STAMATIOS VLACHOS

CONSTRUCTION AND MAINTENANCE OF HIGH VOLTAGE POWER TRANSFORMERS

CENTRAL OSTROBOTHNIA UNIVERSITY OF APPLIED SCIENCES

Abstract

This paper is produced by student Stamatios Vlachos and professor Jari Halme. The main purpose of this research is to gather in one paper information about construction and maintenance of high voltage power transformers. There are included informations about condition monitoring techniques, maintenance techniques and also information about the degradation processes that happened in oil paper insulated transformers.

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CHAPTER 5 Maintenance and testing of power transformers

1. Introduction in power transformers

1.1 What is a transformer?

A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled electrical conductors . A changing current in the first circuit (the *primary*) creates a changing magnetic field . This changing magnetic field induces a changing voltage in the second circuit (the *secondary*). This effect is called mutual induction.

If a load is connected to the secondary circuit, electric charge will flow in the secondary winding of the transformer and transfer energy from the primary circuit to the load connected in the secondary circuit.

The secondary induced voltage (V_S), of an ideal transformer, is scaled from the primary voltage (V_P) by a factor equal to the ratio of the number of turns of wire in their respective windings:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

By appropriate selection of the numbers of turns, a transformer thus allows an alternating voltage to be stepped up — by making N_S more than N_P — or stepped down, by making it less. Transformers are some of the most efficient electrical 'machines', with some large units able to transfer 99.75% of their input power to their output. Transformers come in a range of sizes from a thumbnail-sized coupling transformer hidden inside a stage microphone to huge units weighing hundreds of tons used to interconnect portions of national power grid . All operate with the same basic principles, although the range of designs is wide.

1.2 Historical model of transformers.

The transformer principle was demonstrated in 1831 by Michael Faraday, although he used it only to demonstrate the principle of electromagnetic induction and did not foresee its practical uses. The first widely used transformer was the induction coil , invented by Irish clergyman Nicholas Callan in 1836. He was one of the first to understand the principle that the more turns a transformer winding has, the larger EMF it produces. Induction coils evolved from scientists' efforts to get higher voltages from batteries. They were powered not by AC, but DC from batteries which was interrupted by a vibrating 'breaker' mechanism. Between the 1830s and the 1870s efforts to build better induction coils, mostly by trial and error, slowly revealed the basic principles of transformer operation. Efficient designs would not appear until the 1880s, but within less than a decade, the transformer was instrumental during the “War of currents” in seeing alternating current systems triumph over their direct current counterparts, a position in which they have remained dominant.

Russian engineer Pavel Yablochkov in 1876 invented a lighting system based on a set of induction coils , where primary windings were connected to a source of alternating current and secondary windings could be connected to several “electric candles”. The patent claimed the system could "provide separate supply to several lighting fixtures with different luminous intensities from a single source of electric power". Evidently, the induction coil in this system operated as a transformer.

William Stanley , an engineer for Westinghouse, built the first commercial device . The core was made from interlocking E-shaped iron plates. This design was first used commercially in 1886. Their patent application made the first use of the word "transformer". Russian engineer Mikhail Dolivo-Dobrovolsky developed the first three-phase transformer in 1889. In 189 Nikola Tesla invented the Tesla coil , an air-cored, dual-tuned resonant transformer for generating very high voltages at high frequency.

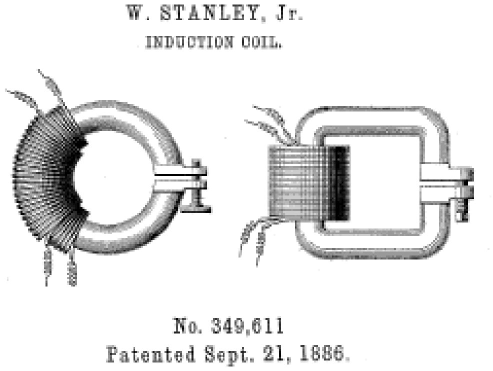


Image 1.1 A historical Stanley transformer.

1.3 Basic principles

The transformer is based on two principles: firstly, that an electric current can produce a magnetic field (electromagnetism) and secondly that a changing magnetic field within a coil of wire induces a voltage across the ends of the coil (electromagnetic induction). By changing the current in the primary coil, it changes the strength of its magnetic field; since the changing magnetic field extends into the secondary coil, a voltage is induced across the secondary.

A simplified transformer design is shown below. A current passing through the primary coil creates a magnetic field. The primary and secondary coils are wrapped around a core of very high magnetic permeability, such as iron; this ensures that most of the magnetic field lines produced by the primary current are within the iron and pass through the secondary coil as well as the primary coil.

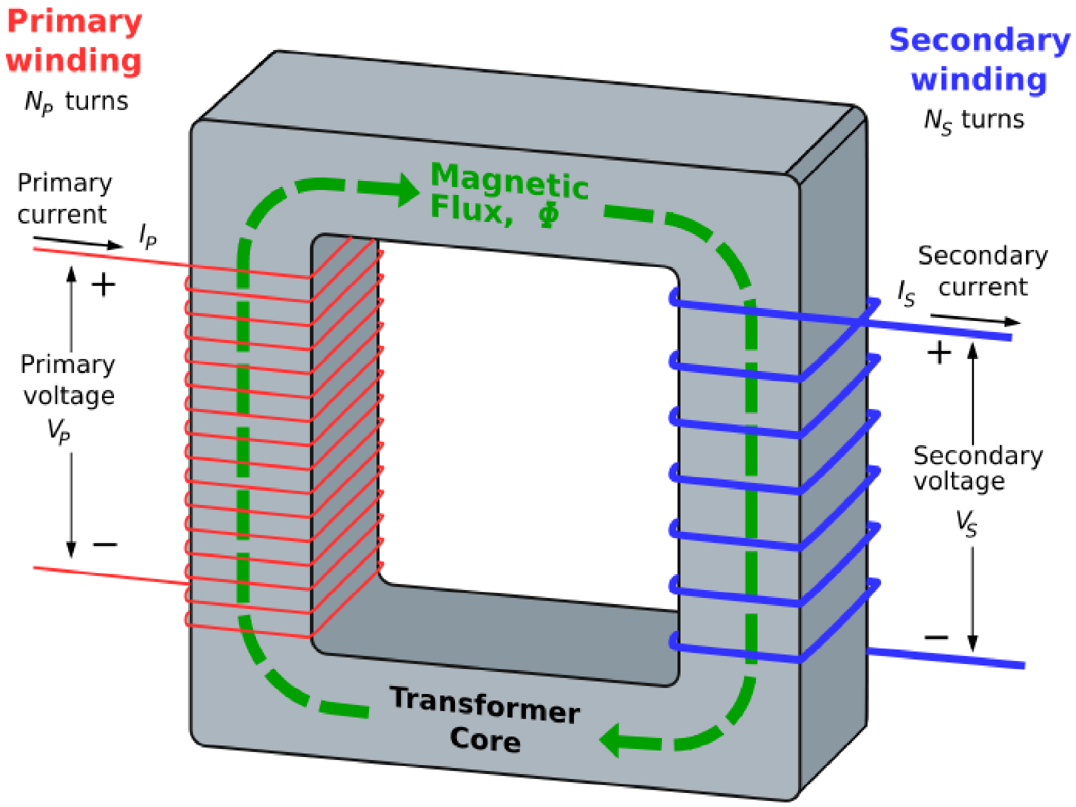


Image 1.2 An ideal step-down transformer showing magnetic flux in the core.

1.4 Energy losses.

An ideal transformer would have no energy losses, and would be 100% efficient. In practical transformers energy is dissipated in the windings, core, and surrounding structures. Larger transformers are generally more efficient, and those rated for electricity distribution usually perform better than 98%.

Experimental transformers using superconducting windings achieving efficiencies of 99.85%. While the increase in efficiency is small, when applied to large heavily-loaded transformers the annual savings in energy losses is significant.

A small transformer, such as a plug-in “wall-wart” or power adapter type used for low-power consumer electronics, may be no more than 85% efficient, with considerable loss even when not supplying any load. Though individual power loss is small, the aggregate losses from the very large number of such devices is coming under increased scrutiny.

The losses vary with load current, and may be expressed as "no-load" or "full-load" loss. Winding resistance dominates load losses, whereas hysteresis and eddy currents losses contribute to over 99% of the no-load loss. The no-load loss can be significant, meaning that even an idle transformer constitutes a drain on an electrical supply, which encourages development of low-loss transformers.

Transformer losses are divided into losses in the windings, termed copper loss, and those in the magnetic circuit, termed iron loss. Losses in the transformer arise from:

Winding resistance

Current flowing through the windings causes resistive heating of the conductors. At higher frequencies, skin effect and proximity effect create additional winding resistance and losses.

Hysteresis losses

Each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core. For a given core material, the loss is proportional to the frequency, and is a function of the peak flux density to which it is subjected.

Eddy currents

Ferromagnetic materials are also good conductors, and a solid core made from such a material also constitutes a single short-circuited turn throughout its entire length. Eddy currents therefore circulate within the core in a plane normal to the flux, and are responsible for resistive heating of the core material. The eddy current loss is a complex function of the square of supply frequency and inverse square of the material thickness.

Magnetostriction

Magnetic flux in a ferromagnetic material, such as the core, causes it to physically expand and contract slightly with each cycle of the magnetic field, an effect known as magnetostriction . This produces the buzzing sound commonly associated with transformers, and in turn causes losses due to frictional heating in susceptible cores.

Mechanical losses

In addition to magnetostriction, the alternating magnetic field causes fluctuating electromagnetic forces between the primary and secondary windings. These incite vibrations within nearby metalwork, adding to the buzzing noise, and consuming a small amount of power.

Stray losses

Leakage inductance is by itself lossless, since energy supplied to its magnetic fields is returned to the supply with the next half-cycle. However, any leakage flux that intercepts nearby conductive materials such as the transformer's support structure will give rise to eddy currents and be converted to heat.

1.5 Types

A wide variety of transformer designs are used for different applications, though they share several common features. Important common transformer types include:

Autotransformer

An Autotransformer has only a single winding with two end terminals, plus a third at an intermediate tap point. The primary voltage is applied across two of the terminals, and the secondary voltage taken from one of these and the third terminal. The primary and secondary circuits therefore have a number of windings turns in common. Since the volts-per-turn is the same in both windings, each develops a voltage in proportion to its number of turns. An adjustable autotransformer is made by exposing part of the winding coils and making the secondary connection through a sliding brush, giving a variable turns ratio.

Polyphase transformers

For three-phase supplies, a bank of three individual single-phase transformers can be used, or all three phases can be incorporated as a single three-phase transformer. In this case, the magnetic circuits are connected together, the core thus containing a three-phase flow of flux. A number of winding configurations are possible, giving rise to different attributes and phase shifts. One particular polyphase configuration is the zigzag transformer, used for grounding and in the suppression of harmonic currents.

Leakage transformers

A leakage transformer, also called a stray-field transformer, has a significantly higher leakage inductance than other transformers, sometimes increased by a magnetic bypass or shunt in its core between primary and secondary, which is sometimes adjustable with a set screw. This provides a transformer with an inherent current limitation due to the loose coupling between its primary and the secondary windings. The output and input currents are low enough to prevent thermal overload under all load conditions – even if the secondary is shorted.

Leakage transformers are used for arc welding and high voltage discharge lamps (neon lamps and cold cathode fluorescent lamps, which are series-connected up to 7.5 kV AC). It acts then both as a voltage transformer and as a magnetic ballast.

Other applications are short-circuit-proof extra low voltage transformers for toys or doorbell installations.

Resonant transformers

A resonant transformer is a kind of the leakage transformer. It uses the leakage inductance of its secondary windings in combination with external capacitors, to create one or more resonant circuits. Resonant transformers such as the Tesla coil can generate very high voltages, and are able to provide much higher current than electrostatic high-voltage generation machines such as the Van de Graaf generator. One of the application of the resonant transformer is for the CCFL inverter. Another application of the resonant transformer is to couple between stages of a superheterodyne receiver, where the selectivity of the receiver is provided by tuned transformers in the intermediate-frequency amplifiers.

Instrument transformers

A current transformer is a measurement device designed to provide a current in its secondary coil proportional to the current flowing in its primary. Current transformers are commonly used in metering and protective relaying, where they facilitate the safe measurement of large currents. The current transformer isolates measurement and control circuitry from the high voltages typically present on the circuit being measured.

Voltage transformers (VTs)--also referred to as *potential transformers* (PTs)--are used for metering and protection in high-voltage circuits. They are designed to present negligible load to the supply being measured and to have a precise voltage ratio to accurately step down high voltages so that metering and protective relay equipment can be operated at a lower potential.

1.6 Applications

A key application of transformers is to increase voltage before transmitting electrical energy over long distances through wires. Wires have resistance and so dissipate electrical energy at a rate proportional to the square of the current through the wire. By transforming electrical power to a high-voltage (and therefore low-current) form for transmission and back again afterwards, transformers enable economic transmission of power over long distances. Consequently, transformers have shaped the electricity supply industry, permitting generation to be located remotely from points of demand. All but a tiny fraction of the world's electrical power has passed through a series of transformers by the time it reaches the consumer. Transformers are used extensively in electronic products to step down the supply voltage to a level suitable for the low voltage circuits they contain. The transformer also electrically isolates the end user from contact with the supply voltage.

