DEGREE PROJECT IN ELECTRICAL ENGINEERING,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2017

Analysis of reliability improvements of transformers after application of dynamic rating

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Analys av tillförlitlighet förbättringar av transformatorer efter tillämpning av dynamisk rating

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June 2017,
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Abstract

In this project dynamic thermal rating for transformers and its effect on transformer reliability are investigated. A literature review is done on different thermal models used for this purpose and at the end differential equations model from IEC 60076-7 and bottom oil model from IEEE C57.91-1995 standard are selected to calculate hot spot temperature. A wind farm connected transformer is selected to implement the models. This transformer belongs to Ellevio AB and manufactured by ABB AB. Load data are gathered for every 5 minutes during 2016. Loss of life of transformer is calculated and it is concluded that by considering this factor, the transformer is overdesigned. The optimum size of transformer by utilizing dynamic rating is selected which results in a reduction in investment cost. This method can be used to select the appropriate size of transformer by taking advantages of ambient temperature variations and overload the transformer beyond nameplate ratings without exceeding transformer temperature limitations. Moreover, the risk of overloading the transformer at any time during 2016 is calculated. The risk of overloading is quantified as loss of life of transformer. It is shown that this risk is a function of ambient temperature and the duration of overloading. Finally, an economic analysis is done to demonstrate economic benefit of expanding wind farm by overloading the existing transformer by reducing the transformer life expectancy while keeping it in a safe limit.

Sammanfattning

I detta projekt undersöks dynamisk värmeklassificering för transformatorer och dess effekt på transformatorns tillförlitlighet. En litteraturöversikt görs på olika termiska modeller som används för detta ändamål och i slutet av differentialekvationsmodellen från IEC 60076-7 och bottenoljemodellen från IEEE C57.91-1995 standard väljes för att beräkna varmpunktstemperatur. En transformator med vindkraftpark väljs för att genomföra modellerna. Denna transformator tillhör Ellevio AB och tillverkas av ABB AB. Lastdata samlas in för var 5: e minut under 2016. Transformatorns livslängd beräknas och det slutsatsen att transformatorn är överdesignad med hänsyn till denna faktor. Den optimala storleken på transformatorn genom att använda dynamisk rating väljs vilket resulterar i en minskning av investeringskostnaden. Denna metod kan användas för att välja lämplig storlek för transformatorn genom att dra fördel av omgivande temperaturvariationer och överbelasta transformatorn bortom märkskyltar utan att överskrida transformatortemperaturbegränsningar. Dessutom beräknas risken för överbelastning av transformatorn när som helst under 2016. Risken för överbelastning kvantifieras som förlust av livslängd för transformatorn. Det visas att denna risk är en funktion av omgivande temperatur och varaktigheten av överbelastning. Slutligen görs en ekonomisk analys för att visa ekonomisk nytta av att expandera vindkraftparken genom att överbelasta den befintliga transformatorn genom att minska transformatorens livslängd samtidigt som den hålls i en säker gräns.

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1 Introduction

Traditionally power system utility owners are willing to use existing infrastructure and components more efficiently, because of limited budget in one hand and increasing demand and proliferation of distributed generations on the other hand. However, increasing renewable energy resources penetration results in many changes in power system design. One of the main changes is the irregularity in power generation which results in non-cyclic load on components such as transformers. By forecasting probability distribution of these loads, a better understanding of component can be achieved which results in more efficient component design. Renewable energy connected transformers normally experience load variations more than conventional energy connected transformers which results in inefficient use of transformer capacity based on nameplate rating. Dynamic rating for such transformers can be applied to select most efficient transformer size. Moreover, liberated driven power system in which many entities participate in power generation, transmission and distribution, leads to more competition pressure on participants. As a result of this pressure, players need to utilize existing infrastructures more efficiently while maintaining the same level of reliability. Dynamic rating is proposed as a solution to this optimization problem. Currently, dynamic rating is conducted for three main components of power system: overhead lines, cables and transformers [5]. One of the key components in power systems is transformer. Transformer accounts for the largest portion of the investment in substations [6]. Furthermore, transformers outages have significant economic impact on power system operation [6]. Therefore it is a challenge for utilities to increase loadability of transformers while maintaining reliability and life expectancy of transformers in an acceptable range [7]. Life expectancy of transformer is a function of insulation aging. Winding hot spot temperature is the most influential factor in transformer insulation aging. Transformer's aging is a function of temperature, moisture, and oxygen content [2]. Today's new technologies help modern oil-immersed transformers to minimize the effect of moisture and oxygen content on transformer insulation life, which leaves the temperature as the most important factor controlling transformer's aging [2]. It is noticed that increasing transformers loading beyond current utilization, which is based on nameplate rating and standard load guidelines, results in significant benefits to utility owners [8]. Therefore it is crucial for utility owners to optimize transformer loading and insulation aging. To achieve this goal, it is needed to monitor the transformers conditions continuously. Currently, transformers are designed conservatively to withstand extreme scenarios of loading and weather conditions. These two parameters affect heat generation in transformers which consequently affects transformer capacity and life expectancy [6]. However, loading and weather conditions are changing variables. Therefore transformer capacity is changing constantly which needs real-time monitoring of conditions to prevent any damage caused by overheating the transformers.

There are also environmental concerns which create some difficulties when trying to gain permission to build new power system infrastructure [9]. By practicing dynamic rating, need for investing on larger transformers to respond to growing load decreases [10]. By using dynamic thermal rating techniques, transformers can be utilized for loads more than their nameplate ratings based on environmental conditions. In other words, dynamic thermal rating is used

to maximize usable capacity of components in power system which means that dynamic rating allows more power transfer through the network. This method is recommended by International Council for Large Electric Systems Working Group (CIGRE) as a financially reasonable technology to unlock network capacity [11].

In this master thesis project, Section 2 reviews the literature on background of dynamic rating and different methods to implement it in oil-immersed transformers. The effect of hot spot temperature on loss of life and aging acceleration factor calculations for transformer are discussed. The main focus in this chapter is on standard thermal models from IEEE [2] and IEC [1]. Thermal models from aforementioned standards are selected to be used in the next section. In Section 3, based on thermal model selected at the end of the previous section, hot spot calculations will be done for a real case. The examined transformer is a wind farm connected transformer manufactured by ABB AB and operated by Ellevio AB. Loss of life and aging acceleration factors based on calculated hot spot are calculated. Different scenario are investigated to study the effect of increase in transformer load by expanding wind farm on transformer loss of life. Additionally, maximum contingency loading for the transformer is calculated. At the end of this section, economic analysis is done to show how applying dynamic rating concept can affect the utility and manufacturer economically. The application of dynamic rating in design phase of transformer is also studied. In Section 4, a discussion on results and recommendations for future works are presented.

2 Literature review

In this section, dynamic rating concept is defined. To do that, first it is needed to define conventional rating which is called static rating and then the dynamic rating is defined in contrast with static rating. The necessity of dynamic rating and applications are discussed and finally approaches to implement dynamic rating are presented.

