Analysis of Loss of Life of Dry-Type WTSU Transformers in Offshore Wind Farms

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Abstract- Currently, dry-type transformers are commonly installed as wind turbine step-up (WTSU) transformers, especially in offshore wind farms. Due to their low flammability and resistance to moisture, their performance is optimal in offshore platforms. Nonetheless, their thermal-electrical degradation must be carefully considered given the special wind and weather conditions in marine environments. The present paper studies the thermal aging of dry-type WTSU transformers in offshore wind farms considering the most thermally stressed location i.e. the winding hot-spot. The estimation of the transformer lifetime consumption introduced in this work can be applied in the framework of digital twins for diagnostic and prognostic monitoring purposes The thermal degradation study is based on a typical offshore load profile and includes the analysis of the impact of several transformer characteristics and operating conditions. As a result of the analysis, it can be concluded that lower temperature insulations, forced air cooling systems, a lower mean winding temperature rise and cool ambient temperatures lead to decreased loss of life values. Also, the present work suggests the suitability of considering thermal degradation studies as an optimal sizing factor for offshore WTSU given the low ambient temperatures in marine environment and the low capacity factors.

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

1. Introduction

Wind farms are going offshore. According to [1], 409 new offshore wind turbines were connected to the grid in 2018 in Europe, corresponding to 18 projects. Therefore, the net capacity was increased by 2,649 MW. Europe has now a total installed offshore wind capacity of 18,499 MW. The average size of newly-installed offshore wind turbines in 2018 was 6.8 MW and the largest turbine in the world was connected in the UK with a size of 8.8 MW.

Several transmission topologies have been proposed for offshore wind farms [2], in which dry-type transformers are popular as wind turbine step-up (WTSU) transformers in offshore wind farms. However, manufacturers also sell liquid-filled transformers with fire retardant fluids. Air-cooled dry-type transformers are the preferred technology [3],[4]. In addition to the transformer inflammability, other issues should be also considered, such as the performance under harsh environmental and operational conditions, reliability at increased ratings and voltages, energy losses, maintenance or environmental protection.

Regarding environmental conditions, given that marine air is humid and salty, dry-type transformers can suffer from corrosion. They are sensitive to condensation, electrical creepage, partial discharges, cracks, temperature variations and pollution, too [5]. However, in cast-type dry transformers those issues are mitigated by the protective enclosure. Other aspects to bear in mind in offshore platforms are the vibrations caused by wind gusts and the footprint of the transformers. For offshore platforms, the lighter weight and compactness of dry-type transformers is certainly an advantage.

Operational conditions are severe in offshore wind farms. Electrical problems point to variable load cycles, harmonics, transient and switching surges, fault current, voltage variations and load increase, mainly [6], [7]. Precisely, one of the main causes of failure of dry-type transformers is the variability of the wind speed. WTSU transformers may be subject to varying load cycles several times a day conditioned by wind variability. Compared to conventional distribution transformers that often see only a single load cycle a day WTSU transformers are subject to low load valleys and high load peaks several times a day, depending on local winds.

Those thermal cycles can cause repeated thermal stresses in the windings, the clamping structure, and seals [8]. The thermal cycle accelerates the aging and the damage of the electrical connections of the transformer and the appearance of partial discharges ends up affecting the reliability of the insulation. Thus, dry-type transformers finally fail due to insulation faults to ground, between phases or between windings.

Related to the thermal aging of dry-type transformers, the loss of life can be estimated based on the thermal study of the most thermally stressed location in the winding i.e. the winding hot-spot. Then, the winding hot-spot temperature shall be used for diagnostic and prognostic monitoring purposes, in the framework of digital twins of offshore wind farms. 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 an offshore 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 [9], which show the highest failure rates in wind farms [10].

