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Dynamic rating assists cost-effective expansion of wind farms by utilizing the hidden capacity of transformers

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ABSTRACT

Dynamic rating of power transmission devices is a technology that allows better equipment utilization through real-time monitoring of the weather conditions and the load. Dynamic rating of transformers is a fairly new technology if compared to the dynamic rating of power lines, and has a high potential for significantly improving component utilization while lowering investment costs on installing new transformers.

The following work investigates how to utilize already operational transformers, which are used for wind farm connection, for expanding wind generation capacity. Also, this paper shows improvements that dynamic transformer rating can bring to both power grid operators and wind farm owners by exploring the economic benefits of expanding wind parks without investing in new power transformers. Connecting additional wind turbines at sites with high wind potential after the wind park is already in exploitation can assist in lowering electricity price and provide a possibility of less risky investment in the wind energy sector. This paper uses transformer thermal modelling and wind farm expansion techniques such as convolution method and product method to investigate to which extent existing wind farms can be expanded using already installed transformer units.

Five transformer locations and nine units are studied for finding the potential of dynamic transformer rating for network expansion applications. The analysis shows that the optimal expansion of wind power from a generator perspective is around 30% to 50%, although, it can be limited further by network restrictions. A possibility to use a large component, such as power transformer, closer to its full potential can provide material and cost savings for building new devices and decrease investment costs on manufacturing, transportation and installation of new units. Dynamic rating of power transformers can also increase the socio-economic benefits of renewable energy by lowering electricity price from renewables and incentivize an increased share of green power in electricity markets.

1. Introduction

Optimal power grid infrastructure, more efficient utilization of materials and energy resources, as well as improved grid planning strategies, play a crucial role in providing cost-effective and sustainable power supply for years to come. While much attention is paid to developments in renewable power generation sector (e.g. wind, solar, hydro and energy storage), it is essential to remember that grid connection infrastructure requires high material and monetary investments. Significant scale power components such as power lines, underground cables, switchgears and transformers will play a crucial role in building a more sustainable power grid and allowing for renewable energy resources to be more competitive on the electricity market.

Power transformers are responsible for a large part of the investment costs and play a key role in power delivery. By using methods that can improve their performance, transformer owners can reduce investment costs when purchasing new transformers, or increase revenue by utilizing already installed transformers closer to their design limits. The maximum loading capacity of a transformer largely depends on thermal limitations, with the winding hot spot temperature (HST) and the top oil temperature (TOT) generally considered the most critical [1]. These temperatures will vary based on weather conditions, and

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Nomenclature

$\Delta\theta_{hr}$	Hot-spot-to-top oil gradient at rated current, [K]
θ_o	Top-oil temperature, [°C]
$\Delta\theta_{h1}$	Hot-spot temperature rise before the effect of changing oil flow past the hot-spot, [K]
$\Delta\theta_{h2}$	is varying rate of oil flow past the hot-spot, [K]
$\Delta\theta_h$	Hot-spot-to-top-oil gradient at the load considered, [K]
$\Delta\theta_{or}$	Top-oil temperature rise at rated losses, [K]
τ_o	Oil time constant, [min]
τ_w	Winding time constant, [min]
θ	Temperature, [°C]
θ_a	Ambient temperature, [°C]
$\theta_{h,r}$	Rated winding hot spot temperature, [°C]
θ_h	Winding hot spot temperature, [°C]
$\widetilde{F}_g$	Load duration curve of generation
A	Arrhenius equation pre-exponential factor, [1/h]
A_r	Rated Arrhenius equation pre-exponential factor, [1/h]
B	Load increase factor
C_i	Net cash flow in period i, [SEK]
C_o	Installation cost, [SEK]
$conv$	Indicates convolution method
$D_{new,t}$	New load at time t, [p. u.]
$D_{old,t}$	Load before expansion at time t, [p. u.]
$E_{a,r}$	Rated activation energy, [kJ/mol]
E_a	Activation energy, [kJ/mol]
g_r	Average-winding-to-average-oil (in tank) temperature at rated current, [K]
G_s	New turbine generation in scenario s, [p. u.]
K	Load factor (load current/rated current), [p.u.]
k_{11}	Correction factor for top-oil time constant
k_{21}	Transformer specific thermal model constant
k_{22}	Transformer specific thermal model constant
LOL	Loss of life, [h]
NPV	Net present value, [SEK]
$p_{g,i}$	Probability of state i of generator g
p_s	Probability of scenario s
R	Ratio of load losses at rated load to no-load losses
r	Discount rate
R_c	Ideal gas constant (8.314 J/(kg·mol))
s	Indicates the type of scenario
t	Time in service, [h]
t_1	is the beginning of a time period, [h]
t_2	is the end of a time period, [h]
V	Relative aging rate
y	Exponential factor of winding

consequently, the same goes for the maximum loading capacity.

Dynamic transformer rating (DTR) is a strategy, which allows extending capacity limits above nameplate rating by estimating the value of transformer's hot spot temperature (HST), based on real-time weather conditions without affecting projected lifetime or increasing the risk of failure [2–4]. The characteristics of wind power, especially its variability in time and low capacity factor, make wind generation a right candidate for DTR implementation. Power transformers that serve for connecting wind parks to the grid are specified for peak generation time and, since wind park rarely operates at its rated power, most of the time these transformers are utilized well below their nameplate capacity limit. Potentially, an implementation of DTR can benefit wind farm owners, since better utilization of this resource can allow either expansion of the existing wind park or choosing smaller transformer size at the specification stage when building new wind farms.

Connecting new wind generation to the grid has a positive influence on the power quality. By increasing number of wind turbines connected to the node, wind farm owners can supply smoother power production by reducing turbulent peaks at higher wind speeds [5–7]. Wind power generation in Sweden represented 10.2% of the total electricity production in 2016, with around 6.4 *GW* installed and a production of 15.4 TWh [8]. Wind power share has significantly increased over the recent years, which is partly explained by fast construction time compared with traditional generation; a 50 *MW* plant can be built within six months [9]. This creates additional challenges for DSOs, which have to provide grid connection for newly installed wind farms rapidly.

Dynamic rating of power lines is a topical research area nowadays, and there exists a high number of various literature resources, which explore dynamic line rating models [10–12], their implementation [13–15] as well as benefits of DLR for wind energy integration [16–19]. However, a field of dynamic transformer rating is depicted in literature significantly less than dynamic line rating and only begins to gain popularity between researchers.

Significant portion of literature resources is devoted to improving thermal models for DTR as is shown in [2,4,20–22] and additional methods for measurement [23] and prediction [24,25 of the transformer's state. A few articles explore the reliability impact of dynamic transformer rating [26–28]. In [29,30], studies focus on the modelling of the thermal parameters for DTR. In [31], sixteen medium voltage transformers are dynamically rated and the predictive potential of DTR is explored. The case study in [32,33] explores loading benefits of DTR and evaluates to which extent transformer can be loaded above the nameplate rating.

