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DETERMINATION OF TOP OIL AND HOT SPOT TEMPERATURE OF A POWER TRANSFORMER USING FUZZY LOGIC

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ABSTRACT

Monitoring the temperature of a power transformer has a crucial role to keep it's good performance, prolonging its lifetime, as well as, ensuring stability of the whole electric system. In this paper, we've estimated the top-oil temperature and the coil hotspot. A fuzzy logic-based methodology was developed leading to satisfying results compared to the IEEE-C5791 model. A significant accomplishment, since this method could provide monitoring with better precision, in a simpler way, without the need for short-circuit tests and internal transformer data, allowing companies and engineers to perform upfront maintenance in the substations equipment's.

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INTRODUCTION

The power transformer is one of the most expensive equipment in the electrical system. Performing regular maintenance of this equipment avoids unnecessary failures and shutdowns, minimizing forced (unscheduled) shutdowns and, hence, decreasing revenue loss for the transmission agents. Brazil has a large number of electrical system equipment's with many years of operation. It can be stated very precisely that the current average age of the installed equipment is close to 30 years old, and that approximately 65% of the equipment is in use for more than 25 years (Suñé et al. 2013). In 2017, a study was carried out where, out of a total of 219 power transformers, 50 were over 35 years old, 13 over 50 years old and two of them started to operate 62 years ago (SCHMITZ et al.). Regular maintenance on the electrical plants is essential to ensure the proper behavior of the present equipment in substations. According to the statistical analysis report of forced disconnections of ONS equipment's (National Electric System Operator), in 2018, from all transformer disconnections, 18.52% originated from the switch and 12.96% from the windings (ONS 2019).

These faults can be detected by monitoring some quantities. For the switch, it is necessary to evaluate the vibration and temperature, while, for the windings, are evaluated the concentration of gases dissolved in the oil, temperature and partial discharges are monitored. Another fact that shows the importance of monitoring the transformer's internal temperatures is that its increase directly affects the aging of the power transformer, thus reducing the useful life of this equipment (Gezegin et al. 2020). Generally speaking, between 90% and 95% of the solid insulation of transformers is influenced by the oil temperature. From 5% to 10% of cellulose are found in the vicinity of electrical current conductors that operate in the range 10°C to 20°C above the temperature of the transformer oil in operation and a small percentage of cellulose operates at temperatures higher than 30°C above oil temperature (de Senna 2010). New transformers are assembled with many types of sensors. In relation to the oil temperature, the most common sensor is the Bourdon spiral (Suñé et al. 2013). For the temperature of the winding, the most used method is thermal vision. It is also possible to use a fiber optic sensor for direct measurement, but this type of sensor must be installed during the manufacture of the transformer, since it has a high cost and presents difficulties in maintenance, in case it is defective (Suñé et al. 2013).

Given the age of the Brazilian electric park, this type of measurement is strictly used, so indirect methods are widely used to estimate the temperature of the windings. The top oil and the hot spot temperatures can be obtained and estimated through an indirect measurement, using mathematical models, such as IEEE C57.91 (2011), Swift and Susa models xiaofeng 2012 simulation, such models can be seen and compared in (Sönmez and Komurgoz 2018). Computational techniques such as neural networks, Fuzzy logic and thermovision are widely used for indirect temperature measurements. In (Nguyen et al. 2007) the top oil temperature was estimated using a neural network model and compared with the conventional model. In (Ebenezer and Nair 2010) the current and ambient temperature were used to estimate the winding temperature using models of neural networks, Fuzzy logic and Neuro-Fuzzy. In (Majzoobi et al. 2017) a study was carried out to verify the loss of useful life of power transformers using intelligent techniques, based on the IEEE-C5791 model standard. Changes in various quantities can influence the temperature of the transformer, such as ventilation, loading, ambient temperature, humidity and pressure (Kashyap and Kansal 2015). In the present article, the study used the loading of a single-phase autotransformer and the ambient temperature, for the estimation of the top oil temperature and hot spot winding, using Fuzzy logic, comparing with IEEE-C5791 model, to confirm its accuracy.

