DYNAMIC THERMOELECTRIC MODELLING OF OIL-FILLED TRANSFORMERS FOR OPTIMIZED INTEGRATION OF WIND POWER IN DISTRIBUTION NETWORKS

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ABSTRACT

Oil-filled power transformers are some of the most critical components in the distribution network. The grid upgrade cost along with congestion challenges associated with rapid increase in onshore wind energy integration in the distribution system can partly be resolved by dynamic loading of transformers. Distribution transformers can be dynamically rated if the temperatures, especially Top-Oil (TOT) and Hot-Spot (HST) temperatures, are accurately determined. This paper presents industry's well-proven and established differential equations-based thermo-electric models for transformers. The models are validated, and the performances are compared with the measured temperatures for a 6.8 MVA wind turbine transformer. Moreover, the thermal lifetime utilization of the test transformer is calculated based on its loading and ambient conditions history for the year 2017, using the recommendations of international loading guides. The annual thermal variations and lifetime utilization of test distribution transformer are assessed for an increase in wind energy production in 2017. Based on this analysis, further wind energy integration is facilitated by deferring grid expansion costs related to transformers

I. INTRODUCTION

Wind energy is a major contributor to the annual electricity generation in Denmark and it is projected to increase even further by 2030 [1]. Windfarms on land have traditionally been connected to the power system through the distribution grids. The integration of wind energy in the distribution network is hindered by a number of challenges. Some of these challenges associated with grid congestion due to integration of this additional load in the existing grid can be resolved by dynamically rated operation of the components that are the usual bottlenecks in the system. Moreover, dynamic rating of these components can also improve the energy contribution during high-wind periods.

Oil-filled transformers are not only used widely across the distribution networks, but also large wind turbines have dedicated transformers in the nacelle or in the tower base. The extensive presence of this component in the network, the absence of winding temperature monitoring systems and the capital investment related to transformers make it relevant to consider dynamic rating of transformers in the distribution network [2]. In order to load the transformers beyond the nameplate rating without violating their transient and steady-state thermal limits, comprehensive information of the temperatures critical for their operation is required. The high cost of the temperature monitoring equipment though makes it necessary to estimate/calculate these temperatures for distribution transformers. This paper focuses on the thermoelectric modeling and estimation of Top-Oil (TOT) and Hot-Spot (HST) temperatures of oil-immersed distribution transformers.

The transformer loading guides IEEE C57.91 [3] and IEC 60076-7 [4] present thermal models based on differential or exponential based functions. These models are relatively simpler to formulate as compared to *more-accurate, non-linear, differential-equations-based* thermoelectric models of [5] [6] [7] [8], which provides the basis for their popularity, also in the distribution network applications [2] [9]. This publication provides the state-of-the-art for these models and compares the physics and structure behind the formulation of differential-based models of [3] [6] [7]. Moreover, the grave dependence of these models on transformer parameters obtained through heat-run tests is also discussed. The TOT calculated through these differential-based models are then validated with the measured TOT for a 6.8 MVA Wind Turbine Generator (WTG) transformer based on its actual load and ambient condition history for 2017. The validation results are then presented for two different week-long periods with considerably different ambient and load conditions in winter and summer. The calculation of HST is then performed using the more accurate model.

International loading guides [3] [4] discuss the impacts of varying HST on transformer paper insulation aging, critical for defining transformer lifetime. These guides also give out recommended thermal limits for TOT and HST for dynamic loading of distribution transformers. The present paper makes use of this analysis to assess the lifetime utilization of the test WTG transformer based on its loading history in 2017. Its annual utilization pattern is found to be noticeably similar to windfarm transformers or distribution transformers close to windfarms. Hence, the impacts of further wind energy integration on thermal aging of distribution transformers is tested by increasing the annual wind power injected in 2017 by 0 to 80% allowing identification of optimal transformer utilization.

The remaining paper is structured as follows. The relevant thermoelectric models are presented in Section II. Section III discusses the phenomena of thermal aging. Section IV provides the details for test transformer and presents the case study, while the results are discussed in Section V. Section VI concludes the paper.