In this context, the present paper describes the dry-type WTSU thermal modelling and the estimation of lifetime consumption in offshore wind farms based on a study case. Previously in the literature, the authors Davood Azizian et al presented in [11] the dynamic thermal modeling of molten resin transformers based on genetic algorithms, where they estimated and validated the model parameters with the help of experimental data extracted from different load cycles. Other authors have also calculated the increase in the average temperature of the winding surface, establishing a hot-spot temperature calculation model for the dry type transformer based on finite element modeling [12] [13]. Industrial thermal modelling procedures for transformers have been introduced in several papers, both for oil-immersed transformers [14] [15] [16] and dry-type transformers [17] [18]. Finally, dynamic rating of transformers for wind energy have been analysed in [19], [20], but an analysis for dry-type WTSU transformers is missing in the literature and special offshore conditions have not been studied so far.

Therefore, the main contributions of this work are:

- The presentation of the main issues related to the operation of dry-type transformers, with an emphasis on the specific ambient and operational conditions in offshore wind farms.
- The explanation of the calculation procedure for a thermal degradation study in dry-type transformers according to industrial standards, including the definition of the expected lifespan, the aging rate and the corresponding loss-of-life.
- The application of the thermal degradation study to a typical offshore dry-type WTSU with usual construction and operational conditions.
- The analysis of the impact of cooling, insulation, mean winding temperature, transformer rating and ambient temperature on the thermal degradation of dry-type WTSU transformers and the corresponding estimation of loss-of-life.

2. Thermal Modelling of Dry-Type Transformers

The critical variable for the estimation of the loss of life in a transformer is its hottest spot temperature [21]. The hot-spot temperature can be either estimated or monitored by means direct measurement. Industrial standards such as IEC 60076-12 [22] and IEEE C57.96-2013 [23] are applied in the estimation of the thermal aging of dry-type transformers, based on the transformer loading, its characteristics as well as ambient conditions. The present paper is based on the application of IEC 60076-12 for the thermal study of the winding hot-spot and lifetime estimation of dry-type WTSU transformers installed in offshore wind farms. The influence of other heating factors such as an insufficient cooling, harmonics, over-excitation or any special conditions are also studied in IEC 60076-11, but beyond the scope of the present work.

The standard IEC 60076-12 introduces mathematical models to evaluate the thermal aging due to loading, at different coolant temperatures and including transient or cyclic variations over time. The models provide the calculation of the temperature of the hottest point of the winding (henceforth hot-spot). This hot-spot temperature θ_{HS} in Eq. (1) is used to estimate the number of hours of lifetime consumed during a particular period of time.

$$\theta_{HS} = \theta_A + \Delta\theta_{HS} \quad (1)$$

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

The hot-spot temperature must not exceed the nominal value of the hot-spot winding temperature indicated in IEC 60076-11 [24]. Hot-spot rise shall be computed for steady-state load or transient state. Eq. (2) and Eq. (3) introduce the calculation for steady-state operation under air natural (AN) and under air forced cooling (AF), also named air blast.

$$\Delta\theta_{HS} = Z\cdot\Delta\theta_{wr}\cdot I^{2\cdot m} \quad (2)$$

$$\Delta\theta_{HS} = Z\cdot\Delta\theta_{wr}\cdot I^{2\cdot CT} \quad (3)$$

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

After a load step, the hot-spot temperature reaches the ultimate hot-spot temperature when it can stabilize. Instantaneous values of the hot-spot temperature at any instant during load change $\Delta\theta_{HS,t}$ can be calculated by Eq. (4).

$$\Delta\theta_{HS,t} = \Delta\theta_{HS,I}+(\Delta\theta_{HS,u}-\Delta\theta_{HS,I})\cdot(1-e^{-t/\tau}) \quad (4)$$

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

The time constant can be specified by means of tests or otherwise calculated by Eq. (5).

$$\tau = \tau_R \cdot [(\Delta\theta_{HS,u}/\Delta\theta_{HS,r})-(\Delta\theta_{HS,1}/\Delta\theta_{HS,r})]/[(\Delta\theta_{HS,u}/\Delta\theta_{HS,r})^{1/m}-(\Delta\theta_{HS,1}/\Delta\theta_{HS,r})^{1/m}] \quad (5)$$

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

3. Calculation of Loss-of-Life of Dry-Type Transformers

Manufacturers typically assume normal lifetime spans of 180,000 hours for dry-type transformers [22]. Nonetheless, transformers rarely operate at 100% of their rated capacity throughout their whole lifetime, especially in wind farms with low loading and cyclic loading depending on wind conditions. Ambient temperature conditions vary, too. As a consequence, the expected lifespan L is assumed to change along with hot-spot temperature θ_{HS} according to Arrhenius' equation introduced in Eq. (6).

$$L = a \cdot e^{b/\theta_{HS}} \quad (6)$$

where a and b are Arrhenius' constants which are dependent on the insulation class of the transformer.