IEEE C5791-2011

There are numerous metrics that guide the measurement of the transformer's temperature, the IEEE developed in 1981 the standard C5791 (IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators), which assists engineers in estimating the maximum temperature of the oil and winding. The calculation of the winding temperature depends directly on the maximum oil temperature; both quantities depend on the transformer load and ambient temperature. For the calculation, the IEEE model recommends for the room temperature, use average daily temperature for the month involved, averaged over several years. The average of the maximum daily temperatures of the month involved for several years can also be used (IEEE 2012).

$$\theta e = \theta amb + \Delta\theta o + \Delta\theta e \tag{1}$$

It is known that:
θe: Winding hottest-spot temperature, °C
θamb: Ambient temperature during the load cycle to be studied, °C
$\Delta\theta o$: Top-oil rise over ambient temperature, °C
$\Delta\theta e$: Winding hottest-spot rise over top-oil temperature, °C
The calculation of the oil temperature rise over the ambient temperature is given by equation (02):

$$\Delta\theta o = [\Delta\theta o(f) - \Delta\theta o(i)]\left(1 - e^{\frac{-\Delta t}{60\tau o}}\right) + \Delta\theta o(i) \tag{2}$$

Where:

$\Delta\theta o$(f): Ultimate top-oil rise over ambient temperature for load L, °C
$\Delta\theta o$(i): initial top-oil rise over ambient temperature for t = 0, °C
Δt: The duration of load, min
τo: Transformers's oil time constant for any load L and any difference of temperatures between the ultimate top-oil rise and the initial top-oil rise
The initial and final temperature of the oil temperature rise over the ambient temperature is given in equation (03) and (04), respectively:

$$\Delta\theta o(i) = \Delta\theta o,r\left(\frac{Ki^2R+1}{R+1}\right)^n \tag{3}$$

$$\Delta\theta o(f) = \Delta\theta o,r\left(\frac{Kf^2R+1}{R+1}\right)^n \tag{4}$$

It is known that:

$\Delta\theta o,r$: Top-oil rise over ambient temperature at rated load on the tap position to be studied, °C
Ki: The ratio of initial load L to rated load, per unit
Ku: The ratio of ultimate load L to rated load, per unit
R: The ratio of load loss at rated load to no-load loss on the tap position to be studied
n: Transformer oil coefficient for each cooling mode, ONAN=0,8; ONAF=0,9

The oil time constant (τo) and the nominal oil time constant (τo, r) are calculated using equations (05) and (06), respectively:

$$\tau o = \tau o,r\left(\frac{\frac{\Delta\theta o,f}{\Delta\theta o,r}-\frac{\Delta\theta o,f}{\Delta\theta o,r}}{\left(\frac{\Delta\theta o,f}{\Delta\theta o,r}\right)^{\frac{1}{n}}-\left(\frac{\Delta\theta o,i}{\Delta\theta o,r}\right)^{\frac{1}{n}}}\right) \tag{6}$$

$$\tau o,r = \frac{C\Delta\theta o,r}{Pt,r}$$

Where:

C: Thermal capacity of the transformer, W-h/°C
Pt,r: Total loss at rated load, W

The thermal constant of the oil is calculated using the formulas (07) for ONAN and (08) for ONAF:

C = 0,1323*(weight of core, Kg) + 0,0882*(Weight of tank, Kg) + 0,3513*(Liters of oil) (07)

C = 0,1323*(weight of core, Kg) + 0,1323*(Weight of tank, Kg) + 0,5099*(Liters of oil) (08)

After calculating the rise in oil temperature over room temperature, the rise in winding temperature over room temperature is calculated using formula (09).

$$\Delta\theta e = [\Delta\theta e(f) - \Delta\theta e(i)]\left(1 - e^{\frac{-\Delta t}{60\tau w}}\right) + \Delta\theta e(i) \tag{9}$$

$\Delta\theta e$(f): Ultimate winding hottest-spot rise over top-oil temperature for load L, °C
$\Delta\theta e$(i): Initial winding hottest-spot rise over top-oil temperature for t = 0, °C

