The Role of High Voltage Testing in Plant Risk Control

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Introduction

As a leading provider of High Voltage Testing Services for over 50 years, the Electrical group of Connell Wagner (previously Pacific Power International) is often asked to justify the reasons as to why a plant owner should invest in carrying out high voltage testing. The simplest answer is that it proves a degree of certainty that no other method can. Due to technological and economic constraints, asset owners can never really know the complete condition of their high voltage plant. High voltage tests are a proven and internationally accepted means of demonstrating condition and serviceability.

It can be stated without doubt, that a properly conducted program of high voltage testing carried out to appropriate Standards will reduce the risks that an organisation will carry and allow for a more controlled application of capital. This benefit will extend to the whole capital cycle and will have flow on benefits for many other areas of the company's business. High voltage testing acts to focus the company's resources on real problems and allows for effort to be applied to where it will result in the greatest economic benefit.

For new plant, HV tests act as acceptance tests and for old plant they act to monitor degradation, aging and the efficacy of repairs. A well structured test program allows for timely intervention into conditions that would otherwise almost invariably lead to catastrophic failure.

Even the most honest and diligent of repairers may, through no fault of their own, produce a less than adequate product which results in a marked reduction in the expected plant life. Such plant may last for a number of years before failure making it difficult to determine the true cause. Over a period of time the plant owners may even be convinced that it is the duty that they are applying that is causing the early failure. The net result is that the plant has lost production and incurred considerable additional expense in dealing with the consequences of plant that was not manufactured to a sufficiently high standard in the first instance. Only through the application of appropriate high voltage testing, can an asset owner have any confidence that new or repaired plant will deliver anticipated economic life.

This document outlines the roles that High Voltage Testing plays in controlling the plant owner's risk and where it is best applied to ensure that the maximum benefit is obtained.

Risk Cycle

From a plant owner's perspective, high voltage plant is subject to the same sort of risk cycle as other plant. High voltage plant though has a well demonstrated potential for catastrophic failure and when this is combined with a long time for repair or replacement, then the commercial implications can be severe.

The evolution and trajectory of the risk of failure can be thought of as a cycle of risk that is punctuated by opportunities to significantly alter the level of risk and who will bear it. If we reflect on readily identifiable stages in this cycle we see the opportunity to impact on the ultimate life of the plant. Whilst there are many possible formulations, below is a simple risk trajectory that can define the life of the plant,

- Specification
- Design
- Construction
- Factory Testing
- Delivery
- Installation
- Commissioning
- Acceptance
- Operation
- Maintenance

At any one of these stages, decisions that are made or events that occur can have a profound impact on the life expectancy of the plant. Plant that would otherwise readily last for 40 years or longer may be reduced to scrap in a matter of weeks or months due to seemingly small and inconsequential acts or omissions.

As far as plant owners are concerned it is vital that all issues that result out of the supply contract are vested with the contractor. The mechanism for which is the vendor's warranty and the only recognised test is a high voltage test to a recognised standard. These tests are generally applied as the final site test to ensure appropriate supply and installation. They should also be carried out prior to warranty expiry to ensure that no incipient conditions have germinated, for which the contractor should be held responsible.

After warranty expiry the asset needs to be monitored with a regime appropriate to the asset class, production impact, duty and present known condition. If not before, then certainly at major outages tests should be repeated to gauge the requirement for maintenance and determine the state of degradation or aging.

It can be stated that not withstanding random or induced failure (such as a through fault, etc), that plant that has,

- been properly acceptance tested, as well as tested before expiration of warranty,
- had applied a monitoring and testing program appropriate to the asset and its environment, and
- is operated within its rating,

is unlikely to fail from electrical causes without sufficient warning to enable the safe and timely removal of the plant from service. In fact such a regime when applied to HV motors with epoxy mica insulation would often give many months or years of notice for the vast majority of failure modes.

Design & Construct

Over the years high voltage plant design has evolved from an empirical discipline to a science revolving around computer based methods such as Finite Element Analysis. The computer-based design of plant is so refined that it can be stated, almost without exception, that every design works 100% in theory. This is really a statement underscoring that when the simulation indicates that the design is correct, this is the end of the stage where critical evaluation of the design takes place. Any errors not indicated during this stage are built into the next stage.

