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Study of Useful Life of Dry-Type WTSU Transformers

A. Etxegarai[1], V. Valverde[1], P. Eguia[1] and E. Perea[2]

[1] Department of Electrical Engineering
University of the Basque Country UPV/EHU
Ing. Torres Quevedo 1, 48013 Bilbao (Spain)
e-mail: agurtzane.etxegarai@ehu.eus (corresponding author)

[2] Energy and Environment Division, Tecnalia Research and Innovation
48160 Derio, Spain
e-mail: eugenio.perea@tecnalia.com

Abstract. Dry-type transformers are rapidly becoming popular as wind turbine step-up (WTSU) transformers, especially in offshore wind farms. Cast resin transformers are not flammable and are also resistant to moisture. However, their thermal-electrical degradation must be carefully analysed given the special conditions of wind farm installations. The present paper studies the remaining useful life (RUL) calculation of dry-type WTSU transformers based on the most thermally stressed location i.e. the winding hot-spot. The estimation of the loss of life of the transformer can be used for diagnostic and prognostic monitoring purposes in the framework of digital twins. The methodology is then applied to a typical WTSU load profile and the impact of several transformer characteristics and operating conditions are compared to the reference case.

Key words. Wind energy, dry-type transformer, hot spot temperature, loss of life, digital twin.

1. Introduction

Renewable energy sources play an increasingly important role due to the increasing demand for electrical energy worldwide. Wind energy is positioned as one of the energies with the greatest potential to face this energy boom while respecting the environment. The specific operating conditions of wind farms (mainly variable load conditions of wind turbines due to the variability of wind speed and exposure to adverse weather conditions) raise the failure rates associated with their electrical components, which mainly affect wind turbine step-up (WTSU) transformers and the cables of the wind farm's collector system. In addition, in the case of offshore wind farms, these transformers face corrosion problems due to the salinity and humidity present in the environment in which they work, so the risk of failure is increased [1].

The most common causes of failure in transformers include electrical aspects, mechanical aspects and chemical aspects such as corrosion [2]. These failures can cause premature transformer failure and reduce the reliability of the wind farm. In general, electrical problems point to the variable load cycle, harmonics, transient and switching surges, fault current, voltage variations and load increase, mainly. As for mechanical problems, vibrations, cooling, insulation failures and problems related to dimensions are included. This paper focuses on electrical-thermal degradation, discarding mechanical and chemical problems.

The objective of the present paper is the study of the electrical-thermal degradation of dry-type WTSU transformers due to the temperature rise of the winding. Dry-type transformers are rapidly becoming popular as WTSU transformers, especially in offshore wind farms. With respect to oil transformers, transformers with resin-based insulation are not flammable and are also resistant to moisture, these being their main advantages. For offshore platforms, a lighter weight and compactness are also key. However, dry-type transformers are more sensitive to condensation, electrical creep, partial discharges, cracks, temperature variations and contamination than oil filled transformers [3].

Thus, related to the effect of temperature variations of dry-type transformers, the remaining useful life (RUL) can be estimated based on the thermal study of the most thermally stressed location i.e. the winding hot-spot. Then, it can be used for diagnostic and prognostic monitoring purposes, in the framework of digital twins. The authors of this paper belong to the VIRTUAL project work team under the Basque Government funding (project ELKARTEK KK-2018/00096). In this project, a digital twin of a wind farm is being developed based on the individual models of the different electrical components i.e. generators, power converter, WTSU transformers and MV cable [4]. In this context, the present paper describes a dry-type WTSU thermal modelling and RUL estimation.

2. Thermal Modelling of Dry-Type Transformers

The critical variable for the estimation of the remaining useful life (RUL) of a transformer is the hottest spot temperature [5]. The calculation of this variable is a complex task and it can be either estimated or monitored through direct measurement. Industrial standards proposed by IEC [6] and IEEE [7] are widely used for the calculation of the hot-spot, based on the transformer loading, transformer characteristics and ambient conditions. The present paper uses IEC 60076-12 for the thermal study of the winding hot-spot and lifetime estimation of dry-type WTSU transformers. Other heating factors such as insufficient cooling, harmonics, over-excitation and/or special conditions are described in IEC 60076-11, but are beyond the scope of the present paper.

