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Energy limit of oil-immersed transformers: A concept and its application in different climate conditions

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Abstract

The reality of modern power grids requires the use of flexibilities from generation, load and storage. These flexibilities allow system operators to modify a transformer loading in a smart way. Therefore, power constraints of transformers can be overcome by using the appropriate flexibility. However, transformers have a physical limit of energy transfer which cannot be overpassed. This energy limit represents the unique transformer's loading profile, ensuring the highest energy transfer under a given ambient temperature profile.

The paper explains how the energy limit can be calculated. Typical characteristics of an energy limit are estimated in cold continental climate of Russia and warm temperate climate in France. Maximal, minimal and mean loadings are identified for each month. Loading durations of energy limit are determined for each cooling system. It is found that winding temperatures of transformers, operating at energy limits, remain in the vicinity of design winding temperature. Therefore, transformer operation at energy limit avoids a high temperature stress and simultaneously maximizes the energy transfer.

The application of energy limits for power system problems is briefly explained along the paper. Energy limit application can reduce an energy cost, maximize a renewable generation and increase a hosting capacity of distribution network.

1 | INTRODUCTION

1.1 | Context of modern power systems

In the coming years, the congestion management becomes especially relevant due to integration of renewable energy systems (RES), aimed to address a climate change. For instance, European Network of Transmission System Operators for Electricity, ENTSO-E, estimated that RES deployment will cause 80% of grid congestions in Europe [1]. In some USA network companies, power equipment is already loaded close to the nominal rating even under normal operation [2]. Meanwhile, a traditional solution—network reinforcement, earlier used to mitigate congestions, becomes inefficient due to a high cost, long lead times and non-technical constraints. These non-technical constraints [2] are related to economic, environmental, political, social and regulatory issues. Thus, system operators are forced to investigate other options for ensuring both RES integration and congestion management for short and middle-term horizon.

Although congestion management shall target both lines and power transformers, this paper focuses on oil-immersed transformers only. In contrast to overhead lines, oil-immersed transformers withstand loadings much higher their nominal ratings. This can be explained by a higher thermal capacity of transformers because of a large mass of oil and windings. Due to high costs of transformers and intermittent output of RES, it is not cost-efficient to size a power transformer equally to RES installed capacity [3]. Therefore, recent studies suggest to size transformers below RES installed capacity, using a thermal capacity of transformer with lower ratings and cost [3–10]. Special IEC standards are being introduced for transformers operating with RES [11].

However, such approach of transformer sizing can lead to congestions e.g. if an interconnection of new RES facilities will exceed the initially planned capacity of RES. Even if transformers are not undersized, congestions are still possible. For instance, almost 90% of distribution transformers will be overloaded due to the growth of load and new generating facilities in the Netherlands by 2040 [12]. Therefore, some share of RES generation must be curtailed during certain periods of time [13]. This leads to the underuse of RES installed capacity (reducing the efficiency of measures against climate change) and/or to the high cost of transformer replacement. Nevertheless, modern strategies of active network operation [12, 14–18] implying the use of flexibilities [19] from generation, storage and load allow to minimize RES curtailments as well as transformer congestions. Thus, new RES facilities can be interconnected to "congested" transformers if flexibilities are applied. Therefore, modern power systems are operated in a specific context: RES integration, new transformer sizing and active operation strategies (flexibilities) among others.

1.2 | Motivation for investigation of energy limits

Despite promising advantages of active strategies [12, 14–18], transformers have a physical limit which theoretically makes further development of any active strategy inefficient. We suggest that this occurs when a transformer reaches its limit of energy transfer. This energy limit represents the unique transformer's loading profile, ensuring the highest energy transfer under given ambient temperature conditions. Once a transformer reaches the energy limit, transformer reinforcement becomes an inevitable option, even if it was earlier deferred by active strategies or by load transfers to another substation.

It is worth explaining why the energy limit was not explored in the past and why it becomes relevant today and in the future. In the past, there was no technical possibility to reach an energy limit before a power limit. In other words, a loading profile of a transformer could not be thoroughly controlled to match some theoretical loading profile, ensuring the highest energy transfer. That is why, transformer limits are usually calculated in accordance to the shape of a given load profile. For instance in ref. [20], we found power limits able to maximize the energy transfer through the transformer for a given load profile. However, one should not call the obtained power limits as the energy limit since the energy transfer was maximized for a given load profile and there can be another load profile, transferring more energy. The modification of a load profile can be performed by modern flexibilities from generation, load and storage. For instance, a transformer peak load can be shaved by increasing a power output of distributed generation, located nearby consumers. Another option is to reduce a substation load by activating a demand response programs or by using a storage for valley filling [21]. Such system services are already provided in practice by new market players—aggregators [22]. Thus, the loading profile of a transformer represents a controllable parameter in modern power systems.

The interest of energy limits application can be found in problems, where transformer is a limiting element. For instance [23], reports that transformers reduce the ability of generation, located in West PJM[1] and East MISO[2], to supply loads in PJM operating area. Specifically, the Cloverdale transformer was recognized as the second constraint among top 25 constraints in PJM [24]. The congestion cost of one Cloverdale transformer in 2018 amounted to \$87.5 million or 6.7% of PJM's total congestion cost [24]. Similarly to operating areas inside of country, transformers can reduce interconnection capacities among countries as it happens in Europe [25]. Such transformer congestions can affect cross border exchanges and a generation scheduling in the power system. This is of great interest for system operators since a scheduling solution has a heavy impact on cost of energy generation. For instance, FERC estimated that 5% improvement of world-wide scheduling solution can save \$87 billion each year [26]. The general situation of congested transformer between operating areas or countries can be represented by the simple case shown in Figure 1.

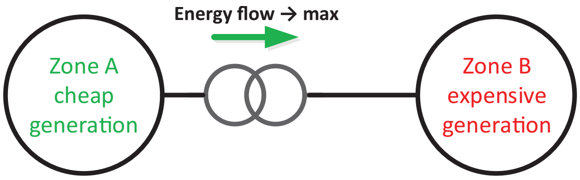

FIGURE 1 Transformer, limiting an energy transfer between two zones

It is important to mention that the European regulation [27] states that system operators should not limit the interconnection capacities (which can be limited by transformers) to solve a congestion inside of their operating area. In other words, cross border exchanges with other countries remain the priority for system operators and it seems a maximization of energy transfer through them as well.

