11125
A2 – PS2

Session 2022

Type Testing of 80 MVA Power Transformer with a new Bio-based, Biodegradable and Low Viscosity Insulating Liquid

C. WOLMARANS*, A. GAMIL[2], A. AL-ABADI[2], M. MILONE[2], J. JORDAAN[3], R. HELLBERG[4]**
Nynas[1], SGB-SMIT Group (Regensburg[2], Pretoria[3]), WESTNETZ GmbH[4]
South Africa[1],[3], Germany[2,4]

cawo@nynas.com* , ahmed.gamil@sgb-smit.group**

SUMMARY

In this paper a detailed report will be given concerning the successful use and type testing of an 80 MVA ONAF 115/21 kV power transformer filled with NYTRO BIO 300,4X, where the reference liquid used originally in the transformer design was a Gas-To-Liquid (GTL) insulating liquid complying to IEC 60296. NYTRO BIO 300X is a low viscosity, bio-based and biodegradable hydrocarbon type liquid. Due to the liquid's very low viscosity profile, as well as low density and high specific heat, particular attention was given to thermal modelling and special analysis of the cooling curves during the temperature rise test to help quantify the potential benefit to thermal optimisation. In addition, lightning impulse and Partial Discharge (PD) testing, as well as other required tests were successful. The temperature rise test and resulting thermal analysis demonstrated that the lower viscosity profile compared to another mineral insulating oil of more standard viscosity profile, led to a reduction in top oil temperature, an improved gradient, shorter time constant, and better inter-winding heat distribution. This combined with the low density of the NYTRO BIO 300X means that there is potential for thermal optimisation of the unit perhaps resulting in more compact and lighter units or saving in the cooling system footprint. On the other hand, if one makes use of a more standard design but retains the thermal enhancement given by the liquid then the margin to the guaranteed temperature rises increases and effectively the power transformer can have a higher long term overload rating (depending on the current ratings of accessories). Another key aspect when dealing with the choice of alternative liquids is design adaptation – whilst ester liquids can have other advantages such as a higher fire point other key liquid differences (particularly thermal and dielectric) lead to the need for rather significant design changes on a power transformer. The first experiences showed herein point to the fact that with NYTRO BIO 300X one can achieve a transformer with a more environmentally friendly footprint with the added benefit of thermal enhancement, without very onerous design changes. In addition, the fact that the NYTRO BIO 300X meets the IEC 60296 specification means the liquid shares many similarities with mineral insulating oils.

KEYWORDS

Transformer, Alternative Liquid, Biodegradable, Sustainability, Thermal, Overload

1 INTRODUCTION

The power transformer is a high value and key substation asset. Reliability, life expectancy, carbon footprint, environmental impact, and sustainability are all key topics in the spotlight regarding power transformers. The chosen insulating liquid influences transformer design (both dielectric and thermal), as well as its temperature related properties. Moreover, the sustainability and biodegradability of the liquid influences that of the transformer. In recent years there have been a number of publications focusing on alternative liquids [1-9]. In this paper, results of a new fully bio-based, readily biodegradable, and recyclable hydrocarbon type insulating liquid NYTRO BIO 300X tested in an 80 MVA ONAF 115 kV power transformer and the main results of the factory test are reported and compared to the original transformer (of same design), which was filled with a Gas-To-Liquid (GTL) insulating liquid (to IEC 60296).

2 INSULATING LIQUID

In this section of the paper, the results of a factory acceptance test on a power transformer will be the focus. The two main insulating liquids that are compared are: (*i*) a typical GTL liquid (according to IEC 60296) and (*ii*) NYTRO BIO 300X a bio-based hydrocarbon type insulating liquid (which meets and exceeds IEC 60296). Hereinafter the NYTRO BIO 300X will be abbreviated as Bio-Based Hydrocarbon (BIO) for improved readability.

2.1. Overview

In Table 1 below the main physical and chemical properties of the BIO and the GTL, as well as for comparative purposes a typical mineral insulating oil NYTRO Lyra X are provided. BIO is a hydrocarbon type liquid produced from bio-based feedstocks and thus is rather similar to typical mineral insulating oils in many ways but with some differences. The BIO has much lower viscosity than typical mineral oils (3.7 mm²/s at 40°C vs around 10 mm²/s at 40°C). The BIO also has rather low density and is free of significant aromatic hydrocarbons. In addition, the BIO is also readily biodegradable.

