Evaluation of Performance of Data Driven Dynamic Rating for Grid Transformers

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Abstract: *The dynamic thermal rating (DTR) technique, which safely establishes the thermally limitations of power compounds based on ambient variables, is the subject of this study. The work assesses DTR for various current and temperature limitations. In contrast to similar studies, the work takes into account all limiting factors (current, HST and TOT) and their combinations. This allowed us to assess those parts of DTR, which were usually omitted in similar studies. DTR assessment showed that the main limiting factor is very sensitive to the chosen formulation of current and temperature limitations*

Keywords: Transformers, DTR, HST, TOT.

I. Introduction

To accommodate various scenarios of renewable intermittency, the capabilities and operations of existing grids must be improved and made adaptable. Simple remedies to the aforementioned issue include the construction of new transmitting corridors and the bolstering of current power assets. However, they are pricey, take a while to produce, and may not be achievable because of space limitations. Before new or improved grids are available, renewable power plants, such wind turbines and solar panels, can be quickly commissioned and made ready for electricity generation.

The dynamic thermal rating (DTR) technique, which safely establishes the thermally limitations of power compounds based on ambient variables, is the subject of this study. DTR is sometimes referred to as real-time thermal rating (RTTR) or flexible thermal rating because the power rating of this system fluctuates over time and appears flexible (FTR). Because it reveals latent power capabilities, this flexible rating method has significant advantages over the traditional static thermal rating (STR) methodology, automatically increasing the power supply and grid hosted capability for renewables.

Transmission line capacity can be significantly increased by using dynamic thermal rating (DTR) depending on actual environmental data. DTR can reduce the inconsistency among electrical use and supply and enhance line usage, both of which have significant economic advantages. By using a lineampacity calculation model based on CIGRE standard, DTR may be calculated. The transmitting lines' ambient environmental factors are important aspects that influence the DTR, but it is also important to consider the uncertainty of the DTR and the discrepancy between the measured value and the true value.

Transformers transform energy from a source into the power the load needs. Businesses need to know how much power their specific transformers can supply them in order to use them efficiently. That information can be found in a transformer's rating.

A main winding and a secondary winding make up the transformer's conventional two windings. Through the primary winding, power is input. The power is subsequently converted by the secondary winding and sent to the load via its input lines. The rating, often known as size, of a transformer refers to its kilovolt-ampere output.

Transformers are designed by manufacturers based on the voltage and current needed to operate the transformer. Then they specify this in terms of VA on the transformer's nameplate (Volt-Amps). This is referenced to as a transformer's rating. The maximum current and voltage that can be applied to the transformer safely can also be included in the transformer's rating. A transformer's rating is based on temperature increase, which depend on the loses in the transformers. However, by employing the right cooling, the temperatures can be kept within acceptable ranges.

The rating of the transformer increases with the cooling program's efficiency (and vice versa). The ratings of an electrical machine for a specific cooling system is indirectly influenced by the losses existing in the machine. A high winding working temperature causes insulation to deteriorate more quickly, which accelerates the life of the transformers. Although it is not at a single set location, the highest temperature, or hotspots temperature, is found near the winding

conductors and depends on a variety of factors, including the transformer's cooling system, ambient temperature, oil temperature, winding loses, and age effects.
"The maximum loaded which the transformers may acceptably withstand under time-varying load and/or environmental conditions," is the official definition of transformers dynamics rating/loading. Most of the time, dynamic rating will be higher than nameplate rating; nevertheless, there are some circumstances where dynamics rating may be lower than nameplate value, such as when environmental or transformers conditions are much worse than the model predictions. The components serving as the foundation for dynamic loading are;
1) Changing the environment's temperature
2) Thermodynamic insulation oil constant
3) The cumulative nature of thermal deterioration of insulation
Equations based on chosen models are used to determine the interested parameters at each time interval, such as the rise in topsoil temperature and subsequent hotspot temperatures, the number of fatalities, etc. This approach is repeated until all of the intervals for the selected load profile of an average day have been covered. Real-time or offline planning can be used to carry out a broad dynamic ratings procedure, as shown in Figure 1.