Moreover, operating areas in Figure 1: zone A and zone B correspondingly can be an MV distribution network and LV microgrid or vice versa. These networks, if having enough flexibility can be seen as operating areas but at lower MV or LV level. Whatever voltage level is, if one succeeds to transfer more energy from low-cost zone to the zone with expensive generation, the total energy cost can be reduced.

The maximization of energy generation from RES becomes another important problem due to the climate change. Since a lead time of RES projects is many times less than a lead time of network reinforcement, it seems that RES curtailments will grow up each year. For instance, wind curtailment in Germany already increased by 27 times (from 0.13 to 3.53 TWh) as well as congestion management cost increased 15 times (from 58.6 to 859.4 €m) [28]. At the same time, following the government decision, German system operators can tolerate only 3% of wind curtailment (wind energy produced) in their development plans to avoid expensive grid reinforcement [28].

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[1] PJM—Pennsylvania New Jersey Maryland Interconnection

[2] MISO—Midcontinent Independent System Operator

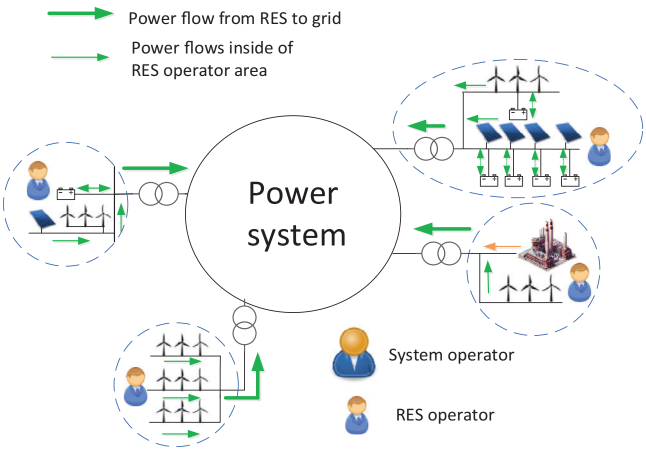

FIGURE 2 Maximization of the energy generation using flexibilities by RES operators

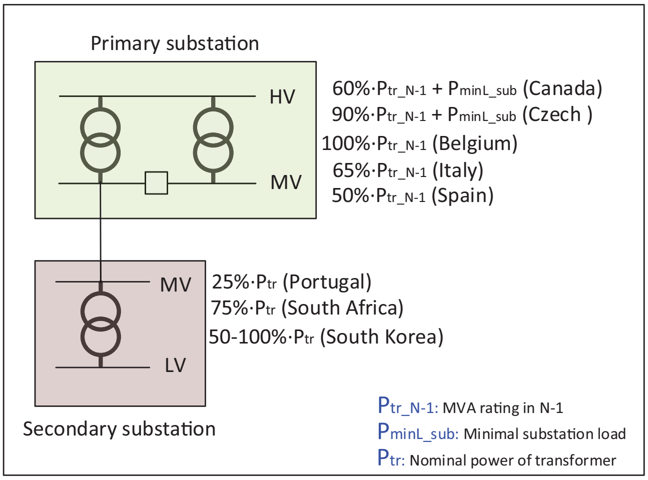

FIGURE 3 Criteria of thermal ratings for DER interconnection in different countries [29]

To minimize RES curtailments, RES operators can use the energy limits together with flexibilities of storage and their generation. We suppose that RES operators can adjust (by flexibilities) their production equal to the energy limit of transformers and submit it as final planning production of RES for a system operator who can then perform a day-ahead scheduling of the net load. Scheduling the RES in accordance to energy limits allows RES operators to maximize the energy transfer from their generating facilities. This is especially relevant if RES transformers were undersized and/or new RESs have to be installed in addition to initially planned RES capacity. For instance, Figure 2 shows a case where RES operators, using active strategies and energy limits, can maximize the energy transfer to power system.

It is important to highlight that system operators accept all RES power flows and balance the remaining system load (i.e. a net load) by fast ramping up generation facilities, storage or demand response if available. Otherwise, RESs are curtailed to keep a power balance or prevent the congestions among others. However, system operators strive to keep RES curtailments as a last resort for the management of network constraints [28]. Therefore, one can assume that power flows from RES (and energy limits) should be kept unchanged as long as possible.

Another problem, where energy limits can be applied, consists in determination of hosting capacity of distribution networks for interconnection of load and distributed energy resources (DER). For DER interconnection, transformers capacity is traditionally used as one of critical limitation (Figure 3).

Moreover, the real case study [30] demonstrated that transformers remain the main limiting element of hosting capacity for DER interconnection because of their high CAPEX[3].

For load interconnection, the available transformer capacity is traditionally used as the primary criterion for decision making. In both situations (for load and DER), a transformer capacity is usually represented by power limit, corresponding to some % of nominal rating, given by the manufacturer. Such approach seems very conservative since the DER power variation in time is not considered [31].

It seems that the application of active strategies can increase the hosting capacity of the network if time-series profiles are taken into account. If so, system operator can procure a robust flexibility from DER to ensure a daily smart balancing of more distributed generation (DG) interconnections. At the same time, we suggest that energy limit is a final constraint which active strategies cannot overpass simply due to physical limitations of a transformer to transfer additional energy. In such case, the only option left is a reinforcement of transformers. Knowing the energy limit and actual load profile, system operators can procure the robust flexibilities to postpone the reinforcement of existing transformers while additional DER and loads are interconnected to substations. It is important to highlight that the share of DER i.e. available flexibilities, are growing very fast, the world installation rate of DER already overpasses the installation rate of centralized generation [32]. Meanwhile, a transformer, once installed, remains in operation for 20–30 years and even more. Thus, a transformer, having some energy limit, can be a permanent constraint for the development of active strategies, as well as for network hosting capacity.