Also, the aging rate k can be estimated by Eq. (7) as the ratio of expected lifetime to normal lifetime amounting to 180,000 hours).

$$k = L/180{,}000 \quad (7)$$

Therefore, over a time period t in hours, the loss-of-life (LOL) or lifetime consumption corresponds to Eq. (8). Then, by substracting LOL to the normal lifetime the remaining useful life (RUL) can be computed.

$$LOL = k \cdot t \quad (8)$$

4. Thermal Aging of a Dry-Type WTSU Transformer in an Offshore Wind Farm

4.1. Introduction to Base Case

For the present paper, the hot-spot temperature calculation is based on the methodology specified in standard IEC 60076-12, which has been applied to the wind turbine load profile in an offshore wind farm over 44 hours. The production profile is based on the data introduced by Pinson in [25] and it is shown in Figure 1. A high variability and a low capacity factor with an average of 0.35 p.u. can be observed, which corresponds to a typical wind farm pattern.

Table 1 summarises the characteristics of the dry-type WTSU transformer connected to the wind turbine under study for the base case, hereinafter called Case 0. It must be noted that for the base case the WTSU transformer has been sized to match the wind turbine rating. Therefore, the transformer load index equals the wind turbine loading as indicated in Fig. 1. Also, the calculations are based on a constant ambient temperature of 10 ºC for Case 0.

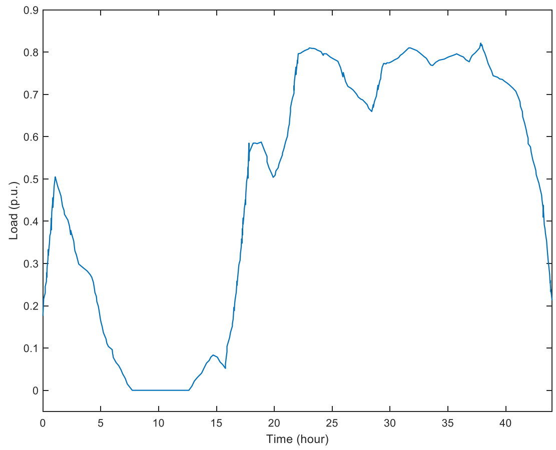

Figure 1. Wind turbine production in an offshore wind farm.

Table 1. Transformer characteristics in Case 0

Feature	Name	Value
Cooling	C	AN
Insulation	I	180 ºC (Class H)
Rated time constant	τ_R	0.5 hour
Mean winding temperature rise	$\Delta\theta_{wr}$	125 K

4.2. Description of study cases

Besides, the influence of several aspects on the thermal aging has been analysed, including the design and construction aspects of the dry-type transformer (i.e. transformer rating, cooling system, insulation class), operational conditions (namely the mean winding temperature rise) and environmental conditions (i.e. ambient temperature). Those additional study cases are introduced in Table 2, which only includes the difference features with respect to Case 0.

Study Case 1 considers the impact of the underrating of the WTSU transformer under study on thermal degradation and aging rate. Related to the construction and design characteristics of the dry-type transformer, the present paper includes Study Case 2, Study Case 3 and Study Case 4. They analyse respectively the impact of cooling, simulation class and mean winding temperature. Finally, Study Case 5 varies ambient temperature in the offshore location.