Since the accuracy and safety of DTR implementation is highly dependent on weather parameters, it is essential to evaluate how different methods of obtaining real-time information on transformer temperature balance can affect the rating limit. In [34], a probabilistic risk evaluation approach is used to perform a one-step-ahead prediction of dynamic transformer rating using weather forecast. The impact of additional risks and reduced transformer availability brought by application of DTR are assessed in [35–37], concluding that the cost impact is low. A reliability analysis and economic impact of reducing the size of the transformer for wind farm connection is evaluated in [38] [39,40] by performing a case study on already installed wind farm transformer. A transformer thermal behaviour under wind farm load conditions and possible economic impact of overloading the transformer above the nameplate rating are depicted in [41]. Power dispatch optimization and transformer optimal lifetime utilization are addressed in [42]. In [43], the economic benefits of combining DTR with dynamic line rating (DLR) for day-ahead dispatch optimization are shown on a case study for a network with high penetration of wind generation. Additionally, case studies for offshore wind farms are presented in [44,45].

Currently, literature sources explore many important areas connected to dynamic transformer rating implementation, such as transformer thermal models; implementation of DTR; DTR prediction; reliability impact of DTR; economic impact of DTR and case studies on transformers connected to onshore and offshore wind farms. However, even though there is enough information on how to increase transformer ratings, it remains unclear how to integrate DTR into old and new power grids. Partially it is possible to plan new grids with having DTR in place. However, since the lifetime of a single transformer is usually expected to be around 40 years, it would be beneficial to utilize both new and existing components in a better way.

This paper addresses a new niche in the area of dynamic transformer rating - how to use already installed transformers to their full potential. One novel area of particular interest is illustrated in this paper: the possibility of planning the expansions of wind farms with utilizing the capacity of already installed power transformers. Grid connection of wind generation with DTR is an interesting case-study to address and is opening a new area of dynamic transformer rating research.

The present study evaluates the possibility of expanding existing wind farms with additional wind turbines and using previously installed transformers for connecting these additional generators to the grid. An objective is to determine the maximum potential size of wind farm expansion depending on the rate of insulation degradation and transformer's loss of life (LOL). The analysis continues with an estimation of HST's effect on the LOL calculation and wind power curtailment.

A final goal is to provide wind farm owners and system operators with additional knowledge on how they can potentially utilize benefits of DTR for wind farm expansion. Additionally, this study aims to promote better usage of material resources and open possibilities for reducing electricity price for renewable generation by minimizing monetary spendings associated with grid supporting infrastructure.

2. Methodology

2.1. Transformer thermal models and their implementation

The IEC 60076–7 difference equation model [1] is chosen to determine the HST during operation in the present analysis. In the investigation reported in [38], the IEEE Annex G model [46] is also used, with both models leading to similar results and conclusions, with the IEC model requiring less input.

The model is based on the following assumptions: oil temperature rises linearly from bottom to top; the temperature difference between winding and oil is constant along the winding; the winding and oil time constants are static; the oil viscosity is invariable. The model estimates the HST for a period of time based on the load, the ambient temperature, the transformer thermal parameters and the thermal behavior on the previous period of time. The main differential equation describing the top-oil temperature is presented in (1).

$$\left[\frac{1+K^2R}{1+R}\right]^y\cdot(\Delta\theta_{or}) = k_{11}\tau_o\cdot\frac{d\theta_o}{dt} + [\theta_o - \theta_a],\ \ [°C] \tag{1}$$

where K is the load factor, [p. u]; R is the ratio of load losses to no-load losses; y is the winding exponent; $\Delta\theta_{or}$ is the top oil gradient at rated losses, [°C]; k_{11} is an empirical thermal constant; τ_o is the oil time constant, [min]; θ_o is the top-oil temperature, [°C];and θ_a is the ambient temperature, [°C].

The hot-spot temperature rise $\Delta\theta_h$ in (2) is obtained by subtracting the differential equation solution (3) from (4). Whereas, the final hot-spot temperature is obtained with Eq. (5).

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2},\ \ [°C] \tag{2}$$

$$k_{21}\cdot K^y\cdot\Delta\theta_{hr} = k_{22}\cdot\tau_w\cdot\frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1},\ \ [°C] \tag{3}$$

$$(k_{21}-1)\cdot K^y\cdot\Delta\theta_{hr} = (\tau_o/k_{22})\frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2},\ \ [°C] \tag{4}$$

$$\theta_h = \theta_o + \Delta\theta_h,\ \ [°C] \tag{5}$$

where $\Delta\theta_h$ is the hot spot to top oil temperature gradient, [K]; $\Delta\theta_{h1}$ represents the hot-spot temperature rise before the effect of changing oil flow past the hot-spot, [K]; $\Delta\theta_{h2}$ represents the reduction in hot-spot temperature rise due to the varying rate of oil flow past the hot-spot, [K]; k_{21} and k_{22} are thermal model constants; τ_w is the winding time constant, [min]; $\Delta\theta_{hr} = Hg_r$ is the hot spot to top oil temperature gradient at rated current, [°C]; y is the winding exponent; θ_h is the hot spot temperature, [°C].

2.2. Transformer aging estimation

The thermal aging model from the main part of IEC loading guide [1] is used to determine the effect of loading on transformer technical life. The degradation of paper insulation is a complicated process affected by temperature as well as the content of moisture and oxygen. A measure commonly used to determine the quality of the paper insulation, is the degree of polymerization (DP). DP reflects the average number of glycosidic rings in a cellulose macromolecule. The aging process reduces the number of rings, thus lowering paper's mechanical and dielectric strength. In [1], it is stated that a reduction to 35% retained tensile strength, or 200 DP indicates the end of life of the paper insulation. The initial value of the transformer insulation is assumed to be 1000 DP.

The relationship between temperature and aging is modelled with the Arrhenius reaction equation. If a rated condition of aging is defined, the relative aging rate for the paper is calculated using (6).

$$V = \frac{A}{A_r}\exp\left(\frac{1}{R_c}\left(\frac{E_{a,r}}{\theta_{hr}+273} - \frac{E_a}{\theta_h+273}\right)\right), \tag{6}$$

where V is the relative aging rate; A is an empirical pre-exponential value, [1/h]; A_r is rated A, [1/h]; R_c is the ideal gas constant; E_a is the required activation energy, [kJ/mol]; E_{ar} is rated E_a, [kJ/mol]; θ_{hr} is rated HST, [°C]; θ_h is actual HST, [°C]. The main part of [1] proposes values of E_a and A without considering moisture or oxygen content. In that case, $E_a = E_{ar}$ and $A = A_r$, and Eq. (6) is simplified, only becoming a function of hot spot temperature. In an annex of [1], values for E_a and A for different moisture content and paper type are shown. In this investigation, rated HST is assumed to be $\theta_{hr} = 110$ °C.

The LOL over a period of time is calculated with Eq. (7).

$$LOL = \int_{t_1}^{t_2} Vdt,\ \ [h] \tag{7}$$

where t_1 is the beginning of the time period; [h]; t_2 indicates the end of time period, [h]; V is the relative aging rate.

To perform the aging estimation, the HST over time is required. If the transformer is fitted with fiber optic sensors, an estimate of the HST is immediately available, and the LOL can be directly obtained from 7 without further modeling. However, it should be recognized that the location of the real hot spot may be different from the sensor, and underestimate the LOL. [47] The correct location for installation of the fiber optic sensor can be obtained through detailed thermal simulation. [48].

If direct measurements are not available, the hot spot temperature has to be obtained through modeling. The dynamic thermal models described in the standards require the transformer thermal parameters that are measured during the heat run test. For very old transformers, documentation may have been lost, or the heat run test may not have been performed. To fill the gaps in required data, a set of assumptions should be made with consideration of the standards and typical values for transformers with similar characteristics.

