Natural Ester Fluids applications in Transformers as a sustainable dielectric and coolant.

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Abstract. New requirements for a better sustainable energy policy around the world is easy to observe, many projects in sustainable energy are developed wherein the academia works together the authorities and commercial firms such as electrical grid utilities. In distribution transformers one of the suggested solutions is to replace mineral oils used as dielectric and coolant for natural ester fluids, they provide improved technical properties making them a safe substitute of mineral oil. Natural esters are based on clean technology in order to guarantee requirements from utilities. The main goal of the present paper is to present a technical-economic analysis obtained from five years of applications of oil-immersed transformers using natural ester fluids in Colombia. The methodology considers forty-four oil-immersed distribution Transformers, a half use mineral oil and the other side use natural ester, operating under the same load regime. Results evidenced the feasibility of implementing this technology because the costs are very similar and the reduction of risks and environmental impact is considerable.

Keywords: Distribution transformers; Mineral Oil; Natural ester fluids; safety operation in power distribution system

INTRODUCTION

Electrical Power Systems require high voltage levels in order to reduce losses in transport a great amount of electricity to final users, which commonly are located far away from power plants. Final users require distribution transformers near their electrical installations in order reduce voltage values suitable for their electrical installations and utilities (Ab Ghani et al., 2017). During the last century, cities have increased in the use of distribution transformers which is related with technological growth and development (Delgado et al., 2015). The oil-immersed technologies are the most common applications used in transformers which contains as dielectric and coolant oil derived from fossil fuels (Mcshane, 2002).

These oils came on to the marked in 1899, when the first mineral-oil refinery started to produce oil for transformers specifically as dielectric and coolant. From the XX century to the present day, researches have not stopped to improve the properties on this oils and esters. During 1930s and motivated by technological advances manufactures, retailers and utilities started to promote nonflammable liquids such as halogenated dielectric fluids and chiefly askarel fluids operating with mineral oil where safety conditions focused on increase fire point levels which is preferred for a safe application obtaining less-flammable fluids in order to qualify liquids with a safety fire point level operation, higher than 300 °C. Most of uses were distribution networks near final users or indoor applications (Rycroft, 2014).

However, in 1976, these mineral oils were targeted as dangerous and toxic for human health due to the presence of Polychlorinated biphenyls PCBs (Asano & Page, 2014). That led the developed of new projects such as dry-type transformers improvements for indoor applications and the development of project to replaced based PCB oils by PCB-free liquids such as Synthetic Esters and Silicones with High-Temperature or High-Molecular-Weight Hydrocarbons (HMWHs). But, they are not considered biodegradable and can cause an environmental risk in case of be spilled(Ciuriuc et al., 2012). These legal constraints prompted companies to start working on the development of new products as dielectric liquids towards cleaner production policies(Sagastume Gutiérrez et al., 2018).Besides to meet their chemical, physical and electric properties, they must be non-toxic, biodegradable, recyclable and non-hazardous (Ab Ghani et al., 2017).

These properties aimed to use nonpetroleum derived with nontoxic properties during uses and derived from renewable resources such as natural esters which are derived from natural agricultural products obtained from sunflower seeds, Canola/Rapeseed, soybean seeds, among others. These esters are completely biodegradable (95% - 100%) and non-toxic due to its natural components and natural additives (CIGRE working group A2-35, 2010), also they were certified by environmental agencies such as EPA (Environmental Protection Agency) (EPA, 1998). Even, they are considered one of "The less flammable insulating liquid" and classified by the IEC with high flash point level, exceeding the 300 °C (Hopkinson, 2009; Li, Zhang et al., 2012), and its combustion point in the range of 340°- 360°C (Bashi et al., 2006; Murphy Member & Graham, 2009).

Application and uses began at the earlier 1990s based on research and development process as a result of environmental regulations and searching a safety operation (Mcshane, 2002). In 1997, there were installed several oil-immersed transformers using natural esters at utilities and industrial sites in the United Stated. Similar projects have been installed in Latin America with pad-mounted technologies (Navas et al., 2012; Rebolledo, 2014). In Colombia, the Caribbean Coast Region utility installed in 2015 twenty-two power distribution transformers operating with natural esters in the range of 37.5 kVA, 50 kVA and 75 kVA (Silva et al., 2016). Table 1 describe the benefits of use natural esters in distribution transformers.

Table 1. Benefits of using natural ester as a dielectric and refrigerant in distribution transformers.

