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Sizing power transformers in power systems planning using thermal rating

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ABSTRACT

It has already been shown in the literature that power transformers may be more accurately sized by their thermal limits than by their rated power limit. In practice however, thermal limits are usually considered only in operations; but not at planning stage, where the more usual notion of rated power is used. This paper proposes a novel method to take into account (and benefit from) thermal limits directly at planning stage. This is made possible by quantifying separately the impact of each generator and load on the temperature of the distribution transformer. Decoupling the effect of individual generators and loads is achieved by linearizing and rewriting the analytical expression of the hot-spot transformer temperature. The practical value of the method is assessed using a real-world dataset, by estimating the increase in the hosting capacity of the considered transformer for additional generators and loads. Significant gains are obtained when the transformer is sized by generation, in particular when photovoltaic (PV) generators are involved.

1. Introduction

Distribution transformers and power (HV/MV) transformers are predominant assets in a distribution grid, and sizing them well is a crucial task for distribution system operators (DSOs). When replacing, reinforcing or adding a transformer, DSOs should find a compromise between the high capital cost of oversizing it, and the risks (in terms of endangering the reliability of electrical energy supply) of undersizing it.

The typical steps of a planning study aiming at sizing a transformer are the following. Some assumptions must first be made regarding future loading conditions, in order to generate a set of “extreme” scenarios for load and generation that will be used as stress-tests to size the transformer. For transformers sized by generation (not consumption), a typical example of such a scenario, currently used some DSOs, is to consider that all generators will output their rated power and that the load will reach its lowest possible value [1], while taking into account forecasts of the future evolution of load and generation.

After loading scenarios have been defined, one of the following two categories of methods may be used [2]:

- The first and simpler one is to simply define physical limits, typically on instantaneous active power but possibly on other criteria, and to size the equipment so that these limits are not violated in any of the stress-tests.
- And the second, more elaborate one, is to perform a so-called “lower cost optimization” that aims at finding an economical trade-off between a smaller transformer that will be heavily loaded and undergo accelerated aging and increased losses, and a larger one that will cost more but not suffer from increased aging and losses [3,4,15].

The second method involves estimating the loss of life of the transformer depending on its loading conditions — see for example [5] where the impact of high PV penetration on transformer lifetime is studied, and [6,7] where the impact of Electric Vehicles (EVs) on transformer lifetime is investigated. However, predicting with great accuracy the useful lifetime of a transformer based on its loading condition is currently considered difficult if not impossible [3], and as a consequence this paper will focus on the first method, namely, sizing transformers using physical limits.

The simplest criterion is to never exceed the rated current (or power). It is the method most commonly used by DSOs, and it is used in several recent research papers on the topic of distribution network planning [8,9]. This method may however be too restrictive since even a current peak of short duration above the threshold would be forbidden – although such a peak would actually have little impact on transformer temperature, and thus on aging and deterioration. An improvement over this criterion is thus to use a criterion with thermal limits [3,4,10] (most importantly on the hot-spot temperature), which makes it possible to benefit from the thermal inertia of the transformer, in particularly the thermal inertia of its oil. This criterion is the core of dynamic thermal rating (DTR) and real-time thermal rating (RTTR),

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Nomenclature

Variables

K	load factor (load current/rated current), pu
K_o	smoothed load factor, $= K/(1 + k_{11}\tau_o s)$, pu
K_{th}	thermal load factor, $= K/(1 + \alpha) + \alpha K_o/(1 + \alpha)$, pu
θ_a	ambient temperature, °C
θ_h	hot-spot temperature, °C
θ_{hr}	hot-spot temperature at rated current, °C
θ_o	top-oil temperature, °C
$\Delta\theta_h$	hot-spot-to-top-oil gradient, °C
$\Delta\theta_o$	Top-oil temperature rise, °C

Parameters

k_{11}	thermal model constant
k_{21}	thermal model constant
k_{22}	thermal model constant
R	ratio of load losses at rated current to no-load losses
x	oil exponent
y	winding exponent
α	transformer constant stating the relative influence of K and K_o onK_{th}
γ	benefit from using the thermal criterion, %
τ_o	average oil time constant, min
τ_w	winding time constant, min
$\Delta\theta_{hr}$	hot-spot-to-top-oil gradient at rated load, °C
$\Delta\theta_{or}$	top-oil temperature rise at rated load, °C

two technologies that are studied in Ref. [10–13,16] and that allow to operate a transformer closer to its thermal limit and to extend its useful life. These two approaches have much in common with the method proposed in this paper, with the crucial difference that they do not address planning stage but only operations. The already existing approaches help to monitor the thermal state of the transformer while operating above the nominal power, but they cannot be used in planning stage to size a new transformer with its thermal limits – instead of nominal power. This paper aims at bridging this gap.