1.3 | Literature review on transformer limits

There are two fundamental approaches, used by many scientists so far: the first approach developed by Norris [33] in 1928 and the second approach by Sealey and Hodtum [34] in 1944. Norris suggested that transformers should operate below a continuous (rated) temperature limit (typically 105 °C at that time). This allows to avoid any acceleration of insulation ageing and, therefore, to operate a transformer without sacrificing its design life. However, Sealey and Hodtum suggested that one can actually violate the rated temperature limit for a short time if at other time interval the actual temperature will be sufficiently

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[3] CAPEX stands for CAPital EXpenditure

below the rated temperature. In such case, the accelerated insulation ageing, caused by high temperatures, will be compensated by slow insulation ageing at low temperatures. Thus, it is still possible to operate transformer without sacrificing a design life even if rated temperature is violated. That is why, the modern IEC loading guide [35] allows normal overloading of a transformer up to 120 °C, whereas a rated winding temperature can be 98 °C for non-thermally upgraded insulation (or 110 °C for thermally-upgraded insulation). These two approaches became the fundamental base for thermal ratings of transformers and they are widely applied by industry and academic experts.

The concept of dynamic thermal rating (DTR), initially developed for overhead lines, was further expanded for power and distribution transformers [14, 15, 17, 36–39]. The main idea of DTR, firstly presented by Davis [40], was to correct thermal ratings in accordance with real-time environmental conditions. This allows DTR releasing the unused capacities of power equipment in contrast to precalculated ratings. Later, DTR features were implemented in different online-monitoring systems for transformers [41–47] and their relay protection [17, 48–54]. After more than twenty years followed first publication on DTR, Douglass and al. presented results of field project, investigating DTRs of overhead lines, cables and transformers in Philadelphia [55, 56]. In 2016, the total number of DTR projects reached 2000 in 50 countries [57]. DTR are found to be especially efficient together with flexibilities [14, 15, 18, 39, 58, 59]. In recent years, DTR application is investigated for RES integration [13].

In the past, a load profile was assumed uncontrollable. That is why, many researchers were calculating DTR through a load multiplier i.e. a constant or dynamic coefficient for the given shape of load profile. For instance, in 1995, Nguyen [60] proposed an optimization formulation with a load multiplier to find normal cyclic and long-term emergency loadings. In 2008, Savaghebi et al. [61] and Shahbazi et al. [62] applied a dynamic loading factor (i.e. a load multiplier) for given load profiles. In 2012, Zhang et al. [63] scaled a shape of load profile until temperature limits were reached. In 2015, Pasricha and Crow [64] also used a load multiplier for power limit determination but with consideration of transformer bushings and OLTC[4] limit. In 2019, Alvarez et al. [65] used load multipliers (both constant and dynamic) to reach a top-oil limit. In the same year, Bunn et al. [66] used a similar principle of load multiplier for given shape of load profile to increase the utilization of transformers.

New findings in thermal transformer modelling made thermal models more accurate and detailed [67, 68, 69]. Therefore, researchers added new parameters into the procedure of rating determination. For instance, in 2007, Savaghebi [70] among others determined the loading capability as a function of voltage variation (including over-excitation) and in 2008 [61] for non-linear currents (harmonics). Other factors, affecting transformer limits, can be grouped as follows: economical [42, 71–74]; probabilistic [62, 75–82]; statistical [38, 77, 83–90].

In 2001, Yasuoka et al. [45], suggested a transformer allowable power predictor, calculating an admissible MVA rating for few hours ahead. In the same year, Lachman et al. [91] developed the advanced DTR algorithm, whose goal was to find a maximal load that can be maintained for various periods of time without violating the temperature and ageing limits. In 2007 Lee et al. [92] developed a dispatch strategy, maximizing the remaining life of transformers in case of emergencies.

In 2012, Bochenski et al. [93] presented a computer program, calculating normal and emergency ratings (based on IEEE and IEC standard) of 800 transformers in Canada. In 2013 Hazra et al. [94] proposed an optimizer which can choose an admissible overloading from the risk/profit ratio. In 2014, Huang et al. [37] used a failure rate limit of power transformer together with their winding temperature limits. In 2016, Dorostkar-Ghamsari et al. [95] maximized a load transfer through substation with two transformers in case if one of them is failed.

In 2018 El-Bayeh et al. [96] suggested a transformer's critical power limit as a function of ambient temperature and ageing factors. Also in 2018, Djamali et al. [97] suggested a method to compute the real-time loading capability of indoor transformers. In 2018–2019 Bracale et al. [80, 81] addressed DTR with probabilistic point of view.

In 2019, Viafora et al. [8] developed the DTR to provide the optimal utilization of transformer life. Besides, in [98] Viafora et al. combined the DTR of transformer and lines in day-ahead dispatch optimization. In the same year, Fang et al. [99] proposed a DTR application in optimal power flow problem to maximize a lead time before next contingency. In that time, authors of this paper also conducted a research [20]. There, we applied a receding horizon control for determination of DTR at intraday planning.

1.4 | Paper goals and contributions

One can notice that the papers above consider a transformer limit in many various forms: power, failure rate, temperature, insulation life, economic, efficiency or risk-profit limits but never as physical limit of energy transfer. The reason is that defining an energy limit requires to explicitly control a shape of transformer loadings which was not possible without flexibilities. Thus, the problem has never been formulated in terms of energy limit of oil-immersed transformers. Moreover, authors did not find any papers, investigating the energy limit of other network equipment such as overhead lines or cables.

In Section 1.2, we identified the problems of power systems where the application of energy limits can be beneficial. Despite the existence of relevant problems, no research has studied energy limits of transformers yet. Due to its novelty, it is logical to firstly eliminate the theory gap on energy limits and further focus on their application for power systems problems. Nevertheless, brief explanations, concerning the practical application, are given in Section 1.2 and some comments are provided over the course of the paper.

