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Reliability considerations and economic benefits of dynamic transformer rating for wind energy integration

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ABSTRACT

An increasing share of renewable energy on the electricity market creates the need for economic and efficient production, operation and integration technologies, associated with the specific behavior of renewable energy sources (RES). Dynamic rating (DR) provides a possibility to apply improvements to the system both during planning and operation stages. The DR benefits are well described in various literature sources. However, DR is often focused on more efficient exploitation of power lines, not power transformers. Power transformers are costly equipment and their efficient usage and planning can have drastic effect on total costs.

Our analysis focuses on the dynamic transformer rating (DTR) for wind energy applications. The main objective is to study reliability effects of DTR from the component perspective. We utilize existing knowledge about transformer heat balance models from IEC and IEEE standards to obtain information on the loss of life (LOL) of the transformer under investigation and propose possible improvements for the system in question. The method can be employed for identifying the appropriate transformer size by taking into account ambient temperature and load variations and then overloading the transformer beyond nameplate ratings. The reliability of the proposed application is ensured by calculating the risk of overloading the transformer for each day of the year. A risk of overloading is quantified as LOL of the transformer. The risk is presented as a function of ambient temperature and duration of an overload. The final step consists of an economic analysis, which demonstrates economic benefits of DTR application.

1. Introduction

In recent years, utility owners have been facing challenges related to more efficient utilization of the grid infrastructure. Questions such as increasing power demand and integration of renewable energy sources require new solutions in power system design. The irregularity of power generation and consumption brings the need in more dynamic solutions for ratings of power system components. Availability of low cost solutions also supports the development of renewable energy and decreasing prices of electricity from RES. Spendings on transformers account for a big portion of the investment in new substations.

From the reliability point of view, transformer outages can have drastic impact on the economy of power system operation. The life expectancy of transformer is typically considered as a function of insulation degradation, which in turn depends on winding hot spot temperature, moisture, and oxygen content [1,2]. New technologies help oil-immersed transformers to minimize the effect of moisture and oxygen content on insulation life, which leaves the winding hot spot temperature as the most important factor that controls transformer aging.

Currently, transformers are designed conservatively to withstand extreme scenarios of loading and weather conditions. These two parameters affect the heat balance in transformers, which consequently affects transformer capacity and life expectancy. Load and weather conditions are changing variables, therefore, the transformer capacity also changes constantly. When the transformer's loading is increased above nameplate rating and standard load guidelines, the power network operators can have significant level of cost savings and increased return of investment [3]. It has long been recognized that by introducing a dynamic transformer rating (DTR) that takes changing load and

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weather conditions into account, it is possible to safely load transformer above nameplate rating without adverse effects on lifetime or increased risk of failure [4–6].

A requirement for successful implementation of DTR is the development of accurate thermal models, which has been the focus of several previous studies, e.g. the models of [7,8] which have later been included in the loading guides [1,2]. These models are typically based on parameters that are measured at the production facility. In [9] it was found that the predictive capacity could be improved by adjusting the parameters based on field measurements.

Until recently, the main driver for studying DTR has been to optimize operation and defer investments in existing transformer fleets. Traditionally, transformers are designed for a 24 hour duty cycle [2] and the advantage of DTR is then limited to handling variations in ambient temperature or emergency overloading. One case study is presented in [10]. In [11], ambient temperature data has been used to calculate monthly DTR limits for unit loss-of-life operation. In [12] measured data during real-time operation is compared to weather forecasts, demonstrating the predictive potential of DTR. In [13] a controlled measurement corresponding to emergency overload conditions is described.

With the increasing penetration of distributed power generation, additional benefits of DTR are becoming apparent. This is particularly true for transformers that connect wind power generators to the grid, where the load profile is intermittent and unpredictable. Here, DTR could potentially allow for using smaller size transformers and therefore result in better economy and saving on investment costs. So far, only a limited number of publications have addressed this topic. In [14] the transformer case study is limited to solar, which follows a 24 hour cycle and therefore is similar to the conventional load cycle. In [15], important features of DTR for wind power transformers are highlighted including economic analysis, but there are no modeling results or lifetime estimates. Failure modes for wind power transformers are presented in [16], which includes a discussion on the unpredictable load but does not include thermal modeling.

There is therefore a clear need for better understanding of DTR in the context of wind power transformers, which is the focus of this study.

2. Background and method description

The study presented in this article is focused on application of DTR thermal models to a real case power transformer, which is connected to a wind farm. The information from DTR calculation and load data are used to perform reliability analysis, specifically connected to studies on component loss of life. The calculation of a daily loss of life for given transformer is followed by determination of possible improvements that DTR can provide for transformers connected to wind power plants and economic analysis of these improvements. The following steps were completed in this study:

1. calculation of dynamic transformer rating by using established models;
2. calculation of transformer's daily loss of life;
   - determination of critical days;
3. suggestion of possible improvements with DTR and their economic analysis;
   - decreasing transformer size;
   - increasing wind farm size;
   - limiting hot spot temperature.

2.1. Dynamic rating determination methods

Transformers are rarely designed to serve more than 40 years under any operation conditions. In the case o varying temperature and wind conditions, transformer insulation does not undergo planned loss of life at the end of service life. Therefore, there is a potential capacity increase that can be used more efficiently and allow to decrease investment costs, when connecting renewable energy generation units to the grid. Dynamic rating is proposed to unlock transformer available capacity while keeping high system safety. This concept is based on a real situation, when the ambient temperature is not constant.

Dynamic rating can be defined as "The maximum loading which the transformer may acceptably sustain under time-varying load and/or environmental condition"[17]. This implies that the component can have varying rating based on real-time measurements or estimates.

