NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY POLITEHNICA BUCHAREST

DOCTORAL SCHOOL OF ELECTRICAL ENGINEERING

SUMMARY
PHD THESIS

CONTRIBUTIONS TO THE MONITORING AND CONTROL OF PRIMARY EQUIPMENT IN MEDIUM AND HIGH VOLTAGE POWER SUBSTATIONS

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BUCHAREST
2023

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KEYWORDS

Transformer, ageing, loss of life, insulation resistance, thermal model, hot-spot temperature, loading, monitoring system, sensor, measurement, electrical, thermal, technical condition, electrical equipment, high and medium voltage, substation, reliability, statistical, linear regression.

CHAPTER 1. INTRODUCTION

In this chapter I presented general aspects on the development trends of transmission and distribution electricity networks and the main challenges for network operators in increasing the reliability of equipment in medium and high voltage substations. I also presented the main elements on which digital substations are based compared to conventional ones, extracted from the literature and why it is necessary to monitor the technical condition of equipment in a substation to increase their availability.

1.2. OPERATION OF MEDIUM AND HIGH VOLTAGE POWER SUBSTATIONS

Electrical substations are nodes within the power grids whose main role is to increase or decrease the voltage level, thus providing the link between transmission and distribution power lines. Power substations ensure the safe operation of power grids through switching and protection equipment, thus contributing to the safe supply of electricity to consumers. [8]

1.2.1. Challenges encountered in the operation of conventional power substations

Many of today's power distribution/transmission substations use outdated technology, partially refurbished or in the process of being refurbished. They have been in operation for more than 40 years, and very important equipment such as power transformers, which in the event of a failure would lead to substantial power shortages, are outdated. Since commissioning, some of them have been upgraded using various technologies from different suppliers. A common problem in the operation of power substations is that of electrical faults which can occur for various reasons, often due to wear caused either by environmental conditions or the way they are operated.

1.4. MONITORING THE TECHNICAL CONDITION OF PRIMARY EQUIPMENT IN A SUBSTATION

Monitoring of equipment in a substation means real-time acquisition of data from the equipment for the purpose of analysing the technical condition of the equipment and for reporting to the operating staff when thresholds for certain parameters are reached or failures occur.

The installation of monitoring systems primarily ensures that equipment is safer in operation, its reliability and service life is increased, incidents are prevented and operational maintenance costs are optimised. [26]

Given the long operating times of equipment, the fact that equipment failure rates increase as they age, and the fact that interventions on equipment often require it to be taken out of service for extended periods of time, real-time monitoring of equipment is even more important. [27]

The IEC 61850-90-3 standard defines the concept of condition monitoring, where device sensing and data acquisition/aggregation levels correspond to the station area where measured data are collected. Also, the level of surveillance/statistical processing and the level of diagnosis/analysis, maintenance and action planning correspond to the operational area where equipment is monitored and maintenance decisions are made. [28] [29]

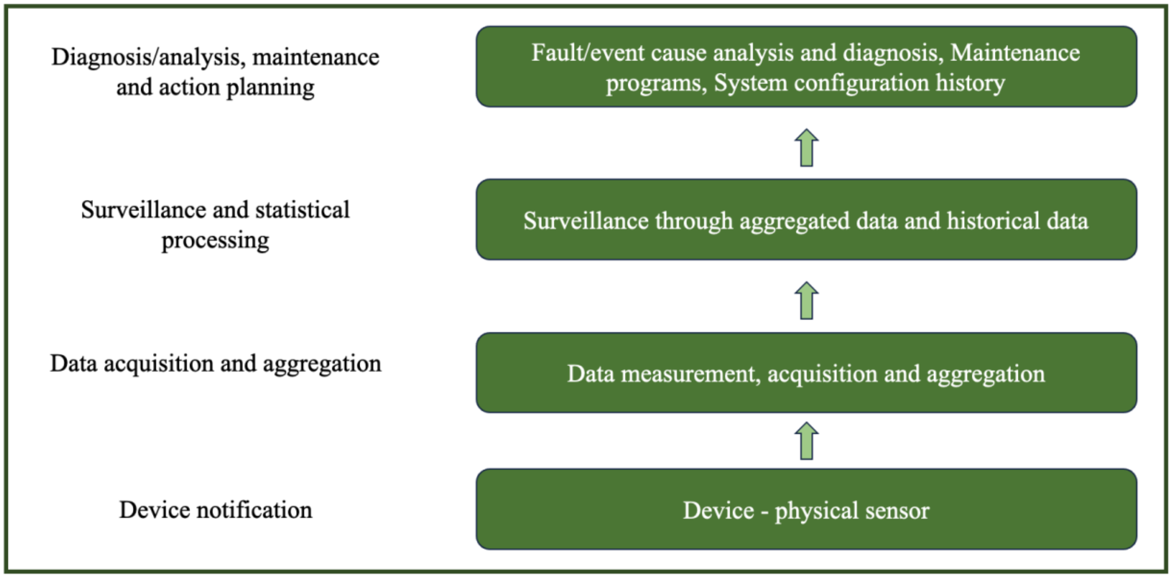

Fig. 1.7. The structure of the technical condition monitoring concept according to IEC 61850-90-3 [28] [30]

Depending on the type of equipment monitored, the status of the following subsystems is monitored:

- Transformation and compensation units:
    - Active part;
    - Bushings;
    - Plot switch;
    - Cooling system;
    - Auxiliary elements (Buchholz relay, conservator tank etc.);
    - Operating data (electrical parameters);
- Circuit breakers:

    - Insulation medium (SF6 usually);
    - Contacts;
    - Operating mechanism (motor, hydraulic pump);
    - Operating data (electrical parameters);
- Disconnectors:
    - Operating mechanism;
    - Operating data (electrical parameters);
- Voltage/ Current transformers:
    - Insulation medium;
    - Operating data (electrical parameters);
- Surge arresters:
    - Operating data (electrical parameters). [28]

Technical condition monitoring systems for electrical equipment within substations consist of digital technologies that allow the condition of this equipment to be analysed and decisions to be taken based on the analysis, using the following basic functions:

- diagnostics - determines status of the equipment or baseline value;
- prognosis - predicts/anticipates how the "health" of equipment will change over time;
- maintenance - performs maintenance activities to keep the equipment "healthy" (within the parameters set by the standards) or restores its "health" to baseline conditions (those set at the design stage). [31]

In addition to technical condition monitoring systems, high availability of electrical equipment in a power substation can also be achieved through the use of technological developments in the industry, such as augmented reality technology, which allows the monitoring of power installations in a much more secure, digital way, and also enables real-time support from remote technical experts. [32] [33]

CHAPTER 2. THE INFLUENCE OF MONITORING SYSTEMS ON THE RELIABILITY OF EQUIPMENT AND ELECTRICITY SUPPLY SERVICE

In this chapter I presented the main concepts used in the energy industry concerning the reliability of an electrical equipment and the indicators that can indicate the level of reliability it has had in a given time interval. Using these terms, I assessed the reliability of the transformers affected by incidents in the Romanian Transmission Grid over a sample of 5 years, in the period 2017-2021, where I calculated the system reliability indices: SAIFI, SAIDI, CAIDI, ASAI.

One of the main technical means used by transmission and distribution grid operators to maintain the highest reliability of the electrical equipment they operate is the installation of technical condition monitoring systems. [34] On the basis of the results and recommendations provided by these systems, the staff operating the electrical equipment can take decisions on the planning of its maintenance.

In this chapter I also analysed the contribution that the technical condition monitoring systems used in the Romanian Transmission Grid have brought, or could have brought, in relation to the reliability of the transformers that are the subject of the case study. Thus, I analysed the technical contribution brought by the monitoring systems on the transformers or on the grid area where they have been installed, as well as the potential contribution if they had been installed on all the analysed transformers. In addition, I also analysed the energy that was not delivered to consumers, the hours of unavailability, the subsystems that contributed to the occurrence of faults or the variation in reliability of the transformers involved in the incidents during the period studied according to the region, the year of occurrence or the power of the transformers.

2.3. CASE STUDY: ANALYSIS OF THE INFLUENCE OF MONITORING SYSTEMS ON TRANSFORMER RELIABILITY

2.3.2. Reliability analysis of the transformer units affected by incidents over 5 years at Power Transmission Grid level

For the analysis of the reliability of the PTG transformer units affected by a number of 201 incidents in this case study, over the period 2017-2021, I calculated the main indices described in § 2.2: SAIFI, SAIDI, CAIDI, ASAI to determine the level of interruptions for each transformer unit.

In this sub-chapter there will be only 119 cases, corresponding to the 119 transformation units that were involved in incidents during the period under review.

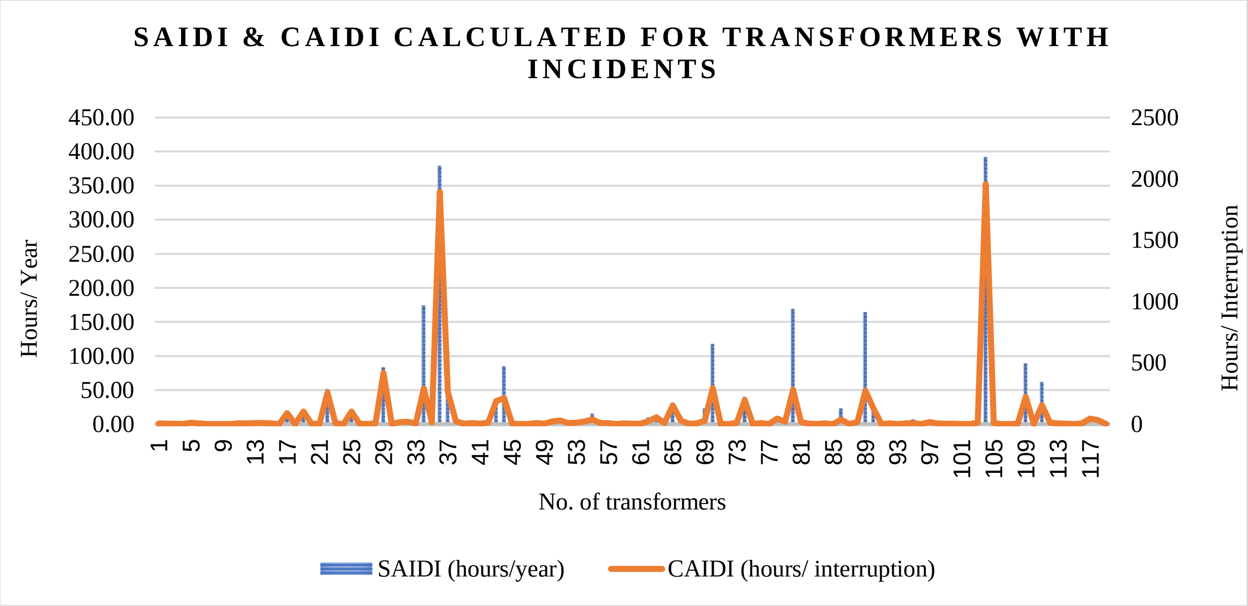

Fig. 2.10. Representation of SAIDI and CAIDI reliability indices for transformers involved in incidents

Thus, in Fig. 2.10 can be seen the representation of the SAIDI indices, showing the situation of the outage hours/year corresponding to each transformer involved in the 201 incidents, and the representation of the CAIDI indices, showing the situation of the average outage hours resulting from the incidents corresponding to each transformer.

What is important to note in the previous graph are transformers 36 and 104, where both the SAIDI and CAIDI indices had the highest values, as they correspond to incidents 103 and 130, which introduced the highest values of unavailability, referred to the whole period analysed. This shows that a single major incident regarding unavailability for each of the transformers also significantly influences the values of these reliability indices, which also predominate in this graph.