The dynamic thermal models also require measurement of ambient temperature and load. If top oil temperature are available it can be used, otherwise it can be calculated by the models. The ambient temperature information is preferably measured on site. For the following analysis weather information is obtained from the neighbouring weather stations and interpolated to match the site conditions using a inverse distance weighted method [49].

Load and temperature data covering the full history of the transformer should preferably be used. If such extensive data is not available, a shorter time period can be used and assumed representative of the time where data is lacking, keeping in mind annual variations and other changes in loading pattern. A high sampling rate, with time intervals shorter than the winding thermal time constant, can yield more accurate results as the dynamic behavior of the load is captured to a further extent. For existing installations, the availability of data is a limiting factor, and the analysis has to be performed based on what is available.

With this inputs and parameters, the IEC thermal model is used to calculate the HST of each time step. Afterwards, the Eq. (7) is used to determine the LOL for the period in question. The expected lifetime before expansion is calculated based on the assumption that the aging will behave in the same way for the upcoming years.

2.3. Wind farm expansion calculation

The study is centered on the expansion of existing wind farms, therefore a the load expansion modeling is required. Adding a constant load to the existing base generation is not possible as it would overestimate the stress on the transformer. A way to model the load based on the characteristics of wind speed in the area is proposed. The load expansion considers two methods: the product method and the convolution method. The product method assumes that the new added generation has perfect correlation with the existing generation. Therefore, the load for the expansion scenarios is the registered load multiplied by an expansion factor, as shown in Eq. (8).

$$D_{new,t} = B \cdot D_{old,t}, \quad [\text{p. u.}] \tag{8}$$

where $D_{new,t}$ is the new load at time t, [p. u.]; B is the load increase factor; and $D_{old,t}$ is the load before expansion at time t, [p. u.].

The convolution method assumes that the new wind turbine generates power without any correlation with the existing generation. The load duration curve of wind generation can be discretized in a step function, in which each step has a generation G_s and a probability p_s [50]. For this study, the load duration curve of the new generation is a fit of the historic wind speed measurements to a Class 1 wind turbine at 100 meters above curve. The load duration curve is divided into five scenarios using a forward selection method to reduce the computational burden. The generation of each scenario is simplified as

$$D_{new,t,s} = D_{old,t} + B \cdot G_s, \quad [\text{p. u.}] \tag{9}$$

where $D_{new,t,s}$ is the new load at time t for scenario s, [p. u.]; and G_s is the generation in scenario s, [p. u.].

For each scenario, the corresponding calculations are made and the final result is calculated by multiplying the scenario result with the corresponding probability. The LOL using the convolution method is then obtained by (10).

$$LOL_{conv} = \sum_{i}^{N_g} p_s \cdot LOL_s, \quad [\text{h}] \tag{10}$$

where LOL_{conv} is the LOL for the convolution method, [h]; p_s is the probability of scenario s;LOL_s is the calculated LOL for the load in scenario s, [h].

The validity of the assumption of no correlation between the wind power sites depends on the distance between them. For reference [51] is shown that there is correlation between wind power sites at 500 km distance or more. For intermediate distances, a superposition of the result of the product method and the convolution method can be used.

1. the minimum lifetime of the transformer is estimated;
2. the LOL is calculated for a specific year and it is assumed that during the rest of operation, the LOL will follow similar behavior;
3. since aging is an accumulative process, the amount of aging for each year is added up to the rated value of 20.5 years of equivalent aging.;
4. an increase of 0.05 p. u. of the nominal capacity of the transformer is done for four different maximum HST limits: 110 °C, 120 °C, 130 °C and 140 °C;
5. if the maximum HST is surpassed or the current in a period of time surpasses the maximum allowed value, curtailment is required.

The analysis described above yields three main results:

- the minimum load increase at which curtailment is required;
- the load at which the expected lifetime is 50 years that is the maximum monetization age for Energimarknadsinspektionen (Swedish Energy Markets Inspectorate);
- the curtailment at the latter result

A limit of 2.0 p. u of the installed capacity is set. Furthermore, the limitation on current from [1] for Medium Power Transformers is enforced strictly so that the load never exceeds 1.5 p. u. This means that if the installed capacity goes beyond 1.5 p. u, curtailment will occur at maximum power generation. The limitation on current reflects that there are temperature limits apart from the winding hot spot that may be exceeded at high loading, e.g. temperature limits on bushings and tap changers. If the transformer is appropriately designed for high loading performance, then this limitation on current can be increased, and further wind power expansion may be possible.

The HST limits are set to 110 °C, 120 °C, 130 °C and 140 °C motivated by the long term emergency limits. The transformer can operate at HST up to 140 °C without any operation hinder except for an accelerated insulation aging. Given the load factor and generation profile of the wind farm, increasing maximum allowable HST can increase the efficiency of the transformer and give more flexibility for grid connection.

2.4. Single node analysis

A single node analysis is performed to determine the optimal wind farm expansion rate. The time horizon of 25 years is selected as the projected wind farm lifetime. The objective of optimization is to maximizes the net present value (NPV) from the generator perspective using (11). A generation for every year is assumed to follow the same pattern as a base year and it is monetized using hourly electricity price. This analysis evaluates benefits of using DTR for wind farm expansion for the electricity network by evaluating the difference between the income from electricity export and the cost of electricity import. Wind power is assumed to have no variable costs and the curtailment is assumed to not be monetized. The load is considered to increase in three scenarios.

$$NPV = \sum_{i=1}^{t} \frac{C_i}{(1+r)^i} - C_o, \quad [\text{SEK}] \tag{11}$$

where NPV is the net present value, [SEK]; i is time of cash flow (number of the period); t is the total number of periods (i.e. 25 years in this analysis); C_i is the net cash flow during period i, [SEK]; r is the discount rate; C_o is the cost of installation, [SEK].

The information from the single node analysis is required to determine the economic feasibility of including new generation from a wind park owner perspective. Additionally it gives insight on the transformer as an stand-alone apparatus.

2.5. Network limitations

The third stage considers the network limitations. Wind power curtailment is allowed, if the maximum transmission capacity of any component in the network is surpassed. For this study, a DC power flow is used for simplification of the analysis. Thereby, the voltage and reactive power supply are not considered in this analysis. The limits defined during stage 1 and 2 are being applied also during 3rd stage to reduce the computational time. The time horizon, demand, prices, and generation are kept same as in stage 2.

Stage 3 is done using following logic:

1. a transformer is selected;
2. if there are on-site temperature measurements, they are used for calculations. Otherwise, the information from the previous time period is used;
3. the maximum load is set using the thermal model so that the HST in the next period is bellow the maximum allowed HST;

4. the expected load for a given period is obtained;
5. if the expected load is larger than the maximum allowable load, wind generation curtailment is allowed;
6. a DC power flow is performed to determine, if there are power violations in any component
7. if there are power violations in any of the components, curtailment is done until limits are not breached;
8. a new estimated aging is calculated and the values are stored for the next hour calculation;
9. this process is repeated for the number of expected years of wind farm operation;
10. an optimal wind park expansion and the benefit for society are calculated under given constraints.