Δt: The duration of load, min

τw: Winding time constant at hot spot location, min

The initial and final temperature of the winding temperature rise over the ambient temperature is given in equations (10) and (11), respectively:

$$\Delta\theta e(i) = \Delta\theta o,rKi^{2m} \tag{10}$$

$$\Delta\theta e(f) = \Delta\theta o,rKf^{2m} \tag{11}$$

Where:

$\Delta\theta e,r$: The winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied, °C
m: Transformer oil coefficient for each cooling mode, ONAN=0.8; ONAF=0.8

FUZZY MODEL

Fuzzy Logic is a widely used tool for system control, decision-making andpattern recognition. Counting on a set of rules to create an approximate modelof the real system, being an unconventional, non-binary logic, where a statecan be more than just true or false (Zimmermann 2011). It is also widelyapplied in the analysis of uncertainties in non-linear systems, when its modelis unknown, as in systems called black box where there is input and outputdata but there is no internal knowledge of the system, and it is not possible tocreate a model based on the laws of physics (white box). Fuzzy logic is dividedinto 3 main parts (Quiros et al. 2016):

- Fuzzification: It consists in the creation of linguistic variables and membership functions.
- Inference: Process meaningful linguistic expressions, based on a set ofrules that controls the system.
- Defuzzification: Represents the inverse of fuzzification, converts the Fuzzyoutput, transforming the result, composed by linguistic variables, into realnumbers, with the centroid method being the most used.

The system has two inputs and one output. The system inputs are theload (MVA) and room temperature ∘ C). The system has seven membership functions for the load and five to room temperature, resulting in 35 rules, which are composed in the form of If-Then:

- If (amb2 is b) and (car2 is b) then (oleo is b).
- If (amb2 is b) and (car2 is mb) then (oleo is mb).

The IEEE standard was also used to analyze the transformer behavior inorder to extract the necessary information for the development of the membership functions and rules used by the fuzzy logic. Tables 1 and 2, respectively, represent the rules for estimating the temperature of the top of the oil and the hot point of the winding, being: BB(Low Low), B (Low), MB (Medium Low), M (Medium), MA (Medium High),A (High) and AA (High High).

In Figures 1 and 2 respectively it is possible to see the membership functions of load and ambient temperature. Figures 3 and 4, on the other hand, show the pertinence functions for thetop oil temperature and winding hot spot, respectively. Figures 5 and 6 respectively represent the system mapping generated bythe rules.

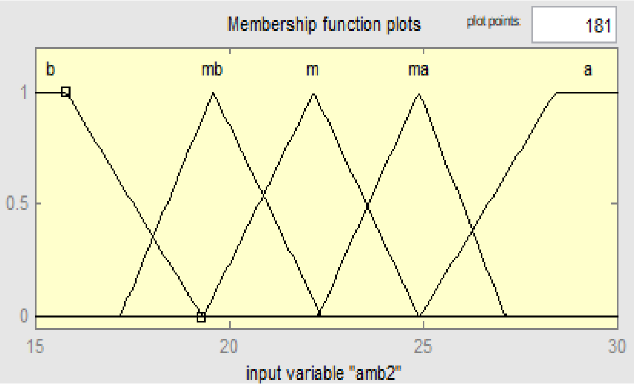

Fig. 1. Membership functions of ambient temperature

Table 1. Top Oil Temperature Rules

CAR\AMB	B	MB	M	MA	A
BB	B	B	B	MB	MB
B	B	B	MB	MB	M
MB	MB	MB	MB	M	M
M	MB	MB	M	M	M
MA	M	M	M	M	MA
A	MA	M	MA	MA	A
AA	MA	MA	A	A	A

Table 2. Hot Spot Temperature Rules

CAR\AMB	B	MB	M	MA	A
BB	B	B	B	B	MB
B	B	B	B	MB	MB
MB	MB	MB	MB	M	M
M	MB	MB	M	M	M
MA	M	M	M	MA	MA
A	M	MA	MA	MA	MA
AA	MA	MA	A	A	A