2.1 Dynamic rating definition

To understand dynamic rating for transformer first it is needed to define static rating. Static rating is nameplate rating of transformer calculated based on worst case scenario. Worst case scenario conditions are considered to calculate transformers nameplate rating, to make sure that without any monitoring, transformers can operate safely. Since worst scenario rarely happens, this keeps the transformer a safety margin. In other words, static thermal rating means same rating limit for every time intervals regardless of ambient temperature. When there is no time limit for static rating it is static thermal rating under "normal" operation and is referred to "nameplate". However if there is a time limit, that static rating is referred to "emergency" rating [12]. The manufacturer estimates the life of transformer if the nameplate rating for different operation modes is not exceeded. IEEE standard C57.91 provides guideline for oil immersed transformers and recommends the reference hottest-spot temperature for $65°C$ and $55°C$ average winding rise transformers to be $110°C$ and $95°C$, respectively. Ambient temperature is typically defined as $30°C$. The exact value for reference ambient temperature can be found in transformer heat run test data. Although static rating guarantees that the transformer rarely exceeds the critical temperature, it limits the transformer load. To overcome this problem, dynamic rating is proposed to unlock transformer available capacity while operating below limitations. This concept is based on a real situation where the ambient temperature is not always constant. Dynamic rating can be defined as "The maximum loading which the transformer may acceptably sustain under time-varying load and/or environmental condition" [13]. This implies that the component can have varying rating based on real-time measurements or calculations.

Based on [2], the transformer's nameplate rating is determined under the following conditions:

- Ambient temperature equals to almost $30°C$. The ambient temperature should be averaged over 24 hours.
- Winding hot-spot rises over ambient is almost $80°C$ for $65°C$ average winding rise. Therefore hottest-spot temperature would be $110°C$ [2].
- Rated frequency and voltage.

The exact values for ambient temperature and hot spot temperature rise over ambient at rated load can be found in heat run test. It can be noticed that changes in any of these conditions can change the transformer's rating. For instance, during conditions that ambient temperature is less than $30°C$, the actual rating of transformer is more than nominal rating. To use transformers

Table 1: Improvement in component rating as a result of applying dynamic rating [3]

Component	**Average dynamic rating times the static rating**
Overhead lines	1.7-2.53
Cables	1-1.06
Transformers	1.06-1.10

efficiently, it is needed to monitor real-time data to calculate transformers rating in each period of time. Using dynamic rating, maximum capacity of transformers can be utilized. However, due to low cost efficiency, currently, dynamic rating for transformers with low rating is not widely practiced [10]. In order to take advantage of dynamic rating efficiently, it is recommended to apply this method on multiple circuit components simultaneously [12]. In other words, if dynamic rating is only done for one component of a circuit we need to make sure that the new rating resulted by dynamic rating is not limited by other components static rating. Thermal limit of a circuit is determined by thermal limit of power components. For instance, it has been shown in [12] that for studied transmission circuits in New York, transformer accounts for slightly less than 10% of thermal limits in the circuits.

Dynamic rating motivation

Employing dynamic rating for transformer increases transformer available capacity and defers investments needed to respond to growing demand [5]. In renewable resource connected transformers, using dynamic rating in designing phase, the transformer can be designed more efficiently and may be more cost efficient. In currently installed transformers, the transformer capacity for further renewable energy harvesting expansions can be determined by dynamic rating. Table 1 shows the improvement in component rating caused by applying dynamic rating. It may seem that overhead lines have greater potential which can be exploit by dynamic rating. However, since transformers account for major cost in power systems, even small increase in rating may have large impact. The ability to predict dynamic rating provides the power system owner with more accurate information about real network capacity when deciding about dispatching generation in day ahead market. Having reliable knowledge about transformer hot spot temperature gives utility owner a solid information about the cost of transformer overloading. Cost of transformer loading can be defined as loss of life. In some cases, utility owners are willing to sacrifice transformer life to get the benefits from responding to demand or increasing the power generation to exploit maximum energy available in renewable resources. However this method is applicable if only the transformer is newly installed or the knowledge about actual age of transformer is available. To perform economic analysis such as cost benefit analysis, exact value of loss of life needs to be calculated. As Sweden rarely experiences ambient temperature equal to $30°C$ hot spot temperature barely reaches the limits. In this case, the difference between actual transformer rating and nameplate rating is considerable. It has been noticed that if the difference between the hottest and coldest day is considerable,

dynamic thermal rating would be more beneficial [11].

Employing transformer dynamic rating

To monitor dynamic rating for a transformer following data are required:

- Load
- Ambient temperature (from weather stations)
- Cooling operation

These data can be collected using monitoring devices such as sensors. In the output, top oil temperature and loss of life in insulation are also calculated in order that transformer does not exceed the limits stated in the standards [10]. When calculating transformer's dynamic rating, the rating in some occasions is higher than nameplate rating. However, it cannot take any possible value. To keep a safety margin, IEC 60076-7 [1] provides some limitations which are presented in Table 2.

Table 2: IEC60076-7 Current and temperature limits applicable to loading beyond nameplate rating [1]

Type of loading	Distribution transformers	Medium power transformers	Large power transformers
Normal cyclic loading:			
Current (p.u.)	1.5	1.5	1.3
Winding hot spot temperature ($°C$)	120	120	120
Metallic hot spot temperature ($°C$)	140	140	140
Top-oil temperature ($°C$)	105	105	105
Long-time emergency loading:			
Current (p.u.)	1.8	1.5	1.3
Winding hot spot temperature ($°C$)	140	140	140
Metallic hot spot temperature ($°C$)	160	160	160
Top-oil temperature ($°C$)	115	115	115
Short-time emergency loading:			
Current (p.u.)	2	1.8	1.5
Winding hot spot temperature ($°C$)	-	160	160
Metallic hot spot temperature ($°C$)	-	180	180
Top-oil temperature ($°C$)	-	115	115

As it is noticed in the guideline [1] the temperature and load limits are not intended to be valid simultaneously. To prevent any unknown mechanical and electrical stress on the transformer, it is recommended in [1] and [2] that the rating should not be more than 150% and 200% of nameplate rating, respectively. In case the calculated value is more than these limitations, the rating will set to the maximum limits.

It has been shown that utilizing dynamic rating has increased security [10]. Because the actual rating of transformers is higher than nameplate when the ambient temperature is less than $30°C$ which allows the utility owners, in case of fault in a transformer, load the other transformers safely even more than their nameplate rating.

Transformer loading

The higher the load, the more pressure on electrical and mechanical part of transformer. The higher load results in higher current through the transformer's winding which increases the loss. The electrical loss is converted to heat and increases the winding temperature. Therefore transformer load is one of the influential factors in estimating hot spot temperature.

Transformer cooling operation

The transformer cooling system is basically determined by following characteristics [3]:

1. The coolant fluid: oil (O) or air (A).
2. The convection around the core: natural (N) or forced (F).
3. The external refrigerating fluid: air (A) or water (W).
4. The external convection method: natural (N) or forced (F).