No	Types of benefits	Highlights Using Natural Ester Fluids	References
1	Thermal	A lower inflammation risk during operation. Certain trademarks of natural ester are listed as Fire Resistant fluids by Factory Mutual Global (FM) and Underwriters Laboratories (UL) for use in compliance with requirements established by National Electric Code (NEC) and industry safety standards.	Bertrand & Hoang, 2004; Mcshane, 2002.
2		A Higher flash point: in ASTM D 6871 and IEC 62770, an acceptable temperature of 300°C or higher is established	ASTM, 2003; International Electrotechnical Commission, 2013)
3		A Higher fire point, in ASTM D 6871 and IEC 62770, an acceptable temperature of 275°C or higher is established.	ASTM, 2003; International Electrotechnical Commission, 2013.
4		Several trademarks of natural ester fluids have been considered by FM, UL® and NEC® as less flammable insulating liquids (>300°C).	Arief et al., 2014; Cargill, 2013; GlobalTox International Consultants, 1999; Mcshane, 1999.

No	Types of benefits	Highlights Using Natural Ester Fluids	References
5	Environmental	Readily (95- 100%) Biodegradable and no Bio-accumulative, exceeding the standard level recommended by the United States Environmental Protection Agency EPA.	ASTM, 2003
6		Zero toxicity: It has been proven to be non-toxic as its natural origin, it has edible additives, classifying it as non-toxic.	Aluyor et al., 2009; Fofana, 2013.
7		Recyclable and adjusted to different final applications	Brettis, 2013.
8		No PCB´s: It does not contain Polychlorinated Biphenyls (PCB´s) and does not generate them either due to its natural origin.	Bertrand & Hoang, 2004; Boss & The, 2000; Rebolledo, 2014.
9	Technical	Longer equipment life-time: natural esters extends the transformer life-time due to its thermal properties.	Asano & Page, 2014; Bertrand & Hoang, 2004)
10		Safer facilities: Allowing the reduction of risk levels indoor and guarantying safe condition operations.	Arief et al., 2014; Cargill, 2013; GlobalTox International

This paper describes economic, technical and environmental benefits of the use of distribution transformers that operate with natural ester in Colombia, emphasizing that its application worldwide has a wide use and acceptance during the last two decades. Also derived products such as ethyl esters derided from natural estersdemonstrate its uses(Villardi, Leal, et al., 2017). Also trends are working in Hydro deoxygenation process of natural esters are recent research activities (Chistyakov et al., 2017) in the field. A technical and normative comparison of the oil is made, showing the operating characteristics and its positive impact on the environment.

METHODOLOGY

A descriptive and applied methodology was applied for this research, the technical and economic feasibility of using full-filled distribution transformers with natural ester instead of mineral oil was analyzed. Two factors were considered: the purchase and installation costs and the thermal behavior of the oil, the second factor is fundamental in transformer life-time and in the compliance with its technical requirements.

Tested Samples

The number of power distribution transformers analyzed were forty-four in the pilot Project. The half of the samples operate using mineral oil and the rest use natural ester. The study considered a couple of transformers with the same technical characteristics and charge regimen. Table 2 shows distribution transformers installed by department and their nominal power capacity.

Table 2. Nominal power capacity in kVA and location in Caribbean Coast Region of Colombia.

Department	Distribution transformer using mineral oil		Distribution transformer using natural ester fluid	
	Power (KVA)	**Number**	**Power (KVA)**	**Number**
GUAJIRA	75	1	75	1
	37.5	1	37.5	1
	50	1	50	1
MAGDALENA	50	2	50	2
CORDOBA	37.5	1	37.5	1
	75	1	75	1

Department	Distribution transformer using mineral oil		Distribution transformer using natural ester fluid	
	Power (KVA)	Number	Power (KVA)	Number
	37.5	1	37.5	1
SUCRE	75	1	75	1
	50	1	50	1
BOLIVAR	50	2	50	2
	75	2	75	2
	25	1	25	1
CESAR	37.5	1	37.5	1
	30	1	30	1
ATLANTICO	50	2	50	2
	75	1	75	1
	75	1	75	1
	50	1	50	1
TOTAL	---	22	---	22

Purchase and installation cost analysis

In order to buy a product in Colombia it is mandatory to pay a tax value equal to the 19% of the product price. In the case of full-filled transformers using natural ester fluids the tax value does not apply because Colombia´s government established that products based on energy efficiency, renewable energy and environmental protection, do not have to pay taxes. This is supported in Colombian law 1715-2014 (Congreso de Colombia, 2014) and UPME resolution No. 0563-2012 (UPME, 2012).