IEC 60076-12 provides mathematical models to evaluate the consequence of different charges, with different coolant temperatures and with transient or cyclic variations over time. The models provide the calculation of operating temperatures in the transformer, particularly the temperature of the hottest point of the winding (henceforth hot-spot). This hot-spot temperature $\boldsymbol{\theta_{HS}}$ in (1) is used to estimate the number of hours of life time consumed during a particular period of time.

$$\boldsymbol{\theta_{HS}} = \boldsymbol{\theta_A} + \Delta\boldsymbol{\theta_{HS}} \tag{1}$$

where $\boldsymbol{\theta_A}$ is the ambient temperature (ºC) and $\Delta\boldsymbol{\theta_{HS}}$ the hot-spot temperature rise over ambient temperature (ºC).

The hot spot temperature shall not exceed the rated value of the hot-spot winding temperature specified in IEC 60076-11 [8]. It can also be used for allowing the operation of the transformer near its thermal limit, called dynamic thermal rating of the transformer.

Hot-spot rise can be calculated for steady-state load or for transient state. (2) and (3) indicate the calculation for steady-state operation for natural cooling and forced cooling, respectively, when no test data is available.

$$\Delta\boldsymbol{\theta_{HS}} = \boldsymbol{Z} \times \Delta\boldsymbol{\theta_{wr}} \times \boldsymbol{I}^{\boldsymbol{2\times m}} \tag{2}$$

$$\Delta\boldsymbol{\theta_{HS}} = \boldsymbol{Z} \times \Delta\boldsymbol{\theta_{wr}} \times \boldsymbol{I^2} \times \boldsymbol{C_T} \tag{3}$$

where $\Delta\boldsymbol{\theta_{wr}}$ is the mean winding temperature rise at rated load (K), $\boldsymbol{I}$ the load index (p.u.) and $\boldsymbol{C_T}$ the temperature correction for the temperature dependence of resistance. $\boldsymbol{m}$ is an empirical constant, which is assumed to be 0.8 if not other data is available. Also for $\boldsymbol{Z}$ a value of 1.25 is assumed when no experimental data is available.

After a change in load, the hot-spot temperature reaches the ultimate hot-spot temperature if it is allowed to stabilize. Momentary values of hot-spot temperature at any time during load change $\Delta\boldsymbol{\theta_{HS,t}}$ can be calculated by (4).

$$\Delta\boldsymbol{\theta_{HS,t}} = \Delta\boldsymbol{\theta_{HS,1}} + \left(\Delta\boldsymbol{\theta_{HS,u}} - \Delta\boldsymbol{\theta_{HS,1}}\right) \times \left[\boldsymbol{1} - \boldsymbol{e^{-t/\tau}}\right] \tag{4}$$

where $\Delta\boldsymbol{\theta_{HS,u}}$ is the ultimate hot-spot temperature rise (K), $\Delta\boldsymbol{\theta_{HS,1}}$ is the initial hot-spot temperature rise (K)and $\boldsymbol{\tau}$ is the time constant of the transformer.

The time constant can be determined by tests or otherwise calculated by (5).

$$\boldsymbol{\tau} = \boldsymbol{\tau_R} \times \frac{\left(\frac{\Delta\boldsymbol{\theta_{HS,u}}}{\Delta\boldsymbol{\theta_{HS,r}}}\right) - \left(\frac{\Delta\boldsymbol{\theta_{HS,1}}}{\Delta\boldsymbol{\theta_{HS,r}}}\right)}{\left(\frac{\Delta\boldsymbol{\theta_{HS,u}}}{\Delta\boldsymbol{\theta_{HS,r}}}\right)^{\boldsymbol{1/m}} - \left(\frac{\Delta\boldsymbol{\theta_{HS,1}}}{\Delta\boldsymbol{\theta_{HS,r}}}\right)^{\boldsymbol{1/m}}} \tag{5}$$

where $\boldsymbol{\tau_R}$ is the time constant for rated load and $\Delta\boldsymbol{\theta_{HS,r}}$ is the rated hot-spot temperature rise (K).

