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Assessment of dynamic transformer rating, considering current and temperature limitations

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Abstract

Nowadays, transformers can be operated close to their thermal limits. The state of the art in transformer thermal limits are Dynamic Thermal Rating (DTR). DTR can be based on two temperature limits: either a design temperature or maximal-permissible temperature. However, many papers estimate DTR with the design temperature only. Therefore, the true DTR is still underestimated since temperature limit is ignored as well as current limits (in some papers). Moreover, many papers rely on the conservative assumption of typical historical load profile or net load profile (considering the distributed generation, storage, electric vehicles). However, modern DSO can control the shape of (net) load profile. This can make a DTR estimation, assuming some typical (net) load profile, valuable only for a particular shape of (net) load profile but not for its modifications. This paper suggests a DTR feasible region which is constructed from current and temperature limitations and does not rely on typical load profiles. As a case study, we investigate DTR in cold and warm climates: one case in Russia with a continental climate and another in France with a temperate climate. In these climates, we assess DTR for the most common combinations of current and temperature limitations, used in standards and literature. As a result, DTR can ensure an additional capacity up to 45%. DTR, based on temperature limits, are 100 % of time higher than nominal rating. Moreover, the limiting factors of DTR are quantified based on analysis of 34-year ambient temperature data. Finally, comprehensive recommendations for transformer overloading are formulated.

Keywords: Dynamic thermal rating, transformer, limiting factor, current limit, temperature limit, capacity

1. Introduction

Nowadays, the thermal rating assessment is a relevant problem for engineers and researchers dealing with power system operation and planning. Thermal ratings have a strong impact on the optimal solution of a power system scheduling [1], a wind power integration [2–4], a hosting capacity of substations [5],[6], an asset management [7] among many others [8]. Moreover, due climate change problem the system operators should manage a power system with a large share of Distributed Energy Resources (DER) [9]. To avoid congestions caused by new DER, system operators have to know the true thermal ratings of existing network. This is especially relevant since the lead time of DER is much less than that of network reinforcement [10].

For many years, thermal ratings have been defined as Static Thermal Ratings (STR) [11]. STR is a constant limit, expressed in current or power units and usually calculated for daily-mean ambient temperature (T_{amb}). For instance, Table 1 shows STR of power transformers used for power system scheduling in Russia [12]. Similar STRs are used in other countries.

Table 1: STR of power transformer as a function of daily mean T_{amb}

Mean T_{amb} , °C	-20	-10	0	+10	+20	+30	+40
STR, pu	1.20	1.20	1.15	1.08	1.0	0.91	0.82

Despite the long history of using STR, it has been repeatedly proven that STR is only a rough approximation of true thermal ratings [13–16]. This is explained by the fact that STR does not consider both the shapes of T_{amb} and load profile. Consequently, many scientists investigate Dynamic Thermal Rating (DTR) [13,17–21]. DTR represents a daily profile of admissible loadings, expressed either by current or power limits. DTR is usually higher than STR but for extreme ambient conditions DTR can be set lower than STR to avoid the network equipment overheating and/or mechanical damage. DTR is investigated for almost all network equipment [22]: power and distribution transformers [21], overhead lines [23–25] and cables [26].

This paper focuses on DTR of oil-immersed transformers. Unlike other network elements, oil-immersed transformers have a significant loading (overloading) capability above their nominal rating [27]. This overloading capability allows operating a transformer above nominal ratings without sacrificing its design life [28]. To ensure safe operation of a transformer, especially above nominal rating, one should meet current and temperature limitations [29]. Normally, these limitations are set for the current, hot spot temperature (HST) of a winding and top-oil temperature (TOT) in the tank. For instance, the Table 2 shows current and temperature limitations given in international and national standards for normal cyclic loading (i.e. without accelerated ageing).

Table 2: Current and temperature limitations

Limiting parameters	International		National (Russian)		
	IEC [29]	IEEE [30]	STO [12]	GOST [31]	GOST [32]
Current, pu	1.5	2	-	1.5	1.5
HST, °C	120	120	138	140	140
TOT, °C	105	105	105	95	105

Despite these standard limitations, many scientists use a design HST as an alternative temperature limit. This design HST is equal to 98 °C for non-thermally upgraded paper and 110 °C for thermally-upgraded paper whereas the HST limit for both papers starts from 120 °C (see Table 2). Transformers can continuously withstand a design HST during the full-service life since the insulation paper life is then equal to this service life. However,

if transformers operate at HST limit all the time then the insulation life will be reduced at least 12,9 times faster for non-thermally upgraded paper and 2.7 times faster for thermally upgraded paper correspondingly [29], [30]. Consequently, transformers should be operated only for the short time at HST limit. Thus, we can define two types of DTR : DTR, based on the design HST [33] and DTR, based on the HST limit [34]. The latter has a larger loading capability due to higher temperature limit. At the same time, DTR based on design HST allows to avoid any increased HST, but this can lead to less efficient optimization solution.

The existence of two DTR poses a problem: both DTRs should be estimated in the geographical area. At the same time, obtained DTR should be considered as representative if DTR estimations are based on long-term data (not few days or weeks). Only few studies estimate transformer limits in different areas over a long-term period. For instance, authors of [35] estimate a loadability of ONAF power transformer for a typical load profile and 30 year monthly-mean T_{amb} in Turkey. In [36], authors estimate DTR for ONAN power transformer based on the annual T_{amb} in United Kingdom. The one-year DTR benefits are studied in [37] for ONAN and OFAF power transformers in Milton Keynes, United Kingdom. The paper [38] assesses peak-load transformer capability based on three months hour T_{amb} and load data in Manitoba, Canada. The data-driven approach is suggested in [39] to estimate residential transformer overloading based on two-year T_{amb} in West Canada. The paper [40] investigates the loadability of ONAN power transformer in Egypt based on the mean-daily T_{amb} at each month.

Although two types of DTR exist, none of the papers above estimates them simultaneously. Mostly all papers [35–37,40] consider DTR based on design HST i.e. DTR based on HST limit is omitted. Therefore, a real DTR capability is not fully revealed. Meanwhile, the paper [39] estimating DTR based on temperature limit does not consider limitations of current. The lack of current limit makes the DTR estimation incomplete. Thus, no study mentioned above investigates DTR in accordance with temperature *and* current limitations simultaneously. Meanwhile, the limiting factor of DTR can shift between the current and temperature. For instance, the following extract

from IEC 60076-7:2005 describes this problem of factor shifting: “The temperature and current limits are not intended to be valid simultaneously. The current may be limited to a lower value than that shown (in Table 2 of this paper) in order to meet the temperature limitation requirement. Conversely, the temperature may be limited to a lower value than that shown (in Table 2) in order to meet the current limitation requirement”. Consequently, DTR estimation, in terms of power limits, is challengeable and not evident. It is less evident if various temperature and current limitations are used (Table 2). Thus, DTR estimation with different current and temperature limitations is the first problem addressed in this paper.

The second problem that we address is the issue of a typical load profile in estimation of DTR. Many papers [35,38,39,41–47] assume a typical shape of load profile and they upscale this shape until temperature limits are met. The upscaled shape of load profile is then considered as DTR. We believe that the assumption of typical load profile becomes outdated in the modern era of smart grids. In the past, typical load profiles were indeed relevant since DSO could not actively control the shape of load profile and DER share could not affect this load shape. However, the fast integration of DER into distribution network changes the shape of a typical load profile. Thus, a load profile of consumers is not a reference for transformers anymore unlike a net load profile, whose shape is determined by DER and load.

Nevertheless, whatever a (net) load profile is given, modern DSO can actively change a shape of (net) load profile, using controllable DER: distributed generation, storage and demand response [48–53]. Aggregators, new market players, already provide such services to DSO [54],[55]. This poses another problem for estimation of DTR: DTR should not target a single typical (net) load profile but multiple possible (net) load profiles.

