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Fuzzy Logic Based Energy Efficient Transformer Cooling Control

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Abstract
Cooling is the most important way that can be used to extend the life of overloaded transformers, especially by reducing the aging rate due to temperature, and to ensure that the transformer can be loaded above its rated power. In addition to increasing the load capacity of the transformer, good cooling is also required to be energy efficient. In this study, an energy efficient transformer cooling control method is presented. The proposed method was developed by revising the differential equations method, which is one of the transformer temperature calculation methods given in the IEC 60076-7:2018 standard. With this method, transformer hot-spot temperatures are calculated. For energy efficient cooling control, transformer winding currents and top-oil temperature are first measured and transformer windings' loading rates and hot-spot temperatures are calculated. Afterwards, the highest loading rate of the transformer windings and the highest hot-spot temperature value are given to the input of a fuzzy logic controller, and the on-off signals of the cooling fans used to cool the transformer are generated. The fuzzy logic controller performs the fuzzification process with three membership functions for the loading rate and hot-spot temperature, and performs the defuzzification using the Takagi-Sugeno model. The method has been investigated by experiments performed in the laboratory environment using short-circuit experiments on an ONAF cooled transformer with a power of 50 kVA. Test results showed that as the hot-spot temperature and loading rate of the transformer increases, more cooling fans are activated, thus the loading capacity of the transformer is significantly increased energy efficiently.

Key words: *Fuzzy logic, transformer, energy efficient, cooling, loadability*

1. Introduction
The climate crisis that threatens the world due to global warming directs countries to take measures to reduce carbon footprint and greenhouse gas emissions. This requires use of energy resources more efficiently and efforts to increase efficiency. Electric power grids come forward as an important area of study in this field. For this purpose, many studies have been and are being carried out to ensure that transformers in electric power grids overheat less and to use the existing capacity more effectively without establishing new facilities.

Generally, transformers are structures that produce heat due to their iron and copper losses. This heat produced in the windings and iron cores of transformers causes the transformer windings to be exposed to thermal stress and therefore their capacity is limited. In practice, 19% of transformer faults encountered are due to winding insulation deterioration [1]. Since the increase in winding temperatures causes the winding resistance to increase, it also has the effect of increasing copper losses. This means that losses will increase even more.

The lifetime of a transformer winding insulation basically depends on the moisture, oxygen in the insulating oil and temperature of the windings. With today's modern oil preserving techniques, the moisture and oxygen content of the oil can be sufficiently minimized [2]. Therefore, the main parameter that limits the capacity of a transformer is the value of critical temperature of the winding insulation. As long as the temperature value remains below the critical temperature, the insulation deterioration and the aging of the transformer occur relatively slowly. However, if the temperature exceeds this limit value, the aging rate will increase exponentially. So much so that every 6 oC increase in the winding insulation temperature above the critical temperature doubles the aging rate [3]. This situation requires structural measures as well as improvement of operating conditions for longer use

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of the transformer. In other words, for more effective and long-term use of the transformer, it is necessary to ensure that the transformer has low losses at the design stage, as well as good cooling during operation. In general, converting an ONAN-cooled transformer to operate in ONAF or OFAF cooling mode increases the loadability capacity (rated power) of the transformer [4].

2. The Method

The production of the necessary signals for the energy efficient transformer cooling control proposed in this study is done with a 2-stage calculation. In the first stage, the loading rates of each phase winding of the transformer and the hot-spot temperatures are obtained by using the transformer current data sampled through current sensors and the transformer top-oil temperature measured with the help of a temperature sensor. In the second stage, these values are given to the designed fuzzy logic structure and fan control signals are produced.

2.1. Computation of Loading Rates and Hot-Spot Temperatures

The hot-spot temperature computation method used in this section is developed by revising a method given in the IEC 60076-7 standard published by IEC [12]. The method given in the standard allows calculating winding and oil temperatures for situations where the environmental temperature and transformer load change randomly. According to the method, the hot-spot temperature of the transformer (θ_H) consists of the sum of the ambient temperature (θ_A) and the top-oil temperature rise over the ambient temperature ($\Delta\theta_{TO}$) and the hot-spot temperature rise over the top-oil temperature ($\Delta\theta_H$).