II. THERMOELECTRIC MODELLING OF OIL-FILLED TRANSFORMERS

Oil-filled transformers can in principle be dynamically loaded if the Hot Spot Temperature (HST), which is critical for transformer operation, is accurately determined [10]. Since the physically available temperature in most cases is the Top Oil Temperature (TOT), both temperatures will be included in the model. Unfortunately, the complex heat transfer phenomenon for oil-filled transformers as compared to other power system components, which makes a correct temperature estimation challenging.

A number of thermal models based on differential equations have been proposed throughout the years to simulate the dynamic thermal response of transformers under varying load, ambient and operating conditions. The models discussed in this section are popular in the industry because the variations in TOT and HST are effectively and accurately determined, while the design process is not as arduous [11]. Computational Fluid Dynamics (CFD) based models are reportedly more accurate for HST and TOT estimation but the complexity of design, requirement of detailed transformer construction information and computational extravagance make these impractical for wide-scale application in the distribution network because from a utility point of view, many of these details might not be available [12].

The well-established thermoelectric models presented in loading guides ANSI/IEEE C57.91 [3] and IEC 60076-7 [4] are accepted throughout the industry. IEC 60076-7 [4] provides 2 alternate models for thermal estimation: exponential-equations-based which are suitable for step load change and differential-equations-based which can be applied to any arbitrary load and ambient temperature variations. The parameters that significantly influence the accuracy of these models are transformer specific and can only be determined using prolonged heat-run tests which makes them unfeasible for distribution system application [9]. Despite this fact, the estimation of model constants for dynamic rating of transformers in distribution networks using [4] have been actively explored [2] [9] [13].

This paper focusses on the following two models for dynamic thermal modeling of distribution transformers: IEEE Claus 7 [3] and Susa [6] [7].

IEEE Clause 7 Model (C57.91) [3]

The differential equations determining the development of transformer TOT and HST are provided in (1) and (2).

$$\tau_0 \frac{d\vartheta_{tot}}{dt} = \Delta\vartheta_{or}\left(\frac{K(t)^2\,R+1}{R+1}\right)^n - [\vartheta_{tot}(t) - \vartheta_{amb}(t)] \quad (1)$$

$$\tau_h \frac{d\vartheta_{hst}}{dt} = \Delta\vartheta_{hr}\,K(t)^{2m} - [\vartheta_{hst}(t) - \vartheta_{tot}(t)] \quad (2)$$

$$\tau_0 = C_{th}\left(\frac{\Delta\vartheta_{or}}{P_T}\right) \quad (3)$$

where ϑ_{amb} is the ambient temperature (°C); K is the transformer load current in p.u. with rated load current as base; ϑ_{tot} and ϑ_{hst} are the calculated Top Oil and Hot Spot Temperatures respectively, expressed in °C; R is the ratio of load losses to no-load losses at rated load; $\Delta\vartheta_{or}$ is the TOT rise over ambient temperature ϑ_{amb} at rated load (°C), while $\Delta\vartheta_{hr}$ is the rated HST rise over TOT for rated load of 1 pu. The thermal time constants (hour) for oil τ_0 and winding τ_h are usually obtained using the heat run test, but τ_0 can also be accurately determined using (3). Where, P_T is total losses at rated load (MW); C_{th} is thermal capacity of the oil (MWh/K) which can be approximated using methods suggested in [3] and [8] that require detail information regarding the mass and material of different transformer components (winding, oil, core etc.).

The empirically derived exponents *n* and *m* vary with transformer cooling mode (ONAN, OFAF etc.). The non-linear dependence of heat flow on temperature difference varies the convective cooling process and is therefore dependent on the cooling mode which also influences the thermal resistance and oil viscosity [5]. The empirical values of these exponents for different cooling modes, as suggested in [3] are given in Table I.

