Some Considerations for New and Retrofill Applications of Natural Ester Dielectric Fluids in Medium and Large Power Transformers

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***Abstract*—Waukesha Electric Systems has been actively involved in exploring and developing the application of natural ester dielectric fluid in medium and large power transformers in both new and retrofill applications. Initial applications of this material have primarily been to take advantage of the fire safety properties it offers. Many of the initial retrofills have been in power generating plants. Environmental biodegradability has been the second major reason for use of this material. Application consideration for use with de-energized tap changers, load tap changers and forced oil pumps will be discussed. Application considerations of higher viscosity, higher oil temperature rise and transformer ratings will be discussed. Application in mobile transformers will be discussed.**

***Index Terms*—Natural ester dielectric fluids, retrofill, generator step-up transformer, unit auxiliary transformer, station service transformer, excitation transformer, mobile transformer, fire safety, environmental biodegradability, slower aging rate of cellulose insulation.**

I. Nomenclature

Natural ester insulating fluids are dielectric coolants whose base is derived from vegetable oils. Retrofills are transformers that were originally manufactured and filled with mineral oil and that are subsequently drained and filled with alternative fluids such as natural esters. Less- flammable high flashpoint oils refer to a class of insulating oils that have flashpoints in excess of 300 C. Tapchangers are multiposition switches that are intended for connecting alternative winding taps in power transformers, to obtain desired voltage ratios. Tapchangers for de-energized operation are designed for switching connections only when the transformer is de-energized. Load tap changers are designed for switching when the transformer is energized and carrying full load.

II. Introduction

THIS document will describe several application considerations of natural ester based fluids in power transformers. Application at power generating plants has been primarily to take advantage of this material's fire safety properties. Application in mobile transformers will be discussed as it seems a good fit for all three beneficial properties that natural ester dielectric fluids have over mineral oil, these being 1) fire safety, 2) environmental biodegradability and 3) slower rate of aging of cellulose insulation. Natural ester dielectric fluids appear to be more stable than mineral oil and silicone for use with de-energized tap changer materials in common use today. There are some concerns for application in load tap changers as they are typically free breathing compartments. Forced oil pumps would normally be addressed in a new transformer application due to the materials higher viscosity and should be addressed in a retrofill application to insure the pumps function as expected.

III. Application of Natural Ester Fluid Filled Transformers

A. De-rating or re-rating of power transformers after retro-filling with natural ester dielectric fluid

Natural ester dielectric fluids have a higher viscosity than mineral oil. For this reason, a power transformer designed to operate with mineral oil will typically have a higher operating temperature after being retrofilled with natural ester dielectric fluid. If a transformer were operated with mineral oil at a higher temperature, the operating life of the cellulose insulation would be shortened. However, one of the properties of natural ester dielectric fluids is that the cellulose insulation ages more slowly at a given temperature than would the same cellulose insulation in mineral oil. Another paper being presented by C. P. McShane [1] of Cooper Power Systems describes how cellulose insulation can operate at 21°C higher temperature rise in natural ester dielectric fluid and have the same loss of life as cellulose insulation operating in mineral oil.

The author's company, reran temperature rise calculations for dozens of existing power transformer designs and changed the fluid characteristics in the design program to show what the calculated temperatures were assuming operation with a natural ester dielectric fluid. None of the calculated temperature rises was greater than 21°C higher than when the design program assumed mineral oil as the dielectric fluid. For this reason, Waukesha Electric Systems has not been de-

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rating or re-rating transformers when retro-filled with natural ester dielectric fluid. Even if the temperature is higher, as long as it is not more than 21°C higher (according to data compiled by Cooper Power Systems) the cellulose insulation should last longer than when operating at it's original design temperature filled with mineral oil.

B. *Generating station transformers*

There have been a couple of dozen or so medium and large power transformers retro-filled with natural ester based fluids in the United States over the last several years. Most of these have been in the last year and a half. The largest size unit retrofilled to date has been a 200 MVA Generator Step-up transformer with a high voltage rating of 161 kV.

Natural ester based fluids have significant characteristics that are quite different from mineral oil including; 1) fire safety, 2) environmental biodegradability and 3) slower aging rate of cellulose insulation. Of the retrofills performed by my company, fire safety has been the main reason for retrofilling, followed by environmental considerations.

Most of the natural ester based fluid retrofills of medium and large power transformers that the author is aware of, have been at generating plants. Generator step-up transformers, unit auxiliary transformers, station service transformers and excitation transformers have been retrofilled. All of these classes of transformers are typically located very close to or inside of generation plant buildings. This location creates the need for attention to and special consideration of fire safety.