Table 2. Description of study cases

Feature	Study Case	Value
Rating	1a	90% of wind turbine rating
	1b	80% of wind turbine rating
	1c	70% of wind turbine rating
Cooling	2	AF
Insulation	3a	105 ºC (Class A)
	3b	120 ºC (Class E)
	3c	130 ºC (Class B)
	3d	155ºC (Class F)
	3e	220 ºC
Mean winding temperature rise	4a	100 K
	4b	115 K
	4c	130 K
	4d	140 K
Ambient temperature	5a	20 ºC
	5b	30 ºC
	5c	40 ºC

The cooling modes and insulation classes included in the paper have been extracted from [26]. For Study Case 3, it must be noted that along with the insulation, also the mean winding temperature rise will be affected. Hence, values as indicated in IEC60076-11 have been used in the paper. Regarding ambient temperature, wind turbines are usually designed for the operation at ambient temperatures in the range of -10 ºC to +40 ºC. Therefore, ambient temperatures exceeding the ambient temperature in Study Case 0 have been studied, i.e. constant values of 20 ºC, 30 ºC and 40 ºC.

4.3. Thermal aging for the base case

The evolution of hot-spot temperature over 44 hours is plotted in Figure 2. Figure 3 shows the corresponding aging rate. The total loss of life during this period amounts to 0.0126 hours.

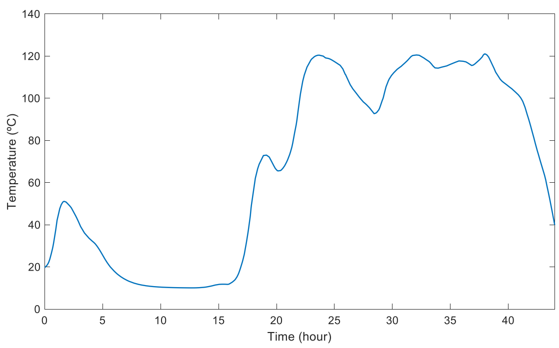

Figure 2. Hot-spot temperature for base case.

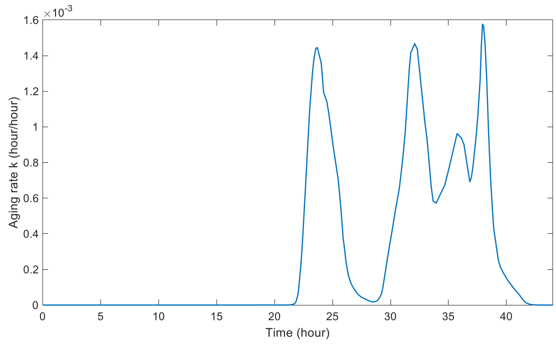

Figure 3. Aging rate for base case.

5. Analysis of Influencing Factors on the Thermal Aging of Dry-Type WTSU Transformer in Offshore Wind Farms

5.1. Influence of Transformer Rating: Study Case 1

In order to assess the thermal aging of the WTSU transformer, the load index of the transformer must be used. However, as this data was not available in [15], calculations are based on wind turbine loading considering several transformer rating approaches. In wind farms, given usual low capacity factors, transformers are usually not overrated. In fact, they are often slightly underrated, even if a temporary overload can occur [17]. Therefore, for the present study four transformer ratings have been used as presented in Table 2. Resulting load index profiles are shown in Figure 4, as a simple scaling of the base case.

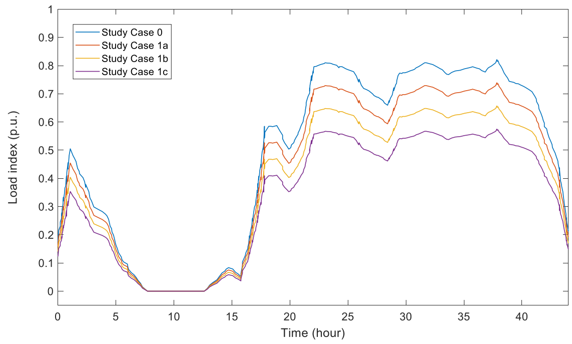

Figure 4. WTSU transformer load index for Study Case 1.