2.6. Model validation

The study is based on historical values and there is no guarantee that the estimations will reflect the actual aging of the transformer in the 25 year spam. Thereafter, it is important that proper monitoring is performed during the implementation to reduce the risk of implementation and validate the proposed method. A first stage implementation is to determine if the paper insulation degradation of the transformers in operation yield similar results as the model; this can be done by estimation on the degree of polymerization of paper. Additionally, it is recommended that periodic oil sampling and temperature measurements are performed to determine any possible hazards from the implementation. The oil samples can be part of the regular maintenance campaigns of the substation.

3. Case study

This study is performed for a population of nine transformers distributed around 5 locations in Sweden. The transformers are listed in Table 1. The power level of transformers under investigation ranges from 12 *MVA* to 100 *MVA*. None of the transformers have been fitted with fiber optic sensors during the heat run test. The load duration curve for one transformer at each location is presented in Fig. 1. The ambient temperature data is retrieved from SMHI [52]. Since there are no weather stations located directly at the transformer's location, all the active weather stations in a radius of 55 *km* from the transformer's geographical location are used for ambient temperature and wind speed estimation. The hourly load data for transformers is available from February of 2017 until November of 2018.

For the single node analysis and the network analysis, a 50 *kV* subtransmission network in south of Sweden is analyzed. There are three additional wind parks with a total installed capacity of 36 *MW*. The system has an aggregate load of 92 *MW* and is connected to the grid with two parallel 130/50 *kV* transformers. The used parameters for the analysis for the upcoming 25 years are shown in Table 2.

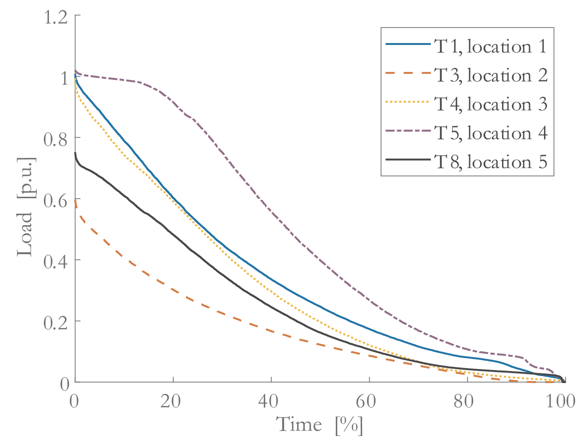

Fig. 1. Load duration curve of some relevant studied transformers.

Table 2
Parameters for the single node and network analysis.

Voltage level	50 kV
Additional wind power	36 MW
System installed demand	92 MW
Load shape	Nordpool SE4 price zone 2018 [53]
Low demand scenario	95% of 2018 load by 2030 89% of 2018 load by 2050 [54]
Base demand scenario	110 % of 2018 load by 2030 120% of 2018 load by 2050 [54]
High demand scenario	126% of 2018 load by 2030 151% of 2018 load by 2050 [54]
Electricity price	Nordpool SE4 price zone 2018 [53]
Electricity price increase	1.5% as average producer price index of the last 10 years [55]
Onshore installation cost	1800 USD/kWh [56]
Discount rate	6.75% [57]

3.1. Implementation of the methodology

The implementation of the method can be considered in four different stages. This are to be implemented to the population of studied transformers. The first stage is to model the expected aging of the transformer based on the gathered historical load and temperature information, and the thermal characteristics of the apparatus. This way it is possible to make an early assessment of the degree of utilization of the transformer. The next stage is to make an assessment of the transformer based on the gathered data, using the transformer aging estimation described in 2.2. Afterward load increase scenarios are developed to determine the load limit of each transformer based on the expected lifetime of the transformer. In the third stage the effect of the curtailment is considered from an economic perspective via the one node analysis. The final stage considers network restrictions which limit even further the possibility of expansion without having additional investments in the network.

Table 1
List of investigated transformers with parameters for dynamic modeling.

Unit	Location	Rated power, [MVA]	Cooling mode	R	$\Delta\theta_{or}$, [K]	g_r, [K]	H	τ_o, [min]	τ_w, [min]
T1	1	63	ONAF	11.35	55.6	12.5	1.3	146	4.2
T2	1	63	ONAF	11.35	55.6	12.5	1.3	146	4.2
T3	2	12	ONAN	6.872	52.1	10.4	1.3	210	10
T4	3	100	ONAN	6	56	20	1.3	210	10
T5	4	25	ONAN	7.22	56	20	1.3	210	10
T6	4	25	ONAN	7.22	56	20	1.3	210	10
T7	5	16	ONAN	7.27	51.6	15	1.3	210	10
T8	5	25	ONAN	5.53	51.2	12.3	1.3	210	10
T9	3	100	ONAF	7.481	52.4	15.154	1.3	150	7

4. Results and discussion

4.1. Effect of the wind farm expansion or load increase on the aging of transformer

The load duration curve to be used for the convolution method is shown in Fig. 2. It is obtained from fitting the calculated historic wind speed measurement from the site to the wind turbine power curve.

In Table 3 is presented the relative aging rate of the population of transformers under the measured loading conditions. A value of 100% would indicate that the transformer insulation would reach end of life after 50 years. None of the investigated transformers are close to this limit. The difference in the expected aging of the transformer is explained by the difference in the load in the studied period. There is a direct correlation between the capacity factor and the aging of the transformer.

Three distinct groups of transformer aging performance can be recognized. The first group, corresponding to locations 1 and 3, are loaded up to the nameplate rating and has a capacity factor of about 30%. The second group, corresponding to location 4, are likewise loaded up to the nameplate rating but with a higher capacity factor of about 50%. Finally, the third group, corresponding to location 2 and 5, have a capacity factor of 30% or less, and are loaded below the nameplate rating. If a transformer has a lower load due to redundancy in the network, dynamic rating may still be applicable, but to a lesser extent than the present results indicate.

Fig. 3 shows the curtailment of the wind generation (Fig. 3(a)) and corresponding transformer loss of life (Fig. 3(b)) as an hourly percentage of the nominal capacity for T1, which is obtained using the product method for calculating projected wind power generation. The curtailment does not occur for load increase below 1.2 p. u. for any value of maximum allowable HST. The higher the limiting temperature is, the less curtailment the system will experience. Fig. 3(b) shows that the lower maximum allowed HST is, the lower is the aging rate and corresponding transformer's loss of life. The marginal aging rate for new load is higher for higher HST limit. A load increase of 1.65 p. u with HST limit of 140 °C has an expected lifetime below 20.5 years, whereas a load of 1.6 p. u. yields a lifetime of 45 years, which should in theory satisfy wind parks with 20–25 years projected lifetime. However, it is important to mention that 45 years projected lifetime can still possess risks to the wind farm investment, since the impact of higher HSTs on other parts of the transformer are not a part of this analysis.

The results for the convolution method of wind park expansion are shown in Fig. 4. Similarly to the product methods, Fig. 4(a) shows that the lower the HST limit is, the higher the wind power curtailment is required. With the convolution method, there are fewer load curtailments compared to the product method; the reason for this is because the load is increasing uniformly and does not accentuate the peaks of generation as in the product method. The interval between curtailments is similar for both expansion methods. Fig. 4(b) shows the loss of life for transformer after expanding wind park using the convolution method, aging rate is higher for the conservative limits compared to the product method, but is significantly lower for HST = 140 °C compared to the product method. Convolution method allows increasing the generation by further extent compared to the product method due to the smoothing effect created by new generation units. A limit of 1.8 p. u. of load increase is set for the HST = 130 °C case, whereas the HST = 140 °C case limit is increased up to 1.65 p. u.