The critical variable in dynamic transformer rating is the hottest spot temperature [18]. Although, calculating this variable is a difficult and complex task, there exists a number of different methods for dynamic rating application, which are categorized into direct and indirect. Direct DTR methods involve real-time monitoring devices, that use up-to-date measurements to calculate current transformer rating. Indirect methods include a variety of standards and models, that use information on weather and load conditions to predict transformer rating for the next period of time.

One main factor that affects the accuracy of dynamic rating is thermal model. There are several different models for calculation of the transformer heat balance that are commercially available. The models that attract the most attention today are described in IEEE and IEC standards. Because of validation in industry and academia, industrial standards proposed by IEEE [2] and IEC [1] are widely used for this purpose.

IEEE standard C57.91 provides guideline for oil immersed transformers and recommends the hot-spot temperature to be 110 °C [2]. Ambient temperature is defined in IEEE standard C57.12.00 as maximum 40 °C with maximum possible daily average of 30 °C [19].

Static rating is a guarantee of safe operation, but it limits efficient utilization of power equipment. In our analysis we will employ heat transfer models from IEEE [2] and IEC [1] standards, to calculate the real-time rating of the transformer. Both IEEE and IEC are proposing two models for transformer's heat balance calculation:

- IEC 60076-7 [1]
  Exponential equations solution: suitable for load variation according to step function
  Difference equations solution: suitable for arbitrarily time varying load factor and ambient temperature
- IEEE C57.91-1995 [2]
  Top oil model (Clause 7)
  Bottom oil model (Annex G): Changes in load loss and oil viscosity, and ambient temperature variations are considered.

There exist several assumptions necessary for the implementation of thermal models: the oil temperature rises linearly from bottom to top; the temperature's difference between winding and oil is constant along the windings; oil temperature changes by ambient temperature and winding with the same time constant [18,20]. When calculating LOL and transformer life expectancy, only the winding insulation aging is considered as an influencing factor.

IEC Difference equations solution and IEEE Bottom oil model are used in the analysis presented in this article; a detailed comparison between input parameters for each of the models is presented in Table 1, where "✓" means that the parameter is required as an input to the model and "☆" means that the parameter needs to be calculated from the hot spot temperature value.

IEEE Annex G model proposes calculation of the hot spot temperature as in (1) [2].

$$\theta_H = \theta_A + \Delta\theta_{BO} + \Delta\theta_{WO/BO} + \Delta\theta_{H/WO}, \quad [^\circ C] \tag{1}$$

where θ_H is the winding hottest spot temperature, [°C]; θ_A is the ambient temperature, [°C]; $\Delta\theta_{BO}$ is the bottom fluid rise over the ambient, [(°C]; $\Delta\theta_{WO/BO}$ is the temperature rise of fluid at winding hot spot location over bottom fluid, [°C]; $\Delta\theta_{H/WO}$ is the winding hottest spot

Table 1
Comparison of the required data for IEEE annex G model and IEC difference equations model.

Type of data	IEEE	IEC
Top oil temperature rise at rated load	✓	✓
Hot spot temperature rise over top oil at rated load	✓	✓
Loss ratio at rated load		✓
Winding time constant	✓	✓
Oil time constant		✓
Type of cooling	✓	✓
Average winding temperature rise at rated load	✓	☆
Average oil temperature rise at rated load	✓	☆
Bottom oil temperature rise at rated load	✓	
Losses (no-load, load, stray, eddy)	✓	
Weight of core, coil, tank and oil	✓	☆
Winding and tank material	✓	
Type of fluid	✓	
Hot spot factor	✓	☆

temperature rise over fluid next to the hot spot location, [°C] [2].

The process of hot spot temperature calculation can be divided into step-by-step computation of the following values:

- average winding temperature;
- winding duct oil temperature rise over bottom oil;
- winding hottest spot temperature;
- average oil temperature;
- top and bottom oil temperature.

The detailed method of obtaining IEC Difference equation model is specified in the Annex C of the standard [1]. Time step in the difference solution should be selected as small as possible and should not exceed one-half of the smallest time constant in the equations [1]. The difference equation method is described by (2).

$$D\theta_0 = \frac{Dt}{k_{11}\tau_0}\left[\frac{1+K^2R}{1+R}\right]^x \Delta\theta_{0r} - (\theta_0 - \theta_A) \tag{2}$$

where D is the difference operator; θ_0 is the top oil temperature, [°C]; k_{11} is the thermal model constant; τ_0 is the average oil time constant, [min]; K is the load factor, [p.u.]; R is the ratio of load losses to no-load losses at rated current; x is the oil exponent; $\Delta\theta_{0r}$ is the top oil temperature rise during steady state for rated losses, [°C]; θ_A is the ambient temperature, [°C] [1].

The calculation steps for obtaining hot spot temperature with IEC Difference equations model are presented in (3)–(9) [1].

$$\theta_0(n) = \theta_0(n-1) + D\theta_0(n) \tag{3}$$

$$D\Delta\theta_{H1}(n) = \frac{Dt}{k_{22}\tau_w}(k_{21}\Delta\theta_{Hr}K^y - \Delta\theta_{H1}) \tag{4}$$

$$D\Delta\theta_{H2}(n) = \frac{Dt}{\frac{1}{k_{22}}\tau_w}((k_{21}-1)\Delta\theta_{Hr}K^y - \Delta\theta_{H2}) \tag{5}$$

$$\Delta\theta_{H1}(n) = \Delta\theta_{H1}(n-1) + D\Delta\theta_{H1} \tag{6}$$

$$\Delta\theta_{H2}(n) = \Delta\theta_{H2}(n-1) + D\Delta\theta_{H2} \tag{7}$$

$$\Delta\theta_H(n) = \Delta\theta_{H1}(n) - \Delta\theta_{H2}(n) \tag{8}$$

$$\theta_H(n) = \theta_0(n) + \Delta\theta_H(n) \tag{9}$$

where n is the time step; $\Delta\theta_H$, $\Delta\theta_{H1}$ and $\Delta\theta_{H2}$ are the hot spot to top oil temperature gradients, [°C]; k_{21} and k_{22} are the thermal model constants; τ_w is the winding time constant, [min]; $\Delta\theta_{Hr}$ is the hot spot to top oil temperature gradient at the rated current, [°C]; y is the winding exponent; θ_H is the hot pot temperature, [°C] [1].

