

EFFECTIVE CONDITION ASSESSMENT OF MV SWITCHGEAR



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Abstract - There is a general trend within electricity distribution companies and operators of large private electricity networks to extend maintenance periods for MV switchgear. This brings with it a need for interim condition assessment and the application of diagnostic techniques to give confidence in the continuing safety and reliability of the equipment. There are a number of techniques available for assessing the condition of insulation and the mechanical operation of circuit breakers. Appropriate use of these tools provides valuable data that can effectively target maintenance and ensure resources are more efficiently deployed during outage periods. This paper will describe the most appropriate techniques for assessment of MV switchgear and how data can be collated to provide the best possible information on the condition of the assets.

1. Introduction

The drive towards extending maintenance intervals for medium voltage switchgear coupled with the pressure to maximise equipment availability, particularly on industrial networks, means greater reliance must be made on condition monitoring techniques (and in particular non-intrusive techniques) to provide information on the condition of assets and ensure a safe and reliable network is maintained.

There are a myriad of condition assessment tools available to provide condition data, however, it is essential that the most appropriate tools are employed and best use is made of the collected data. It is all too easy to concentrate on the collection of data and not turn this into the information required to most effectively manage the assets.

The starting point in developing a condition assessment program must be the analysis of historical fault and failure information for similar types of equipment. This will help assess the cause of problems and ensure appropriate weighting is placed on techniques that deal with these causes.

Spending 80% of a condition assessment budget to tackle a failure mode that contributes to 5% of failures will not be the most appropriate use of funds.

2. MV Switchgear Fault Causes

It is sometimes difficult to obtain definitive information on the causes of faults of MV switchgear, however, some information is available and can be used as a guide to typical problems encountered. Figure 1 shows a breakdown of the causes of faults for MV vacuum switchgear operating on electricity distribution networks within the UK [1]. The fault information shown includes defects identified during operation or maintenance as well as disruptive failure of the switchgear.

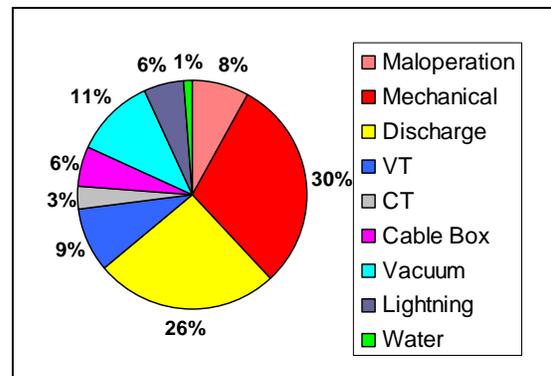


Fig. 1 Composition of faults reported in vacuum switchgear (UK)

Figure 1 shows that for vacuum switchgear (which will in general have air insulated chambers), the biggest contributor to faults are mechanical problems accounting for 30% of faults, when maloperation is included in this the figure rises to 38%.

The second largest fault cause was associated with partial discharge activity (26%). It should also be noted that faults reported with cable termination boxes (6%), Voltage Transformers (VTs) (9%) and Current Transformers (CTs) (3%) will often be

associated with partial discharge activity and therefore the actual figure for partial discharge related problems will actually lie somewhere between 26% and 44%.

Targeting potential mechanical problems and detecting the onset of partial discharge activity are therefore two of the key factors in effective condition assessment of this type of medium voltage switchgear. The general construction of SF6 switchgear is comparable with vacuum switchgear and it is therefore not unreasonable to suggest that a similar fault breakdown will exist with this type of MV switchgear also.

The situation is slightly different when it comes to oil filled switchgear. A lot of research has been carried out into how bulk oil filled switchgear ages and degrades and it has been established that the condition of the oil is a key indicator of the overall condition of the switchgear [2, 3].

What analysis of this historical information establishes are the key criteria that need to be considered in any condition assessment program for MV switchgear i.e. mechanical operation, partial discharge activity and in the case of oil filled switchgear, the condition of the oil. It must also be stated that data from visual examination of the switchgear should also be taken into consideration when developing an overall assessment of the condition of the asset.