Susa *et al.* Model [6] [7] [8]

This model builds upon the fundamental thermoelectric model concepts for transformers proposed by Swift *et al.* in [5] and introduces the impact of temporal variation of oil viscosity and load losses with respect to temperature. The TOT and HST evolution with respect to load and ambient conditions are governed by the following first-order, non-linear, multivariable, differential equations:

$$\tau_0 \frac{d\vartheta_{tot}}{dt} = \Delta\vartheta_{or}\left(\frac{K(t)^2\,R+1}{R+1}\right) - \left(\frac{\vartheta_{tot}(t) - \vartheta_{amb}(t)}{\left[\mu_{pu}(t)\,\Delta\vartheta_{hr}\right]^{1-n'}}\right)^{1/n'} \quad (4)$$

$$\tau_h \frac{d\vartheta_{hst}}{dt} = \Delta\vartheta_{hr}\,K(t)^2\,P_{pu}(\vartheta_{hst}) - \left(\frac{\vartheta_{hst}(t) - \vartheta_{tot}(t)}{\left[\mu_{pu}(t)\,\Delta\vartheta_{hr}\right]^{1-m'}}\right)^{1/m'} \quad (5)$$

Where all the symbols similar to IEEE C57.91 model represent the same quantities. The oil viscosity μ_{pu} in pu is time variant and temperature dependent as it is the ratio between actual oil viscosity μ_o at time *t* and oil viscosity at rated TOT rise μ_{or}, as mentioned in (6). The dependence of load losses on temperature is introduced by the term $P_{pu}(\vartheta_{hst})$, calculated using (7), which takes into account the temperature dependence of both the copper $P_{cu,pu}$ and eddy losses $P_{e,pu}$ expressed in pu with P_T as base. Finally, the empirical constants *n'* and *m'*, representing the oil circulation mechanism inside the tank and heat dissipation through free or forced convection, are similarly obtained as for the IEEE model and tabulated in Table I.

TABLE I - EMPIRICAL CONSTANTS FOR IEEE [3] AND SUSA [6] MODELS

Transformer Cooling Mode	IEEE C57.91		Susa et al. *	
	n	***m***	***n'***	***m'***
Oil Natural Air Natural (ONAN)	0.8	0.8	0.8	0.67
Oil Natural Air Forced (ONAF)	0.9	0.8	0.83	0.67
Oil Forced Air Forced (OFAF)	0.9	0.8	0.83	0.67
Oil Directed Air Forced (ODAF)	1.0	1.0	0.83	0.67

** values for onload condition (circulating oil) with external cooling are provided*

$$\mu_{pu}(t) = \frac{\mu_o(t)}{\mu_{or}} = e^{\left(\frac{2797.3}{\vartheta_{tot}(t)+273} - \frac{2797.3}{\vartheta_{amb}(t)+\Delta\vartheta_{or}+273}\right)} \quad (6)$$

$$P_{pu}(\vartheta_{hst}) = P_{cu,pu}\left(\frac{235+\vartheta_{hst}(t)}{235+\Delta\vartheta_{hr}}\right) + P_{e,pu}\left(\frac{235+\Delta\vartheta_{hr}}{235+\vartheta_{hst}(t)}\right) \quad (7)$$

Comparison of models

Both the thermal estimation models seem to follow a similar pattern (Change in Temperature = Heat In – Heat Out). Heat-in is driven by the time variant load (resulting in losses) while heat-out is driven by the relevant temperature difference. The introduction of temperature dependent oil viscosity in the Susa *et al.* model effectively addresses the temperature-variant convective cooling property of the oil, which is complemented by the presence of temperature dependent load losses. But the distinct difference between the two models is the position of empirical exponents. In the IEEE model, these exponents are located at the heat-in section of the equation, while Susa *et al.* model puts these on the heat-out expression which is thermodynamically more accurate. It is observed that both the models obtain similar forms if the constants are set to 1 but differ significant otherwise. The dependence of each of these models on parameters obtained through the heat-run test is considerable, which can result in poor performance if the appropriate protocols are not followed during the temperature-rise test.

