Oil as a Main Insulation Component in Liquid Filled Power Transformers

Quality and Consistency of Product

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FOR SOME, OIL IS AN AFTER-THOUGHT, JUST ANOTHER COMPONENT THAT COMES WITH THE TRANSFORMER. BUT OIL PLAYS A VITAL ROLE AS ONE OF TWO MAIN ELEMENTS OF THE INSULATION SYSTEM OF THE APPARATUS.

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William Stanley's invention of the commercial transformer in 1886 and his subsequent AC electrification of Great Barrington, Massachusetts in that same year [1], pioneered the development of commercially viable electrical distribution systems. The first transformers were dry types using insulation made of cambric cloth and other cotton materials. In order to achieve higher voltages a better insulating medium was needed, and as early as 1887 [2] paraffinic mineral oil along with cotton-based materials were used to form the insulation system of early transformers. Although plentiful, early paraffinic oils would often solidify near temperatures of 4°C or lower, causing retention of heat in the windings [3] that eventually led to failure. As a result, naphthenic oils with naturally occurring low pour points became the insulating oil of choice in the early 20th century – and is still the majority of what it is used today in most countries.

Oxidation of transformer mineral insulating oils occurs over time, at a rate that is dependent on the composition of the fluid and the conditions to which it is exposed while in service, such as temperature, oxygen and catalysts. Mineral oil filled transformers in the early 20th century were free breathing, which allowed a constant oxygen supply. Coupled with the poor refining practices of the time, which was a simple distillation cut of the crude that resulted in oils that were oxidatively unstable, the mineral oils in service tended to sludge and polymerize. This often resulted in solid terminal byproducts that had to be physically removed from the transformer with shovels. This caused operational headaches for utilities in that many transformer maintenance activities were engaged in to remediate oil issues.

As a result, there was a need to develop tests that could determine the quality and oxidative stability of the oil. In 1898, ASTM was formed as a forum to help industry leaders develop test methods for a variety of products including crude oil. ASTM committee D02 (then called committee N), founded in 1904 [4], was the first committee to take on the responsibility of establishing test methods for crude oil from which transformer mineral oil is refined. The very first methods did not come into existence until the decade between 1910 and 1920 and were limited to the evaluation of mostly physical characteristics; they did not address oil quality or oxidation stability. It wasn't until the 1940s through the 1960s that oil quality and oxidation tests were established for use. In the 1950s, the ASTM D27 Committee on Insulating Fluids was established and split out of D02, and serves as the committee that produces standards for specifying, sampling and testing of insulating fluids.

Nevertheless, the problem of oxidation of transformer oils was recognized early. In 1921, Dr. Van H. Manning authored a paper entitled "The Pioneer's Field in Petroleum Research". In that paper, Dr. Manning listed issues to be addressed in the petroleum industry, one of which was the prevention of oxidation of mineral oils in transformers [5].

In June 1923, the Massachusetts Institute of Technology (MIT) began a research study of the mechanism of the oxidation of mineral oils and of the action of negative catalysts (inhibitors) [6]. Inhibitors were known to bind with free radicals thus terminating the propagation process of oxidation. A year later in 1924, 177 substances were tested for anti-oxygenic protection of transformer oil, and 48 appeared to have inhibitory properties. Additional investigations were undertaken both in the United States and other parts of the world which identified other possible materials that could suppress oxidation [6]. Researchers in Russia [7,8], France [9] and England were embarking on a similar path at about the same time.

However, those were not the only issues to overcome. Viscosity was a well-known factor that dictated the ability of the oil to dissipate heat from the windings and thus oils with lower viscosities became desirable. Corrosive sulfur was another issue of concern with oils at the time as it caused corrosion of the copper and silver components it was in contact with, leading to failure of the apparatus. Probably one of the most overlooked issues, which is still persistent today, is the interaction of the oil with the materials of construction of transformers, including gaskets, coatings, paints and other materials. The effects were a mutual problem with the oil causing the components to degrade, which resulted in leached material from the components contaminating the oil leading to compromised chemical, electrical and physical properties.

OIL SERVES AS AN IMPORTANT HEAT DISSIPATION MEDIUM HENCE THE MAKEUP OF THE OIL IS CRUCIAL TO PROPER AND SAFE OPERATION. POOR QUALITY OR IMPROPER APPLICATION CAN RESULT IN A HOST OF ISSUES, SUCH AS CORROSIVE SULFUR ATTACK OR GASKET INCOMPATIBILITY, MANY OF WHICH CAN RESULT IN FAILURE.

For some, oil is an after-thought, just another component that comes with the transformer, but it plays a vital role as one of two main elements of the insulation system (the other being the cellulosic insulation) of the apparatus and it further serves as an important heat dissipation medium. Hence the makeup of the oil is crucial to proper and safe operation. Poor quality or

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improper application can result in a host of issues, such as corrosive sulfur attack or gasket incompatibility, many of which can result in failure, and so it must be selected with care and diligence. And once selected, the oil needs to be monitored over the life of the apparatus, not only to ensure the oil quality is maintained so it can continue to serve its intended purpose, but also as a means of evaluating the operation of the transformer itself, through diagnostic tests such as dissolved gas-in-oil analysis (DGA), and the condition of the other main insulating component – paper, through such chemical markers in the oil as furanic compounds and alcohols.

As a result, standards were devised and published to ensure transformer oils meet certain minimum characteristics. These standards and the tests that comprise them can be used to compare products and to evaluate the consistency of a product from year to year. One of the earliest specifications was the Canadian standard CSA-C50 [10] published in 1938, but it was not until 1961 that Doble Engineering company published a truly comprehensive standard called "Transformer Oil Purchase Specification (TOPs)" [11]. Other major specifications for new mineral insulating oils, ASTM D3487 [12] and IEC 60296 [13], were not published until the 1970s. All of these standards undergo regular revisions and are still published today and have many tests in common, but there are distinct and important differences. Thus, the user must be able to navigate these specifications, understand the significance of the tests, and decide which is most suitable for a given application.