Table 2
Transformer specification.

Transformer specification			
Power	19,400 kVA	Load losses	137,500 W
Primary voltage	44,000 V	No load losses	7370 W
Secondary voltage	22,000(11,000) V	Temperature reference	75 °C
Rated HV current	254.6 A	Temperature rise of top oil over ambient	55.8 °C
Rated LV current	509.1(1018) *A*	Rated ambient temperature	23.9 °C
Cooling operation	ONAN	Primary winding hot spot factor	1.16
Cold resistance of HV winding	539 mΩ	Secondary winding hot spot factor	1.21
Cold resistance of LV winding	98.5 mΩ	Temperature rise of average oil	44.1 °C
Hot resistance of HV winding	679 mΩ	Temperature rise of winding	63.5 °C
Hot resistance of LV winding	123.35 mΩ	Hot spot temperature rise of winding	78.3 °C

2.2. Input parameters

The input parameters for the IEC and IEEE models implementation are provided by the transformer specification and heat run test in Table 2. Load data, provided by Ellevio AB, is collected for every 5 minutes during 2016. Loads are from primary side with minimum load of 0 and maximum load of 1.07, therefore primary rating current is used to calculate per unit load. Since the transformer is connected to a wind farm, the load is composed by the power generated from wind and is a function of wind speed. Fig. 1 is a load probability distribution and shows that around 50% of the time load is less than 0.2 per unit. Hourly ambient temperature data is collected at the nearest meteorological weather station and can be accessed at Swedish Meteorological and Hydrological Institute (SMHI) [21]. The hourly data is interpolated to match the time increment of 0.5 minutes. Thermal model constant, winding and oil time constants for the analysis are selected from [1].

2.3. Reliability and component loss of life

The reliability of a transformer is the prediction of its performance under specified conditions for a certain period of time [22]. The dynamic rating reliability is a balance between decreasing failures and increasing network efficiency and life of components [23]. Unlike power lines, overloading of transformers over a certain temperature limit can drastically decrease its lifetime. Moderate overloading

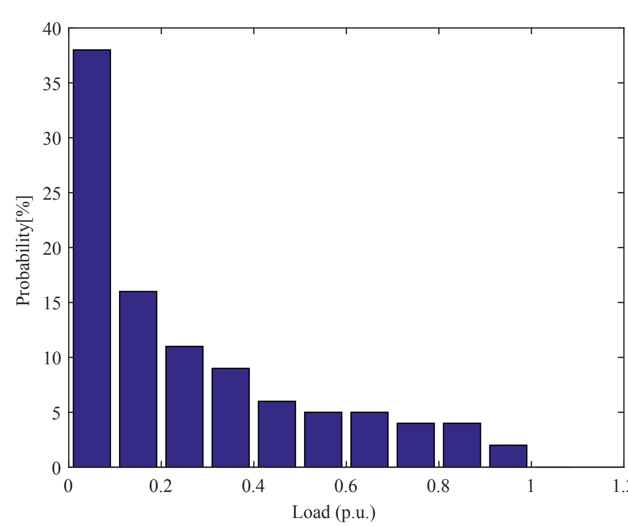

Fig. 1. Probability distribution of per unit load during 2016.

accelerates the aging of transformer insulation. More extreme cases of overloading result in formation of bubbles in the oil, which leads to a reduction of dielectric strength [24]. The reduction of dielectric strength increases the risk of failure in transformers. Thermal rating provides more information on transformer critical temperatures and improves reliability [25].

The actual conditions of transformer are a concern of utility owners. This factor gains more weight when the transformer is overloaded during short or long periods. Therefore it can be said that there is a trade-off between the gain from overloading and loss from aging of transformer. To make a better decision, it is important to study the effect of increasing transformer load on loss of life. Transformers' aging affects the reliability of power system and is an important criterion in asset management. As the age of transformer increases, its capability to withstand severe events such as short circuit faults decreases; this results in increased probability of failure [26].

One of the main causes of failures in transformers is deterioration of paper insulation. Insulation deterioration is a result of oxygen and humidity content in oil. An oil temperature acts as a catalyst in this chemical reaction [27]. Thus, in a situation with constant oxygen and humidity in oil, temperature is the only factor that must be controlled. By monitoring the hot spot temperature, the aging rate of a transformer can be estimated, and used to schedule next maintenance time. Additional information on the transformer aging can provide possibility of using condition-based maintenance as an alternative to traditional time-based maintenance [26].

Transformers are designed to work continuously with nameplate rating and under normal operation, which requires hot spot temperature to equal 110 °C [2]. If a transformer has lower hot spot temperature during its operation, transformer's life expectancy increases. Higher hot spot temperature results in shorter lifetime.