Three limits are considered for the study: the load point increase at which first curtailment occurs, the point at which the expected lifetime of the transformer is 50 years, and the curtailment in that period of time. This values are presented in Table 4 for the product method. A higher maximum allowed HST causes that the first curtailment occurs at a higher increase level. This impacts the management of the units as there is no need of in detailed monitoring and scheduling when there is no curtailment. When the limit is set to 110 °C, the lifetime limit is not surpassed due to the load variability and the load ambient temperatures. As a trade back, there are higher curtailments. With an increase in the maximum allowed HST, the maximum load in the transformer is reduced. The three transformer groups can also be analyzed. The heavily loaded transformers have curtailment over 20% when the maximum HST is 110 °C and the load at which the maximum expected lifetime is 50 years is less than the first curtailment. The second group has the first curtailment between 1.25 and 1.55 p. u. and the curtailments when the curtailments when the load is doubles is between 4 and 7% of the base capacity. The third group is lightly loaded, present little or no curtailment independent of the maximum allowed HST, and the expected lifetime is not reached when the load is doubled.

Table 5 shows the points of interest for the convolution method. The effect of a higher maximum allowed HST is the same and the expected lifetime is greater than 50 years when it is 110 °C. With the convolution method, the curtailment is reduced but the load for reaching the expected lifetime of 50 years is less. The product method gives worse results for heavily loaded transformers, whereas set stronger limits to lightly loaded transformers. This can be explained by the normalization nature the convolution method has.

Fig. 5 has the maximum wind power that could be added to an existing wind park transformer if the expected lifetime of the transformer is above 50 years. When the limit is set to 110 °C, the lifetime limit is not surpassed due to the load variability and the load ambient temperatures. With an increase in the maximum allowed HST, the maximum load in the transformer is reduced.

Similarly to the previous case, the safety correction significantly reduces additional expansion capacity of the transformer. The curtailment in Fig. 6 at this level is reduced for higher HST limit. The dispersion in lower HST is greater than in higher HST. There is a clear trade-off between curtailment and lifetime, that is explored in the following subsection.

4.2. Single node analysis

Since the transformers T5 and T6 behave differently from the rest of the population as they have higher load capacity, shown in Table 3, they have been selected for single node analysis; other transformers in population have significantly higher remaining lifetime and are expected to yield more promising results compared to T1 and T5. Fig. 7 shows the revenue of adding more generators to an existing wind park; the blue lines represent the maximum aging based on the analysis of Section 2.3. For T1, there is a linear increase in revenue up to 1.2 p. u. independently of the maximum allowed HST. After the thermal limit is surpassed, curtailment is required and an increase in the installed wind

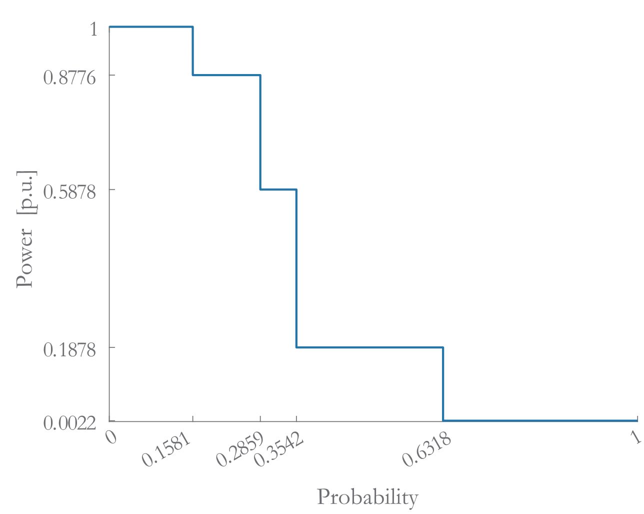

Fig. 2. Load duration curve for the new generator in T1.

Table 3
Estimated remaining lifetime of the population of transformers without HST correction and a maximum allowed HST of 140 °C.

Unit	Location	Capacity factor, [%]	Relative aging rate, [%]	Rated power, [*MVA*]	Maximum load, [p. u.]	Product method load, [%]		Convolution method load, [%]	
						Without curtailment	At 50 years insulation lifetime	Without curtailment	At 50 years insulation lifetime
T1	1	33.25	0.269	63	1.0086	145	160	145	165
T2	1	33.12	0.269	63	1.0195	145	160	145	165
T3	2	16.57	0.005	12	0.5970	200	200	195	200
T4	3	29.47	0.198	100	0.9939	150	160	150	165
T5	4	47.43	5.258	25	1.0202	130	125	130	135
T6	4	47.64	4.873	25	1.0139	135	130	135	130
T7	5	22.54	0.025	16	0.8345	185	200	175	200
T8	5	24.58	0.018	25	0.7524	200	200	180	200
T9	3	27.75	0.112	100	0.9910	155	170	155	165

power is not reflected equally by revenue. The transformer's lifetime is also limited to be more than 50 years. For T1 the maximum revenue is obtained after load is increased by 50% and a maximum allowable HST is 130 °C, and for T2 maximum revenue happens for combination of load increase up to 1.4 p. u and the limiting HST equal to 120 °C. The maximum revenue for T1 is larger as it requires less curtailment. For both cases, there are no curtailment due to over-current.

The loss of life for T1 and T5 is shown in Fig. 8. The loss of life is significantly increased for both transformers, but the lifetime is still limited to a minimum of 50 years; this is indicated by the horizontal lines which are the result from the wind farm expansion calculations. The transformers are utilized in a more efficient way as the monetization lifetime is lower than the expected technical lifetime. Analysing Fig. 7 and 8 it is possible to conclude that the load increase up to 1.35 p. u. and HST limit of 130 °C give the most significant revenue increase while maintaining lower rate of LOL.

If the export of energy is represented as an income and the import is represented in a form of cost, the revenue can be calculated as the difference between export and import. Fig. 9 shows the imports and exports for a maximum HST of 110 °C and the three load scenarios. Low loads allow higher energy exports and reduce the energy cost. Additionally, an increase in wind power generation reduces the amount of imported energy in the same proportion. The cost of energy is reduced with the further incorporation of load.

4.3. Network analysis

Fig. 10 shows the expected revenue and LOL for T5, when the wind farm expanssion is also limited by the grid restrictions. The revenue starts decreasing after 1.15 p. u. compared to 1.2 p. u. for single node analysis. The effect is not exclusively due to HST limitations, compared to the single node analysis, and is explained by the network limitations. The revenue decrease occurs during time periods of low electricity demand and high generation from wind. The maximum revenue is achieved at 1.35 p. u and is 25% more than the original capacity. The expected lifetime is kept above the 50 year limit.

Fig. 11 shows the wind farm curtailment for scenarios of low, base and high power demand and two maximum allowed hot spot temperature levels: 110 °C in Fig. 11(a) and °C in Fig. 11(b). The low demand scenario requires more curtailment since it brings more stress into the network. The base and high demand scenario have similar behavior. Additionally, the maximum allowed HST has a significant effect on amount of curtailment, which is also reflected by the total revenue. The curtailment are more common at a lower generation level compared to the single node scenario.