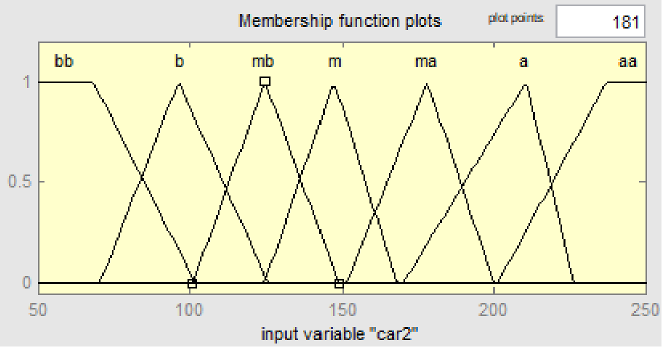

Fig. 2. The load Membership functions

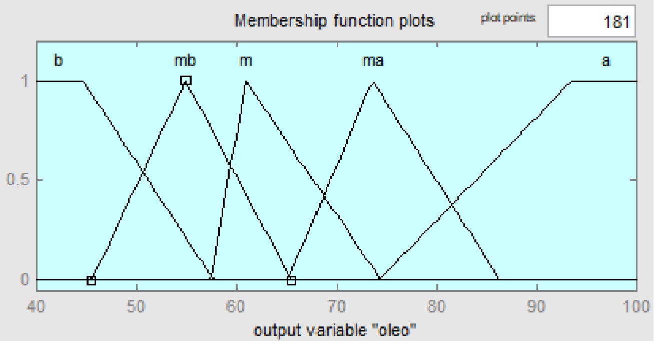

Fig. 3. Membership functions top-oil temperature

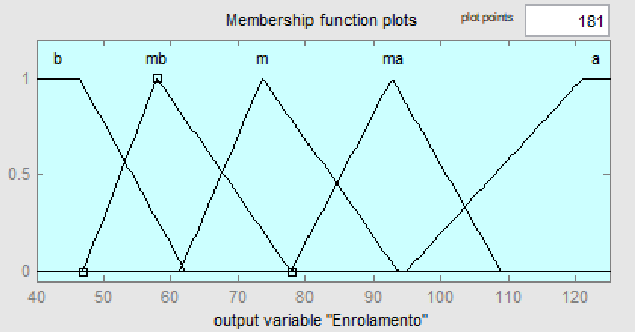

Fig. 4. Membership functions of Winding hot spot temperature

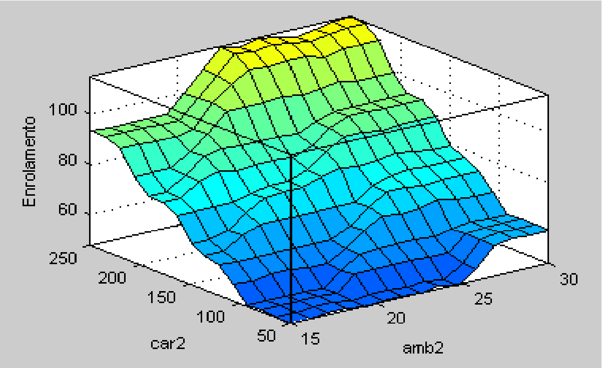

Fig. 5. Top oil temperature mapping

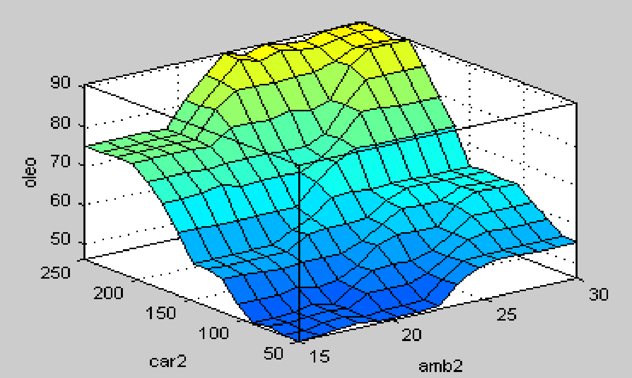

Fig. 6. Winding hot spot temperature mapping

ANALYSIS AND RESULTS

In this work, a real loading data from a single-phase auto transformer, Blumenau substation, were used, accounting for December 17, 18, 19 and 20, 2019, as shown in Figure 7. In addition to the apparent power and technical data of the autotransformer, were used ambient temperature data from the city of Itajaí-SC, the closest meteorological station to Blumenau-SC. Figure 8 shows the ambienttemperature curve for 17,18,19 and 20 December 2019.