In any cooling operation cycle, the cooling fluid is cooled at radiator by heat exchanging with ambient. Then the fluid goes up in winding ducts. In this stage, fluid absorbs heat generated at winding and core and exits the ducts to the tank with top ducts temperature. The fluid in the tank goes into the radiator with top oil temperature. Oil pumps, fans and spray cooling can be employed to increase the transformer thermal rating [12].

Ambient temperature

Ambient temperature input error has significant impact on accuracy of dynamic rating. Therefore, accurate ambient temperature monitoring is crucial.

If the meteorological data at the transformer location are not available, inverse distance interpolation technique can be used [14]. In this technique the ambient temperature measured at weather station (i) close to transformer location (k) are used based on their distance to desired location $d_{i,k}$.

$$\theta_{A,k} = \frac{\sum_i (1/d_{i,k}^2)\theta_{A,i}}{\sum_i (1/d_{i,k}^2)} \tag{1}$$

2.2 Transformer dynamic rating technologies

Currently, there are many technologies used to implement dynamic rating for transformers. In this part a brief review of some of these technologies are presented.

- EPRI (DTCR)

This system is described in [5]. Released in 1999, Dynamic Thermal Circuit Rating system calculates thermal rating for every component of the circuit based on actual load and weather conditions. To do that, this system uses corresponding thermal model for each component of power transmission including transformers, overhead lines, underground cables, current transformers, air disconnect

switches, circuit breakers, line taps and buses circuit. DTCR is developed by EPRI. The aim of this project was to "improve the power system operator's estimates of circuit thermal rating through the monitoring of weather, soil, and electrical loading" [12]. Java and C are used for graphic user interface and calculations, respectively [5].

Alstom project

Currently Alstom has commercialized products for dynamic line rating (DLR). By employing DLR, reliability and loading would be increased. But there is not any commercial product for transformer dynamic rating yet.

Kinectrics

This company provides software named "Kinectrics DTR" for power transformers' and phase shifting transformers' temperature, ratings and loss of life calculations.

2.3 Transformer thermal models

Hottest spot temperature is the most critical variable in transformer thermal model for two reasons. First, when the temperature exceeds the temperature limit, it leads to formation of bubble in oil which in turns reduces the dielectric insulation strength. The other reason is that the higher winding temperature results in acceleration of aging. Therefore it is crucial to calculate this parameter accurately. This temperature is normally located in transformer windings. The location varies due to changes in transformer such as cooling operation and surrounding oil temperature, load and losses [15]. Therefore, it is difficult to measure this parameter accurately. The alternative option is using thermal models to calculate hot spot temperature. Recently fiber optic cables facilitate hot spot measurements in newly installed transformers. One of the main factors that affects the accuracy of dynamic rating is thermal model. Because of validation in industry and academia, industrial standards proposed by IEEE [2] and IEC [1] are widely used for this purpose.

2.4 Dynamic rating determination methods

The critical variable in transformers dynamic rating is hottest spot temperature [16]. However calculating this variable is a difficult and complex task. In this section, different approaches to exploit dynamic rating in transformers are investigated

- Direct monitoring techniques: Include laser, fiber optics and temperature sensors, loading cells [17].
- Indirect monitoring techniques: Use meteorological data and transformers thermal model based on IEEE, IEC, or CIGRE industrial standards [17].

In this approach, hot spot temperature is calculated based on standard loading guidelines such as [2] and [1]. These thermal models are based on following assumptions [16]:

- the oil temperature rises linearly from bottom to top
- Temperature difference between winding and oil is constant along the winding.
- Oil temperature changes by ambient temperature and winding with the same time constant.

IEEE and IEC thermal models are developed based on this approach. As the exact location of hot spot at winding is not known and the high cost of direct measurement techniques, indirect approaches are developed by researchers [18].

2.5 IEEE thermal models

IEEE C57.91-1995 guideline for oil immersed transformers suggests two thermal models to calculate hot spot temperature. In this section these thermal models will be discussed.

Top oil thermal model

This method is simple and requires no iterative procedures. It is one of the oldest thermal model proposed in 1945. At that time equipments to measure hot spot temperature were not available. Later it was shown that during overload, the result from the model is lower than measured values [13]. Hot spot temperature is summation of ambient temperature (θ_A), top oil temperature rise over ambient ($\Delta\theta_{TO}$)and hot spot temperature rise over top oil temperature ($\Delta\theta_H$).

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \tag{2}$$

Where $\Delta\theta_{TO}$ and $\Delta\theta_H$ are calculated as:

$$\Delta\theta_{TO} = (\Delta\theta_{TO,U} - \Delta\theta_{TO,i})(1 - \exp(-\frac{1}{\tau_{TO}})) + \Delta\theta_{TO,i}, \tag{3}$$

$$\Delta\theta_H = (\Delta\theta_{H,U} - \Delta\theta_{H,i})(1 - \exp(-\frac{1}{\tau_w})) + \Delta\theta_{H,i}. \tag{4}$$

In these equations, $\Delta\theta_{TO,i}$ and $\Delta\theta_{H,i}$ are initial top oil temperature rise and hot spot temperature rise. $\Delta\theta_{TO,U}$ and $\Delta\theta_{H,U}$represent ultimate top oil temperature rise and hot spot temperature rise. τ_{TO} and τ_w are oil and winding time constant, respectively. Ultimate top oil temperature rise and hot spot temperature rise are calculated using equations

$$\Delta\theta_{TO,U} = \Delta\theta_{TO,R}\left[\frac{K_U^2 R + 1}{R + 1}\right]^n, \tag{5}$$

and

$$\Delta\theta_{H,U} = \Delta\theta_{H,R} K_U^{2m}, \tag{6}$$

where, R is load loss to no load loss ratio, K_U is per unit load, $\Delta\theta_{TO,R}$ is top oil rise at rated load, $\Delta\theta_{H,R}$ is hot spot temperature rise at rated load and m and n are coefficients based on cooling operations presented in Table 3. If $n = 1$Oil

Table 3: Exponents in IEEE Clause 7 equations [2]

Type of cooling	**m**	**n**
ONAN	0.8	0.8
ONAF	0.8	0.9
OFAF or OFWF	0.8	0.9
ODAF or ODWF	1	1

time constant can be calculated using (7) for any load. Otherwise it can be only used for rated current and equation is used to modify it for arbitrary load.

$$\tau_{TO,R} = \frac{C\Delta\theta_{TO,R}}{P_{T,R}} \tag{7}$$

$$\tau_{TO} = \tau_{TO,R}\frac{(\frac{\Delta\theta_{TO,U}}{\Delta\theta_{TO,R}}) - (\frac{\Delta\theta_{TO,i}}{\Delta\theta_{TO,R}})}{(\frac{\Delta\theta_{TO,U}}{\Delta\theta_{TO,R}})^{\frac{1}{n}} - (\frac{\Delta\theta_{TO,i}}{\Delta\theta_{TO,R}})^{\frac{1}{n}}} \tag{8}$$

In (7), C is thermal capacity and based on transformer cooling operation is calculated by (9) or (10). For ONAN and ONAF cooling operation:

$$C = 0.0272M_{CC} + 0.01814M_{Tank} + 5.034V_{Oil} \tag{9}$$

For forced oil cooling operation:

$$C = 0.0272M_{CC} + 0.0272M_{Tank} + 7.305V_{Oil} \tag{10}$$

M_{CC}, M_{Tank}, and V_{Oil} are weight of core and coil in kilograms, weight of tank in kilograms and volume of oil in liters.