3. Diagnostic Tools

An important factor in selecting the most appropriate diagnostic tools is the ability to non-intrusively determine switchgear condition. However in some instances this is very difficult to achieve. For example in order to effectively assess the condition of circuit breaker mechanisms invariably requires the mechanism to be operated.

It is often possible to switch circuits individually due to the level of redundancy built into networks. Indeed, due to the problems associated with stiction in circuit breaker mechanisms, most UK electricity companies have a policy of regularly exercising the mechanism. Condition assessment should ideally be carried out when the mechanism is being operated for exercise or maintenance.

Provided that the diagnostic tools that are employed do not interfere with the mechanism or auxiliary components of the switchgear then they can be considered to be non-intrusive.

3.1 Mechanical Monitoring of Circuit Breakers

The basic principle of mechanical condition monitoring of HV circuit breakers is to detect deteriorating conditions within a circuit breaker operating mechanism prior to any malfunction or failure. In turn, this leads to improved system reliability and more effective maintenance. It is important that diagnostic equipment employed for the assessment of the mechanical condition of a circuit breaker can be used with the switchgear in the service position. The main advantages of testing circuit breakers in the service position are the obvious time saving in not having to isolate the circuit breaker and the fact that the first trip can be monitored. Testing the circuit breaker during operation of the first trip gives an indication of how the circuit breaker would have performed if called upon to trip in an actual fault situation.

There are a number of systems and instruments available for carrying out mechanical testing in the service position. The simplest type of test simply monitors the opening and close times of the circuit breakers. The problem with such a simple device is that it is not possible to diagnose the reason for an abnormal time. Consequently, it is possible for a component with a close tolerance to be deteriorating but, because of other components (or travel movements) with larger tolerances, it may not be possible to detect it.

If a network owner is going to operate a circuit breaker to assess the condition of the mechanism, then ideally as much useful condition information should be derived from the test as possible. For this reason it is preferable for more sophisticated equipment to be employed that will produce additional condition data and help establish the cause of any identified problem. There is now established circuit breaker monitoring equipment in the market that helps with this assessment. In general the equipment works by temporarily (or sometimes permanently) installing sensors on the control circuitry of the circuit breakers to be monitored. Parameters that are monitored include the current profile in the DC trip coil, the current on the secondary side of the ammeter to provide main contact opening time and the battery voltage.

The monitoring systems will capture and store the data from each circuit breaker operation for comparison with previous data from the same unit and also for comparison against other circuit breakers of the same design. The effectiveness of these types of mechanical monitoring systems is therefore dependent on a good background database with which measurements can be compared. Provided this database is available, valuable information on the condition of the

mechanical mechanism can be quickly and easily obtained.

Figure 2 shows traces from three consecutive trip operations on the same circuit breaker. The trace shows how the operating time for the first trip (blue trace) is significantly longer than for the subsequent two trips. Knowledge of the system will quickly allow the operator to conclude that the problem was associated with stiction in the slug or plunger. The figure also shows how the operating time for trips 2 and 3 were back within the acceptable or normal times. This demonstrates why it is important to capture the first trip as this is how the circuit breaker would have operated for a genuine fault on the network.

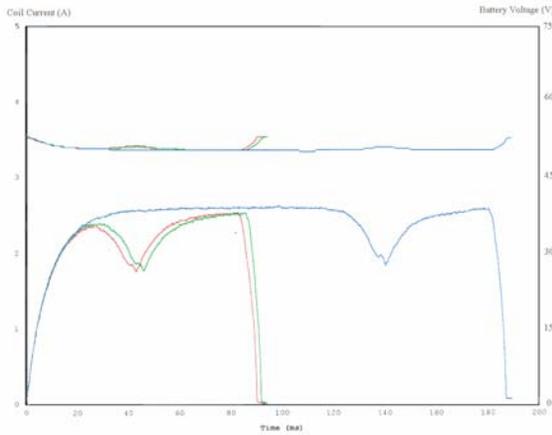


Fig. 2 Trip profile from an 11kV circuit breaker

3.2 Partial Discharge Testing

Partial discharge is an electrical discharge or spark that bridges a portion of the insulation between two conducting electrodes. The discharge can occur at any location within the insulation system (between the two electrodes) where the electric field strength exceeds the breakdown strength of that portion of the insulating material. Discharge can occur in voids within solid insulation, across the surface of insulating material due to contaminants or irregularities, within gas bubbles in liquid insulation or around an electrode in gas (corona activity).