Table 3 Autotransformer data

Transformer Model	AMOVC – NF
Power	3x224 MVA
Primary Voltage	525 KV
Secondary Voltage	230 KV
Tertiary Tension	13,8 KV
Nominal frequency	60 Hz
Cooling Type	ONAN/ONAF/ONAF2
Class	65ºC
Maximum Ambient Temperature	40ºC
Weight of Core and Windings	160000 Kg
Weight of Tank and Accessories	59500 Kg
Liters of oil	95500 l
Empty Losses	163 KW
Load Losses	517 KW

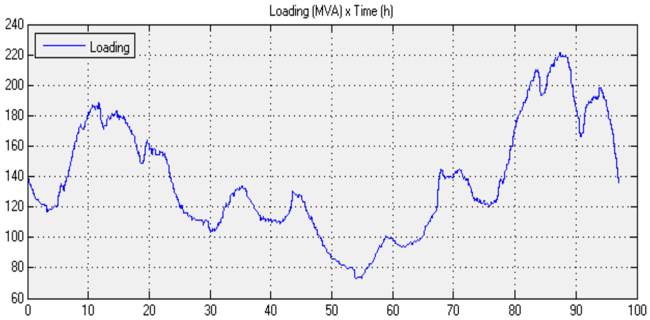

Fig. 7. Loading (MVA) x Time (h)

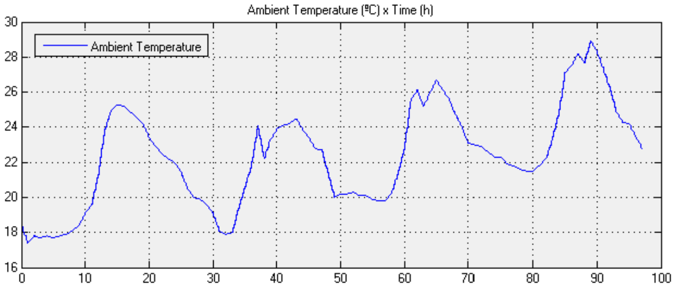

Fig. 8. Ambient Temperature

The work was carried out in two stages, in the first stage the oil andwinding temperatures were estimated using the IEEE model with variable ambient temperature, aiming to extract with greater precision the information necessary to create the rules used by the fuzzy logic. In the sequence, a model with Fuzzy logic was developed capable of estimating the temperature of thetop of the oil and the hot spot of the transformer winding. Figures 9 and10 show the oil top and winding temperatures, respectively, using the IEEE model with variable ambient temperature and Fuzzy logic. The model with the Fuzzy logic provided the internal temperature values very close to those obtained by the traditional method. The new methodology requires a smaller set of information compared to the IEEE model, which requires data on loss tests and transformer data sheet. The IEEE C5791-2011 model suggests that the average of daily temperatures or the maximum temperatures of the last years should be used for theambient temperature, so the second and third stage, the transformer internal temperatures estimations were redone, using as input a constant room temperature, according to the IEEE C5791-2011 standard. That way, it was possibleto make a comparison between the IEEE model and fuzzy logic. For the second simulation, the constant ambient temperature was considered for the IEEE model, Figures 11 and 12, shown respectively the top-oil and hotspot temperatures with the average of the daily ambient temperatures and the average of maximum room temperatures. In table 04 and 05 are shown the differences between the fuzzy logic and the IEEE model for both estimations, top-oil temperatures and hotspot, respectively.