Factory Mutual Global has rated Natural Ester as a less flammable fluid. As such they allow a transformer filled with this material to be located near buildings without the use of deluge systems or firewalls to protect the building. There have been some cases where fire suppression did not exist and the utility's insurance carrier insisted that fire suppression be installed. Generally the options were a deluge system, fire wall(s) or both or retrofill with a less flammable fluid such as a natural ester based fluid. In the situations that the author is aware of, retrofilling with a natural ester based fluid was the most economical method to achieve the desired fire safety. In one case the retrofilling option was about half of the deluge system / firewall estimate.

Another reason that the retrofilling option is attractive is that it can typically be done in a very short time frame. This retrofilling activity can be accomplished in as little as 3 days depending on voltage class and quantity of oil. When the oil is removed, this is a very opportune time to do other maintenance or repair activities such as regasketing, bushing replacement, painting, cooler replacements or upgrades, etc. These additional activities would increase the time of the outage by one to several more days. However, this is still typically shorter than the time to install a deluge system or firewall. Also the retrofill approach does not require as much engineering effort as deluge systems or firewalls do.

An additional benefit of retrofilling with natural ester fluid to gain additional fire safety is that the user also gets the other benefits of slower aging rate of the cellulose and environmental biodegradability. These two other benefits are not realized when deluge systems or firewalls are used for fire safety with mineral oil instead of natural ester based fluids.

C. *Application in mobile transformers*

Mobile transformers are expected to be a good application for natural ester dielectric fluids, as they would benefit from all three attributes of these fluids. Mobile transformer designs often have compromised short circuit integrity, have decreased dielectric design margins and have sacrificed cellulose insulation life due to higher operating temperatures, all in an effort to get the transport size and weight down so that these devices can be moved without having to get special permits or in the case of larger mobiles, to be able to be moved at all, over highways. It is not uncommon for a mobile transformer to be designed with a 75°C top oil temperature rise. This higher operating temperature will reduce the size and weight of the transformer. However, this higher operating temperature will also significantly shorten the life of the cellulose insulation. Alternative insulating materials such as DuPont's Nomex® have been used to withstand the higher operating temperatures without significant loss of life. For existing mobile transformers insulated with cellulose insulation, retrofilling with natural ester dielectric fluid would slow the rate of aging of the insulation. The benefit would be more pronounced for those mobiles with elevated hot spot temperature rises.

Extended insulation life would seem the primary benefit of retrofilling a mobile transformer with a natural ester dielectric fluid but the other two fluid properties may also be significant for this application. The high environmental biodegradability could be beneficial in the event of a leak where insulating fluid can be spilled on the ground. Mobile transformers get moved far more than normal transformers and may be more susceptible to leaks due to this duty cycle. As a mobile is typically used for emergency power restoration, they may be operated with less oil containment capability than permanent transformer applications. If a mobile transformer were leaking while being transported, the cost of cleanup could go up dramatically due to the potentially huge area that would require clean up. As natural ester dielectric fluids are very biodegradable, the remediation required in the event of a spill or leak may be less than what might be required if mineral oil were spilled.

Environmental regulations can be local (town, city, county) or state or federal. At the time of the writing of this paper, a conclusive statement about what cleanup methods may be required are not uniform and beyond the scope of this paper.

D. *Application at hydroelectric power generation plants*

It is not uncommon for Generator step-up transformers at hydroelectric generating plants to be located on the backside of the damn directly over the water. As many of these damns existed before current oil containment rules came into being, sufficient oil containment may be difficult if not impossible due to tight physical constraints. This would seem a natural application for natural ester dielectric fluids considering their high biodegradability and significantly lower toxicity levels to fish.

One study conducted under the Environmental Protection Agency's Environmental Technology Verification Program [3] has shown one brand of natural ester dielectric fluid to be essentially non-toxic to fish fry. There were no fish killed when natural ester dielectric fluid was added to the water. If a leak were to occur on a transformer mounted on or in a damn, the oil might well enter the surrounding waterway. This could cause significant environmental harm, cost of clean up and unfavorable public relations. Retro-filling these transformers with natural ester dielectric fluids would seem to lessen the ill effects of this possibility.

E. Considerations for forced oil pumps

Some medium and large power transformers use electrically driven pumps as part of the cooling system to force the oil to flow faster. Typical natural ester based fluids have a higher viscosity than does mineral oil. In a new transformer design application, the pump designer would take this higher viscosity into account when selecting the appropriate pump for the application. When considering retrofilling a transformer that has forced oil pumps, the rating of the pump and motor need to be reviewed to determine if they will function properly when operating with a more viscous fluid.