The resulting hot-spot temperature computed according to IEC 60076-12 is shown in Figure 5. The direct correlation between the transformer loading and the heating of the hottest spot in the transformer is remarkable. The smaller the rating of the transformer, the higher the transformer loading and the thermal aging (Figure 6). The impact on the transformer loss of life is significantly higher for Study Case 1c, where the transformer is almost continuously overloaded after hour 20. Table 3 compares the lifetime consumption of the transformer under study for the four approaches.

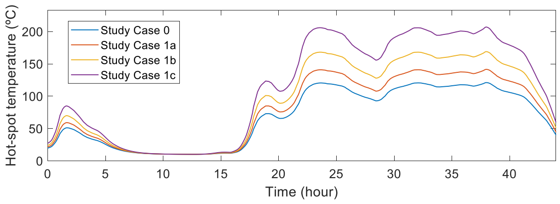

Figure 5. Hot-spot temperature for Study Case 1.

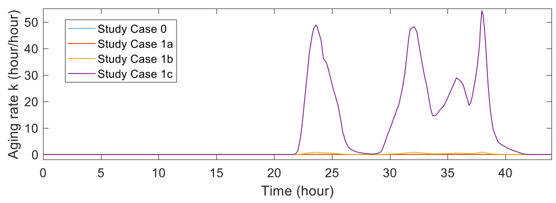

Figure 6. Aging rate for Study Case 1.

Table 3. Loss of life in hours for Study Case 1

Study Case	Lifetime consumption
0	0.0126 hours
1a	0.2137 hours
1b	6.3373 hours
1c	373.5767 hours

It can be concluded that for an optimal sizing of the WTSU transformer, apart from economic aspects, also the thermal degradation should be considered. This aspect is further developed in the Discussion section.

5.2. Influence of cooling system: Study Case 2

As expected, a forced air cooling system decreases the temperature rise in the winding due to loading (Figure 7), and hence, the aging rate of the transformer (Figure 8). The curves for forced cooling systems that represent the hot-spot temperature and the aging rate are lower than for natural air cooling systems i.e. the base case. Thus, the total life consumption over 44 hours amounts to 0.0028 hours opposed to the already low value of 0.0126 hours for Study Case 0.

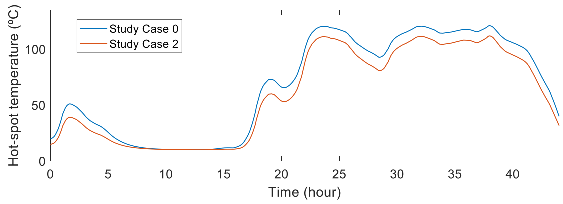

Figure 7. Hot-spot temperature for Study Case 2.

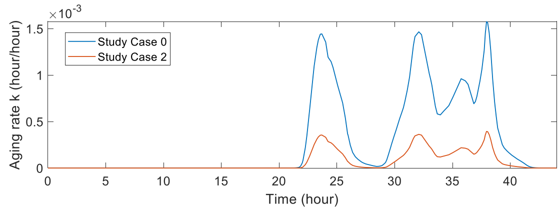

Figure 8. Aging rate for Study Case 2.

5.3. Influence of insulation class: Study Case 3

Figure 9 shows the comparison of the hot-spot temperature evolution over 44 hours of study for all subcases in Study Case 3 with respect to the base case. Also, Figure 10 includes the comparison of the aging rate for Study Case 3. It can be observed that maximum hot-spot temperature values correspond in time with highest lifetime consumption values. The profiles for all subcases follow the same trend in both the hot-spot temperature evolution and the loss-of-life graph. The most significant lifetime consumption values correspond to Study Case 3a with 0.2047 hours and Study Case 3b with 0.1477 hours.

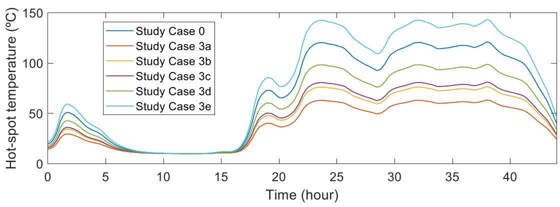

Figure 9. Hot-spot temperature for Study Case 3.