Partial discharge may occur in aged, defective or poor quality insulation and can propagate and develop until the insulation is unable to withstand the electrical stress and flashover and failure occurs. When partial discharge activity occurs, it emits energy in the following ways:

- Electromagnetic:
 - Radio
 - Light
 - Heat
- Acoustic:
 - Audio
 - Ultrasonic
- Gases:
 - Ozone
 - Nitrous oxides

Non-intrusively, the most practical methods of locating partial discharge activity involve the detection of both the radio frequency part of the electromagnetic spectrum and airborne ultrasonic emissions. These techniques are complimentary and their application enables a comprehensive assessment of the condition of insulation on medium voltage switchgear to be non-intrusively determined.

3.2.1 Electromagnetic Detection

The most commonly used method for the detection of electromagnetic emissions from partial discharge activity on MV switchgear is through use of instrumentation that uses the Transient Earth Voltage (TEV) measurement technique. When a discharge occurs in the phase to earth insulation of an item of medium voltage plant such as a metal-clad switchboard or a cable termination, a small quantity of electrical charge is transferred capacitively from the medium voltage conductor system to the earthed metal-cladding. Electromagnetic waves propagate away from the discharge site in both directions. Due to the skin effect the transient voltages on the inside of the metalwork cannot be directly detected outside the switchgear. However, at an opening in the metal cladding, such as the gasketed joint the electromagnetic wave can propagate out into free space. The wave front impinges on the outside of the metal cladding generating a transient earth voltage on the metal surface. Hence the technique is called TEV for transient earth voltage.

The TEV magnitude is a function of the amplitude of the discharge and the attenuation of the propagation path and can be measured with a capacitive probe placed on the earthed metalwork of the switchgear. The technique is particularly useful for the detection of internal partial discharge activity within the bulk of solid insulation e.g. caused by voids and for surface discharge activity to earthed metalwork. The insulation medium of the switchgear is not a critical factor and the TEV signals will propagate from all types of chambers irrespective of whether the chambers are sealed, i.e. the technique can be readily applied to gas insulated chambers, as well as oil, bitumen and air insulated chambers.

3.2.2 Ultrasonic Detection

The sound produced by partial discharge breakdown of insulation can be detected with ultrasonic detectors. In order for ultrasonic detectors to pick up ultrasonic noise, they must be in media of similar densities because the propagation of ultrasonics between low and high density mediums is poor due to most of the energy being reflected. Airborne ultrasonic detectors are therefore successful in detecting surface discharge activity where there is a good acoustic path. For this reason the technique is of little use on gas insulated switchgear or on oil or bitumen filled chambers but is an important tool for the detection of surface discharge within air insulated switchgear e.g. on a dry termination in a vented cable box.

The amplitude of the ultrasonic signal greatly depends on the characteristics of the transducer and instrument as well as the discharge activity and the attenuation of the transmission path. Therefore, quantifying the seriousness of detected ultrasonic signals can be difficult and the fact that ultrasonic activity has been detected can often result in the need for further investigation irrespective of the signal level

3.3.3 Employing the techniques

The combination of the two techniques is very powerful and allows a comprehensive assessment of the condition of MV insulation to be carried out non-intrusively with no disruption to the network. Ultrasonic detectors identify discharge activity taking place on the surface of insulation and will locate switchgear components that need to be visually examined under outage. The TEV technique will also detect potential failure sites that would never have been identified during any visual examination of equipment i.e. defects within solid insulation. The type of instrumentation available for the detection of TEV activity varies from small, simple handheld devices through to large permanent monitoring installations [4]. Ultrasonic detection primarily involves the use of hand held instruments although monitoring systems are available.