F. Considerations for de-energized tap changers

At least three transformer manufacturing companies have conducted material compatibility tests of natural ester based fluids with other materials commonly found in medium and large power transformers. Of those materials found in current vintage transformers, the only material that the author is aware of that is adversely affected by natural ester based fluids is PVC, but at a degree less than that of mineral oil. Copper and silver plated copper as commonly found on de-energized tap changes, do not seem to be affected by natural ester based fluids. The author is also not aware of any problems related to de-energized tap changes being affected by natural ester based fluids after being retrofilled with natural ester based fluid and returned to normal service.

G. Considerations for Load Tap Changers

Many load tap changers in service today and available on new power transformers are housed in free breathing compartments. There is typically a dehydrating breather at the point the compartment opens to the atmosphere so that the dehydrating material (typically silica gel) removes a significant amount of moisture from the air before it enters the LTC in an attempt to keep the insulating oil dry. The primary reason that these compartments are normally free breathing is to allow arcing gasses created during a tap change operation to escape. Natural ester dielectric fluids have a higher rate of oxidation than does mineral oil and will polymerize if left exposed to the atmosphere. This is perhaps the main reason that natural ester dielectric fluids have not been applied to free breathing load tap changers yet. The author is aware of one systems being developed to overcome this issue.

One manufacturer of step voltage regulators has started offering them filled with natural ester dielectric fluid. These devices have tap changers in them that are similar to load tap changer mechanisms but these devices are sealed tanks with pressure / vacuum bleeders and so don't see much oxygen ingress as would a free breathing device with a dehydrating breather.

H. Temperature Rise

As stated in section A of this paper, the author's company reran temperature rise calculations for dozens of existing designs of power transformers. The range of temperature rise differentials between mineral oil and natural ester fluid was a low of 1 °C and a high of 20 °C with the natural ester fluid design always being higher than the mineral oil design. Typically the natural ester fluid designs had a 5-10 °C higher rise than did the same design assuming mineral oil in the calculation.

A thermal design program that uses the thermal properties of the materials and the physics of thermodynamics and heat transfer, as the basis for temperature calculation is needed to accurately make these kinds of calculations. The author's company has this kind of program and the characteristics for natural ester fluids were substituted for the properties of mineral oil in the program to make the above mentioned calculations. Other thermal calculation programs that are based on regression analysis of a data set of test values would not be suitable as the change in characteristics of the dielectric cooling medium renders the data set invalid.

I. Capacitance

Manufacturers and users of transformers filled with natural ester dielectric fluids should be aware of the differences in transformer parameters due to the inherent differences between mineral oil and natural ester dielectric fluids. The winding capacitance will likely measure higher with natural ester dielectric fluids than with mineral oil. In the author's opinion, there is not a large enough data sample size to accurately state anticipated capacitances but increase in the 5% to 50% range would not be surprising. Since the change in the dielectric constant affects both the series capacitance and the ground capacitance of the coil, the higher dielectric constant of the natural ester is not expected to change the ratio of these capacitances. Therefore the overall impulse voltage distribution of the coil using the natural ester is expected to be similar to the voltage distribution with mineral oil.

J. Insulation Dissipation Factor

Another transformer parameter that becomes significantly different due to the inherent nature of natural ester dielectric fluids is the insulation dissipation factor or power factor. The author's company has noted increases in the power factor from 18% higher to upwards of double. The increase in the power factor will be more for a higher percentage of liquid dielectric as compared to the percentage of the total insulation space occupied by solid insulation. In the author's opinion, there is not a large enough data sample size to accurately predict anticipated increases in power factor. Inherently higher power factor is neither good nor bad, it is just different. Higher dielectric loss may actually improve the transformer's ability to absorb and damp high frequency transients.

J. *Insulation Resistance*

A third significant difference in transformer parameters is insulation resistance. Transformers filled with natural ester dielectric fluid will likely test much lower insulation resistance than the same transformer filled with mineral oil. This difference has been observed to be in the range of an order of magnitude lower. Again, this doesn't mean it is good or bad, it is just different and may prove to be beneficial to high frequency performance as stated above. In addition, some experts have theorized that this lower d.c. resistance can reduce the risk of static electrification developing. Both phenomenon need more investigation and are beyond the scope of this paper.

K. *Dissolved Gas Analysis*

This very useful diagnostic tool for assessing the condition of mineral oil filled transformers is also a useful tool for natural ester dielectric fluid filled transformers. The key gas analysis as described in ANSI C57.104 [2] is still valid for use with natural ester dielectric fluid filled transformers. For example a DGA showing acetylene is still indicative of a high-energy discharge and likely to be a problem that should be investigated further.

There are different gas ratios used to help distinguish among different possible causes of gas generation. Unfortunately, these ratios are not calibrated for natural ester dielectric fluid filled transformers and should not be used.