Signal and audio transformers are used to couple stages of amplifiers and to match devices such as microphones and record player cartridges to the input impedance of amplifiers. Audio transformers allowed telephone circuits to carry on two-way conversation over a single pair of wires. Transformers are also used when it is necessary to couple a differential-mode signal to a ground-referenced signal, and for isolation between external cables and internal circuits.

2. Construction and design of power transformers.

2.1 Construction.

The construction of a transformer depends by the application is designed for. Cores, windings and coolant are different for each type of transformer.

2.1.1 Cores

Laminated steel cores

Transformers for use at power or audio frequencies typically have cores made of high permeability silicon steel. The steel has a permeability many times that of free space, and the core thus serves to greatly reduce the magnetizing current, and confine the flux to a path which closely couples the windings. Early transformer developers soon realized that cores constructed from solid iron resulted in prohibitive eddy-current losses, and their designs mitigated this effect with cores consisting of bundles of insulated iron wires. Later designs constructed the core by stacking layers of thin steel laminations, a principle that has remained in use. Each lamination is insulated from its neighbors by a thin non-conducting layer of insulation. The universal transformer equation indicates a minimum cross-sectional area for the core to avoid saturation.

The effect of laminations is to confine eddy currents to highly elliptical paths that enclose little flux, and so reduce their magnitude. Thinner laminations reduce losses, but are more laborious and expensive to construct. Thin laminations are generally used on high frequency transformers, with some types of very thin steel laminations able to operate up to 10 kHz.

One common design of laminated core is made from interleaved stacks of E-shaped steel sheets capped with I-shaped pieces, leading to its name of "E-I transformer".Such a design tends to exhibit more losses, but is very economical to manufacture. The cut-core or C-core type is made by winding a steel strip around a rectangular form and then bonding the layers together. It is then cut in two, forming two C shapes, and the core assembled by binding the two C halves together with a steel strap. They have the advantage that the flux is always oriented parallel to the metal grains, reducing reluctance.

A steel core's remanence means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remaining magnetism is reduced, usually after a few cycles of the applied alternating current.

Overcurrent protection devices such as fuses must be selected to allow this harmless inrush to pass. On transformers connected to long, overhead power transmission lines, induced currents due to geomagnetic disturbances during solar storms can cause saturation of the core and operation of transformer protection devices.

Distribution transformers can achieve low no-load losses by using cores made with low-loss high-permeability silicon steel or amorphous metal alloy. The higher initial cost of the core material is offset over the life of the transformer by its lower losses at light load.

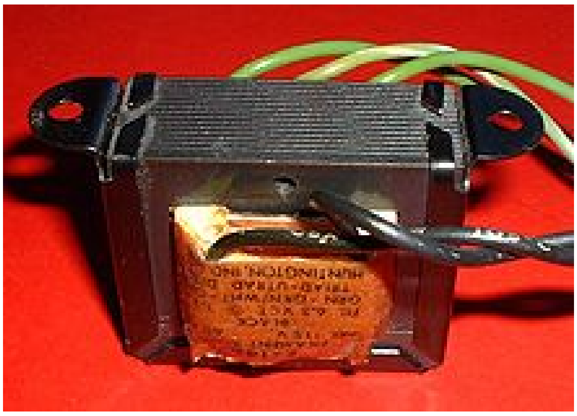


Image 2.1 Laminated core transformer showing edge of laminations at top of unit.

Solid cores

Powdered iron cores are used in circuits (such as switch-mode power supplies) that operate above main frequencies and up to a few tens of kilohertz. These materials combine high magnetic permeability with high bulk electrical resistivity. For frequencies extending beyond the VHF band, cores made from non-conductive magnetic ceramic materials called ferrites are common. Some radio-frequency transformers also have movable cores (sometimes called 'slugs') which allow adjustment of the coupling coefficient (and bandwidth) of tuned radio-frequency circuits.

Toroidal cores

Toroidal transformers are built around a ring-shaped core, which, depending on operating frequency, is made from a long strip of silicon steel or permalloy wound into a coil, powdered iron, or ferrite. A strip construction ensures that the grain boundaries are optimally aligned, improving the transformer's efficiency by reducing the core's reluctance. The closed ring shape eliminates air gaps inherent in the construction of an E-I core. The cross-section of the ring is usually square or rectangular, but more expensive cores with circular cross-sections are also available. The primary and secondary coils are often wound concentrically to cover the entire surface of the core. This minimizes the length of wire needed, and also provides screening to minimize the core's magnetic field from generating electromagnetic interference.

Toroidal transformers are more efficient than the cheaper laminated E-I types for a similar power level. Other advantages compared to E-I types, include smaller size (about half), lower weight (about half), less mechanical hum (making them superior in audio amplifiers), lower exterior magnetic field (about one tenth), low off-load losses (making them more efficient in standby circuits), single-bolt mounting, and greater choice of shapes. The main disadvantages are higher cost and limited rating.

Ferrite toroidal cores are used at higher frequencies, typically between a few tens of kilohertz to a megahertz, to reduce losses, physical size, and weight of switch-mode power supplies. A drawback of toroidal transformer construction is the higher cost of windings. As a consequence, toroidal transformers are uncommon above ratings of a few kVA. Small distribution transformers may achieve some of the benefits of a toroidal core by splitting it and forcing it open, then inserting a bobbin containing primary and secondary windings.

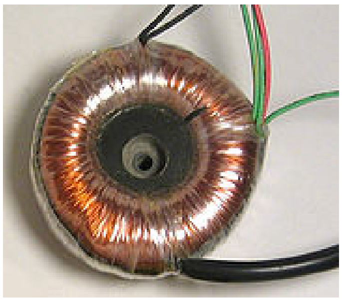


Image 2.2 Small toroidal core transformer

Air cores

A physical core is not an absolute requisite and a functioning transformer can be produced simply by placing the windings in close proximity to each other, an arrangement termed an "air-core" transformer. The air which comprises the magnetic circuit is essentially lossless, and so an air-core transformer eliminates loss due to hysteresis in the core material. The leakage inductance is inevitably high, resulting in very poor regulation, and so such designs are unsuitable for use in power distribution. They have however very high bandwidth, and are frequently employed in radio-frequency applications, for which a satisfactory coupling coefficient is maintained by carefully overlapping the primary and secondary windings.

2.1.2 Windings.

The conducting material used for the windings depends upon the application, but in all cases the individual turns must be electrically insulated from each other to ensure that the current travels throughout every turn. For small power and signal transformers, in which currents are low and the potential difference between adjacent turns is small, the coils are often wound from enamelled magnet wire, such as Formvar wire. Larger power transformers operating at high voltages may be wound with copper rectangular strip conductors insulated by oil-impregnated paper and blocks of pressboard.

High-frequency transformers operating in the tens to hundreds of kilohertz often have windings made of braided litz wire to minimize the skin-effect and proximity effect losses. Large power transformers use multiple-stranded conductors as well, since even at low power frequencies non-uniform distribution of current would otherwise exist in high-current windings. Each strand is individually insulated, and the strands are arranged so that at certain points in the winding, or throughout the whole winding, each portion occupies different relative positions in the complete conductor. The transposition equalizes the current flowing in each strand of the conductor, and reduces eddy current losses in the winding itself. The stranded conductor is also more flexible than a solid conductor of similar size, aiding manufacture.

For signal transformers, the windings may be arranged in a way to minimize leakage inductance and stray capacitance to improve high-frequency response. This can be done by splitting up each coil into sections, and those sections placed in layers between the sections of the other winding. This is known as a stacked type or interleaved winding.

Both the primary and secondary windings on power transformers may have external connections, called taps, to intermediate points on the winding to allow selection of the voltage ratio. The taps may be connected to an automatic on-load tap changer for voltage regulation of distribution circuits. Audio-frequency transformers, used for the distribution of audio to public address loudspeakers, have taps to allow adjustment of impedance to each speaker. A center-tapped transformer is often used in the output stage of an audio power amplifier in a push-pull circuit. Modulation transformers in AM transmitters are very similar.

Certain transformers have the windings protected by epoxy resin. By impregnating the transformer with epoxy under a vacuum, one can replace air spaces within the windings with epoxy, thus sealing the windings and helping to prevent the possible formation of corona and absorption of dirt or water. This produces transformers more suited to damp or dirty environments, but at increased manufacturing cost.

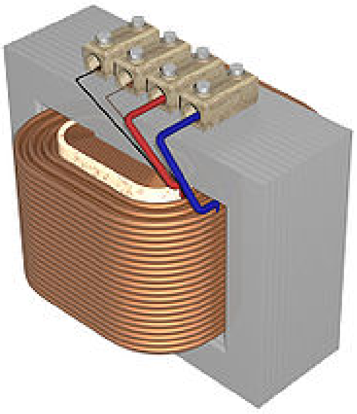


Image 2.3 Windings are usually arranged concentrically to minimize flux leakage.

2.1.3 Coolant

High temperatures will damage the winding insulation. Small transformers do not generate significant heat and are cooled by air circulation and radiation of heat. Power transformers rated up to several hundred kVA can be adequately cooled by natural convective air-cooling, sometimes assisted by fans. In larger transformers, part of the design problem is removal of heat. Some power transformers are immersed in transformer oil that both cools and insulates the windings. The oil is a highly refined mineral oil that remains stable at transformer operating temperature. Indoor liquid-filled transformers must use a non-flammable liquid, or must be located in fire resistant rooms. Air-cooled dry transformers are preferred for indoor applications even at capacity ratings where oil-cooled construction would be more economical, because their cost is offset by the reduced building construction cost.

The oil-filled tank often has radiators through which the oil circulates by natural convection; some large transformers employ forced circulation of the oil by electric pumps, aided by external fans or water-cooled heat exchangers. Oil-filled transformers undergo prolonged drying processes to ensure that the transformer is completely free of water vapor before the cooling oil is introduced. This helps prevent electrical breakdown under load. Oil-filled transformers may be equipped with Buscholz relays, which detect gas evolved during internal arcing and rapidly de-energize the transformer to avert catastrophic failure.

Polychlorinated biphenyls have properties that once favored their use as a coolant, though concerns over their environmental persistence led to a widespread ban on their use. Today, non-toxic, stable silicon-based oils, or fluorinated hydrocarbons may be used where the expense of a fire-resistant liquid offsets additional building cost for a transformer vault. Before 1977, even transformers that were nominally filled only with mineral oils may also have been contaminated with polychlorinated biphenyls at 10-20 ppm. Since mineral oil and PCB fluid mix, maintenance equipment used for both PCB and oil-filled transformers could carry over small amounts of PCB, contaminating oil-filled transformers.

Some "dry" transformers (containing no liquid) are enclosed in sealed, pressurized tanks and cooled by nitrogen or sulfur hexafluoride gas.

Experimental power transformers in the 2 MVA range have been built with superconducting windings which eliminates the copper losses, but not the core steel loss. These are cooled by liquid nitrogen or helium.

2.2 Design and cooling methods.

In general, power transformers refer to liquid filled units and are loosely divided into 3 size categories, small power — under 10 MVA, medium power — 10 to 50 MVA, and large power above 50 MVA. These are not official categories as recognized by ANSI/CSA/IEEE, but are more often ranges referred to by consultants and manufacturers when specifying or building transformers. For example, a transformer manufacturer that builds units in the size range of 10 to

300 MVA will often have one plant facility that builds up to 50 MVA and then another plant that only builds units above 50 MVA and they will refer to these plants as their medium and large power assembly manufacturing facilities respectively.

A transformer's life expectancy is based on a number of factors, the most important of which is the quality of its insulation system over time. The oil used in power transformers is particularly susceptible to moisture and its insulating value is seriously reduced when even small amounts of water are present. In addition to this, the oil's insulating quality and performance as a cooling medium can be reduced by oxidization as well. It is, therefore, extremely important that the design of the transformer be such that it impedes the contact of the insulation system to the outside atmosphere, which contains both moisture and oxygen. Since the oil in the transformer will expand and contract with temperature and load, a number of systems have been developed to help preserve the overall insulation quality of the transformer. These designs include open style, sealed tank, conservator style, and automatic gas pressure.

Open style design refers to a tank design that is free breathing and vented to the atmosphere. There is an air or gas space in the main tank above the oil level. The insulating oil, inside the tank, expands and contracts with load and temperature, thus ultimately breathing in and venting to the outside atmosphere. This is an older style design normally used only in smaller size ranges. The benefits of this type was an initial lower cost base, but at the same time, this is the least former's insulating system.

In the sealed tank design, the core/coils and oil are completely enclosed in the main tank with no ventilation to the atmosphere . The gas space above the oil is normally 10 to 15 percent of the volume of oil at 25°C and is made up of either dry air or nitrogen. This prevents any outside atmosphere from contact with the oil. This style offers better protection against the ingression of moisture and other containants that can have a negative effect on the integrity of the transformer's insulation system. Units of this style are often used in small to medium size designs with their top MVA size really being limited by the physical shipping height requirements of the main tank due to the fact that a gas headspace had to be incorporated above the oil. One drawback to this style is if a weld, flange or gasket develops a leak in the gas head space above the oil, this can lead to direct exchange with the outside atmosphere, which is not good for the oil. Overall this style offers a cost-effective advantage with good insulation protection.