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \tag{1}$$

In this case, the hot-spot temperature will be equal to the sum of the top-oil temperature and the hot-spot temperature rise over the top-oil temperature.

$$\theta_H = \theta_{TO} + \Delta\theta_H \tag{2}$$

Therefore, the hot-spot temperature rise over the top-oil temperature is given by the equation below.

$$\Delta\theta_H = \Delta\theta_{H1,u} - \Delta\theta_{H2,u} \tag{3}$$

The changes of $\Delta\theta_{H1}$ and $\Delta\theta_{H2}$ parameters in this equation at the end of a time interval Dt ($D\Delta\theta_{H1}$ and $D\Delta\theta_{H2}$) is given by,

$$D\Delta\theta_{H1} = \frac{Dt}{k_{22}\tau_W}\left(k_{21}x\Delta\theta_{Hr}K^y - \Delta\theta_{H1,i}\right) \tag{4}$$

$$D\Delta\theta_{H2} = \frac{Dt}{(1/k_{22})\tau_o}\left((k_{21}-1)x\Delta\theta_{Hr}K^y - \Delta\theta_{H2,i}\right) \tag{5}$$

Therefore, the ultimate values can be obtained by adding these changes to the initial values of $\Delta\theta_{H1}$ and $\Delta\theta_{H2}$ parameters

$$\Delta\theta_{H1,u} = \Delta\theta_{H1,i} + D\Delta\theta_{H1} \tag{6}$$

$$\Delta\theta_{H2,u} = \Delta\theta_{H2,i} + D\Delta\theta_{H2} \tag{7}$$

Here,

$\Delta\theta_H$: is the hot-spot temperature rise over top-oil temperature,

$D\Delta\theta_{H1}$: is the change in the parameter $\Delta\theta_{H1}$ at the end of the time interval Dt,

$D\Delta\theta_{H2}$: is the change in the parameter $\Delta\theta_{H2}$ at the end of the time interval Dt,

$\Delta\theta_{H1,i}$: is the value of the parameter $\Delta\theta_{H1}$ at the beginning of the calculated time interval,

$\Delta\theta_{H1,u}$: is the value of the parameter $\Delta\theta_{H1}$ at the end of the calculated time interval,

Dt : is time interval,

τ_W : is winding temperature time constant,

τ_o : is oil temperature time constant,

$\Delta\theta_{Hr}$: is rated value of the hot-spot temperature rise over the top-oil temperature and,

K : is the loading rate during the computed time interval.

Also, the parameters y, k_{21} and k_{22} given in the above equations represent constants whose values are determined depending on the operating mode of the transformer and are given as 1.3, 2 and 2 respectively for ONAF cooling.

These equations are valid for the case where 3-phase transformer currents are balanced. However, since this is not always possible in practice, calculations are made separately for each of the three windings of the transformer. That is, in each step of the calculations, the transformer winding currents are first sampled and the loading rates K^R, K^S and K^T are obtained for the phases R, S and T respectively. Additionally, the value of the top-oil temperature (θ_{TO}) is measured by a temperature sensor placed in the upper oil pocket of the transformer. By using these values in the equations given above, the values of θ_H^R, θ_H^S and θ_H^T at the end of each time interval are obtained.

The loading rates in the equations given above are obtained from the phase winding current sampled with the help of current sensors. For this purpose, let us define the N-number of phase winding currents sampled during a nominal period in the form of

$$i = [I_0\ I_1 \ldots \ldots . I_{N-2}\ I_{N-1}] \quad (8)$$

Then, the following equation is used to calculate the effective value of the current.

$$I = \sqrt{\frac{1}{N}\sum_{k=0}^{N-1} {I_k}^2} \quad (9)$$

The loading rate (K) is calculated by dividing the effective value of the current (I) by the rated current (I_n).