This document is organized as follow. A quick study of possible benefits obtained by using thermal limits is carried out in Section 2. Section 3 introduces a way to formalize the commitments that the various distributed generation (DG) owners should take with respect to the DSO in order to enforce the thermal limits. It will be seen that the thermal criterion needs to be linear; so, the model from IEC 60067–7 will be linearized in Section 4.

2. Benefit of a thermal criterion in planning

2.1. Thermal limit and sizing criterion

Currently, transformers are often sized by setting a limit to the maximal RMS current they can tolerate. The corresponding criterion is that the instantaneous current K, here expressed in the "per unit" system, should not exceed the rated current:

$$K \leq 1pu \tag{1}$$

Besides, it is possible to set less constraining limits. According to IEC 60076-7 [3], it is possible to load the transformer beyond nameplate rating while keeping a normal ageing rate of the transformer. To achieve this, the transformer needs to have a "normal cyclic loading", which is a loading complying with the three limits from Table 1.

Three limits are thus defined; one of them is however always less stringent than the other two. Indeed, the difference of temperature limits between the winding hot-spot and top-oil is $120 - 105 = 15^{\circ}C$. In addition, if current exceeds its nominal value, then $\Delta\theta_h \geq \Delta\theta_{hr}$ and $\Delta\theta_{hr} \geq 15^{\circ}C$ for every type of transformers (see Table 2). The winding hot-spot temperature limit is thus always reached before the top-oil temperature limit, and there is no need to study the latter.

So the limits for a large power transformer under normal cyclic loading are a current limit and a hot-spot temperature limit (2).

$$\begin{cases} K \leq 1.3pu \\ \theta_h \leq 120^{\circ}C \end{cases} \tag{2}$$

The limit $K \leq 1.3\,pu$ used here for power transformers becomes $K \leq 1.5\,pu$ for distribution transformers and medium power transformers.

2.2. Presentation of the thermal model

In a planning study, in order to compute the hot-spot temperature θ_h, one may use the model from the standard IEC 60076-7, presented on Fig. 1. In this paper, we take this well-known model for granted; that is to say, it is assumed that the model is accurate and it is used as a black-box, without discussing the physical meaning of the equations and parameters. The important question of assessing the value of the various parameters contained in this model is discussed in [7].

Three temperatures are involved in the model: the ambient temperature θ_a, the top-oil temperature θ_o and the hot-spot temperature θ_h. Parameter $\Delta\theta_o$ is defined as the top oil temperature rise ($\Delta\theta_o = \theta_o - \theta_a$) and parameter $\Delta\theta_h$ is the hot-spot-to-top-oil gradient ($\Delta\theta_h = \theta_h - \theta_o$). Then θ_h can be computed using (3).

$$\theta_h = \theta_a + \Delta\theta_o + \Delta\theta_h \tag{3}$$

The unknowns $\Delta\theta_o$ and $\Delta\theta_h$ each depend on K through an ordinary differential equation given here by its Laplace transform (denoted by $\mathscr{L}$):

$$\Delta\theta_o(s) = \Delta\theta_{or}\mathscr{L}\left\{\left[\frac{1 + K(t)^2 R}{1 + R}\right]^x\right\}\frac{1}{1 + k_{11}\tau_o s} \tag{4}$$

$$\Delta\theta_h(s) = \Delta\theta_{hr}\mathscr{L}\{K(t)^y\}\left(\frac{k_{21}}{1 + k_{22}\tau_w s} - \frac{k_{21} - 1}{1 + (\tau_o/k_{22})s}\right) \tag{5}$$

Table 1
Current and temperature limits applicable to loading beyond nameplate rating for a normal cyclic loading (extract from [3]).