The paper has two goals: (1) find the energy limit of a transformer and its typical characteristics. In accordance with our

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[4] OLTC stands for an On-Load Tap Changer

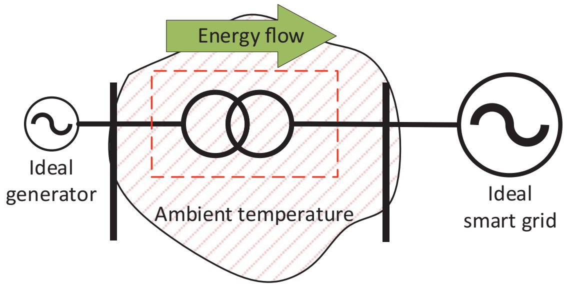

FIGURE 4 Case study for investigating the highest energy transfer through transformers

definition, the energy limit depends on ambient temperature only. The shape and amplitude of ambient temperature profiles can vary within time and space. Therefore, we will (2) estimate energy limits in various climate conditions. To do that, this paper investigates what would be the energy limits of the same transformers but in different climate conditions Two types of climates are investigated: Cold continental climate in Russia (Tomsk city in Siberia) and warm temperate climate in Europe (Grenoble city in France).

The paper contributions are the following: (1) The formulation of the energy-limit concept for oil-immersed transformers is introduced and (2) the impact of climate on the energy limit is studied.

The paper is organized as follows: In Section 2 we explain how to find an energy limit. In the same section, we provide a typical shape of energy limit. In Section 3 we study the climate impact on the energy limits.

2 | DETERMINATION OF ENERGY LIMIT: A CONCEPT

In this section, we model the energy limit of oil-immersed transformers. To find a true energy limit, one should use a specific test case, presented in Figure 4. This simplified test case is intentionally chosen to avoid any case-specific impact of other external factors on energy limits.

We assume that an ideal generator in the left side does not have any constraints and all the energy flow produced would be absorbed by the power system in the right side. Thus, this right side represents an ideal smart grid, able to deal with any internal constraints. We avoid a situation when specific factors as a network topology/load distributions/voltage or angle stabilities/power quality issues as harmonics/technology imperfection/flexibility unavailability from generation, network or demand side can affect the true energy limit of a transformer. These imperfections of existing technologies can be overcome in the future and situation with flexibility unavailability can be changed [100]. The assumption of ideal generator and ideal smart grid allows us to focus on transformer thermal constraints only. Despite of the ideal generator and smart grid assumption, the ambient temperature could not be controlled yet. This means that the shape of energy limit depends on the ambient temperature only. Thus, it is necessary to determine an energy limit for given ambient temperature conditions.

The transformer is represented by the thermal model, provided in IEC standard [35]. IEC standard also provides typical characteristics (see Table 1) for a power transformer with ONAN[5], ONAF[6], OD[7], OF[8] cooling systems as well as ONAN distribution transformer.

The objective is to find the optimal loading curve of given transformers, $S_{(t)}$, to maximize the energy transfer through them (under given ambient temperature conditions), E_{TR}, as stated by Equation (1).

$$\begin{gathered}\max_{S} E_{\mathrm{TR}}\,(S)\\ S=\begin{bmatrix} S_{(1)}\\ \cdots \\ S_{(T_1)}\end{bmatrix}\\ E_{\mathrm{TR}}\;(S)=\sum_{t=1}^{T_2}\frac{\sum_{i=(t-1)\times 60}^{t\times 60} S_{(i)}}{60}\end{gathered} \tag{1}$$

S is a vector of size $1\times T_1$ representing the transformer loading curve in per units with a time step Dt of 1 min over 1 day ($T_1 =$ 1440 min). We assume that a transformer loading is constant during 1 h. Thus, the energy is computed with a time step of 1 h over 1 day ($T_2 = 24$ h).

The solution of such an optimization problem is a loading profile of transformer, maximizing the energy transfer under given ambient temperature or in other words an energy limit which we are looking for. This optimization problem is subjected to a set of constraints related to transformer loadings Equation (2), temperature limitations Equations (3) and (4) and equivalent loss of insulation life Equation (5).

$$S_{(t)} \leq 1.5\ \mathrm{pu},\ \forall\ 0 \leq t \leq T_1 \tag{2}$$

$$\theta_{0(t)} \leq 105^{\circ}C,\ \forall\ 0 \leq t \leq T_1 \tag{3}$$

$$\theta_{h(t)} \leq 120^{\circ}C,\ \forall\ 0 \leq t \leq T_1 \tag{4}$$

$$\mathrm{LoL}\ =\frac{\int_0^{T_1} 2^{\frac{\theta_{h(t)}-98}{6}}\,dt}{T_1}\ \leq\ 1\ \mathrm{pu} \tag{5}$$

where $\theta_{0(t)}$, $\theta_{h(t)}$ are calculated using Equations (6)–(9) for $t = 0$ and Equations (10)–(13) for $t > 0$

$$\theta_{0(0)}=\left[\left[\frac{1+{S_{(0)}}^{2}R}{1+R}\right]^{x}\cdot\Delta\theta_{or}+\theta_{a(0)}\right] \tag{6}$$

$$\theta_{h(0)}=\theta_{o(0)}\ +\Delta\theta_{h1(0)}-\Delta\theta_{h2(0)} \tag{7}$$

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[5] ONAN—Oil Natural Air Natural
[6] ONAF—Oil Natural Air Forced
[7] OD—Oil Directed
[8] OF—Oil Forced

TABLE 1 Thermal characteristics of transformers [35]