$$K = \frac{I}{I_n} \quad (10)$$

2.2. Control Signal Production for Cooling Fans

The transformer used in this study is assumed to have natural cooling with oil and forced cooling with fan (ONAF). For energy efficient cooling control of fans, it is aimed to produce on-off signals of the fans according to the closeness of the hot-spot temperatures and loading rates of the phase windings to critical values ($T_{critical}$ and I_n). $T_{critical}$ value is the temperature value at which the aging rate of the winding insulation paper rapidly increases, and in this study, this value is assumed to be 105 oC. Since the rated current flows through the transformer windings when the loading value is 1 and currents above the rated current are excessive for the transformer, the critical value for the loading rate is taken as $K_{critical} = 1$. The ultimate goal of cooling is o prevent the hot-spot temperatures reaching critical values. Since the loading rate is one of the main input in reaching this value, the loading rates (K^R, K^S and K^T) as well as the hottest point temperatures (θ_H^R, θ_H^S and θ_H^T) are used as input signals for the control of the fans.

In this study, a fuzzy logic-based controller structure is proposed for the generation of on-off signals of fans. Fuzzy logic is one of the artificial intelligence methods developed to use quantitative linguistic expressions or words in decision-making processes. There are three loading and three temperature values that determine the temperature of the 3-phase transformer and the highest of these values of them are used as input signals of the fuzzy logic-based controller. That is, as controller input signal, the parameters K_{max} and θ_{Hmax} that is defined as

$$K_{max} = max[K^R, K^S, K^T] \quad (11)$$
$$\theta_{Hmax} = max[\theta_H^R, \theta_H^S, \theta_H^T] \quad (12)$$

are used. In this study, the linguistic expressions “small, medium and high” are defined as fuzzy logic membership functions for the hot-spot temperature and loading rate variables. Trapezoidal membership functions are used as given in Figure 1, considering that the winding hot-spot temperature values close to or above the critical temperature are assumed high, lower values are assumed medium, and temperature values that can be considered cold are assumed small.

Similarly, by considering the loading rates close to 1 and above as high, lower values as medium and values close to zero as small, trapezoidal membership functions are formed as shown in Figure 2.

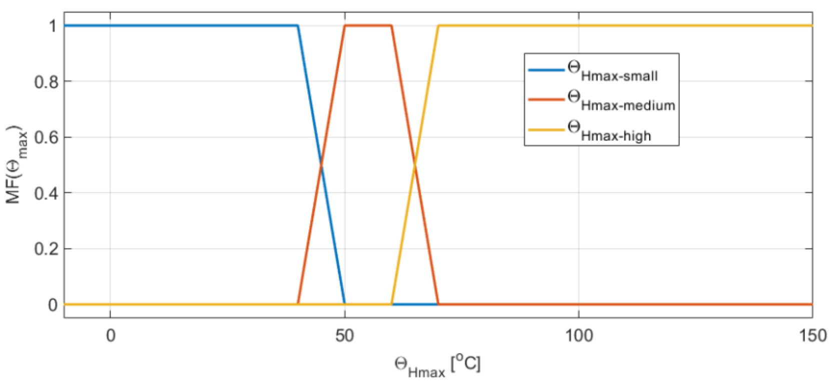

Figure 1. Membership functions for hot-spot temperature

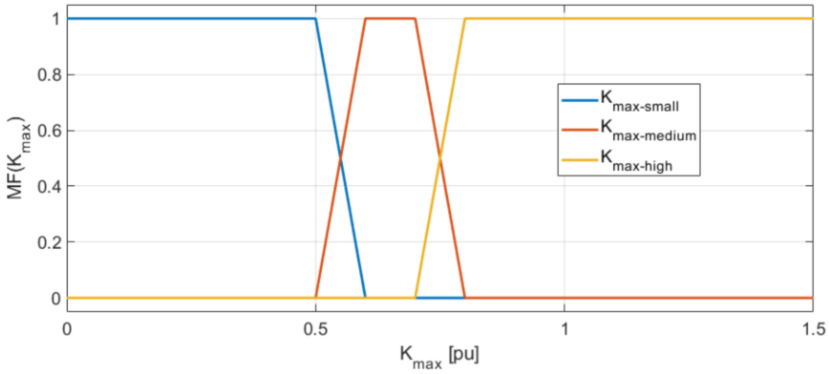

Figure 2. Membership functions for loading rate

The membership functions given in Figure 1 and Figure 2 are functions used for fuzzification the input values. The fuzzification process is done by calculating the values of the input variables in each membership function. The membership functions and their parameters used are defined as follows.