That stated, we can move to the practical elements of design that can lead to a shortening of the life expectancy of the plant and over which the designer has some control. Issues can arise out of the,

- specification and its interpretation
- economic constraints in design and production
- number of contingencies considered
- competence of the designer
- limitation of manufacturer

The contract has to be won competitively and only a small portion of the contract price can be allocated to the design phase.

In order to meet economic and client demands the designers are constantly driven to use newer, cheaper elements that have had little or no service time on which to calibrate or refine design rules. This is a constant, even items from the same contract may have variations attributable to design modifications or supply chain variability. This can mean that what would otherwise be considered a homogeneous population of plant might be better considered as clusters that will chart different courses through to failure. It is not uncommon these days that some components or even complete plant would be made in different countries for the same contract so this may be more common than is realised and complicates the interpretation of the condition of the plant. In recognition of this CIGRE has recommended that plant owners should where possible, use statics from their own populations rather than relying on general databases or rules of thumb.

The bottom line here is that there may be design issues that the designer is not or cannot be aware of and that the consequences may not become evident for many years.

When construction takes place, errors may occur that introduce or alter stresses within the plant, examples of which could be,

- Bad or incorrect materials or components
- Poor workmanship
- Poor cleanliness
- Inappropriate storage and handling
- Misinterpretation of plans
- Inappropriate work methods
- Errors in work methods
- Poor Quality Control
- Inadequate testing

Over the years Connell Wagner has attended to many items of failed or degraded high voltage plant that have lost the majority of their economic life due to circumstances that have arisen from causes such as these. Many serious in-service failures have been averted by the application of a testing regime appropriate to the plant and in accordance with the recommendations of Standards.

Factory Testing

The factory testing period is often a high pressure time. The contractor's management believes that the plant is ready and that they only have to go through the formality of the factory test to get the plant out and free up the testing bay for other plant coming off the assembly line. In this area I put forward the following cardinal sins,

- Not specifying the tests required
- Not specifying the pass fail criteria
- Not witnessing the commissioning tests
- Sending unqualified persons to witness the tests
- Not recording appropriate data

In all of these cases vital elements in ensuring that the plant meets the highest standards have been lost. Indeed in many supply contracts it would be advisable to witness the plant at various crucial stages of construction as well. This is as the plant can pass electrical tests but still not deliver the maximum economic life due to underlying built-in mechanical or thermal weaknesses. It must be acknowledged that even in factories there is not always a comprehensive test capability and in Australia there is no short circuit testing of transformers occurring due to the requirement of a very costly and infrequently used facility.

Testing regimes are as follows,

- Type Testing
- Acceptance Testing

Type tests are generally only carried out once in the factory to ensure that no gross errors attributable to design have occurred and that the materials used are suitable for the duty required by the specification. Acceptance testing is carried out at much higher levels than the routine or site tests and confirms to the extent measurable the correct execution of the design.

The acceptance test shows that the unit (*identical* to the type tested unit), meets the requirements of the contract. Hopefully the contract references appropriate Standards and as such relies on the distilled wisdom of experts in that type of plant. Often a single Standard does not indicate all of the required tests and as such it is necessary to draw from a number of Standards to obtain a comprehensive testing and benchmarking regime. The Standards aren't perfect but they are immensely better than the situation of not referencing them.

Without expert witnesses to these tests, interpretation of ambiguous or vague elements of the Standard may not be in the long term interests of the plant owner and the product will be of lessor quality than would otherwise be the case. With an increasing trend to source plant internationally and often in countries with poor quality assurance systems, there is an even greater need for tight specifications and appropriate witness testing procedures.

Delivery & Installation

Delivery is best defined as the period from when the plant was last witnessed at the factory to when it arrives at the plant owner's site. This is a mysterious time where strange and disturbing events can transpire. These days it is not uncommon for plant to be shipped or even flown from Europe or Asia. The plant is sometimes fitted with acceleration monitors to determine if any undesirable shocks had occurred in transport. If these devices make it in tact then the question often arises as to what these recorded levels really mean for the plant?

Large power transformers are most affected, as they are heavy and comprise many components and systems to support them. These components can often play the roles of support and insulation simultaneously and are thus readily compromised. Large items such as power transformer are generally delivered in a partially assembled state, generally without HV bushings and oil. This results in an intrusive reassembly process, under site conditions, which is a significant risk.

The final site commission test is the last time prior to service that any shortcomings can be identified. Often the commissioning tests are indicated in the contract without reference to relevant Standards and the extent of testing may be totally left to the discretion of the contactor. This is a significant weakness in the contract, the outcome of which is the shifting of risk from the Contractor to the Principal. These Commissioning or Acceptance High Voltage tests are crucial to risk management and must be carried out to the full requirements of the relevant Standards.