This paper suggests to use the DTR feasible region depending only on T_{amb} to overcome two above mentioned problems. Feasible region allows to estimate thermal ratings of a power transformer without using a typical (net) load profile. The paper estimates DTR in cold and warm climates: one in Russia (Tomsk city in Siberia) with continental climate and another in France (Grenoble city in Alpes) with temperate climate. The paper focuses

on the most common combinations of current and temperature limitations given in the Table 2.

Contributions of this paper are: (1) we suggest a DTR feasible region considering both current and temperature limitations. The feasible region encompasses many shapes of (net) load profile. (2) DTRs are estimated for the most common combinations of current and temperature limitations. (3) The recommendations based on proposed feasible region are formulated for transformer overloading.

The paper is organized in the following way: in section 2 we show how feasible region can be built and used to estimate DTR for a majority of load profiles. In section 3, authors estimate DTR for the most common combinations of current and temperature limitations. In Section 4, we present recommendations on transformer overloading.

2. The feasible region

The subsection 2.1 introduces a feasible region of loadings. In subsection 2.2, we present feasible regions limited by each of the factors described.

2.1. The feasible region of transformer loadings

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 [56]. 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 (Table 2). 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. In this paper, we use thermal characteristics of ONAF transformer given in the IEC standard [29],[57] (Table 3).

Table 3: Thermal characteristics of an ONAF power transformer

Parameter, units		Value
Oil exponent, no unit	x	0.8
Winding exponent, no unit	y	1.3
Loss ratio, no unit	R	8
Oil time constant, min	τ_o	150
Winding time constant, min	τ_w	7
Design hot spot temperature, °C	θ_h	98
Design ambient temperature, °C	θ_a	20
Hot-spot to top-oil gradient at rated current, K	$\Delta\theta_{hr}$	35
Top-oil temperature rise, K	$\Delta\theta_{or}$	45
Thermal constant, no unit	k_{11}	0.5
Thermal constant, no unit	k_{21}	2
Thermal constant, no unit	k_{22}	2

To convert temperature limitations into equivalent loading limits, one should build dependencies between steady-state loading and T_{amb} (Fig. 1). To draw each line in Fig.1, one can use an algorithm shown in the right side.

Algorithm: Dependencies between loading and T_{amb} :

Input: 1) Vector of T_{amb} [-50 °C...+50 °C]; 2) Transformer thermal characteristics (Table 3); Temperature limits for HST [98°C 120 °C 140 °C] and for TOT [95 °C 105 °C]; 4) Horizon = 24 hours;

% The drawing the Loading – T_{amb} dependency:

```

for each value from  $T_{amb}$  vector [-50 °C...+50 °C]
  set  $T_{amb}$  = const and Loading = 0.01 pu during 24 hours;
  while Temperature is not equal to Temperature limit
    Loading = Loading +  $\Delta$ , where  $\Delta$  is any small value;
    calculate Temperature by IEC 60076-7 (difference method) for given Loading and  $T_{amb}$ ;
  end
  save Loading reaching the temperature limit;
end
plot (Vector of  $T_{amb}$  as x-axis and Loadings as y-axis)
  
```

Fig. 1 shows the relation between steady-state loading and T_{amb} obtained by the above-mentioned algorithm. First of all, we should define possible combinations of current and temperature limits (see them on the left side of Fig.2).

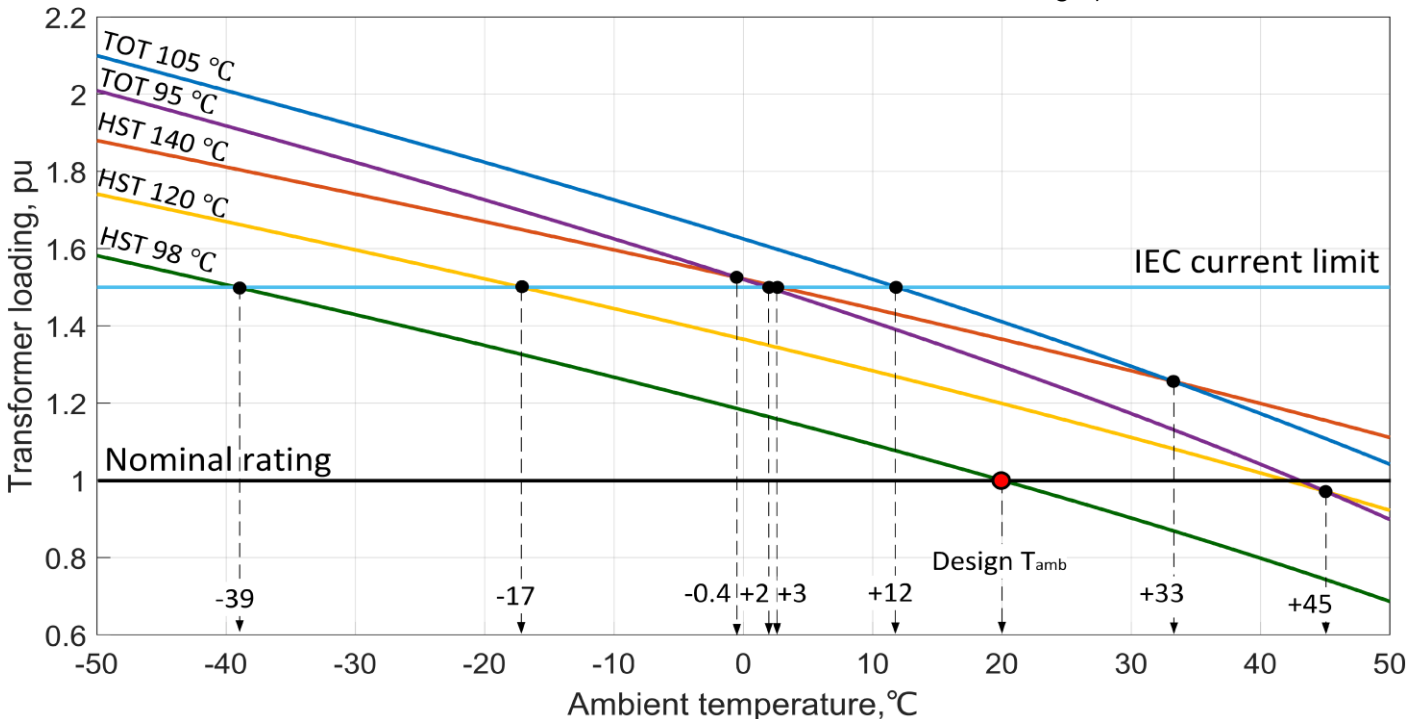


Figure 1: Transformer loadings equal to HST and TOT limits as a function of T_{amb}