Type of loading	Distribution transformer	Medium power transformer	Large power transformer
Current (pu)	1.5	1.5	1.3
Winding hot-spot temperature (°C)	120	120	120
Top-oil temperature (°C)	105	105	105

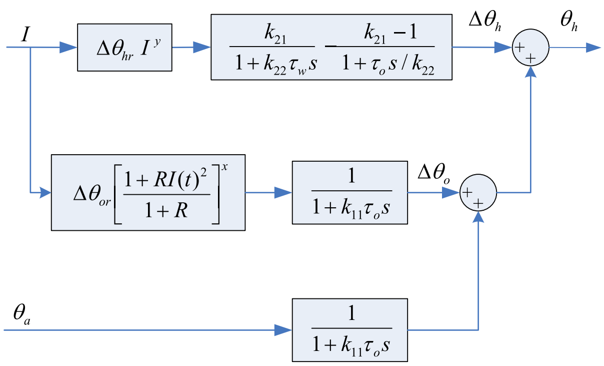

Fig. 1. Block diagram representation of the thermal model.

2.3. Case study: Load, PV, wind

Three examples of currents and temperatures of a distribution transformer are plotted over one day on Fig. 2. In the first case, the transformer is assumed to feed a typical residential load; in the second, it is used to connect a wind farm; and in the last one, to connect a PV farm on a sunny summer day.

The hot-spot temperature θ_h is computed using the IEC model. The ambient temperature is assumed to be constant, $\theta_a = 42^{\circ}C$, which is chosen such that θ_h would reach $120^{\circ}C$ when $K = 1pu$ for a long time. Note that $40^{\circ}C$ is a standard maximal ambient temperature [4,14]. One may notice that the temperature is "smoothed" with respect to current, as current peaks are damped by the thermal inertia of the transformer.

For each example, and by construction, the current K reaches its maximal value according to criterion (1): according to this criterion, the transformer is fully loaded in all three test-cases, and the remaining hosting capacity is zero. However, for the load and the PV curves, and contrary to the wind curve, some hosting capacity margin does remain according to the thermal criterion (2): the red temperature curve does not reach the $120^{\circ}C$ limit. We conclude that for a transformer sized by a typical load or by a PV, criterion (1) may lead to slightly oversizing the transformer. However, for a wind farm (and by extension all plants except PV) there is nothing to gain as the power may remain close to its maximum for a long period.

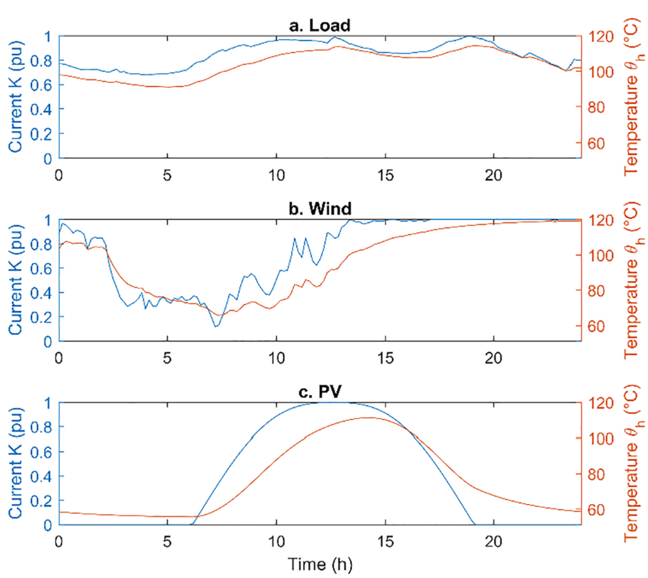

Fig. 2. Evolution over one day of the current of a transformer and its computed temperature θ_h with (a.) a load, (b.) a wind farm, (c.) a PV farm.

2.4. Benefit of thermal criterion for a PV farm

In this section, the benefit of using a thermal limit criterion (2) over a limit on the current criterion (1) is computed. This study is carried out with a dataset of 518 generation curves obtained from real-world measurements over one year for existing photovoltaic generators and using the parameters of two different transformers: an ONAN distribution transformer (MV/LV) and an ONAN power transformer (HV/MV).

The indicator chosen to measure the benefit is the ratio γ between the maximal allowable current using criterion (2) and the maximal allowable current under criterion (1), namely $max(K) = 1\,pu$. For example, if the maximal current using (2) is $K = 1.1\,pu$ then the ratio γ is 1.1, and using the thermal criterion yields a hosting capacity increase of 10%.