For the prediction of transformer normal life the transformer's aging was determined. Degree of polymerization was chosen as a determination factor for the insulation lifetime and is described in Table 3. It can be seen, that loss of life is highly dependent on hot spot temperature. This dependence indicates the importance of accurate calculations of the hot spot temperature. In this study, the effect of harmonics on hot spot temperature is not considered; voltage and current are assumed to be sinusoidal. The impact of harmonics on hot spot temperature and loss of life is discussed in [28]. IEEE and IEC standards [2,1] relate hot spot temperature to loss of life. Hot spot temperature is normally located in transformer winding. The location varies due to different parameters such as cooling operation and surrounding oil temperature, load and losses [29].

2.4. Loss of life or transformer thermal aging

Insulation degradation is as a result of the chemical reaction. Therefore, aging rate can be expressed as the reaction rate constant K_0 [2].

$$K_0 = A' e^{\frac{B}{\theta + 273}}, \tag{10}$$

where A' and B are empirical constants and θ is the dimensionless temperature. To calculate aging rate regardless of the end of lifetime,

Table 3
Normal insulation life of transformer at the reference temperature of 110 °C [2].

Basis	Normal insulation lifetime	
	Hours	Years
50% retained tensile strength of insulation	65 000	7.42
25% retained tensile strength of insulation	135 000	15.41
200 retained degree of polymerization in insulation	150 000	17.12
Interpretation of distribution transformer functional life test data	180 000	20.55

per unit life is defined by (11)

$$Per\ unit\ life = A e^{\frac{B}{\theta_H + 273}},\ [p.\ u.\ ] \tag{11}$$

where A is selected is such a way that when $\theta_H = 110$ °C the per unit life becomes "1".

Aging rate constant varies between 11 350 and 18 000 partially due to the differences in experimental conditions [2]. The value suggested in [2,1] is 15 000; this value is used in given analysis as aging rate constant.

A tensile strength is the mechanical characteristic that can be utilized as an age indicator and is defining element of normal life. The tensile strength is defined as a percentage of initial strength. Another indicator of transformer's age is an absolute value of the degree of polymerization (DP). For power transformers IEEE standard proposes $DP = 200$ for an end point of insulation life, the value of DP can be lower for distribution transformers. Considering DP value proposed by IEEE, 17.12 years is used as normal lifetime of transformer with constant hot spot temperature of 110 °C. However, industrial applications usually require higher life expectancy. The moisture level is selected to be between 0.2% and 0.3% depending on weight [2].

Per unit life equals to "1" at 110 °C, when temperature increases, per unit life decreases. A relative aging factor [1] or an aging acceleration factor F_{AA} is defined in both IEC [1] and IEEE [2] in a similar manner and is calculated by (12).

$$F_{AA} = e^{\frac{15{,}000}{110+273} - \frac{15{,}000}{\theta_H + 273}} \tag{12}$$

The aging acceleration factor can be presented as a function of hot spot temperature [2]. It is equal to "1" for reference hot spot temperature 110 °C and for any temperature higher than the reference value an aging acceleration factor increases, while for temperatures below the hot spot temperature, aging factor decreases. Normal insulation life can be defined using Table 3. Loss of life is calculated using Eq. (13) [1].

$$LOL = \int_{t_1}^{t_2} F_{AA}\, dt, \quad \text{[hours]} \tag{13}$$

where, LOL is loss of life during time period between t_1 and t_2, [hours].

2.5. Economic analysis

An economic analysis was conducted to determine the size of wind farm expansion. The increased number of wind turbines leads to the increase in wind farm electricity generation and results in the revenue growth. However, the investment and operation costs will increase accordingly. In our analysis we have taken into account costs associated with:

- Transformer loss of life
- Operation
- Investment

Given analysis is viewed as an optimization problem, with the net income as an objective function, which needs to be maximized. In order to simulate the real life scenario the optimization problem should take into account constraints associated with grid expansion such as land area and electrical system properties. However, for simplification of the computation process, performed analysis did not take into account constraint associated with the wind farm expansion.

The input parameters to the optimization problem included:

- purchase costs for each wind turbine;
- installation costs for each wind turbine;
- operation costs;
- electricity price for each kW of generated power.

Electricity price was gathered from Nord Pool [30] and a support scheme for increasing the share of renewable energy in Sweden (El-certificat) is added [31].

The bigger is a wind farm size, the more investment is needed per wind turbine. In this analysis the investment costs are neglected, but one can compare these scenarios to select the best option:

1. A wind farm 20% bigger than the existing wind farm with 20% higher revenue and investment cost for building wind farm to generate 20% more power. The transformer size is decreased and will be depreciated after 40 years.
2. A wind farm 50% bigger than the existing wind farm with 50% higher revenue and investment cost for building wind farm to generate 50% more power. The transformer size kept as original and will be depreciated after 40 years.

An NPV analysis can be done by having all investment cost and yearly revenues to select the most effective option.

3. Results and discussion for the case study

3.1. Application of thermal models

Hot spot temperature was calculated using IEEE Annex G and IEC Difference equations models. After running the IEEE Annex G model, top oil, bottom oil and hot spot temperatures are calculated for every 0.5 minutes. Top oil and hot spot temperatures are also calculated using IEC model. Figs. 2–5 show hot spot temperatures calculated for four sample days for both IEEE and IEC models. The random days were chosen to illustrate that load variations do not follow a cyclic pattern. In Figs. 2–5 results from IEEE model and IEC model follow nearly the same hot-spot temperature distribution pattern.

3.2. Critical days

Critical days are defined as days with highest LOL during the year. LOL for both IEEE Annex G and IEC Difference equations models is calculated using results of hot spot temperature calculation. After one year of operation $LOL = 0.22$ [days/year] or, formulated in a different manner, at the end of 2016 the transformer has lost 0.22 [days/year] or 5.3 [hours/year] of its expected lifetime. The equivalent aging factor for the entire year is 0.00059. In Figs. 6 and 7 critical days are referred to as the points with the sharpest slope in temperature distribution. Table 4 illustrates these days based on IEEE model and IEC model calculations.