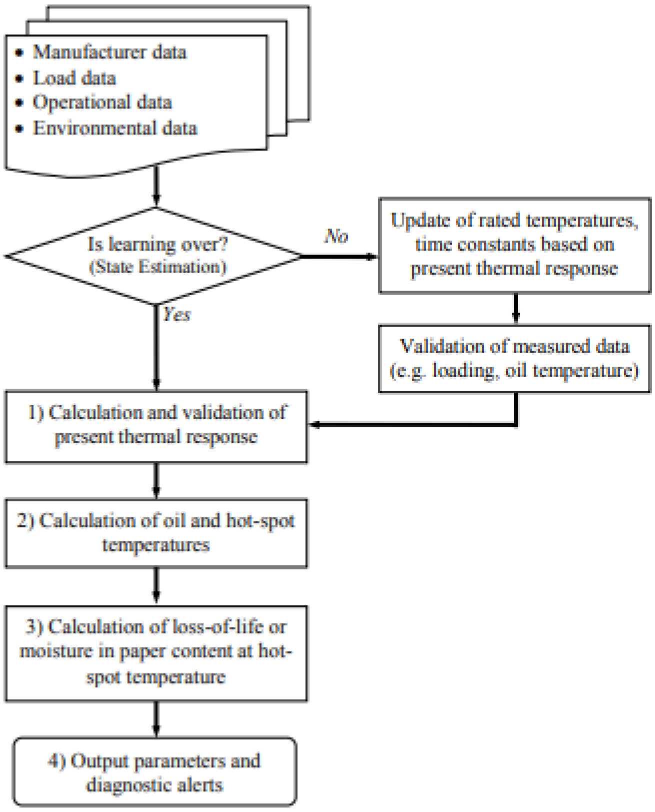

Figure 1 Overview of Transformer Rating

Power lines, cables, and power transformers are typically subject to real-time component rating values. However, as overhead lines (OHL) are the most effective means of DTR application, the objective of this project is on the DTR system's use on OHL. CIGRE, International Electrochemical Commission (IEC), and IEEE are the three organizations that have created the three recognized standards for determining the OHL capability in real time. The IEEE standard 738 is chosen as the standard in the USA for determining line ratings. The IEC version is the easiest to use but also the least accurate, according to a comparative evaluation of the three standards.

II. LITERATURE REVIEW

N. Viafora, et al.[1] This study suggests a day-ahead dispatching optimisation issue based on DC-Optimal Power Flow, where dynamically line rates of chosen transmission lines and dynamics of transformers top oil and hot spots are explicitly taken into account. The IEEE RTS 24 bus system is mapped to simulated weather data from an actual power grid, enabling the estimation of DLR on various lines and the impact of ambient temperature on transformer rating. Results show the possible advantages that combining DLR and DTR could offer for the best power systems dispatching. The suggested method not only demonstrates benefits over normal rating situations, but also demonstrates the beneficial effects of dynamic line ratings on releasing transformer limitations and vice versa.
Alice Vieira Turnell,et al[2] DTR has the potential to develop into an economically advantageous technology because its use in outdated substations allows for the delay of the investing in infrastructure power transformers. For a transformers linked to a wind farm and consequently for a situation with a high variability load, a quantitative risk and economic

analysis of DTR use is conducted. Based on the Arrhenius-Weibull model, the hazards examined in this study include the risk of increasing insulation life losses and the risk of dielectric failure. The cost-effectiveness of switching from a 19.4 MVA transformer to a 16 MVA dynamically rated transmitter has been examined using a comparison net present value calculation. A methodology is created to assist transformer manufacturers and potential clients, including distribution system operators, in the decision-making processes for acquiring dynamically rated transformers for wind power generation. The practicality of DTR applicability is examined.

S. Karimi et al.[3]. Actual current-carrying capability of overhead lines is determined by real-time operating conditions using dynamic thermal rating of transmission lines. The application, goals, and results of Dynamic Thermal Line Rating (DTLR) techniques differ greatly from study to study. Existing literature has offered a number of DTLR adoption techniques. This essay offers a thorough analysis of the DTLR literature. It provides an overview and assessment of various DTLR technologies, DTLR hardware, deployments issues, real-world applications, and potential future DTLR implementation strategies. The way the work is organized makes it easy for the reader to comprehend and contrast different DTLR methodologies.

A.N.M.M. Haque et al.[4] This article suggests a way for managing MV/LV transformers congestion in real time. To calculate the overloading costs, a thorough thermal model of the transformers is used. To mix distributed and computational intelligence for the best possible purchasing of flexible, an agent-based scalable architecture is used. Through network simulations for a representative Dutch LV network, the effectiveness of the suggested mechanism is examined. The approaches can efficiently relieve network congestion while retaining the necessary levels of consumer comfort, according to simulation data.