Table 6 represents the cost reduction for the system compared with the installed capacity. An increase in the installed capacity has a positive impact on society, especially in the low demand scenario. The effect of increasing the maximum allowed HST is important at higher load levels and is related to the curtailment of power. The effect comes mainly from energy export rather than a reduction of energy input, as the latter occur for lower wind speeds.

Each stage of the wind park expansion method increases the restriction on the systems, thus reducing the allowed capacity of the network. Determining the point, at which the first curtailment occurs, is important, because it is a point where the wind power must be monitored, affecting the operation of the transformer and generation in the control center; allowing higher transformer HST reduces the need for monitoring, but increases the loss of life of transformer insulation and creates additional risks for transformer operation. Nevertheless, it is better to have on-line monitoring of the temperature in the transformer to have an accurate estimation of the aging. Moreover, the reduction of

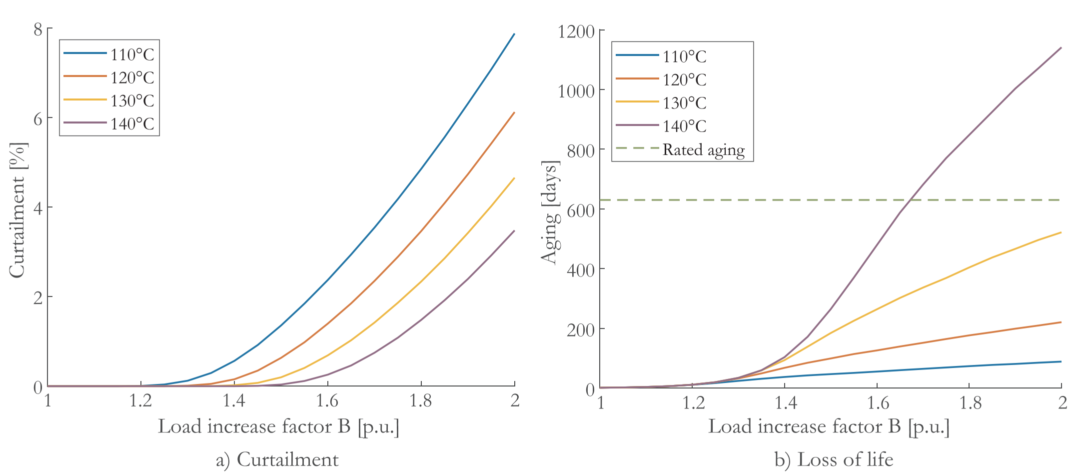

Fig. 3. Curtailment (a) and LOL(b) for an increase of load by a factor B for the studied period.

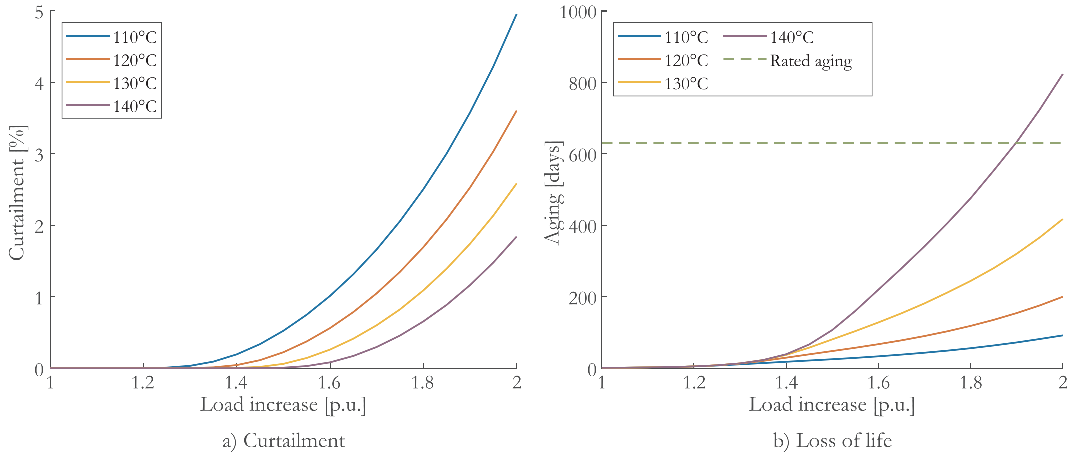

Fig. 4. Curtailment (a) and aging (b) for the convolution method for the studied period.

Table 4
Load at which there is the first curtailment of power, load at which the expected lifetime is around 50 years and curtailment for the latter for two maximum HST limits, for the product method.

Unit	Load First Curtailment, [p. u.]		Load lifetime 50 years, [p. u.]		Curtailment lifetime 50 years, [%]	
	110 °C	140 °C	110 °C	140 °C	110 °C	140 °C
T1	1.25	1.5	2	1.55	6.60	0.04
T2	1.25	1.5	2	1.55	6.60	0.04
T3	2	2	2	2	0	0
T4	1.25	1.55	2	1.6	5.57	0.04
T5	1.05	1.3	2	1.2	23.59	0
T6	1.1	1.35	2	1.25	23.50	0
T7	1.55	1.85	2	2	1.15	0.20
T8	1.85	2	2	2	0.16	0
T9	1.3	1.55	2	1.7	4.59	0.22

Table 5
Load at which there is the first curtailment of power, load at which the expected lifetime is around 50 years and curtailment for the latter for two maximum HST limits, for the convolution method.

Unit	Load First Curtailment, [p. u.]		Load lifetime 50 years, [p. u.]		Curtailment lifetime 50 years, [%]	
	110 °C	140 °C	110 °C	140 °C	110 °C	140 °C
T1	1.25	1.5	2	1.7	4.04	0.02
T2	1.25	1.5	2	1.55	4.04	0.02
T3	1.7	1.95	2	2	0.42	0.01
T4	1.25	1.5	2	1.65	5.81	0.05
T5	1.05	1.3	2	1.3	14.33	0
T6	1.1	1.35	2	1.35	11.47	0
T7	1.5	1.75	2	2	0.97	0.23
T8	1.65	1.8	2	2	0.7	0.19
T9	1.3	1.55	2	1.7	4.68	0.21

the safety margins for the HST calculations might increase the capacity of the transformers even further.

Single node analysis performed for two transformers with lowest remaining lifetime in the population still has shown increase in revenue and possibility to load transformers up to 1.2–1.4 p. u. of the nameplate rating, while maintaining LOL below 5 days per year. However, after considering network limitations maximum capacity of the transformer is reduced to 1.1–1.25 p. u. while maintaining low aging rate. Scenarios of increased power demand allow to increase power delivery, minimize wind power curtailment and increase the revenue.

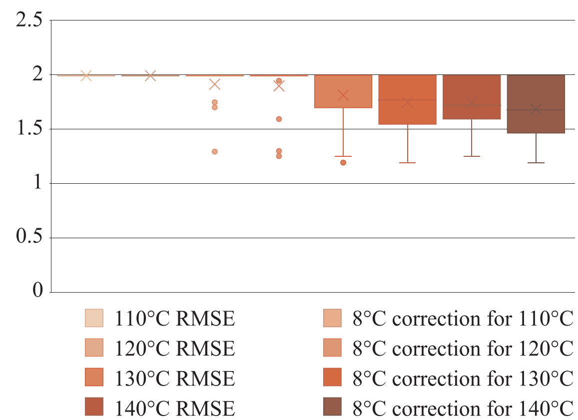

Fig. 5. Load at which the expected aging is around 50 years. RMSE represents the HST correction due to errors in ambient temperature estimation. 8 °C represents the correction due to HST model underestimation.