A good product and a consistently refined product are of ultimate importance. Evaluating oil to these published standards can help ensure such a product is selected. Detailed oil specifications should be part of new transformer specifications and the product delivered should be tested to verify specifications are indeed satisfied. Any purchase of oil should have the same specifications met to ensure only compatible products that meet standards are introduced into the transformer during its lifetime.

A good product provides the right mix of electrical characteristics required by the insulation system, the lack of corrosive sulfur (responsible for attacking the copper and silver in transformers and causing copper sulfide deposition in the paper), good oxidation characteristics so the oil lasts the lifetime of the apparatus without sludging or degrading rapidly, and appropriate flow characteristic (as defined by pour point and viscosity) for operation in the intended climate and to meet heat dissipation needs. In addition, it is important to assess the actual chemical makeup of the oil as this has an impact on compatibility with other materials of construction in the transformer. For example, if a user decides to change out a high aromatic oil with a low aromatic oil, the gaskets will contract, and leaks will develop which can be costly to remedy. Knowledge of additives is another important factor to consider and a good product should have nothing added that has not been mutually agreed on with provider and end user. Most modern specifications include a limit for furanic compounds, oil-soluble compounds used as an indirect measure of the condition of the cellulosic insulation in a transformer. 2-furfual is the main compound used for diagnostic purposes, but it can also be used in refining of transformer oil during a solvent extraction process. If not properly removed prior to use, it may lead to an incorrect evaluation of the cellulose insulation as indications of overheated or aged paper insulation in a transformer. Specifications should also contain any other specific requirements. For example, applications such as cables, bushings and some transformers, may require the use of a negative gassing tendency oil.

For those that purchase transformers and other apparatus outside of their home country, knowledge of international standards and products is very important. The apparatus will contain residual oil from factory testing or depending on the size, may come fully filled. Knowing which oil product was used along with the qualities of that oil is essential in making sure no unwanted oil characteristics are transferred over to the new electrical apparatus. For transformers, approximately 7% to 10% of the factory test oil remains in the apparatus when drained after factory testing is completed, and if this retained oil is problematic, it can be enough to contaminate acceptable new oil used to fill the apparatus during commissioning. From 2001 to 2007, this very scenario played out and caused severe, to the point of failure, corrosive sulfur contamination in new apparatus around the world. In these cases, the original test oil used at the factory

PROBABLY ONE OF THE MOST OVERLOOKED ISSUES, WHICH IS STILL PERSISTENT TODAY, IS THE INTERACTION OF THE OIL WITH THE MATERIALS OF CONSTRUCTION OF TRANSFORMERS, INCLUDING GASKETS, COATINGS, PAINTS AND OTHER MATERIALS.

DETAILED OIL SPECIFICATIONS SHOULD BE PART OF NEW TRANSFORMER SPECIFICATIONS AND THE PRODUCT DELIVERED SHOULD BE TESTED TO VERIFY SPECIFICATIONS ARE INDEED SATISFIED. ANY PURCHASE OF OIL SHOULD HAVE THE SAME SPECIFICATIONS MET TO ENSURE ONLY COMPATIBLE PRODUCTS THAT MEET STANDARDS ARE INTRODUCED INTO THE TRANSFORMER DURING ITS LIFETIME.

OILS COME FROM DIFFERENT CRUDE SOURCES WHICH ARE PROCESSED USING A VARIETY OF REFINING METHODS, SO THE CHEMICAL MAKEUP OF THE END PRODUCTS WILL DIFFER EVEN THOUGH ALL MAY MEET THE SAME FUNCTIONAL SPECIFICATION. IDENTIFYING CHANGES IN DELIVERED PRODUCT IS EASIER WHEN ONE WITH CONSISTENT PROPERTIES IS USED.

was corrosive or in some cases was provided for commissioning on site as part of a turnkey project. These incidents highlight the importance of specifications containing test methods and limits that are rigorous enough to ensure suitable product is provided. Additionally, a detailed and comprehensive oil specification must be a part of the purchase process for transformers and updated on a regular basis.

Along with satisfying specifications, consistency of product should be considered. Oils come from different crude sources which are processed using a variety of refining methods, so the chemical makeup of the end products will differ even though all may meet the same functional specification. Identifying changes in delivered product is easier when one with consistent properties is used. It should also be noted that the chemical makeup of an oil can also impact gas formation under certain conditions; Dissolved Gas Analysis (DGA) is widely used as a diagnostic tool and knowing how an oil behaves in the equipment on a system from year to year can eliminate an unknown when diagnosing potential issues.

Specification testing of oil products can be undertaken periodically to monitor consistency. Oil surveys of transformer oils are available where oil products are compared year-to-year and results tracked. Doble Engineering Company has been performing such surveys either semi-annually or annually since 1953. In the early days, reports were specific for oxidation tests only, as that was the main issue at that time. Current testing is much more comprehensive with 30+ tests being incorporated and provides the user with a detailed analysis for each of the submitted oils. Oils are solicited from refiners around the world and then tested to Doble TOPS and ASTM D3487 specifications and the data along with the analysis of that data is then published. Utilities have used the report as the primary selection criteria of the oils to be considered for purchase.

In conclusion, insulating mineral oils should be selected on a quality basis, the ability to withstand oxidation, the characteristics which are needed and overall consistency of a product from year to year. Detailed oil and transformer specifications should be used to ensure suitable quality product is provided.

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