$$K_{max-small}(K_{max}) = trapezoid(K_{max}, [0\ 0\ 0.5\ 0.6]) \quad (13)$$
$$K_{max-medium}(K_{max}) = trapezoid(K_{max}, [0.5\ 0.6\ 0.7\ 0.8]) \quad (14)$$
$$K_{max-high}(K_{max}) = trapezoid(K_{max}, [0.7\ 0.8\ 1.5\ 1.5]) \quad (15)$$
$$\theta_{Hmax-small}(\theta_{Hmax}) = trapezoid(\theta_{Hmax}, [-10 - 10\ 40\ 50]) \quad (16)$$
$$\theta_{Hmax-medium}(\theta_{Hmax}) = trapezoid(\theta_{Hmax}, [40\ 50\ 60\ 70]) \quad (17)$$
$$\theta_{Hmax-high}(\theta_{Hmax}) = trapezoid(\theta_{Hmax}, [60\ 70\ 150\ 150]) \quad (18)$$

In fuzzy logic, decision making is done with the help of rules. Decision-making rules are determined to activate more fans if the temperature and loading rates approach critical values. Considering that there are four fans in total to cool the transformer, there are 5 different situations, including the situation where no fan is working. Therefore, five different membership functions are defined in the defuzzification layer of the fuzzy logic controller. These membership functions are named no_fan, fan1, fan12, fan123 and fan1234. A total of 9 different fuzzy logic rules are defined to connect 6 different membership functions used for fuzzification to 5 different membership functions used for defuzzification, and these rules are as follows:

1. If K_{max} small and θ_{Hmax} small no-fan (19)
2. If K_{max} small and θ_{Hmax} medium fan1 (20)
3. If K_{max} small and θ_{Hmax} high fan12 (21)
4. If K_{max} medium and θ_{Hmax} small fan1 (22)
5. If K_{max} medium and θ_{Hmax} medium fan12 (23)
6. If K_{max} medium and θ_{Hmax} high fan123 (24)
7. If K_{max} high and θ_{Hmax} small fan12 (25)
8. If K_{max} high and θ_{Hmax} medium fan123 (26)
9. If K_{max} high and θ_{Hmax} high fan1234 (27)

All nine rules perform the decision-making process by combining input variables with the “and” operator. Multiplication or minimization can be used to mathematically implement this operator. In this study, the minimization process is applied to provide that the input variables produce vales for output variables in each rule.

In general, fuzzy logic interface operations are carried out using Mamdani and Takagi-Sugeno interface models. In this study, it is preferred to use the Takagi-Sugeno model. In the Takagi-Sugeno model, constant values created from the values of the input variables are used as output membership functions. In cases where the output values do not depend on the input values, the output membership functions are called zero-order Takagi-Sugeno fuzzy membership functions. Zero-order Takagi-Sugeno fuzzy membership functions are defined as constant numbers. In this study, zero-order Takagi-Sugeno output membership functions are used and the constant values of the functions are formed as shown in Figure 3.