The plant owner must live with the asset for the remainder of its economic life, it is vital that every indication is given that the life will exceed the warranty and will not be limited by the failings that have been outlined in this document. This is also the best opportunity to obtain comprehensive benchmarking data that will be required to manage the asset into the future.

The plant must be adequately operated before the warranty period, ie, don't just put it into store and forget about it. This practice shifts the risk of premature failure, which the warranty is meant to cover, completely over to the plant owner. The plant owner is then totally reliant on the underlying relationship with the supplier to provide access to warranty provisions.

Operations Support

High voltage tests and testing regimes can be used to support operations by answering the following questions,

- What is the electrical condition of my plant?
- How aged is my plant, and what is the rate of deterioration?
- How should I operate my plant to minimise the rate of deterioration of the plant?
- Do I have anything to worry about?
- Should I be planning a maintenance or replacement for an item of plant?

Every item of HV plant, even a new one, already has a history when the plant owner takes responsibility for it. The current state of the plant and where it will head in the future are common question answered by the application of High Voltage testing techniques and condition assessments methods.

Maintenance

High voltage tests are typically carried out on equipment after repair to show that the repairs have achieved their aim and that the plant has been restored to a serviceable condition with no additional or unexpected loss of life.

These types of tests are generally carried out after,

- Rewinds
- Overhauls
- Component replacement
- Internal inspections
- Post fault

Basically anything that disturbs the insulation or introduces elements into the insulation systems should be considered. It is not uncommon for the following to be picked up during post maintenance tests,

- Incorrect connections
- Damaged components
- Loss of insulating materials
- Contamination
- Change in component quality
- Lack of oil
- Poor workmanship
- Clearance problems
- Changes in operating characteristic
- Plant not fit for service

HV and Associated Tests

The tests commonly applied in HV testing scenarios are outlined in brief below,

Insulation Resistance
Measure the resistance of the insulation typically to earth. Used to determine the basic state of insulation the higher the value the better, very temperature dependant.

Polarisation Index
The ratios of the 10 min IR to the 1 min IR. Is a measure of moisture and contamination of the insulation.

DC Ramp Test
A DC voltage is applied to the insulation relative to earth and is raised very slowly whilst noting the apparent resistance. This test is used to determine ground wall insulation properties of windings in motors and generators. Tends not to be used if a full AC testing capability is available.

Winding Resistance/Circuit Resistance
Basic measure of the continuity and bulk DC resistance of the winding. Requires temperature correction and 4 wire measurements. Provides phase balance check (<1%).

Ratio
It is a requirement of the Standards that the measured ratios of transformers be within 0.5% of the values indicated on the nameplate. This is a requirement mainly for operational reasons and is rarely related to condition assessment. The test will though find errors in connections, particularly after OLTC maintenance.

Dielectric Dissipation Factor (DDF)
Measures the AC loss when the insulation is raised in voltage. The characteristic of the relation between DDF and voltage is a good indicator of the bulk properties of the insulation. It will detect voids, partial discharge and corona, which can point to problems in area such as,

- Electric stress levels and clearances
- Contamination of windings and bushings
- Delamination of windings
- Burning of insulation or other such damage
- Thermal Runaway
- Aging of the bulk insulation system

In general the higher the value of DDF for the same voltage level, material and temperature, the poorer is the condition of the insulation.

Capacitance
The capacitance is generally measured at the same time as the DDF and should have a very small voltage coefficient in a healthy insulation system. A departure from this state can be indicative of insulation damage.

Partial Discharge Testing (PD)
PD testing is by far the most insightful method of determining the state of a degrading insulation system. The measurement works by detecting the small electric discharges that occur as parts of the insulation degradation process. PD measurements can reveal the,

- number of insulation degrading voids present
- size of individual voids in energy terms
- distribution of voids within the insulation
- voltage and conditions at which the voids become active
- whether the discharges are to earth, air, oil, floating objects or within the insulation material
- state of degradation of the insulation system
- bar bounce
- clearance issues

The absence of PD's at test voltages is the strongest indication that the insulation system is in good condition and is not subject to degradation from the eroding action of partial discharges. These measurements are made on all types of insulation systems including individual motor coils and assemblies of coils.

