-Domain Reflectometry (TDR) can be used for fault location.

Low voltage networks have the added issue of many joints and branches per hundred metres and the voltages of use are much lower than would normally be expected to generate partial discharges: the classic diagnostic measurement.

Overhead Lines and Poles. As is to be expected from the relatively low value of individual assets compared to their equivalent in the transmission network, the distribution overhead line has had much less attention and sees even less real time monitoring. Moreover overhead lines are not used in UK urban environments, so distribution overhead lines tend to be in rural areas with low population densities. At low voltages then, on-line monitoring provides little value, and the approach taken is normally to replace on failure, with emphasis being given to rapid detection and repair rather than predictive on-line condition assessment. Nonetheless routine inspection allows maintenance scheduling to be optimised.

A major distinction between transmission and distribution networks is the use of wood-poles as support infrastructure at the lower voltages. The main challenge presented by wood-poles is to detect rotting below ground level. Acoustic propagation methods are now commercially available to quantify levels of rot [45] allowing optimisation of replacement programs. At the top end of the pole, moisture ingress can lead to unacceptable leakage currents which can result in tracking and combustion [46]. In Australia, a camera mounted on a telescopic pole fixed to the rear of a four-wheel drive vehicle is used to check on the condition of the pole tops.

A further distinction between distribution and transmission networks arises from their height. Flora and fauna have a direct physical impact on the distribution network. Whilst bird nesting can be an issue on transmission towers (especially with listed species), birds can short-out distribution phases because of their small separation; more importantly tree growth can interfere with distribution lines.

At lower voltages ceramic insulators continue to offer excellent performance, and these are not routinely monitored. The use of polymeric composite insulators is well established in distribution networks, with silicone rubber and EPDM routinely installed at the higher voltages. The main tool of condition monitoring continues to be visual inspection.

AC Substations and Transformers. As with the specific assets considered in this paper, technology for distribution substation equipment monitoring filters down from the transmission level once the sensor and data logging systems become cheap enough to justify against the lower cost of the distribution assets. However, there are some instances where the distribution substation requirements differ from transmission, and a specific set of technologies are studied and implemented for MV.

One area is monitoring of the physical security of the substation against threats such as intrusion, fire, and flooding. This may be more of an issue at distribution levels than transmission due to the generally poorer network visibility, making it harder to identify substation-level problems from a centralized control room without specialist sensors. Physical threat monitoring can be achieved by remote video monitoring [47,48], which may include automatic object detection [49]. Liquid level sensors are another approach [50]. Such data can be crosschecked against SCADA to verify whether incidents are localized to the substation, or network-related.

In comparison to network automation at the transmission levels, distribution automation systems are often single-case installations used to solve a particular problem, often across rural areas with reduced infrastructure. This makes them inherently more fragile than general-case transmission solutions, and in some cases necessitates on-line monitoring. This can be addressed by simply designing monitoring communication into the specialized feeder automation scheme [51,52], or by using intelligent systems to monitor the health of the communications network itself based on the frequency and type of messages passed between network nodes [53].

The research and use of fault current limiters is more widespread at distribution levels than transmission, with a small number of commercial deployments [54]. Currently, research is still ongoing into devices and characteristics of a range of FCLs [55,56]. One of the key challenges with respect to monitoring of FCLs is the lack of understanding of ageing mechanisms and long term behaviour of superconducting materials. Finally, distribution level GIS monitoring using acoustic emissions has been studied in the past [57,58], but there seems to be less interest than at transmission levels.

The number of transformers in a distribution network is extensive and generally at lower voltage levels; these are seen as relatively low cost items that can be replaced following failure in a reasonably short period of time. All of the techniques used for condition monitoring of transmission transformers are equally applicable at distribution level, but the cost of on-line monitoring needs to be considered against individual asset value and time to effect repair/replacement.

Summary of the current situation

There are a large number of examples of good practice and a significant range of techniques that are applied to assess asset health. Through study of the literature it is clear that in some areas of condition monitoring there are commercial disincentives to sharing best practice, and information about areas that need specific attention (including data on failures) are not readily available. From the review of existing practice some potential areas for future development have become apparent.

Where do we go from here

In the case of some existing assets it is clear that specific issues need to be addressed. For example, the problems associated with corrosive sulphur in transformers and tap changers have been widely reported but as of yet condition monitoring strategies for transformers suspected of containing corrosive sulphur have not been established. This is an area of ongoing research and through activities such as Cigre's Working Group in this specific area, potential strategies are being identified and assessed.