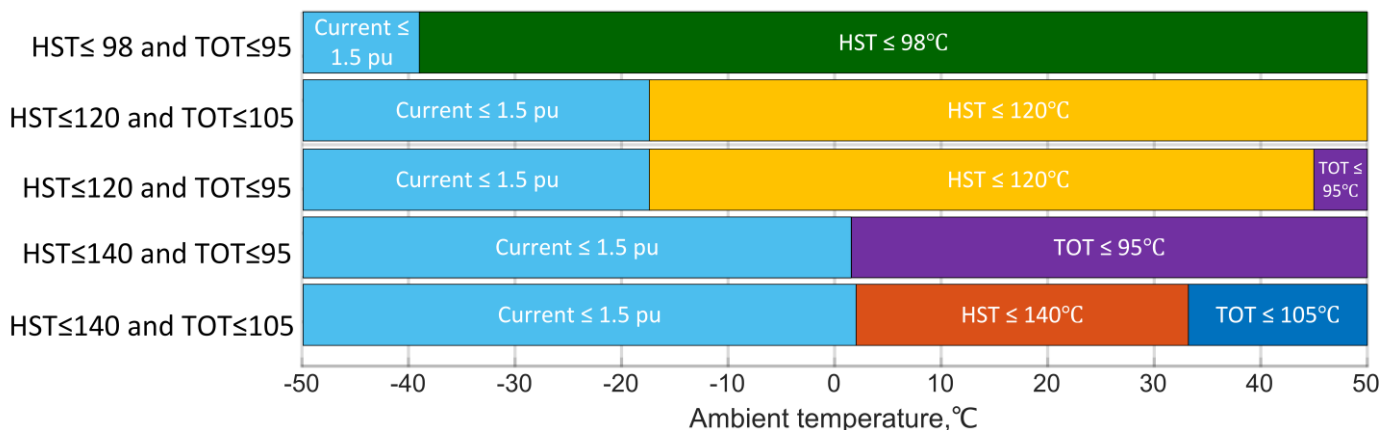


Figure 2: Limiting factors in the range of T_{amb}

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.2 shows the limiting factors using horizontal bars plotted as a function of T_{amb} (x-axis in Fig.2). The bar color represents a limiting factor calculated from Fig.1. For instance, let us take the example of the 3rd bar: $HST \leq 120^\circ C$ & $TOT \leq 95^\circ C$. The yellow line ($HST = 120^\circ C$) in Fig.1 crosses the current limit at $T_{amb} = -17^\circ C$ and $TOT = 95^\circ C$ at $T_{amb} = +45^\circ C$. This means that:

- for $T_{amb} \in [-50^\circ C; -17^\circ C]$, the current limit of 1.5 pu is the limiting factor (a blue area in the third bar of Fig.2)
- for $T_{amb} \in [-17^\circ C; +45^\circ C]$, the $HST = 120^\circ C$ is the limiting factor (yellow area in the third bar of Fig.2)
- for $T_{amb} \in [+45^\circ C; +50^\circ C]$, the $TOT = 95^\circ C$ is the limiting factor (purple area in the third bar of Fig.2).

We point out that Fig.1 and Fig.2 are obtained for a studied ONAF power transformer (Table 3) and not for all ONAF transformers. Latter ones can have distinct critical T_{amb} (black dots) due to the transformer design variations.

Once the loading- T_{amb} dependencies are known, we assume that we have a specific T_{amb} profile and build a feasible region for a studied ONAF transformer. Fig. 3 shows a daily feasible region (yellow area) calculated for a given T_{amb} profile.

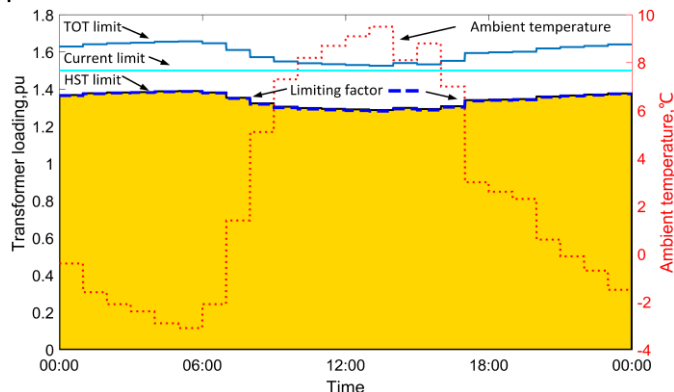


Figure 3: Feasible region (yellow area)

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 $^\circ C$ and therefore, they should be converted into power units, pu. This means that for each given value of T_{amb} profile in Fig.3 we find loadings in Fig. 1 corresponding to

e.g. $HST \text{ limit} = 120^\circ C$ and $TOT \text{ limit} = 105^\circ C$. Once we converted each temperature limits to loadings for each value of T_{amb} , we can plot three lines corresponding to HST, TOT and current limits. For example, at 12:00, the ambient temperature is $9^\circ C$. In Fig.1, it can be seen that the transformer loading is limited by the HST to 1.3 pu, by the IEC (current) to 1.5 pu and by the TOT to 1.53 pu correspondingly. The lowest line (the HST line) among three lines shows us a top line of the feasible region. In other words, HST limit is reached earlier than current and TOT limit. Thus, HST limit is a limiting factor for DTR for the given T_{amb} profile.

It would be useful to define a part of this feasible region, which causes the normal insulation ageing (i.e. DTR based on design HST). To show it, we add a line (loadings), corresponding to the design HST = $98^\circ C$ (the calculation is similar to HST limit). The area below this new line is shown by green color, the other part, above this new line, remains yellow (Fig. 4).

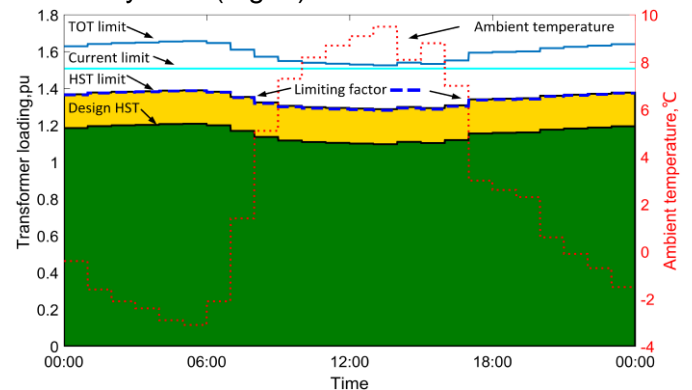
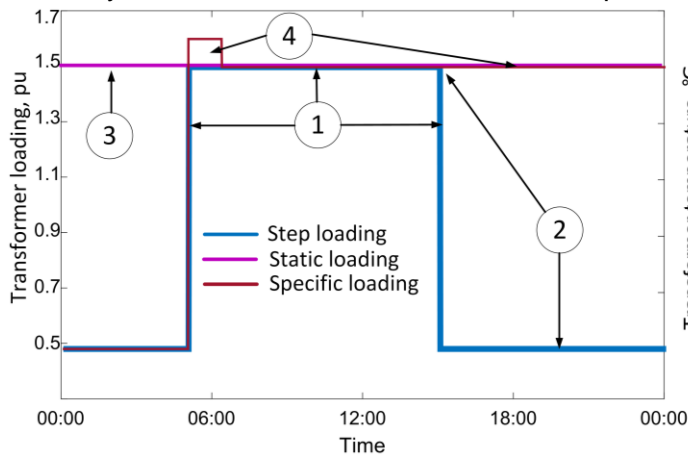


Figure 4: Same feasible region, but showing the loadings with normal ageing (green area)

Thus, the green area represents DTR based on a design HST whereas the yellow area represents DTR based on HST limit. The difference between two DTRs in this example is always around 0.2 pu i.e. 20 % of the nominal rating. In other words, if DTR is based on the design HST alone then 20 % of actual transformer capacity would be neglected.

Once the construction of feasible region is explained, it is necessary to discuss the insulation ageing issue in feasible region. As the reader may note a feasible region is based on current and temperature limitations only. This means that an accelerated ageing is possible if transformer loadings exceed the green area (the design HST). Nevertheless, IEC standard clarifies the accelerated ageing: "this is not serious if there are

otherwise long periods of time (usually the case) at relatively low hot-spot temperatures”. This quote refers to the example, given in IEC standard, where cumulative ageing during 2 hours exceeds the normal ageing in 74 times. In other words, for 2 calendar hours a transformer has lost the insulation resource equivalent to 6 days of normal operation ($=2 \text{ h} \cdot 74 / 24 \text{ h}$). Indeed, such a high ageing rate in one day can be compensated by low ageing during other days, week or month. We note that IEC suggested this assumption at the time when DSO cannot actively control the shape of load profiles. Nowadays, however, DSO can control the shape of



a loading profile. Therefore, this IEC assumption becomes more realistic. Thus, the suggested feasible region is explicitly determined for current and temperature limitations and implicitly for ageing. More details on dealing with accelerated ageing are presented in Section 4.