The conservator- or expansion-type design has the main tank completely filled with oil and a smaller expansion tank positioned above the main tank with about 5 to 10 per cent the volume of the main. As the oil expands and contracts with temperature and load, atmosphere moves in and out through a uni-directional moisture removing breather. Only a small surface area of oil in the expansion tank has exposure to the atmosphere and the expansion tank is designed in such a way so that if moisture should get in, it remains trapped in the expansion tank and cannot be exposed to the paper/wood insulation and clamping system of the core and coils. This is the most cost-effective design in higher MVA units and also offers the easiest versatility in shipping because the main tank is totally immersed in oil with no top head space. Newer designs can also incorporate an air bag in the expansion tank which virtually eliminates any oil contact with the outside atmosphere.

The gas regulation design is very similar to the sealed tank design with the exception that the air space above the oil is kept at a positive pressure at all times by a gas regulation system. With this style, as long as the gas bottle and regulation system are intact, a positive pressure is automatically maintained on the tank, allowing no atmosphere to oil contact. This system is quite reliable, however, it does come with a higher initial price tag and maintenance cost factor.

2.3 Tappings and tapchangers

Almost all transformers incorporate some means of adjusting their voltage ratio by means of the addition or removal of tapping turns. This adjustment may be made on-load, as is the case for many large transformers, by means of an off-circuit switch, or by the selection of bolted link positions with the transformer totally isolated. The degree of sophistication of the system of tap selection depends on the frequency with which it is required to change taps and the size and importance of the transformer.

Transformer users require tappings for a number of reasons:

-To compensate for changes in the applied voltage on bulk supply and other system transformers.

-To compensate for regulation within the transformer and maintain the output voltage constant on the above types.

-On generator and interbus transformers to assist in the control of system VAr flows.

-To allow for compensation for factors not accurately known at the time of planning an electrical system.

-To allow for future changes in system conditions.

All the above represent sound reasons for the provision of tappings and, indeed, the use of tappings is so commonplace that most users are unlikely to consider whether or not they could dispense with them, or perhaps limit the extent of the tapping range specified. However, transformers without taps are simpler, cheaper and more reliable. The presence of tappings increases the cost and complexity of the transformer and also reduces the reliability. Whenever possible, therefore, the use of tappings should be avoided and, where this is not possible, the extent of the tapping range and the number of taps should be restricted to the minimum. The following represent some of the disadvantages of the use of tappings on transformers:

-Their use almost invariably leads to some variation of flux density in operation so that the design flux density must be lower than the optimum, to allow for the condition when it might be increased.

-The transformer impedance will vary with tap position so that system design must allow for this.

-Losses will vary with tap position, hence the cooler provided must be large enough to cater for maximum possible loss.

-There will inevitably be some conditions when parts of windings are not in use, leading to less than ideal electromagnetic balance within the transformer which in turn results in increased unbalanced forces in the event of close-up faults.

-The increased number of leads within the transformer increases complexity and possibility of internal faults.

-The tapchanger itself, particularly if of the on-load type, represents a significant source of unreliability.

2.4 Transformer tanks

The transformer tank provides the containment for the core and windings and for the dielectric fluid. It must withstand the forces imposed on it during transport. On larger transformers, it usually also provides additional structural support for the core during transport. All but the smallest transformers are impregnated with oil under vacuum: the tank acts as the vacuum vessel for this operation.

Transformer tanks are almost invariably constructed of welded boiler plate to BS 4630 although in the case of some large transformers manufactured in the UK in the 1960s, aluminium was used in order to enable these to remain within the road transport weight limitations. The tank must have a removable cover so that access can be obtained for the installation and future removal, if necessary, of core and windings. The cover is fastened by a flange around the tank, usually bolted but on occasions welded more on this aspect later usually at a high level so that it can be removed for inspection of core and windings, if required, without draining all the oil. The cover is normally the simplest of fabrications, often no more than a stiffened flat plate. It should be inclined to the horizontal at about 1° , so that it will not collect rainwater. Any stiffeners should also be arranged so that they will not collect water, either by the provision of drain holes or by forming them from channel sections with the open face downwards.

The tank is provided with an adequate number of smaller removable covers, allowing access to bushing connections, winding temperature Cts, core earthing links, off-circuit tapping links and the rear of tapping selector switches. Since the manufacturer needs to have access to these items in the works the designer ensures that adequate provision is made. All gasketed joints on the tank represent a potential source of oil leakage, so these inspection covers should be kept to a minimum. The main tank cover flange usually represents the greatest oil leakage threat, since, being of large cross-section, it tends to provide a path for leakage flux, with the resultant eddy-current heating leading to overheating and degradation of gaskets. Removable covers should be large enough to provide adequate safe access, able to withstand vacuum and pressure conditions and should also be small and light enough to enable them to be handled safely by maintenance personnel on site. This latter requirement usually means that they should not exceed 25 kg in weight.

Tanks which are required to withstand vacuum must be subjected to a type test to prove the design capability. This usually involves subjecting the first tank of any new design, when empty of oil, to a specified vacuum and measuring the permanent deformation remaining after the vacuum has been released. The degree of vacuum applied usually depends on the voltage class which will determine the vacuum necessary when the tank is used as an impregnation vessel. Up to and including 132 kV transformer tanks, a vacuum equivalent to 330 mbar absolute pressure is usually specified and for higher voltage transformers the vacuum should be 25 mbar absolute.

The welding of transformer tanks does not demand any sophisticated processes but it is nevertheless important to ensure that those welds associated with the tank-lifting lugs are of good quality. These are usually crack tested, either ultrasonically or with dye penetrant. Tanks must also be given an adequate test for oil tightness during manufacture. Good practice is to fill with white spirit or some other fairly penetrating low-viscosity liquid and apply a pressure of about 700 mbar, or the normal pressure plus 350 mbar, whichever is the greater, for 24 hours. This must be contained without any leakage.

3 Degradation processes in oil-paper insulated transformers.

3.1 Insulation.

It is hardly necessary to emphasize the importance of a reliable insulation system to the modern power transformer. Internal insulation failures are invariably the most serious and costly of transformer problems. High short-circuit power levels on today's electrical networks ensure that the breakdown of transformer insulation will almost always result in major damage to the transformer. However, consequential losses such as the non-availability of a large generating unit can often be far more costly and wide reaching than the damage to the transformer itself.

Today's transformers are almost entirely oil filled, but early transformers used asbestos, cotton and low-grade pressboard in air. The introduction of shellac insulated paper at the turn of the century represented a tremendous step forward. It soon became the case, however, that air and shellac-impregnated paper could not match the thermal capabilities of the newly developed oil-filled transformers. These utilised kraft paper and pressboard insulation systems supplemented from about 1915 by insulating cylinders formed from phenol-formaldehyde resin impregnated kraft paper, or Bakelised paper, to give it its proprietary name. Usually referred to as s.r.b.p. (synthetic resin-bonded paper), this material continued to be widely used in most transformers until the 1960s and still finds many uses in transformers, usually in locations having lower electrical stress but where high mechanical strength is important.

Kraft paper

Paper is among the cheapest and best electrical insulation material known. Electrical papers must meet certain physical and chemical standards; in addition they must meet specifications for electrical properties. Electrical properties are, in general, dependent on the physical and chemical properties of the paper. The important electrical properties are:

- high dielectric strength;
- dielectric constant in oil-filled transformers as close as possible a match to that of oil;
- low power factor (dielectric loss);
- freedom from conducting particles.

The dielectric constant for kraft paper is about 4.4 and for transformer oil the figure is approximately 2.2. In a system of insulation consisting of different materials in series, these share the stress in inverse proportion to their dielectric constants, so that, for example, in the high-to-low barrier system of a transformer, the stress in the oil will be twice that in the paper (or pressboard). The transformer designer would like to see the dielectric constant of the paper nearer to that of the oil so the paper and oil more nearly share the stress.

Pressboard.

At its most simple, pressboard represents nothing more than thick insulation paper made by laying up a number of layers of paper at the wet stage of manufacture. Of necessity this must become a batch process rather than the continuous one used for paper, otherwise the process is very similar to that used for paper. As many thin layers as are necessary to provide the required thickness are wet laminated without a bonding agent. Pressboard can, however, be split into two basic categories:

- That built up purely from paper layers in the wet state without any bondingagent, as described above.
- That built up, usually to a greater thickness, by bonding individual boards using a suitable adhesive.

Pressboard in the first of the above categories is available in thicknesses up to 8 mm and is generally used at thicknesses of around 2 3 mm for interwinding wraps and end insulation and 4.5 6 mm for strips. The material is usually produced in three subcategories.

The first is known as calendered pressboard and undergoes an initial pressing operation at about 55% water content. Drying by means of heat without pressure then follows to take the moisture level to about 5%. The pressboard thus produced has a density of about 0.90 1.00. Further compression is then applied under heavy calenders to take the density to between 1.15 and 1.30.

The second category is mouldable pressboard which receives little or no pressing after the forming process. This is dried using heat only to a moisture content of about 5% and has a density of about 0.90. The result is a soft pressboard with good oil absorption capabilities which is capable of being shaped to some degree to meet the physical requirements of particular applications.

The third material is precompressed pressboard. Dehydration, compression and drying are performed in hot presses direct from the wet stage. This has the effect of bonding the fibres to produce a strong, stable, stress-free material of density about 1.25 which will retain its shape and dimensions throughout the stages of transformer manufacture and the thermal cycling in oil under service conditions to a far better degree than the two boards previously described. Because of this high-stability precompressed material is now the preferred pressboard of most transformer manufacturers for most applications. Laminated pressboard starts at around 10 mm thickness and is available in thicknesses up to 50 mm or more. The material before lamination may be of any of the categories of unlaminated material described above but generally precompressed pressboard is preferred. This board is used for winding support platforms, winding end support blocks and distance pieces as well as cleats for securing and supporting leads.

3.2 Transformer oils.

For both the designer and the user of an oil-filled transformer it can be of value to have some understanding of the composition and the properties of the transformer oil and an appreciation of the ways in which these enable it to perform its dual functions of providing cooling and insulation within the transformer. Such an understanding can greatly assist in obtaining optimum performance from the transformer throughout its operating life. Transformer oil has a dual role. It is appropriate to look a little more closely at each of these aspects.

Oil as a coolant

In discussion of the other basic materials, iron and copper, mention has already been made of the energy losses which their use entails. These, of course, manifest themselves in the form of heat. This results in a rise in temperature of the system, be it core and windings, core frames, tank, or other ancillary parts. These will reach an equilibrium when the heat is being taken away as fast as it is being produced. For the great majority of transformers, this limiting temperature is set by the use of paper insulation, which, if it is to have an acceptable working life, must be limited to somewhere in the region of 100° C. Efficient cooling is therefore essential, and for all but the smallest transformers, this is best provided by a liquid.

For most transformers mineral oil is the most efficient medium for absorbing heat from the core and the windings and transmitting it, sometimes aided by forced circulation, to the naturally or artificially cooled outer surfaces of the transformer. The heat capacity, or specific heat, and the thermal conductivity of the oil have an important influence on the rate of heat transfer.

Oil as an insulator

In most electrical equipment there are a number of different parts at different electrical potentials and there is a need to insulate these from each other. If this equipment is to be made as economically as possible the separation between these different parts must be reduced as much as possible, which means that the equipment must be able to operate at as high an electrical stress as possible. In addition, transformers are often required to operate for short periods above their rated voltage or to withstand system transients due to switching or to lightning surges.

The oil is also required to make an important contribution to the efficiency of the solid insulation by penetrating into and filling the spaces between layers of wound insulation and by impregnating, after they have been dried and deaerated by exposure to vacuum, paper and other cellulose-based insulation material. As an indication of the importance that is placed on electrical strength, it should be noted that for a long time, since the early days of oil-filled transformers, a test of electrical strength was the sole indicator of its electrical quality. Even today, when there are many more sophisticated tests, the electrical withstand test is still regarded as the most simple and convenient test for carrying out in the field.

3.3 Chemical stability

All petroleum oils are subject to attack by oxygen in the atmosphere. Transformer oil is no exception although the extent to which this takes place depends on many factors.

The subject of oxidation, the reasons why it is important to prevent this, and the ways in which this can be achieved will be discussed at some length later in this section. Selectivity in the types of oil, or more precisely, the constituents of the oil that is used, and control of the factors which affect oxidation are the most effective strategies. Three factors are most evident: temperature, availability of oxygen, and the presence of catalysts.

Oils consisting of high molecular weight hydrocarbon molecules can suffer degradation due to decomposition of these molecules into lighter more volatile fractions. This process is also accelerated by temperature. It is desirable that it should not occur at all within the normal operating temperatures reached by the plant, but it cannot be prevented at the higher temperatures generated by fault conditions.

3.4 Theory of gas evolution.

The composition of the gas produced in a fault is decided by many factors. In addition the gases which are seen in any sample taken for analysis are further influenced by factors other than those relating to the fault. The previous history of the transformer, the loading regime, the amount of insulation that it contains and the dryness of this insulation as well as the precise location of the fault are just some of these. Nevertheless, it is possible to relate certain patterns of gas evolution to temperatures existing at the fault and from a knowledge of these, along with a careful assessment of all other relevant factors, to obtain some appreciation of the nature and seriousness of the fault.