Table 4 contains the list of 17 days, when the cumulative $LOL_{sum} = 0.113$ [day/year] or in other words equals to 50% of LOL for the year. The analysis has shown that 80% of yearly loss of life happens during only 30 days through year. If one wants to control loss of life, these days are the ones to be monitored and controlled.

Fig. 8 illustrates the loss of life at the end of year as a function of percentage of load during first four critical days. When studying one day, the load during other days remains unchanged. On October 29th, if the load decreases by 10% the loss of life would become 0.28 [days/

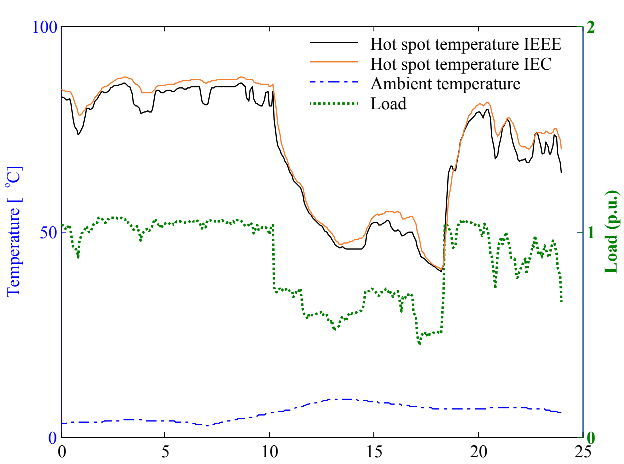

Fig. 2. Hot spot temperature calculated using IEEE and IEC models 2016-10-29.

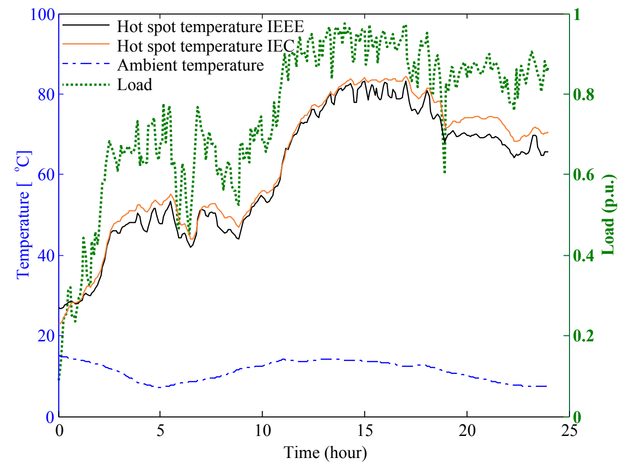

Fig. 3. Hot spot temperature calculated using IEEE and IEC models 2016-06-08.

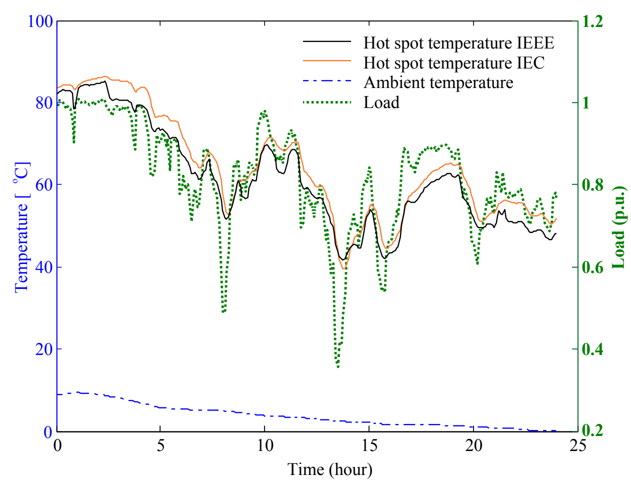

Fig. 4. Hot spot temperature calculated using IEEE and IEC models 2016-12-05.

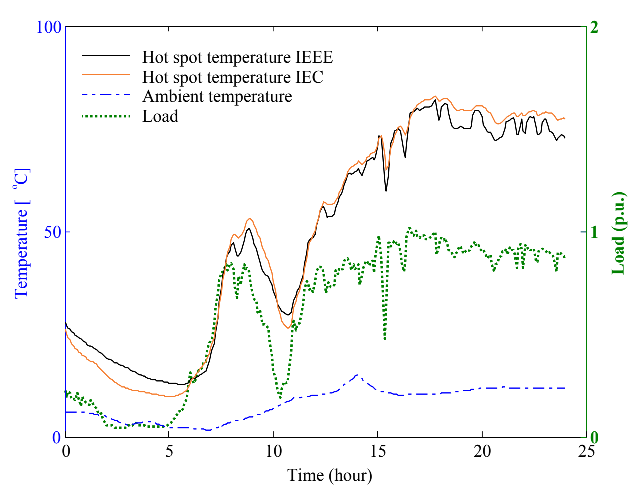

Fig. 5. Hot spot temperature calculated using IEEE and IEC models 2016-09-29.