Z. Radakovic et al.[5] This study presents a dynamic thermal analysis of an indoors transformers stations with compartments for low voltage and high voltages situated in a kiosk with ventilation apertures at the input and output. With the addition of numerical modelling for the kiosk's walls, roof, and ventilation holes, the well-known transient thermal modeling of an oil-immersed distribution transformer is expanded. On each of the outside surfaces, the effect of wind speed and direction on convective heat transfer is taken into consideration. A.N.M.M.

Raqueet al.[6] In this study, a novel real-time congestion management approach is put forth with the goal of addressing the MV/LV transformers congestion issue. To reap the rewards of demand flexibility, detailed models for various loads and thermally overload of the MV/LV transformer are constructed. A simulation using a typical Dutch LV networks has been used to confirm the overall effectiveness of the integrated method for distribution networks.

O. Arguence and F. Cadoux et al.[7] This research suggests a novel approach to consider (and profit from) thermal restrictions right at the planning phase. This is made possible by calculating the individual effects of the each generating and loads on the distributing transformer's temperatures. The analytical formula of the hot-spot transformers temperatures is linearized and rewritten to disentangle the influence of specific generators and loads. By evaluating the increases in the hosted capability of the investigated transformer for extra generators and loads, the method's applicability is evaluated using a real-world dataset. When the transformers is sized by generation, especially when photovoltaic (PV) generators are included, significant advantages are gained.

G. Coletta et al.[8] An actual case study based on a thermal limited power transmission line in the north of Italy is used in this paper's attempt to address these difficulties by providing a thorough examination of the most viable solution strategies that have been suggested in the literature.

David L. Alvarez et al.[9] In order to evaluate the overloading capacity throughout short and long timeframes, this study proposes an online technique to estimate and prediction transformers' ratings. The top-oil temperature is used to calculate the overloading factors. The primary feature of this concept is that the environment cooling conditions are taken into account when operating the transformers by fitting the parameters of a straightforward effective heat circuits to use an extended Kalman filter. The data given by standard transformers ratings monitoring devices is used to verify the algorithm's implementation. As a result, field measurement data collected during the regular operation of two power transformers is used to confirm the algorithm's usefulness and efficiency.

T. Zarei et al.[10] The primary goal is to investigate how DTR impacts reliability from a component standpoint. We make use of currently available knowledge regarding transformer heat balancing models from IEC and IEEE standards to learn more about the loss of life (LOL) of the transformers under inquiry and to make suggestions for potential system upgrades. By accounting for load changes and ambient temperature before overloaded the transformers beyond nameplate specifications, the approach can be used to determine the right transformer size. By assessing the danger of overloaded the transformers for every day of the year, the validity of the proposed application is ensured. Transformer LOL is a measure of the overloading risk. The risk is displayed in relation to the surrounding temperature and the length of an overload. An economic study, which shows the financial advantages of DTR implementation, makes up the final step.

G. Kosec et al.[11] The critical power line temperatures, which depends on the size of the transferred current and the environmental parameters, such as ambient temperature, wind, precipitation, etc., frequently limits the transfer capacities of overhead power lines. Dynamic assessment of the thermally ratings is necessary to utilize existing power lines more efficiently and safely with regard to the essential power line temperatures and to enforce safety measures during potentially hazardous situations. The most significant weather occurrences are covered by the Dynamic Thermal Rating model that is provided in this study, with a focus on rain. The model takes into account a dynamical heat generation caused by Joule losses inside the conductors and heat exchange with the environment in terms of convective, radiating, evaporation, rain impingement, and solar heating. The power line's skin and core temperatures are compared to measurements made under accurate environmental conditions to validate the model.

J. Teh, C.-M. Lai et al.[12] This study offers a paradigm for risk-based management of transmission lines with dynamic thermal rating systems. In this framework, the auto-regressive moving-average model is used to estimate future wind speed values needed to calculate conductor temperatures. The IEEE 738 standard served as the foundation for the thermal analysis models used in this study. On the basis of the Harvey model, the anticipated conducting temperatures is utilized to calculate the associated conductivity loss of tensile strength, or the conductor's degrees of annealed. For lost tensile strength, a cost profile is also given. The findings demonstrate that risk can be reduced by lowering either the conductor temperatures or the conductor's applied time. Additionally, a favorable prognosis of wind speed values also carries less risk and the opposite is also true. The sensitivity analyses demonstrate that the factors taken into account when developing the framework are reasonable and only have an impact on the numerical results, demonstrating that the suggested framework is resilient to different operating conditions of the parameters taken into account in the frame - work.