III. THERMAL AGING & LIMITS FOR OIL-FILLED TRANSFORMERS

One of the key components defining the thermal lifetime of an oil-filled transformer is the lifetime of its paper insulation. The location of HST, typically at or close to the top winding paper insulation, is known to have maximum thermal stress. Therefore, a transformer's lifetime can be determined by tracking the HST which is crucial for its dynamic loading [10]. The loading guides ANSI/IEEE C57.91 [3] and IEC 60076-7 [4] utilize the Arrhenius reaction rate theory to determine thermal aging of the insulation. The aging acceleration factor F_{AA} determining the relative aging rate of the transformer insulation is given by (8), while (9) determines the transformer loss of life LOL.

$$F_{AA}(t) = e^{\left(\frac{15000}{\vartheta_{h,ar}+273} - \frac{15000}{\vartheta_{hst}(t)+273}\right)} \quad (8)$$

$$LOL(t) = \int_{t_0}^{t} F_{AA}(\tau)\, d\tau \quad (9)$$

The aging acceleration factor F_{AA} is unit-less and it not only depends upon the actual hot spot temperature (ϑ_{hst}) in °C but also on $\vartheta_{h,ar}$ which is HST for designed lifetime of the insulation. The value of $\vartheta_{h,ar}$ is 110 °C for thermally upgraded paper insulation and 98 °C for non-upgraded paper. LOL is the cumulative loss-of-life for the period between t_0 and t, whose unit depends on the period τ. LOL is expressed as days in this paper. It must be mentioned that the loss-of-life represents the aging of paper insulation only, which is the predominant aging phenomenon for transformers that have been in the field for < 20 years [14]. Other phenomena including residual moisture content in oil/paper, degradation products etc. and the respective aging impacts are not addressed in this paper.

The thermal limits for distribution transformers specified in [3] [4] for different dynamic loading periods are summarized in Table II. The acceleration in chemical reactions and formation of gas bubbles beyond HST of 140 °C can jeopardize the transformer dielectric strength [4]. Transformer manufacturers, however, recommend maximum continuous HST of 110 °C for thermally upgraded paper. Nevertheless, even this limit is hardly ever reached because of protection designs, favorable ambient conditions and conservative operation philosophies.

TABLE II - THERMAL LIMITS FOR DISTRIBUTION TRANSFORMERS [3] [4]

	Normal Cyclic Loading	**Emergency Loading** (long-term)	**Emergency Loading** (<30 min)
HST	120 °C	140 °C	140 °C
TOT	105 °C	115 °C	110 °C

IV. TRANSFORMER UTILIZATION & WIND ENERGY INTEGRATION - CASE STUDY

The performance of the IEEE C57.91 and Susa *et al.* thermoelectric models is evaluated by comparing the TOT calculated using these models with the measured TOT for 2 different weeks in 2017 with considerably different ambient conditions for a transformer unit with external cooling. The 6.8 MVA, 34 kV / 0.69 kV, Dyn11, OFAF cooled test transformer is a wind turbine transformer used to connect the Wind Turbine Generator (WTG) to the array cable system. The MVA and voltage ratings of the test transformer in supplement with the connection types and cooling methods allow the study to be suitable for distribution system transformers. HST is not used as a parameter for performance evaluation because of unavailability of HST measurements for test transformer.

Wind energy generation has 2 distinguished features: intermittent-pattern and low-dispatch-cost. Therefore, actual loading and temperature patterns along with ambient condition history of the 6.8 MVA WTG transformer for the year 2017 with 10-minute sampling rate are used and the utilization of transformer over the year is evaluated. Windfarm transformers or distribution transformers close to windfarms would undoubtedly have a comparable loading pattern. The test case evaluates the impacts of increasing wind energy integration in the distribution network on transformer's health without changing its size, by assessing the paper insulation's loss-of-life in 1 year. These impacts are emulated by upscaling the actual wind energy production in 2017 over the range of 0 to 80%. Two critical parameters are used to assess these impacts on transformers: transformer lifetime utilization (LOL) at the end of the year and the probability of violating the Cyclic and Emergency loading limits of Table II for Hot Spot Temperature. The later parameter is evaluated using the term *'prob(HST_{max})'*, which calculates the probability of 2 possibilities: how frequently the HST limit of 140 °C is crossed and for how long the cyclic and emergency limits are continuously sustained. The resulting value ranges between 0 and 1, where 0 suggests that the considered limits are never violated throughout the year and 1 represents the contrary extreme condition.