Thermal analysis

The Infrared thermography (IRT) is a technique applied in electrical and mechanical systems and medical applications due to its non-intrusive feature, allowing to analyze data obtained from a non-contact thermal imaging device (Arfaoui et al., 2012). This research compares thermal in both technologies. The temperature was measured in distribution transformer cube using mineral oil and natural ester with the same properties, the same day and the same hour in maximum hour scenario registered during evenings. The results were compared according with the established in international standards as ASTM D 6871-03 (ASTM, 2003) and the ASTM D 3487-16 (ASTM, 2016), that are the referents for natural esters and mineral oil, respectively.

RESULTS

Economic benefits

The following table summarizes the economic benefits of use natural ester fluids in transformers, which makes them competitive in comparison with mineral oils, showing economic benefits considering environmental benefits established according to Resolution 0563 of 2012 established by the Energy and Mining Planning Unit (UPME) in Colombia.

Table 3. Economic benefits using natural ester fluids as dielectric and coolant oils in Colombia

Powerdistributiontransformers (KVA)	Filled withMineral Oil.	Initial Investmentdifference aftertaxes.	Final taxvalues(+19 %)	Filled with Natural Ester	Final Investment before taxes.	Final Investment before taxes.
25	*$ 855*	17%	$1.017	$ 1.026	$1.026	-1%
50	*$ 1.201*	20%	$1.429	$ 1.501	$1.501	-5%
75	*$ 1.516*	23%	$1.804	$ 1.971	$1.971	-8%
112.5	$ 2.070	11%	$2.464	$ 2.338	$2.338	5%
600	*$13.333*	9%	$15.867	$ 14.632	$14.63	8%

1.1 Thermal behavior

Table 4 shows measured values realized in power distribution transformers. All registered values using IRT are lower using full-filled distribution transformers using natural esters.

Table 4. Temperature measured in transformers with natural ester fluids and mineral oil using IRT.

Department	Power (KVA)	Mineral oil	Natural Ester
GUAJIRA	75	37,9	36,8
	37.5	40,4	37,8
	50	40,1	37,3
MAGDALENA	50	44,9	41,7
	50	42,5	40,3
CORDOBA	37.5	45,4	39,6
	75	43,4	37,5
	37.5	44,5	38,3
SUCRE	75	39,7	37,4
	50	43,9	39,8
BOLIVAR	50	39,9	36,5
	50	44,1	40,5
	75	40,7	38,6
	75	46,2	41,47
	25	42,8	38,7
CESAR	37.5	43,6	38,7
	30	43,9	39,1
ATLANTICO	50	43,1	39,7
	50	42,7	39,3
	75	43,7	40,2
	75	45,6	41,8
	50	46,3	42,5

The following figures show that the temperature in distribution transformers using natural ester is lower than in mineral oil full-filled technology for all capacities, which indicates, according to experts, a greater probability of having a longer useful life and even capable of having a thermal performance with greater benefits for transformer and its elements.

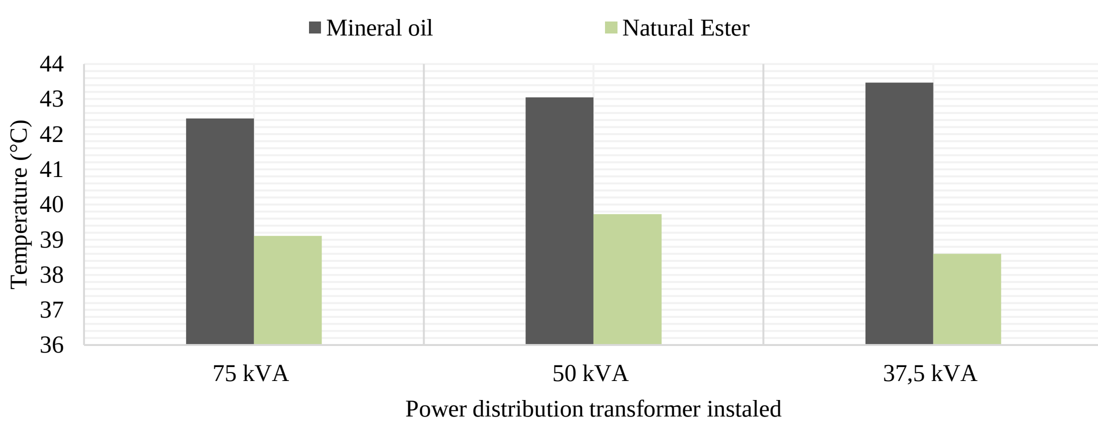
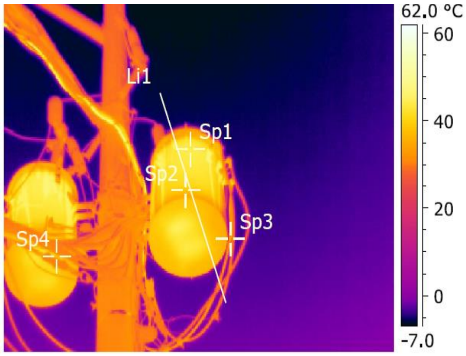