Parameter, units		Distribution	Medium or largepower transformer			
		ONAN	ONAN	ONAF	OF	OD
Oil exponent, no unit	x	0.8	0.8	0.8	1.0	1.0
Winding exponent, no unit	y	1.6	1.3	1.3	1.3	2.0
Loss ratio, no unit	R	5	6	6	6	6
Oil time constant, min	τ_o	180	210	150	90	90
Winding time constant, min	τ_w	4	10	7	7	7
Ambient temperature, °C	θ_a	20	20	20	20	20
Hot-spot temperature, °C	θ_h	98	98	98	98	98
Hot-spot to top-oil gradient at rated current, K	$\Delta\theta_{hr}$	23	26	26	22	29
Top-oil temperature rise, K	$\Delta\theta_{or}$	55	52	52	56	49
Thermal constant, no unit	k_{11}	1.0	0.5	0.5	1.0	1.0
Thermal constant, no unit	k_{21}	1.0	2.0	2.0	1.3	1.0
Thermal constant, no unit	k_{22}	2.0	2.0	2.0	1.0	1.0

$$\Delta\theta_{h1(0)} = k_{21} \cdot \Delta\theta_{hr} \cdot \boldsymbol{S}_{(0)}{}^{y} \tag{8}$$

$$\Delta\theta_{h2(0)} = (k_{21} - 1) \cdot \Delta\theta_{hr} \cdot \boldsymbol{S}_{(0)}{}^{y} \tag{9}$$

$$\theta_{0(t)} = \theta_{0(t-1)} + \frac{Dt}{k_{11}\tau_o}\left[\left[\frac{1+\boldsymbol{S}_{(t)}{}^{2} \cdot R}{1+R}\right]^{x} \cdot\Delta\theta_{or} + \left[\theta_{o(t-1)} - \theta_{a(t)}\right]\right] \tag{10}$$

$$\theta_{h(t)} = \theta_{0(t)} + \Delta\theta_{h1(t-1)} + \frac{Dt}{k_{22}\tau_w}\left[k_{21} \cdot \Delta\theta_{hr} \cdot \boldsymbol{S}_{(t)}{}^{y} - \Delta\theta_{h1(t-1)}\right] - \Delta\theta_{h2(t-1)} - \frac{Dt}{(\frac{1}{k_{22}})\tau_o}\left[(k_{21}-1) \cdot \Delta\theta_{hr} \cdot \boldsymbol{S}_{(t)}{}^{y} - \Delta\theta_{h2(t-1)}\right] \tag{11}$$

$$\Delta\theta_{h1(t)} = \Delta\theta_{h1(t-1)}\left(1 - \frac{Dt}{k_{22}\tau_w}\right) + \frac{Dt}{k_{22}\tau_w}k_{21} \cdot \Delta\theta_{hr} \cdot \boldsymbol{S}_{(t)}{}^{y} \tag{12}$$

$$\Delta\theta_{h2(t)} = \left(1 - \frac{Dt}{\left(\frac{1}{k_{22}}\right)\tau_o}\right) \cdot \Delta\theta_{h2(t-1)} + \frac{Dt}{\left(\frac{1}{k_{22}}\right)\tau_o}(k_{21}-1) \cdot \Delta\theta_{hr} \cdot \boldsymbol{S}_{(t)}{}^{y} \tag{13}$$

With $S_{(t)}$, the transformer loading at time t, $\theta_{0(t)}$, the top-oil temperature at time t, $\theta_{a(t)}$, the ambient temperature at time t, $\theta_{h(t)}$, the hot-spot temperature at time t and LoL, the equivalent loss of life on the studied period.

We solve the optimization problem Equations (1)–(13) in MATLAB by fmincon (SQP algorithm) for each transformer cooling type. Figure 5 shows the optimal loading of transformers, depending on its technology and on ambient temperature (input data), which maximizes the energy transfer through transformers. The values of the constraints (hot-spot and top-oil temperatures) are also represented. In each case, the loss of insulation life reached 1 pu exactly.

Looking on Figure 5, one can notice an analytical regularity, common for all types of transformers. In the beginning and in the end, we see a step rise of loadings whereas in other time intervals loadings are changing smoothly. The step changes of loadings at the beginning and at the end take an advantage of winding thermal inertias to transfer the additional energy. The

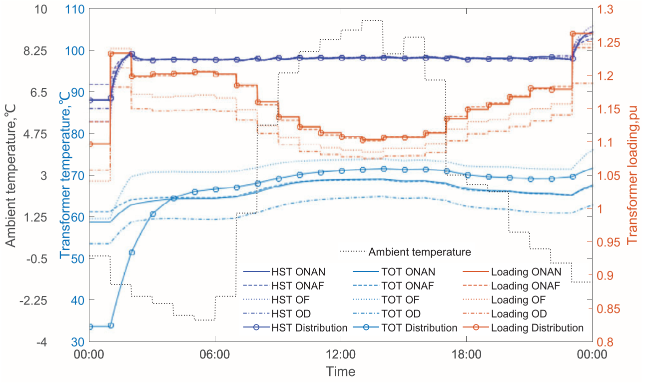

FIGURE 5 Optimal transformer loading, $S_{(t)}$, with corresponding HST[9] and TOT[10]

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[9] HST—Hot Spot Temperature

[10] TOT—Top-Oil Temperature

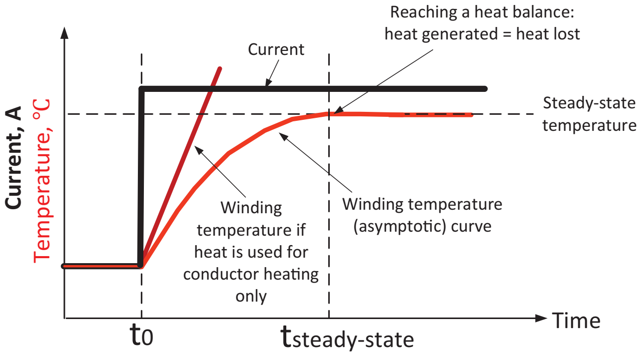

FIGURE 6 Heating of winding conductors based on ref. [101]

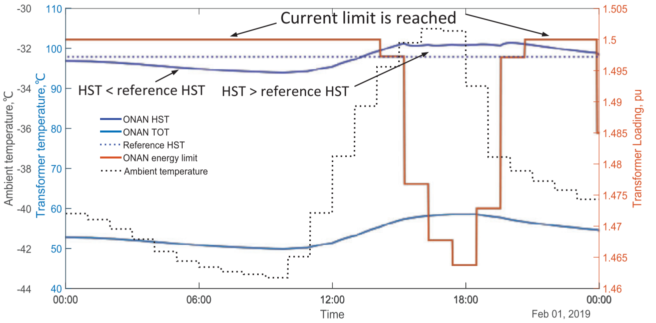

FIGURE 7 Energy limit (loading profiles) in cold ambient temperature

thermal inertia is a physical phenomenon, explaining why a temperature does not change simultaneously with a current. When a current is passing through winding conductors, it generates heat. This heat is then divided into two parts: one part goes for conductor heating and another part is released into surrounding oil. That is why, a winding temperature has an asymptotic curve approaching to steady-state temperature [101]. If the heat would be used only for a conductor heating, then the temperature will change as a straight line (unrealistic case), as shown in Figure 6.