The histogram of γ spreads over a wide range of values. Looking into the details of the simulations that yielded extreme values of γ, we observed that the lowest values of γ were obtained for photovoltaic generators whose power output exhibits a clear plateau during sunny days (the power output seems to saturate, possibly because the power converter was slightly undersized with respect to the peak power of photovoltaic modules). Also, Fig. 3 shows that the typical value of the hosting capacity increase, for a pure mix of "normal" PV generators that exhibit no power output saturation, would be in the range of 10 to 40% for distribution transformers, and 2–20% for ONAN power transformers.

In a real distribution system however, PV generators would probably be mixed with other types of generators and loads, solar irradiance would be different from one place to another, etc. These impediments probably explain why the hosting capacity gain associated with thermal limits remains currently untapped: calculating the exact factor by which a given transformer may be overloaded in order to account for its thermal inertia would depend on many local details and prove difficult for planning engineers. The sequel of the paper is thus motivated by the will to find a *practical* way to include the thermal inertia of transformers in planning studies.

3. Thermal Criterion: Limits in practice

To take into account thermal limits in planning study, the hot-spot temperature must be calculated. Two cases are considered as this computation will not be done the same way if the transformer just feeds a local PV plant, or feeds a distribution grid. In the first case, the transformer feeds a pure mix of PV generators, and the transformer

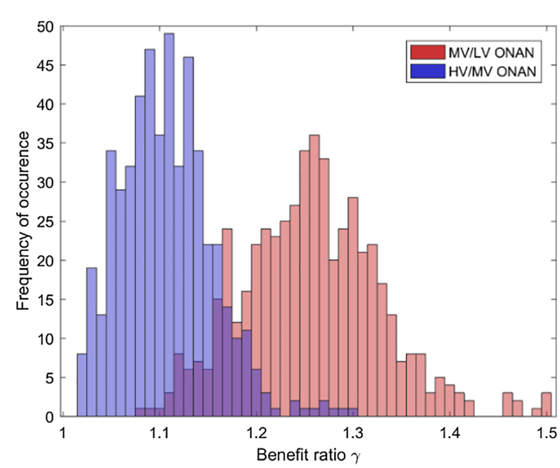

Fig. 3. Histrogram of the benefit of thermal criterion γ for 518 PV.

owner knows every technical detail of the PV plant, which makes planning easier. In the second case, loads and generators are mixed, and the utility company only has access to partial information about the current and future mix of generators and loads that the transformer will serve, which makes planning more complex.

3.1. Transformer feeding a single PV plant

For a local PV plant, it should be possible to forecast the power produced by the plant under optimistic solar irradiation conditions. Then, using measured parameters of the transformer or standard parameters, the IEC model [3] may be used directly to compute the future hot-spot temperature and check whether the transformer reaches its maximum allowed value. The histogram from Fig. 3 gives an idea of the possible benefit for a transformer loaded by solar panels. Provided that the technical details of the transformer and PV plant are accurately known, the only caveat of this approach is that the ambient temperature might be difficult to forecast. Techniques are presented in [4] to tackle this problem.

3.2. Transformer feeding a distribution grid

A transformer in the public distribution network may aggregate a lot of different producers and consumers, who change over time, so it is obviously impossible to forecast the current $K(t)$ that will flow through the transformer over its entire lifetime, with sufficient accuracy to directly compute the temperature using IEC model [3]. As observed above, this is probably the reason why the hosting capacity gains that may be unlocked by using thermal limits at planning stage are currently untapped: DSOs generally do not use the thermal criterion (2) today, but use a limit on rated current or power.

We argue that the current impossibility to use a thermal criterion at planning stage fundamentally results from the following fact: the expression of hot-spot temperature from the IEC model [3], described by Fig. 1, is not proportional to the current. Indeed, with a linear expression, it would be possible to study separately the impact of each generator and load, and then sum up everything to check if the constraint is satisfied. In particular, individual "thermal constraints" could be set to individual customers in addition to their maximum power or current limit, and implementing these individual limits would guarantee that transformer temperature remains acceptable.

In Section 4.3 below, we investigate how a DSO could set a new limit within the grid connection contract of each individual customer. This new limit would be less constraining than the original limit on RMS current or active power. In order to fulfil the new constraint, customers could decide to implement load or generation curtailment, although this would by no means be mandatory.

To get a linear criterion that is equivalent to a limit on the temperature, a 1st order Taylor expansion will be used. The mathematical proof of this criterion and its analysis is the subject of Section 4.