Table 1: Comparison of key physical and chemical properties of the insulating liquids

Property	Method	Unit	NYTRO Lyra X (Mineral)	NYTRO BIO 300X (BIO)	GTL
Specification	-	-	IEC 60296	IEC 60296	IEC 60296
Biodegradability	OECD 301	-	Inherently	Readily, OECD 301	Inherently
Bio-Based carbon content	ASTM D6866	%	0%	>99%	0%
Density at 20°C	ISO 12185	kg/dm³	0.868	0.785	0.806
Specific heat at 40°C	ASTM D2766	kJ/kg.K	1.90	2.15	2.02
Thermal conductivity at 40°C	ASTM D7896-19	W/m.K	0.114	0.133	0.131
Viscosity at 40°C	ISO 3104	mm²/s	9.5	3.7	9.5
Viscosity at -30°C	ISO 3104	mm²/s	780	52	382
Viscosity at -40°C	IEC 61868	mm²/s	≈3000	≈150	Approaching Pour Point
Pour point	ISO 3016	°C	-54	-66	-42
Flash point, PM	ISO 2719	°C	146	145	190
Interfacial tension	IEC 62961	mN/m	>43	>43	>43
Aniline point	ASTM D611	°C	86	99	114
Aromatic content	IEC 60590	%	≈4	Not detectable	Not detectable
Relative Permittivity at 90°C	IEC 60247		2.09	1.99	2.03

2.1.1. Sustainability & Environmental considerations

There are four main aspects to consider regarding sustainability and environmental friendliness of the insulating liquid:

- Feedstock, bio-based carbon content
- Biodegradability
- Eco-toxicity
- Useful lifetime and recyclability

It is important that bio-based carbon content and biodegradability as concepts are not confused, the bio-based carbon content refers to whether the carbon is fossil-based or bio-based, this is an issue of feedstock source and is measured using a radiocarbon analysis method ASTM D6866. NYTRO BIO 300X is fully bio-based having a typical bio-based carbon content of >99% [10]. GTL type liquids are produced by the Fischer-Tropsch process from natural gas and are thus typically purely fossil-based and thus will have no bio-based carbon. This is the same situation as for traditional mineral oils which are crude oil based. The advantage of a high bio-based carbon content is the contribution to the net reduction in CO_2 emissions. Biodegradability implies the ability of microorganisms to breakdown the substance and this is in fact independent of the bio-based carbon content. NYTRO BIO 300X is readily biodegradable according to OECD 301 [11] predominantly because it is a relatively low molecular weight hydrocarbon. NYTRO BIO 300X is also non eco-toxic and fully recyclable using the same techniques used on mineral insulating oils, this is because its physical/chemical properties and ageing behaviour are equivalent to oils meeting IEC 60296 Ed 5 [10].

2.1.2. Viscosity and thermal properties

The viscosity of an insulating liquid is the predominant factor that determines convective heat transfer [13] in a power transformer. See Table 1 for the thermal conductivity and specific heat comparison as well as Figure 1 below which compares the dynamic viscosity of the NYTRO BIO 300X and the GTL. The lower viscosity profile across the functional temperature range of the NYTRO BIO 300X means that one expects higher convective heat transfer and thus improved heat dissipation from winding to oil and therefore a reduced winding temperature gradient. Therefore, additional heat will be transferred to the cooling system, at a faster rate, and then dissipated to the ambient air. Due to the low density of the BIO an improved thermal buoyancy force is expected which is the key factor for improving the resulting oil axial gradient and hence, achieving lower top oil temperature.

