Chemistry Behind the Life of a Transformer

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Introduction

Transformer life management [1] is an essential part of a modern power operation system. Oil filled transformer technology has been used for more than 100 years. The principle of operation has not changed over many decades. Many transformers that were built and installed in post World War still remain in service. A properly maintained power transformer can function for 50 to 75 years. However, the maintenance of the insulation system largely determines the extent of a transformer's life. Future transformers will no doubt have increased capacity and size and their design may require the use of new materials. Transformers may operate at higher temperatures and in turn demand transformer oils of greater stability.

Types and Ranges of Transformers

Keywords
Transformers, maintenance, insulation system.

Power transformers and distribution transformers are used in numerous public and private sector set-ups involved in electricity consumption, distribution and generation. An ideal transformer should have a negligible winding resistance, perfect coupling between windings and an ideal core (*Figure* 1).

The transformers used in India range from 10 KVA capacity to 150 MVA. Reliable electrical supply has become one of the basic needs for development of society with the ever-increasing gap

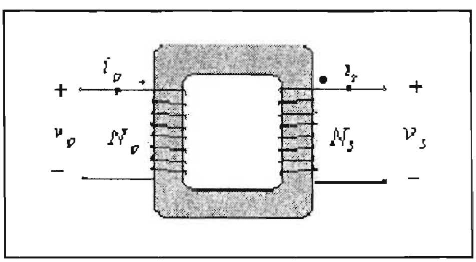


Figure 1. Sketch of an ideal transformer.

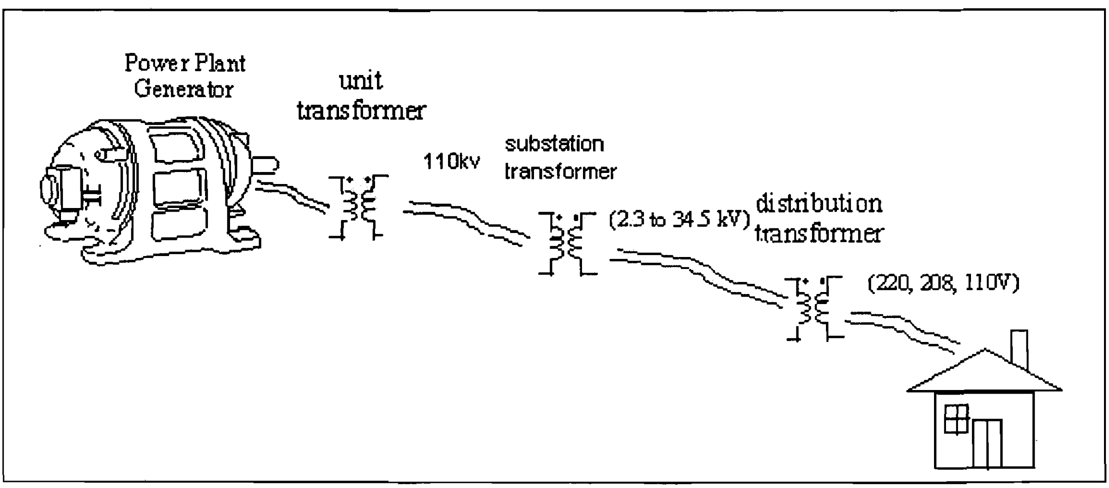
between demand and supply of electrical power. It is essential to utilize the existing power network to its optimal design capability. Economic factors usually favor continued operation of a power system as long as possible. The power transformer is an important and one of the costliest equipments in electrical power transmission system (*Figure* 2).

Insulation System of the Transformer

When electrical energy is transformed from one voltage to another, heat is developed. This temperature must be within limits so that it will not adversely affect the dimensional stability of the materials used in the construction of the transformer. In power transformers, the high electrical stresses and amount of heat developed require both solid and liquid insulation, with the fluid conducting the generated heat away to cooling surfaces, where it gets dissipated. The combination of oil and cellulose products has remained unchanged for reasons of electric strength and cost. The amount of insulating oil and cellulose vary with different types of transformers based on function and voltage class.

The life of the transformer is actually the life of the internal insulation system. The most widely used systems are liquid insulation (transformer oil) and solid insulation (kraft paper,

Figure 2. Electrical power transmission system.



pressboard, wood i.e. cellulose products). The insulating oil provides approximately 80% of the dielectric strength of a transformer. Transformer oil is a good insulating medium and when impregnated in paper, board and cloth, increases the dielectric strength of it further. The low viscosity of oil also allows it to penetrate the solid insulation setting up convection currents for conveying the heat from the core materials to the radiators. The liquid insulation therefore also serves as a coolant and its oxidation stability allows it to operate at high temperatures for long periods.