4. Linear thermal criterion

4.1. Calculations to get a simple linear criterion

To get a simpler and linear criterion, calculations are performed and can be separated in three steps (each one is detailed in appendices):

1. The expression of θ_h is simplified and τ_w is neglect, see Appendix A.
2. θ_h is linearized around its nominal working point, see Appendix B.
3. The thermal limit studied is changed to incorporate the ambient temperature θ_a, see Appendix C.

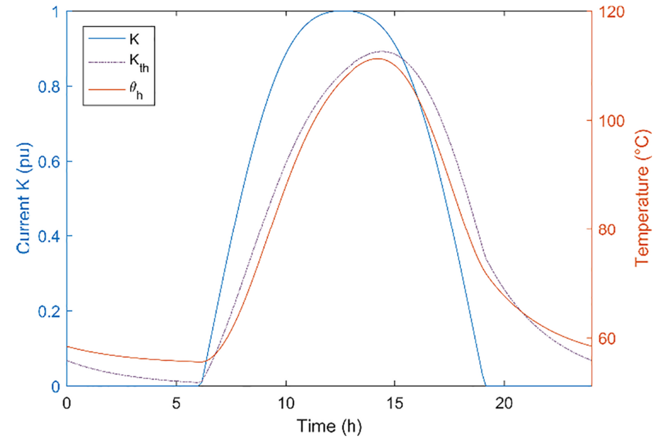

Fig. 4. Variation of the load factor K, the thermal load factor K_{th} and the hot-spot temperature during a PV daily load cycle for a distribution transformer of type "ONAN".

In the end, a new indicator K_{th} defined by (7) is introduced. This new indicator is called the "thermal load factor". The new thermal criterion is (6) which is a replacement of the limit in temperature $\theta_h \leq 120^{\circ}C$:

$$K_{th}(t) \leq 1 \tag{6}$$

In the definition (7) of K_{th}, the new variable K_o is a "smoothed load factor" (subscript "o" stands for oil) defined by (8) and α is a constant specific to the considered transformer, defined by (9).

$$K_{th}: = \frac{1}{1+\alpha}K + \frac{\alpha}{1+\alpha}K_o \tag{7}$$

$$K_o: = \frac{K}{1 + k_{11}\tau_o s} \tag{8}$$

$$\alpha: = \frac{\Delta\theta_{or} x \frac{2R}{1+R} - \Delta\theta_{hr} y (k_{21} - 1)}{\Delta\theta_{hr} y k_{21}} \tag{9}$$

Parameter α expresses the relative weight of both variables K and K_o (see typical values of α in Table 2). Eq. (7) expresses that K_{th} is the arithmetic weighted mean of K and K_o with weights $1/(1+\alpha)$ and $\alpha/(1+\alpha)$, and it should remain below $1pu$ according to (6).

The dynamics of K, K_{th} and θ_h is illustrated by Fig. 4, showing the close dynamic behaviour of θ_h and K_{th}.

In the end, the sizing criterion (2) for power transformers becomes (10) which is called "linear thermal criterion".

$$\begin{cases} K \leq 1.3pu \\ K_{th} \leq 1pu \end{cases} \tag{10}$$

4.2. Interpretation of the thermal model

Three parameters determine the value of using a thermal criterion instead of a limit on instantaneous current:

- Firstly, the shape of loading curve. The longer the current curve stays close to its maximum value, the higher K_o, which is detrimental, the worst-case scenario being that the current remains high for so long that K_o would reach its steady-state value. All benefits of using a thermal criterion would then be lost. This is what happened for a pure mix of wind generators on Fig. 2.
- Secondly, the oil-time constant, or more exactly the product $k_{11}\tau_o$: a

larger time constant makes K_o smoother and is thus beneficial.

- A third crucial parameter is α. It is also determined by the physics of the considered transformer; the higher its value, the more K_o is weighted in K_{th}, which is beneficial.