Figure 1. Thermal comparison of distribution transformers installed.

Figure 2 show thermal images examples captured for one distribution transformer. The points on the thermal image represents the zones of interest in the transformer to be studied.



a)

b)

Figure 2. IRT comparison of distribution transformers installed.

CONCLUSIONS

The results obtained during the development of the research and the pilot application project demonstrate the high competitiveness of full-filled transformers using natural ester fluids due to their operating properties which allow them to have a much higher fire and flash point than mineral oils, as well as their biodegradability, non-toxic properties and easy recycling process. The costs of installation and assembly are very similar and are justified by the application of Law 1715-2014 in Colombia and Resolution 0563 of 2012 established by the Energy and Mining Planning Unit (UPME) in Colombia (UPME, 2012).The results show that full-filled transformers using natural ester and dielectric and coolant have lower temperatures under operating conditions and a reduced environmental impact compared to the results obtained for mineral full-filled distribution transformers using mineral oil.

REFERENCES

1. Ab Ghani, S., Muhamad, N. A., Noorden, Z. A., Zainuddin, H., Abu Bakar, N., & Talib, M. A., "Methods for improving the workability of natural ester insulating oils in power transformer applications: A review". Electric Power Systems Research. 163, 655-667, 2018.
2. Aluyor, E. O., Obahiagbon, K. O., and Ori-jesu, M., "Biodegradation of vegetable oils : A review". Scientific Research and Essays ,4(6), 543–548.2009.
3. Arfaoui, A., Polidori, G., Taiar, R., & Popa, C., "Infrared Thermography in Sports Activity". In Infrared Thermography, 141–168. 2012.
4. Arief, Y. Z., Ahmad, M. H., Lau, K. Y., and Oil, A. T., "A Comparative Study on the Effect of Electrical Ageing on Electrical Properties of Palm Fatty Acid Ester (PFAE) and FR3 as Dielectric Materials", IEEE International Conference on Power and Energy (PECon). IEEE,128–133.2014,
5. Asano, R., and Page, S. A., "Reducing Environmental Impact and Improving Safety and Performance of Power Transformers With Natural Ester Dielectric Insulating Fluids", IEEE Transactions on Industry Applications 50(1), 134–141.2014.
6. ASTM. D6871-03: Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus, 10ASTM 14–162003, http://doi.org/10.1520/D6871-03R08.2
7. ASTM. D3487-16: Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus, 2016.
8. Bashi, S. M., Abdullahi, U. U., Yunus, R., and Nordin, A., "Use of Natural Vegetable Oils as Alternative Dielectric Transformer Coolants". Journal of the Institution of Engineers, Malaysia, 67(2), 4–9.2006.
9. Bertrand, Y., and Hoang, L., "Vegetable oils as substitute for mineral insulating oils in medium-voltage equipments". Session CIGRE. 2004.
10. Boss, P., Sc, C., and the, I., "Insulating fluids for power transformers", 1–8.2000