The immediate effect of the breakdown of the hydrocarbon molecules as a result of the energy of the fault is to create free radicals as indicated in Image 3.1. These subsequently recombine to produce the low molecular weight hydrocarbon gases. It is this recombination process which is largely determined by the temperature, but also influenced by other conditions.

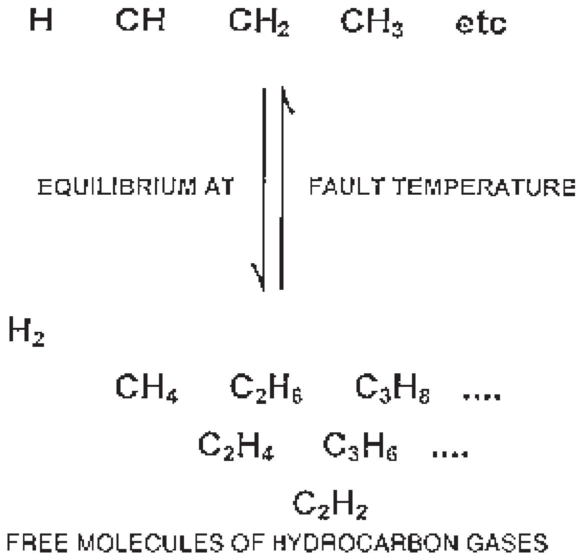


Image 3.1 Free radicals resulting from the heating of mineral oil.

The result is that the pattern of gases appearing in the oil has a form as shown in the chart of Image 3.2. For the lowest temperature faults both methane and hydrogen will be generated, with the methane being predominant. As the temperature of the fault increases ethane starts to be evolved, methane is reduced, so that the ethane/methane ratio becomes predominant. At still higher temperatures the rate of ethane evolution is reduced and ethylene production commences and soon outweighs the proportion of ethane. Finally, at very high temperatures acetylene puts in an appearance and as the temperature increases still further it becomes the most predominant gas. It will be noted that no temperature scale is indicated along the axis of Image 3.2, but the diagram has been subdivided into types of fault. The area indicated as including normal operating temperatures goes up to about 140° C, hot spots extend to around 250° C, and high-temperature thermal faults to about 1000° C. Peak ethylene evolution occurs at about 700° C.

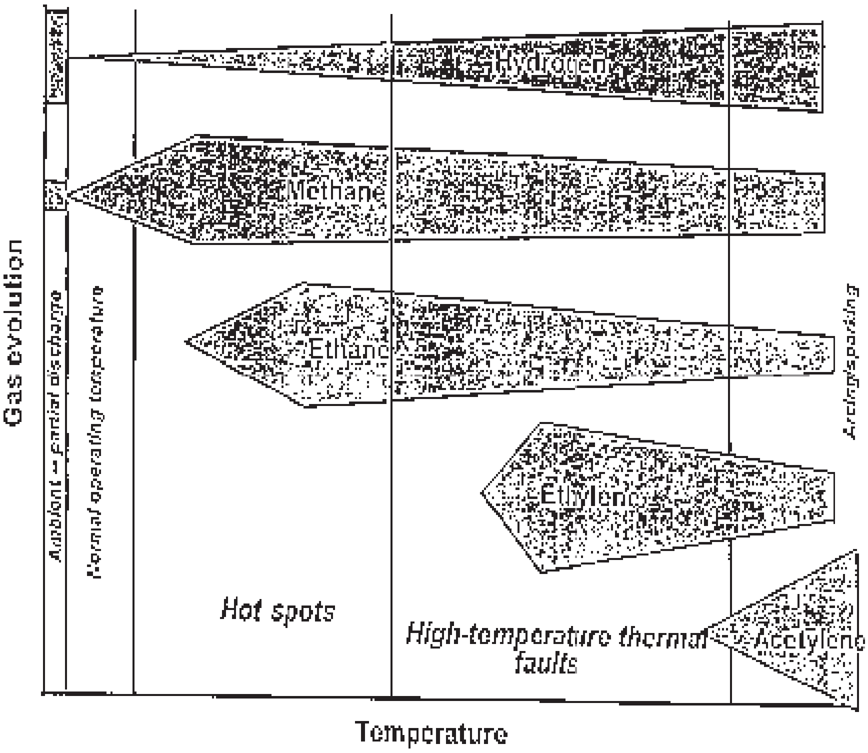


Image 3.2 Chart of hydrocarbon gas evolution in mineral oil against temperature.

3.5 Origin of Furanic Compounds in Thermal Degradation of Cellulosic Insulating Paper

The extent of chain scission of cellulosic winding insulation in electrical transformers can be determined by measuring the concentration of specific furanic degradation products in the transformer oil. The state of degradation of the paper determines its mechanical properties and hence its ability to effectively act as an insulator. Because the paper insulation is normally not accessible, sampling of the oil provides a convenient means to assess the condition of the paper. Furanic compounds from the paper can be quantified in the oil by HPLC. Image 3.3 shows those furanic compounds that are detectable in transformer oil that has been in contact with degraded cellulosic insulation. Despite much work over the last decade, the origin of these furanic compounds is still not clear. Although it is accepted that they arise exclusively from the degradation of paper insulation, their precise mechanism of formation has not been fully elucidated. For instance, it has been proposed that furans come from the pentosans (five-carbon sugars) component of Kraft paper usually used in transformers. Furthermore, a substantial body of literature points to levoglucosan (1,6-anhydro- β-D-glucopyranose) (LG), which is a product of the thermal degradation of cellulose, as the precursor of furanic compounds in polysaccharide degradation.

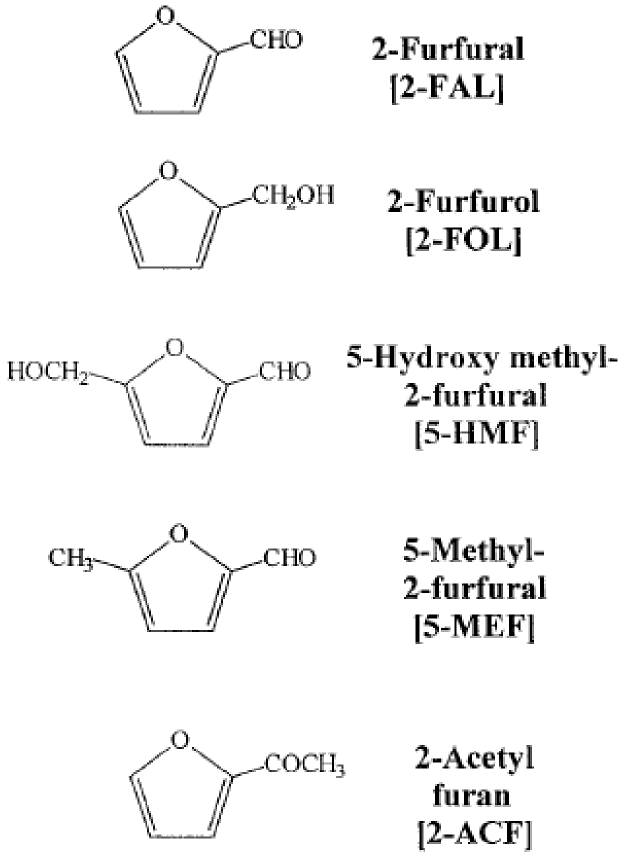


Image 3.3 Fouranic compounds detectable in transformer oil that has been in contact with aged cellulosic insulation.

It is generally recognized that the most important step in the chain scission of cellulose is the heterolytic scission of the glycosidic linkage by intramolecular transglycolysation in a manner that is analogous to acid hydrolysis. This process results in the formation of two shorter cellulose chains, one with a short-lived resonance-stabilized glucosyl cation that gives rise, via intramolecular nucleophilic attack on O_6 , to an LG end group (see Image 3.4).

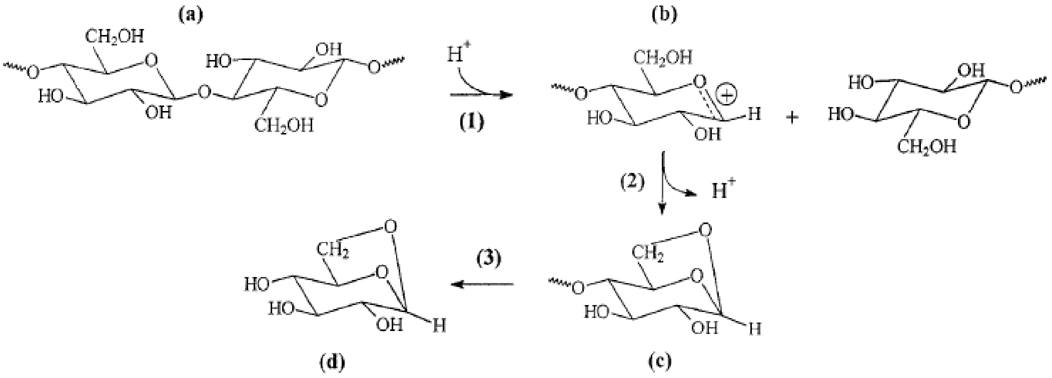


Image 3.4 (a) Formation of the (b) resonance-stabilized glucosyl cation which gives (c) an LG end group via intramolecular nucleophilic attack on O_6. The LG end group can unzip from the rest of the chain by repetition of steps 1–2 to yield (d) a molecule of LG.

Subsequently, LG formation proceeds through free chain ends; once the reaction chain is initiated, the whole chain may unzip. LG can be produced at levels up to 60% at temperatures in the vicinity of 200 C. Because high concentrations of LG are possible in cellulose during heating at moderate temperatures, LG has been viewed as a major potential source of furanic compounds, for example, via the mechanism in Image 3.5.

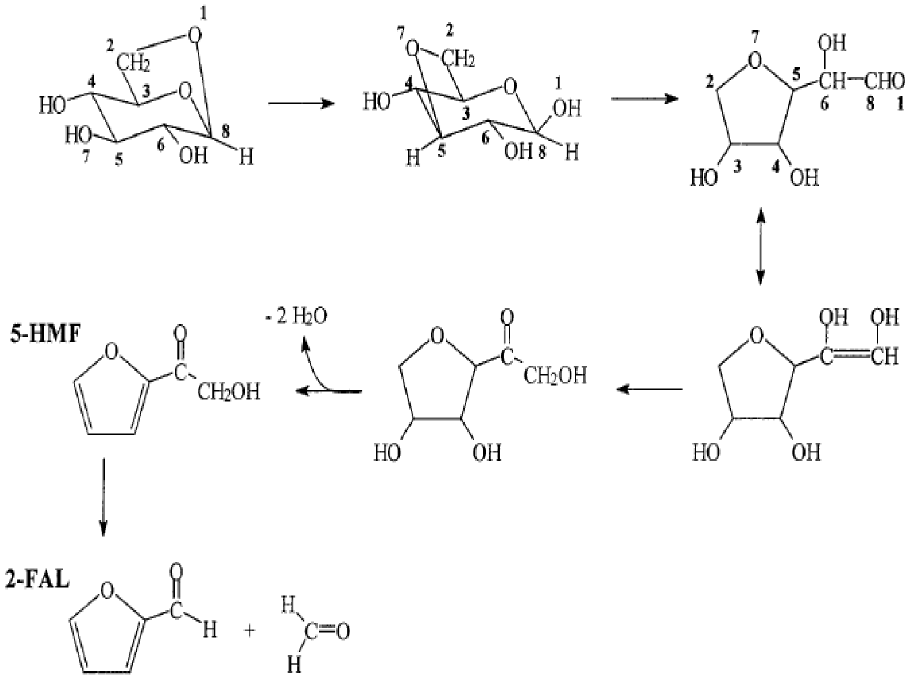


Image 3.5 Production of 5-HMF and 2-FAL from LG

Furthermore, the glucosyl cation precursor to LG can also lead to furanic compounds such as 5-hydroxymethyl-2-furfuraldehyde (5- HMF) and 2-furfural (2-FAL) by the mechanism shown in Image 3.6.