Once the asymptotic curve reaches its steady-state value, the heat, used for conductor heating, and heat, released to oil, reach their balance. In state of the heat balance, the winding temperature does not rise anymore and remains constant, until a current or an ambient temperature changes. Thanks to a time lag between current and temperature response, transformers can transfer a little bit more energy in comparison to steady-state operation. Therefore, one can derive an analytical explanation of transformer energy limits. The energy limit is a loading profile, which most of the time keeps a heat balance (at the design HST) and, in the beginning, and in the end of time interval gets the advantages of thermal inertias to transfer additional energy.

From this analytical explanation (energy limits represents the operation at design HST most of the time), one can deduce that energy limit tends to the form of temperature limit suggested by Norris [33] in 1928. To remind, Norris suggested to limit transformer loadings in a way to avoid overpassing a continuous (design) HST. This continuous HST limit (in °C) can be expressed by steady-state power limit [96] in terms of power units (pu or MVA). The latter conclusion allows us to suppose that energy limits can be approximated by steady-state power limits [33, 96].

The steady-state power limits are well known in the industry [96]. Therefore, an energy limit, approximated by steady-state power limits could be easily calculated and many researchers already apply steady-state power limits [6, 39, 97, 99, 102]. However, steady-state power limits are not energy limits, even if energy limits can be approximated by these steady-state power limits. Any power limit represents an absolute value of power at each time step whereas the energy limit is an integral of all power limits at whole time interval. Following these differences, one can deduce that power limits have many feasible loading profiles, located below these power limits. However, the energy limit represents the unique loading profile of transformer, which is exactly equal to steady-state power limits. Thus, power limits are limits in their classical meaning: with many feasible loading profiles possible. On the contrary, the energy limit is one single shape (trajectory) of loading, enabling the maximal energy transfer through transformer. This fundamental difference affects the way how transformer limits are formulated mathematically. If one takes a power limit then it is necessary to formulate this constraint as an inequality (power flow ≤ power limit). However, for energy limit, one should use an equality constraint (power flow = power limit). Once again, making power flow equal to steady-state power limit became possible thanks to the development of active strategies (flexibilities) in power system. These mathematical formulations explain why steady-state power limits (including DTR) are not the energy limit but they can be used for approximation of energy limit.

Although steady-state power limits can be used for energy limits approximations, there are specific ambient temperatures which does not allow to do that. For instance, Figure 7 shows the optimized energy limit of ONAN transformer for cold ambient temperature in Tomsk in 1 February 2019. The loss of insulation life is equal to 1 pu.

As it is seen from the Figure 7, the optimized shape of energy limit in cold ambient temperature does not correspond to the typical shape of steady-state power limits where HST is quasi-constant. Instead, the energy limit corresponds to the HST shape which follows the logics of Sealey and Hodtum [34]—short operation above rated HST. However, such extreme ambient conditions are rare and therefore typical characteristics of energy limit (expressed by steady-state power limits) should remain valid for most of the time.

Whatever the shape of energy limit is, the HST remains in the vicinity of rated HST as well as TOT is much below TOT limit. Thus, energy limits maximize the energy transfer and simultaneously avoid a high thermal stress of transformers. This brings a particular benefit of energy limits to power systems operation.

3 | ESTIMATION OF ENERGY LIMITS IN DIFFERENT CLIMATES

The estimation of energy limits in different climates allows to obtain characteristics of transformer loading profile, if all

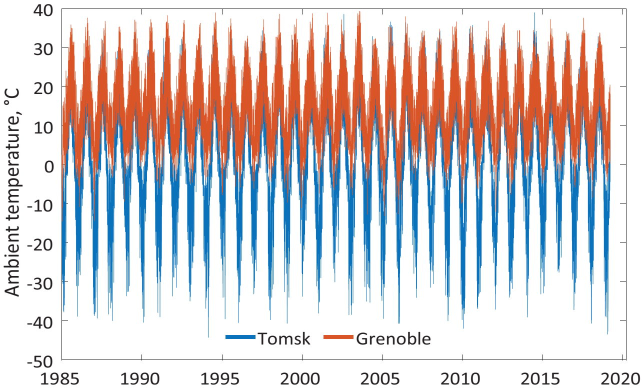

FIGURE 8 Hourly ambient temperature in Tomsk and Grenoble from 1985 to 2019

potential of active strategies (flexibilities) was applied to control its loading. Thus, the energy limit, estimated in this section, should represents loadings of the transformer, operating at its physical limit in the context of smart grids. As we mentioned earlier in Section 1.2, such transformer operation can be beneficial for interconnections, the maximization of RES generation as well as increasing the hosting capacity of distribution networks.

In this section we estimate energy limits of oil-immersed transformers in cold climate of Tomsk, Russia and warm climate of Grenoble, France. Section 3.1 provides initial data and assumptions. Section 3.2 shows the results. Section 3.3 provides a short discussion of limitations.

3.1 | Initial data: Ambient temperature in Tomsk and Grenoble

Firstly, a time horizon should be defined to investigate the impact of the climate on energy limit, if latter depends only on ambient temperature. The climate normal, used in the climate science, states that all weather anomalies in a geographical area can be considered within previous 30 years [103]. In other words, the studied period should be at least 30 years long. That is why, Figure 8 shows a simulated mean-hourly ambient temperature from 01 January 1985 to 29 March 2019 (day of data download) [104].