Once, ageing effects are explained, we need to justify the borders of feasible region which are based on the steady-state loadings (Fig.1). To do that, one should address the Fig. 5, showing the interrelations (circles 1-4) between representative loadings (left side) and their temperatures (right side).

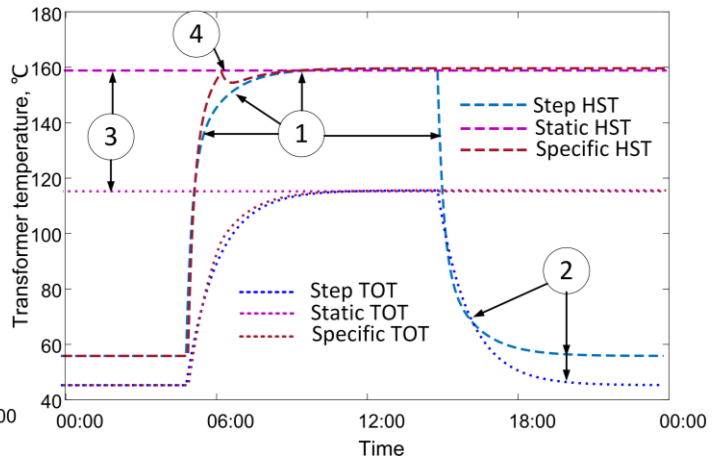


Figure 5: Interrelations between transformer loading and temperatures, calculated by IEC thermal model

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. Similarly, a load profile does not violate the HST limit, if its loadings are located in the yellow area.

Important notice should be discussed. The green area in Fig. 4, should be considered as the area without accelerated ageing only for the load profiles fully located within the green area. If even a small part of a load profile is located in the yellow area, the green area should not be referred to the area without accelerated ageing. Let us explain why: the circle 2 in Fig. 5 shows that even if the load is instantaneously reduced, the temperatures take time to reduce to new steady-state value. Thus, the transient temperature could be still in yellow areas while a loading returned back to the

green area. Moreover, while temperature is reducing to a steady-state value, the ageing will be accelerated since the temperature is still higher than the design temperature. Despite the fact that this interrelation affects the ageing, it does not affect the feasible region of current or HST limit. Therefore, the suggested feasible region is still valid for current and temperature limitations.

Another important observation should be discussed. There is a specific load profile(s) (brown line in Fig. 5) with the loading higher than steady-state DTR around 06:00 but their transient temperatures still remain below the steady-state temperature (see circle 4). Therefore, we conclude that the feasible region, obtained earlier in the Fig. 4, can be actually even higher in terms of loadings. Although we agree with this statement, we note that such a load profile can be obtained only under DSO control (reducing a transformer loading just after its HST reaches its steady state limit). Therefore, such load profiles have the advantage for short-term planning [58],[59]. Thus, we neglect them in the suggested feasible region, which we use for long-term estimation of DTR. Moreover, this

neglection actually reduces a feasible region that allows estimating DTR with margin.

Summarizing above-mentioned results: all load profiles located in the green area only are always feasible for both normal ageing and current/temperature. In contrast, all load profiles located in the yellow area only are always not feasible for normal ageing but feasible for current/temperature limitations. Load profiles, located in yellow and green areas, could be either feasible or infeasible from ageing point of view but always feasible for current/temperature limitations. Thus, we find a feasible region that always complies with temperature and current limitations. This compliance means that the suggested feasible region encompasses multiple load profiles.

Main results of this subsection: (1) temperature and current limitations are expressed in the same units – pu. This allows to (2) plot the feasible region of loadings considering majority of load profiles. (3) the areas of normal and accelerated ageing are determined and their limitations are explained.

2.2. Examples of feasible regions with different limiting factors

In this subsection we describe feasible regions with different limiting factors. We identify 6 possible combinations of limiting factors: 1. Current only; 2. HST only; 3. TOT only; 4. Current + HST; 5. HST + TOT; 6. Current + TOT. The case 2 (HST only) was already presented in Fig. 4. Thus, in this subsection we present main examples of feasible regions (case 1, 3, 4).

Current limit only: Fig.6 shows a feasible region built for limitations HST 120 °C & TOT 105 °C and T_{amb} profile on January 11, 2019 in Tomsk, Russia.

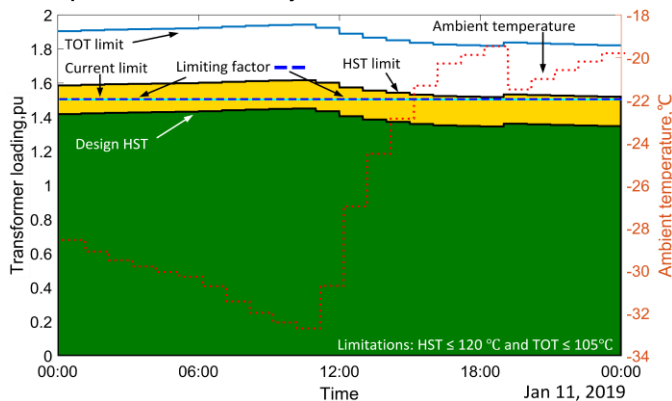


Figure 6: Feasible region limited by the current only
From the Fig. 6 we see that the top line of the feasible region corresponds to the current limit (dash line). To explain why the current is a limiting

factor, one should compare the range of the given T_{amb} profile with T_{amb} axis (in Fig. 1) corresponding to current and HST limit =120°C. There we see that the current limit remains a limiting factor for T_{amb} below – 17°C. At the same time, given T_{amb} profile (varying between -19°C and -33°C) remains always lower than this critical T_{amb} . Thus, current limit remains a limiting factor all day long.

TOT limit only: Fig. 7 shows a feasible region built for limitations HST 140 °C & TOT 95 °C and T_{amb} profile on July 07, 2018 in Grenoble France.

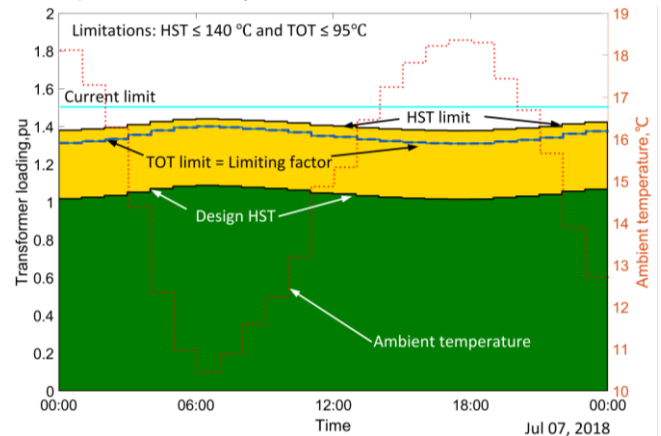


Figure 7: Feasible region limited by the TOT only
Similarly, we use Fig. 1 to explain why TOT is a limiting factor. For given current and temperature limitations, TOT limit (95 °C) is a limiting factor for $T_{amb} > +2$ °C. At the same time, T_{amb} profile varies in the range between +10 °C and +18 °C, which is higher than this critical T_{amb} : This explains why TOT is a limiting factor all day long.

Current+HST limit: Fig. 8 shows a feasible region built for HST limit =120°C & TOT limit =105°C and T_{amb} profile on January 15, 2019 in Tomsk.