V. RESULTS & DISCUSSION

Validation of Thermoelectric Models and Performance Evaluation

The validation of IEEE Clause 7 (1) and Susa *et al.* (4) TOT thermoelectric models is performed for the test transformer for weeks 04 and 30 in 2017. The results including transformer load, TOT, HST and ambient temperature are plotted in Figures 1 and 2. It is perceivable that the temporal evolution of measured TOT is much closer to the TOT calculated using Susa *et al.* model as compared to the IEEE model. Also, the TOT calculated using Susa model is almost always slightly higher than the measured one, thereby resulting in a conservative estimation which would prevent transformer damage during dynamic loading. The Susa model also results in conservative estimations for HST as compared to IEEE, which is crucial for safe dynamic loading operation. The performances of the TOT models are compared by calculating the respective accumulated error (%) for the entire year with respect to the measured TOT. As anticipated, the accumulated error of Susa *et al.* model for TOT is 30.76% less than that of the IEEE model, which is also expected for the HST model. Consequently, the Susa *et al.* model is used for rest of the analysis related to HST in this paper.

Thermal Utilization of WTG Transformer in 2017

The load and temperature distribution of the test transformer for 2017 has been provided in Figure 3, along with lifetime utilization of the transformer calculated using (9). The WTG transformer is found to be slightly over-dimensioned which is also usually the case for distribution transformers. Despite this, the transformer is often moderately loaded because of the intermittent nature of wind energy. Consequently, the TOT and HST distributions are also on the lower-side most of the time. As a result, the utilization of thermal lifetime for the test transformer is also well below its designed lifetime and thermally, the transformer loss-of-life is total of 13 days out of the 365-day period in 2017.

Increase in wind energy integration

The discussion so far has substantiated two attributes. Firstly, the test transformer exhibits similar utilization patterns as corresponding windfarm transformers or distribution transformers close to windfarms. Secondly, the traditional dimensioning criteria for wind energy transmission transformers results in significant under-utilization. Therefore, the impact of further wind energy integration on the utilization of the same transformer in 2017 is evaluated.

