COLUMN

Trends in Power Transformer Failure Analysis

ABSTRACT

The transformer failure can be initiated by many factors, but the results of a failure can be the same. Diagnostic tests provide indication of incipient failure. One must have a good understanding of the system conditions to which the transformer is exposed and an understanding of the transformer construction to properly investigate the cause and effect of conditions.

This will facilitate arriving at a conclusion of the analysis. Each construction type has its own advantages and an awareness of these aids in the determination of the root cause.

Many initiators – few outcomes

There are many initiators of transformer failures, but those which can potentially lead to catastrophic failure are:

1. mechanical failure
2. dielectric failure

In both cases, the transformer is no longer able to perform its intended function of carrying load and stepping down (or up) the voltage.

Test techniques are designed to detect the two failure modes

Throughout the world, dissolved gas analysis (DGA, the measurement and monitoring of dissolved gas in the insulting liquid) has become the most popular diagnostic tool in use. Depending on the DGA results, one may detect an incipient fault which is the result of one of the initiators, and if left undetected or untreated, might result in one of the catastrophic failure modes.

Alphabet tests: Some symptoms can show in test results before complete failure

The discussion of diagnostic testing was very thorough in the last issue of Transformers Magazine. To refresh your memory, let's review the significant diagnostic field tests.

DP: Transformers can operate with essentially failed insulation only if there is no movement or abrasion of the insulation which would result in a short circuit. Transformer

Experience and data collection a crucial components of problem analysis

insulation in this condition has reached the end of life and chemical tests would show a loss of strength measured as degree of polymerisation (DP). However, this is an invasive test since the insulation most vulnerable to failure is often deep inside the winding.

DGA: As previously mentioned, the DGA results can show trends. These trends can be monitored and there is a large body of data which guides the user to determine the course of action to take. There are several guides and standards for measurement and analysis of dissolved gas in the most popular insulating liquids.

SFRA: SFRA or (S)weep (F)requency (R)esponse (A)nalysis, detects changes in circuit impedance which are the result of movement of winding position or the result of shorted winding turns. These changes are measured by applying various frequencies to the terminals and measuring the circuit impedance. Guides for performing this test have emerged in the past 10 years which aid in the interpretation of the test results. It is important to have base-line SFRA results to which to compare. Small changes can be detected before major damage has occurred. The guides for SFRA exist in both the IEEE Standards and IEC Standards environment.

DFR: (D)ielectric (F)requency (R)esponse, also referred to as dielectric response analysis, has become a tool for detecting deficiencies in the insulating mediums including the liquid and paper insulating materials. Its main value has been shown in determining the moisture content of the insulating material. It can also detect other causes of high insulation power factor, such as carbon tracking. This is another diagnostic test which needs a baseline test value for comparison. Work is being done to develop guides for use of the test. CIGRE Task Force D1.01 has presented several papers on the techniques and the IEEE Transformers Committee has established a Working Group to develop C57.161 IEEE Guide for DFR Measurement.

All of these tests rely on either a baseline test or a body of data accumulated in the industry for comparison with the current test results. There are some other comparisons that can be made. For example, an SFRA test result can be compared to other phases of the same transformer or to identical units. However, when this is done, certain limitations must be accepted in interpreting the results.

Understanding the effect of system conditions can aid in the analysis of symptoms

Examples of system conditions which effect transformer condition include through-fault events, lightning strikes to nearby lines, loading beyond nameplate and numerous other conditions for which the transformer was not designed.

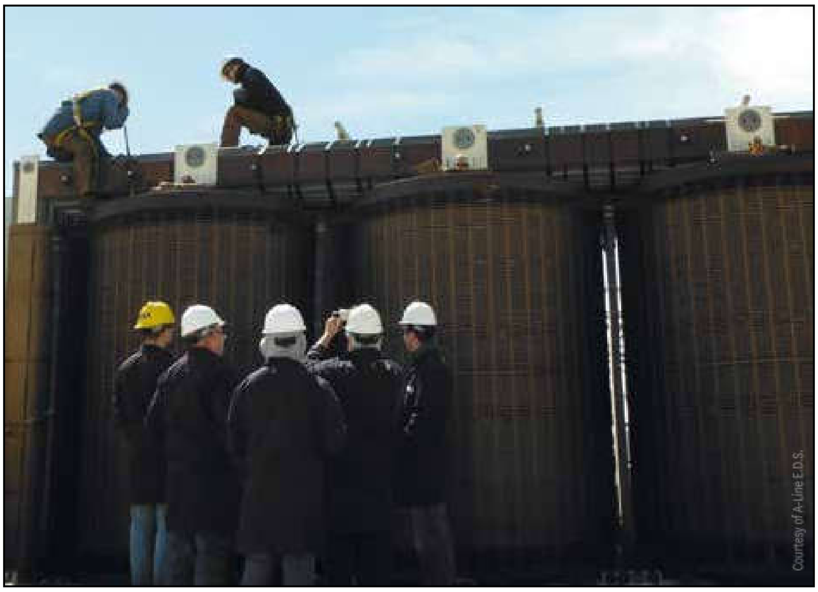
Through-fault events can cause winding movement which might eventually lead to insulation wear and dielectric breakdown.