Lujia Wan et al.[13] A series of pre-physical modeling techniques was proposed and integrated into the transient thermal modeling process with the purpose of optimizing the major thermal parameters separately in order to uncover greater potential of design specifications beyond nameplate information. In this method, a global oil movement methodology was built taking the flow resistance into account, as well as a whole oil flow thermal model was produced based on the idea of temperature distribution and energy conservation to address the issue of heat transfer among windings, oil flow, and radiators. The value of the exponents was then measured using a double logarithmic regression analysis. The temperature projected by the current models under multiple over- loads is clearly different from the temperature increase, according the overloaded heat run tests, but estimates from the new dynamic thermal modelling procedure with optimised thermal characteristics are more precise.

Jiashen Teh et al[14]. Real-time line capacity is determined by the DTR system, and studies have shown that dynamic line rating is typically substantially higher than static line rating. The DTR system is advantageous for enhancing power system reliability, varying line investments, and safe cost as a result. The two basic standards for the DTR system are first contrasted in this review paper. The DTR program's process of finding are then examined as they have been created so far. Important studies that have examined how the DTR system affects the electricity network's reliability are also evaluated. This includes interaction with other smart grid technology and its capacity to integrate and use wind electricity. To further comprehend reliability, the topic of power system reliability is also studied.

Antonio Bracale,et al[15] This study examines how oil-immersed distribution transformers are loaded and suggests a probabilistic method based on the observation of electricity and environmental factors. The strategy entails first predicting the transformer's dynamic rating's predictive distribution, and then predicting the transformer's permitted current. In fact, it chooses the allowable current thru an index that takes account both the possibility that the allowable current will be higher than the predicted dynamic rating and the corresponding probability load curtailment. The probabilistic approach considers the unavoidable uncertainties involved in the thermal modeling of the transformer. Real-world data is used in numerical applications to assess the success of the suggested approach.

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III. METHODOLOGY

The term “feasible region” is introduced to consider all admissible loadings in accordance with current and temperature limitations. It is taken from the mathematical optimization area. Generally, the feasible region represents a set of all possible solutions of an optimization problem satisfying all given constraints. In case of a daily transformer loading, these constraints are current and temperature limitations. However, one cannot draw a DTR feasible region in one x-y axis until their limitations are given in different physical units: pu (or A) for current and ◦C for temperature. We remind that DTR, as any thermal rating, is traditionally measured in the units of current/power or their per units. Thus, temperature limitations should be also presented in the units of current/power or their pu as a function of T_{amb}. Such expression is more convenient for energy specialists working with network operation and transformer operation in particular. To harmonize units, one should know thermal characteristics of a transformer.

To convert temperature limitations into equivalent loading limits, one should build dependencies between steady-state loading and Tamb.

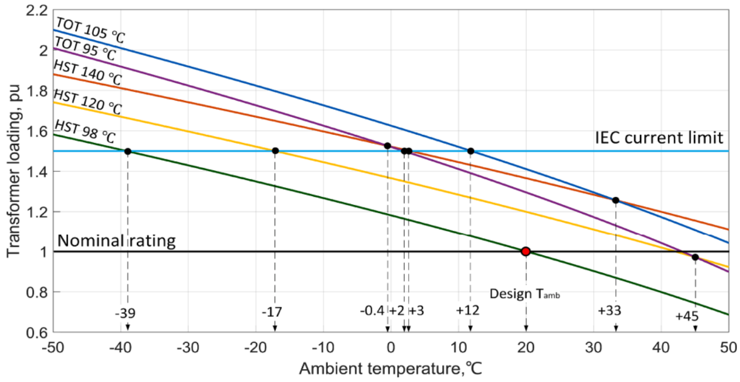

Figure 2 Transformer loadings equal to HST and TOT limits as a function of Tamb

Depending on the maximal admissible values of HST and TOT, the loading of the transformer will be limited either by the current (IEC standards fix its maximal value at 1.5 pu) or by the temperature. Fig. 3 shows the limiting factors using horizontal bars plotted as a function of Tamb.