Ultrasonic or Acoustic Emission Detection (UES or AES)
This method can be used to indicate the location of the corona or discharges in air, oil or transmitted down connection pipe work or surfaces. When combined with location methods on transformer tanks it is commonly used in conjunction with PD measurement equipment to localise the position of sources of strong discharges. On the basis of this location information and internal drawings a decision about the severity and urgency of the problem may be able to be determined.

Applied and Induced Tests

These tests are the most basic HV proving test and demonstrate the insulation's ability to withstand the rigours of the service environment from a voltage standpoint. The test involves applying a voltage at a level and for a time prescribed by the Standard, in the indicated configuration. The test is a go/no go test. It can be carried out with a PD test at the same time to add additional diagnostic capability. In transformers this is a routine test.

Ring Flux Test
This test is used to indicate damage to the laminations of motor and generator stators. It induces a flux at about 80% of normal into the core and a thermal imaging camera is used to show any areas of excessive temperature rise. Temperature is a major aging and degrading factor for windings with a 10ºC temperature rise halving insulation life.

Electric Core Imperfection Test (EL CID)
Small signal equivalent of the Ring Flux test. A special instrument is used that measures the loss associated with a flux of approximately 3%-4% of the rated level. In this case there is no temperature rise of significance to measure. A determination of the localised loss is made using a small search coil that is moved about the core. The measured values are related to predicted temperature rise for the fully fluxed condition.

Recovery Voltage Measurement (RVM) / Frequency Domain Spectroscopy (FDS) / Polarisation Depolarisation Analysis (PDA)
These methods can loosely be regarded as equivalent and are generally used to determine the equivalent paper moisture of transformers and cables. This is an important parameter as moisture in the insulation accelerates aging dramatically and reduces the strength of insulation.

Frequency Response Analysis (FRA)
FRA is a method of determining the transfer function between different elements of the windings of typically a transformer. It captures the electrical and therefore the geometric relation between physical elements of the windings, core and earth. It is used to indicate movement or deformation of the windings that can readily occur during transport or close in faults.

Dissolved Gas Analysis (DGA)
DGA is used to find evidence of and give insight into the nature of the insulation degradation process in oil filled plant, typically power and instrument transformers. DGA can provide evidence of,

- arcing
- overheating
- moisture
- aging
- paper or metal involvement in degradation
- show the need for oil reclamation

Other oil tests include corrosive sulphur, electrical strength, resistivity, DDF, acidity, aromatic content and particle analysis.

Furan Analysis
Furans are commonly used to give a measure of the equivalent paper degree of polymerisation. This is a very important factor in transformers that have the bulk of the winding insulation made of paper and associated materials made from cellulose. The measure though is not very precise and thus must be interpreted with caution.

Impulse Tests
Impulses to simulate lighting and switching surges are applied to the plant to determine if the insulation system can withstand such conditions. Due to the nature of the test equipment, impulse tests are generally carried in a laboratory or at the OEM's test facility.

Very Low Frequency (VLF) Test
VLF testing is generally applied to highly capacitive plant such as XLPE cables. The purpose of the test is to accelerate the growth of water trees that bridge the insulation and result in cable failure during the test. This enables the affected areas to be removed from the cable which in theory leaves the cable without water trees present. The primary reason for the test is that can be performed with much smaller equipment than the equivalent AC tests on cables. The AC tests though are not intended to fail the cable during tests and are typically carried out in conjunction with PD tests.

Test method and applicability to plant type

	IR	PI	WR / CR	DC Ramp	DDF	Cap	Ratio	PD	UES	Applied	Induced	Ring Flux / ELCID	RVM / IDA / PDA	FRA	DGA	Furan	RSO	Impedance	VLF
Motors	X	X	X	X	X	X		X		X		X					X	X	
Generators	X	X	X	X	X	X		X		X		X							
Power Transformers	X	X	X		X	X	X	X	X	X	X		X	X	X	X			
Instrument Transformers	X	X			X			X	X	X			X		X	X			
Cables	X	X	X		X	X		X		X			X						X
Switchgear	X	X	X		X			X		X									

On-line Systems
On-line monitoring systems have been around in one form or another since very early times. They are a great benefit in certain circumstances and will enable the economic life of a plant to be fully delivered. They almost invariably suffer from a much lower level of reliability than the plant that they are monitoring and thus can be considered an expensive alternative to time based monitoring if applied to all of the plant. Monitors that are improperly applied or operated can at best result in considerable expense in unnecessary additional testing of the plant, at worst they can fail to perform their basic task of monitoring and lead to a false sense of security.