And at a general level, from Fig. 2.10 we can however observe a rather flat evolution among the transformers involved in the incidents, which means that apart from a few exceptions, the vast majority of the incidents resulted in rather small outages over the 5 years, so the reliability was quite high.

If we extract the SAIDI values exceeding 150 hours/year, they are represented by one 220/110 kV 200 MVA autotransformer and two 110/20 kV 40 MVA and 16 MVA transformers respectively. Again, the lower power transformers are the ones with the lowest reliability.

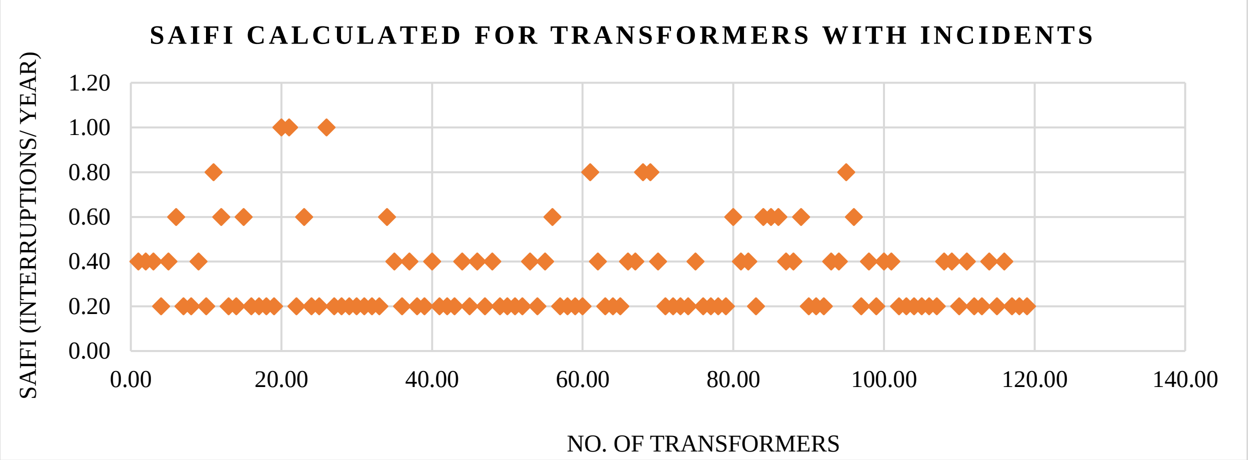

Fig. 2.11. Representation of SAIFI reliability indices for transformers involved in incidents

Regarding the SAIFI index representation showing the distribution of the number of interruptions per year for each of the 119 transformer units, it can be seen in Fig. 2.11 how the values are in the range of 0.2 and 1, which means interruptions between 1 and 5 in the period 2017-2021. The vast majority of cases are in the range of 0.2 and 0.4 values respectively, indicating an overall good level of reliability from the SAIFI index perspective. In the upper range with values of 1 and 0.8 respectively, i.e. a very poor level of reliability, there are only 8 transformers, of which three are below 100 MVA, two 200 MVA, one 250 MVA and two 500 MVA. Of these, the 500 MVA transformers are the ones that attract particular attention, as they carry significant power flows at the transmission power grid level and require more detailed diagnosis in order to identify the elements that led to these incidents and to urgently limit potential future outages.

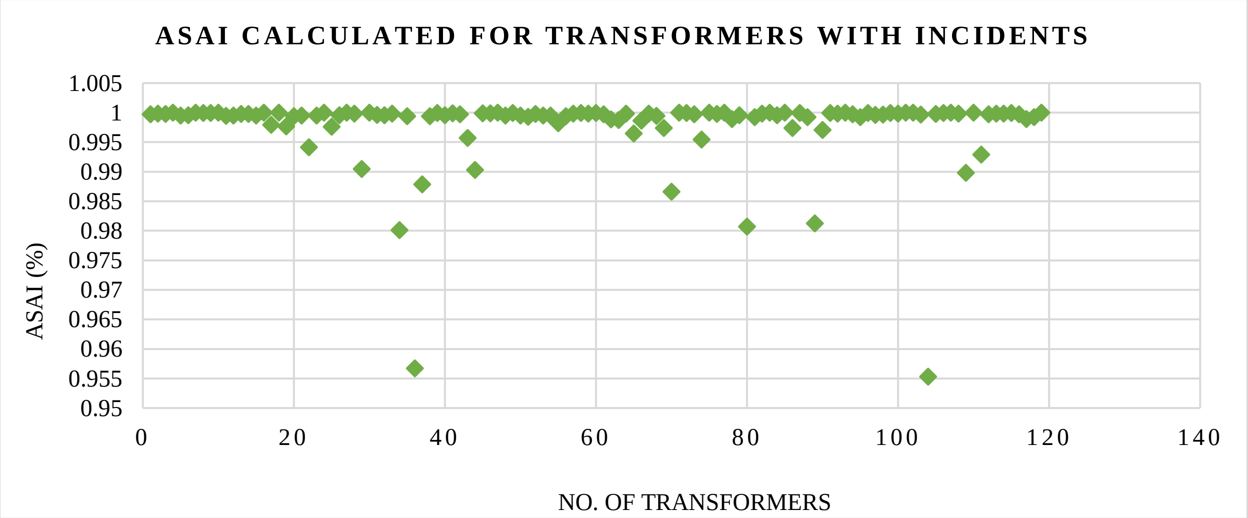

Fig. 2.12. Representation of ASAI reliability indices for transformers involved in incidents

In Fig. 2.12 I plotted the distribution of the ASAI index, which indicates the average operational readiness of transformers involved in incidents over this period. Most cases fall within very good reliability margins with values above 99% and 98% respectively. Among these there are only two cases that are below the 98% margin, namely the transformers involved in incidents 103 and 130 described above, where the long unavailability of 1895 and 1958 total outage hours respectively impacts the ASAI index values which are very low at 95.7% and 95.5% respectively.

2.3.3. Analysis of the influence of technical condition monitoring systems on the reliability of transformers affected by incidents over a 5-year period

Next, in order to determine the influence that technical condition monitoring systems had or could have had in the equation of this case study, for the transformers in the 201 incidents that occurred during 2017-2021, I made the following statistical graphs.

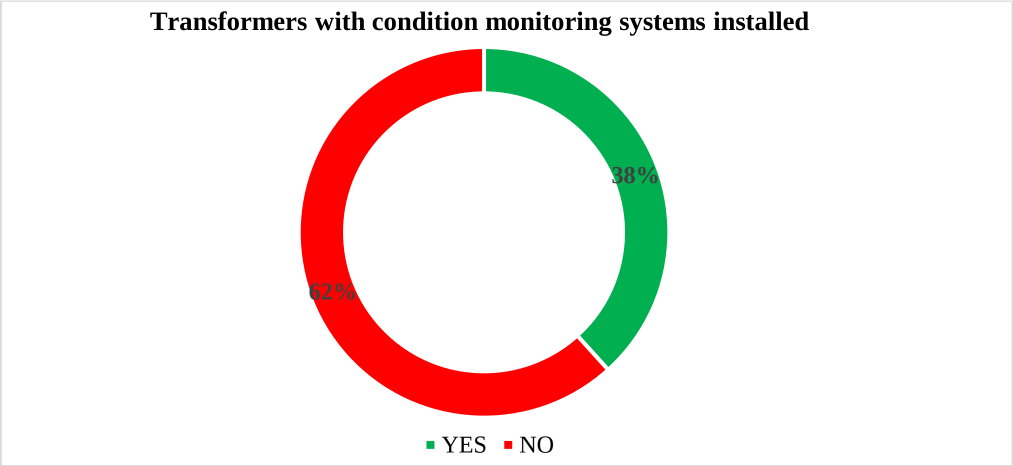

Fig. 2.15. Percentage of transformers with monitoring systems installed at the time of the incident

As can be seen in Figure 2.15, 38% of the transformer units involved in the 201 incidents in this case study had condition monitoring systems installed, while 62% of them did not. In the following paragraphs we have addressed both segments of transformers in order to identify the contribution they could make in limiting the number of future incidents.

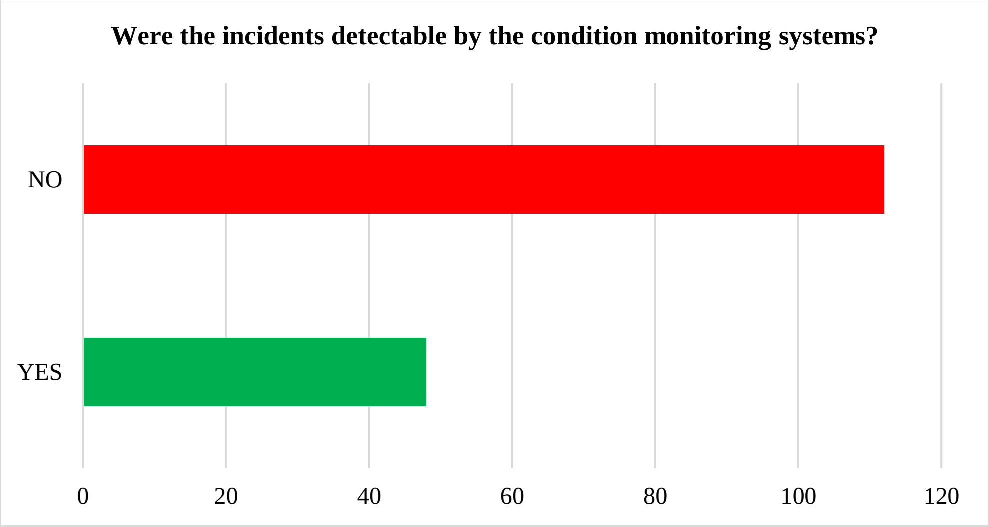

Fig. 2.17. Proportion of incidents occurring on transformer subsystems that can usually be monitored by monitoring systems

In order to better understand whether the monitoring systems could have prevented the occurrence of incidents on the transformers on which they are installed, I made the graph in Fig. 2.17, where the incidents were divided into two categories, as follows:

- incidents detectable by monitoring systems: i.e. incidents where the affected subsystem that caused the unavailability of the whole transformer could be monitored via the monitoring system sensors. For example, in the case of a fault occurring in the primary terminal insulators, by carrying out preventive maintenance following analysis of the results of the electrical and thermal parameters measured by the system, there was a good chance that the incident could have been avoided;
- incidents not detectable by the monitoring systems: i.e. incidents that occurred as a result of causes beyond the systems' monitoring capabilities. For example, an incident in the distribution grid that also resulted in the tripping of the transformer.