3. Estimation of Remaining Useful Life of Dry-Type Transformers

Experience indicates that the normal life span of a transformer is a few tens of years. Manufacturers typically assume a normal lifetime span of 180,000 hours [6]. However, a transformer rarely operates at 100% of its assigned current throughout its lifetime. Ambient conditions do also change. Therefore, the expected lifespan $\boldsymbol{L}$ is assumed to vary with hot-spot temperature $\boldsymbol{\theta_{HS}}$ according to Arrhenius' equation as indicated in (6).

$$\boldsymbol{L} = \boldsymbol{a} \times \boldsymbol{e^{b/\theta_{HS}}} \tag{6}$$

where $\boldsymbol{a}$ and $\boldsymbol{b}$ are Arrhenius' constants which depend on the insulation class of the transformer and can be extracted from [6].
Then, the aging rate $\boldsymbol{k}$ can be calculated by (7) as the ratio of expected lifetime to normal lifetime (i.e. 180,000 h).

$$\boldsymbol{k} = \frac{\boldsymbol{L}}{\boldsymbol{180,000}} \tag{7}$$

Hence, over a time period $\boldsymbol{t}$ (h), the lifetime consumption $\boldsymbol{L_C}$ corresponds to (8).

$$\boldsymbol{L_C} = \boldsymbol{k} \times \boldsymbol{t} \tag{8}$$

Finally, the RUL of the transformer can be calculated by (9).

$$\boldsymbol{RUL} = \boldsymbol{180,000} - \boldsymbol{L_C} \tag{9}$$

4. Description of Case Study

In the present study, the hot-spot temperature calculation is based on the methodology introduced in IEC 60076-12 [6], which has been applied to a typical WTSU load profile and ambient conditions in a late September day (24 hours) in a Northern European country [9]. The load index evolution of the WTSU transformer under study for a whole day is shown in Fig. 1. A high variability and a low capacity factor, especially during early hours of the morning can be observed. It corresponds to typical wind farm patterns. It must be noted that for the present study the WTSU transformer has been sized to match the generator rating.

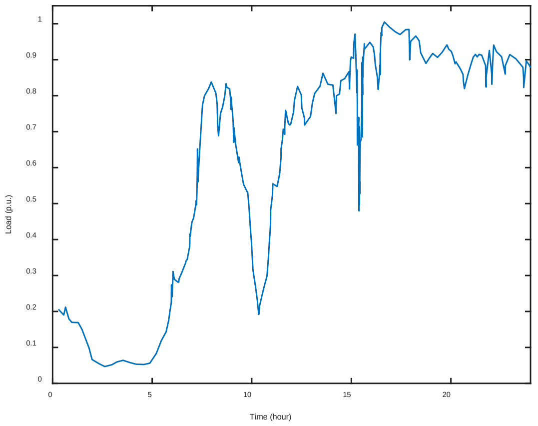

Fig.1. Load profile of the case study.

Regarding the WTSU transformer under study, Table I summarizes the transformer characteristics that have been used for the hot-spot temperature calculation in the reference case, hereinafter called Case 0.

Table I. – Transformer characteristics for reference case (Case 0)

CHARACTERISTIC	NAME	VALUE
Cooling	C	Natural cooling
Insulation	I	180 ºC (Class H)
Rated time constant	$\boldsymbol{\tau_R}$	0.5 hour
Mean winding temperature rise	$\boldsymbol{\Delta\theta_{wr}}$	125 K

Besides, the effect of insulation class, cooling system, transformer characteristics such as rated time constant and transformer operating conditions namely the mean winding temperature rise have also been analysed for the present work. Additional study cases are described in Table II. The characteristic abbreviations in Table I have been used. In each study case only aspects included under the VALUE concept have been modified. The rest of the characteristics do not change with respect to the reference case.