When switchboards are of a critical nature then the cost of permanent monitoring can be justified. Permanent monitoring for partial discharge allows evolving faults to be monitored and can help with the preparation of rectification work to be carried out during planned shutdown periods. Figure 3 shows an example of one such case. The discharge activity can be seen to develop over a 5 month period. The problem was associated with a voltage transformer from an 11kV switchboard and this early warning allowed spare components to be sourced and be ready to be fitted when an outage opportunity became available.

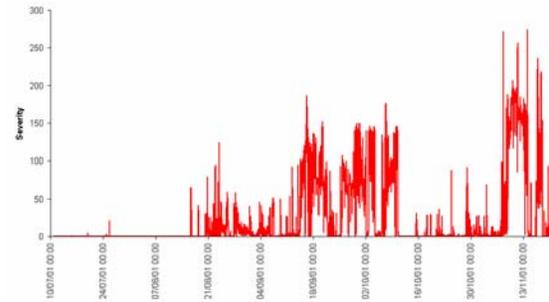


Fig. 3 Partial discharge activity monitored on an 11kV voltage transformer

Permanent monitoring also allows quick action to be taken to rectify problems and remove potential faults on critical switchgear if partial discharge activity suddenly initiates or goes through a step change in severity. Figure 4 shows one example where the level of partial discharge activity on a 33kV cable termination on a GIS switchboard dramatically increased in severity. The early warning enabled the potential source of failure to be removed from the system within a matter of hours.

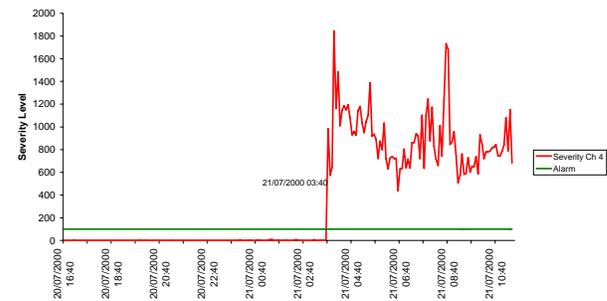


Fig. 4 Partial discharge activity monitored on a 33kV cable termination

The benefits of permanent monitoring for partial discharge activity are clearly demonstrated in these two examples and it would be absolutely ideal if continuous monitoring could be incorporated on all MV switchgear. However, in reality this is not a practical or cost effective option. There are however, relatively low cost handheld instruments available that can detect both ultrasonic and TEV activity. Using this type of instrumentation as part of routine substation inspection can greatly enhance the condition information collected during the visits to the substation with minimal additional cost or effort. Therefore, application of partial discharge detection equipment need not be restricted to the most important switchboards on networks but can easily be applied to all MV switchgear on the network.

3.3 Switchgear Oil Analysis

Extensive research into the condition and degradation of oil filled switchgear [2, 3] has revealed that oil condition is the critical factor in determining the need for maintenance. Consequently the performance and degradation of oil has also been studied in detail. One very significant output from this work was the development of specific test procedures designed to maximise the amount of information obtainable from an oil sample from switchgear.

In addition to the measurement of moisture, acidity and breakdown strength, which are standard procedures routinely applied to oil samples, it has been identified that filtration of the sample and assessment of the nature and quantity of solid material recovered gives an indication of the interaction between the oil and materials within the switchgear and therefore the condition of the switchgear internal components. Consequently, oil test results can be used to identify the need for maintenance for individual units.

In order to take advantage of this development, a technique was devised to allow oil samples to be removed from switchgear (Ring Main Units and extensible switches) whilst part of the switchgear remained live and supplies were maintained. The process involves access to the oil tank via the test probe access point with only feeder isolation and earthing necessary to open the test access. Therefore the sampling is undertaken when some parts of the switch within the oil tank are live. A reusable cover plate (manufactured specifically for each switchgear type) fits over the test probe access and an oil sample is removed through a specially machined orifice using a sampling tube and syringe. Figure 5 shows one such cover plate and sampling tube.