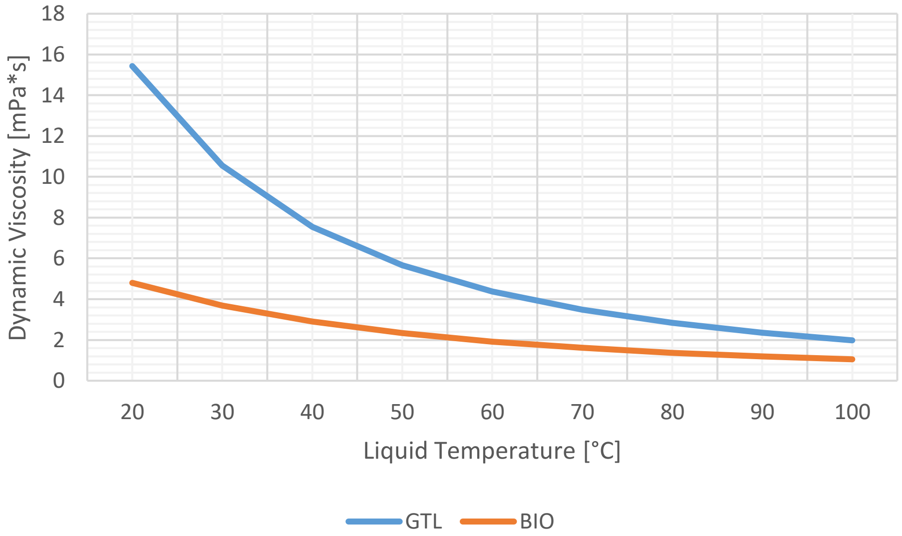

Figure 1: Dynamic Viscosity comparison between NYTRO BIO 300X and the GTL.

3 TRANSFORMER PERFORMANCE

3.1. Case study – 80 MVA Power Transformer

This section presents results of the 80 MVA ONAF unit (which also has a 63 MVA ONAN rating) whose specifications are found in Table 2.

There were 2 units built based on the exact same design. One unit was filled and tested with GTL liquid and the other with the BIO liquid (see Table 1). Prior to the use of the BIO liquid (NYTRO BIO 300X) and the completion of the liquid filling and factory testing stages a short design review was conducted. Regarding dielectric design electric field stresses were re-checked because the BIO has slightly lower permittivity than both typical mineral oils and GTL (see Table 1), the resulting electric field stress distribution was only marginally different from that of the original GTL design and all stresses were found to be compliant with the factory specific design rules for the particular unit. The design of the specific unit mentioned herein remained unchanged and all accessories and materials were the same for the original unit which was GTL filled.

All relevant type and routine tests (including losses, impedance, resistance, turns ratio, harmonics, insulation tests including impulse and partial discharge, sound, and the temperature rise test) according to IEC 60076. These were performed on both units and the BIO filled unit passed all requirements of the Factory Acceptance Test (FAT). Apart from the temperature rise tests which are discussed in detail in Section 3.1.2, all other parameters showed comparable results. Results that will be presented herein are those of the temperature rise test and the induced overvoltage withstand test with PD measurement.

3.1.1. Nameplate details

Table 2 lists the key nameplate details of the power transformer design used in the case study described herein. Figure 2 depicts a photograph of the type of unit in question.

Table 2: Key nameplate details of the transformers

Frequency	50 Hz
Power Rating	80 MVA
Cooling	ONAF
Voltage	115 ± 9 ×1.778% / 21 kV
Impedance	16%
Vector group	YNyn0(d)
Test voltages	HV: LI 550 AC 230
Temperature rise guarantees	60K (Top oil) / 65K (Winding) / 78K (Hot Spot)
Tap changer	OLTC
Liquid volume	18000 litres
Sealing	Conservator, Free Breathing

Figure 2: Photograph of the completed 80 MVA unit filled with NYTRO BIO 300X.

3.1.2. Temperature rise test

Temperature rise tests were conducted in accordance with IEC 60076-2 on both transformers (one filled with GTL, the other with BIO). The winding temperatures, gradients and hot spots were determined using a Thermal-Hydraulic Network Model (THNM) which is based on applying the heat and mass conservation principles with pressure balance in closed loops of all windings in operation and the radiators. The THNM was successfully coupled to the dynamic thermal behavior based on cooling curve analysis using the two exponential functions in an iterative way for the calculation of the heat convection. For an oil-filled transformer, the oil motion inside the transformer, which is generated by the thermal buoyancy driven force, is governed by the heat convection. This heat gained by the oil is dissipated by the radiator to the ambient air. For detailed information about the thermal model and the cooling curve analysis method see [11, 12]. The results are presented in Table 3 and the two units are compared. The BIO led to a reduction in 4K to the top oil temperature as well as 5 to 6 K reduction in hot spot with a 1 to 2K saving in winding average and gradient. Figures 3 and 4 show the top oil, bottom oil and ambient temperature during the heating up phase of the temperature rise test whist equilibrium is being established – the lower oil temperature rise of the BIO is evident. It should also be noted that the thermal time constants are reduced in the case of BIO.

Table 3: Measured results from the temperature rise tests of the two transformers.