Table II. – Description of study cases

STUDY CASE	CHARACTERISTIC	VALUE
1	C	Forced cooling
2a	I	155 ºC (Class F)
2b	I	200 ºC
2c	I	220 ºC
3a	$\boldsymbol{\tau_R}$	0.4 hour
3b	$\boldsymbol{\tau_R}$	0.6 hour
4a	$\boldsymbol{\Delta\theta_{wr}}$	100 K
4b	$\boldsymbol{\Delta\theta_{wr}}$	115 K
4c	$\boldsymbol{\Delta\theta_{wr}}$	130 K
4d	$\boldsymbol{\Delta\theta_{wr}}$	140 K

The mean winding temperature rise $\Delta\theta_{wr}$ for study cases 2a, 2b, 2c is indicated in Table III.

Table III. – Mean winding temperature rise $\boldsymbol{\Delta\theta_{wr}}$

STUDY CASE	CHARACTERISTIC	VALUE
2a	$\boldsymbol{\Delta\theta_{wr}}$	100 K
2b	$\boldsymbol{\Delta\theta_{wr}}$	135 K
2c	$\boldsymbol{\Delta\theta_{wr}}$	150 K

5. Results and discussion

A. Results of reference case

The resulting hot-spot calculation according to IEC procedure is then depicted in Fig.2.

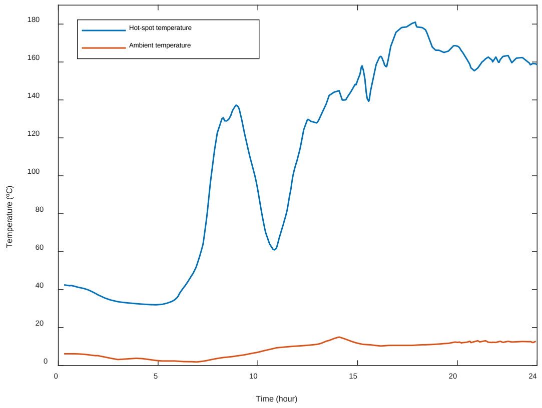

Fig.2. Hot-spot temperature and ambient temperature for the reference study case.

Based on Arrhenius' law the evolution of aging rate k has been also computed and is shown in Fig 3. Aging rate is related to the life loss in hour per operation hour of the transformer. It can be observed that the maximum value corresponds to 3.512 h/h at t=17.9 h. This instant corresponds to the maximum hot-spot temperature instant as well. The shadowed area under the graph in Fig. 3 is the total lifetime consumption of the WTSU transformer under study for 24 hours and it amounts to 7.596 hours. Then, RUL can be calculated by substracting L_C to 180,000.

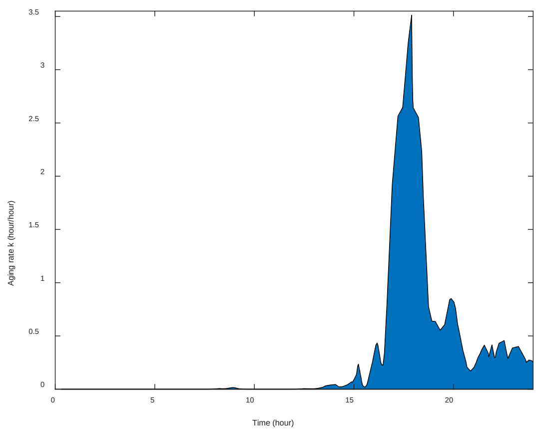

Fig.3. Aging rate for the reference study case.

B. Influence of cooling system

The resulting hot-spot calculation according to IEC procedure for forced cooling is then depicted in Fig.4.

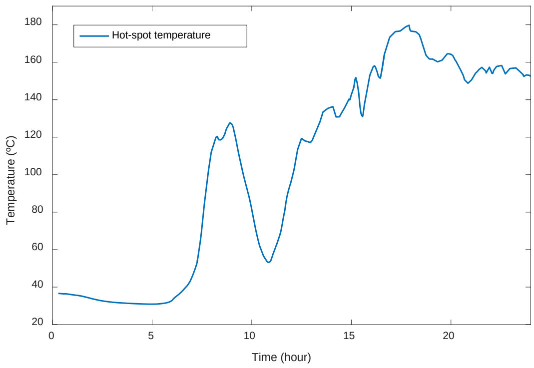

Fig.4. Hot-spot temperature for study case 1.