The bar color represents a limiting factor calculated from Fig. 4.1. For instance, let us take the example of the 3rd bar: HST ≤ 120 ◦C & TOT ≤ 95 ◦C. The yellow line (HST = 120 ◦C) in Fig.1 crosses the current limit at Tamb - 17 ◦C and TOT = 95 ◦C at Tamb + 45 ◦C. This means that: for Tamb ∈ [-50 ◦C; - 17 ◦C], the current limit of 1.5 pu is the limiting factor (a blue area in the third bar of Fig.3. for Tamb ∈ [-17 ◦C ;+45 ◦C], the HST = 120 ◦C is the limiting factor (yellow area in the third bar) for Tamb ∈ [+45 ◦C;+50 ◦C], the TOT = 95 ◦C is the limiting factor (purple area in the third bar).

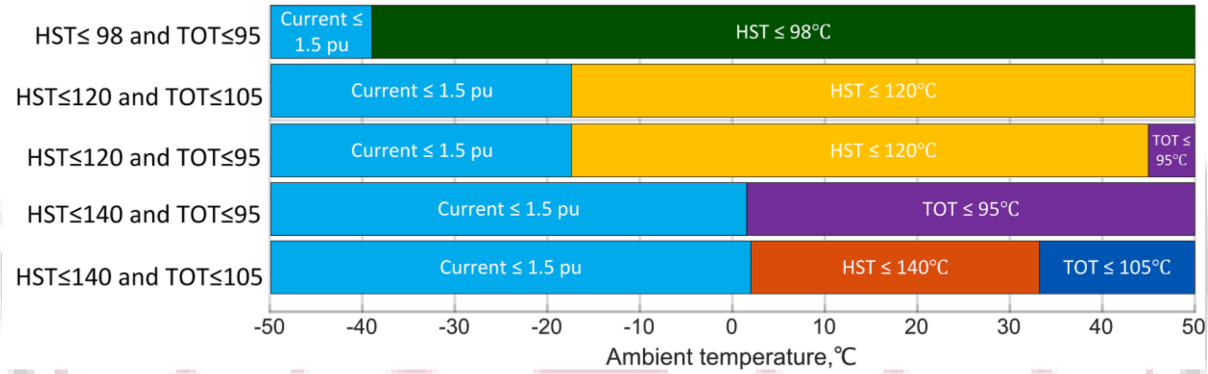

Figure 3 Limiting factors in the range of Tamb.

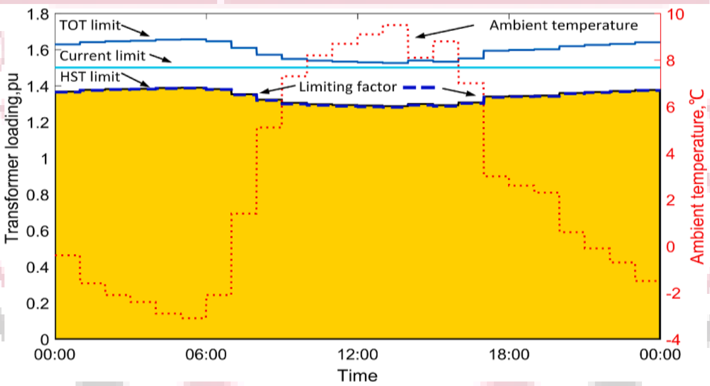

Figure 4 Feasible region (yellow area).

Fig. 4 shows a daily feasible region (yellow area) calculated for a given Tamb profile. To build a feasible region, we suggest to plot current and temperature limitations independently from each other. As we have mentioned earlier, temperature limitations are in ◦C and therefore, they should be converted into power units, pu. Once we converted each temperature limits to loadings for each value of Tamb, we can plot three lines corresponding to HST, TOT and current limits.

The area below this new line is shown by green color, the other part, above this new line, remains yellow (Fig.5). Thus, the green area represents DTR based on a design HST whereas the yellow area represents DTR based on HST limit.