Position	**Temperature rise**		**Difference**	**Comments**
	GTL	BIO		
Top oil [K]	54.5	50.5	-4	by thermocouple
HV winding average [K]	55.0	53.6	-1.4	by ohmic resistance
LV winding average [K]	49.7	47.7	-2	
HV to oil Gradient [K]	18.5	17.6	-0.9	Calculation [11,12]
LV to oil Gradient [K]	13.2	11.7	-1.5	
HV hot spot [K]	75.4	70.4	-5	
LV hot spot [K]	69.3	63.6	-5.7	
Oil Thermal Time Constant [min.]	88.7	85.8	-2.9	
Windings thermal time constant [min.]	6.8	5.7	-1.1	

In addition, Table 4 reflects the simulated results based on thermal models of the transformer and the liquid thermal data [11,12]. In general, there is good agreement between simulated and measured temperatures whilst the gradients in both cases are slightly overestimated (well within generally accepted tolerances) in the simulation. Comparing the predicted improvement between BIO and GTL there is good agreement between the simulation and the measured results.

Table 4: Simulated results from the temperature rise tests of the two transformers

Position	**Temperature rise**		**Difference**	**Comments**
	GTL	BIO		
Top oil [K]	54.7	50.9	-3.8	Simulation [11,12]
HV winding average [K]	59.9	57.6	-2.3	
LV winding average [K]	51.7	49.5	-2.2	
HV to oil Gradient [K]	20.3	19.1	-1.2	
LV to oil Gradient [K]	12.1	11	-1.1	
HV hot spot [K]	77.6	72.5	-5.1	
LV hot spot [K]	68.3	63.2	-5.1	

The improved temperature rises test results seen in the unit filled with NYTRO BIO 300X are attributed primarily to the lower viscosity profile of the liquid than the GTL (see Figure 1). These results mean that there is potential for thermal optimization of designs using BIO especially if one considers short time overloading.

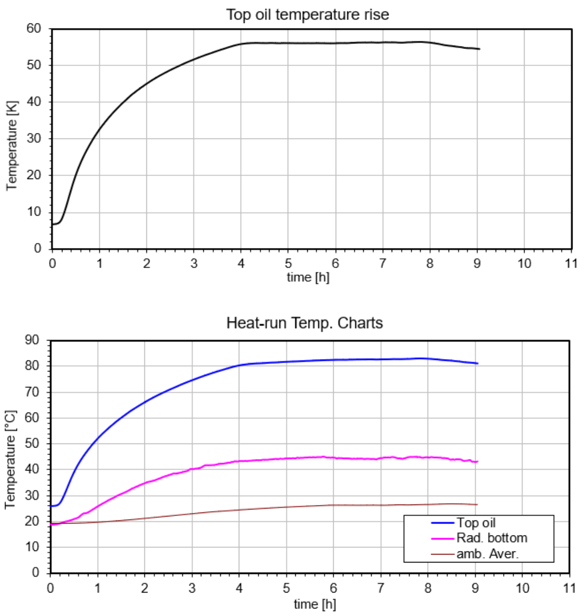

Figure 3: Top oil temperature rise (top graph) and top oil, bottom oil and ambient temperatures (bottom graph) during the temperature rise test, 80 MVA unit filled with GTL.

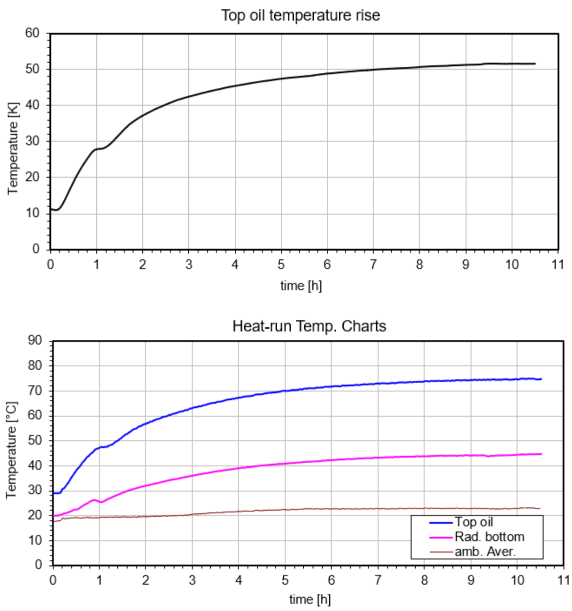

Figure 4: Top oil temperature rise (top graph) and top oil, bottom oil and ambient temperatures (bottom graph) during the temperature rise test, 80 MVA unit filled with BIO.