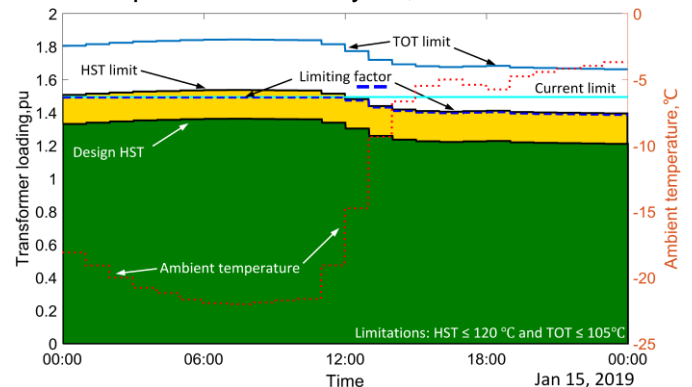


Figure 8: Feasible region limited by current and HST
From Fig. 8 we see that once T_{amb} crosses the critical $T_{amb} = -17$ °C (Fig.1), the limiting factor shifts from current = 1.5 pu to HST limit = 120 °C.

The main result of this subsection: examples of T_{amb} profiles are shown for different limiting factors.

3. Assessment of dynamic transformer ratings

This section presents the results of DTR assessment in Tomsk and Grenoble. To obtain representative results, DTR estimations are based on long-term data of T_{amb} in each geographical area. For instance, the climate science recommends to consider at least 30-year-long interval for representative estimations [60]. Therefore, we use hour T_{amb} [61] for the 34-year period from January 01, 1985 to March 29, 2019 (time of data downloading) in Tomsk, Russia and Grenoble, France (Fig. 9).

From T_{amb} data, shown in Fig. 9, we have 12 506 daily T_{amb} profiles in each city. For these T_{amb} profiles, we define 12 506 daily feasible regions corresponding to different combinations of temperature and current limitations (Fig. 10).

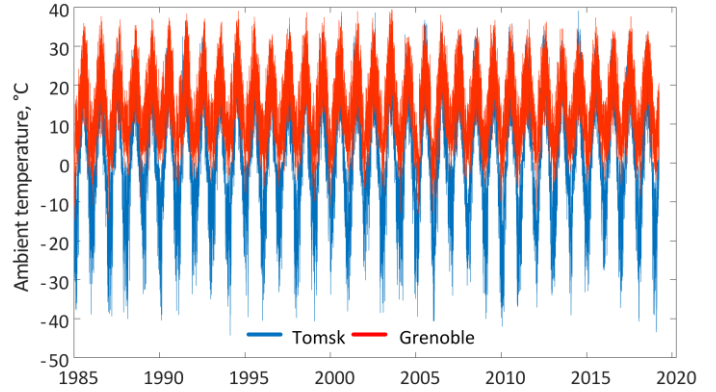


Figure 9: Hourly T_{amb} from 1985 to 2019 in Tomsk and Grenoble

From Fig.10 we see that the black line shape (a limiting factor) of these feasible regions is variable. To quantify this DTR variability, mean DTR and its maximum and minimum deviations are estimated for the most common formulations of current and temperature limitations. (Fig.11)

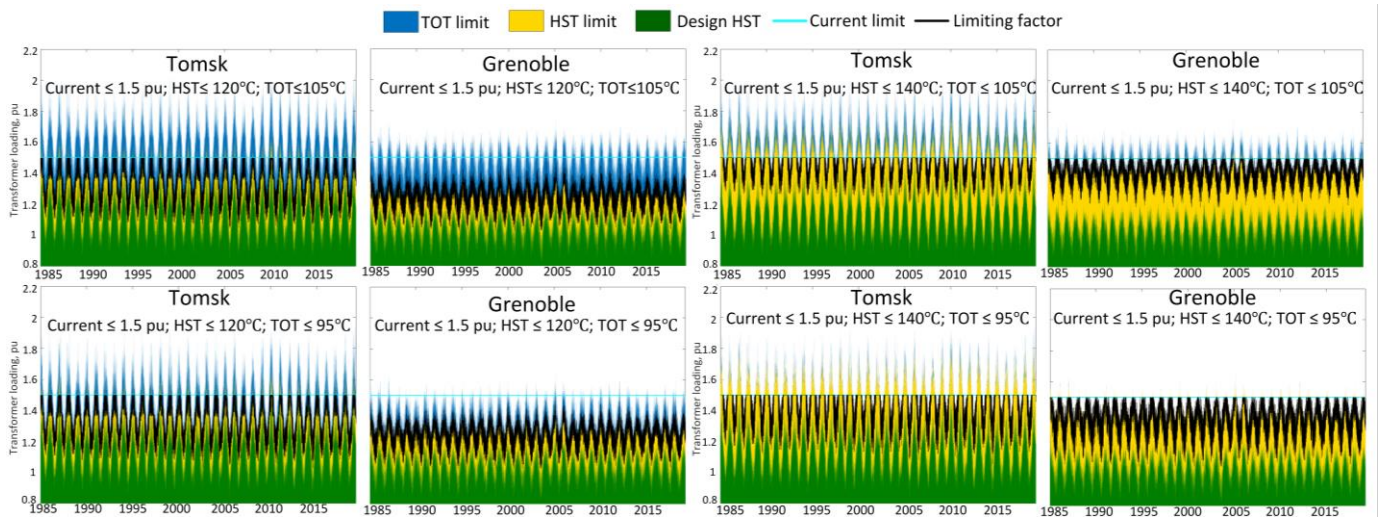


Figure 10: Estimation of feasible regions during 34 years

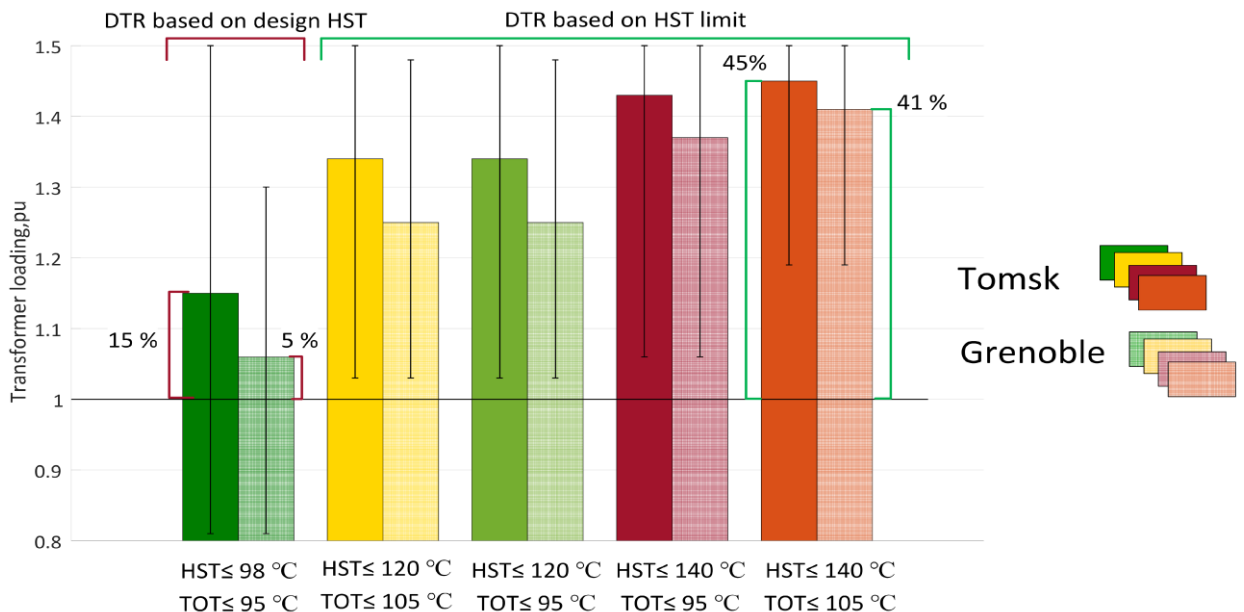


Figure 11: Mean DTR with maximum and minimum deviations during 34 years

The bars in Fig. 11 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. For instance, in [36,37] authors estimated that DTR provides 10% additional capacity in United Kingdom. This correlates with our dark green bars where mean DTR provides 15 % of additional capacity over nominal rating in Tomsk Russia and 5% in Grenoble France. Nevertheless, if one compares

dark green bars with other bars then DTR can ensure up to 45 % of additional capacity in Tomsk and 41% in Grenoble. This is 30-36 % more power in comparison to the DTR, based on the design HST (dark green bars). It is noteworthy that this additional power leads to an increased HST. However, DSO can control this load amplitude and duration using the flexibility from DER.