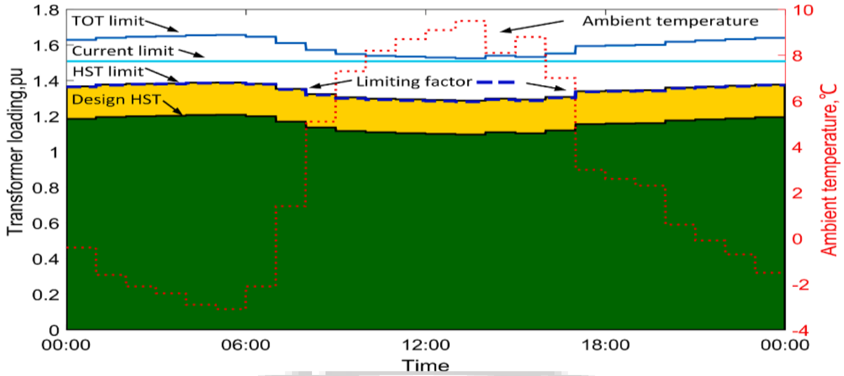

Figure 5 Same feasible region, but showing the loadings with normal ageing (green area).

Once, ageing effects are explained, we need to justify the borders of feasible region which are based on the steady-state loadings. To do that, one should address the Fig.6, showing the interrelations (circles 1–4) between representative loadings (left side) and their temperatures (right side). One can notice that after blue load steps up, the transient blue temperatures (circle 1) reach a steady-state value (purple lines, circle 3) without exceeding it. This interrelation allows us to formulate an important conclusion: if loadings are always below the steady-state loading then transient temperatures are also below the steady-state temperature. Therefore, load profiles do not exceed the design HST if their loadings are located in the green area.

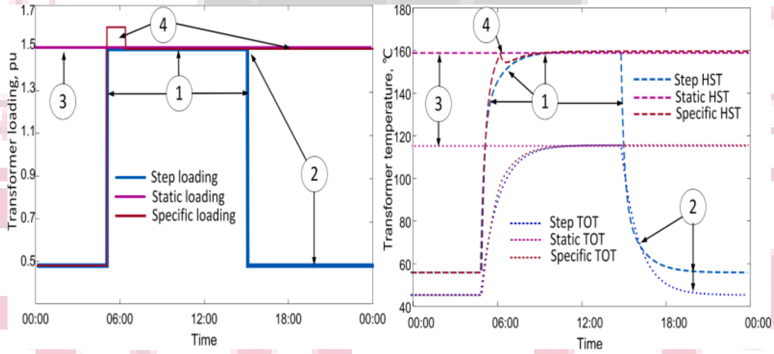

Figure 6 Interrelations between transformer loading and temperatures, calculated by IEC thermal model

IV. RESULT AND DISCUSSION

This section presents the results of DTR assessment. To obtain representative results, DTR estimations are based on long-term data of Tamb in each geographical area. For instance, the climate science recommends to consider at least 30-year-long interval for representative estimations. Therefore, we use hour Tamb for the 34-year period from January 01, 1985 to March 29, 2019 (time of data downloading) in Russia and France (Fig. 7). From Tamb data, shown in Fig. 7, we have 12 506 daily Tamb profiles in each city. For these Tamb profiles, we define 12 506 daily feasible regions corresponding to different combinations of temperature and current limitations (Fig.8).