To retrieve useful information from Figure 8, we convert it to ambient temperature duration curves (Figure 9). The duration curve can show how much time in the past the ambient temperature was higher (or lower) than a design ambient temperature (+20 °C for IEC transformers). For instance, in Figure 9, the real ambient temperature was exceeding a design temperature during 12.4% of time in Tomsk and 22.6% in Grenoble.

To plot a duration curve, one can sort historical values of the ambient temperature in a descending order. The ambient temperature duration (x-axis) is obtained as following:

$$\text{Duration}\,(1:\text{end}) = \frac{N\,(1:\text{end})}{N\,(\text{end})} \times 100\% \qquad (14)$$

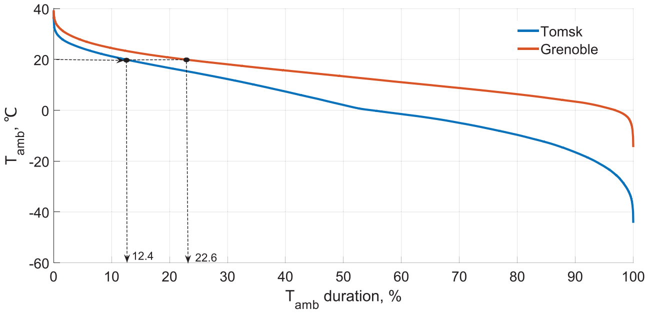

FIGURE 9 Ambient temperature duration curves in Tomsk (Russia) and Grenoble (France)

where N—the array representing a numerical order of ambient temperature values (sorted in a descending order).

To compare energy limits in Tomsk and Grenoble, one should ensure equal conditions. Thus, we assumed that new transformers were installed in 01 January 1985 in both cities. The insulation life of these new transformers is assumed to be equal to 34 years, which is the period of ambient temperature data availability. All transformers have a Kraft paper with a rated HST equal to 98 °C.

From Figure 8, we have 12,506 daily ambient temperature profiles in hour resolution. For each daily temperature profile (or for 34 years), we can solve an optimization problem (Equations 1–13) and find 12,506 daily energy limits (or one energy limit for 34 years). However, solving the optimization problem with 12,506 days can take up to 10 days so we decided to approximate the energy limit by steady-state power limits [96], as we found them admissible to reach approximately the same energy transfer. The power limit for each hour during 34 years is adjusted to keep the transformer operation at rated HST (98 °C). Thus, we obtain a loading curve, representing an energy limit of the transformer in each climate. Energy limits represent a dynamic loading curve having: (1) Maximum, (2) minimum, (3) mean value, as well as (4) duration and (5) energy transfer. Therefore, we use (1)–(5) as metrics to compare the energy limits in two climates. Metrics (1)–(3) are calculated for each month and the energy transfer (5) is calculated for the whole period studied—34 years.

3.2 | Results: Metrics of energy limit in each city

The duration of energy limit loadings is obtained similarly to the curve of ambient temperature duration. Firstly, we found a loading which corresponds to the rated HST for each ambient temperature during 34-year history. Further, the obtained loading array was sorted in a descending order. The resulting duration curves are of specific interest because they define how much of time the loadings of energy limit are higher or less than specific loading. For instance, Figure 10 shows that loadings of energy limit are higher than the nominal loading of transformer for 79% of time in Grenoble and 88.6% in Tomsk correspondingly.

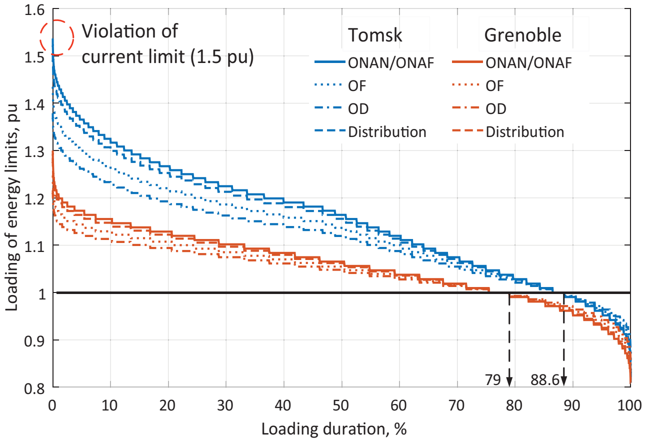

FIGURE 10 Loading duration for all transformers in Tomsk and Grenoble

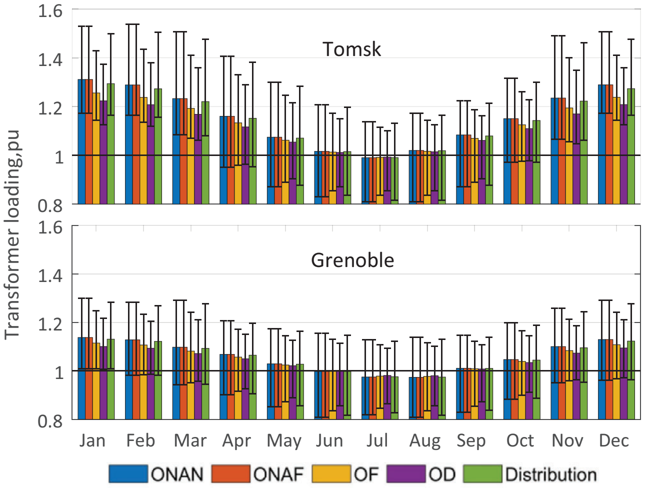

FIGURE 11 Maximal, minimal and mean loadings of energy limits in each month

From Figure 10, we see that the current limit was violated in Tomsk for very small duration of time (because we used approximation instead of optimization). This confirms our suggestion that cold ambient temperature rarely affects typical shape of energy limits. No violation of current limit is found for Grenoble. No violation of TOT limits is detected in both cities. Thus, typical characteristics of energy limits (steady-state power limits) remain always true for Grenoble and most of time for Tomsk.

Notably, the loading duration curve is very similar to the ambient temperature duration curves but twice reflected: horizontally and vertically. If so, the colder ambient temperature, the larger difference between transformers in the energy transfer. The same conclusions can be found if we quantify a typical loading amplitude for each month. Figure 11 shows maximal, minimal and mean loadings of energy limits in each month.