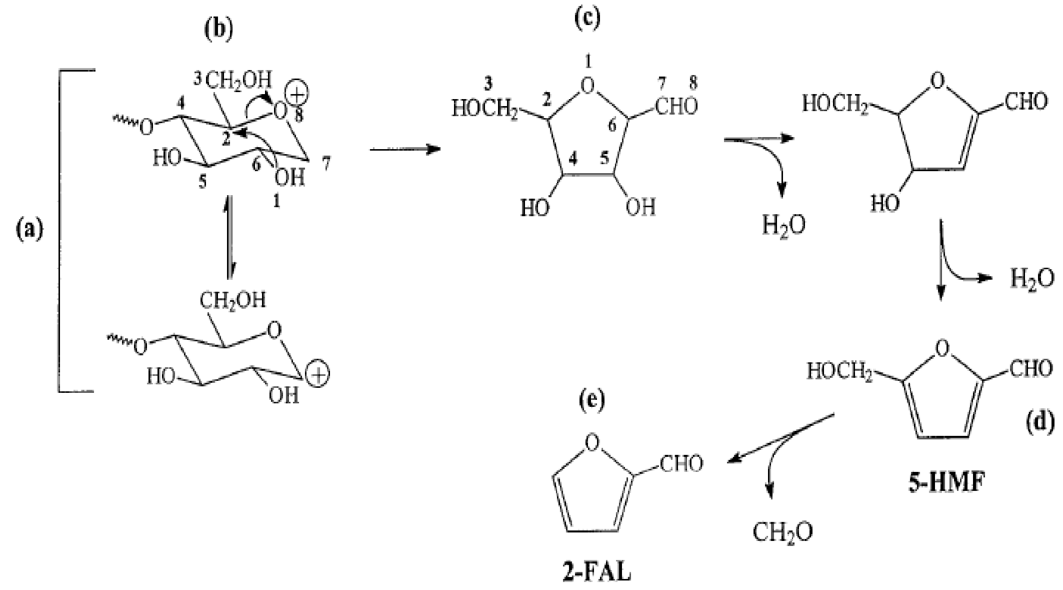


Image 3.6 Mechanism of production of 5-HMF and 2-FAL from the (a) resonance- stabilized glucosyl cation by attack of the (b) hydroxyl group on C2 onto C5 to give (c) ring contraction and the furanic precursor. Two consecutive water elimination steps give (d) 5-HMF and elimination of formaldehyde ultimately gives (e) 2-FAL.

More recently, however, a relationship has been established between the rate of furan production and the fractions of glycosidic bonds broken. This suggests that LG (which is formed by unzipping) is not involved in the main mechanism of furanic formation in Kraft paper at relatively low temperatures that are typical of transformer operation between 60 and 150 C.

A factor that makes studying the production of furanic compounds from Kraft paper difficult is that Kraft winding paper is a multicomponent product. The Kraft pulping process employed to manufacture electrical winding insulation paper reduces the lignin and hemicellulose content of wood by approximately 80 and 90%, respectively. The resultant paper, however, still contains between 3 and 7% lignin and 2 and 4% hemicellulose. In addition to these residues are metallic cations along with an absorbed moisture content in the range of 2–4 wt %. The amount and type of hemicellulose may be an important factor in the production of furanic compounds from cellulosic paper. Beating processes in paper manufacture distribute the hemicellulose throughout the pulp. Because hemicellulose is 3–10 times less thermally stable than cellulose, it is conceivable that furans may originate initially from pentoses in the hemicellulose such as xylan.

Another factor that complicates the investigation of the formation and mechanism of furanic compounds from cellulosic insulation is the influence of water. It has been known for some time that the hydrolytic degradation of cellulose can lead to the formation of furanic compounds, particularly 2-FAL. It has been observed in operating transformers that highest rates of furfural production occur when moisture in the transformer is allowed to accumulate. This suggests that hydrolysis reactions are important for the production of furanics at low temperatures. Indeed, has been identified 2-FAL, 5-HMF, and 5-methyl-2-furfural (5-MEF) as major products of the hydrolytic degradation of cellulose in the temperature range of 100–200 C. Although water clearly promotes furanic formation, the mechanism by which this occurs is unclear. A mechanism for hydrolytic formation of 5-HMF and 2-FAL from cellulose shown in Image 3.7

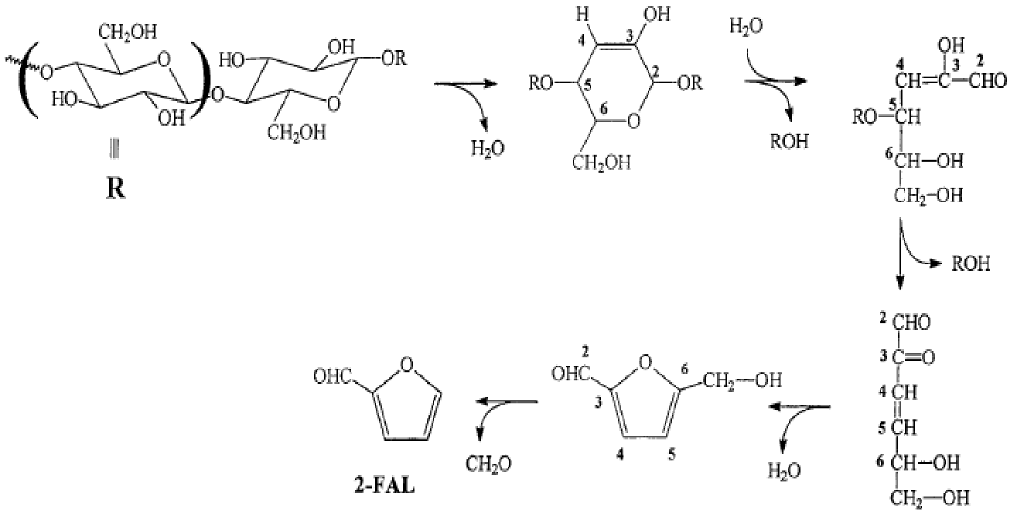


Image 3.7 Production of 5-HMF and 2-FAL from acid-catalyzed, hydrolytic thermal degradation of cellulose; R represents the cellulose chain.

4 Condition monitoring techniques

4.1 On-Line Monitoring of Liquid-Immersed Transformers

On-line monitoring of transformers and associated accessories (measuring certain parameters or conditions while energized) is an important consideration in their operation and maintenance. The justification for on-line monitoring is driven by the need to increase the availability of transformers, to facilitate the transition from time-based and operational-based maintenance to condition-based maintenance, to improve asset and life management, and to enhance failure-cause analysis.

Benefits

Various issues must be considered when determining whether or not the installation of an on-line monitoring system is appropriate. Prior to the installation of on-line monitoring equipment, cost-benefit and risk-benefit analyses are typically performed in order to determine the value of the monitoring system as applied to a particular transformer. For example, for an aging transformer, especially with critical functions, on-line monitoring of certain key parameters is appropriate and valuable. Monitoring equipment can also be justified for transformers with certain types of load tap changers that have a history of coking or other types of problems, or for transformers with symptoms of certain types of problems such as overheating, partial discharge, excessive aging, bushing problems, etc. However, for transformers that are operated normally without any overloading and have acceptable routine maintenance and dissolved gas analysis (DGA) test results, monitoring can probably not be justified economically.

Categories

Both direct and strategic benefits can arise from the installation of on-line monitoring equipment. Direct benefits are cost-savings benefits obtained strictly from changing maintenance activities. They include reducing expenses by reducing the frequency of equipment inspections and by reducing or delaying active interventions (repair, replacement, etc.) on the equipment. Strategic benefits are based on the ability to prevent (or mitigate) failures or to avoid catastrophe. These benefits can be substantial, since failures can be very damaging and costly. Benefits in this category include better safety (preventing injuries to workers or the public in the event of catastrophic failure), protection of the equipment, and avoiding the potentially large impact caused by system instability, loss of load, environmental cleanup, etc.

4.2 Direct benefits

Maintenance Benefits

Maintenance benefits represent resources saved in maintenance activities by the application of on-line monitoring as a predictive maintenance technique. On-line monitoring can mitigate or eliminate the need for manual time-based or operation-based inspections by identifying problems early and allowing corrective actions to be implemented.

Equipment Usage Benefits

Equipment usage benefits arise because additional reinforcement capacity may be deferred because on- line monitoring and diagnostics allow more effective utilization of existing equipment. On-line monitoring equipment can continuously provide real-time capability limits, both operationally and in terms of equipment life.

4.3 Strategic Benefits

Strategic benefits are those that accrue when the results of system failures can be mitigated, reduced, or eliminated. A key feature of on-line monitoring technology is its ability to anticipate and forestall catastrophic failures. The value of the technology is its ability to lessen the frequency of such failures.

Service Reestablishment Benefits

Service reestablishment benefits represent the reduced need for repair and/or replacement of damaged equipment because on-line monitoring has been able to identify a component failure in time for planned corrective action. Unscheduled repairs can be very costly in terms of equipment damage and its potential impact on worker safety and public relations.

System Operations Benefits

System operations benefits represent the avoidance of operational adjustments to the power system as a result of having identified the component failure prior to a general failure. System adjustments, in the face of a delivery-system breakdown, can range from negligible to significant. An example of a negligible adjustment is when the failure is in a noncritical part of the network and adequate redundancy exists. Significant adjustments are necessary if the failure causes large, baseload generation to experience a forced outage, or if contractual obligations to independent generators cannot be met. These benefits are driven in part by the duration of the resulting circuit outage.

Outage Benefits

Outage benefits represent the impact of component failure and resulting system breakdown on end-use customers. A utility incurs direct revenue losses as a result of a system or component failure. A utility's customers, in turn, may also experience losses during failures. The magnitude and/or frequency of such losses may result in the customer's loss of significant revenues.

4.4 On-Line Monitoring Systems

The characteristics of transformer on-line monitoring equipment can vary, depending on the number of parameters that are monitored and the desired accessibility of the data. An on-line monitoring system typically records data at regular intervals and initiates alarms and reports when preset limits are exceeded. The equipment required for an on-line transformer monitoring system consists of sensors, data-acquisition units (DAU), and a computer connected with a communications link.

Sensors

Sensors measure electrical, chemical, and physical signals. Standard sensor output signal levels are 4 to 20 mA, 0 to 1 mA, and 0 to 10 V when an analog representation is used. The sensors can be directly connected to the data acquisition unit(s). Another category of sensors communicates in serial format, as is characteristic of those implemented within intelligent electronic devices (IED).

Information/data about a function or status that is being monitored is captured by a sensor that can be attached directly to the transformer or within the control house. Once captured, the data are transferred to a data-acquisition unit (DAU) that can also be attached to the transformer or located elsewhere in the substation. The transfer is triggered by a predefined event such as a motor operation, a signal reaching a threshold, or the changing state of a contact. The transfer can also be initiated by a time-based schedule such as an hourly measurement of the power factor of a bushing, or any other such quantity.

The method of data collection depends on the characteristics of the on-line monitoring system. A common characteristic of all systems is the need to move information/data from the sensor level to the user. The following represent examples of possible components in a data-collection system.

Data-Acquisition Units

A data-acquisition unit collects signals from one or more sensors and performs signal conditioning and analog-to-digital conversions. The DAU also provides electrical isolation and insulation between the measured output signals and the DAU electronics. For example, a trigger could cause the DAU to start recording, store information about the event, and send it to a substation computer.

DAU-to-Computer Communications Line

The data-collection process usually involves transferring the data to a computer. The computer could be located within the DAU, elsewhere in the substation, or off-site. The data can be transferred via a variety of communications networks such as permanent direct connection, manual direct connection, local-area networks (LAN), or wide-area networks (WAN).

Computer

At the computer, information is held resident for additional analysis. The computer may be an integral part of the DAU, or it may be located separately in the station. The computer is based on standard technology. From a platform point of view, software functions of the substation computer program include support of the computer, the users, communications systems, storage of data, and communications with users or other systems, such as supervisory control and data acquisition (SCADA). The computer manages the DAUs and acts as the data and communications server to the user-interface software. The computer facilitates expert-system diagnostics and contains the basic platform for data acquisition and storage.

Data Processing

The first step in data processing is the extraction of sensor data. Some types of data can be used in the form in which it is acquired, while other types of data need to be processed further. For example, a transformer’s top-oil temperature can be directly used, while a bushing’s sum current waveform requires additional processing to calculate the fundamental frequency (50 or 60 Hz) phasor. The data are then compared with various reference values such as limits, nameplate values, and other measurements, depending on the user’s application.

In situations where reference data are not available, a learning period may be used to generate a baseline for comparison. Data are accumulated during a specified period of time, and statistical evaluation is used to either accept or reject the data. In some applications, the rejected data are still saved, but they are not used in the calculation of the initial benchmark. In other applications, the initial benchmark is determined using only the accepted data.

The next data-processing step is to determine if variations suggest actual apparatus problems or if they are due to ambient fluctuations (such as weather effects), power-system variables, or other effects. A combination of signal-processing techniques and/or the correlation of the information obtained from measurements from locations on the same bus can be used to eliminate both the power-system effects and temperature influences.

The next step in processing depends on the sophistication of the monitoring system. However, the data generally need to be interpreted, with the resulting information communicated to the user. One common approach is to compare the measured parameter with the previous measurement. If the value has not changed significantly, then no data are recorded, saved, or transmitted.

4.5 Diagnostic techniques for assessing insulation condition in aged transformers

The insulation system of a power transformer consists mostly of hydrocarbon oil and paper. Many of these power transformers within electric utilities around the world are approaching the end of their design life. Insulation degradation is a major concern for these aged transformers. Insulation materials in transformers degrade at higher operating temperatures in the presence of oxygen and moisture. Practicing engineers currently use a number of modern diagnostic techniques to assess the insulation condition of aged transformers. Among them moisture analysis in transformer oil, dissolved gas analysis , degree of polymerization . Measurement and furan analysis by high performance liquid chromatography are frequently used.

Molecular weight studies by single point viscosity measurements are of limited value when dealing with a complex polymer blend such as Kraft paper as used in transformers , particularly in cases where the molecular weight distribution of the paper changes significantly as the degradation proceeds. In these instances, a new technique, gel permeation chromatography is found to be more useful than the viscosity method, because it provides information about the change in molecular weight and molecular weight distribution. A variety of information can be obtained from the X-ray photo-electron spectroscopy, which includes chemical state information, elemental information, and variation of composition with depth, variation of chemical composition spatially on the surface and thickness of layers. Oxidation changes the colour of the oil and this colour change can be monitored by the change in absorbance of the oil. This can commonly be examined by UV visible spectroscopy. The results from these experiments have been presented in reference. Fourier transform infrared and near- infrared spectroscopy have been used to characterize the ageing of cellulosic paper, with the long term aim of developing a technique to assess the condition of paper insulation in electrical transformers.