In some cases it is clear that the application of condition monitoring is limited due to basic economics and future systems must be developed that will allow widespread deployment. For example, there is a general recognition that secondary, auxiliary, and lower value primary assets can all impact the reliability of the system, and there is some need to monitor the condition of these. One approach is to concentrate on the development of low cost sensors, along with clear value propositions for utilities that are also critical to the widespread deployment of integrated asset models. However, there is little standardization of approaches to monitoring, and the real challenges surround data collection, archival, and interpretation in a low cost way. Standards such as IEC 61850 and the move towards smart grid technologies more generally will provide the types of platform which online continuous monitoring can be built upon, making it easier to support a case for deployment of monitoring for lower value assets. However, until such standards and communications platforms are ubiquitous, the wide gap that exists between what is possible and what is feasible to monitor in substations will remain.

As demand requirements and points of connection to sources of generation change, the need to drive more power down existing transmission circuits is likely to lead to substantial re-engineering of overhead lines and cable circuits to meet demand, and reduce opportunities for routine maintenance [59,60]. There is therefore likely to be a merging between the need for asset management and for optimisation of power flow, leading to real time measurement of the network, its working environment and component performance. Key to this is determining the granularity required. For example, how many spans or towers in a line need to be continually or occasionally monitored? In terms of overhead lines, the most pressing need for improved assessment is likely to be in towers and their foundations.

It is also clear that evident increases in climatic extremes in the UK, such as a record drought being followed by record rainfall in 2012, lead to a requirement for more than simply improved condition monitoring. Better knowledge of the working environment is needed as that is changing, driven by new generation and load requirements, as well as increases in weather extremes. The dynamic working environment, termed 'circumstance monitoring' needs to be considered, along with condition monitoring of individual plant items and system operation, so that condition monitoring can be fully interpreted [61]. Key Challenges for improving condition monitoring are the development of an understanding of the spatial granularity required, and also the interpretation of condition in terms of present and future working circumstances. Increasing levels of high wind speed, for example, are critical in determining design and reliability factors for overhead structures. Such requirements are presently being developed in the context of stochastic models, and this is likely to continue.

It is clear that over the next decade considerably more new technology is going to be implemented on the networks and issues relating to condition monitoring should be considered as part of the development process ideally prior to or during demonstration rather than once pre-energisation testing has been completed. In some cases, there are already significant challenges to be addressed when considering on-line condition monitoring. For example, the development of an offshore transmission network will employ long HVDC bipole cables, but it is currently only possible to monitor the first 80-100 km of either end. With connections planned in excess of 400 km long, this is a pressing problem, as at transmission levels in the future, loss of an HVDC link could take several months to repair and have serious implication in terms of operational security of supply.

Whereas at the demand side, it is clear that smart meters present new challenges and opportunities for condition monitoring. On the one hand, consumers will be equipped with a wide range of differing devices which are all more complex than existing meters, and hence may be expected to suffer greater reliability problems. On the other hand, utilities will be gathering far more fine-grained data than ever before about the habits and behaviours of those consumers. More data suggests a greater ability to detect problems, either due to metering defects or fraud. However, these issues do not seem to be addressed within the literature. The EU-funded HiPerDNO project [62] is considering potential applications of aggregate smart meter data, such as the ability to infer distribution network asset health or remaining life. Instead of estimating load on these assets, utilities will have access to more accurate data from smart meters. This data may show unexpected peaks which have a stronger effect on asset health than current load estimates suggest.

The authors plan to develop an on-line questionnaire to gather additional information from asset managers and other interested parties. This will be available from the HubNet website and responses will assist in the development of the future research roadmap element of this position paper. It is intended to map the range of potential areas for future research and development against technology readiness levels (TRL) and time to achieve progress from TRL1 (Transition from scientific research to applied research: Identification of essential characteristics and behaviours of systems and architectures. Descriptive tools are mathematical formulations or algorithms.) up to and including TRL7 (demonstration in an operational environment at the near scale of the operational system) will also be mapped. The final position paper will be made available via the HubNet website (http://www.hubnet.org.uk/)

The full set of references used in this work is included in the following pages; the authors would like to thank the conference organisers for the invitation to present this work at Insucon 2013.

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