Understanding the design of the transformer as well as the operational history is essential for making reliable diagnosis. The design of the components must enhance the life expectancy of the assembly as a whole. Due to operations under extreme conditions, rapid aging and wear and tear will occur, thereby shortening the life of the transformer. Many of the items like tap changer contacts, bushings [2], pumps and fans can be replaced in a timely manner to extend the life of the transformer. But oil-cellulose insulation system is one component of the transformer which, once subjected to normal and/or abnormal loading conditions cannot be replaced.

A transformer's life begins at the factory and its future performance will be influenced by the care and skill exercised during the whole manufacturing process. Quality assurance systems attempt to ensure that this care and skill is applied in a continuous and consistent manner. For this it is necessary to consider how a premium quality refined oil can deteriorate.

Liquid Insulation

The aging or deterioration of insulating oil is normally associated with oxidation. Due to the omnipresence of oxygen and water, insulating oil oxidizes even under ideal conditions. The insulating properties of the oil are also affected by contaminants from the solid materials in the transformer dissolving in the oil. The reaction between unstable hydrocarbons in the oil and oxygen, moisture or other chemicals in the atmosphere, with the assistance of accelerators such as heat, results in decay products in the oil.

Mineral oil insulating fluids undergo oxidative degradation in the presence of oxygen to give a number of oxidation products. The final products of oxidation are acidic materials that can affect the characteristics of the insulating fluid as well as damage the components of the electrical unit. The high temperatures in due course cause the fluid to oxidize and ultimately produce sludge and soluble acid in sufficient quantity to impair its heat transfer and dielectric efficiency. Sludge formation is the terminal stage of the deterioration process. The acids formed in the process of oxidation attack on the cellulose fibers and metals forming metallic soaps, lacquers, aldehydes, alcohols and ketones which precipitate as heavy tarry acidic sludge on the insulation. Sludge appears faster in heavily loaded, hot running and abused transformers causing shrinkage of the insulation through leaching out varnishes and cellulose materials. Oxygen is a diradical species and the reactions of the oxidative process are complex and involve free radical reactions. A few possible reactions are given here.

$$\text{R-H} + \text{In} \rightarrow \text{R}^{\cdot} + \text{InH}$$
$$\text{R}^{\cdot} + O_2 \rightarrow \text{R-O-O}^{\cdot}$$
$$\text{R-O-O}^{\cdot} + \text{RH} \rightarrow \text{R-O-OH} + \text{R}^{\cdot}$$
$$\text{R-O-OH} \rightarrow \text{R-O}^{\cdot} + \text{OH}^{\cdot}$$
$$\text{RO}^{\cdot} + \text{RH} \rightarrow \text{ROH} + \text{R}^{\cdot}$$
$$\text{OH}^{\cdot} + \text{RH} \rightarrow H_2O + \text{R}^{\cdot}$$

($\text{In}^{\cdot}$ = any chemical with one or more unpaired electrons, including O_2, capable of abstracting a hydrogen atom from a hydrocarbon.)

The first stage of oxidation is the attack of oxygen on hydrocarbon molecule to form peroxides which dissociate to form free radicals which can act as initiators for chain reactions involving free radicals and hydrocarbons. The propagation reactions are further capable of repetition over a number of cycles for each hydrocarbon free radical supplied by the initiation reaction.

Oil oxidation unfortunately cannot be eliminated but can be controlled or slowed down by preventive maintenance procedures. One way is to incorporate an oxidation inhibitor that will interrupt and terminate the free radical process of oxidation. If a compound (RH) with labile hydrogen atom is added to the system to compete with the hydrocarbon, it will produce a relatively inactive radical ($A^{\cdot}$) which will break the chain sequence and inhibit the overall reaction. Inhibited transformer oil contains oxidation inhibitors or antioxidants (AH). They terminate chains by donating hydrogen atom to the intermediate radical.

$$R^{\cdot} + AH \rightarrow RH + A^{\cdot}$$
$$RO^{\cdot} + AH \rightarrow ROH + A^{\cdot}$$
$$R\text{-}O\text{-}O^{\cdot} + AH \rightarrow R\text{-}O\text{-}OH + A^{\cdot}$$
$$OH^{\cdot} + AH \rightarrow H_2O + A^{\cdot}$$

The inhibitors used in transformer oils are invariably amines and hindered phenols which offer stability for a limited time. This is known as the 'induction period' after which the oil oxidizes at the normal uninhibited rate. The useful life of the oil is extended by the amount of time the inhibitor remains effective, before it becomes depleted i.e. usually in a few years. The two most commonly used phenolic inhibitors are 2,6-ditertiarybutylphenol (DBP) and 2,6-ditertiarybutyl-4-methyl phenol or 2,6-di-tertiary butyl-*p*-cresol (DBPC). The DBPC has found almost universal approval and is a very desirable inhibitor with outstanding properties. Even in small concentrations, it is a stable and effective oil oxidant.