The shadowed area under the graph in Fig. 5 is the total lifetime consumption of the WTSU transformer under study case 1 for 24 hours and it amounts to 5.3469 hours. Therefore, it is lower if compared to the reference case with natural air cooling.

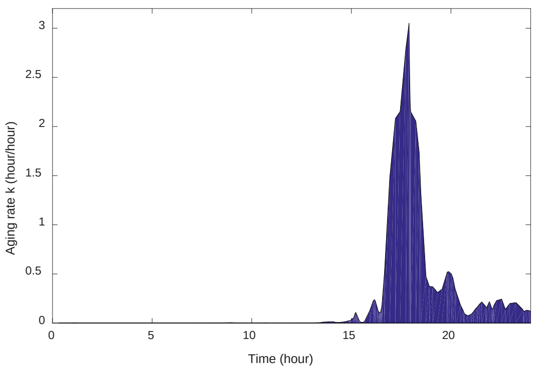

Fig.5. Aging rate for study case 1.

C. Influence of insulation class

In order to analyse the impact of insulation class on both the thermal degradation and loss of life of the WTSU transformer under study, calculations have been repeated over the load profile in Fig. 1 for several insulation classes. Note that the mean winding temperature rise $\Delta\theta_{wr}$ is also modified in each case according to Table III. Fig. 6 compares the hot-spot temperature evolution for different insulation classes and Fig. 7 compares aging rate. Note that highest aging rate instant occurs almost simultaneously in all cases. Maximum value of aging rate and total lifetime consumption are compared in Table IV.

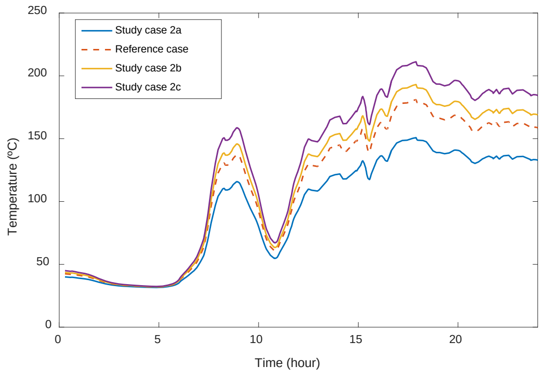

Fig.6. Hot-spot temperature as a function of insulation class.

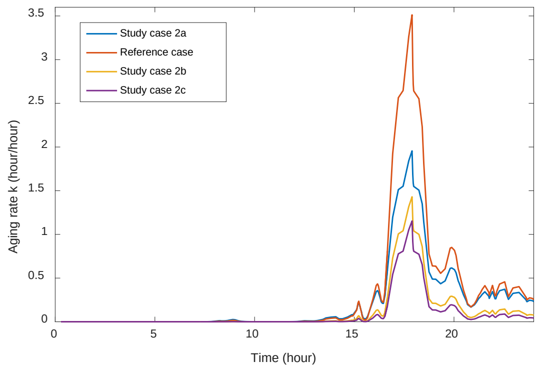

Fig.7. Aging rate for study cases 2a, 2b, 2c.

Table IV. – Study of aging rate k for study cases 2a, 2b, 2c and reference case

STUDY CASE	MAXIMUM k (hour/hour)	TOTAL LIFETIME CONSUMPTION IN 24 h (hours)
Reference case	3.5121	7.5964
2a	1.9552	5.2011
2b	1.4298	2.7563
2c	1.153	1.9796

C. Influence of time constant

The time constant barely influences the thermoelectric degradation of dry transformers, as can be seen in Fig. 8. Therefore, the influence on the life of the transformers is also low. The highest loss of life corresponds to a time constant τ_R of 0.4 hours, amounting to 7.9568 hours over 24 hours. The difference with the highest time constant under study is really low, given that the life consumption is 7.2635 hours.