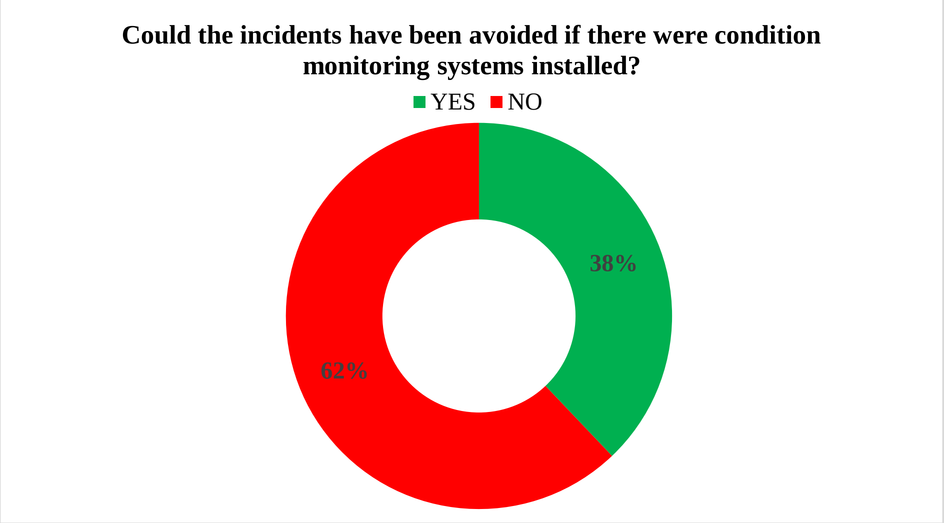

Fig. 2.18. Percentage of theoretically avoidable incidents if they had monitoring systems in place

Fig. 2.18 is intended to show the incidents which, out of the total of 201, could theoretically have been avoided if the transformers without monitoring systems installed still had these systems, so that the technical condition parameters could be monitored and preventive maintenance carried out in order to avoid failure of the various sub-assemblies. Out of the total number of incidents, 38% of incidents were caused by failures of sub-assemblies that could be monitored by the systems. In the case of these 38% of transformers involved in these incidents, theoretically if the subsystems that failed had been monitored, the incidents could have been avoided by linking them to preventive and predictive maintenance actions. An example of such an incident that could have been avoided by using monitoring systems is an internal fault with arcing of the transformer windings, which by monitoring oil dissolved gas levels and internal temperatures could be seen as a fault evolving over time.

CHAPTER 3. THERMAL AGEING EVALUATION OF TRANSFORMERS

In this chapter I presented the mathematical models standardised by both IEC and IEEE for the assessment of the loss of life of transformers, which have been used in the power industry for more than 15 years by grid operators. [62] [63] They are used in power substations by installing transformer condition monitoring systems that measure in real time parameters related to the condition of the equipment, which are then used for the automatic calculation of the system's lifetime. [64] [65] [66] Since the main internal parameters of the transformer that are used to determine its ageing are the TOT and HST temperatures, in the study this model was called thermal model [48].

I also presented how these thermal models "translate" into a transformer condition monitoring system used in industry and the results produced by it for 10 different transformer units in terms of years of operation, powers or voltage levels served. I used this type of monitoring system installed on the 10 power transformers to extract hourly data over a one-year sample (year 2022) for both the calculated loss of life of the transformer and the various parameters that influenced its lifetime during operation. Variations of the loss of life as a function of electrical parameters such as currents or voltages on the primary terminals of the transformers, or thermal parameters such as the internal temperatures of the transformer, were plotted to identify the elements that have the greatest influence on the ageing of the equipment. As a result of these graphical representations I identified a series of results of the evaluation of the loss of life using thermal models, which set the premises of chapter 4 where I approached a new method of ageing evaluation, with the help of which I obtained a new model that corrects the classical one for certain operating conditions of transformers.

At the same time, coupled with the evaluation of the condition of the transformers using monitoring systems, I have also carried out a series of multispectral inspections to evaluate their thermal behaviour using a different method in order to confirm the results of the system.

3.1. EVALUATION OF THE LOSS OF LIFE OF TRANSFORMERS BASED ON THERMAL MODELS

3.1.1. Introduction

Of all the parameters that can be measured in the operation of transformers, the hot spot temperature plays the most important role in relation to the rate of insulation degradation. [47] For the calculation of the hot spot temperature there are different mathematical models, but the one most used in industry at European level for mineral oil transformers is the one promoted by the IEC 60076-7 standard. [48] [49]

Also, the main cause of defects in transformers is the failure of their insulation by internal arcing, which reduces their lifetime. [50] Among the main such causes that can produce internal defects are:

- transformer overload;
- moisture in the tank;
- low-quality oil;
- low-quality oil-impregnated paper.

The lifetime of a transformer is directly proportional to the condition of its insulation, represented by the condition of the oil and paper, influenced by how the transformer is operated at different loads and operating regimes. [59] Humidity, heat and oxygen are some of the most important parameters that cause hot-spot temperatures and lead to deterioration of the oil-impregnated paper and reduced transformer life. [48] [60] [61]

3.1.3. Determination of the Loss of Life (LOL)

The lifetime of transformers is directly proportional to the quality of their insulation, i.e. the quality of the oil and the oil-impregnated paper. However, the most important factor influencing transformer lifetime is the condition of the oil-impregnated paper. Also, the most important parameters that lead to the highest internal operating temperature of the transformer (hot spot temperature) relate to humidity, heat or oxygen, and directly damage the paper and decrease the life of the equipment. [48]

3.1.3.1. LOL determination based on the IEEE C57-91 standard

According to the IEEE standard, the experimental basis accumulated over time has proven that transformer insulation deterioration due to temperature and aging follows the Arrhenius reaction rate theory, which has the following form:

$$Per\ Life\ Unit = Ae^{\left[\frac{B}{\theta H+273}\right]} \tag{3.56}$$

The per unit life curve of transformer insulation, represents the evolution of the transformer insulation life at hot-spot temperature. This curve can be used as a reference for both distribution and power transformers as both types are manufactured using the same type of insulation. By using this curve, the degree to which the ageing rate is accelerated above normal for a reference temperature of 110°C and is reduced below normal for a temperature below 110°C is indicated. The equation characterising this curve is:

$$Per\ Life\ Unit = 9.8 \times 10^{-18} e^{\left[\frac{15000}{\theta H+273}\right]} \tag{3.57}$$

Thus, the curve per unit life of the transformer insulation can be used in two ways. It is the basis for the calculation of the ageing acceleration factor (F_{AA}) for given or varying loads and temperatures for a period of 24h. The ageing acceleration factor has a value greater than 1 for hot-spot temperatures above the reference temperature of 110°C and less than 1 for temperatures below 110°C. The equation for determining the F_{AA} is:

$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta H + 273}\right]} \tag{3.57}$$

Equation (3.57) is used to calculate the relative ageing of the transformer. The equivalent ageing factor at reference temperature over a period of time and a given temperature is as follows [69]:

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA,n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \tag{3.58}$$

The transformer life curve can also be used to calculate the percentage of total loss of life. For this, it is necessary to define the normal lifetime of the transformer insulation at a reference temperature. Then, the hours of the total loss of life over the chosen total period of time are determined by multiplying the equivalent ageing determined by equation (3.58) by the time period (t) in hours. This gives the number of hours of loss of life of the transformer at the reference temperature. [72] The percentage of the loss of life over the period considered is the equivalent of the hours of loss of life divided by the normal insulation life (in hours) and multiplied by 100. Typically, the time period chosen is 24h and the resulting equation is [69]:

$$\%\, LOL = \frac{F_{EQA} \times t \times 100}{Normal\ lifetime\ of\ insulation} \tag{3.59}$$

3.1.3.2. LOL determination based on the IEC 60076-7 standard

According to the IEC standard, although the ageing and deterioration of transformer insulation is a function of time that depends on parameters such as temperature, moisture content inside the tank or other dissolved gases in the model described, in the standard only the insulation temperature (hot-spot temperature) is taken into account to determine ageing.

Since the temperature distribution is not uniform, the part of the insulation inside the transformer that will operate at the highest temperature value (hot-spot temperature) will suffer the most damage. Thus, the relative ageing rate "V" is defined according to the equation (3.60) [71]:

$$V = 2^{(\theta_h - 98)/6} \tag{3.60}$$

$$V = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h + 273}\right)} \tag{3.61}$$

Thus, the calculation of the loss of life of the transformer for a given period of time is summarized by the equation (3.62):

$$L = \int_{t1}^{t2} V dt \qquad or \qquad L = \sum_{n=1}^{N} V_n \times t_n \tag{3.62}$$

3.2. CASE STUDY: ASSESSMENT OF POWER TRANSFORMER AGEING USING THERMAL MODELS

In this case study I used a transformer condition monitoring system, complying with IEC 60076-7 standard, installed on 10 transformer units located in different substations within the Power Transmission Grid to determine their loss of life based on the thermal model. [73] Using the installed monitoring system, I obtained and plotted hourly data of the loss of life values for each of the transformers and I was able to observe their dependencies on various electrical or thermal parameters. [74] [75] I have also aimed to use the mathematical models described in § 3.1 to calculate the loss of life of the transformers using their thermal behaviour values and to compare the results with those provided by the system. At the same time, the thermal behaviour data of the transformers is validated for a part of the transformers using infrared and ultraviolet thermal imaging camera inspections.

The transformers and monitoring systems used in this case study provide the basis for the research carried out in Chapter 4, where I proposed a new model for assessing their loss of life.

3.2.3. Assessment of ageing of transformers through the condition monitoring systems for 1 year sample, using the thermal model

Next, with the help of the technical condition monitoring systems [79] presented in § 3.2.1. that were installed on the transformer units presented in § 3.2.2. it was possible to determine the main parameters that influence the lifetime of the transformers.

For all the transformer units, I have extracted historical data measured in real time for 1 year on hourly samples. I extracted the data locally from the monitoring system server installed in the substation, using its software application for each individual transformer unit. The period of 1 year was chosen so that the transformer goes through all the ambient temperature regimes and all the load regimes to which it is subjected depending on the time of year in order to obtain a series of evolutions of the measured parameters and the calculated lifetime as relevant as possible..

Also, in order to make the results as relevant as possible to this case study, I have extracted data from transformer units of different ages, located at geographically different nodes in the transmission power grid, and taking the year 2022 as the reference year in all cases, so that temperature and load variations are proportional.

Installed condition monitoring systems [79] are capable of performing a wide range of measurements that follow the characteristics presented in § 3.2.1., but for the present case study I have extracted only the measurements calculated directly by the system for the lifetime of the transformer and the main measured parameters affecting its lifetime. Thus, the data extracted from the monitoring systems are:

- loading factor;
- ambient temperature;
- hot-spot temperature calculated according to IEC 60076-7;
- hot-spot temperature calculated according to thermal model;
- primary winding current on phases A, B, C;
- secondary winding current on phases a, b, c;
- primary winding voltage on phases A, B, C;
- secondary winding voltage on phases a, b, c;

- loss of life;
- remaining lifetime;
- transformer operating time.

3.2.3.1. *Determination of ageing of study transformers using the thermal model*

In the graphs in fig. 3.31-3.38 is represented the evolution of the loss of life for the transformation units T1, T2, T3, T5, T6, T7, T8 and T10, using 2 sets of data, as follows:

- DVC 1: Set of values for the loss of life, represented by data obtained from measurements made by means of technical condition monitoring systems installed on transformers;
- DVC 2: Set of values of the loss of life, represented by the data obtained from calculations performed according with the IEC 60076-7 thermal model described in § 3.1.2.2 1 and using the hot-spot temperature values measured by the monitoring systems. Basically the DVC 2 data set, represents a set of control values of the results obtained by the monitoring system.

For each of these cases, since we are talking about data covering samples of 1 year of operation, the transformers were able to go through all the temperature ranges of a year and implicitly through all the load ranges (except in the case of faults), according to the characteristic consumptions of the areas they serve.