DTR used together with DER management provides an additional degree of freedom for system operators in power systems scheduling. At the same time, this degree of freedom changes during a year following DTR seasonal variations. Therefore, DTR should be estimated for all current and temperature limitations per month (Fig. 12)

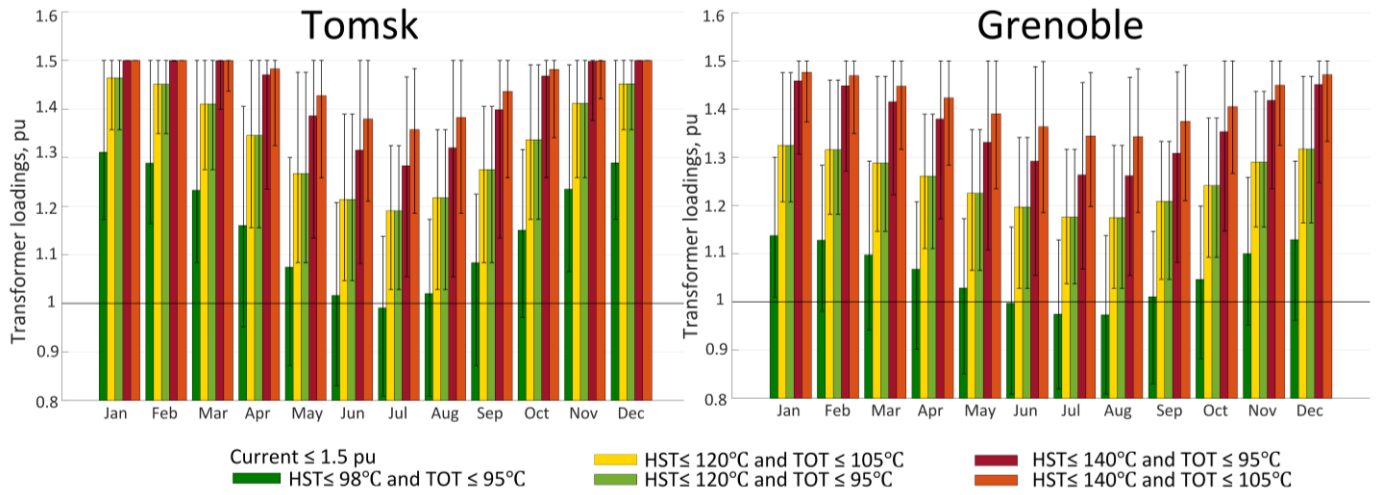


Figure 12: Mean DTR with maximum and minimum deviations in each month

From Fig. 12 we see that dark green bars (DTR based on the design HST) exceed nominal rating of the transformer during almost all months. However, in summer months, such DTR should be set lower than nominal rating to avoid the violation of the design HST. As we said earlier, the dark green bars are a classical example of DTR, studied in many papers [36,37]. However, these papers ignore other bars shown in the Fig.12 This leads to very conservative estimation of DTR. In contrast, this paper allows to determine the part of DTR, which was omitted before.

We would like to explain some particular bars in Fig. 12. For instance, yellow and light green bars are the same in both cities. This means that HST limit = 120 °C is always reached before TOT limit (95 °C or 105 °C) in both climates. This happens since T_{amb} of studied climates is always below than critical $T_{amb} +45$ °C (see Fig. 1). Therefore, HST

remains the unique limiting factor for these two current and temperature limitations.

Moreover, the reader can notice that red and orange bars in Tomsk do not have any deviations in winter months. This means that the current limit is always reached earlier than temperature limits. Thus, bars, whose loading is equal to 1.5 pu, are current-limited and bars, whose loading is below 1.5 pu are temperature-limited. Therefore, Fig. 12 is an example showing how the limiting factor of DTR is shifting between current to temperature during the year. Moreover, Fig.12 represents an example of how different current and temperature limits pre-define the amplitude of DTR.

In addition to DTR amplitude (bars in the Fig.12), we estimate DTR duration. The typical DTR duration curves in Tomsk and Grenoble are calculated and presented in Fig. 13. Therefore, Fig. 13 shows how different current and temperature limits pre-define the duration of DTR.

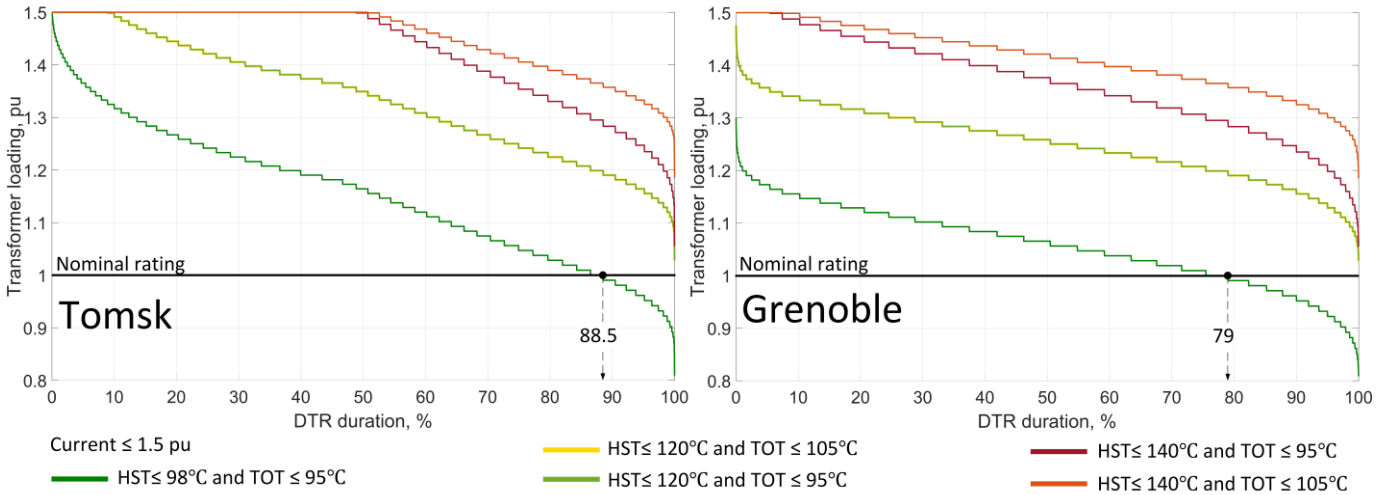


Figure 13: DTR duration curves

To find such a duration curve, one can sort all values of the DTR array (taken from Fig. 10) in a descending order. This gives us the y-data. The DTR duration (x-axis) is obtained as following:

$$Duration(1:end) = \frac{N(1:end)}{N(end)} \times 100\% \quad (1)$$

Where N – a numerical order of y-data (DTR sorted in a descending order).

DTR duration in x-axis shows the amount of time (in %) when DTR exceeds the value selected on the duration curve. For instance, the classical DTR (dark green curve) exceeds a nominal rating of a transformer for 88,5 % of time in Tomsk and 79 % of time in Grenoble. This also means that the classical DTR is below nominal rating for 11.5% and 21 % of time in these cities correspondingly. This result correlates with conclusions of many authors, stating that DTR can be below the nominal rating for a short period of time [36,37]. Meanwhile, we see that duration curves of other DTRs remain higher than the nominal rating for 100 % of time in both cities. These results quantify that part of DTR ignored in similar studies.