Bottom oil model-Annex G

This mode is also called transformer bottom-oil thermal model (From IEEE standard C57.91-1995 Annex G.). This method is more complex compared to previous method, however the results are more accurate specially for transient loading conditions. It has been shown in [19] that in transient state, during overload the temperature of oil in cooling ducts raise rapidly with a time constant equals to winding time constant which results in higher winding hot spot temperature than the predicted value by Clause 7 model [2]. During transient overloading, the hottest spot temperature is higher than expected value calculated from IEEE top oil thermal model [20]. In this model type of liquid, cooling mode, oil viscosity and resistance changes, ambient temperature changes and load changes during a load cycle are considered [2]. This model can be used during short time load variation compare to oil time constant [21]. The main difference compared to IEC model is that IEEE annex G is not just for oil-immersed transformer but the equation s are valid for silicon and HTHC as well.

List of symbols for IEEE bottom oil model (annex G)

Table 4: List of symbols

Equation	Description
C_{Pcore}	Specific heat of core, $W - min/lb\,°C$
C_{POil}	Specific heat of oil $W - min/lb\,°C$
C_{Ptank}	Specific heat of tank $W - min/lb\,°C$
C_{PW}	Specific heat of winding $W - min/lb\,°C$
E_{HS}	Eddy loss at winding hot spot location, per unit of RI^2 loss
V_{oil}	Oil volume, gallons
H_{HS}	Per unit of winding height to hot spot location
I_R	Rated current
K_{HS}	Temperature correction for losses at hot spot location
K_W	Temperature correction for losses of winding
I	Per unit load
M_{CC}	Core and coil weight, lb
M_{core}	Mass of core, lb
M_{oil}	Mass of oil, lb
M_{tank}	Mass of tank, lb
M_W	Mass of winding, lb
$M_W C_{pw}$	Winding mass times specific heat
$P_{C,R}$	Core (no-load) loss, W
P_E	Eddy loss of winding, W
P_{EHS}	Eddy loss at rated winding hot spot temperature, W
P_S	Stray loss, W
P_T	Total loss, W
P_W	Winding RI^2 loss, W
P_{WHS}	Winding RI^2 loss at rated hot spot temperature, W
Q_C	Heat generated by core, $W - min$
$Q_{Gen,HS}$	Heat generated at hot spot temperature, $W - min$
$Q_{Gen,W}$	Heat generated by winding, $W - min$
$Q_{Lost,HS}$	Heat lost for hot spot calculation,$W - min$

Table 5: List of symbols

Equation	Description
$Q_{Lost,O}$	Heat lost by oil to ambient, $W - min$
$C_{Lost,W}$	Heat lost by winding $W - min$
Q_S	Heat generated by stray losses, $W - min$
ρ_{oil}	Oil density lb/in^3
Δt	Time increment for calculation, min
x	Exponent for duct oil rise over bottom oil
y	Exponent of average fluid rise with heat loss
z	Exponent for top to bottom oil temperature difference
θ	Temperature to calculate viscosity, $°C$
θ_A	Ambient temperature, $°C$
θ_{BO}	Bottom fluid temperature, $°C$
$\theta_{BO,R}$	Bottom fluid temperature at rated load, $°C$
θ_{DAO}	Average temperature of fluid in cooling ducts, $°C$
$\theta_{DAO,R}$	Average temperature of fluid in cooling ducts at rated load, $°C$
θ_{TDO}	Fluid temperature at top of ducts, $°C$
$\theta_{TDO,R}$	Fluid temperature at top of ducts at rated load, $°C$
θ_H	Winding hottest spot temperature, $°C$
$\theta_{H,R}$	Winding hottest spot temperature at rated load, $°C$
θ_K	Temperature factor for resistance correction, $°C$
T_{KH}	Correction factor for correction of losses to hot spot temperature, $°C$
θ_{KVA1}	Temperature base for losses at base kVA input, $°C$
θ_{AO}	Average fluid temperature in tank and radiator, $°C$
$\theta_{AO,R}$	Average fluid temperature in tank and radiator at rated load, $°C$
θ_{TO}	Top fluid temperature in tank and radiator at rated load, $°C$
$\theta_{TO,R}$	Top fluid temperature in tank and radiator, $°C$
θ_W	Average winding temperature, $°C$
θ_{WO}	Temperature of fluid adjacent to winding hot spot, $°C$
$\theta_{WO,R}$	Temperature of fluid adjacent to winding hot spot at rated load, $°C$

Table 6: List of symbols

Equation	Description
θ_{wr}	Rated average winding temperature at rated load, $°C$
$\theta_{W,R}$	Average winding temperature at rated load tested, $°C$
$\Delta\theta_{AO,R}$	Average fluid rise over ambient at rated load, $°C$
$\Delta\theta_{BO,R}$	Bottom fluid rise over ambient at rated load, $°C$
$\Delta\theta_{BO}$	Bottom fluid rise over ambient, $°C$
$\Delta\theta_{DO,R}$	Temperature rise of fluid at top of duct over ambient at rated load, $°C$
$\Delta\theta_{DO/BO}$	Temperature rise of fluid at top of duct over bottom fluid, $°C$
$\Delta\theta_{H/A}$	Winding hot spot rise over ambient, $°C$
$\Delta\theta_{H/WO}$	Winding hottest spot temperature rise over fluid next to hot spot location, $°C$
$\Delta\theta_{T/B}$	Temperature rise of fluid at top of radiator over bottom fluid, $°C$
$\Delta\theta_{TO}$	Top fluid rise over ambient, $°C$
$\Delta\theta_{TO,R}$	Top fluid rise over ambient at rated load, $°C$
$\Delta\theta_{KVA2}$	Rated average winding rise over ambient at kVA base of load cycle, $°C$
$\Delta\theta_{W/A,R}$	Tested or rated average winding rise over ambient, $°C$
$\Delta\theta_{WO/BO}$	Temperature rise of fluid at winding hot spot location over bottom fluid, $°C$
μ	Viscosity, cP
μ_{HS}	Viscosity of fluid for hot spot calculation, cP
$\mu_{HS,R}$	Viscosity of fluid for hot spot calculation at rated load, cP
μ_W	Viscosity of fluid for average winding temperature rise calculation, $°C$
$\mu_{W,R}$	Viscosity of fluid for average winding temperature rise at rated load, $°C$
τ_W	Winding time constant, min

Equations

Hot spot temperature consists of following components:

$$\theta_H = \theta_A + \Delta\theta_{BO} + \Delta\theta_{WO/BO} + \Delta\theta_{H/WO} \tag{11}$$

The process to calculate hot spot temperature of winding can be broken down to following tasks.