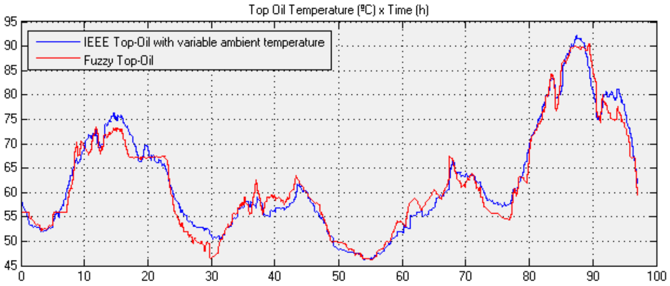

Fig. 9. Top oil temperature

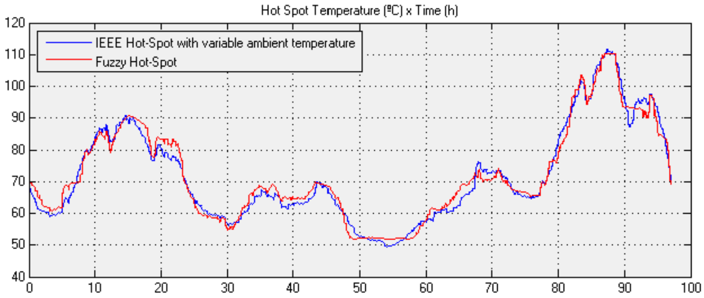

Fig. 10. Hot Spot Temperature

In tables 4 and 5, are shown that the maximum and average errors increased significantly, for the daily average room temperature. The two models with constant ambient temperature had large measurement errors, the model with average daily ambient temperature had worst performance when the room temperature and loading were extreme. On the other hand the model with maximum daily ambient temperature, had greater accuracy at peak loading and ambient temperature, but unfortunately had a huge error for the rest of the day.

Table 4. Top-Oil Estimation Compared to Fuzzy Logic Model

IEEE Top-oil Temperatures	Maximum Error		Average Error	
Variable Ambient Temperature	5,7 ºC	-10,4%	-0,34 ºC	-0,55%
Daily Average Ambient Temperature	10,7 ºC	-18,1%	-1,15 ºC	-2,39%
Maximum Ambient Temperature	-13,1 ºC	-26,9%	-5,25 ºC	-9,21%

Table 5. Hotspot Estimation Compared to Fuzzy Logic Model

IEEE Hotspot Temperatures	Maximum Error		Average Error	
Variable Ambient Temperature	*-6,1 °C*	*-8,4%*	*0,46 °C*	*0,69%*
Daily Average Ambient Temperature	*11,2 °C*	*-13,1%*	*-0,35 °C*	*-0,92%*
Maximum Ambient Temperature	*-13,2 °C*	*-19%*	*-4,45 °C*	*-6,82%*

The IEEE standard is one of the most used methods to estimate the internal temperatures of the power transformer, but as seen in figures 11 and 12 and in Tables 04 and 05, the risk that these measurement errors can cause to the equipment and any system that depends on it, for these reasons fuzzy logic is an excellent option when it is not possible to use sensors for a direct measurement of the internal temperature.