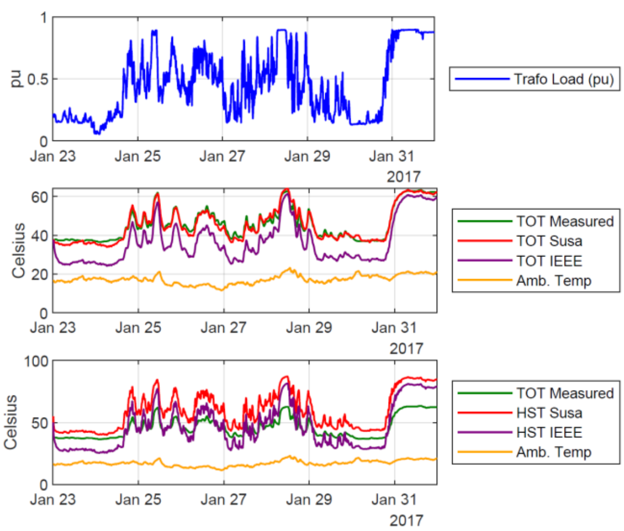

Figure 1 - Validation results for week 04 (Winter) - 2017

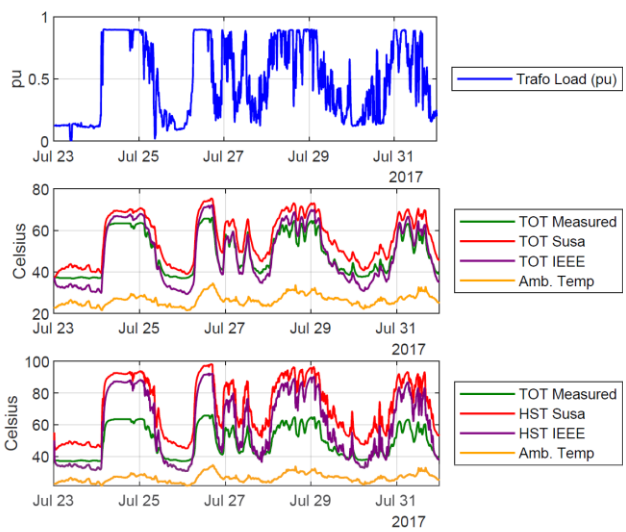

Figure 2 - Validation results for week 30 (Summer) - 2017

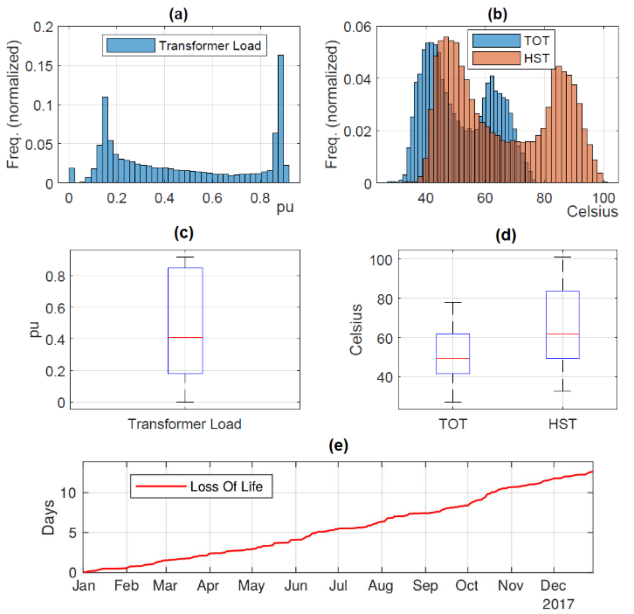

Figure 3 - Transformer utilization in 2017. (a, c) histogram and boxplot for load; (b, d) histogram and boxplot for Temperatures; (e) Calculated loss-of-life for test transformer insulation in 2017

Referring to Figure 4(a), annual lifetime utilization increases substantially beyond the designed lifetime of 1 pu for the test transformer, as the annual wind energy generation for the test WTG is increased by more than 50% in 2017, which is also verified for selected test cases in Figure 4(b). The HST starts violating the limits defined in Table II for annual wind generation increase of more than 45%, for which the expression *'1 - prob(HST_{max})'* reduces to a value less than 1. Hence, the thermal lifetime of the test transformer's paper insulation, under the given constraints, would have been optimally utilized in 2017, if the annual wind generation capacity of the test WTG had been scaled to 1.45 pu. Based on this analysis, further wind energy integration is facilitated by deferring grid expansion costs related to transformers.

VI. CONCLUSION

This paper presents the methods and results from dynamic thermal performance estimations. The industry's well-proven and established differential-equations-based thermoelectric models are presented and the physics behind the model formulation is compared. The validation process with the measured temperatures for a 6.8 MVA wind turbine transformer for the tested models proves the superiority of the Susa *et al.* model. The thermal lifetime utilization of the test transformer is calculated based on its loading and ambient conditions history for the year 2017, using the recommendations of IEC and IEEE loading guides. The annual thermal development and lifetime utilization of transformer suggests that the transformer can be optimally utilized by upscaling the wind energy production to 1.45 pu. Hence, grid expansion costs related to transformers can be deferred for further wind energy integration in the distribution network.

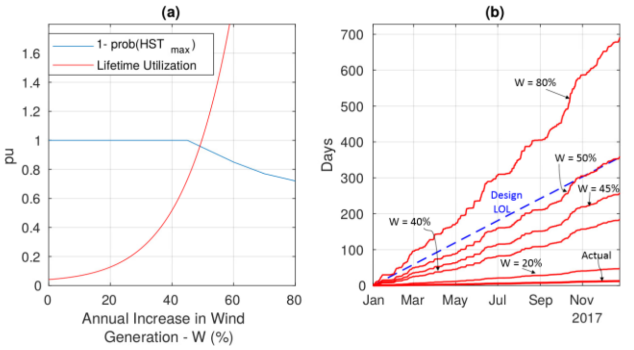

Figure 4 – Impacts of increase in wind energy integration on test transformer. (a) annual utilization in pu. (b) LOL for selected test cases. 'W' represents the upscaling of wind generation (%)

VII. ACKNOWLEDGEMENT

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