- **Average winding temperature**

Average winding temperature at time $t_2 = t_1 + \Delta t$ is a function of average winding temperature at time t_1 and heat generated and lost by winding during Δt.

$$M_W C_{PW}(\theta_{W,2} - \theta_{W,1}) = Q_{Gen,W}[t_1] - Q_{Lost,W}[t_1] \tag{12}$$

$$Q_{Gen,w} = I^2\big(P_W K_W + \frac{P_E}{K_W}\big)\Delta t \tag{13}$$

where

$$K_W = \frac{\theta_{W,1} + \theta_K}{\theta_{W,R} + \theta_K} \tag{14}$$

For $\theta_{W,1}$ less than $\theta_{DAO,1}$, we change the value of $\theta_{W,1}$ and makes it equal to $\theta_{BO,1}$ and therefore winding heat lost would be zero. For the other case, $Q_{Lost,W}$ is calculated using (15) or (19) based on transformer cooling mode.

For OA, FA, and NDFOA cooling modes the heat lost by the winding is

$$Q_{Lost,W} = \left(\frac{\theta_{W,1} - \theta_{DAO,1}}{\theta_{W,R} - \theta_{DAO,R}}\right)^{5/4} \left(\frac{\mu_{W,R}}{\mu_{W,1}}\right)^{1/4} (P_W + P_E)\Delta t, \tag{15}$$

where

$$\theta_{DAO,1} = \frac{\theta_{TDO,1} + \theta_{BO,1}}{2} \tag{16}$$

$$\mu_{W,R} = D \exp\left(G/\left(\left(\theta_{W,R} + \theta_{DAO,R}\right)/2 + 273\right)\right), \tag{17}$$

$$\mu_{W,1} = D \exp\left(G/\left(\left(\theta_{W,1} + \theta_{DAO,1}\right)/2 + 273\right)\right), \tag{18}$$

and where, D and G are constants which depend on fluid material.

Table 7: My caption

Material	**D**	**G**
Oil	0.0013573	2797.3
Silicon	0.12127	1782.3
HTHC	0.00007343	4434.7

For DFOA cooling mode, as the oil is pumped, the effect of viscosity is negligible and the heat loss is

$$Q_{Lost,W} = \left(\frac{\theta_{W,1} - \theta_{DAO,1}}{\theta_{W,R} - \theta_{DAO,R}}\right)(P_W + P_E)\Delta t \tag{19}$$

Winding time constant can be used to estimate mass times specific heat of winding.

$$M_W C_{PW} = \frac{(P_W + P_E)\tau_W}{\theta_{W,R} - \theta_{DAO,R}} \tag{20}$$

Using (12), average winding temperature at t_2 is

$$\theta_{W,2} = \frac{Q_{Gen,W} - Q_{Lost,W} + M_W C_{PW}\theta_{W,1}}{M_W C_{PW}} \tag{21}$$

- **Winding duct oil temperature rise over bottom oil**

For ONAN, ONAF, and OFAF cooling modes, temperature at top of duct at rated load is assumed equal to $\theta_{TO,R}$. For ODAF, it is equal to $\theta_{W,R}$.

$$\Delta\theta_{DO/BO} = \left[\frac{Q_{Lost,W}}{(P_E + P_W)\Delta t}\right]^x (\theta_{TDO,R} - \theta_{BO,R}) \tag{22}$$

$$\theta_{TDO} = \theta_{BO} + \Delta\theta_{DO/BO} \tag{23}$$

Since winding hot spot location is not necessarily at top of winding, the oil temperature adjacent to hot spot location can be calculated using per unit of winding height to hot spot location.

$$\Delta\theta_{WO/BO} = H_{HS}(\theta_{TDO} - \theta_{BO}) \tag{24}$$

$$\theta_{WO} = \theta_{BO} + \Delta\theta_{WO/BO} \tag{25}$$

However, if the temperature at top of duct is less than top oil temperature, then

$$\theta_{WO} = \theta_{TO} \tag{26}$$

- **Winding hottest spot temperature**

To consider additional heat generated at hot spot temperature, Winding heat lost is corrected for hot spot temperature.

$$Q_{Gen,HS} = I^2\big(P_{HS}K_{HS} + \frac{P_{EHS}}{K_{HS}}\big)\Delta t, \tag{27}$$

where

$$K_W = \frac{\theta_{H,1} + \theta_K}{\theta_{H,R} + \theta_K}. \tag{28}$$

For OA, FA, and NDFOA cooling modes the heat lost at the winding hot spot location is

$$Q_{Lost,HS} = \left(\frac{\theta_{H,1} - \theta_{WO,1}}{\theta_{H,R} - \theta_{WO,R}}\right)^{5/4}\left(\frac{\mu_{H,R}}{\mu_{H,1}}\right)^{1/4}(P_{HS} + P_{EHS})\Delta t, \tag{29}$$

and for DFOA cooling mode the corresponding value is

$$Q_{Lost,HS} = \left(\frac{\theta_{H,1} - \theta_{WO,1}}{\theta_{HS,R} - \theta_{WO,R}}\right)(P_{HS} + P_{EHS})\Delta t, \tag{30}$$

and the winding hot spot temperature at time t_2 is

$$\theta_{H,2} = \frac{Q_{Gen,HS} - Q_{Lost,HS} + M_W C_{PW}\theta_{H,1}}{M_W C_{PW}}. \tag{31}$$

- **Average oil temperature**

Fluid in the tank absorbs the heat from duct oil and heat generated by core and stray losses. Heat in duct oil comes from heat lost by winding. In this model, we assume core loss constant.

$$Q_C = P_{C,R}\Delta t \tag{32}$$

Heat generated by stray losses varies with temperature:

$$Q_S = \left[\frac{I^2 P_S}{K_W}\right]\Delta t \tag{33}$$

The heat lost by the oil to ambient is

$$Q_{Lost,O} = \left[\frac{\theta_{AO,1} - \theta_{A,1}}{\theta_{AO,R} - \theta_{A,R}}\right]^{1/y} P_T\Delta t \tag{34}$$

Knowing winding specific heat and using (20) winding mass can be calculated.

$$M_W = \frac{M_W C_{PW}}{C_{PW}} \tag{35}$$

Core mass can be calculated by subtracting the winding weight from total core and coil weight.

$$M_{Core} = M_{CC} - M_W \tag{36}$$

$$\Sigma MC_P = M_{Tank}C_{PTank} + M_{Core}C_{PCore} + M_{Oil}C_{POil} \tag{37}$$

The average oil temperature at time t_2 is

$$\theta_{AO,2} = \frac{Q_{Lost,W} + Q_S + Q_C - Q_{Lost,O} + (\Sigma MC_P)\theta_{A0,1}}{\Sigma MC_P}. \tag{38}$$

- **Top and bottom oil temperature**

$$\Delta\theta_{T/B} = [\frac{Q_{Lost,O}}{P_T \Delta\theta}]^z (\theta_{TO,R} - \theta_{BO,R}) \tag{39}$$

For OA and FA, $z = 0.5$ and NDFOA and DFOA, it is one.

$$\theta_{TO} = \theta_{AO} + \frac{\Delta\theta_{T/B}}{2} \tag{40}$$

$$\theta_{BO} = \theta_{AO} - \frac{\Delta\theta_{T/B}}{2} \tag{41}$$

If bottom fluid temperature calculated in (41) is less than ambient temperature, then

$$\theta_{BO} = \theta_A. \tag{42}$$

If bottom oil fluid either form (41) or (42) is more than Top of duct temperature calculated in step 2, then

$$\theta_{TDO} = \theta_{BO}. \tag{43}$$

2.6 IEC thermal models

IEC 60076-7 has two thermal models to calculate hot spot temperature. These models have different applications. The equations for these solutions are introduced in the next section.