4.3. The linear thermal criterion in practice

Most importantly, the new thermal criterion is a linear expression, an indispensable property to decouple the study of various loads and generators connected to the transformer under consideration. Indeed, in the common situation where information about the total transformer current K is available as a sum of individual generation and consumption profiles K_i, the individual thermal load factor $K_{th,i}$ may be evaluated separately and then summed to check constraint (10). For further simplification, (10) may be conservatively replaced by (11).

$$\begin{cases} \sum_i maxK_i \leq 1.3pu \\ \sum_i max(K_{th,i}) \leq 1pu \end{cases} \tag{11}$$

For DSOs the latter formulation (11) is even easier to use than (10): to each generator or load, we simply associate a maximum current $max(K_i)$ and a maximum thermal load factor $max(K_{th,i})$, that only have to be evaluated once for each generator separately. Then criterion (11) boils down to summing them; a very quick check that may be sufficient to ensure the absence of a constraint. Another advantage of the decoupled formulation (11) is that it provides a basis on which the behaviour of individual generators could be specified in a contract with the DSO. While it is impractical to contract with all customers as a whole and require them to collectively ensure that constraint (10) will be satisfied, it is much more practical to contract with each generator individually, which is what formulation (11) makes possible.

In practice, computing $K_{th,i}$ would be straightforward and could be a new feature embedded inside a standard smart meter without requiring any thermal sensor. The meter could be set to open its internal circuit breaker whenever constraint (11) is reached, allowing for a practical enforcement of the thermal limit. Observe that this scheme would allow enforcing the global constraint — not overheating the transformer — by coordinating the actions of individual customers *without communication*. This is in contrast with the technology of real-time thermal rating [12,13] where thermal constraints must be managed in real-time; implementing such a scheme requires that some “active resources”, loads and/or generators, are available to the DSO upon request, and thus calls for a communication link with these resources.

4.4. Case study: Transformer sized by generation

A HV/MV power transformer has several feeders. The first is connected to a 10 MW plant with wind generators, the second to a 10 MW plant with PV generators, and all the other feeders are only connected to loads, with a maximal consumption of 15 MW, and an estimated minimal consumption of 3 MW. To simplify, a constant voltage will be assumed so K can be assimilated to a power. Then, the two sizing methods can be compared:

- The current method, based on power limits. Both plants would commit to limit their maximal power to 10 MW. Then the maximal power flowing through the transformer would be $\sum K = 10 + 10 - 3 = 17\,MW$. So a transformer with a nominal power of at least 17 MW would be needed.
- The proposed method, based on thermal limits. The wind plant would commit to a 10 MW capacity on both K and K_{th}, but the PV plant would rather commit to a 10 MW capacity on K and to a 9 MW capacity on K_{th}. The K_{th} capacity would be computed beforehand, based on the time-profile of the power generated by the plant, and on the transformer parameters (given by the DSO). The value of 9 MW is an example value consistent with Fig. 3. Then the power balance gives:
- $\sum K = 10 + 10 - 3 = 17\,MW$ and $\sum K_{th} = 10 + 9 - 3 = 16\,MW$. So, a transformer with a nominal power of at least 16 MW would be enough to satisfy criterion (11).

In the end, 1 MW are gained on the sizing of the transformer by considering its thermal capacity instead of its power capacity. In this example, gains are only linked to the PV generation. Further gains might be achieved, but they are expected to be either negligible, either too complicated:

- The K_{th} of the load might also be taken into account and would potentially be strictly lower (e.g. -3.1 MW instead of -3 MW).
- Criterion (10) would give higher gains than (11), but it would be too complicated, if not impossible, to use in planning studies — this is because as stated above, it does not decouple individual loads and generators.

5. Conclusion

This paper proposes a method to size a power transformer using its thermal limit directly at planning stage. The method relies on the linear criterion (11) which is based on so-called thermal load factor K_{th}. K_{th} is an image of the hot-spot temperature θ_h and its expression has been calculated by linearizing θ_h in the vicinity of its nominal value. The method is dependent on the IEC and IEEE models and its accuracy. The linearity of the proposed criterion is a crucial characteristic in practice, as it allows the DSO to contract with each generator and load individually. A case study gives an example of how to use this linear criterion in practice, and the expected benefits. The proposed criterion can also be used for existing transformer in order to size a new PV installation. The paper also provides several figures on the hosting capacity gains which can be expected by sizing transformers with thermal limits. Benefits are substantial when the transformer is sized by generation including PV, which will be more and more common in the future. In the end, using this criterion would facilitate the installation of low-carbon technologies like PV in locations dominated by generators, as it would reduce the cost induced by transformers.

CRediT authorship contribution statement

Olivier Arguence: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Florent Cadoux:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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