Fig. 5 Test access cover plate and sample kit fitted on a Ring Main Unit

Two 50ml samples are removed from the top of the switch tank and analysed with the results being categorised as:

PASS Indicates satisfactory oil condition, which enables an extended maintenance interval to be adopted.

RETEST Indicates evidence of some oil degradation, should be retested in 30-36 months

MAINTAIN Indicates very poor oil quality, unit should be maintained within 6 months.

Live tank oil sampling has been used successfully with the UK for over 6 years. The process has provided condition information which has been used as scientific justification for many of the UK electricity companies to extend their switchgear maintenance intervals.

3.4 Thermal Imaging

Infrared radiation cannot directly penetrate metalwork. Therefore the use of thermal imaging equipment, which only measures the surface temperature of components, is not a viable method for diagnosing internal faults in metalclad switchgear. It is possible for thermal imaging cameras to see through special viewing windows; however, these are not fitted as standard to switchgear and can interfere with type test certification and the internal arc management of switchgear. Detection of faults using infrared techniques also requires line of sight which further limits application and would require extensive use of viewing windows to identify defects in all compartments.

These constraints coupled with the small number of faults attributable to overheating means that the practicality and usefulness of employing the technique on MV metalclad switchgear is very limited.

However, where these constraints do not exist i.e. on open busbar equipment and low voltage equipment where contacts are, or can be, safely exposed then the application of thermal imaging techniques can have some merit.

4. Deriving a Health Index

The diagnostic techniques described above allow useful information to be gathered on the condition of MV switchgear. In certain instances information from a single diagnostic tool will indicate that immediate action is required to bring an item of plant back to an acceptable condition, for example, if there are severe levels of partial discharge activity

within switchgear or the condition of the oil is very poor. However, where there is no over-riding factor, best use of the diagnostic data can be made by combining all the available information that relates directly or indirectly to asset condition such as these diagnostic test results, visual inspection data, maintenance experience, causes of previous failures etc. and deriving an overall Health Index for the assets under review.

The health index is achieved by numerically coding the available information, usually on a scale of 1 to 4, and applying weightings to the factors based on their effect on the probability of failure (POF) of the equipment. The aim is to obtain a value on a scale of 0-10 that is 'calibrated' against a consistent relationship with probability of failure.

The concept of a numeric representation of probability of failure is essentially simple but it provides the basis for a very powerful process that enables future condition, performance and risk to be determined for any future management programme. Moreover as the derivation of the health index is based on utilising engineering knowledge, experience and information the final outcome relates directly to engineering reality. This provides results that are both credible and have a clear 'audit trail' back to the original information supported by the most relevant engineering knowledge and experience.

The health index value represents the extent of degradation.

Low values in the range 0-3.5 represent some observable or detectable deterioration at an early stage, this might be considered normal ageing, the difference between a new asset and one that has been in service for some time but is in good condition. In such a condition the POF remains very low and the condition and POF would not be expected to change significantly for some time.

Medium values of health index, in the range 3.5-6.5, represent significant deterioration, degradation processes starting to move from normal ageing to processes that potentially threaten failure. In this condition the POF although still low is just starting to rise and the rate of further degradation is increasing.

High values of health index, >6.5, represent serious deterioration, advanced degradation processes now reaching the point that they actually threaten failure. In this condition the POF is now significantly raised and the rate of further degradation will be relatively rapid.

By creating numeric representation of condition (health indices) and mathematical relationships to

link the HI to POF and to estimate changes in HI (and therefore POF) with time provides a powerful basis for modeling future condition and performance. Once the parameters have been set it is simple to model the future condition and performance of each asset and to estimate the future failure rates for groups of assets.

An example of a typical Health Index profile for MV switchgear is shown in Figure 6.

The derivation of a Health Index and probability of failure for each asset is the first part of a process called Condition Based Risk Management (CBRM) which can then be used to evaluate maintenance and replacement strategies in terms of probability of failure and in terms of risk [5].