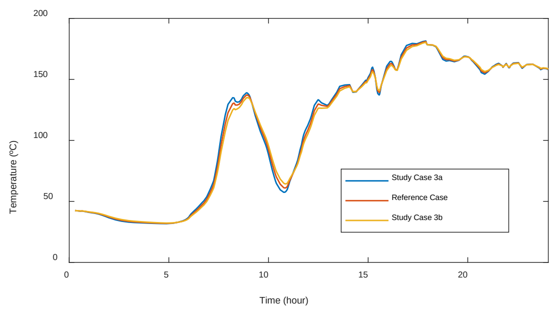

Fig.8. Hot-spot temperature as a function of time constant.

D. Influence of mean winding temperature rise

Finally, the impact of the mean winding temperature rise has also been studied. Several initial temperatures have been considered for the reference case. As can be seen in Figure 9, the higher the average initial increase in the hot spot temperature, the higher the resulting thermodynamic temperature. Thus, life consumption also increases with the average initial hot-spot temperature, as expected. Figure 10 shows the comparison of the aging rate for case study 4. Thus, the worst case corresponds to case 4d, under which conditions the total consumption of life for 24 hours would be 51 hours. This already amounts to a significant degradation in the transformer.

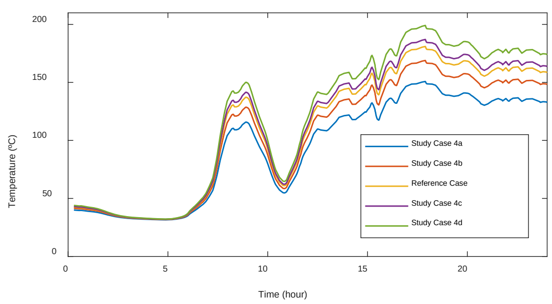

Fig.9. Hot-spot temperature as a function of mean winding temperature rise.

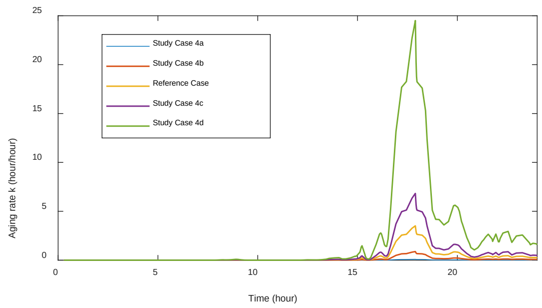

Fig.10. Aging rate for study cases 4a, 4b, 4c, 4d.

5. Conclusions

The present paper has introduced the RUL calculation of dry-type WTSU transformers based on the most thermally stressed location i.e. the winding hot-spot. The methodology is based on IEC 60076-12 standard. With the input of a typical WTSU transformer load profile, aging rate and total loss of life have been computed for a reference case. The close correlation between hot-spot temperature and RUL corresponds to Arrhenius' law. Besides, the effect of insulation class, cooling system, transformer characteristics such as rated time constant and transformer operating conditions namely the mean winding temperature rise have also been analysed for the present work.

It can be concluded that for lower temperature insulations, aging rate decreases along with hot-spot temperature. Also, for forced air cooling systems both the hot-spot and the loss of life decrease. The influence of the transformer time constant is negligible for the values that have been considered. Contrastingly, the influence of the mean winding temperature rise taken into account as initial data for the calculations is highly significant. The higher the average initial increase in the hot-spot temperature, the higher the resulting thermodynamic temperature. Thus, aging rate also increases and can amount to 51 hours of life loss over 24 hours for 140 K. This already results into a significant degradation of the dry-type transformer.

Therefore, for the present study, the loss of life is generally low, which extends the life of the transformer. This is due to the case study selected: on the one hand because of the wind profile present, which is low on the day of study and results in a low load index;. on the other hand, the ambient temperature of the location of the wind farm is also low, which prevents thermal degradation. Therefore, future research works should include other wind patterns resulting into higher load indices, as well as higher ambient temperatures. Thus, a greater impact on thermal degradation could be assessed.

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