IEC thermal model-exponential equations

This method is suitable for a load variation according to a step function and is mainly used to estimate heat transfer parameters [1].

IEC thermal model-Differential equations

This method is suitable for arbitrarily time varying load factor and ambient temperature. Therefore it is applicable for on-line monitoring. This model can be used for short time intervals compare to oil time constant. All symbols are

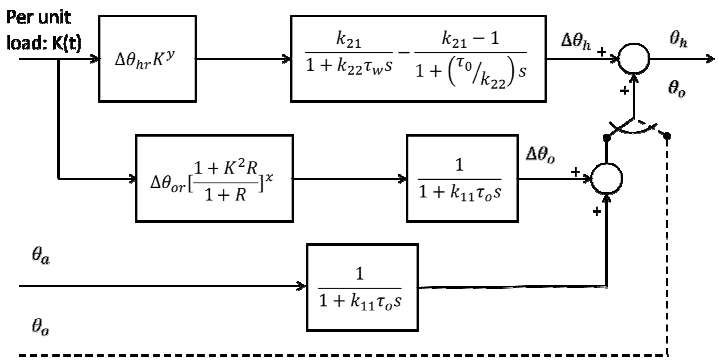

Figure 1: IEC differential equations block diagram representation [1]

defined in Table 8

Table 8: IEC model symbols

Symbol	Definition	Unit
C	Thermal capacity	Ws/K
c	Specific heat	$Ws/(kg.K)$
D	Difference operator	
m_A	Mass of core and coil assembly	kg
m_T	Mass of tank and fittings	kg
m_O	Mass of oil	kg
m_W	Mass of winding	kg
k_11	Thermal model constant	
k_12	Thermal model constant	
k_22	Thermal model constant	
K	Load factor	$p.u.$
P	Supplied losses	W
P_e	Relative winding eddy losses	$p.u.$
P_w	Winding losses	W
R	Ratio of load losses at rated current to no load losses	
x	Oil exponent	
y	Winding exponent	
θ_a	Ambient temperature	$^\circ C$
θ_h	Hot spot temperature	$^\circ C$
θ_o	Top oil temperature	$^\circ C$
τ_o	Average oil time constant	min
τ_w	Winding time constant	min
$\Delta\theta_h$	Hot spot to top oil gradient	$^\circ C$
$\Delta\theta_{hr}$	Hot spot to top oil gradient at rated current	$^\circ C$
$\Delta\theta_o$	Top oil temperature rise	$^\circ C$
$\Delta\theta_{or}$	Top oil temperature rise in steady state at rated losses	$^\circ C$

Top oil temperature equation is:

$$\left[\frac{1+K^2R}{1+R}\right]^x (\Delta\theta_{or}) = k_{11}\tau_o\frac{d\theta_o}{dt} + [\theta_o - \theta_a] \tag{44}$$

Hot spot temperature rise is calculated by

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2}, \tag{45}$$

where

$$k_{21}\, K^y\, (\Delta\theta_{hr}) = k_{22}\, \tau_w\, \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1}, \tag{46}$$

$$(k_{21} - 1)\, K^y\, (\Delta\theta_{hr}) = \frac{\tau_o}{k_{22}}\, \tau_w\, \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2}. \tag{47}$$

Finally, hot spot temperature is calculated by

$$\theta_h = \theta_o + \Delta\theta_h. \tag{48}$$

Figure 1 shows a chart representing differential equations method.

IEC thermal model-Difference equation

The differential equations can be converted to difference equations. This method is discussed in detail in annex C in IEC standard [1]. In case of using this way of solving differential equations,this case time step should be selected as small as possible and shouldn't be larger than one-half of the smallest time constant in the equations which normally belong to oil time constant [1].

$$D\theta_o = \frac{Dt}{k_{11}\tau_o}\left[\frac{1+K^2R}{1+R}\right]^x \Delta\theta_{or} - (\theta_o - \theta_a) \tag{49}$$

$$\theta_o(n) = \theta_o(n-1) + D\theta_o(n) \tag{50}$$

$$D\Delta\theta_{h1}(n) = \frac{Dt}{k_{22}\tau_w}(k_{21}\Delta\theta_{hr}K^y - \Delta\theta_{h1}) \tag{51}$$

$$D\Delta\theta_{h2}(n) = \frac{Dt}{\frac{1}{k_{22}}\tau_w}\left((k_{21}-1)\,\Delta\theta_{hr}K^y - \Delta\theta_{h2}\right) \tag{52}$$

$$\Delta\theta_{h1}(n) = \Delta\theta_{h1}(n-1) + D\Delta\theta_{h1} \tag{53}$$

$$\Delta\theta_{h2}(n) = \Delta\theta_{h2}(n-1) + D\Delta\theta_{h2} \tag{54}$$

$$\Delta\theta_h(n) = \Delta\theta_{h1}(n) - \Delta\theta_{h2}(n) \tag{55}$$

$$\theta_h(n) = \theta_o(n) + \Delta\theta_h(n) \tag{56}$$

2.7 Other thermal models

Besides thermal models recommended by IEEE and IEC standards which are widely accepted, there are other thermal models in the literature. In this section some of these thermal models are discussed.

Linearized top oil form IEEE clause 7 [22] [23]

This model is proposed by [22]. The model is a linear model for nonlinear thermal model presented in IEEE clause 7. In this model, $n = 1$ and constant regardless of cooling mode.

$$T_o\frac{\partial\theta_o}{\partial t} = -\theta_o + \Delta\theta_u + \theta_{amb}$$

$$\Delta\theta_u = \Delta\theta_{oil,R}\left(\frac{I^2R+1}{R+1}\right)^n \tag{57}$$

$$\tau_{oil} = \frac{C_{oil}.\Delta\theta_{oil,R}}{P_{T,R}} \tag{58}$$

Where: R is the ratio of load losses to no-load losses at rated load. I is the ratio of load to rated load. $\Delta\theta_{oil,R}$ is $\Delta\theta_{oil}$ at rated load and ambient temperature.