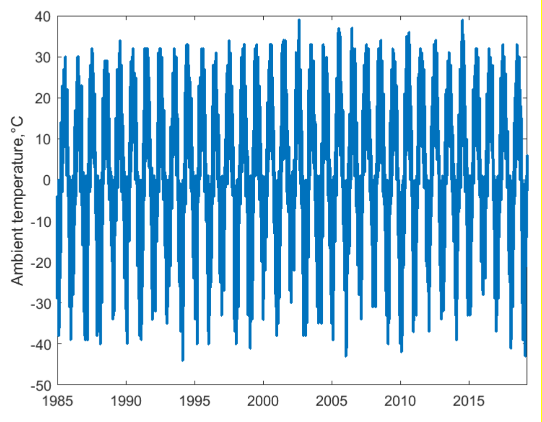

Figure 7 Hourly Tamb from 1985 to 2019

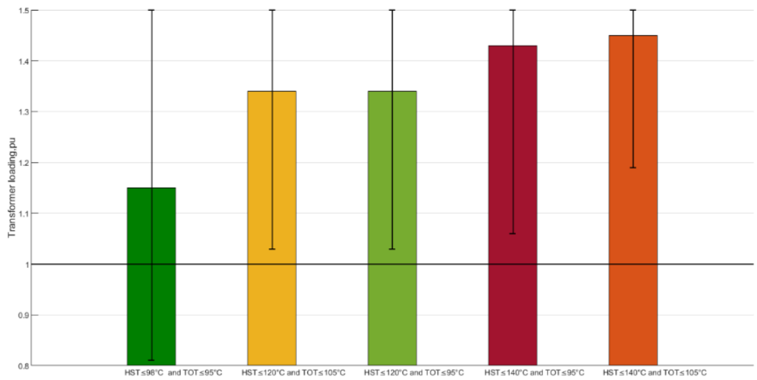

Figure 8 Mean DTR with maximum and minimum deviations during 34 years

The bars in Fig. 9 estimate two types of DTR: DTR, based on design HST (dark green bar) and DTR based on HST limit (other bars). At the same time, the majority of papers estimates DTR using the design HST only (dark green bars). This allows scientists to avoid problems with accelerated ageing which is an advantage. As a drawback, they ignore a substantial part of DTR, confined by current and temperature limitations.

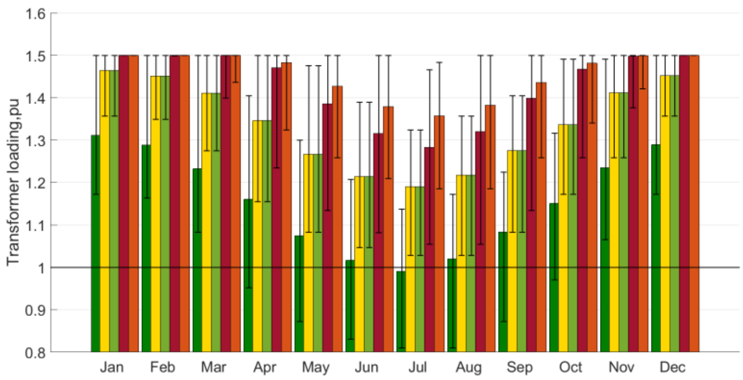

Figure 9 Mean DTR with maximum and minimum deviations in each month

In addition to DTR amplitude, we estimate DTR duration. The typical DTR duration curves are calculated and presented in Fig. 10. Therefore, Fig 10 shows how different current and temperature limits pre-define the duration of DTR. To find such a duration curve, one can sort all values of the DTR array in a descending order. This gives us the y-data. The DTR duration (x-axis) is obtained as following:

$$Duration\,(1:end) = N(1:end)\,N(end) \times 100\% \quad (1)$$

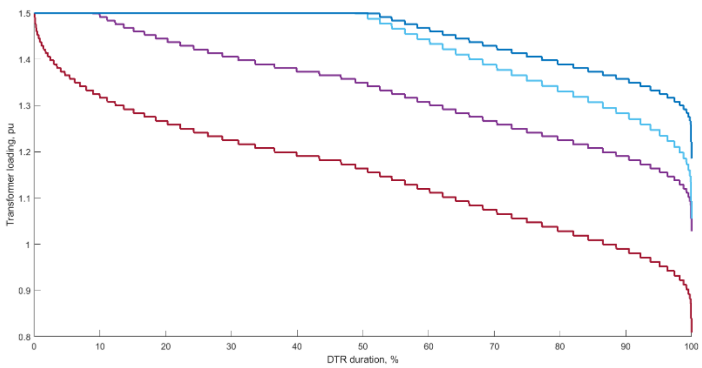

Figure 10 DTR duration curves

These results quantify that part of DTR ignored in similar studies. Finally, we identify the main limiting factor of DTR. The easiest way to do that is to take a Tamb history in each city and see limiting factor for each Tambrange. For this Tamb, the limiting factor is the HST 120 ◦C. Fig. 5.6 shows limiting factors and their occurrence expressed in % of studied period for each DTR formulation. Pie chart colors correspond to colors of lines.