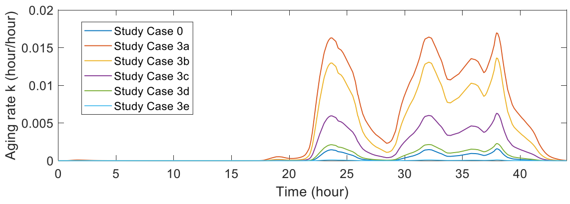

Figure 10. Aging rate for Study Case 3.

5.4. Influence of mean winding temperature rise: Study Case 4

Calculation results for hot-spot temperature evolution are plotted in Figure 11. Figure 12 shows the aging rate of the dry-type transformer under study over the time period under study for the present paper. There is a direct correlation between the mean winding temperature and the thermal degradation of the transformer: the higher Δθwr, the higher the lifetime consumption. For Study Case 4d, the total loss of life in hours is 0.0823 hours.

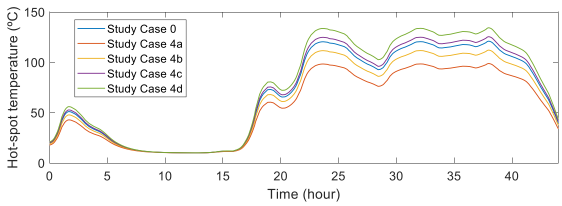

Figure 11. Hot-spot temperature for Study Case 4.

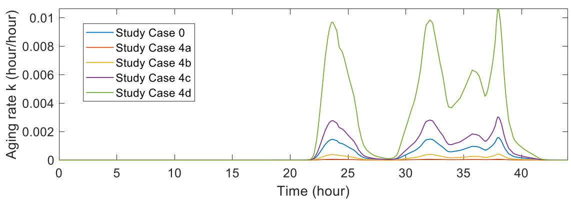

Figure 12. Aging rate for Study Case 4.

5.5. Influence of ambient temperature: Study Case 5

Regarding the analysis of the influence of ambient temperature on the thermal aging of dry-type WTSU transformers, several constant ambient temperatures have been included in the study, ranging from 10 ºC (Study Case 0) to 40 ºC (Study Case 5c). High ambient temperatures increase notably the hot-spot temperature (Figure 13) and as a consequence, the thermal aging of the transformers (Figure 14). All subcases follow the same trend. In particular, for the hot-spot temperature in Figure 13 it can be observed that the difference between the several subcase curves corresponds to the ambient temperature difference. This is in agreement with the theoretical culations suggested by the IEC standard. The total lifetime consumption for the most extreme ambient temperature condition amounts to 0.8492 hours, in contrast to the 0.0126 hours of the base case.

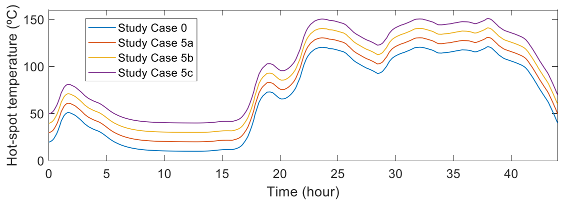

Figure 13. Hot-spot temperature for Study Case 5.

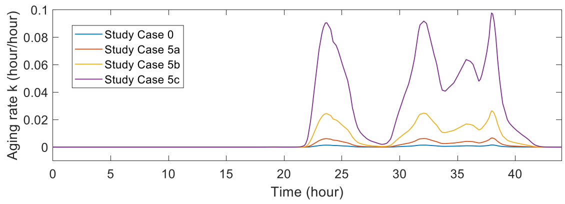

Figure 14. Aging rate for Study Case 5.

6. Discussion

In the present paper, the thermal aging of a dry-type WTSU transformer installed in an offshore wind farm has been analysed. The influence of several aspects on the thermal aging has been studied, including the design and construction aspects of the dry-type transformer (i.e. transformer rating, cooling system, insulation class, rated time constant), operational conditions (namely the mean winding temperature rise) and environmental conditions (i.e. ambient temperature).