Solid Insulation

The solid insulation (cellulose based products) in transformers degrades with time at rates which depends on the temperature, moisture content, oxygen and acids in the insulation system. Heat and moisture are the main enemies of the solid paper insulation with oxidation as the primary accelerator. Aging of the insulation system could accelerate by 40 to 60 years by an increase in operating temperature. Moisture [3] consists of free water, suspended water (trapped in oil decay products), dissolved water and chemically bound water (part of the chemical structure of the glucose molecule and necessary to maintain the mechanical strength of the cellulose). The complete removal of moisture from cellulose insulation is therefore impossible.

When degradation of the solid insulation occurs, the cellulose molecular chains get shorter and chemical products such as furanic derivatives [4] (5 hydroxymethyl-2-furfural, 2 furfuryl alcohol, 2 furfural, 2 acetylfuran, 5-methyl-2-furfural), CO and CO_2 are produced and dissolved in the transformer oil. The furanic compounds soluble in oil are specific to paper degradation, whereas gases can be produced by oil degradation and other organic compounds. Of the furanic compounds, the 2-furaldehyde is the most abundant. Its concentration in oil has been related in many cases to the degree of polymerisation (DP) and consequently to the physical strength of the solid insulation (*Figure* 3). DP is an average measurement of the number of glucose units per molecular chain. An estimate of the remaining paper life is important [5]. DP of less than 400 (50% of remaining life of transformer) is obtained with a 2-furfuraldehyde concentration of more than 1000 ppb by weight. The end of life of a transformer is when the paper reaches DP of 200 or less when the paper becomes very brittle and the short circuit capability is much reduced.

Furan measurement in transformer oil is a reliable indicator of integrated and cumulative extent of degradation of cellulosic material present in the transformer. The furan data on a transformer fluid measures the average decay integrated over the entire volume of the transformer whereas DP measurement of paper is an accurate indicator of aging of paper from a specific and localised place. DP value of paper taken from different places of the transformer varies considerably. The extent of variation of DP from top to bottom of winding can vary up to

Suggested Reading

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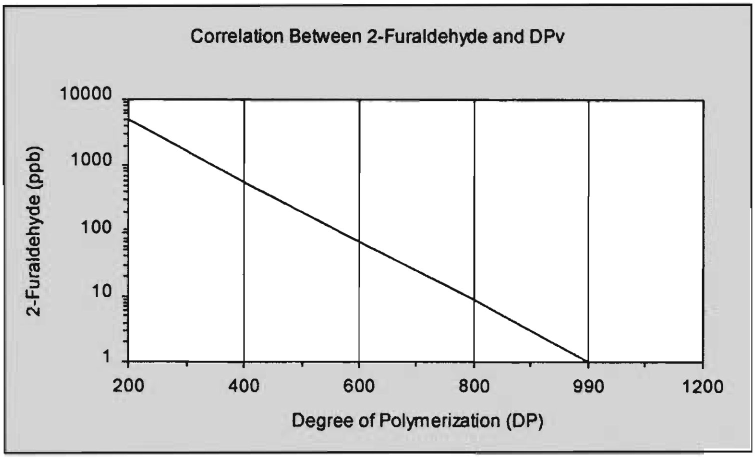

Figure 3.

50% due to thermal profile of the transformer. In the event of failure in any portion of winding insulation, DP analysis can help in identifying the location where cellulosic materials need replacement. The cellulose materials are the weakest link in the insulation system. Since the life of the transformer is actually the life of the cellulose insulation and degradation of the cellulose is irreversible, the decay products should be removed before they can do any further damage to the cellulose. With proper maintance the cellulose can virtually have an indefinite life.

Conclusion

Scientific assessment of the insulation conditions rather than years of service determine the remnant life of the transformer. Insulation age of a transformer is exclusively decided by the life of cellulosic materials. Extent of degradation of cellulosic materials can be quantified by measuring dissolved CO_2 gas content in oil, degree of polymerization of paper and furan content in oil. Transformer life is shortened by a number of events. Taking action to prevent failure from any of these causes is a method of life extension. Maintaining the insulation system in good order and controlling loads by the use of dynamic loading of the equipment make it possible to improve the utilization of the existing transformer capacity.

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