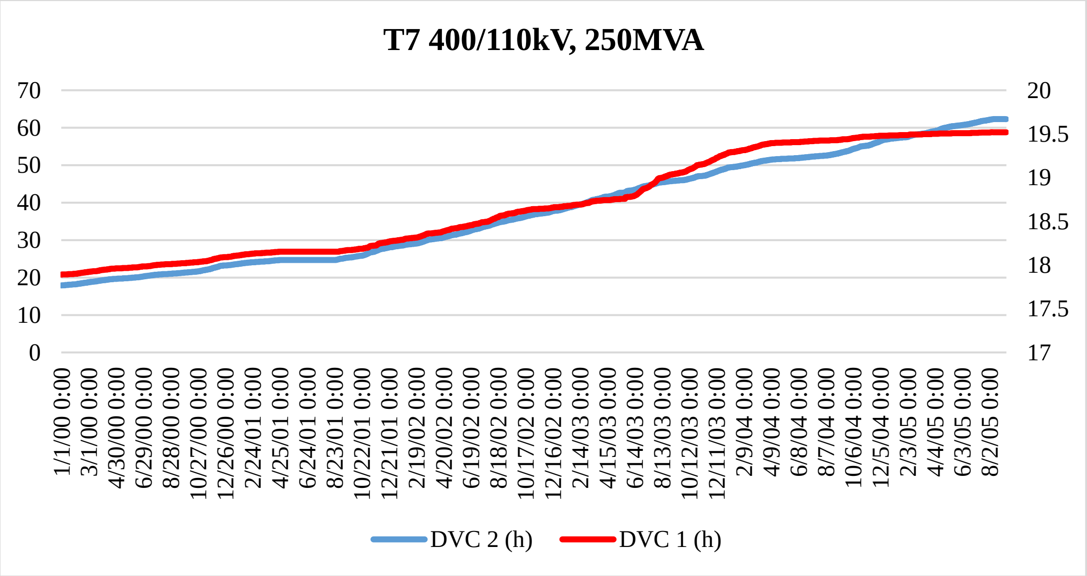

Fig. 3.36. Variations of the loss of life, calculated with monitoring system and individually for T7

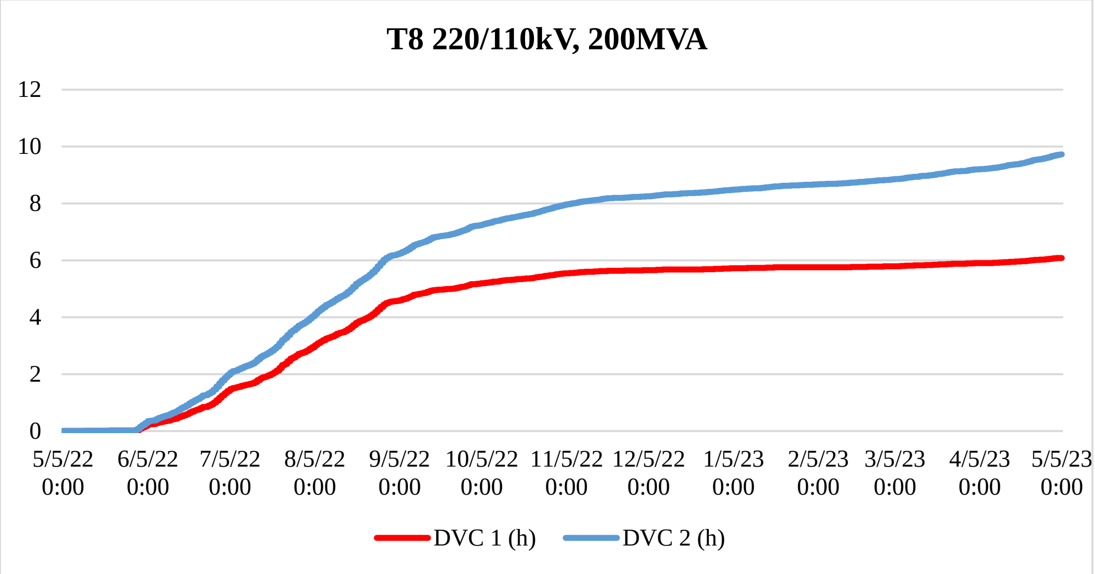

Fig. 3.37. Variations of the loss of life, calculated with monitoring system and individually for T8

Thus, analysing the trends of the DVC 1 loss of life extracted from the monitoring systems, it has been observed that in all the cases shown in the figures that out of a total of 8760 hours, which is the length of a year, the transformers covered by this case study have ageing lives ranging from 6 to 250 hours. Basically, the results produced give the impression that the transformers are operated almost without ageing during a year for more than a few hours or days. But this is obviously false in reality. The mathematical model of the thermal method for calculating the loss of life given by the IEC 60076-7 standard, the most widely used in the industry and by default the one underlying the monitoring system in this case study, shows similar results in table "I.2. Output data for the example". In the example results shown in this table and the graph in Fig. 3.39 extracted from the IEC standard, it can be seen that for internal hot-spot operating temperatures of transformers that are below 90^{o}C corresponding to load loads below 81% (according to table "I.1. Input data for example" in IEC 60076-7), they produce loss of life results of 0 minutes ageing, which also gives the impression that below this range of hot-spot temperature and load the transformer does not age. However, the typology of the mathematical model in IEC 60076-7 produces the results of the loss of life predominantly for values above these values, i.e. for transformer operating regimes at or above nominal level, corresponding to overloads or fault regimes producing loads above 100% and therefore accelerated ageing of the equipment. And under this temperature and load range, the thermal model used produces results with very low ageing values depending on the technical specifications of each transformer, age and operating conditions.

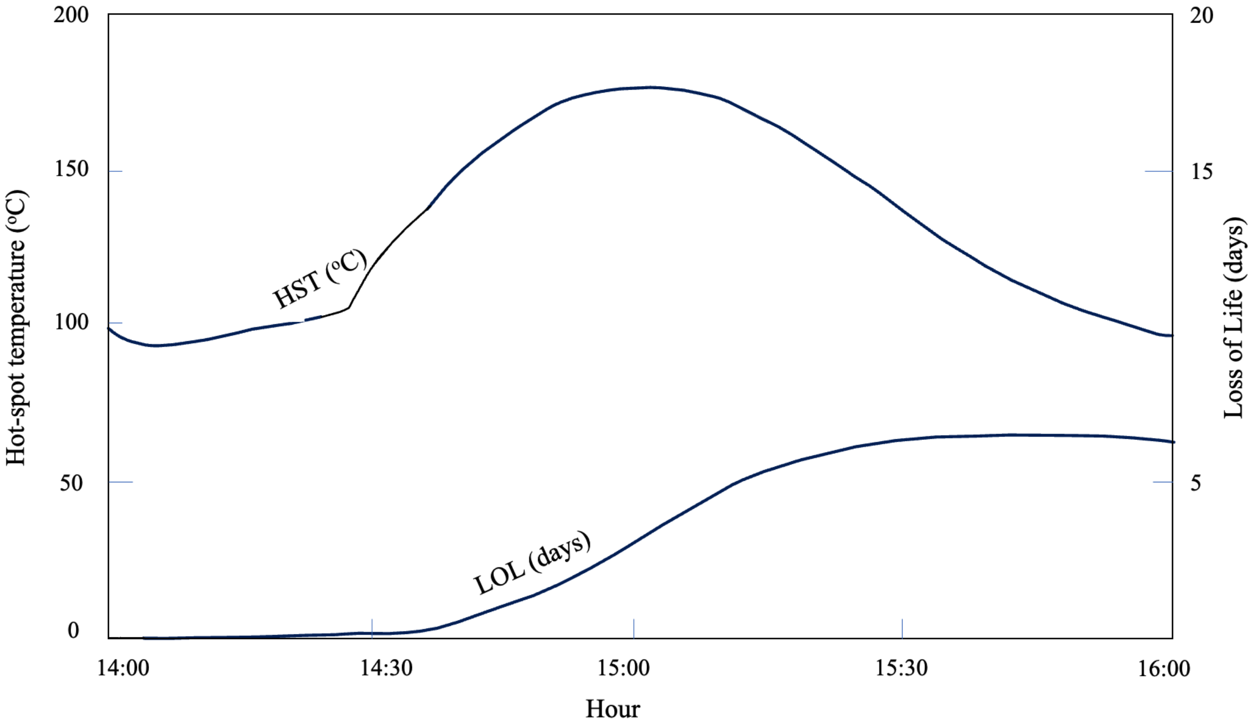

Fig. 3.39. Representation of the evolution of the loss of life as a function of the temperature regime of the transformer according to the example in IEC 60076-7 standard [71]

Next, in the graphs in fig. 3.40-3.48 I have plotted the variations of the calculated DVC 2 loss of life with the calculated values of the relative ageing rates. I have calculated the relative ageing rates for transformers T1-T8 and T10 (Fig. 3.40-3.48) based on hot-spot temperature data measured by the monitoring systems and using the IEC thermal model. This parameter varies directly proportional with the internal operating temperature of the transformer and indicates the actual ageing for each time interval in transformer operation.

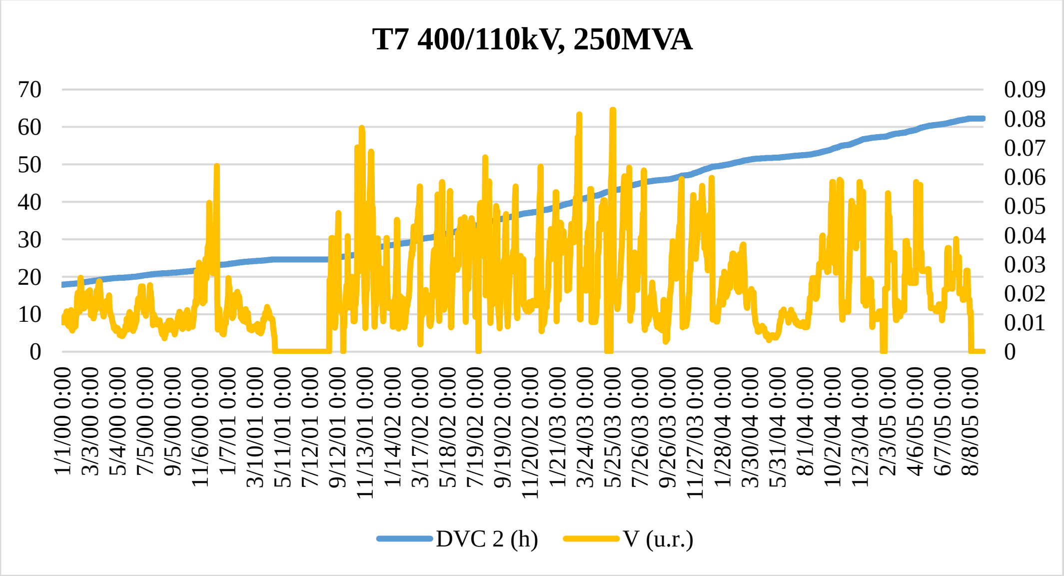

Fig. 3.46. Variation of loss of life in relation to ageing rate for T7

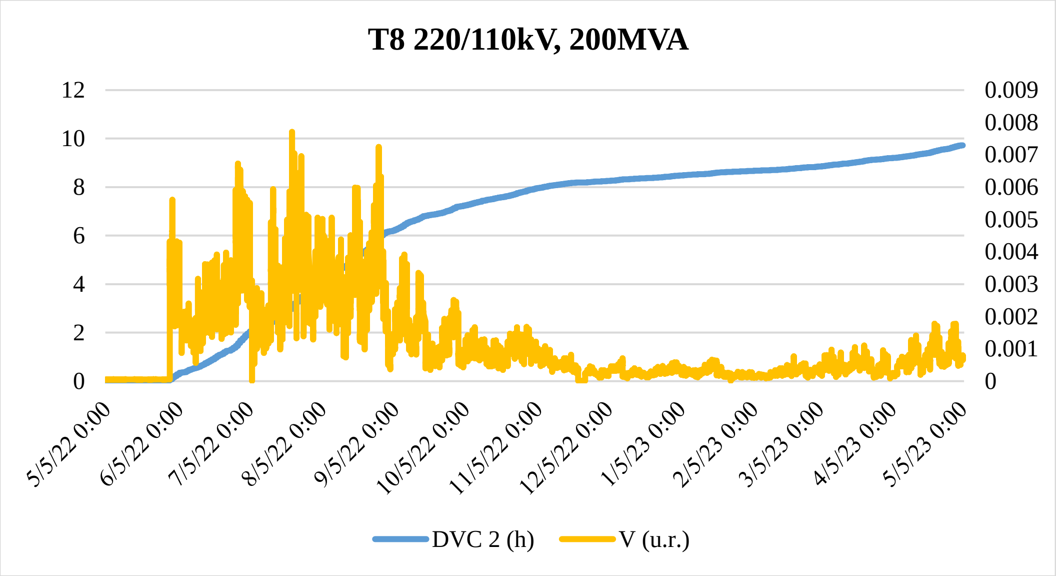

Fig. 3.47. Variation of loss of life in relation to ageing rate for T8

Thus, as can be seen in the graphs above, steep variations in DVC 2 are correlated with high values of V for the respective time intervals. A very relevant example is shown in Fig. 3.47 corresponding to transformer T8 where it can be seen the period June-October 2022 characterized by a significant increase in its ageing, compared to the rest of the year, where there were rather low values of the relative ageing rate and resulted in a flatter evolution of the loss of life. The variation of V is constant because, as previously stated, it is directly influenced by the values of the internal temperatures of the transformer which even at constant loads, will vary according to the external environmental conditions which change throughout the day.