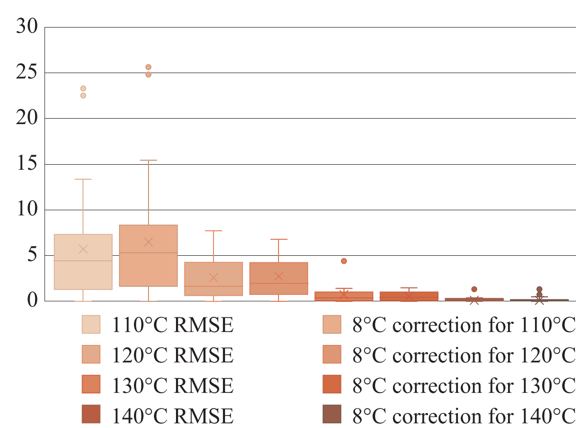

Fig. 6. Curtailment for the load in Fig. 5. RMSE represents the HST correction due to errors in ambient temperature estimation. 8 °C represents the correction due to HST model .underestimation.

5. Conclusion

Dynamic transformer rating has the potential to assist grid operators and wind park owners in providing faster grid connection for new wind turbines. Also, DTR gives an opportunity to use good wind sites to their full potential by installing more wind turbines where it is feasible with no extra cost for building necessary grid connection.

In the presented work, authors have studied the possibility of

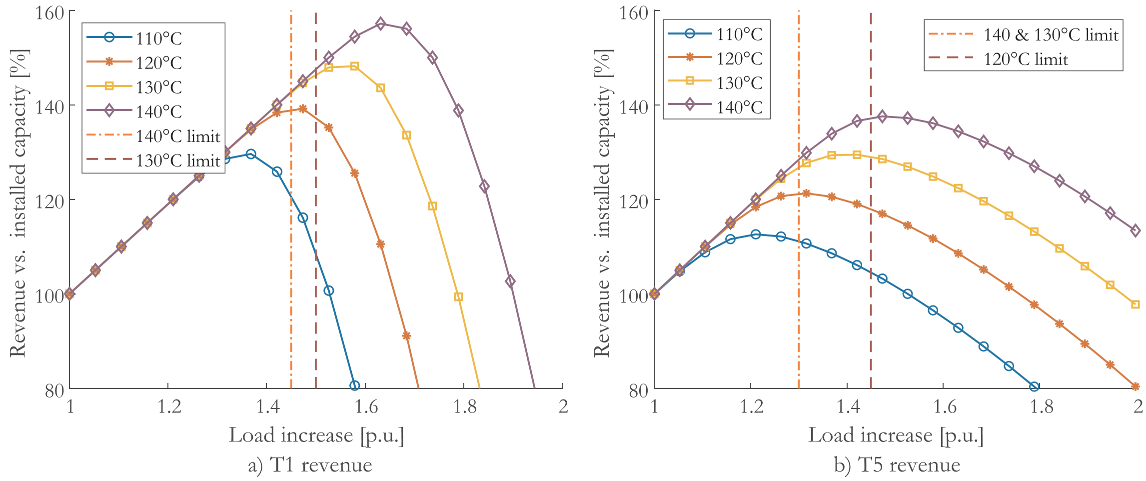

Fig. 7. T1 (a) and T5 (b) revenue in the single node study.

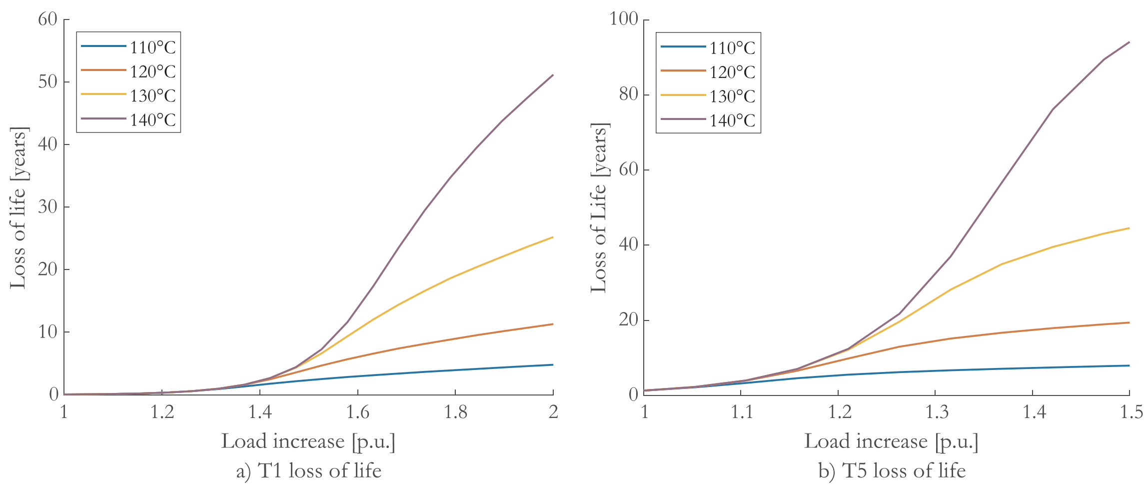

Fig. 8. $T1$ and $T5$ LOL in the single node study.

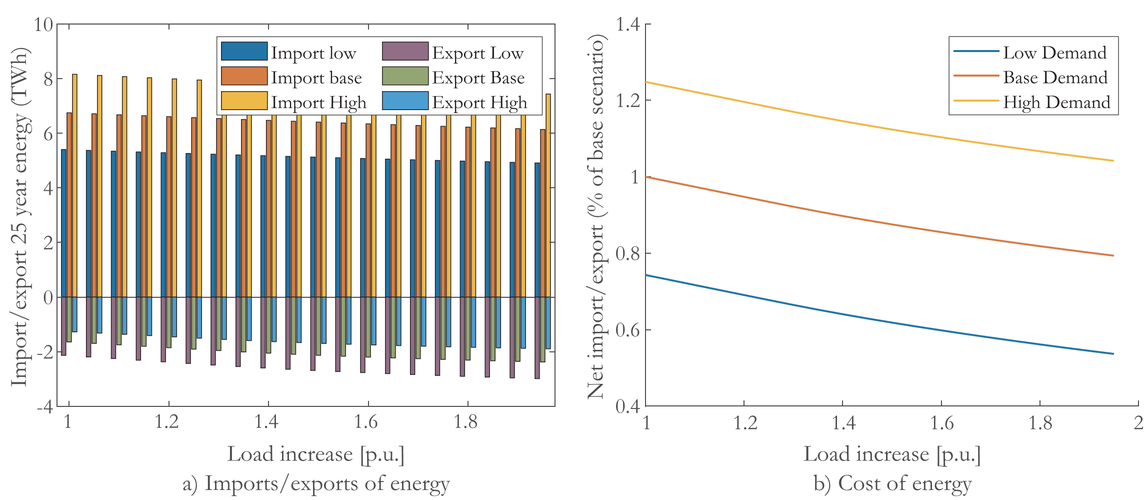

Fig. 9. Imports and exports (a), and cost of energy (b) of the single node analysis. The analysis is done for a HST of 110 °C and it is assumed that the reference case is a transformer with rated installed capacity and the base load increase scenario.