In recent years, new diagnostic methods have been promoted that are complementary to the classical insulation resistance, power frequency dissipation factor and polarization index measurements. This is significantly due to the availability of modern computer controlled instrumentation. These new methods are based on either time or frequency domain polarization measurements. In frequency domain measurement, a sinusoidal voltage is applied and the complex dielectric constant is determined from the amplitude and phase of the current flowing through the sample. On the other hand, time domain measurements are conducted by the application of a step voltage across the insulation object. Time domain measurements based on polarization depolarization current measurement and return voltage measurement have gained significant importance over the last ten years. Particularly, there has been growing interest in the condition assessment of transformer insulation by the return voltage method.

Moisture analysis

Water content in insulation materials increases electric conductivity and dissipation factor and reduces electric strength. It has been a common practice to measure the moisture content in oil by the Karl Fischer titration method and then estimate the moisture in solid insulation by different equilibrium curves. A thin film capacitive humidity sensor was tested for moisture sensing in transformer oil by Oomen. This sensor was found to respond well for oil in transformer in cold and warm weather conditions. Neimanis investigated the near infrared spectroscopy(NIR) for the determination of moisture content in oil impregnated paper . Their results showed that NIR spectroscopy along with their developed multivariate modeling could result accurate estimation of moisture. Gupta reported the effectiveness of NIR spectroscopy technique to detect very small changes in moisture content of paper insulation. A number of polarization based dielectric diagnostic techniques are also currently in use for indirect moisture analysis of oil-paper insulation system .

DISSOLVED GAS ANALYSIS (DGA)

Among chemical techniques, dissolved gas analysis has gained worldwide acceptance as a diagnostic method for the detection of incipient faults. Fault gases are produced by degradation of the transformer oil and solid insulating materials such as paper, pressboard and transformer board, which are all made of cellulose. The rate of cellulose and oil degradation is significantly increased in the presence of a fault inside the transformer. The important gases produced from the transformer operation can be listed as follows:

-Hydrocarbon gases and hydrogen: methane , ethane, ethylene, acetylene, and hydrogen.

-Carbon oxides: carbon monoxide and carbon dioxide.

-Nonfault gases: nitrogen and oxygen.

A healthy transformer should have less than 0.05 ml of combustible gases (hydrogen and short chain hydrocarbons: methane, ethane, ethylene, acetylene) per 100 ml of oil and insignificant levels of higher hydrocarbon gases. Measurements on free breathing transformers show average CO+CO(2) levels of 0.4 ml/100 ml of oil after 15 years. Normally causes of fault gases are classified into three categories:

-Corona or partial discharge

-Thermal heating

-Arcing.

It is commonly accepted that hydrogen gas is produced from the corona effect on oil and cellulose. Methane and ethane are produced from low temperature thermal heating of oil and high temperature thermal heating produces ethylene and hydrogen as well as methane and ethane. Acetylene is only produced at very high temperatures that occur in the presence of an arc. Low temperature thermal degradation of cellulose produces CO(2) and high temperature produces CO. Low energy electrical discharges produce hydrogen and methane, with small quantities of ethane and ethylene. Electrical arcing produces large amounts of hydrogen and acetylene with minor quantities of methane and ethylene. The most commonly used gas-in-oil diagnostic methods include the following:

a) IEEE C57.104-1991.

b) Doernenberg method.

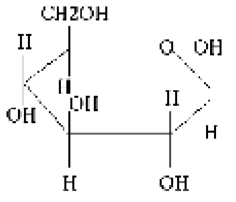
c) Rogers' method.

d)IEC 60599.

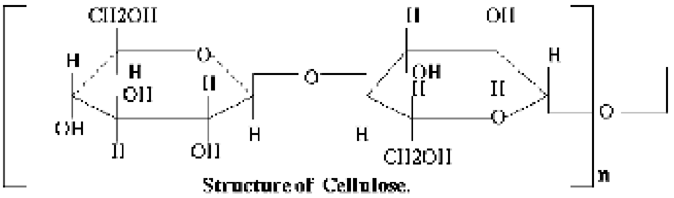
e)Duval's triangle.

Degree of polymerization measurement

The solid insulation (paper, pressboard) used in transformers is a sheet of material made from vegetable cellulose. The main source of cellulose fibre is wood. In a dry condition, wood contains 40 to 50% cellulose, 20 to 30% lignin and 10 to 30% hemicellulose and polysaccharides. Cellulose is a linear polymer composed of individual anhydrous glucose units linked at the first and fourth carbon atoms through a glucosidic bond. The structure of glucose and cellulose is shown in Image 3.3. The good mechanical properties of cellulose and its derivatives, on which their utility depends, are due to their polymeric and fibrous nature. The number of monomer units in the polymer is known as degree of polymerization(DP).



Structure of Glucose.



Structure of Cellulose.

Image 3.3 Structure of glucose and cellulose.

Very often, the quality of the cellulose is measured in terms of its degree of polymerization by the average viscometric method. The length of the cellulose chain thus measured by the average degree of polymerization based on viscosity method will be denoted by DPV.

DPV measurement has been used as a diagnostic tool to determine the condition of transformers by several workers. New Kraft paper has an average chain length of 1000 to 1500. After a long period of service at high temperature with high content of water and oxygen, the paper becomes brittle, changes colour to dark brown and DPV falls to 200 to 250. Sometimes cotton is used as an insulating material. Cotton fibre lengths are greater than those of unbleached soft wood sulphate cellulose, but their diameter is smaller. The average degree of polymerization for new cotton is higher than Kraft paper. For Kraft paper with a DPV of 150 to 200 the mechanical strength of paper can be reduced to 20% of its initial strength and this point is regarded as the end of life criterion for transformer insulation. According to reference at DPV from 900 to 500, the strength of the paper is virtually constant but, in the range 500 to 200, it decreases in direct proportion to DPV.

Furan analysis by high performance liquid chromatography.

Furans are major degradation products of cellulose insulation paper and are found in the insulation oils of operational transformers. Furan analysis offers a more convenient method of analysis than direct measurement on insulation paper. Shroff and Stannett reported on the formation of 2-furfuraldehyde from the degradation of cellulosic insulation papers in accelerated ageing experiments and found that an approximately logarithmic relationship existed between the concentration of 2-furfuraldehyde in the oil and the degree of polymerization of the cellulose in the paper. Burton made an extensive study and measured the rate of furan formation of several furan products over a wide range of temperatures (120- 350 C). They also found an approximately logarithmic relationship between the concentration of 2-furfuraldehyde and the DPV of the paper. Unsworth and Mitchell used HPLC technique to monitor the formation of furan components during ageing of cellulose insulation paper at 20, 80 and 110 C. They correlated their results for the tensile strength of the paper with the concentration of 2-furfuraldehyde and observed that the decrease in the tensile strength of the paper corresponded to an increase in the concentration of the furans in the oil. Hill developed a kinetic model and found that the concentration of furans in the transformer oil should increase in a parabolic form with degradation time.

They also reported that 5-hydroxy methyl-2-furfuraldehyde (HMF) and 2-furfuraldehyde (F) are present in the oil at significantly greater concentrations than any other furan components. Furfuraldehyde is the furan present in greatest amounts. This study also found that the rate of HMF formation is faster with an increase in temperature than the rate of F formation.

New chemical techniques

During ageing, the surface of the paper which is in direct contact with the transformer oil undergoes a colour change and becomes darker. This is particularly evident in the case of the samples aged in air. In order to identify the nature of the changes which are responsible for the change in colour, the paper samples were subjected to analysis by X-ray Photo-electron Spectroscopy, XPS. An analysis of the oxygen and carbon peaks indicates that there are significant concentrations of doubly bonded carbons and oxygen present in the surface of the air aged samples, which probably arise from oxidation products from the oil being attracted to the polar cellulosic surface of the paper. The presence of the hydrocarbon on the surface of the paper even after extensive washing of the paper with the solvent suggests that the hydrocarbon degradation products from the oil are chemically bound to the surface. If this is so, then they are also unlikely to be removed by treatment with hot kerosene (used in the vapour cleaning technique).

During accelerated ageing in an air environment the oil obviously became oxidised and turned brown in colour. However, during the corresponding studies in a nitrogen environment there was no obvious change in the colour of the oil. To monitor any changes, the absorbance of the oil was examined by UV-visible spectroscopy for the samples aged at 145 C w54x. The absorption spectrum is characterized by a strong absorption peak in the region below 400 nm, with a long absorption tail extending into the visible region which is responsible for the brown colour. The spectrum is typical of that observed for species containing a sequence of conjugated double bonds or aromatic groups. There was no evidence of the formation of significant concentrations of the absorbing species for the samples aged under nitrogen. A sample of oil aged in air in the presence of atmospheric moisture, but in the absence of paper or copper also turned brown, showing that the paper and the copper are not responsible for the formation of the absorbing species and that it arises solely from the oxidation of the oil.

Electrical diagnostic methods.

It is often assumed that when the cellulose insulation ages in a transformer the dielectric properties (dissipation factor at power frequency and breakdown strengths at both power frequency and lightning impulse) do not change drastically. Based on this general assumption, very little systematic research had been undertaken in the area of electrical diagnostic techniques for condition monitoring or for studying the degradation of electrical insulation in power transformers until 1990. Although insulation resistance and polarization index (ratio of 10 minute insulation resistance to 1 minute insulation resistance) have been used by the electricity utilities for a long time to ascertain the transformer moisture condition. Partial discharge is an electrical phenomenon that occurs inside a transformer and the magnitude of such discharges can cause progressive deterioration and sometime may lead to insu-

hydrocarbon on the surface of the paper even after extenlation failure. There are vast numbers of papers available on PD processes, PD patterns and fault mechanisms and are beyond the scope of this paper. A number of researchers have worked on the measurement of dielectric strength of pressboard and paper with different wave shapes (power frequency or lightning impulse or switching impulse or combinations of these). However, in recent years new diagnostic methods have been promoted complementary to the classical insulation resistance, power frequency dissipation factor and polarization index measurements.

Recovery Voltage Method (RVM)

If the DGA analysis is performed correctly (proper sampling, storage and calibration), most of the incipient faults in the oil may be detected. The paper insulation is responsible for containing most of the moisture due to ageing and thermal stress. The paper insulation may fail under high electrical stress or may release moisture into the oil insulation. To detect ageing or moisture content it is necessary to analyze low frequency part of polarization spectrum of dissipation factor. A tanδ would have been sufficient but finding a sinusoidal source voltage of 0.001 Hz is very difficult. The alternative is the recovery voltage measurement.

It was found that IR & PI do not reflect complete information on polarization process. Cases were reported where electrical motors having good PI were found to have contaminated windings and also motors having poor PI had no problems in the winding insulation. To resolve this, an one thousand seconds charging and discharging test (DC absorption) was developed. Recovery Voltage Method for transformer seems to be developed from this test.

In RVM, winding is charged for known time and then shorted to ground for pre-decided time. The recovery voltage is then measured and dominant time constant is achieved which is essentially a polarization time constant.

Charging current is given as the sum of displacement current, the polarization current and the conduction current. Polarising current is dependent on material property and state of ageing. The polarization of dielectric can be expressed as sum of various slow polarization phenomena like ion migration, slow relaxation and interfacial polarization. Care must be taken in the interpretation of results of RVM, in particular the relative effects of moisture, genuine ageing and temperature.

5 Maintenance and testing of power transformers

5.1 Test Procedures

The present maintenance trend is to reduce cost, which in some cases means lengthening the intervals of time to do maintenance or eliminating the maintenance completely. The utility, or company, realizes some savings on manpower and material by lengthening the maintenances cycle, but by doing this, the risk factor is increased. A few thousand dollars for a maintenance program could save your utility or company a half-million dollar transformer.

Utility companies have enormous amounts of money invested in transformers of all types, including distribution and power transformers. Utilities also have a long history and have developed methods, procedures, and philosophies that over time have proven very effective in prolonging equipment life. These are collectively referred to as good utility practices and it is instructive to review these practices as applied to power transformers.

Core Ground Test

The core ground test (performed on core form units only) determines the presence of unintentional ground on the transformer core by checking the core ground insulation resistance using a 1000 V megger with the factory core ground disconnected. Test values corrected to 20°C should be 25 MΩ or greater.

Transformer Turns Ratio (TTR) Test

The TTR test measures the turns ratio of the windings and detects open- circuited and short-circuited turns.

- For proper connections to transformers, refer to TTR test set instruction book.

- Perform test on all tap positions.

- Set transformer on tap to be used and retest. Results on each tap should be within 0.5% of the theoretical turns ratio.

Theoretical ration =HV coil rating / LV coil rating

- If satisfactory TTR test results cannot be obtained on all phases, not only the phase or phases that are unsatisfactory, note either of the following:

High exciting current and low voltage on TTR test set (indicative of a short circuit on one of the windings) Normal exciting current and normal voltage but no galvanometer deflection on TTR test set (indicative of an open circuit) .