3.2.3.2. *Determination of the influence of thermal parameters on the loss of life of the study transformers*

In this sub-chapter, I have represented in Fig. 3.49-3.57 the variations of the loss of life in relation to the parameters that directly influence the ageing of T1-T8, T10 transformers, namely the internal hot-spot temperature and the ambient temperature which in turn influences the internal temperature of the transformer. For the analysis of these evolutions, the time sample chosen for which the data were extracted, namely 1 year, is very important, as it allowed each transformer unit represented here to go through a complete cycle of thermal behaviours influenced by the ambient environment.

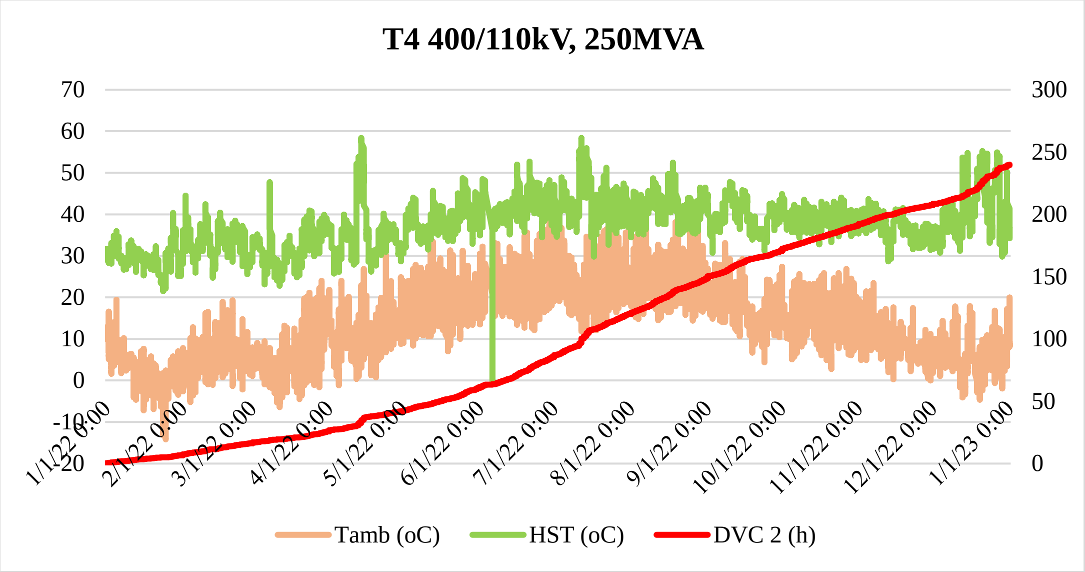

Fig. 3.52. Variation of loss of life in relation to thermal parameters for T4

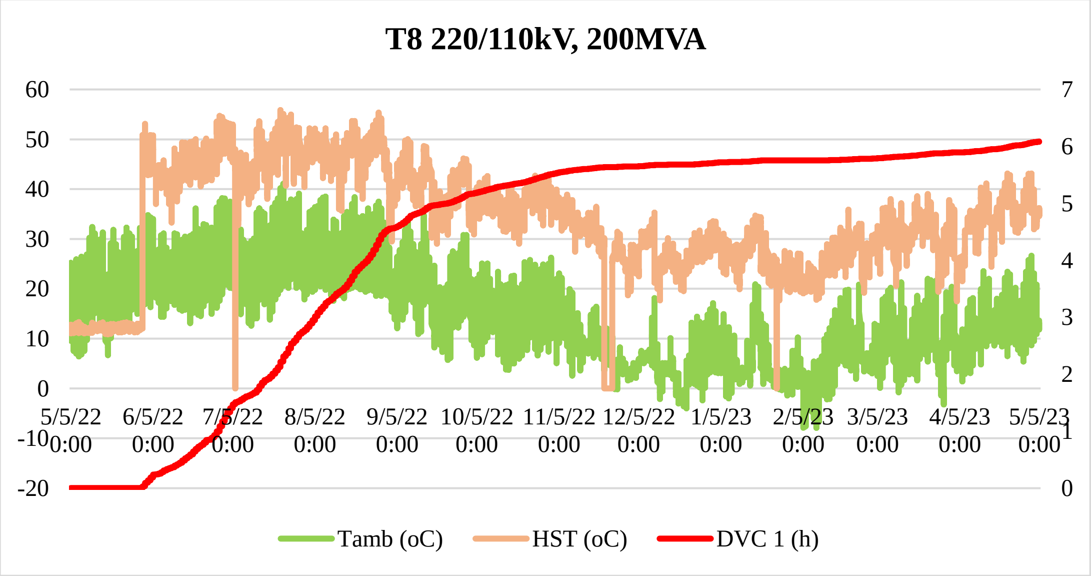

Fig. 3.56. Variation of loss of life in relation to thermal parameters for T8

Thus, it is observed that in all transformers in this case study, their internal hot-spot temperatures vary directly in proportion to the ambient temperature and that in return their loss of life increases with higher values of these temperatures. [82] [83] From this we could conclude that transformers age faster when ambient temperatures are higher, and the better they benefit from cooling as is the case in the cold season period, the lower the internal temperatures, the less the oil-impregnated paper deteriorates and the slower the transformer ages. [84] [85] Therefore the same type of transformer, operated under similar conditions but used in two different climate zones, a cold zone and a warm zone, can produce a result whereby the transformer operated in the cold zone will operate longer. [49] [86] [87]

The most representative for this is Fig. 3.52 corresponding to T4 and fig. 3.56 corresponding to T8, where it can easily be seen how between May and September there are steep increases in the loss of life, while between December and March the ageing of the transformers occurs very slowly and the DVC 1 curve is almost linear.

3.2.3.3. Determination of the influence of electrical parameters on the loss of life of the study transformers

Apart from the environmental conditions that lead to an increase in the internal operating temperatures of transformers, which have been observed in § 3.2.3.2., the most important influence on their ageing process is obviously the operating conditions. As the thermal model of the IEC/IEEE standards shows, the higher the loads, above the nominal level, the faster the ageing of the transformer units.

In the graphs in Fig. 3.59-3.67 I have plotted the variations of the DVC 1 loss of life against the currents, respectively phase voltages on the primary terminals for transformers T1-T8, T10.

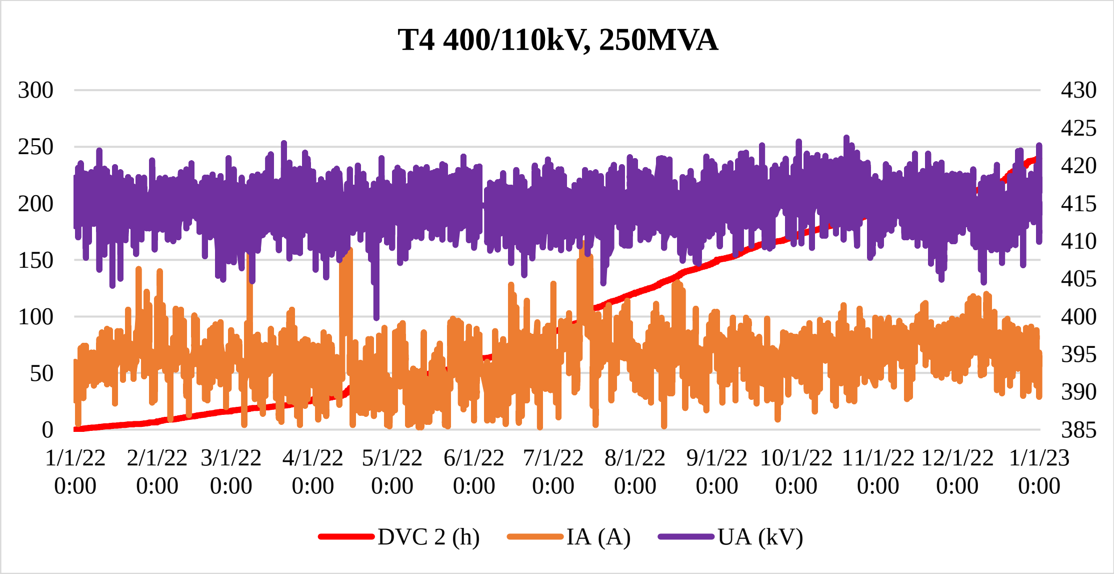

Fig. 3.62. Variation of the loss of life in relation to electrical parameters for T4

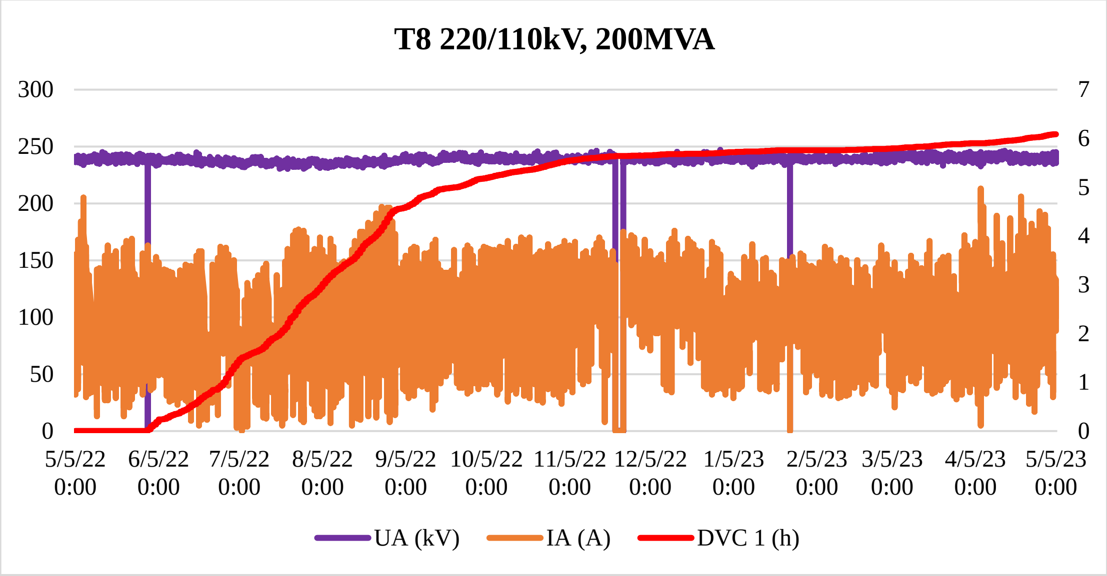

Fig. 3.66. Variation of the loss of life in relation to electrical parameters for T8

We can see that, as expected, the voltages on the transformer phases are electrical parameters that vary quite little within the permissible range of the rated voltages at which it operates. On the other hand, the values of currents are variable depending on the time of the year or times of the day when both the loads on the consumers vary and the power produced in variable power plants such as those from renewable sources which depends on environmental conditions. However, this current variability is hardly noticeable in the increase of the loss of life for currents of small values, as for example is the case of T8 in Fig. 3.66, where although we have a significant increase in DVC 1 in the period June-October 2022, the current values did not exceed the nominal values and remained in a constant, low range of operating values. This means that this significant increase in DVC 1 in that period of time occurred due to the high ambient temperatures during the summer period, as can be seen in the graph in Fig. 3.56.