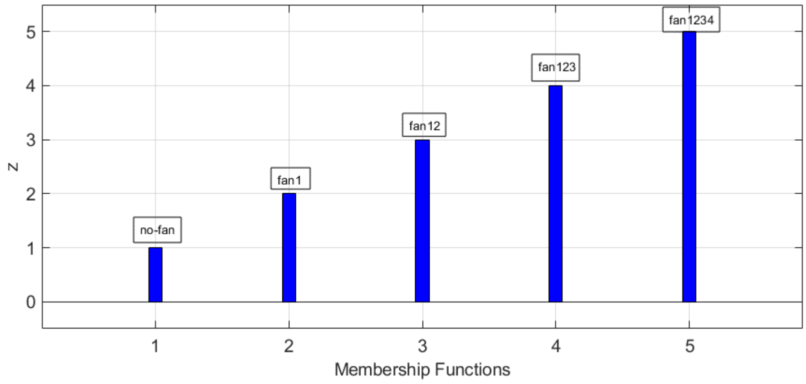

Figure 3. Output membership functions

The value of the output function pointed out by each rule is activated by multiplying it with the weight values obtained by the minimization operator. The final output is calculated by computed the weighted average of all outputs. In other words, as the number of rules is nine, the final output value (F) is calculated with the following equation.

$$F = \frac{\sum_{k=1}^{9} w_k z_k}{\sum_{k=1}^{9} w_k} \quad (28)$$

In the next step of the calculations, the value of F that is calculated by the fuzzy logic controller is rounded to the nearest integer to obtain the fan operating commands pointed out by the relevant membership function. So fan states are obtained according to the following rules.

1. if round(*F*)=1 then no-fan runs (29)
2. if round(*F*)=2 then run fan1 (30)
3. if round(*F*)=3 then run fan1 and fan2 (31)
4. if round(*F*)=4 then run fan1, fan2 and fan3 (32)
5. if round(*F*)=5 then run fan1, fan2, fan3 and fan4. (33)

Structure of the proposed transformer cooling control is given in Figure 4.