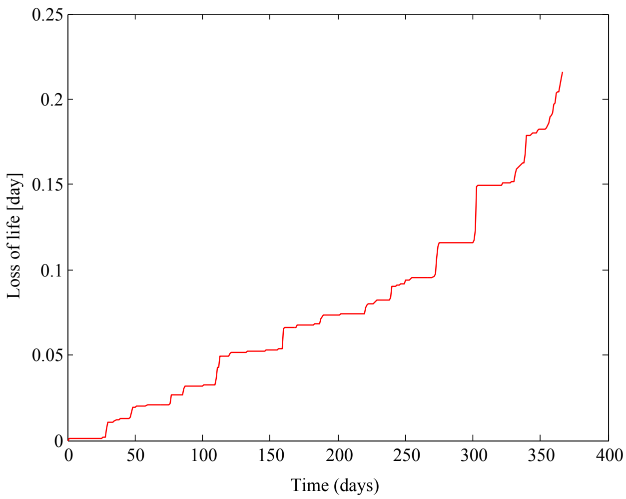

Fig. 6. Daily loss of life calculated by IEEE thermal model.

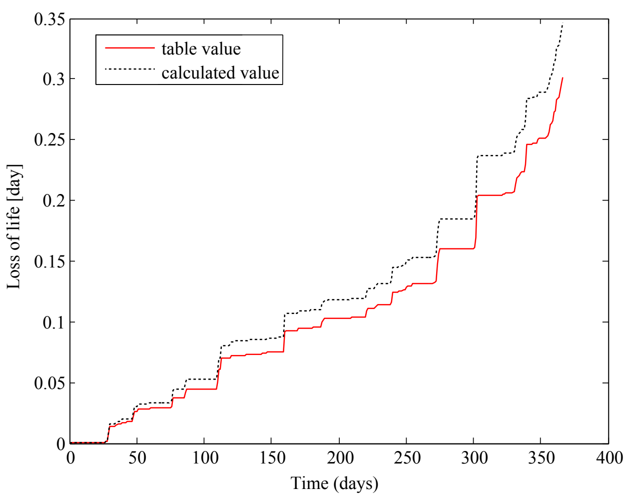

Fig. 7. LOL by IEC model with standard and calculated time constants.

year] and if the load cuts off to zero, the loss of life would be 0.27 [days/year]. In Fig. 8 it is clear that when decreasing load from 100% load to 90%, reduction in loss of life is more than the case that the load decreases from 90% to 80% and so on. If we want to prioritize the most influential reduction steps in the load during these days, slope between each step should be considered. The slope between each reduction step has to be calculated.

The first step is to determine the rate of LOL reduction per each 10% of load reduction for selected critical days. Fig. 8 shows that the important factor is not the absolute value of LOL after load reduction, but the rate of LOL reduction. The rate of LOL reduction for each 0.1 point decrease is presented as the slope in Fig. 8. Rate of reduction is considered as the only influencing criteria. Therefore, it is possible to decrease LOL by reducing load during October 29th by 10% and afterwards reducing the load during June 8th by 10%, followed by December 5th etc.

The possibility of load reduction during critical days is a trade-off between increasing the remaining life of transformer and decreasing income from energy production. Moreover, electricity price is a variable unit and, therefore, becomes an influential factor. As it can be seen in (13) loss of life is highly sensitive to the hot spot temperature. Therefore, to make sure that any error in hot spot calculation is considered, a margin is added to hot spot temperature. The margin value is selected to be equal to the maximum difference between IEC and IEEE results which is equal to 8 °C. This value is added to every hot spot temperature calculated using IEC model. In this case, loss of life has increased 207% and changes from 0.3 [days/year] to 0.82 [days/year].

3.3. Design improvements

For evaluation of the possible improvements in the grid design, we study two approaches: decreasing the size of the transformer and expanding the wind farm that it is connecting to the grid.

3.3.1. Decreasing transformer size

When studying the possible decrease in the transformer size we have kept the risk at a constant level, the weather and load parameters were evaluated for the same period of time, the full year of 2016. The reduced transformer is a 16MVA transformer that is found to be fit to replace the 20MVA transformer for the same application. The difference in the investment cost, loss of life and the estimated transformer lifetime is show in Table 5. As it can be concluded from the result, the 16MVA transformer can be used for connecting the same wind farm, with lover investment cost. The reduction in the estimated transformer lifetime very unlikely will affect safety and security of the connection, because the grid operator is planning for all the transformers to be decommissioned after 40 years of their operation.

3.3.2. Increasing load

The transformer under investigation is already in operation. In the following case, we evaluate the effect of increasing the wind farm power generation on transformer loss of life. Fig. 9 shows the loss of life at the end of year for varying increasing factor, n. Expansion of the wind farm by 60% leads to the $LOL = 1$ year/year at the end of one year of operation. However, if we limit the load during the critical days, the increasing factor for other days would be even higher. The slope increases dramatically as n passes 1.4 point. The LOL is highly dependent of hot spot temperature, a safety margin equal to 8 °C is added to hot spot temperature. The value for safety margin is the absolute maximum difference between hot spot temperature calculated using IEC and IEEE models. The updated LOL with 8 °C safety margin is shown in Fig. 10. If the life of the transformer is set to be 40 years, then the wind farm could be expanded by 47%.

3.4. Economic analysis

Based on existing power generation and electricity price, the revenue of the wind farm is 18.9 million SEK and $LOL = 0.3$ [days/year], which results in 264.06 SEK yearly spendings. The inscrease of the wind farm by 50% increases revenue by 50% to 28.4 million SEK and $LOL = 107$ [days/year]. The limitations to the optimization problem such as land area and grid integration are not taken into account in the following study. The operational costs and investment costs of new wind turbines are neglected in our study, because depending on the size and manufacturer of the wind turbines, prices can significantly vary. If the same wind farm is connected to (16 MVA) transformer with 40 *years* expected lifetime, the wind farm can be expanded by 20%. In this case, the revenue and costs associated with LOL are 22.7 million SEK and 75614.5 SEK respectively.