Figure 15 introduces a comparison of the lifetime consumption in hours for all study cases except Study Case 1. The highest thermal degradation corresponds to Study Case 5 for high ambient temperatures, as well as the insulation class. Study Case 1 involves the transformer rating and has been analysed separately, since the loss of life notably increases. Thus, transformer loading is the most important factor for the thermal aging of dry-type transformers.

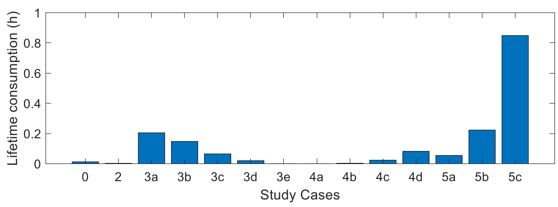

Figure 15. Lifetime consumption for study cases (except Study Case 1).

Thus, given the usual low capacity factors in wind farms and low ambient temperatures (at least in current European offshore wind farms), it would be plausible to install underrated WTSU transformers. Dynamic rating of dry-type WTSU should be considered for offshore locations. Also, it is recommended to consider the thermal degradation for an optimal sizing of dry-type transformers. For the present study, a first attempt has been carried out for the base case (Study Case 0) and an underrating factor of 75% results roughly into loss of life of 44 hours. Thus, the remaining useful life of the transformer under study would still be 180,000 hours. Figure 16 compares the hot-spot temperature evolution of the optimised case (i.e. underrating of 75%) with respect to the base case. Also, Figure 17 presents the thermal aging rate for an underrating of 75%.

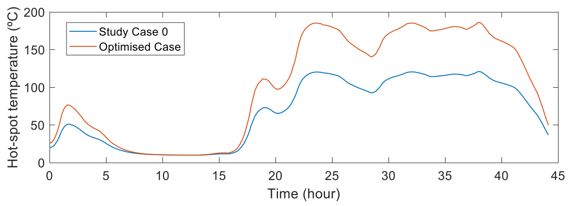

Figure 16. Hot-spot temperature for optimised case.

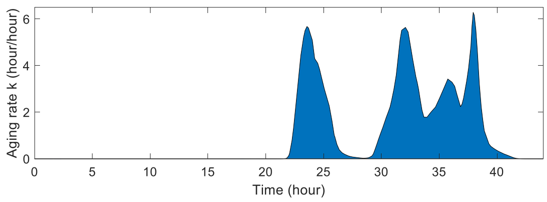

Figure 17. Aging rate for optimised case.

However, note that wind and environmental conditions highly vary in offshore locations due to seasonal and weather factors. As a consequence, probabilistic and optimization tools should be included in a future study.

7. Conclusion

The present paper has introduced the thermal degradation and lifetime consumption estimation 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. Starting from a typical offshore wind turbine load profile, the hot-spot temperature, the aging rate and total loss of life of a dry-type WTSU transformer have been computed for a base case. Given the usual low capacity factor of wind farms and based on a cool ambient temperature, thermal stress is low for the base case. Also, the close correlation between hot-spot temperature and the loss of life of the transformer corresponds to Arrhenius' law.

Besides, the effect of transformer construction characteristics (i.e. cooling system, insulation class), transformer sizing, operating conditions namely the mean winding temperature rise and ambient temperature have also been included 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 study of the influence of the mean winding temperature rise concludes that the higher the average initial increase in the hot-spot temperature, the higher the resulting thermodynamic temperature and the thermal aging of the transformer. However, among environmental conditions and transformer construction characteristics, the highest thermal degradation is due to high ambient temperatures, as well as to the insulation class.

The study of the impact of the transformer rating has resulted into an interesting analysis. Thus, taking into account the usual low capacity factors in wind farms and low marine temperatures, the installation of slightly underrated WTSU transformers can be a practice to consider. Thus, the present paper suggests to include the thermal degradation as an optimal sizing factor for dry-type transformers. For the present study, an underrating factor of 75% results into a negligible loss of life, which does not shorten the usual 180,000 operation hours.

Acknowledgements

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