Voltage excursions such as a lightning strike are mitigated by surge protective devices throughout the system. In addition, winding design will include means to alleviate voltage stresses. However, such an over-voltage condition can lead to dielectric failure after numerous applications of the over-voltage.

Loading beyond nameplate may result in higher internal temperatures and consequently make the insulation system vulnerable to failure.

An understanding of these conditions, the causes, and effects, will aid in the evaluation of the transformer‘s condition at any point in its life. The articles which discuss these topics can be found in Transformers Magazine Volume 1.

Correct setting of protective devices is also critical. While the protective relay may not prevent a failure, it should be able to detect one and isolate the transformer from the system, thus protecting the system from further damage or transients. To correctly set the relays, the known maximum AND minimum fault current conditions must be evaluated. It is out of place here to cover what is necessary to accomplish this, but it is a critical part of the maintenance and operation of an asset as valuable as a transformer. Numerous guides and texts have been written covering the protection methods which should be utilised for transformers and connected equipment.


Courtesy of A-Line E.D.S.

Likewise the protective margin and overvoltage capability as well as the follow-current capability of surge protective devices must be coordinated with the system conditions and the transformer capability. Again, there are standards, guides, and a variety of other literature that covers best practices and best technology for protection.

As a transformer failure investigator, one must be aware and understand the practices and limitations of all of the above mentioned protective schemes. There have been occasions where one part of an organisation has not been made aware of changes in system conditions or configuration which has resulted in the protection scheme under-performing.

Failures appear in different ways, depending on the type of construction

When investigating a transformer failure, one must understand schematically, how the core and winding are constructed in order to correctly analyse the failure mechanisms that have occurred. Best analysis will evaluate the mechanical and dielectric stresses imposed on various parts of the transformer. Mechanical stresses are produced by the flux created by currents in the winding and the dielectric stresses are created by the voltages impressed upon the winding. Stray flux can also play a role in thermal problems.

1. Common failure modes

Some modes of failure can occur regardless of construction type. These might include tap changer failures, bushing failures, tank failures, moisture ingress, and other forms of dielectric fluid contamination. Other failures occur as described in the next sections (1 through 4) without regard to construction type.

Construction type (e.g., core form, shell form, wound core, etc) influences the failure mode. Each type of design has its own set of strengths. However, there are many modes of failure which are common to all construction types.

Core form construction provides a single path for the magnetic flux, while shell-form construction provides multiple paths for the flux. Variations providing five and seven legs to a three-phase core can be constructed.

Regardless of core-type or shell-type construction, the core itself is constructed of the same material. It is stacks of pre-cut laminations of magnetic grade steel. Each lamination is coated with a thin layer of insulating material. When the insulating material is compromised by, for example, a burr or a break in the insulating coating, current can flow along this path and generate heat.

2. Mechanical failures

Cause

Mechanical failures can be the result of shipping damage, seismic activity, and thru-faults. The previously mentioned

Diagnostic testing is critical to determine transformer health

core problems can be included in this category. This discussion will focus on winding mechanical problems.

Results

The obvious result of a mechanical failure is the displacement of winding turns or damage of the turns by the forces exerted during the damaging event. Adequate bracing is provided by the construction method being used to prevent the displacement from happening during shipment or during thru-faults which are within the capability of the transformer design. This is why manufacturers specify the g forces which must not be exceeded during transport. Specifications should define the expected short circuit to which the transformer will be exposed and the design should be adequate for those forces which the specified currents will produce.

Indications

Mechanical failure can result in scalloped conductors (beam failure), conductors which have been looped over adjacent turns by the hoop stress (hoop failure), or in rare cases, conductors which have been severed by the tension applied by the hoop force.

Mechanical failure can be detected by a change in the SFRA test, a change in low voltage excitation current, a change in impedance, and sometimes, the presence of partial discharge (PD) during an induce voltage test. Mechanical failure is often discovered by electrical failures which are the result of mechanical deformation.

Knowledge of system conditions is critical in failure analysis

3. Electrical failures

Cause

Electrical failures are the result of insulation degradation. This can be caused by thermal degradation over the life of the transformer, by thermal degradation due to excessive or frequent fault current, or by dielectric breakdown due to high voltage stress. A dielectric breakdown can also be the result of mechanical forces tearing the insulation or, as suggested in the previous paragraph, by reducing dielectric clearance of components from each other.