Correlated with these representations of the dependence of the loss of life on the current and phase voltage on the primary terminals of the transformer, further in Fig. 3.68-3.75, corresponding to T2-T8, T10 is plotted the variation of the relative aging rate (V) with the load factor (k).

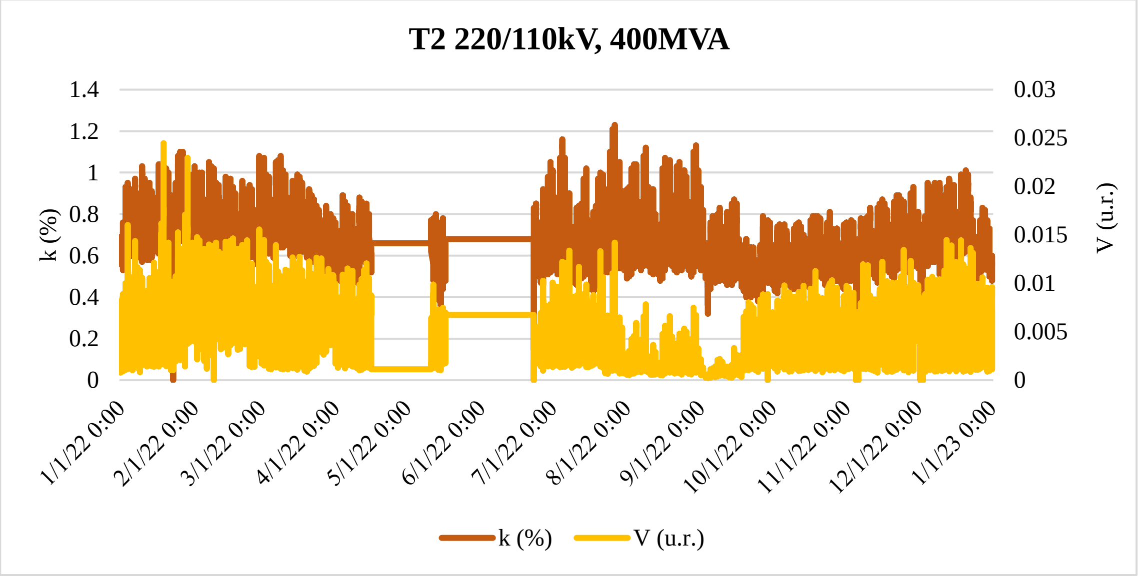

Fig. 3.68. Variation of load in relation with the ageing rate for T2

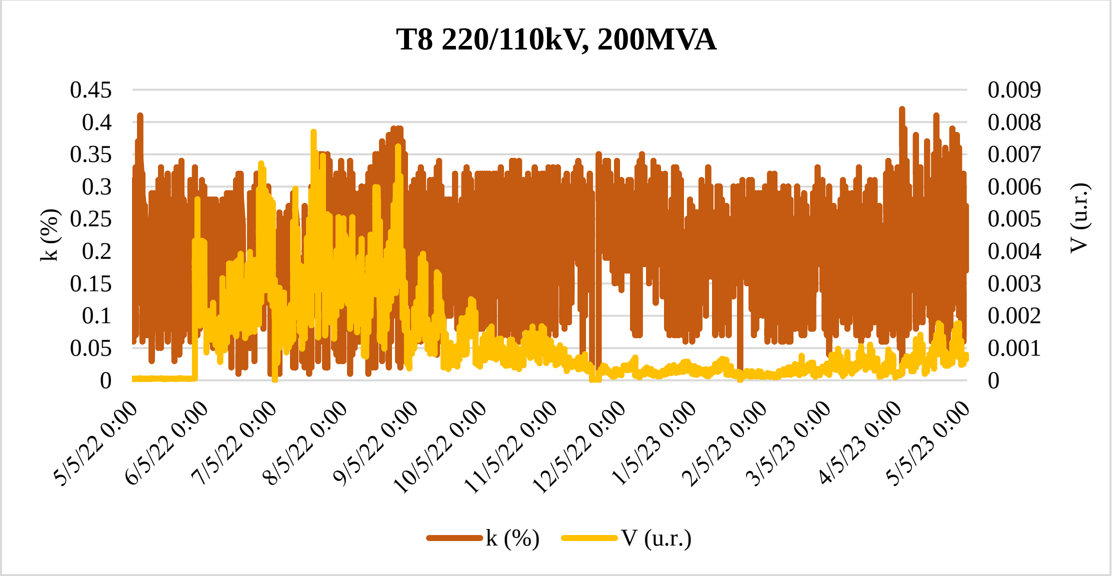

Fig. 3.74. Variation of load in relation with the ageing rate for T8

Similar to the evolution of the values of the loss of life in relation to the currents on the transformer terminals, this can be seen at a more detailed level in the above graphical representations of the load factor - relative ageing rate dependence.

Thus, as I mentioned previously, it can be very clearly observed that, with the exception of T2, in all the cases represented, load values of around 70-80% are not exceeded, so we are talking about sub-nominal operating regimes. In the case of T2 in fig. 3.68 instead, we have an operating regime with higher loads that fall in the range of 50-120%. For this case, it can be best observed how the values of the relative aging rate V, vary directly proportional to the loading factor. [88]

For the other cases instead, we observe quite small loads, which is why the V values are also quite constant and any important increase of this parameter is influenced either by the ambient conditions or by short-term increases in the transformer loads. A very representative example is associated with T8, from fig. 3.74, where although the loads are constant throughout the year, without transient regimes or high loads, we observe a peak of the V evolution during the summer, because here we are seeing the influence of the ambient environment on the aging of the transformer. [89]

CHAPTER 4. EVALUATION OF TRANSFORMER AGEING BY MEANS OF INSULATION RESISTANCE

According to a study [92] [93] carried out by Simtech International and Politehnica University of Bucharest in 2016-2018, a new method was proposed to determine the estimated, consumed or remaining lifetime of an oil-insulated transformer unit, which uses a mathematical model based on transformer insulation resistance values obtained between specific time intervals. This method builds on conventional thermal models used for years in industry to determine transformer ageing and works as a complementary method that is very useful in the operation of these types of equipment, as demonstrated in this chapter.

Basically, with this method a new diagnostic factor is introduced, namely the insulation resistance of the paper-oil insulation system in the transformer, for the assessment of its degradation. With this factor the lifetime consumption of the insulation system is determined, based on the activation energy of a material constant equivalent to the paper-oil insulation, determined from the values of the insulation resistance of the transformer at certain times during its operation [92].

The case study developed and presented in this chapter refers to a series of power transformers in the Romanian Transmission Grid and applies the mathematical model for the evaluation of transformer ageing by means of insulation resistance, as proposed by [92], in a real operational environment of these types of equipment.

In addition, I also carried out a comparative statistical analysis of the results obtained using the thermal models for transformer ageing assessment described in Chapter 3, in order to identify differences in the results. At the same time, I described the cases where the insulation resistance model has important advantages in the assessment of transformer ageing and what is the complementary contribution of this new model compared to the conventional one. [94]

In this chapter I applied for the first time in power systems industry the model for determining the loss of life based on insulation resistance measurements on the 10 transformers presented in Chapter 3. Following the evaluation of the loss of life using this model, I compared by means of a statistical study, the loss of life results obtained using the thermal model and the conclusions showed the difference between them. However, using this model to evaluate ageing based on insulation resistance, it was possible to observe a significant technical contribution for transformers that are loaded below the rated level. According to the conventional, thermal model, the area of operation with below rated loads of the transformers does not produce ageing of the transformers for this type of operation. However, using the insulation resistance model I obtained different results showing that transformers can have considerable aging levels even at below rated operating levels. After obtaining these results, I concluded that the conventional, thermal model can be corrected for the below-rated loading level of transformers.

Thus, I performed a complex statistical study that uses a meaningful dataset from the 10 transformers to produce a model for evaluating the loss of life that also addresses the lower segment of loads. As a result of this study, I obtained a new transformer ageing assessment model that is applicable across the entire range of transformer loads or internal operating temperatures. This new model proposed through the research carried out, can become even more powerful when data from even more transformer units are introduced. Basically, the method of obtaining the model will always be the same, but the model can be "refined" as it benefits from larger datasets.

4.2. DESCRIPTION OF THE MATHEMATICAL MODEL FOR DETERMINING TRANSFORMER AGEING BY MEANS OF INSULATION RESISTANCE

According to the model described in [92] [93], the insulation resistance is the diagnostic parameter used to determine the "a" and "b" coefficients of the transformer life lines based on the Dakin and Montsinger ageing models, i.e. the activation energy associated with ageing under thermal stress.

The lifetime values corresponding to the constant thermal stress on the paper-oil insulation will be determined by the expressions:

$$D_D = A_D exp\left(\frac{b_D}{T}\right) \tag{4.6}$$

$$D_M = A_M exp(-b_M\theta) \tag{4.7}$$

Thus, from equations (4.6) and (4.7), it will be possible to obtain the equations of the lifetime lines corresponding to the two models:

$$lnD_D = a_D + b_D/T \tag{4.8}$$

$$lnD_M = a_M - b_M\theta \tag{4.9}$$

Knowing the values of the parameters of the lifetimes lines$(a_{D,M}\ and\ b_{D,M})$, the estimated lifetimes corresponding to the operation of the components or paper-oil insulation at a constant temperature "T", i.e. $\theta(D_{D,M}(T,\theta))$ can be calculated next. Thus, if the insulation is subjected to a time interval Δt at constant temperature "T", then the loss of life is $D_{cD,M}(T,\theta) = \Delta t$, and the remaining lifetime is $D_{rD,M}(T,\theta) = D_{D,M}(T,\theta) - \Delta t$.

Next, if the insulation was operated at a variable temperature T(t), the relative loss of life can be calculated using one of the equations:

$$D_{crD}(\Delta t) = \frac{1}{A_D}\int_0^{\Delta t} e^{-\frac{b_D}{T(t)}}dt \tag{4.10}$$

$$D_{crM}(\Delta t) = \frac{1}{A_M}\int_0^{\Delta t} e^{b_M\theta}dt \tag{4.11}$$

respectively, the consumed and remaining lifetimes:

$$D_{cD,M}(T,\theta) = D_{D,M}(T,\theta) - D_{crD,M}(\Delta t) \tag{4.12}$$

$$D_{rD,M}(T,\theta) = D_{D,M}(T,\theta) - D_{cD,M}(T,\theta) \tag{4.13}$$

and if the temperature variation curve is not known, then the relative loss of life in the range Δt can be calculated using the equation [92] [93]:

$$D_{cr}(\Delta t) = \frac{R_i(0) - R_i(\Delta t)}{R_i(0) - R_{i,eol}} \tag{4.14}$$

By relating the value of the insulation resistance measured at time t=Δt and the end-of-life criterion to its initial value Ri(0), equation (4.14) becomes:

$$D_{cr}(\Delta t) = \frac{1 - R_{ir}(\Delta t)}{1 - R_{ir,eol}} \tag{4.15}$$

4.3. CASE STUDY: ASSESSMENT OF POWER TRANSFORMER AGEING USING INSULATION RESISTANCE MODEL

Using the mathematical model described in § 4.2 and using the insulation resistance values available for the study transformer units, I determined the loss of life for each of them.