From Figure 11 it is obvious that in summer months the loadings of energy limit in both cities are relatively the same. However, in winter months, the difference can be clearly seen. For instance, in January, the mean loading of energy limit reach 1.3 pu in Tomsk whereas in Grenoble it is only 1.15 pu. Though we used the same transformers, the total energy transfer in both cities is also different (see Figure 12).

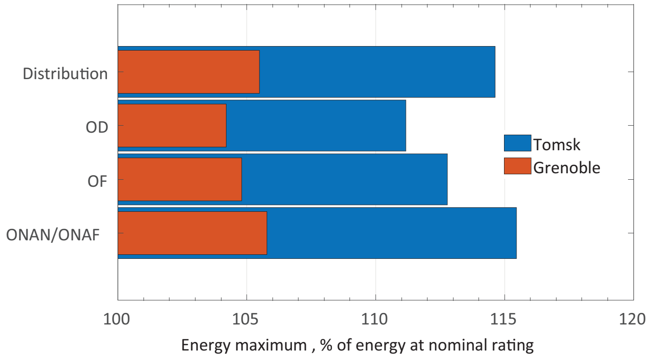

FIGURE 12 Maximal energy transfer through transformers in comparison with energy delivered at constant nominal rating

The maximum of energy transfer is calculated as an integral of loading duration curves from Figure 10. We normalized the energy transfer relatively to the energy, transferred at nominal rating of the transformer. Figure 12 shows that transformers can transfer up to 16% more energy if the transformer loading is equal to the energy limits. Interestingly, if transformers have the thermally-upgraded paper (with rated HST = 110 °C), the total energy transfer can be higher than nominal rating up to 25%.

Such additional energy transfer (16–25 %) can be especially beneficial if transformer is limiting a low-cost generation. Therefore, operating the transformer at energy limit can transfer cheaper energy. This can significantly reduce the energy costs in power systems since they are very sensitive to additional energy production at low-cost generators.

Furthermore, RES generation operators and policy makers can take an advantage of this additional energy transfer (16–25%). The maximization of energy transfer from RES facilities allows to address the climate change and to contribute into decarbonization of the power system operation. Energy limits can be especially relevant for RES maximization if RES transformers are undersized and/or new RES are to be interconnected to the existing transformer.

Last but not the least, a hosting capacity of a distribution network can be increased if knowing the typical characteristics of energy limit (loading profile). The typical energy limit can be analysed together with existing load profile of substation and available flexibility. From this analysis, an operator can make a decision on the interconnection of additional loads and DG and/or procurement of new flexibilities from aggregators to ensure a transformer operation at energy limit.

3.3 | Limitations

This paper is a first attempt, aimed to investigate energy limits therefore the impact of some factors was simplified. For instance, the scope of this paper does not consider: harmonics, unbalancing, short-circuit impact, OLTC operation [51, 67, 105] as well as the effects related to other nature issues as wind speed and direction [106], precipitations [106], solar irradiations [67, 107], and geomagnetically-induced currents [67]. Each of these factors should be considered in relevant situation. For instance, the fast integration of power electronics into electrical network could increase the harmonics which will increase in turn the transformer losses, causing the excessive heating in conductors and other parts. Thus, the harmonics neglection can lead to the underestimation of winding and oil temperatures and thus to the overestimation of energy limits.

Some improvements can be brought to the proposed model concept of energy limit. For instance, due to specific test case in Section 2, the present paper maximizes the apparent energy transfer (i.e. MVAh) which does not necessarily maximize the useful active energy transfer (i.e. MWh). However, application of volt/VAR optimization in distribution network [108] can keep power factors closer to unity and therefore allow maximizing the active energy transfer (i.e. MWh).

In this paper the oil conditions, defined by viscosity, acidity, moisture and oxygen content etc. are assumed to be within normal values [109–112]. However, the deviation from their normal state can negatively affect the energy limits. For instance, the excessive moisture content in insulation-oil system accelerates the insulation ageing [35] and therefore reduces the energy limit. Nevertheless, it is possible to consider the above-mentioned factors if the appropriate transformer thermal model is used.

Thus, the additional research on energy limits is planned to further consider the limitations of transformers and power systems. For instance, we plan to include the modelling aspects of transformer and distribution network, including the effect of losses, volt/VAR control among others.

4 | CONCLUSION

In summary, the energy limit of the oil-immersed transformer is introduced and studied for the first time. Investigations revealed that the energy limit represents the unique loading profile for a given ambient temperature profile. Typical characteristic of this loading profile is that most of the time the transformer operates at quasi-rated winding temperature and in the beginning and the end it increases the energy transfer thanks to thermal inertias of winding. The research also confirmed that in very cold ambient temperature, typical characteristics can be changed. In both cases, the temperatures of energy limit remain in vicinity of a rated HST, making operation of transformer thermally beneficial. Therefore, transformer transfers the maximal energy and avoids a high thermal stress simultaneously.

The quantification of energy limits for the same transformers but in different climates demonstrated that cold climates can facilitate the energy transfer. For instance, in Tomsk the same transformers can transfer up to 10% more energy than in Grenoble, France. Typical duration of energy limit as well as its maximum, minimum and mean loadings are found for each climate conditions. Moreover, it is revealed that in cold climate, current limits can be a constraint. No violation of TOT limit is found. However, it seems that for very hot climate (>+40 °C) TOT limit can also constrain the energy limits. The additional research is required.

The consideration of energy limits accompanied with the use of flexibilities can allow transferring up to 25% more energy through transformers. This additional energy transfer can be advantageous for maximization of energy transfer between operating areas or even countries. Another promising application of energy limit consists in maximization of RES generation. Moreover, energy limits can contribute to increasing a hosting capacity of distribution networks. That is why, our future research will be focused on application of energy limits to the abovementioned problems of a power system.

The scope of energy limits can be extended to other power system components such as overhead lines, cables as well as for synchronous generators, whose energy output depends on ambient temperature.

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