With existing size of wind farm, the revenue for 16 *MVA* and 20 *MVA* transformer is the same. Since both transformers will be decommissioned after 40 *years* of operation. Costs of LOL are not accountable costs and are calculated based on transformer investment. However, transformer investment costs are still dependent on the transformer size. Therefore, for the existing wind farm size it is possible to use the smaller size transformer with DTR. However, one should keep in mind that with the smaller transformer, for 40 *years* depreciation period, the wind farm can be expanded by 20% while with 20 *MVA* transformer, it can be expanded by 50%. Therefore, if the land or network limitations are bounding the wind farm size to only 20% bigger than the existing

Table 4
Critical days based on IEC and IEEE thermal models.

Date	IEC		IEEE	
	Loss of life per day [days]	Cumulative loss of life [days]	Loss of life per day [days]	Cumulative loss of life [days]
2016-10-29	0.0335	0.0335	0.0254	0.0254
2016-06-08	0.0162	0.0497	0.0117	0.0372
2016-12-05	0.0159	0.0656	0.0112	0.0484
2016-09-29	0.0130	0.0787	0.0095	0.0579
2016-12-30	0.0113	0.0901	0.0076	0.0656
2016-04-20	0.0103	0.1004	0.0068	0.0724
2016-09-30	0.0094	0.1099	0.0064	0.0855
2016-04-22	0.0091	0.1190	0.0066	0.0791
2016-12-27	0.0087	0.1278	0.0058	0.1098
2016-02-17	0.0085	0.1363	0.0058	0.1039
2016-10-28	0.0079	0.1443	0.0063	0.0918
2016-08-27	0.0077	0.1520	0.0062	0.0981
2016-12-25	0.0070	0.1591	0.0046	0.1249
2016-03-17	0.0068	0.1660	0.0050	0.1202
2016-12-04	0.0066	0.1726	0.0053	0.1152
2016-01-30	0.0064	0.1791	0.0040	0.1377
2016-11-26	0.0063	0.1854	0.0041	0.1337
2016-01-29	0.0063	0.1918	0.0045	0.1295
2016-12-31	0.0058	0.1976	0.0037	0.1491
2016-12-22	0.0055	0.2032	0.0036	0.1527
2016-04-19	0.0053	0.2085	0.0038	0.1415
2016-11-27	0.0051	0.2137	0.0030	0.1621
2016-08-08	0.0049	0.2187	0.0037	0.1453
2016-07-06	0.0044	0.2231	0.0031	0.1559
2016-03-26	0.0042	0.2274	0.0031	0.1590
2016-10-01	0.0035	0.2309	0.0024	0.1646
2016-12-21	0.0030	0.2340	0.0019	0.1665
2016-03-27	0.0029	0.2369	0.0019	0.1684
2016-09-06	0.0024	0.2394	0.0017	0.1721
2016-07-07	0.0024	0.2418	0.0018	0.1703

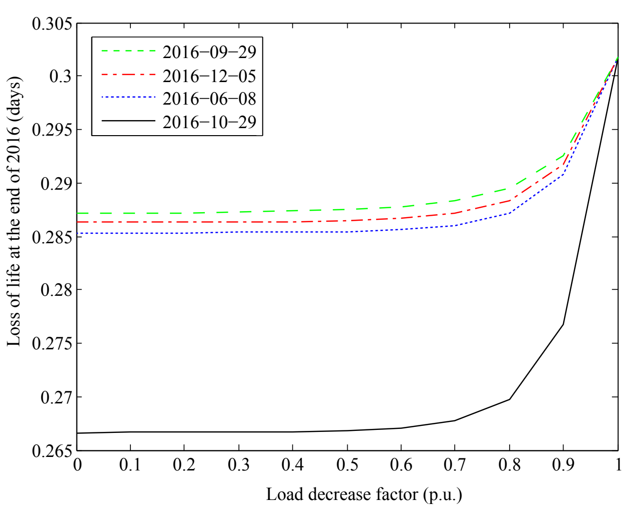

Fig. 8. Loss of life calculation in IEC model for decreased load at critical days.

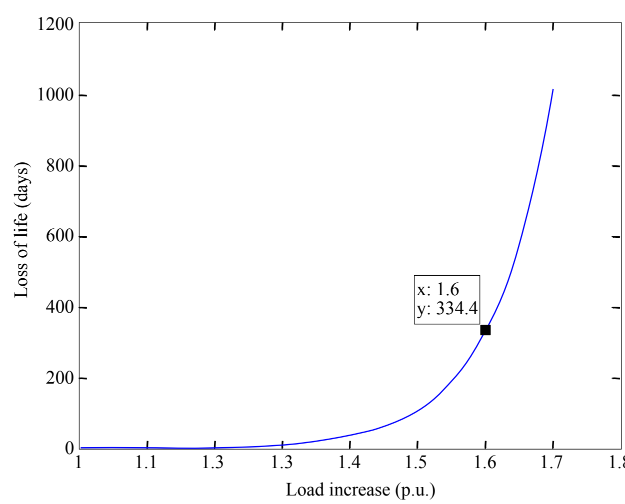

Fig. 9. Loss of life calculation in IEC model for increasing load.

Table 5
Comparing results for two transformer sizes.

Transformer size	16 MVA	20 MVA
Loss of life [hours]	135.84	7.2
Loss of life [days]	5.66	0.3
Life expectancy [years] **based on DP*	1104	20,833
Investment cost [SEK]	4,500,000	5,500,000

one, the smaller size transformer is the better option. However, if there is not any bounding limitation, to maximize revenue the bigger size transformer with wind farm expansion plan to 50% bigger than the existing one should be done.