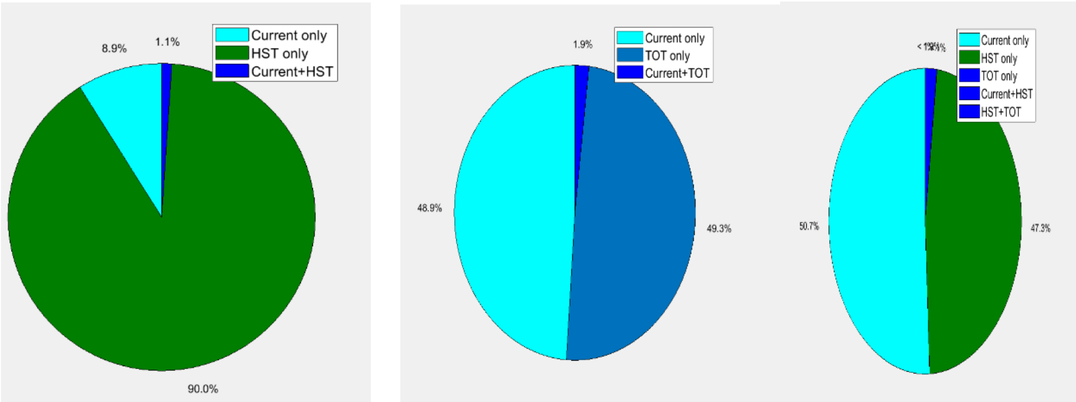

Figure 11 Share of limiting factors. based on 34 years analysis (% are rounded)

Interestingly, some works assume HST as a main limiting factor. Therefore, they use only HST limits as transformer limits in the formulation of an optimization problem. Although such an assumption can be true for the current and temperature limitations chosen in a particular work, other scientists can make an error by using such logic for other DTR formulations or for other Tamb

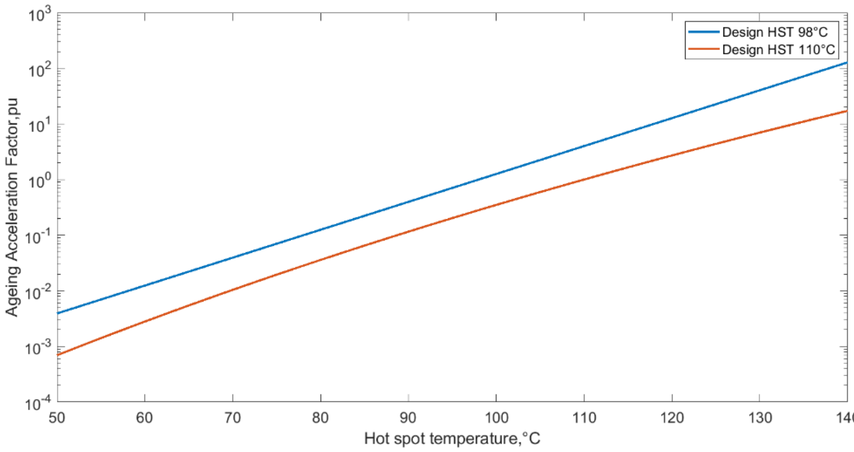

Figure 12 Exponential dependencies of AAF on HST

Actually, the studied transformer ONAF can be still loaded for 64–89% from nominal rating in average. This non-evident result is explained by the exponential interrelation between HST and Ageing Acceleration Factor (AAF) shown in Fig. 12 (y-axis has a log scale). Fig. 12 shows that AAF drastically reduces if HST is decreased linearly. System operators can take advantage of this dependency by keeping the loadings below low HST during some days to compensate the accelerated LoL during 1 day. As we said earlier, for such compensating days, transformers can still operate at 64–89% from their nominal rating.

V. CONCLUSION

In summary, the work assesses DTR for various current and temperature limitations. In contrast to similar studies, the work takes into account all limiting factors (current, HST and TOT) and their combinations. This allowed us to assess those parts of DTR, which were usually omitted in similar studies. At the same time our results showed that this omitted DTR represents a large transformer capacity in the range from 25% to 45% nominal rating. Moreover, DTR duration curves prove that this additional DTR capacity is higher than nominal rating during 100% of time in contrast to classical DTR which is 88,5% and 79% correspondingly. However, we pay attention to the fact that this additional capacity is operated at increased HST. Nevertheless, modern DSO can control the shape of transformer loadings by using DER. This allows controlling the amplitude and durations of transformer loadings and therefore making them feasible from both sides: current /temperature limitations and ageing.

This provides additional degree of freedom for system operators to manage the power systems. This additional capacity can be especially relevant if we recall that the cost of HV/ MV substation can vary from 500 k€ to 1.5 M€. Therefore, DSO can defer large investments into the transformer by taking advantages of DTR and DER. Another important result is that we avoid using a typical (net) load profile for DTR determination. Instead, we built a feasible region of load profiles, which is based on Tamb only. Thus, we consider multiple shapes of load profiles and not only typical ones. Moreover, DTR assessment showed that the main limiting factor is very sensitive to the chosen formulation of current and temperature limitations. For instance, for majority of formulations, HST partially or fully remains a limiting factor but for other cases (HST 140 ◦C and TOT 95 ◦C) HST does not affect DTR at all.

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