11. Brettis. "Aceites Para Transformadores", Modulo 8. Retrieved from http://www.brettis.com/Tutorial/08Transformadores.pdf. 2013.
12. Cargill. Envirotemp™ FR3™ Fluid. R2020 Reference Data.2013.
13. CIGRE working group A2-35., "Experiences in Service with New Insulating Liquids". United Kingdom: Zhongdong Wang (UK).2010.
14. Ciuriuc, A., Vihacencu, M. S., Dumitran, L. M., and Notingher, P. V., "Comparative Study on Power Transformers Vegetable and Mineral Oil Ageing". 12 International Conference on Applied and Theoretical Electricity (ICATE). IEEE, 2012,
15. Chistyakov, A. V., Tsodikov, M. V., Zharova, P. A., Kriventsov, V. V., Corbetta, M., and Manenti, F. "The direct hydrodeoxygenation of vegetable oil over Pt-Sn/Al2O3 catalysts". Chemical Engineering Transactions, 57, 871–876. 2017.
16. Congreso de Colombia. Ley N° 1715 Del 13 De Mayo De 2014,2014, Colombia. Retrieved from http://www.upme.gov.co/Normatividad/Nacional/2014/LEY_1715_2014.pdf
17. Delgado, F., Fernandez, I., Ortiz, F., Renedo, C., Ortiz, A., and Carcedo, J., "Thermal analysis of transformers insulation based on vegetable esters". In 33rd Electrical Insulation Conference, EIC 2015, pp. 606–609. 2015,
18. EPA., OPPTS 835.3100. "Aerobic Aquatic Biodegradation. Fate, Transport and Transformation" Test Guidelines. (Thomas A. Edison Technical Center, Ed.). Franksville (USA): Cooper Power Systems.1998.
19. Navas, D., Cadavid-Ramírez, H., and Echeverry-Ibarra, D. F. "Aplicación del aceite dieléctrico de origen vegetal en transformadores eléctricos". Ingeniería y Universidad, Vol. 16, (1), 201–223.2012,
20. Fofana, I., 2013. "50 Years in the Development of Insulating Liquids", IEEE Electrical Insulation Magazine 29(5), 13-25, 2013.
21. GlobalTox International Consultants. Final Report: Acute Trout Toxicity Testing for Two Envirotemp FR3 Formulations, (2).1999.
22. Hopkinson, P., "Progress Report On Natural Esters For Distribution And Power Transformers". IEEE Power and Energy Society General Meeting IEEE, 2009.
23. International Electrotechnical Commission. IEC 60076-14. Power Transformers - Part 14: Liquid-inmersed power transformers using high-temperature insulation materials, IEC 124. Switzerland.2013.
24. Li, J., Zhang, Z., Grzybowski, S., and Liu, Y., "Characteristics of Moisture Diffusion in Vegetable Oil-paper Insulation", EEE Transactions on Dielectrics and Electrical Insulation 19 (5), 1650–1656.2012,
25. Mcshane, C. P., "Natural and Synthetic Ester Dielectric Fluids : Their Relative Environmental , Fire Safety , and Electrical Performance". In 1999 IEEE Industrial and Commercial Power Systems Technical Conference (pp. 1–8). 1999Sparks, NV: IEEE. http://doi.org/10.1109/ICPS.1999.787238
26. Mcshane, P., 2002, Vegetable-Oil-Based Dielectric Coolants. IEEE Industry Applications Magazine, 8(3), 34–41. http://doi.org/10.1109/2943.999611
27. Murphy, J. R., Member, S., and Graham, J., "Distribution Utility Experience with Natural Ester Dielectric Coolants", 9–11.2009.
28. Rebolledo, L. and, Guissela. A., "Evaluación de la viabilidad técnica y económica de la utilización del aceite dieléctrico vegetal como sustituyente del aceite dieléctrico mineral en transformadores de distribución nuevos y usados en las empresas municipales de Cali. BS thesis,Universidad Autónoma de Occidente.
29. Rycroft, M., 2014, "Vegetable oil as insulating fluid for transformers". Energize, 37–40.2014.
30. Sagastume Gutiérrez, A., Cabello Eras, J. J., Sousa Santos, V., Hernández Herrera, H., Hens, L., and Vandecasteele, C. "Electricity management in the production of lead-acid batteries: The industrial case of a production plant in Colombia". Journal of Cleaner Production, 198, 1443–1458.2018.
31. Silva-Ortega, J. I., Candelo-Becerra, J. E., Umaña-Ibañez, S. F., Mejia-Taboada, M. A., and Palacio-Bonill, A. R., "Power Distribution Transformers using Natural Ester Fluids as Dielectric and Coolant". Inge Cuc, 12(2), 79–85. 2016.
32. UPME. Res. 0536 - 2012 2012, Colombia. Retrieved from http://www1.upme.gov.co/Documents/Normatividad/Resoluciones/RES._0563.pdf
33. Villardi, H. GD., Leal, M. F., Andrade, P. H. D. A., Fernando, L. P., and Salgado, A. M. "Study of the Production of Ethyl Esters of Soybean Industry Using Waste Acid with and without Catalyst". Chemical EngineeringTransactions, 57, 163–168. 2017.