Results

The result of an electrical failure can be simply a turn-to-turn failure which may even allow the transformer to remain in-service if the turn-to-turn voltage is not large. The consequence can be an arc from energised winding to an adjacent winding or to ground (earth).

Indications

Electrical failures will manifest themselves as a source of dissolved gas products. Diagnostic tests will typically show deterioration and the results will provide clues where the failure occurred or where it is about to happen. Winding turns ratio, winding insulation tests, insulation power factor will all give indications and should confirm the DGA results. They frequently show results observed during an internal inspection or tear-down as some form of insulation "burning" which appears as discoloration or carbonisation of cellulose. Those where cellulose is not involved typically show as points of contact on core

steel or tank steel and winding or leads where the conductor is bare.

4. Other common failure modes

Other failure modes can be the result of a grounded core or core clamping structures (such as through-bolts) that develop shorts. These result in a shorted turn (the core) and produce high currents which are often detected by dissolved gas analysis.

5. Failure modes for shell form construction

Shell form construction is resistant to winding deformation due to thru-faults. This is because the coil "pancakes" are arranged in multiple groups to limit force magnitude. The exposure to conductor bending is limited by many support spacers to avoid beam bending. Form fit tank and core prevent movement of the core and winding groups.

Each "pancake" is connected to the one adjacent to it, first on the inner end of the "pancake", then to the next "pancake" on the outer end.

The area which is vulnerable is the edge of the coil where "pancake" windings are connected together. There is a relatively high voltage in the kV range at this point between the same end of odd or even number "pancakes". Failure can be prevented by adequate support of the outer turns.

6. Winding failure modes for core form construction

Core form construction can exhibit failure in several ways. Radial tension failure, also known as hoop tension failure, can occur; conversely, radial compression failure can also occur. Radial failure can collapse the inner winding unless the winding support structure is strong.

Axial failures can occur in both compression and tension. Sometimes the windings telescope, caused by uneven axial forces. The result is typically a tangled mess of winding conductors which eventually arc to ground or each other, and disrupt the force vectors in ways that were not accounted for in the original design.

Each construction method has its own set of strengths and problems

Core form designs have subsets consisting of numerous winding configurations such as layer windings, helical (or spiral-type) windings, continuous disc, and interleaved disc windings. Each has different voltage stress applied to different components of the winding (individual strand-to-strand, conductor-to-conductor, layer-to-layer or disc-to-disc, etc.) so a good understanding of the voltages and forces impressed upon these components is important to investigate.

Layer wound core form transformers are the simplest winding form. They place the wound conductors next to one another. Several layers can be provided on top of one another, usually with spacers to provide cooling ducts. These are frequently used in high current applications and for auxiliary windings such as regulating windings. They are inherently resistant to beam bending of the conductor. However, they are less resistant to axial movement.

Helical windings are multiple conductors stacked and wound together in a screw-like manner along the length of the winding cylinder. They are separated by radial spacers to allow for insulating fluid flow for cooling. The number of spacers used around the circumference of the winding cylinder influences its ability to withstand axial forces which lead to beam bending. Helical windings are also frequently used in high current applications.

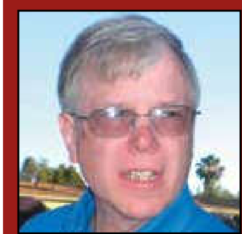
Disc windings are wound in a series of parallel discs using single or multi-strand turns. Their disadvantage is poor distribution of the voltage stresses, especially in the line-end turns due to high winding to ground capacitance. Shields are wound with the load carrying turns to distribute the voltage stress more evenly across the winding. However, with multiple crossovers, brazed connections, and shields connections, they are a more complex winding to build. Interleaved disc windings are more complex still, with additional feature that results in turns being distributed across the winding in a way that results in every other turn on the cylinder being adjacent. This produces a high series capacitance and therefore a more uniform voltage distribution across the winding. If they were a machine they would have the most moving parts.

References

[1] IEEE PC57.125 *Draft Guide for Failure Investigation, Documentation, Analysis, and Reporting for Power Transformers and Shunt Reactors*

[2] James H. Harlow, *Electric Power Transformer Engineering*, 3rd Edition, CRC Press, Taylor & Francis Group, Boca Raton, FL, 2012

Author



Wallace BINDER has experience in scope development, planning, design, construction, start-up, operation, and maintenance of distribution, transmission and customer utilisation substations, back-up power generation, transmission and distribution lines, and systems.

Wallace Binder has been an active member of the IEEE/PES Transformers Committee for more than 30 years. He has served twice as Chair of the Working Group on Failure Analysis, a position he currently holds. He served as Chair of the Transformers Committee for two years in the late 90's and has contributed to numerous guides and standards developed by the Transformers Committee.

Wallace Binder is currently an independent consultant with his office located in Western Pennsylvania. He has served a variety of clients - both manufacturers and users of substation apparatus.