Assuming $n = 1$ and using a forward Euler approximation:

$$\frac{\partial\theta_o}{\partial t} \approx \frac{\theta_0(t) - \theta_0(t-1)}{\Delta t}$$

$$\theta_o = \frac{\tau_o}{\tau_o+\Delta t}\theta_o[t-1] + \frac{\Delta t}{\tau_o+\Delta t}\theta_{amb}[t] + \frac{\Delta t\,\Delta\theta_{O,R}R}{\tau_o+\Delta t(R+1)}\left(\frac{I[t]}{I_{rated}}\right)^2 + \frac{\Delta t\,\Delta\theta_{O,R}}{\tau_o+\Delta t(R+1)}$$

$$\theta_o = K_1\theta_o[t-1] + (1-K_1)\theta_{amb}[t] + K_2 I[t]^2 + K_3$$

Then:

$$K_1 = \frac{\tau_o}{\tau_o + \Delta t} \tag{59}$$

$$K_2 = \frac{\Delta t\, \Delta\theta_{O,R} R}{T_o + \Delta t(R+1)} \tag{60}$$

$$K_3 = \frac{\Delta t\, \Delta\theta_{O,R}}{T_o + \Delta t(R+1)} \tag{61}$$

Using standard least-squares technique (linear regression technique [23]), the values for K_1 to K_3 can be estimated. It is assumed that $n = 1$(forced cooling state) which is based on [1] corresponds to ODAF transformer. In [23] it has been shown that this assumption is true for OFAF transformer as well.

Swift model [24]

This model is based on heat transfer equations and is derived from thermal-electrical analogy. The heat transfer is done by conduction.

- Thermal-electrical analogy

Using Table 9, thermal equivalent of electrical equations are as follow:

Table 9: thermal-electrical analogy [4]

	Thermal	**Electrical**
Through variable	heat transfer rate, q watts	current,i amps
Across variable	temperature, θ degrees	voltage, v volts
Dissipation element	thermal resistance, R_{th} degC/watt	elec. resistance, R_{el} ohms
Storage element	thermal capacitance, C_{th} jouls/deg C	elec. capacitance, C_{el} farads

$$v = R_{el} i \qquad \theta = R_{th} q$$

$$i = C_{el}\frac{\partial v}{\partial t} \qquad q = C_{th}\frac{\partial \theta}{\partial t}$$

For heat transfer, the thermal resistance may not be linear and in this case it can be presented as

$$\theta = R_{th,R} q^n, \tag{62}$$

where, $R_{th,R}$ is rated thermal resistance. Suppose an oil tank without any fan. Heat transfer between oil inside the tank and air outside the tank is a function of temperature difference between air and oil. However when the temperature difference doubled, the heat transfer does not doubled. Actually it becomes more than double due to fact when the air become warmer it becomes lighter and moves faster [4]. Then (62) can be written as

$$q = \frac{1}{R_{th,R}}.(\theta)^{\frac{1}{n}}, \quad \text{with } \frac{1}{n} > 1 \tag{63}$$

In (63), θ is the temperature difference between oil and air. Typically, when there is no fan for cooling operation n is equal to 0.8 and in case air is force to flow faster n is one. Knowing these characteristics of heat transfer in transformers, oil to air heat transfer can be modeled and following equations are derived [4]:

$$q_{Cu} + q_{Fe} = C_{oil}\frac{d\theta_{oil}}{dt} + \frac{1}{R_{oil,R}}.[\theta_{oil} - \theta_{amb}]^{\frac{1}{n}} \tag{64}$$

In (64), q_{Cu}, q_{Fe}, C_{oil}, and $R_{oil,R}$ are losses in windings, losses in core, oil thermal capacity, oil resistance under rated conditions, respectively. Rated condition is when the ambient temperature is $30°C$, load is at rated load and steady state. Then (64) can be rewritten as:

$$\frac{K^2R+1}{R+1}[\Delta\theta_{oil,R}]^{\frac{1}{n}} = \tau_{oil}\frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{\frac{1}{n}} \tag{65}$$

In (65), k is the ration of actual load to rated load, τ_{oil} is $R_{oil,R}.C_{oil}$, R is the ratio of q_{Cu} to q_{Fe} at rated load , $\Delta\theta_{oil,R}$ is $\Delta\theta_{oil}$ at rated load and ambient temperature. Then the difference equation would be:

$$\mathbf{D\theta_{oil}} = \frac{\mathbf{Dt}}{\tau_{\mathbf{oil}}}.\left[[\theta_{\mathbf{oil}} - \theta_{\mathbf{amb}}]^{\frac{1}{n}} - \frac{\mathbf{K^2R+1}}{\mathbf{R+1}}[\mathbf{\Delta\theta_{oil,R}}]^{\frac{1}{n}}\right] \tag{66}$$

Equation (66) calculates the difference between oil temperature at time t compared to previous time. This value is added to old value of oil temperature to calculate oil temperature at time t. Traditionally the temperature that can be used as oil temperature is top oil temperature. In this report, this thermal model is called Swift model. In [4], differential equation corresponding to exponential equation in [2] is derived as

$$\frac{K^2R+1}{R+1}[\Delta\theta_{TO,R}]^n = \tau_{TO,R}\frac{d\Delta\theta_{TO}}{dt} + \Delta\theta_{TO}, \tag{67}$$

where, $\Delta\theta_{TO}$ is the same as $\Delta\theta_{oil}$ in (65), and $\tau_{TO,R}$ is the same as τ_{oil} in (66). The fundamental differences between (67) and (65) are [4]:

- Equation (67) is derived to calculate top oil rise over ambient while the dependent variable in (65) is top oil temperature.
- The placement of n is different.

Susa model [25]

This model is proposed in [25]. In this report we call this model as Susa model. The heat transfer assumed to be in convection mode. This model is developed based on variation in oil viscosity and winding resistance due to changes in temperature.

2.8 Comparison of thermal models

It is claimed in [26] that the top oil model from IEEE (Clause 7) has poor performance compared to top oil models trained with measured data because models using measured data considers unexpected parameters such fouled heat

Table 10: Comparison of required data for IEEE annex G model 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	✓	⋆

exchanger. It has been shown in a study that even a simplified linear model based on measured data has better performance compared to this standard model [27]. More details about IEEE Clause 7 model limitations can be found in [28]. There are efforts to determine the best model to predict the top oil temperature, however there is not any answer yet. One aspect is clear: IEEE Clause 7 would not be the best for several reasons based on [27]:

1. It does not consider the ambient temperature variations in the model [22].
2. It has been shown in [25] and [4] that the placement of n is not optimal.

IEEE Annex G requires more input data such as bottom oil temperature beyond conventional monitored data including load, ambient temperature, and top oil temperature. Currently, monitoring these additional data is rarely done by utility owners [27]. Linear top oil model is unacceptable for $NOFA$ transformers while it is the most accurate model between IEEE Clause 7($NTOP$), $LTOP$, Susa model and Swift model for $FOFA$ transformers [29]. It has been shown that Swift model results is more accurate when used for transformers with oil pumps which results in oil circulation independent of oil viscosity. However in case there is not oil pumps, Susa model performs better compared to Swift model as it considers oil viscosity [29].