3.5. Limiting hot spot temperature

In this part benefit of applying an on-line monitoring system based on IEC standard will be discussed. This monitoring system has load and ambient temperature at each time step as input and can calculate hot spot temperature. Based on calculated hot spot temperature, load at next time step will be controlled to prevent any hot spot temperature more than predefined limitation. By controlling load which leads to control hot spot temperature, loss of life can be controlled. Because loss of life accelerate for hot spot temperature more than 110 °C and by keeping this temperature lower than a threshold we prevent a considerable amount of loss of life caused by short periods of high hot spot temperature. Therefore 110 °C is selected as hot spot threshold.

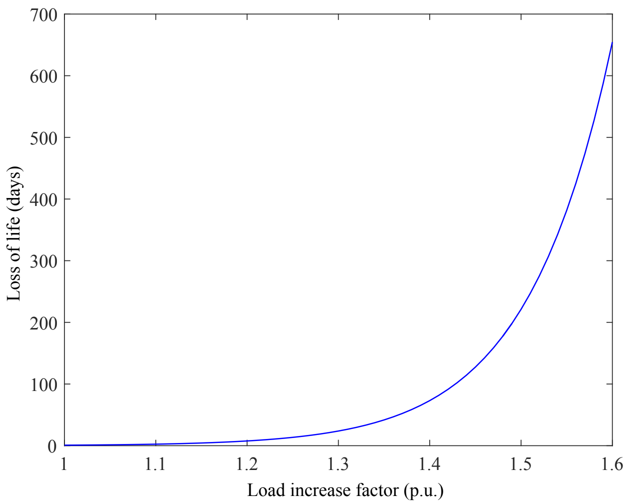

Fig. 10. Loss of life for different increasing factor by considering 8 °C safety margin.

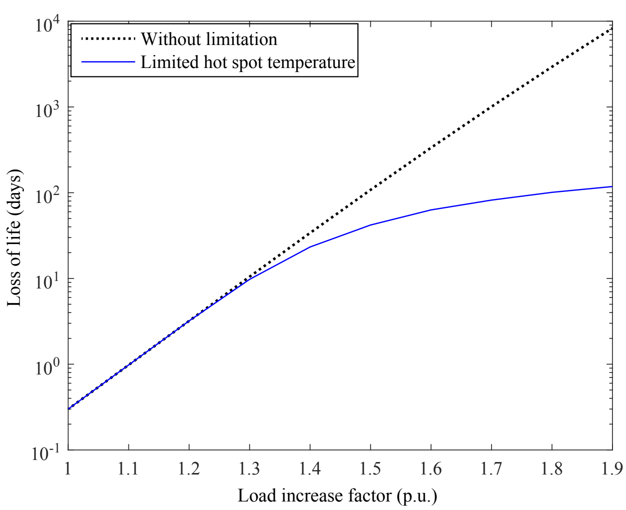

Fig. 11. Loss of life calculation for increased load with and without limited hotspot temperature.

To study how this method can be beneficial two scenario are defined. In one wind farm power generation is increased by a constant factor which means the number of wind turbines have increased without monitoring system. In the other scenario the wind farm increased by constant factor but whenever hot spot temperature reaches the threshold the load decrease so that hot spot temperature decreases to the threshold value. In both cases transformer loss of life and revenue based on generated power are calculated. Results are shown in Figs. 11 and 12 for different wind farm expansion plans.

4. Conclusions

Current trends forecast an increase of the renewable energy share of the power grid capacity, requiring power transmission systems with larger capacity. Our study shows that DTR has a potential to unlock power capacity in existing systems and utilize equipment more efficiently.

The application of DTR requires information on the hot spot, which can be either monitored by fiber optics or calculated using transformer thermal models. After application of thermal models to the existing transformer we were able to determine capacity potential of it by calculating LOL. DTR and obtained information about LOL have a potential to be used during specification phase of a transformer to select more

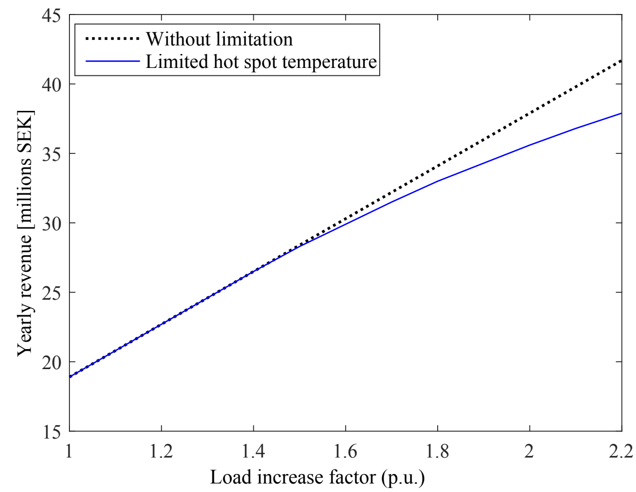

Fig. 12. Revenue comparison for increased load with and without limited hot spot temperature.

appropriate transformer size for each application. As has been shown in economic analysis DTR application could be financially beneficial and decrease investment costs by a significant amount, while providing equal operating performance. Our analysis shows that applying dynamic thermal rating studies for transformers connected to renewable energy helps to reduce investment cost, which is a crucial factor for renewable energy integration.

We predict DTR to have positive economic impact in the society in general, because transformers account for a considerable part of the total investment in power systems, by extracting available capacity of transformers, the need for new investments can be deferred and affect the electricity price. We consider DTR to be a sustainable and environmentally friendly technology, because it provides an alternative way to utilize less material for building new transformers.

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