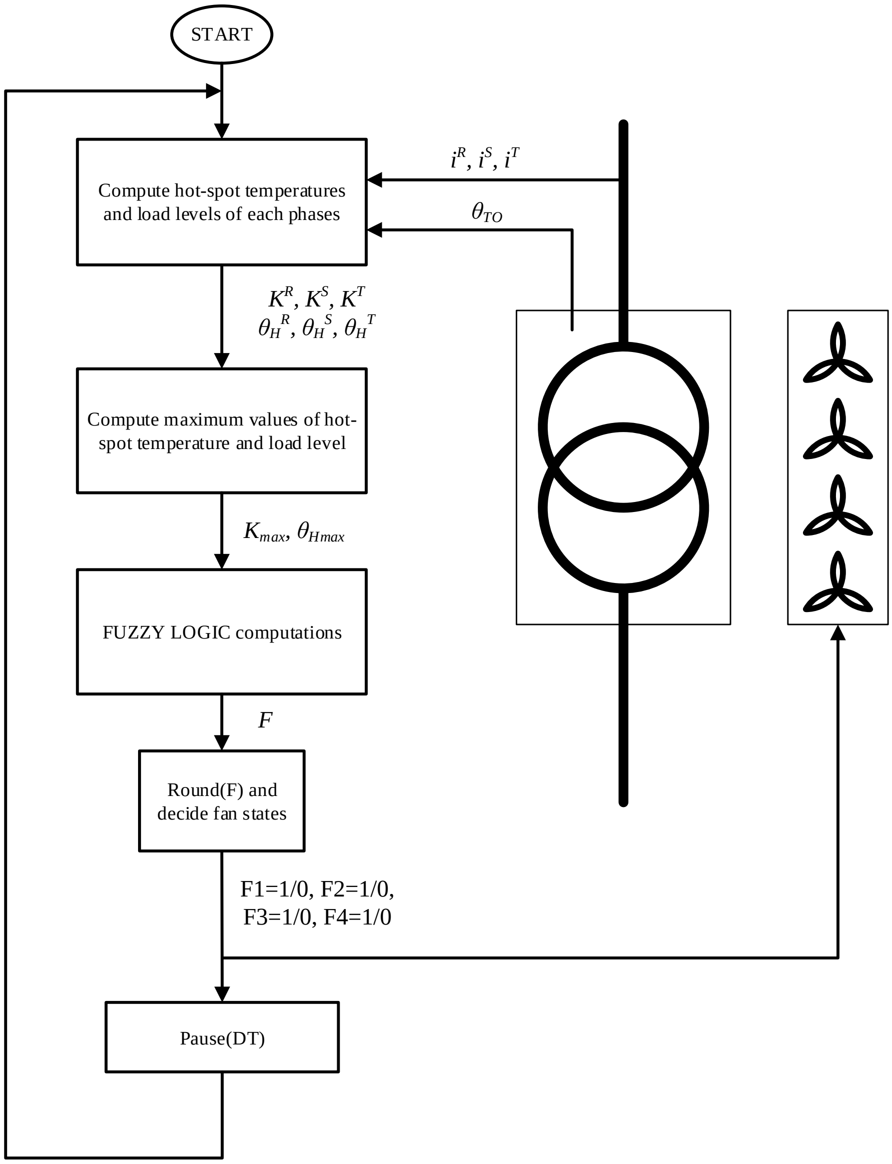

Figure 4. Structure of the proposed transformer cooling control

3. Experiments

In this section, the experimental results of the proposed fuzzy logic-based energy efficient transformer cooling control method are given. An ONAF cooled transformer with a rated power of 50 kVA was used in the experiments. Rated values of the test transformer are given in Table 1.

Table 1. Rated values of the test transformer

Power	50	kVA
Voltages	6300/400	Volt
Currents	4.58/72.2	Ampere
Vector Group	Dyn11	
Cooling Type	ONAF	
Top-oil temperature rise over hot-spot	55.5	K
Hot-spot temperature rise over ambient	10.1	K

The hardware structure of the setup established for experimental works is given in Figure 5. The experiments were carried out by applying short-circuit connection to the transformer instead of on-load operation. By applying variable voltages to the primary of the transformer with the help of an auto-transformer, the winding currents are adjusted and thus the windings are loaded with the desired loading currents.

In the experiments, current measurement was made by connecting 3 Hioki brand 9695-02 model hall effect current transducers to the LV side of the transformer, which is the star-connected side. Thus, measuring the LV winding currents of the transformer via line currents was enabled. These transducers are sensors that produce 10 mV voltage per ampere, and their outputs were connected to the analog-digital converter inputs of an NI USB-6210 model DAQ card from National Instruments. In addition, a PT100 thermoresistance placed in the upper oil pocket of the transformer was used to measure the top-oil temperature of the transformer, and the output terminals of this thermoresistance were connected to the analog-digital inputs of the DAQ card. The DAQ card was connected to a computer and the calculations were carried out under MATLAB installed on the computer. Calculations were carried out with codes written in an m-file. The fan on-off signals obtained as a result of the calculations were applied to the digital outputs of the same DAQ card in real time. The activation and deactivation of the four fans on the transformer was done through relays connected to the digital outputs of the DAQ card.