- Record test results on TTR Test Results form.

Doble Test

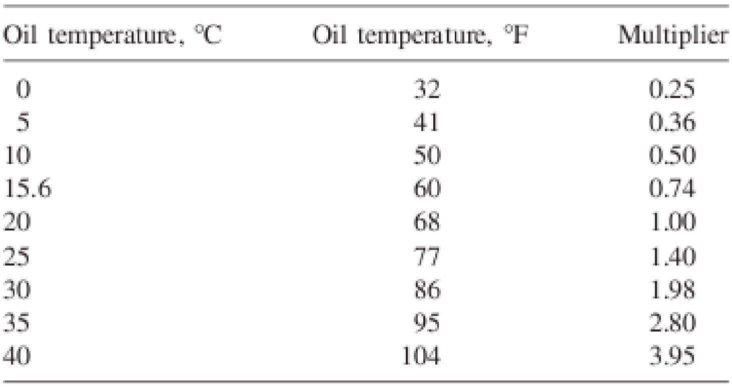
The Doble test is performed on transformer windings and bushings by an Insulation Technician. The test is a relative measure of the condition of the insulation. The Insulation Technician will make recommendations.

Megger Test

The megger test is a measure of the insulation resistance. Remove solid connections of windings to ground. The following tests are made using a 1000 V megger:

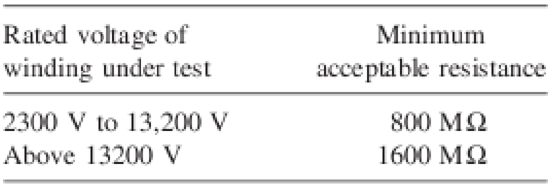
- Measure from the high-voltage winding to the low-voltage winding and ground. (Low-voltage winding is grounded.) H-LG
- Measure from the low-voltage winding to the high-voltage winding and ground. (High-voltage winding is grounded.) L-HG
- Measure from the high- and low-voltage windings to ground. HL-G
- Megger readings are temperature dependent. Correct all the above readings to 20°C by multiplying the megger readings by the multipliers shown in Table 5.1.
- The readings for the H-LG, L-HG, and HL-G tests should be comparable to prior megger readings, with all readings corrected to 20°C (68°F).
- If previous readings are not available, the minimum acceptable resistance for each reading is per Table 5.2.
- Record megger readings on Megger Test Results form.

Table 5.1 Temperature Correction Multipliers for Insulation Resistance Measurements



Oil temperature, °C	Oil temperature, °F	Multiplier
0	32	0.25
5	41	0.36
10	50	0.50
15.6	60	0.74
20	68	1.00
25	77	1.40
30	86	1.98
35	95	2.80
40	104	3.95

Table 5.2 Insulation Resistance Limits



Rated voltage of winding under test	Minimum acceptable resistance
2300 V to 13,200 V	800 MΩ
Above 13200 V	1600 MΩ

Oil Tests

To prevent air from being drawn into transformers with sealed-tank or gas-oil-seal designs, make sure the gas space above the oil is at a positive pressure before opening the drain valve.

For all transformers, perform oil dielectric and acidity tests. Refer to instruction: Insulating Oil: Using, Handling, Sampling, and Testing. Record results on Power Transformer Acceptance and Maintenance Checklist. For new and rebuilt transformers, send oil samples for additional tests to the Chemical Laboratory. A copy of the test results should be sent to Substation Component Engineering.

Oxygen Content Test

High oxygen content results in oxidation of oil, which causes sludging. The gas space in all sealed transformers is to be tested semiannually for oxygen content. Record results on Power Transformer Acceptance and Maintenance Checklist. Oxygen content should not exceed 5%. When necessary, the gas space should be purged with dry nitrogen until the oxygen content is 1% or less.

Excitation Test

This test is done with Doble equipment by the Insulation Technician, who will make recommendations.

Gas-in-Oil Analysis

Semiannually, samples of oil are to be taken for gas-in-oil analyses from all 69 kV and above power transformers and generating station transformers.

5.2 Vacuum Oil Filling

Precautions for Vacuum Oil Filling

- Apply vacuum only to transformers designed for vacuum filling. (Noted on Nameplate.)
- Never stand on top of a transformer while vacuum is applied.
- Never energize a transformer while vacuum is applied.
- Some transformers require removable vacuum bracing; consult manufacturer's instructions and drawings.
- Remove pressure relief devices and sudden pressure relays and seal openings to prevent damage or misoperation due to changes in pressure when vacuum filling.

Procedure for Vacuum Oil Filling

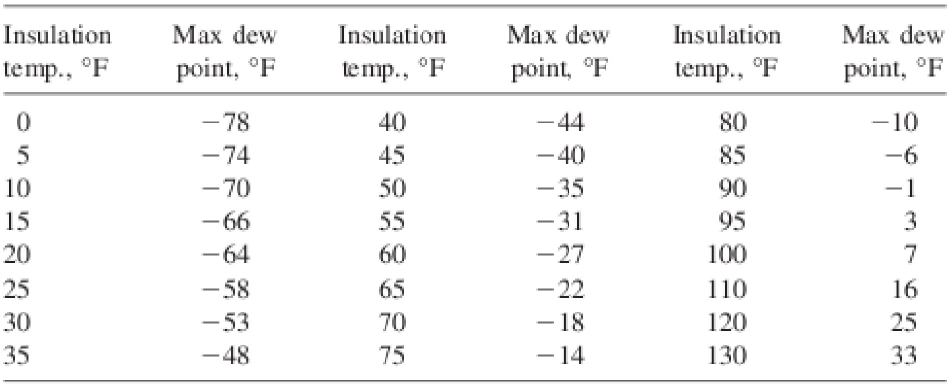
1. Remove all oil from the transformer.
2. Test new, unprocessed oil for dielectric strength using ASTM Method D877. The oil must have a minimum breakdown voltage of 30 kV.
3. After assembly, pressurize the transformer to 2 psig by adding dry nitrogen. Check the transformer for leaks.
4. For transformers rated 115 kV and above, after waiting for a 24 h period, make a dew-point check to determine the dryness of the transformer insulation. For new transformers and transformers in warranty, refer to the manufacturer's instructions for acceptable dew-point readings. For transformers not in warranty, refer to Table 5.3. If it does not pass dew-point test, a hot oil dryout is required. After dryout, repeat step 4.
5. Draw a vacuum of 2 mmHg or less. Hold this vacuum for a period of time specified in the manufacturer's instruction book, if the transformer is new or in warranty. If the transformer is not in warranty, use Table 5.4.
6. Maintaining a vacuum of 2 mmHg or less, admit oil into the top of the transformer connection. Once oil filling is started, it must not be interrupted. Oil degassing equipment is required for transformers rated 115 kV and above.
7. If the transformer is a conservator type, stop filling when oil reaches a level 2 in. below the transformer cover. If the transformer is equipped with a nitrogen bottle, stop filling when the oil level gauge is slightly over the 25°C level. This is to compensate for the transformer expanding when vacuum is broken and for oil cooling.
8. Break the vacuum with dry nitrogen. If the transformer has a conservator with air bag, or air separation membrane, add the remaining oil to the expansion tanks in accordance with the manufacturer's recommendations.
9. Bleed the air from transformer oil pump vents. Turn on all pumps and leave them running while the oil cools.
10. Allow the transformer to stand before energizing (with oil pumps running) according to the

timetable shown in Table 5.5. Run one half of the pumps for half the time and the other half of the pumps for the second half of the time.

11. Prior to energizing the transformer, check oil levels in all compartments. Pump oil into the top, if necessary, to raise the oil level to the 25°C mark.

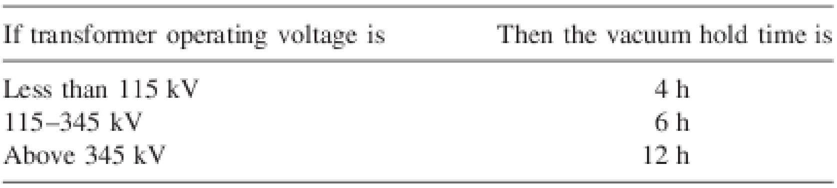
12. Prior to energizing the transformer, shut off all oil pumps and place controls on automatic so that no pumps are running prior to energizing. This is important to eliminate static electrification of the oil, which could cause an internal failure. This hold time must be a minimum of 12 h.

Table 5.3 Dew-Point Limits Based on Insulation Compartments



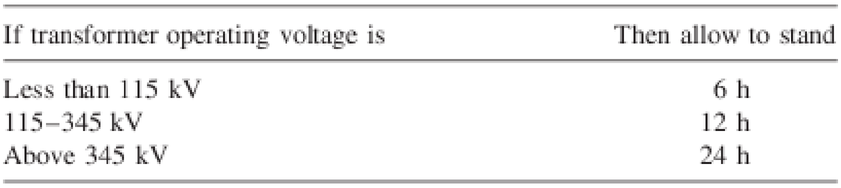
Insulation temp., °F	Max dew point, °F	Insulation temp., °F	Max dew point, °F	Insulation temp., °F	Max dew point, °F
0	−78	40	−44	80	−10
5	−74	45	−40	85	−6
10	−70	50	−35	90	−1
15	−66	55	−31	95	3
20	−64	60	−27	100	7
25	−58	65	−22	110	16
30	−53	70	−18	120	25
35	−48	75	−14	130	33

Table 5.4 Vacuum Hold Time Prior to Oil-Filling Transformer



If transformer operating voltage is	Then the vacuum hold time is
Less than 115 kV	4 h
115–345 kV	6 h
Above 345 kV	12 h

Table 5.5 Stand Time Prior to Energizing a Transformer



If transformer operating voltage is	Then allow to stand
Less than 115 kV	6 h
115–345 kV	12 h
Above 345 kV	24 h

5.3 Maintenance of Spare Transformers

Usable transformers stored as system spares shall receive the following minimum maintenance checks every 6 months except as noted. Failed units awaiting disposition require no periodic maintenance.

- Oil sample and dielectric test (check yearly)
- Nitrogen pressure
- Oil level
- Visual inspection, including check for oil leaks and rust
- Operation of control cabinet heaters

5.4 Preventative maintenance versus predictive maintenance

The aim of preventative maintenance is to keep components from aging and wearing out, or to restore and replace aged or worn components before they fail. Preventative maintenance is scheduled periodically or performed on some other timetable based on past experience of the component failure modes.

The aim of predictive maintenance, on the other hand, is to detect aging or wear in components so that preventative maintenance can be performed before ultimate failure occurs. Predictive maintenance is commonly referred to as testing. The requirements for a good test are as follows:

- The test should have sensitivity; in other words, it should give an early warning of impending trouble.
- The test should have selectivity; in other words, it should not give off false positive indications of trouble and should give a clear indication of what is wrong.
- The test should be practical; in other words, it should not require exotic test equipment or an unusually high skill level to perform the test or interpret the results.
- The test should be nondestructive.

5.5 Factory tests

Every transformer that is manufactured undergoes some form of factory testing. For power transformers, these tests are quite extensive and a certain percentage of test failures do occur. Typically around 5% of the transformers produced will fail at least one of these tests. Test requirements are spelled out in a number of industry standards and specifications.

There is some overlap among industry standards with respect to testing. In recent years ANSI/IEEE Standard C57.12.90 has been generally adopted by the other standards for testing liquid-immersed distribution, power, and regulating transformers. Some of the more significant standard factory tests specified in ANSI/IEEE Standard C57.12.90 are itemized in the following sections.

5.6 Ratio test

This test determines the ratio (TTR) of the number of turns in the high-voltage winding to that in the low-voltage winding. The ratio test shall be made at rated or lower voltage and rated or higher frequency. In the case of three- phase transformers when each phase is independent and accessible, single- phase power should be used, although three-phase power may be used when convenient. The tolerance for the ratio test is 0.5% of the winding voltages specified on the transformer nameplate.

The accepted methods for performing the ratio test are the voltmeter method, the comparison method, and the ratio bridge. With the voltmeter method, the primary winding is excited at rated frequency and the voltage at the primary and the open-circuit voltage of the secondary winding are measured. The ratio is the primary voltage divided by the secondary voltage. The comparison method applies voltage simultaneously to the transformer under test and the open-circuit secondary voltages are measured and compared.

The ratio bridge method is the most accurate method and can easily determine the TTR to the very small tolerances required by the standard. The test apparatus is commonly referred to as a TTR Test Set. One such test set is manufactured by the Biddle Company and has proven to be especially useful as a diagnostic test in the field, so its operation will be described in detail. This test set is shown in Image 5.1.