L. *Dew Point to Moisture Content of Paper Conversion*

It is common practice to check the dew point of a sealed transformer that has been empty of oil for some time. Knowing the dew point and temperature of the gas in the empty sealed transformer, one can use this data to determine the relative humidity of the gas in the drained transformer. While various conversion charts are available to estimate the surface moisture content of the cellulose insulation, the charts are based on mineral oil impregnation. These conversion charts are not presently calibrated for natural ester dielectric fluids and should not be used. However, we do expect that the same levels of relative humidity for transformers containing a natural ester are acceptable if the transformer contained mineral oil. This is another area where additional research is needed.

M. *Moisture Content of Liquid to Moisture Content of Paper Conversion*

This means of estimating moisture content in paper is similar to the paragraph above describing the dew point to moisture content in paper conversion. A method used to determine the moisture content of paper in transformers that are filled with mineral oil is to take a sample of oil and determine the content of water in the oil. Various charts have been devised to estimate moisture content in paper knowing the temperature at which the oil sample was taken and the moisture content of that oil. There tends to be significant variability among the different charts that have been developed for this purpose. Ideally the oil sample should be taken when the temperature of the transformer is stable and above 50°C.

The charts developed for this purpose are likely not calibrated for use with natural ester dielectric fluid and should not be used.

N. Moisture Content in Natural Ester Dielectric Fluids

Natural ester dielectric fluids are capable of holding considerably more moisture in solution than does mineral oil. A paper presented by C. P. McShane [1] describes this attribute further. Moisture content of a few hundred parts per million in natural ester dielectric fluid at 20°C would not be considered detrimental to dielectric performance. Even a level of 500 ppm is below 50% saturation. This ability to hold significantly more moisture is one of the reasons that the cellulose ages more slowly when immersed in natural ester dielectric fluid versus mineral oil.

O. Design Considerations for New Power Transformers

The author's company has approved one supplier's brand of natural ester dielectric fluid for use in any transformer we make. This material has some better dielectric properties than mineral oil. Also, the dielectric constant of natural ester dielectric fluids is closer to that of paper thus lowering the dielectric stress level at the paper / liquid interface. For these reasons, the dielectric designs used are directly suitable for use with natural ester dielectric fluid.

When designing a new transformer to meet a 65°C maximum temperature rise, the higher viscosity and differences in thermal conductivity and heat transfer capability should be taken into consideration. Higher BIL transformers will likely have larger ducts facilitating the more viscous natural ester dielectric fluid. Lower BIL transformers might also benefit from larger cooling ducts. Loss evaluations also have a significant impact on cooling design and may be the overriding factor in the cooling design. All of these factors in combination need to be taken into account to determine what design modifications may need to be made to accommodate natural ester dielectric fluid in the design of a new transformer.

IV. References

Papers Presented at Conferences (Unpublished):

[1] C.P. McShane, Jerry Corkran, John Luksich, Kevin Rapp, "Natural Ester Dielectric Fluid Development," 2005 IEEE/PES T & D Conference Panel Discussion on "Progress report on Natural Esters For Distribution and Power Transformers – P. Hopkinson et. al, New Orleans, USA.

Standards:

[2] *IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers*, IEEE Standard C57.104-1991 (ANSI).

Technical Reports:

[3] The Environmental Technology Verification Program (ETV), U.S. Environmental Protection Agency and California Environmental Protection Agency, ETV Joint Verification Statement, Technology Type: Vegetable oil-based insulating dielectric fluid, Application: Vegetable oil-based insulating dielectric fluid for use in electrical apparatus requiring a liquid dielectric coolant, Technology Name: Envirotemp®FR3™ Insulating Dielectric Fluid, VS-R-02-02, June 2002.

V. Biography

Moore, Steve was born in Wilmington, Delaware in 1952. He graduated from the Milwaukee School of Engineering in 1974 with a B. S E.T.-E. degree. He has also attended month long management seminars at the Schools of Business of the University of Wisconsin, Madison and the University of Southern California. His employment experience has all been with Waukesha Electric Systems and all of it's previous company names. He spent 26 years in new transformers in various marketing capacities including Sr. Application Engineer, Product Manager and Market Manager. He spent 2 years working as Business Development Manager for WES's Power Systems Development subsidiary developing EPC substation projects. For the last 2 years, Steve has been Market Development Manger for WES's Service business unit.

Steve has been an IEEE member for 35 years and was elected to the grade of Senior Member in 1990. Steve and other colleagues were the recipients of The Institute of Management Sciences Franz Edelman Management Science Achievement Award for 1989 for Waukesha Electric System's use of innovative management science. Steve is also listed in the Acknowledgements of NBS Technical Note 1204 titled Calibration of Test Systems for Measuring Power Losses of Transformers, for having made significant contributions to this effort.