Finally, we identify the main limiting factor of DTR in Tomsk and in Grenoble. The easiest way to do that is to take a T_{amb} history in each city and see limiting factor for each T_{amb} range in Fig.1. For instance, we assume that T_{amb} is -10 °C and DTR formulation is current 1.5 pu, HST 120 °C and TOT 105 °C. For this T_{amb} , the limiting factor is the HST 120 °C (see Fig.1). Fig. 14 shows limiting factors and their occurrence expressed in % of studied period for each DTR formulation. Pie chart colors correspond to colors of lines in Fig.1.

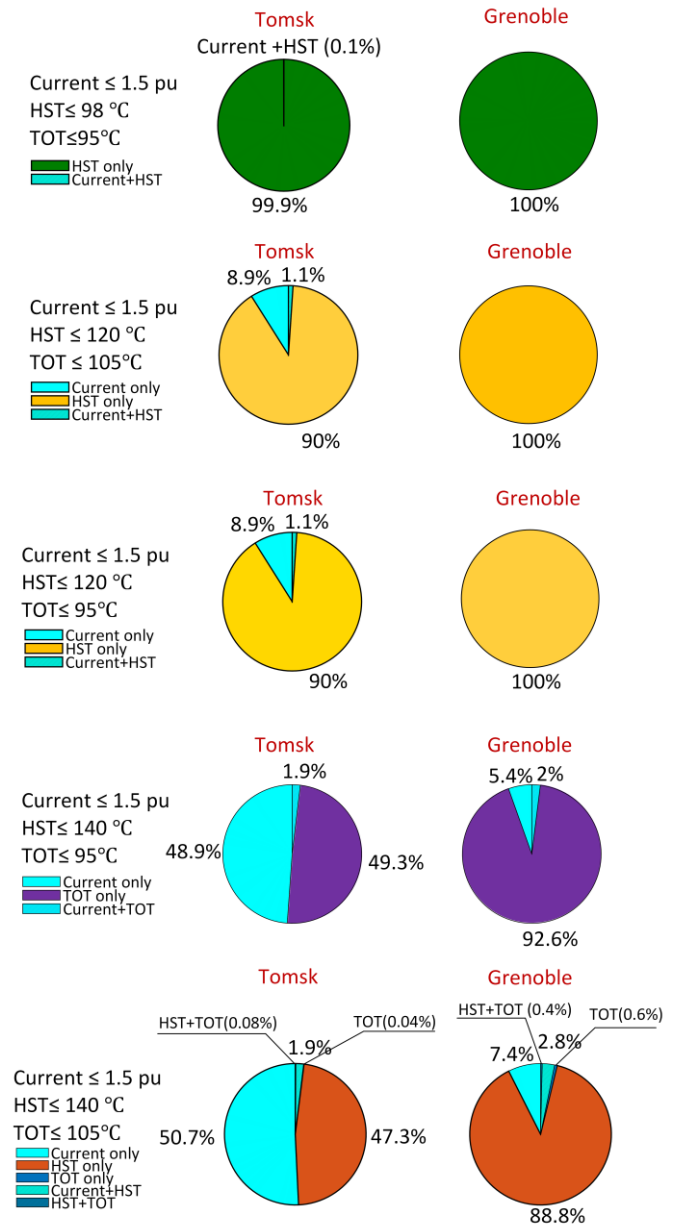


Figure 14: Share of limiting factors: based on 34 years analysis (% are rounded)

Interestingly, some papers [6,62,63] 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 paper, other scientists can make an error by using such logic for other DTR formulations or for other T_{amb} . For instance, Fig. 14 shows that DTR based on the design HST has HST as a limiting factor 99,9 % of time in Tomsk and 100% of time in Grenoble. Indeed, current or TOT limits do not affect the limiting factor of a studied ONAF transformer whatever the climate is chosen. However, if one uses a higher HST limit and TOT limit, we see that current becomes a main limiting factor from 9% to 51 % of time in Tomsk. Notably, the HST is no longer a limiting factor for formulation: current 1.5 pu, HST 140 °C and TOT 95 °C. Therefore, the assumption that HST is always a limiting factor can be fully and partially true but also totally wrong for current 1.5 pu, HST 140 °C and TOT 95 °C.

4. Recommendation for transformer overloading

In this section we suggest recommendations for transformer overloading based on feasible region.

First of all, the green area of the feasible region in Fig. 4, 6, 7 and 8 can be a reference for system operator to avoid any accelerated loss of insulation life (LoL). Thus, system operators can keep the transformer loading always within green area and therefore avoid any accelerated LoL. As we found in Fig. 11 the green area provides 5% of additional capacity in Grenoble and 15 % in Tomsk. Secondly, the yellow area can be a reference to keep the transformer loading within temperature limits. The yellow area provides up to 41 % of additional capacity in Grenoble and 45 % in Tomsk.

However, the system operator should be aware that the operation in the yellow area causes the accelerated LoL. Therefore, we quantify the highest accelerated LoL, which can happen if system operator has to keep the loading within yellow area. To do that, let us assume the worst case of overloading (the amplitude and duration) during 1 day. We believe that the worst overloading happens when the loading is equal to the top border of yellow area during the whole day.

Therefore, the worst case for LoL would be if the top border of yellow is always defined by HST limit (120 °C or 140 °C depending on DTR formulation). In such a case, LoL will be the most severe since the maximum allowable HST is applied. Thus, the most severe LoL can be estimated by Arrhenius formulas (2) – (3):

$$LoL = \begin{cases} \frac{1}{T} \cdot \int_0^T 2^{\frac{HST(t)-98}{6}} dt & \text{if design HST} = 98^\circ\text{C} & (2) \\ \frac{1}{T} \cdot \int_0^T e^{\frac{15000}{110+273} - \frac{15000}{HST(t)+273}} dt & \text{if design HST} = 110^\circ\text{C} & (3) \end{cases}$$

Where T is a duration of studied period (1 day).

Equation (2) corresponds to the case if insulation paper is non-thermally upgraded also known as Kraft paper. The Kraft paper has a design HST= 98 °C which was assumed for studied ONAF transformer. However, a new ONAF transformer can be equipped with thermally-upgraded paper with the design HST =110 °C. In this case, equation (3) should be used. Table 4 shows a LoL estimation by (2)-(3) for HST limit = 120 °C and 140 °C correspondingly.

Table 4 LoL in the worst case, pu = days

The worst LoL		HST limit	
		120 °C	140 °C
Design HST	98 °C	12.7	128
	110 °C	2.7	17.2

The results in Table 4 can be converted to overloading occurrence expressed in days per year. To do that, we suggest using formula (4).

$$(LoL + 1) \cdot x \leq 365 \quad (4)$$

Where x – the occurrence, days per year (unknown);

The meaning of this formula is that the sum of the overloading days and “compensating” days is less or equal to the number of days in the year. Thus, Table 5 shows the admissible occurrence of overloading calculated by equation (4). The number of compensating days is then calculated as difference between 365 days and overloading days.

Table 5 Overloading and compensating days

Overloading days		HST limit	
		120 °C	140 °C
Design HST	98 °C	≈ 26 days	≈ 2 days
	110 °C	≈ 98 days	≈ 20 days
Compensating days		HST limit	
		120 °C	140 °C
Design HST	98 °C	≈ 339 days	≈ 363 days
	110 °C	≈ 267 days	≈ 345 days

The results of LoL estimations (Table 4) mean that depending on insulation paper, the worst day

would consume the same insulation resource as 2.7 days minimum or as 128 days maximum of operation at the design HST. The corresponding overloading occurrence varies from 98 days down to 2 days per year (Table 5). Thus, the number of compensating days varies from 267 days up to 363 days.