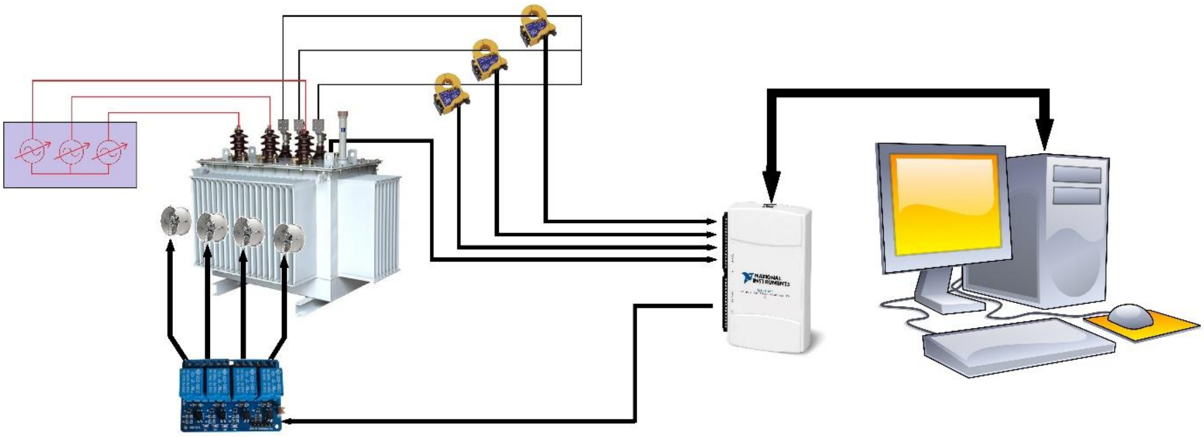

Figure 5. Hardware structure of setup used in experimental works

Experimental studies were carried out in two stages. In the first stage, the transformer current was adjusted to 30%, 60%, 100% and 130% of the rated current for every two hours, respectively, without running the fans. In the second stage, the transformer was loaded and the fans were activated using the proposed method. Before the second stage experiments, the transformer was left de-energized for a long time to guarantee its windings to cool down, ensuring that the winding and oil temperatures were equal to the ambient temperature. The loading rates of the windings throughout the experiments, which lasted 480 minutes in total, are given in Figure 6.

The measured top-oil temperatures and the calculated hot-spot temperatures in cases with and without fan are given in Figure 7 and Figure 8, respectively. The number of fans activated when the proposed method is performed are also given in Figure 9.