expanding existing wind parks without investment in new transformers, while maintaining the expected technical lifetime of the transformer above their economic lifetime. Five transformer locations and nine units have been studied for finding the potential of dynamic transformer rating for network expansion applications. The analysis shows that the optimal expansion of wind power from a generator perspective is around 30% to 50%, although, that can be limited by further restrictions to the network. It is important to note that loss of life estimation remains to be of high importance and is combined with high uncertainty. Therefore, the transformer's loss of life brings additional

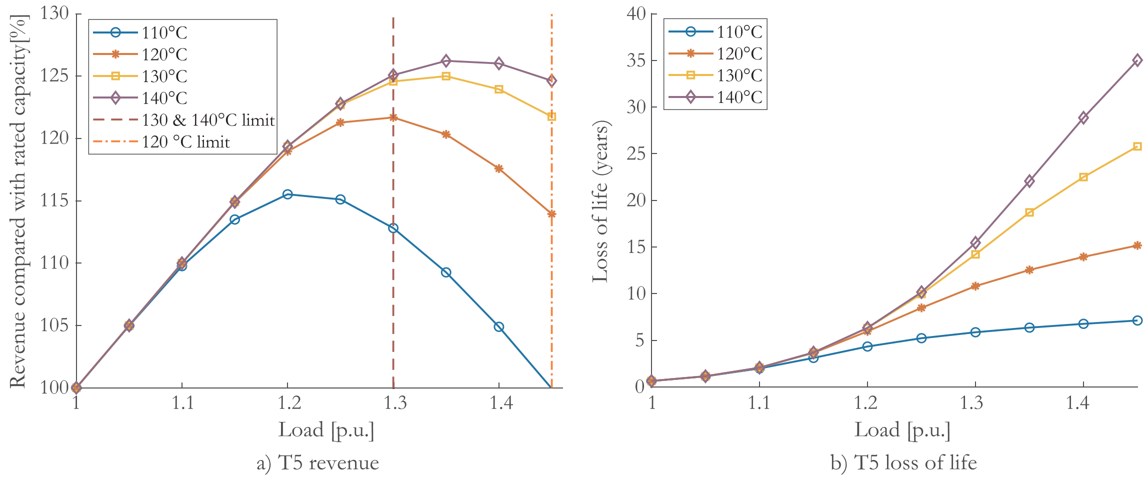

Fig. 10. T5 revenue (a) and LOL (b) for the network study for the base scenario.

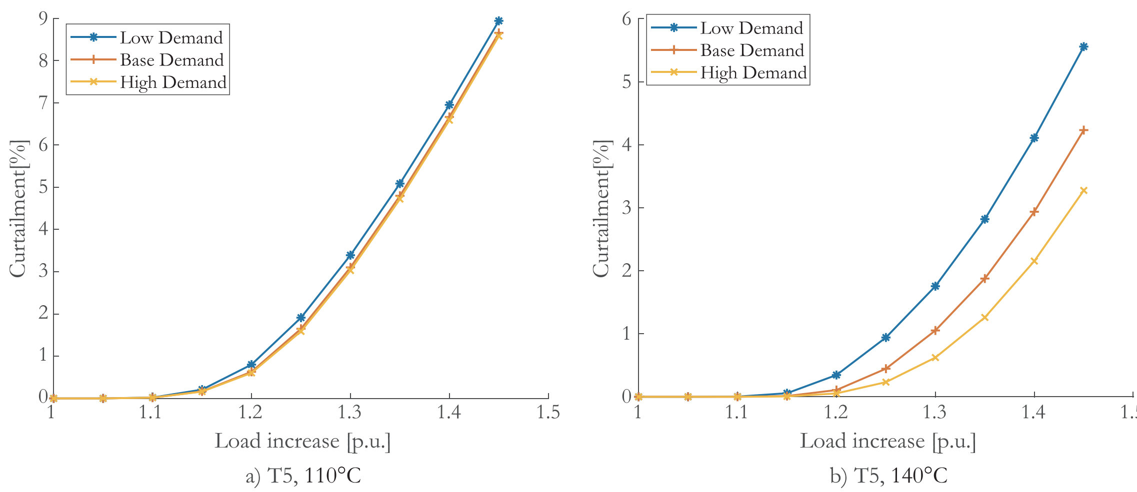

Fig. 11. Curtailment in the network scenario and transformer T5. Maximum HST = 110°C (a) and maximum HST = 140°C (b).

Table 6
Cost of energy for the 25 year period as a percentage of the system without wind park expansion for the network analysis.

	Low Demand				Base Demand				High Demand			
Load	110 °C	120 °C	130 °C	140 °C	110 °C	120 °C	130 °C	140 °C	110 °C	120 °C	130 °C	140 °C
1	100	100	100	100	100	100	100	100	100	100	100	100
1.05	93.9	93.9	93.9	93.9	96.4	96.4	96.4	96.4	97.4	97.4	97.4	97.4
1.1	87.7	87.7	87.7	87.7	92.7	92.7	92.7	92.7	94.8	94.8	94.8	94.8
1.15	81.7	81.7	81.7	81.7	89.2	89.1	89.1	89.1	92.2	92.2	92.2	92.2
1.2	76.2	75.9	75.9	75.9	85.8	85.6	85.6	85.6	89.8	89.6	89.6	89.6
1.25	71.2	70.4	70.4	70.4	82.7	82.2	82.1	82.1	87.6	87.1	87.1	87.1
1.3	66.8	65.5	65.2	65.2	80.0	79.1	78.9	78.9	85.6	84.8	84.7	84.7
1.35	62.9	60.9	60.3	60.2	77.7	76.3	75.8	75.7	83.9	82.8	82.4	82.3
1.4	59.4	56.8			75.6	73.8			82.5	80.9		
1.45	56.2	53.1			73.7	71.5			81.1	79.3		
1.5	53.2				72.0				79.8			

restrictions on the possibility of transformer loading expansion. If there is a possibility to install fiber optic sensors and obtain accurate measurements of HST, safety margins can be significantly reduced, allowing the possibility of even better transformer utilization. In order to overcome network limitations, it could be of interest also to investigate the possibility to remove some congestion by applying dynamic line rating.

Proposed solution has shown to improve utilization of power transformers, which would result in decreasing the environmental impact of wind power generation. From the economic point of view, it also allows a more flexible planning of the electric network, while reducing investment costs. Reducing wind power investment costs would result in lowering the price of green electricity and increase the share of wind energy in the electricity mix.

CRediT authorship contribution statement

Oscar David Ariza Rocha: Methodology, Software, Formal analysis, Investigation, Validation, Writing - original draft, Writing - review

& editing, Visualization. **Kateryna Morozovska:** Conceptualization, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. **Tor Laneryd:** Methodology, Supervision, Project administration, Funding acquisition. **Ola Ivarsson:** Resources, Data curation, Supervision, Project administration. **Claes Ahlrot:** Resources, Data curation, Supervision, Project administration. **Patrik Hilber:** Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ijepes.2020.106188.

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