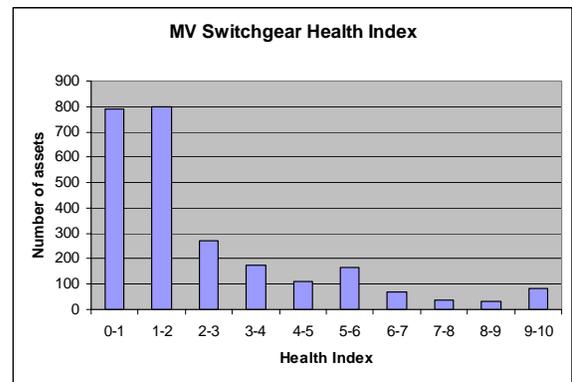


Fig. 6 Example Health Index for MV Switchgear population

5. Condition Based Risk Management (CBRM)

CBRM is a process developed by EA Technology to assist Distribution Network Operators in making asset management planning decisions at a strategic level. It involves combining all available practical and theoretical knowledge and experience of assets to define current condition and then uses this to estimate future condition and performance. In addition it provides a sound engineering basis for evaluating risks and benefits of potential investment strategies. Over a period of several years, EA Technology has developed a working methodology and has practical experience of successful applications.

Separate health indices are calculated for each circuit breaker. These are then fed into an overall risk model that takes into account other risk factors associated with the circuit that are unrelated to its condition (e.g. the number of customers connected, or its criticality to the network etc.). The overall risk model then enables the implications of different

investment strategies to be compared on a circuit by circuit basis.

6. Conclusions

When determining what condition assessment techniques to apply on any asset group it is important that due cognizance is taken on the causes of faults and failures on the equipment. For non-oil MV switchgear, the majority of faults are associated with mechanical problems and partial discharge problems. It is therefore important to ensure that any condition assessment program utilizes techniques to assess the mechanical operation of the switchgear and also assesses the condition of the switchgear insulation. For oil filled switchgear, the condition of the oil becomes a critical factor that also must be considered during the assessment program.

Modern diagnostic techniques and methods allow the majority of the key data to be gathered with minimal or no disruption to supply. Therefore, appropriate use of these techniques can provide vital information on the condition of switchgear and help increase equipment availability.

There are a number of well established diagnostic tools available that can provide key information on the condition of MV switchgear. Available diagnostic instrumentation ranges from small hand held devices through to full continuous monitoring solutions. What solution is best applied within companies will largely be driven by the number and the criticality of assets on the network. When switchgear is absolutely critical to the network and process then continuous monitoring may be a viable option. However, the availability of inexpensive hand held condition assessment tools means the techniques can readily be applied to all types of switchgear on the network and can greatly enhance the information gathered during routine substation inspections.

One of the major benefits of using the diagnostic tools is that it provides the operator and owner of electricity networks with confidence in the continuing safety and reliability of the equipment. Where equipment is found to be in an unacceptable condition, maintenance resource can be quickly targeted to ensure that unsafe plant is removed from the network.

When the diagnostic data does not highlight switchgear in need of immediate attention, best use of the data can be made by combining all the available information that relates directly or indirectly to asset condition such as the results of the diagnostic tests, visual inspection data, maintenance experience, causes of previous failures etc. This enables an overall Health Index for

the assets under review to be derived and effectively ranks the population of similar assets in terms of condition. This provides invaluable information that will feed directly into maintenance schedules and can help form the basis of replacement / refurbishment plans.

The derivation of a Health Index is one of the key stages in a process called Condition Based Risk Management which is being increasingly utilised by owners and operators of MV and HV networks worldwide to evaluate maintenance and replacement strategies both in terms of probability of failure and in terms of risk.

EA Technology's CBRM methodology has been successfully applied with a number of UK Distribution Network Operators as a practical means of meeting strategic objectives and has been well received by the UK electricity industry regulator OFGEM.

7. References

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8. Vita

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