However, these results do not mean that transformer should be out of service during “compensating” days. 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. 15 (y-axis has a log scale)

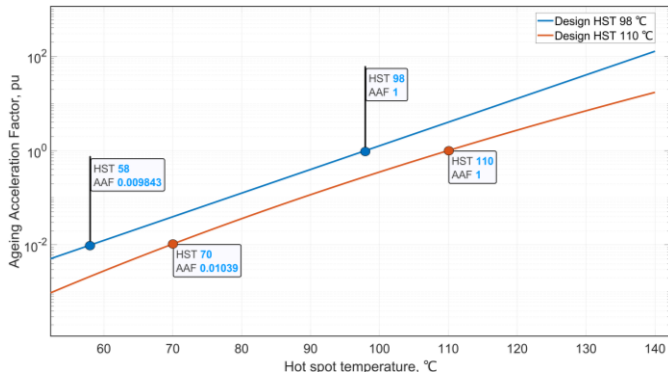


Figure 15: Exponential dependencies of AAF on HST

Fig. 15 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. To explain how 64-89% are calculated let us assume that the transformer operation during compensating days should not cause more than 1 % of normal ageing (% could be set lower if needed). In this case, it is necessary to choose such HST when LoL would be 1 % of normal LoL (see flags in Fig.15). In accordance with equations (2)-(3) for the design HST = 98 °C such $HST_{1\%} = 58\text{ °C}$ and for the design HST = 110 °C such $HST_{1\%} = 70\text{ °C}$ correspondingly. Note that the loading corresponding to these $HST_{1\%}$ would vary as a function of T_{amb} . That is why if we know historical T_{amb} data in Tomsk and Grenoble (shown in Fig.9), then we can find loadings corresponding to these $HST_{1\%}$. To do that, the similar algorithm, presented in the section 2, can be used but instead of a temperature limit, it is necessary to use $HST_{1\%}$.

Fig. 16 shows loadings (black lines) corresponding to $HST_{1\%} = 58\text{ °C}$ and 70 °C in the range of T_{amb} from -50 °C to $+50\text{ °C}$ (x-axis Fig.16). Note that these black lines are true for any geographical area (for given ONAF transformer) but it does not mean that the admissible loadings of the studied ONAF transformer will be the same in each geographical area as latter has a particular T_{amb} conditions. For instance, Fig.16 shows the probability density function (PDF) of T_{amb} in Tomsk and in Grenoble.

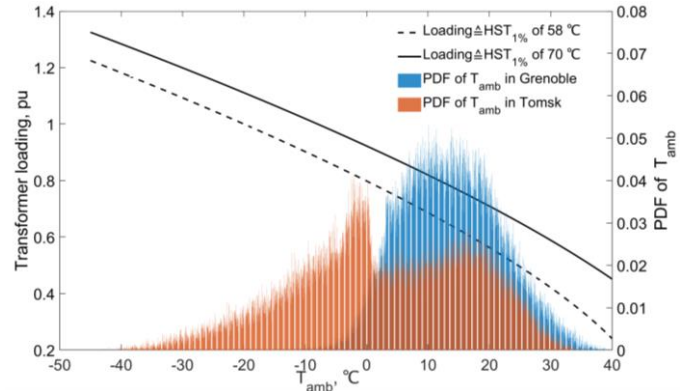


Figure 16: Black lines: transformer loadings corresponding to $HST_{1\%}$. Orange and blue bars: PDF of T_{amb} in Tomsk and in Grenoble based on 34-years history

From Fig. 16 we see that PDF of T_{amb} tends to some particular loadings. To calculate similar PDF of transformer loadings, it is sufficient to take each T_{amb} (on PDF of Fig. 16) and find the corresponding loading (on the black curve in Fig.16). Fig. 17 shows the resulting PDF of transformer loadings in Tomsk and in Grenoble.

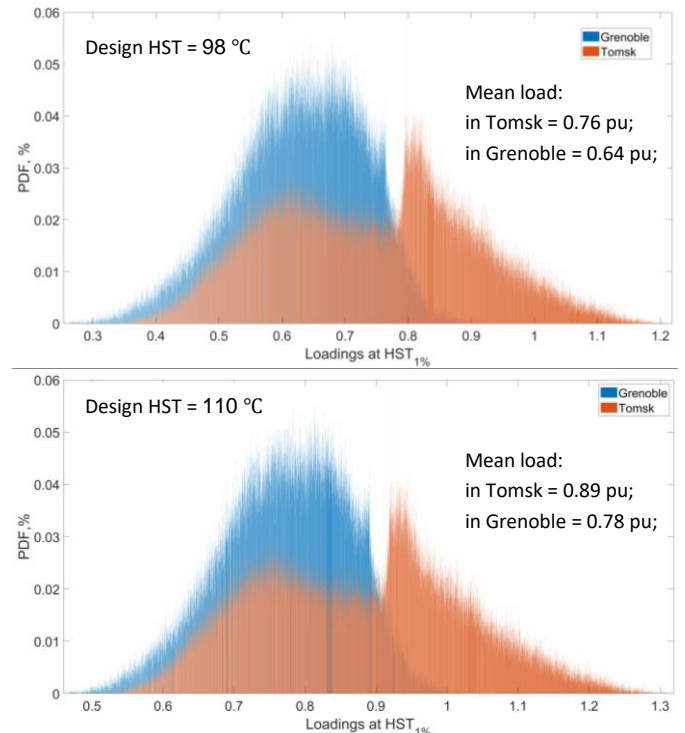


Figure 17: Loadings which can be used for compensation of accelerated LoL (based on historical T_{amb})

The reader could note two observations from PDFs shown in Fig.17. First, the shape of PDF always remains the same, whatever the insulation paper is used. It seems that PDF of T_{amb} in each climate predetermine the PDF shape of loadings. The only difference between two types of insulation paper is a mean loading. The second observation is that a mean loading at HST_{1%} can be higher than a nominal rating (at least for Tomsk). It seems that the reason for such increased admissible loadings is a cold climate in Tomsk. Generally, Fig. 17 proves that system operators can compensate the accelerated LoL even if operating a transformer at loadings close to the nominal rating. For such “compensating” days, system operator can redraw the feasible region by using HST_{1%} as temperature limit.

In addition to recommendations already presented in the paper, we would like to provide important recommendations from other papers, which can be linked, to the feasible region. For instance, system operators could update feasible region at each hour. This would allow them to consider the actual loading and T_{amb} at past intervals to increase/decrease the feasible region at next intervals. The general logic of such DTR updating can be based on receding horizon control [19] also known as model predictive control [64]. It would be also valuable to develop the advanced ageing model linking the LoL and failure effect e.g. as it was done in [65],[66] for DTR of overhead lines or in [67] for transformers. The probabilistic nature of a feasible region can be enhanced based on [68–70]. Moreover, system operators should reduce the current limit of a feasible region to the rating of tap changer or bushings if some of them would limit transformer loadings as it is shown in [45]. The effect of harmonics, unbalancing, moisture in oil-insulation system, oil viscosity among others should be carefully assessed since they can significantly reduce the thermal rating of transformers [71].

5. Conclusion

In summary, the paper assesses DTR for various current and temperature limitations. In contrast to similar studies, the paper 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% in Tomsk and 79 % in Grenoble 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 T_{amb} 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. At the same time, many papers considered HST as the main limiting factor, which is not necessarily true.

Finally, the recommendation is formulated to consider full feasible region of loadings. The worst LoL is quantified and based on that we estimated the admissible number of overloading days per year. Moreover, the paper proves that the compensation of accelerated LoL can be ensured at loading around 64-89% of nominal rating. Thus, system operators can still use transformers at relatively high loadings and at the same time compensate the accelerated LoL.

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