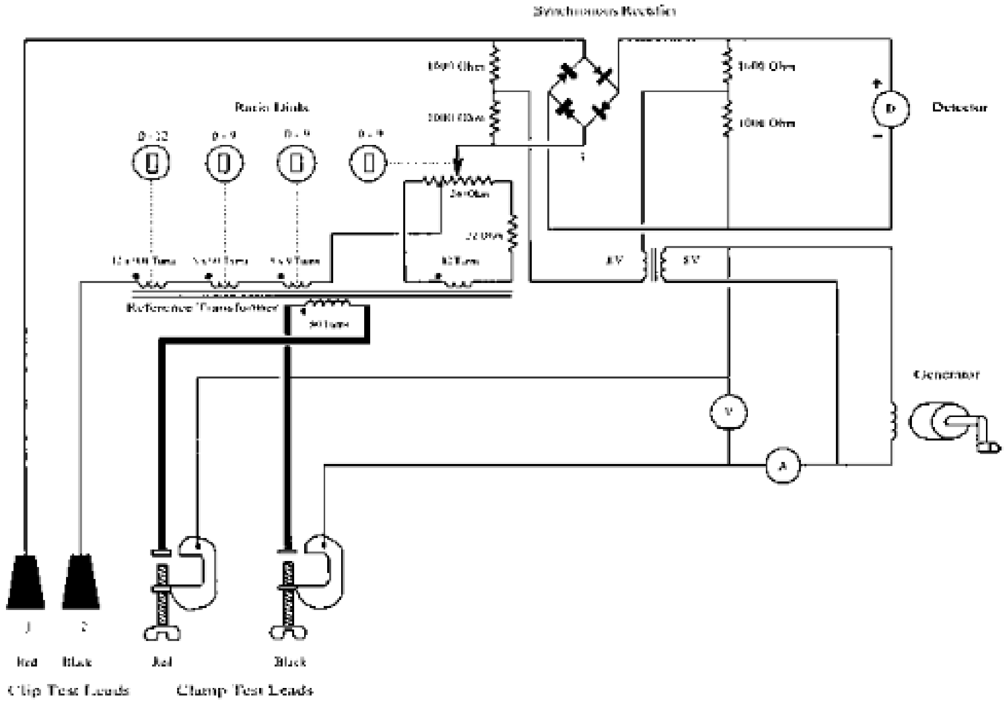


Image 5.1 Circuit diagram of a TTR test set.

The clamp test leads are connected to the secondary winding of the transformer under test and the clip leads are connected to the primary winding under test. The secondary winding of the transformer under test and the secondary of a calibrated reference transformer in the test set are both excited by the same 8 V source voltage from a hand-cranked generator. A voltmeter is used to verify that the correct voltage is being applied.

An ammeter measures the exciting current into the transformer under test. When the voltage developed across the primary of the transformer under test (1-2) is equal to the voltage developed across the primary of the calibrated reference transformer (2-3), then the voltage across the synchronous rectifier is zero and the galvanometer detector reads zero. With more voltage developed across 1-2 than across 2-3, the galvanometer has a negative deflection. With less voltage developed across 1-2 than across 2-3, the galvanometer has a positive deflection. The ratio dials are used to adjust the ratio of the reference transformer.

A simplified equivalent circuit of the TTR test set is shown in Image 5.2. The transformer under test is also shown. Note that the current through the detector, labeled “Det” in the figure, is zero when the voltages developed at the high-voltage terminals of the test-set transformer and the transformer under test are equal. This condition exists when the ratios of the test-set transformer and the transformer under test are equal.

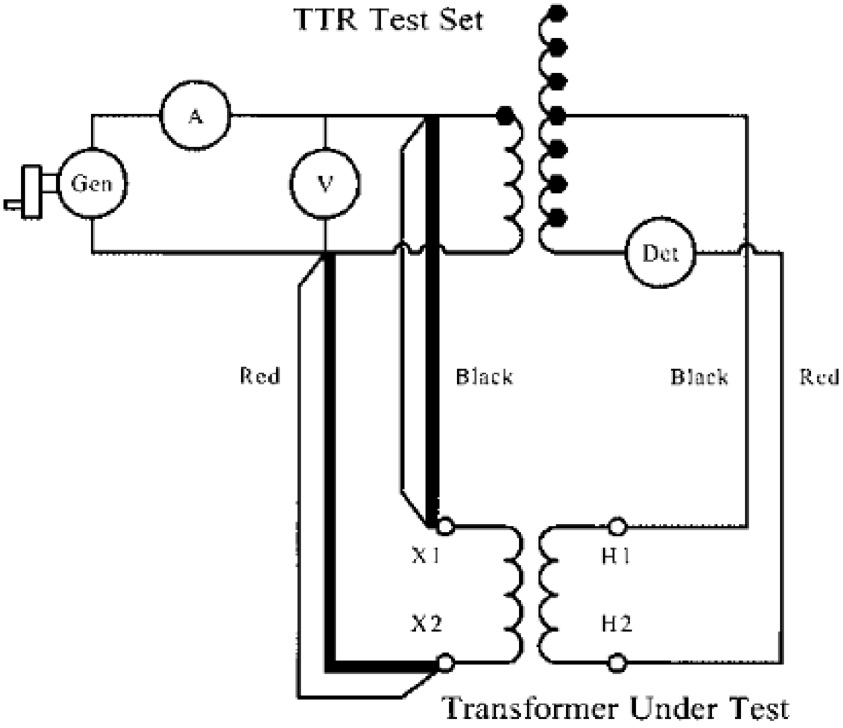


Image 5.2 Simplified circuit of a TTR test set.

5.7 Other factory tests

The remainder of the factory tests are briefly summarized below.

- No-Load Losses. The tests measures the no-load losses at specified excitation voltage and a specified frequency. Sine-wave voltages are used unless a different waveform is inherent in the operation of the transformer. The recommended method is the average-voltage voltmeter method, employing two parallel-connected voltmeters. One voltmeter is an average-responding but RMS calibrated voltmeter and the other voltmeter is a true RMS-responding voltmeter. The test voltage is adjusted to the specified value as read by the average-responding voltmeters. The readings of both voltmeters are used to correct the no-load losses to a sine-wave basis.
- No-Load Excitation Current. This current is measured in the winding used to excite the transformer with the other windings open- circuited. It is generally expressed in percent of the rated

current of the winding. No-load excitation current is not sinusoidal and contains, as we have seen, odd harmonics (predominantly third harmonic current). The ammeter used to record the no-load excitation current is an RMS meter which reads the square root of the sum of the squares of the harmonic currents.

- Load Losses and Impedance Voltage. The transformer must be in a specific state before the load losses and impedance voltage are measured. The temperature of the insulating liquid must be stabilized and the difference between the top and bottom oil temperatures shall be less than 5°C. The winding temperatures must be measured (using a resistance method) before and after the test and the average taken as the true temperature. The difference in the winding temperature before and after the test must not exceed 5°C. The two test methods for measuring load losses and impedance voltage are the wattmeter- voltmeter-ammeter method and the impedance bridge method. These tests generally apply a reduced voltage to one set of windings with the other set of windings short-circuited. For three-winding transformers, these tests are repeated for each combination of windings taken two at a time.

- Dielectric Tests. These tests consist of applied-voltage tests and induced-voltage tests. Applied-voltage tests apply a high voltage to all bushings of a winding, one winding at a time, with the other windings grounded. A 60 Hz voltage is increased gradually over 15 s and held for 40 s and reduced to zero over 5 s. Induced-voltage tests apply a high voltage across a winding with the other windings open-circuited in order to test the quality of the turn-to-turn insulation. In order to prevent core saturation at the higher excitation voltage, the frequency of the induced-voltage test is increased (typically around 120 Hz). The induced voltage is applied for 7200 cycles or 60 s, whichever is shorter.

- Switching Impulse Test. The switching impulse test applies a switching impulse wave between each high-voltage line terminal and ground. The test series consists of one reduced voltage wave (50%– 70% of specified test level) followed by two full-voltage waves. Either positive or negative polarity waves, or both, may be used. A voltage oscillogram is taken for each applied wave. The test is successful if there is no sudden collapse of voltage. Successive oscillograms may differ because of the influence of core saturation.

- Lightning Impulse Test. The test sequence consists of one reduced full wave, two chopped waves, and two full waves. Tap connections are made with the minimum effective turns in the winding under tests and regulating transformers are set to the maximum buck position. Oscillograms are taken of each wave. The general technique for interpreting the results is to look for differences in the shapes of the reduced full wave and the two full waves, which indicate turn-to- turn insulation failure. Additional test criteria are found in IEEE Std. C57.98-1993. The impulse tests probably have the highest likelihood failures among all of the factory tests that are typically performed.

- Partial Discharge Test. This test detects radio-frequency (0.85–1.15 MHz) noise generated from partial discharges within voids in the insulation. An applied voltage is gradually increased until partial discharge starts to occur, which is the inception voltage. The voltage is then decreased until the partial discharge stops, which is the extinction voltage. The extinction voltage must be less than the operating voltage of the transformer; otherwise, once partial discharge starts in the field (due to some voltage transient), it would continue indefinitely and possibly cause damage or failure.

- Insulation Power Factor. Insulation power factor is the ratio of the power dissipated in the insulation in watts to the apparent power (volt-amperes) under a sinusoidal voltage. The applied 60 Hz voltage of this test is generally lower than the operating voltage of the transformer. The Doble Test Set is designed specifically to carry out this test. Portable versions are used to measure the insulation power factor of transformers in the field. This test usually must be done by a trained technician. The test results are temperature-corrected to a reference temperature of 20°C.

- Insulation Resistance. This test applies a high-voltage DC voltage to one winding at a time with the other windings grounded. The leakage current is measured and the insulation resistance is calculated using Ohm's law. A Megger Test Set is designed specifically to carry out this test, and its meter is calibrated in megohms in order that the calculation may be avoided. The Megger is a portable instrument that can easily carried around in the field.

- Noise Measurement. The noise measurement test is carried out while the transformer is energized at rated voltage with all of the cooling equipment running. Room geometry can greatly affect the measurements, so it is preferable that the transformer be inside an anechoic chamber; however, if such a chamber is not available, no acoustically reflecting surface may be within 3 m of the measuring microphone other than the floor or ground. The recording microphones are positioned in 1 m intervals around the perimeter of the transformer, with no fewer than four microphone positions for small transformers. Sound power levels are measured over a specified band of frequencies. The sound power levels are converted into decibels (dB).

- Temperature Rise (Heat Run). The transformer is energized at rated voltage in order to generate core losses. The windings are connected to a loading transformer that simultaneously circulates rated currents through all of the windings in order to develop load losses. Naturally, the excitation voltage and the applied circulating currents are electrically 90° apart to minimize the KW requirements for this test. Nonetheless, a large power transformer can consume up to 1 MW of total losses and the heat run test is an expensive test to perform. Therefore, in order to reduce the total expense, heat run tests are normally performed on only one transformer on a purchase order for multiple transformers, unless the customer chooses to pay for testing additional units.

- Short-Circuit Test. The short-circuit test is generally reserved for a sample transformer to verify the design of a core and coil assembly unless the customer specifies that a short-circuit test be performed on transformers that are purchased. The customer should be cognizant of the ever-present risk of damaging the transformer during short-circuit tests. A low-voltage impulse (LVI) current waveform is applied to the transformer before and after the applications of short-circuit test. The ‘‘before’’ and ‘‘after’’ oscillograms of the LVI currents are compared for significant changes in waveshape that could indicate mechanical damage to the windings.

5.8 Field tests

There are a number of field tests that are considered good predictive maintenance practices and these should be performed periodically to spot trouble. These tests are also useful for diagnosing transformer trouble. A Megger test consists of applying a high DC voltage, usually 1000 V, to each winding with the other windings grounded and to all windings connected in parallel. The Megger readings are in megohms and these must be temperature corrected for meaningful results. The megger readings should be compared to earlier test results to detect any downward trend in resistance values. The voltage produced by a megger is high enough to cause insulation breakdown if there are gross faults, but is really not sensitive enough to detect minor problems in transformers in the higher voltage classes.

A Doble test is somewhat more sensitive than the Megger test. An AC voltage, up to 10 kV, is applied to the winding insulation and leakage current is measured. In addition to the leakage current, the power factor of the insulation is computed. A high power factor indicates lossy insulation, which can mean imminent trouble. In addition to the winding insulation, the Doble test is used to measure the power factor of bushing insulation. When testing condenser type bushings, the capacitance tap is utilized. The Doble test set is also used to measure the excitation current through the winding by applying an AC voltage across the winding. High power factor readings during this test can indicate flaws in the turn-to-turn insulation.

A TTR test can be used as a diagnostic test in the field. Always connect the TTR test set clamp leads to a secondary winding of the transformer under test. Connect the TTR test set clip leads to the primary winding that is on the same core leg as the secondary winding being tested, observing that the polarity of the red clip test lead matches the polarity of the red clamp test lead. Set the ratio dials just above zero and give the generator wheel a half turn. The galvanometer should deflect to the left, indicating the ratio dials need to be raised. A deflection to the right means that the polarity of the test leads is incorrect. This can be corrected by swapping the two clip test leads. After the correct polarity has been verified, slowly turn the generator and make the appropriate adjustments to the ratio dials in order to keep the galvanometer needle centered (zero current in the clip test leads). When the ratio dials are almost set to the right ratio, the generator can be cranked faster to get the proper voltage indication on the voltmeter (8 V).

If the voltmeter reads low voltage with the ammeter reading high current, this is usually an indication of shorted turns, either in the primary or in the secondary. A zero deflection on the galvanometer at every ratio settings indicates an open primary winding because no current can flow in the clip test leads. If the galvanometer deflection is always to the right and cannot be corrected by reversing the test leads, then this may indicate an open secondary winding and voltage cannot be generated in the primary winding.

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