3.1.3. Partial Discharge test

Dielectric tests as per IEC 60076-3 were done on both power transformers and the standard lightning impulse tests were satisfactory on both units. Induced over voltage withstand test with PD measurement according to IEC 60076-3 was also done and results shown herein. The maximum allowable PD value was maximum 250 pC at 158% UN over 60 minutes. during the testing. See Table 4, Table 5 and Figure 5 for the results. While it is doubtful that the difference in pC values of the two units is due solely to the properties of the BIO, one does notice the lower pC values in the unit filled with BIO. It is plausible that the very low viscosity of BIO will lead to faster and more complete insulation impregnation, and this may be a contributing factor to the excellent factory test results that were obtained. Nonetheless both units passed the test satisfactorily.

Table 5: Factory PD test results, BIO, 80 MVA

HV-Phase-to-Earth [kV]	*Time*	*1U [pC]*	*1V [pC]*	*1W [pC]*
0,0	0 s	2	3	4
79,7	0 s	3	5	4
79,7	1 min	3	4	4
104,9	0 s	5	5	5
104,9	5min	3	4	4
132,8	48s	-	-	-
104,9	0s	5	5	5
104,9	5 min	3	4	3
104,9	10 min	3	4	3
104,9	15 min	3	4	5
104,9	20 min	3	5	5
104,9	25 min	3	4	5
104,9	30 min	3	4	5
104,9	35 min	3	4	4
104,9	40 min	3	4	4
104,9	45 min	3	4	4
104,9	50 min	3	4	4
104,9	55 min	3	4	4
104,9	60 mln	3	4	4
79,7	0 s	4	4	5
79,7	1 min	3	3	4
0,0	0 s	3	3	4

Table 6: Factory PD test results, GTL, 80 MVA

HV-Phase-to-Earth [kV]	*Time*	*1U [pC]*	*1V [pC]*	*1W [pC]*
0,0	0 s	3	3	4
79,7	0 s	4	14	6
79,7	1 min	3	17	7
104,9	0 s	6	16	9
104,9	5min	5	15	6
132,8	48s	-	-	-
104,9	0s	6	16	9
104,9	5 min	5	15	6
104,9	10 min	3	3	3
104,9	15 min	3	4	3
104,9	20 min	3	3	3
104,9	25 min	3	3	3
104,9	30 min	3	3	3
104,9	35 min	4	4	3
104,9	40 min	4	3	3
104,9	45 min	10	5	3
104,9	50 min	15	7	3
104,9	55 min	5	3	3
104,9	60 mln	5	3	3
79,7	0 s	4	5	6
79,7	1 min	5	3	3
0,0	0 s	3	4	4

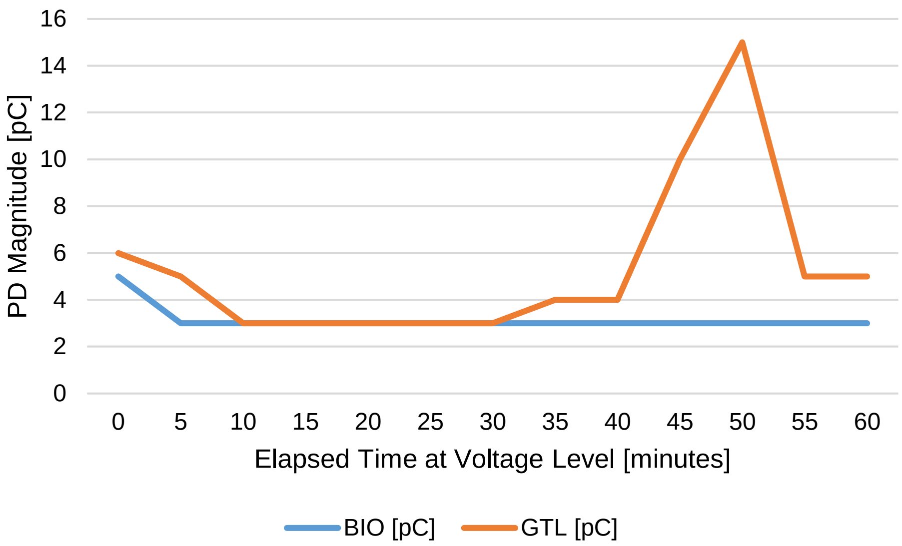

Figure 5: Phase U PD result for each transformer during 104.9 kV (1.58 Un). There was a period of slightly elevated PD in the unit filled with GTL compared to the one with BIO, although the levels in both cases are well below the limit of maximum 250 pC.