In the case of transformers T4, T5, T6 and T7, as they are newly commissioned units between 2020 and 2021, the only insulation resistance measurements were those made during installation, site testing and commissioning. For this reason, for these transformers I was able to determine the ageing rate only for one month.

Thus, it can be seen how the ageing values vary from 0 to 23903 hours for a single year (8760 hours), and a first element that differs from the calculation based on the thermal model is that the vast majority of the values are higher than the results obtained in chapter 3 for the case of a single year.

As used in Chapter 3, the abbreviation for the loss of life will be "DVC", followed by the number 3, the first two (DVC1 and DVC2) being those described in Chapter 3, which are based on the classical, thermal model.

For the evaluation of the loss of life of the 10 transformer units, three insulation resistance values were required for each of the values obtained in Table 4.1. Two of these refer to the resistance values measured between two moments representing the calculation period; in this case, the values of two consecutive years. And the third value refers to the insulation resistance at the end of the transformer life. As we are talking about power transformers installed in the Romanian Transmission Power Grid, to obtain these reference values, I have used CNTEE Transelectrica SA's specifications from "NTI-TEL-R-002-2007 - Internal Technical Standard on tests and measurements of electrical equipment in the Transmission Power Grid". [98]

For a better overview of the differences resulting from the evaluation of the loss of life for the 10 transformer units described in § 3.2.2. with both the thermal and insulation resistance models, I made the graph in Fig. 4.2.

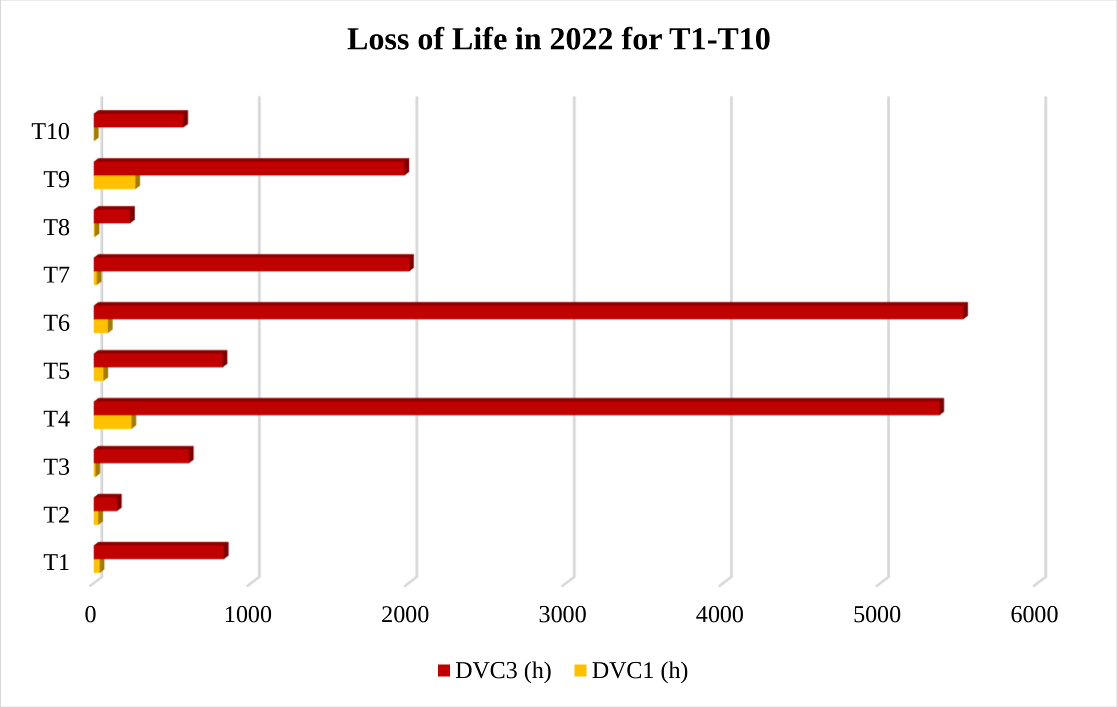

Fig. 4.2. The obtained loss of life for 10 transformers
power transformers with thermal model, and insulation resistance model

The thermal model allows the evaluation of the loss of life at any stage of time, as it depends on the measurement of the internal temperature of the transformer that can be carried out during its operation through dedicated sensors. In contrast to this model, in the case of the insulation resistance-based model, the evaluation of the loss of life can only be performed when scheduled measurements of the insulation resistance are performed.

Thus, with these data plotted in Fig. 4.2 above, it can be seen that for all 10 transformers, the values of the loss of life using the insulation resistance model exceed the values obtained using the thermal model every time. While for the DVC1 case (thermal model) in each of the 10 cases, the transformers depreciate their lifetime very little in one year, with values in the order of hours, in the DVC3 case (insulation resistance model), there are ageing values ranging from a few hours to more than half a year, depending on the transformer.

This is mainly due to the fact that all 10 transformers were loaded during 2022 at the below-rated level, as seen in § 3.2.3.3, and the thermal model for such cases provides very low transformer ageing results. Different from the thermal model, the insulation resistance model provides higher results also for this type of below-rated operation, which shows that transformer units depreciate their lifetime also for this type of operation.

If we look at these results taking into account the operating experience, whereby the average lifetime of a transformer is 30-40 years, even for those operated similarly to those in this case study, it is clear that the values of the loss of life are closer in reality to the results provided by the insulation resistance model. Over the course of a year, even if there were no overloads or fault regimes, the transformer still went through a process of wear and ageing, and values in the order of days or months are closer to the operating experience than values in the order of hours, based on a full year of continuous operation.

Thus, we can see how the model based on insulation resistance produces results on transformer ageing also for the lower range of internal operating temperatures corresponding to the below-rated load level. Differently, the thermal model instead produces very good results, validated for many years in industry, when transformers are loaded at least at rated level and especially for overloads.

However, the insulation resistance model is particularly applicable for transformers that have been in service for at least 5 years and where the oil-impregnated paper starts to deteriorate and produce different insulation resistance values from year to year when measurements are taken. For new transformer units, the paper maintains its dielectric properties very well in the first few years and can only produce significantly different values from one year to the next in this first stage of its "life" if the transformer has been overloaded by loads above 100% or has gone through transient operating regimes.

4.4. COMPARATIVE STATISTICAL ANALYSIS BETWEEN THE LOSS OF LIFE RESULTS OBTAINED WITH THE THERMAL MODEL AND THE INSULATION RESISTANCE MODEL

4.4.2. Preliminary statistical study conducted for 7 transformation units using „Paired t-Student" test technique

In this sub-chapter I have performed a "Paired t-Student" statistical test for pairs of data. I used a t-test to compare two population means, where we have two samples in which observations from one sample can be associated with those from the other sample.

I have checked the status of the DVC1 and DVC3 methods. The results of the test are as follows:

Tabel 4.6. Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	DVC1	37912.6143	7	48448.65525	18311.87045
	DVC3	38202.0254	7	48616.38573	18375.26661

Tabel 4.7. Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	DVC 1 & DVC3	7	1.000	.000

Tabel 4.8. Paired Samples Test

					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig.
Pair 1	DVC1 & DVC3	-289.4111	305.84589	115.59888	-572.27137	-6.55082	-2.504	6	.046

The p-value obtained for a single tail is $\frac{0.046}{2} = 0.023$, which is lower than the threshold of 0.05. Under these conditions, the alternative hypothesis is accepted and the null hypothesis is rejected, which means that the two methods produce different results.

4.4.3. Final statistical study conducted for 10 transformation units using multivariate linear regression technique

4.4.3.1. *Input data*

The input data are represented by the calculated loss of life using both thermal and insulation resistance models for the 10 power transformers described in Chapter 3. Thus, in the study, the loss of life data has been abbreviated as follows:

- DVC1 – the loss of life, estimated by monitoring systems using the thermal model;
- DVC3 – the loss of life, calculated with the insulation resistance model.

The values given by the DVC3 method will be considered as reference values, and on the basis of the statistical study to be carried out, a model will be found which will allow the DVC1 method to produce results similar to the DVC3 method.

The data collected from the 10 transformation units using the 2 methods of calculating the loss of life will be used as follows:

- From 9 of the 10 transformation units, for training the statistical model;
- From 1 of the 10 transformation units, for statistical model validation.

Thus, in the first stage of statistical analysis I checked several algorithms for approximating the evolution of the data, as shown in Fig. 4.3 below.

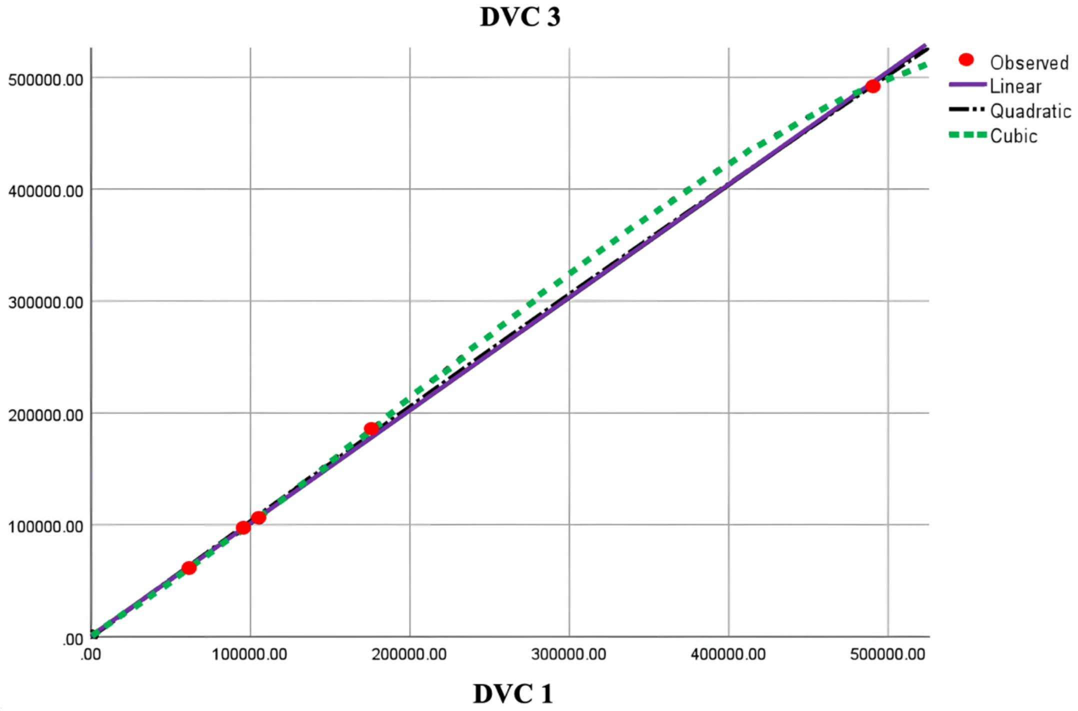

Fig. 4.3. Approximation of the evolution of the data obtained with the 2 methods DVC1 and DVC3

It can be seen how the 3 linear, quadratic and cubic interpolation algorithms, which approximate the evolution of the points belonging to the 2 methods of evaluation of the loss of life, produce very similar results and in the following the linear regression model due to its ease of implementation will be studied.