It is the view of Connell Wagner that the choice of an on-line system for high-voltage plant should be made when plant is critical or has a known defect likely to lead to catastrophic failure. If appropriate high voltage testing has been carried out then there should be ample indication of incipient faults to better support the decision of where to install on-line systems to nurse through deteriorating plant.

It is important to understand that on-line systems are not a substitute for HV testing of HV plant. The failure modes of high voltage insulation systems are subject to considerable non-linear behaviour and early warning of many types of failure modes can only be obtained through high voltage testing. Certainly, acceptance and warranty testing should only be performed though high voltage testing methods. On-line systems can only show the presence of a condition when it is already active at the operating condition of the plant and have limited early warning capability. In motors and generators though with epoxy mica insulation systems there is generally a considerable warning period of months or years of insulation degradation and on-line systems are best applied to the final stages of the process to ensure that the full economic life is obtained and capital is conserved.

Mechanical failures are in a different category and many can lead to failure or significant loss of life in minutes or hours, eg, bearing or lubrication failure. The proven methods of vibration and temperature are invaluable in these instances.

Standards

Standards have evolved over the years to embody the current collective wisdom in relation to the area to which they apply. The production of a Standard is a Herculean effort spanning a number of years on the part of members of Standards Committees. Initially an agreement to change the Standard has to be reached, and then changes have to be codified, voted on, approved and instigated before a new revision of a Standard is released. Standards Committees are generally made up of academic and industry participants, with no requirements as to the numbers or ratios of interested and often competing groups. Given this a degree of compromise must be made in order to get changes accepted and from time to time the development of Standards can be stifled by vested interests. Changes that are deemed too difficult to comply with for commercial reasons are unlikely to ever reach a final version of a Standard. State of the art methods for fault diagnosis are also unlikely to make their way into a Standard.

Standards should be considered as the minimum requirement for the plant to which they apply. They generally also greatly lag the current diagnostic capability in relation to the defection of defects. In the application of a rational risk management process, relying on the requirements as laid out in Standards should be the minimum requirement and any effort to impose lessor requirements should be carefully considered in light of the guarantees provided and the associated costs and risks. Lessor requirements are invariably a signal that the balance of risk is being passed onto the owner of the plant.

Even though the Standard is subject to considerable review, it can still be left with areas of ambiguity and often elements have to be interpreted by experienced people in order to ensure that the intent of the Standard is delivered. An example in point is the definition of partial discharge, which leaves significant room to manoeuvre and allows plant to leave the factory that on impartial assessment would have been deemed not to have met the requirements of the Standard.

Below is a partial list of applicable standards for HV plant,

Rotating Electrical Machines	AS1359, IEC60034, IEEE 432, IEEE 56
HV Test Techniques	AS1931, IEC60060
Partial Discharge Measurement	AS60270, IEC60270
Power Transformers	AS2374, IEC60076
Switchgear	AS2560, IEC62271
Bushings	AS1265, IEC60137
Voltage Transformer	AS1243, IEC60044
Current Transformer	AS1675, IEC60044
Cables	AS1429, IEC60502
Shunt Capacitors	AS2897, IEC60871

Note that HV plant should be tested in accordance with the Standard to which it was made rather than the latest Standard.

Conclusion

High voltage plant typically has a long operating life and is very costly; the ability to identify degradation that would otherwise lead to a gross reduction in plant life or catastrophic failure is of great economic importance. The consistent and appropriate application of risk management practices for HV plant involving the use of tests applicable to the failure modes of the plant, is a key element of HV asset management. Identifying the most appropriate times to assess the condition of the plant is of strategic importance in the control of plant risk. The concept of the plant Risk Cycle is a useful model in identifying key instances when the impact of condition assessments can result in major benefits.

Contracts that refer to Standards protect against inadvertent or intentional risk transfer to plant owners. Critical areas in the Standards though may need to be specifically identified with pass-fail criteria to ensure the desired quality. Witnessed factory testing to ensure compliance at the manufacturer's works is an integral component of this process. It must be remembered that Standards contain the agreed minimum acceptable levels and customers can specify their own requirements.

After site acceptance tests, a well conceived and executed asset management plan covering condition monitoring, maintenance, and including online and offline tests, will help to ensure that the full economic life of these valuable assets is obtained.