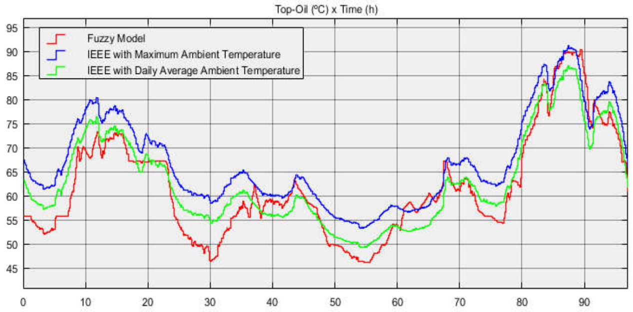

Fig. 11. Top Oil Temperature

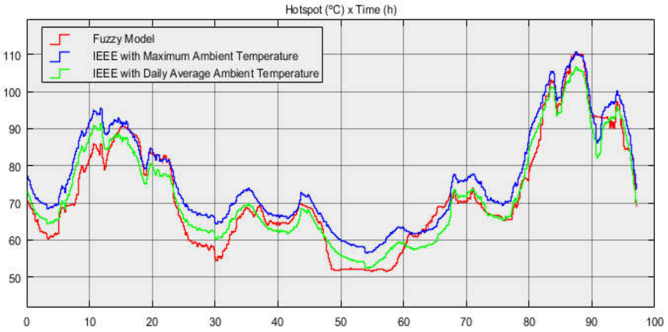

Fig. 12. Hot Spot Temperature

CONCLUSION

In this work, a new methodology was presented using Fuzzy logic, to perform the estimation of the internal temperature of the power transformers, together with an analysis of the IEEE-C5791 standard with regard to the use of constant ambient temperature throughout the day. As shown, the diffuse logic was able to estimate the top oil temperature and the winding hot spot accurately, proving to be advantageous in relation to the IEEE-C5791 standard as it requires technical data from the power transformer to estimate the temperatures, as data sheet, empty and short-circuit tests, which makes the Fuzzy logic simpler and more efficient. A more accurate monitoring of temperatures will also be of great importance to prevent the insulating paper from aging and consequently reducing the transformer's life. Regarding the IEEE-C5791 standard, it is understood that the use of constant ambient temperature throughout the day, implies an increase in the error of the estimates, which can be determinant for the good performance ofthe system. Therefore, whenever possible, the ambient temperature should be considered as variable throughout the day. This undoubtedly ensure greater accuracy in maintenance, with predictability of possible preventive exchanges, which would result in improved management and decision-making in the sector, with consequent stability of the electric system of the country.

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REFERENCES

de Senna, S.L. Computação evolucionária aplicada ao diagnóstico de falhas incipientes em transformadores de pot^encia utilizando dados de cromatografia (2010)

Ebenezer, M. P.C. Nair, Determination of winding temperature of a distribution transformerusing soft computing techniques, in 2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India, IEEE, 2010, pp. 1-6. IEEE.

Gezegin, C. O. Ozgonenel, H. Dirik, A monitoring method for average winding and hot-spottem peratures of single-phase, oil-immersed transformers. IEEE Transactions on Power Delivery (2020)

IEEE, Ieee guide for loading mineral-oil-immersed transformers and step-voltage regulators. IEEE Std C57.91-2011 (Revision of IEEE Std C57.91-1995), 1-123 (2012).doi:10.1109/ IEEESTD. 2012.6166928

Kashyap, M. S. Kansal, Temperature control in transformer using intelligent system, in 2015 2nd International Conference on Recent Advances in Engineering & Computational Sciences (RAECS), IEEE, 2015, pp. 1-6. IEEE

Majzoobi, A. M. Mahoor, A. Khodaei, Machine learning applications in estimating transformer loss of life, in 2017 IEEE Power & Energy Society General Meeting, IEEE, 2017,pp. 1-5. IEEE

Nguyen, H. G. Baxter, L. Reznik, Soft computing techniques to model the top-oil temperature of power transformers, in 2007 International Conference on Intelligent Systems Applications to Power Systems, IEEE, 2007, pp. 1-6. IEEE

ONS, Relatório de an´alise e statística de desligamentos forçados de equipamentos (2019)

Quiros, A.R.F. R.A.Bedruz, A.C. Uy, A. Abad, A. Bandala, E.P. Dadios, Machine vision of traffic state estimation using fuzzy logic, in 2016 IEEE Region 10 Conference (TENCON), IEEE, 2016, pp. 2104-2109. IEEE

SCHMITZ, W. L. CANHA, T. MARCHESAN, Ranking de subestações para manutenção ou substituição de transformadores de potência com foco na manobrabilidade e flexibilidade

Onmez, O. S¨G. Komurgoz, Determination of Hot-Spot Temperature for ONAN Distribution Transformers with Dynamic Thermal Modelling, in 2018 Condition Monitoring andDiagnosis (CMD), IEEE, 2018, pp. 1-9. IEEE

Suñé, J. L. Heredia, A. de Brito, C. Dupont, C. Gonza¸calves, C. dos Santos, E. Brito, G.Amorim, H. Bezerra, J. Carneiro, et al., Guia de manutenção para transformadores depotência. Proc. 2013 XXIV Semin´ario Nacional de Produção e Transmissão de Energia Elétrica, 135-139 (2013)

Zimmermann, H.-J. Fuzzy set theory|and its applications (Springer Science & Business Media, 2011)

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