4.4.3.3. *Working methodology*

Before running the linear regression model, it is necessary to check the following working assumptions:

- if the variables chosen are independent: the „Durbin-Watson" statistical test is used;
- if the variables chosen are correlated: the „Pearson" test is used;
- if there is a statistically significant relationship between the input and output variables: the „Anova" statistical test is used.

If all these conditions are met simultaneously, then a multivariate linear regression model can be performed.

4.4.3.4. *Durbin-Watson statistical test on power transformers*

Tabel 4.12. Durbin-Watson Statistical Test

					Change Statistics				
Model	R	R^2	R^2 Adjusted	Std. Error of the Estimate	R^2 Change	F Change	df	Sig. F Change	Durbin-Watson
1	1.000[a]	1.000	1.000	3447.8458	1.000	16958.47	7	.000	2.467

After performing the Durbin-Watson statistical test, I determined the value of 2.467 which falls within the range -3 ÷ 3, which allowed me to conclude that the variables chosen are ind.

4.4.3.5. *Pearson correlation test performed on power transformers*

Tabel 4.13. Pearson Statistical Test

		DVC3	DVC1
Pearson Correlation	DVC3	1.000	1.000
	DVC1	1.000	1.000
Sig. (1-tailed)	DVC3	.	.000
	DVC1	.000	.
N	DVC3	9	9
	DVC1	9	9

According to the results obtained in Table 4.12, on the basis of the Pearson coefficient I have established that there is a strong correlation between the chosen variables.

4.4.3.6. *Anova statistical test performed on power transformers*

Tabel 4.14. Anova Statistical Test

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	201596208068.491	1	201596208068.491	16958.471	.000[b]

Residual	83213484.575	7	11887640.654		
Total	201679421553.066	8			

where:

a dependent variable: DVC3

b independent variable: DVC1

Thus, for a loading level of 95% ($p \le 0.05$), the level is in this range and F is high enough to reject the null hypothesis and admit the alternative hypothesis. Therefore, I have considered that there is a statistically significant relationship between the independent variables and the dependent variable.

4.4.3.7. *Determination of linear regression coefficients*

Determining the coefficients of a linear regression involves identifying the numerical values that best describe the linear relationship between the independent variables and the dependent variable in a data set. These coefficients are essential parameters of the linear regression model and are used to predict the values of the dependent variable based on the values of the independent variables. To determine them I have used the method of least squares, obtaining as follows:

Tabel 4.15. Determination of linear regression coefficients

	Unstandardized Coefficients		Standardized Coefficients		
Model	B	Std. Error	Beta	t	Sig.
Constant	890.545	1400.096		.636	.0545
DVC1	1.007	.008	1.000	130.225	.000

Thus, the equation of the multiple linear regression model will be:

$$DVC3 = DVC1 \times 1.007 + 890.545 \tag{4.47}$$

4.5. CONCLUSIONS OF THE ANALYSIS ON THE VALIDATION OF THE MODEL FOR ASSESSING TRANSFORMER AGEING BASED ON INSULATION RESISTANCE

The main difference found from this statistical analysis is that the insulation resistance model obtains transformer ageing results for the lower temperature range corresponding to the below-rated transformer loads. Although operating experience has shown that they age through wear in continuous operation regardless of the load level, the standardised thermal model used in the industry does not provide results for the lower temperature range, and ageing starts practically at an internal hot-spot temperature of the transformers of about 90^{o}C according to the standards.

Thus, given these issues, through the case study addressed in this chapter I have developed a model for evaluating transformer ageing that is applicable over the entire temperature range and comes as a complementary model to that already used in industry. The model is applicable for the internal hot-spot temperature range of transformers below 90^{o}C, and its final output is represented by equation (4.47) where the correction coefficients applied to the thermal model are observed, so that the new model produces loss of life results including the lower temperature range and loads.

The algorithm of the method underlying the developed model is represented in the logic diagram in Fig. 4.4. where it can be seen the distinction of the calculation steps for the evaluation of the loss of life according to the temperature range.

Basically, the model obtained proposes, by means of the applied correction coefficients, to assign a value of the loss of life in one year for an evaluated transformer, of 890.545 hours to which is added a variable value of the loss of life calculated with the thermal model, which increases with increasing hot-spot temperature.

It is important to note that this developed model is only applicable if the transformers have operated continuously in one year. If the transformer has had interruptions in operation over extended durations, then the model will no longer produce valid results. Another important aspect is that this method is limited in nature given the number of transformers used and the number of years studied. In the case of a larger set of data and transformers, the resulting correction coefficients could differ and the proposed model would also be different. However, the actual method of obtaining the model for the assessment of the loss of life for the whole temperature range will always be the one proposed in this chapter.

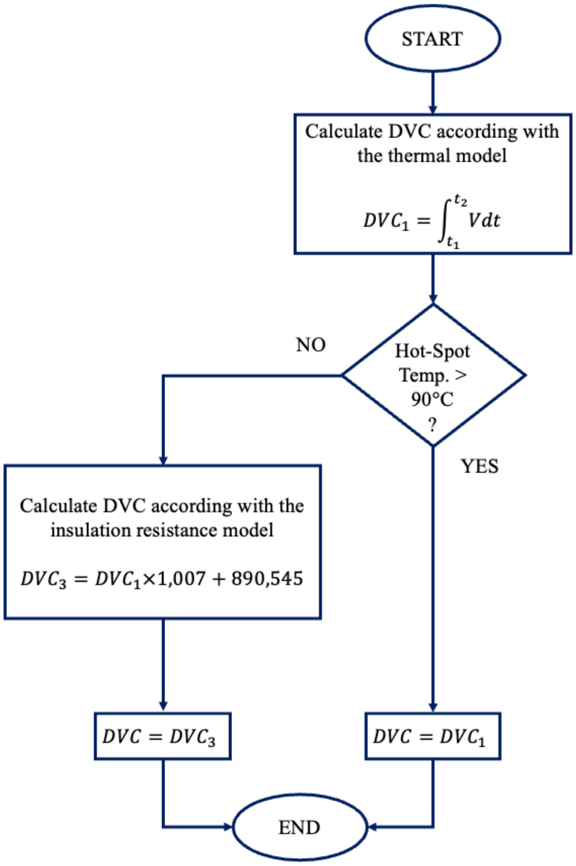

Fig. 4.4. Logic diagram of the proposed transformer ageing assessment model

Thus, the model for evaluating the ageing of transformers over the whole temperature range could become more powerful and applicable in the power industry as more transformers and their operating data are integrated. If we refer to the whole Romanian Transmission Power Grid, it will be necessary to use datasets for at least 59 transformer units. However, this depends on the existence of technical condition monitoring systems of the type presented in the previous chapter capable of assessing the loss of life using the thermal model.

CHAPTER 5. CONCLUSIONS

5.1. GENERAL CONCLUSIONS

The research studies presented in this PhD thesis focus on the use of a new method to assess the ageing of transformers and the proposal of a new assessment model to provide power grid operators more accurate results in estimating the maintenance or investment activities required for the transformers they have in operation. This leads to the following conclusions:

- The research included in the PhD thesis aims to use for the first time in the power systems industry a new model to evaluate the ageing of transformers used in medium and high voltage substations and to identify the results produced by it in relation to thermal models, already used in the industry for many years;
- The model for evaluating the loss of life of transformer units based on insulation resistance produces different final results from the thermal model, but statistical analysis simulations showed that the evolution of the variations in the data obtained are very close;
- The main conclusion identified from the use of the insulation resistance model is that it produces very good results for the lower internal operating temperature range of the transformers, which is different from the classical thermal model that does not produce results at all for below-rated loads;
- Thus, with these premises obtained from the preliminary research carried out on the transformers included in the case study, I have developed a model for the evaluation of the loss of life that is applicable over the entire internal operating temperature range, thus for any type of load. It is basically a complementary model to the thermal model, used in industry today, which corrects the loss of life values for the hot-spot temperature range below 90^oC;
- Both the developed model and the method for evaluating the loss of life of transformers based on insulation resistance are proposed to be used in the industry to obtain better results at lower costs;
- The proposed model has limited applicability and only covers transformers that have operated continuously for the period of time evaluated. At the same time, the model can become more powerful the more transformers are evaluated and therefore the more input data represented by the loss of life results with both the thermal and the insulation resistance based model are used;
- I have presented a condition monitoring system complying with industry standards installed on the 10 transformer units covered by the case study and how transformer "health" data is obtained with it;
- I have represented the dependencies of the loss of life values for the study transformers on different electrical, thermal parameters or load values;
- I have studied the thermal behaviours of 2 transformer units using infrared and UV multispectral inspections in order to compare them with the results obtained from condition monitoring systems;
- In the PhD thesis I have also studied the reliability of the transformer units involved in incidents in the Romanian Transmission Power Grid on a 5-year sample. Also, in relation to the reliability data obtained I studied the contribution of technical condition monitoring systems in avoiding these incidents. Moreover, I analysed the contribution that these

monitoring systems could have made in limiting the energy not delivered to consumers resulting from the incidents that occurred during the study period;
- I have presented the main technologies that support the concept of digital power substations and the benefits they bring. And also how these digital technologies translate today in transmission and distribution operators' substations. A main element increasingly used in recent years for electrical equipment in substations in order to increase their "health" is represented by technical condition monitoring systems, which form the premises of the study presented in the PhD thesis.

5.2. PERSONAL CONTRIBUTIONS

The main personal contributions made through scientific research in the PhD thesis are represented by:

- First-time application in a real, operational environment of a new model for assessing the ageing of transformers in medium and high voltage substations using insulation resistance;
- Comparison of the insulation resistance-based transformer ageing assessment model with the thermal model, based on the extraction of historical data on one-year samples from the operational power station environment where they are installed;
- Performing a statistical test to determine whether the two methods produce statistically similar results;
- Presenting research results demonstrating the applicability of the model based on insulation resistance for the lower hot-spot operating temperature range of transformers corresponding to below-rated loads;
- Development of a model for evaluating the loss of life of transformer units for the whole temperature range, whereby a number of correction coefficients are applied to the conventional thermal model;
- Propose both the new model obtained from the research and the method of obtaining it for industry, to be used by grid operators to assess as accurately as possible the consumed and remaining life of the transformers they have in operation;
- Use of a technical condition monitoring system to assess the condition of the case study transformers and the main parameters leading to their ageing over time;
- Validation of the thermal behaviour of 2 case study transformers by means of multispectral inspections, both in the infrared and UV spectrum, against the results obtained with the condition monitoring systems installed on them;
- Promote the results of the studies at international conferences: IEEE, CIGRE, WEC, etc.

5.3. PROPOSALS FOR FURTHER RESEARCH

The extension of the research carried out in the PhD thesis is particularly important in view of the technical contribution that the model obtained for the evaluation of the ageing of transformers over the whole temperature range could bring to the power industry and in particular to grid operators. Thus, the following proposals for further research are made:

- In order to obtain the most accurate model for the evaluation of the loss of life of transformers, as many datasets as possible need to be entered into the statistical program created by the presented method;

- The main proposal for further research is to extend this model to the entire population of transformer units at the level of the Romanian Transmission Power Grid, for which I have calculated a need of at least 59 transformers to be entered into the model.

At the same time, I have demonstrated the applicability of the ageing assessment model based on insulation resistance which can already be used by the transmission or distribution grid operators in their operating procedures to assess the loss of life of the transformers they have in operation.

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