4 CONCLUSION

A project involving two 80 MVA power transformers, filled and tested with different insulating liquids, allowed the comparisons of a GTL type insulating liquid and BIO (NYTRO BIO 300X). Factory testing was successful for the BIO filled unit and the most notable difference was that of the temperature rise test. Oil and winding temperatures were improved thanks to the comparably lower viscosity of the BIO. There is potential for power transformers with specific improved overload ratings or having an optimized design with less cooling equipment (or less material) when using the NYTRO BIO 300X (BIO) liquid.

In addition, design review concluded that there was no need to change any design parameters of the unit and the standard IEC 60076-3 dielectric tests all passed satisfactorily. Notwithstanding the dielectric suitability of a transformer design to a specific liquid must be considered when using newly available and alternative liquids.

BIBLIOGRAPHY

[1] D. Vuković, M. Milone, O. Hjortstam, and H. Faleke, "Experimental Discharge Initiation Study for Paper and Pressboard Insulated Electrodes in Mineral Oil and Synthetic Ester Fluid," in 2019 IEEE 20th International Conference on Dielectric Liquids (ICDL), 2019, pp. 1-5: IEEE.

[2] U. M. Rao et al., "A review on pre-breakdown phenomena in ester fluids: Prepared by the international study group of IEEE DEIS liquid dielectrics technical committee," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 27, no. 5, pp. 1546-1560, 2020.

[3] D. Kweon, K. Koo, J. Woo, and Y. Kim, "Hot spot temperature for 154 kV transformer filled with mineral oil and natural ester fluid," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, no. 3, pp. 1013-1020, 2012.

[4] C. Wolmarans and R. Abrahams, "Widening the landscape of transformer utilisation & optimisation using a novel insulating liquid," presented at the Advanced Research Workshop on Transformers 2019, Cordoba, Spain, 7-9 October, 2019.

[5] F. Negri and A. Cavallini, "Comparison of the charge trapping tendency between ester impregnated cellulose sheets and mineral oil ones," in 2019 IEEE 20th International Conference on Dielectric Liquids (ICDL), 2019, pp. 1-4: IEEE.

[6] C. Y. Perkasa, N. Lelekakis, T. Czaszejko, J. Wijaya, and D. Martin, "A comparison of the formation of bubbles and water droplets in vegetable and mineral oil impregnated transformer paper," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 21, no. 5, pp. 2111-2118, 2014.

[7] S.-H. Choi and C.-S. Huh, "The Lightning Impulse Properties and Breakdown Voltage of Natural Ester Fluids Near the Pour Point," Journal of Electrical Engineering and Technology, vol. 8, no. 3, pp. 524-529, 2013.

[8] R. Frotscher, J. Harthun, C. Perrier, D. Vukovic, M. Jovalekic, and M. Schafer, "Behaviour of ester liquids under dielectric and thermal stress-from laboratory testing to practical use," CIGRE Technical Programme, pp. D1-105, 2012.

[9] I. Radic, J. Branka, I. Sitar, and A. Majcen, "Synthetic Esters in Power and Special Transformers," presented at the International Colloquium Transformer Research and Asset Management Dubrovnik, 2012.

[10] NYNAS, "Product Data Sheet - NYTRO BIO 300X," ed. www.nynas.com, 2020.

[11] A. Gamil, A. Al-Abadi, M. Schiessl, F. Schatzl and E. Schlücker, "Improvements on Thermal Performance of Power Transformers: Modelling and Testing," 2019 6th International Advanced Research Workshop on Transformers (ARWtr), 2019, pp. 13-18, doi: 10.23919/ARWtr.2019.8930180.

[12] A. Gamil, A. Al-Abadi, F. Schatzl and E. Schlücker, "Theoretical and Empirical-Based Thermal Modelling of Power Transformers," 2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE), 2018, pp. 1-4, doi: 10.1109/ICHVE.2018.8642180.

[13] D. Susa, "Dynamic thermal modelling of power transformers," Doctorate, Helsinki University of Technology, Espoo, 2005.