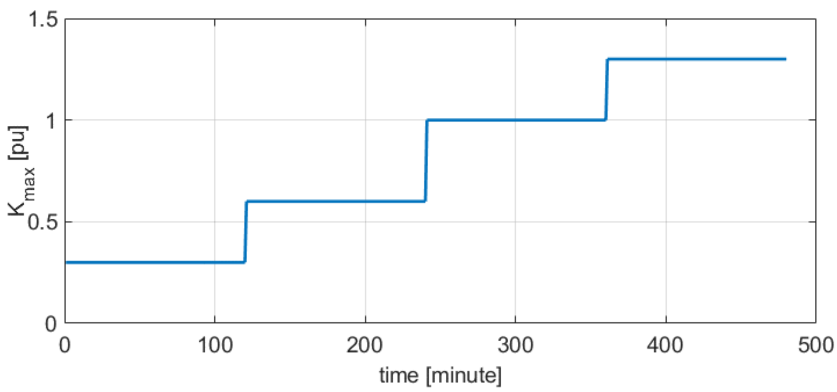

Figure 6. Loading rates throughout the experiments

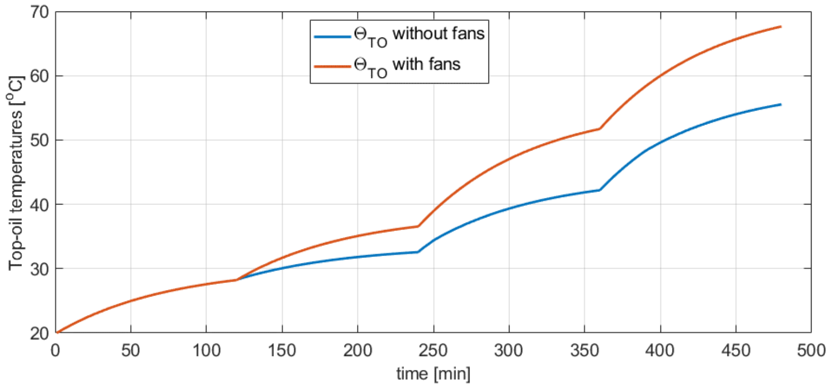

Figure 7. Top-oil temperatures in cases with and without fan

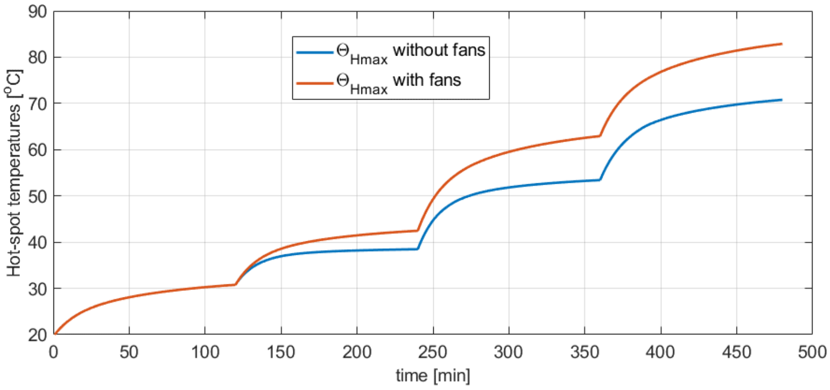

Figure 8. Hot-spot temperatures in cases with and without fan

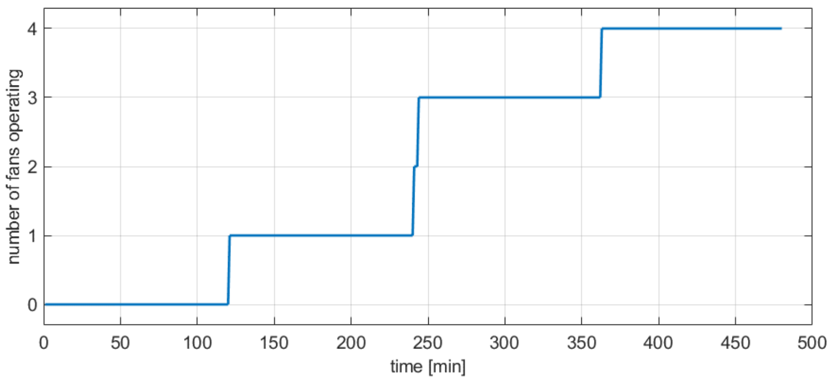

Figure 9. The number of fans activated in case of the proposed method

As can be seen in the Figure 7, top-oil temperatures can be reduced significantly with cooling. So much so that, while the top-oil temperature measured was around 67 °C in the case without fan, this temperature decreased by approximately 12 °C and was measured around 55 °C by the proposed method. A similar change was also observed in the calculated hot-spot temperatures of the transformer. Such that when the proposed method applied, the highest hot-spot temperature could be reduced from 82 °C to 70 °C. Reducing the hot-spot temperature, which is important in terms of the usage capacity and aging speed of transformers, by 12 °C is a very important achievement. While the hot-spot temperature is reduced by cooling, it should also be emphasized that fan cooling was done in an energy efficient manner. Such that as the loading on the transformer increases and/or the hot-spot temperature increases, the number of fans activated has increased, thus ensuring energy efficient cooling.

4. Conclusions

The most important parameter that determines the lifetime and the capacity of transformers is the winding hot-spot temperature. The value of this temperature depends on the heat energy resulting from the copper and iron losses of the transformer, the ambient temperature and the heat transfer properties between the transformer and the environment. Therefore, it is clear that cooling will have positive effect on transformer lifetime and power capacity. In this study, a fuzzy logic-based and energy-efficient cooling control structure that can be used if an ONAN-cooled transformer is converted to ONAF cooling mode is presented. The highest values of hot-spot temperature and loading rate of the windings are used as inputs of the cooling control system. In the proposed method, the hot-spot temperatures is calculated using the differential equations method given in the IEC 60076-7:2018 standard and given to the input of a fuzzy logic controller along with the loading rate. Both input parameters of the fuzzy logic controller are fuzzified using three membership functions and connected to five output membership functions with the help of nine fuzzy logic rules. Takagi-Sugeno defuzzification technique is used for defuzzification, and the resulting output value was rounded to the nearest integer to reach the required number of cooling fans. The method was tested on a transformer with a rated power of 50 kVA with the help of a test setup established in laboratory environment. The method was tested for both fanless and fanned cases and a significant improvement was achieved in the transformer hot-spot temperature. Such that it has been observed that top-oil and hot-spot temperatures can be reduced up to 12 ºC in the case of fan compared to the case without fan. This shows that the transformer capacity can be increased significantly. It is possible to say that it is energy efficient because cooling is done with fans that are activated gradually depending on the increase in temperature and loading rate.

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