IEC and IEEE comparison

In [25] it has been noticed that hot spot temperature calculated in IEEE Annex G model is an accurate estimation of measured value while the top oil results do not follow the measured values accurately. A comparison between IEEE annex G and IEC difference equations regarding required data is presented in Table 10

2.9 Reliability

Based on [30] reliability is defined as "the probability that a transformer will perform its specified function under specified conditions for a specific period of time". In addition to increasing network efficiency, decreasing failures and increasing life of components are among the main purposes of dynamic rating of power components [31]. Overloading does not have any impact on failure rate in some power system components such as aerial lines, circuit breakers and busbars, while it increases the failure rates in other components such as transformers [32]. Overloading in transformers results in formation of bubbles in oil which leads to reduction of dielectric strength. This phenomenon increases the risk of failure in transformers. By employing thermal rating a better monitoring of transformer critical temperatures is achieved which can increase the reliability [5].

2.10 Loss of life

Transformers are designed to work continuously with nameplate rating and under normal operation which means constant hot spot temperature equal to $110°C$. In this conditions transformer does not exceed its normal life. There are different definitions for normal life [2]. If a transformer has a lower hot spot temperature during its operation, then the life expectancy increases while higher hot spot temperature results in shorter life expectancy. Traditionally, insulation paper tensile strength is being used as age determination.Based on this criteria transformer normal life can be defined as it is shown in Table 12.

Table 11: Aging rate constant [2]

Source	**Basis**	**B**
Dakin [33]	20% tensile strength retention	18000
Sumner [34]	20% tensile strength retention	18000
Head [35]	Mechanical/DP/gas evolution	15250
Lawson [36]	10% tensile strength retention	15500
Lawson [36]	10% DP retention	11350
Shroff [37]	250 DP	14580
Lampe [38]	200 DP	11720
Goto [39]	Gas evolution	14300
ASA C57-92-1948	50% tensile strength retention	14830
ANSI C57-92-1981	50% tensile strength retention	16054
ANSI C57-91-1981	DT life tests	14594

Actual age of transformer is of a concern to 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 load of transformer on loss of life. Aging of transformers affects the reliability of the system and is an important criterion in transformer's asset management. As the age of transformer increases, the capability of transformer to withstand severe events such as short circuit faults decreases which results in increase in probability of failure [40]. Deterioration of paper insulation is one of the main causes of failures in transformers.

Insulation deterioration is as a result of existence of oxygen and humidity in oil. Oil temperature acts as a catalyst in this chemical reaction [41]. Thus, in a situation with constant oxygen in oil and oil humidity, temperature is the only factor which needs to be controlled. By monitoring the hot spot temperature, utility owners can have an estimation on transformer aging process and decide on the most appropriate time to do maintenance service. Therefore maintenance would be condition-based rather than traditional time-based which may result in reduction of maintenance programs [40].

As it can be seen loss of life is highly dependent on hot spot temperature which indicates the importance of accuracy in hot spot temperature calculations. In this master thesis project, the effect of harmonics on hot spot temperature is not considered and voltage and current are assumed to be sinusoidal. The impact of harmonic on hot spot temperature and loss of life is discussed in [42]. IEEE standard [2] relates hot spot temperature to loss of life.

In this report, loss of life and transformer life expectancy are calculated based on the assumption that winding insulation aging is the only influencing factor.

Thermal aging

As it is mentioned previously, insulation degradation is as a result of a chemical reaction. Therefore aging rate can be expressed as a reaction rate constant K_0 [2]. This equation was first proposed by Dakin [33] and known as Dakin relationship or Arrhenius reaction rate equation [2].

$$K_0 = A' e^{\frac{B}{\theta+273}}, \tag{68}$$

where, A' and B are empirical constants and θ is temperature is $^\circ C$. To calculate aging rate regardless of end of life point, per unit life is defined as

$$\text{Per unit life} = \text{A} e^{\frac{B}{\theta_H+273}}. \tag{69}$$

Aging rate constant, B, is the same as in (68) and A is selected so that for θ_H equals to $110^\circ C$ the per unit life becomes one. Several researches have been done on finding the value of B. Results are shown in Table 11.

As it can be seen in Table 11 there is not a single value for aging rate constant and it varies between 11350 to 18000. One reason for that can be the differences in experimental conditions [2]. In this report, as it is suggested in [2] and [1], 15000 is selected for aging rate constant. To define the normal life a transformer, a mechanical characteristic is needed to be evaluated. Tensile strength is a mechanical characteristic that can be utilize as age indicator [2]. The only drawback is that it depends on initial strength as it is defined as percent of initial strength [2]. Another indicator of transformer age is absolute value of degree of polymerization (DP) as there is a correlation between mechanical properties and DP [2]. In IEEE, 200 is considered for DP for an end point for insulation life for power transformers. This value can be lower for distribution transformer. Considering DP equal to 200 for end point of life indicator for power transformers, 17.12 years would be acceptable normal life in this report while in industry, normally life expectancy is higher than 17 years. The reference value for DP is 200 when the moisture level is 0.2% to 0.3% by weight [2]. The

effect of water content on normal life is shown in [43].

$$\text{Normal life at}\%H_2O = \frac{\text{Normal life at reference}H_2O}{2 \times \%H_2O} \tag{70}$$

$$\text{Per unit life} = 9.8 \times 10^{-18} e^{\frac{15000}{\theta_H + 273}} \tag{71}$$

Per unit life is one at $110°C$, and when the temperature increases, per unit life decreases.

Relative aging factor [1] or aging acceleration factor F_{AA} is defined similarly in both IEC [1] and IEEE [2] and is calculated in (72)

$$F_{AA} = e^{\frac{15000}{110+273} - \frac{15000}{\theta_H + 273}} \tag{72}$$

Figure 2 illustrates aging acceleration factor as a function of hot spot temperature. It is equal to one for reference hot spot which is $110°C$ and for any temperature higher than reference value the aging factor accelerate while for lower hot spot temperature it decelerates.

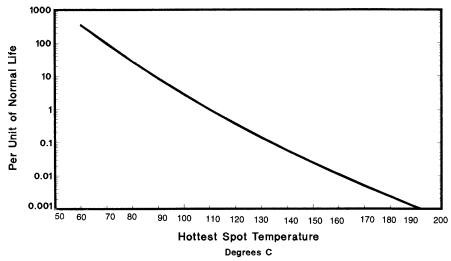

Figure 2: Transformer insulation life [2]

$$\%\text{Loss of life} = \frac{100\, F_{EQA}.t}{\text{Normal insulation life}} \tag{73}$$

Normal insulation life can be defined using Table 12. Loss of life is calculated using equation as it is suggested in [1] as

$$L = \int_{t_1}^{t_2} F_{AA} dt, \tag{74}$$

where, L is Loss of life during time period between t_1 and t_2.

Remaining life

By accepting 20% of tensile strength or 200 for DP as end point of life indicator, by having per unit life, retained tensile strength and retained DP can be calculated in (75) and (76), respectively.

$$\text{Retained Tensile Strength (RTS)} = 97.05 e^{-1.58T} \tag{75}$$

$$\text{Retained Degree of polymerization (RDP)} = 622 e^{-1.135T} \tag{76}$$

T is per unit life and it should be more than 0.24 to have accurate result in (76). Having calculated RTS or RDP remaining life can be calculated.

$$\text{Remaining Life} = 1 + 0.633 \ln \frac{RTS}{97.05} \tag{77}$$

$$\text{Remaining Life} = 1 + 0.88 \ln \frac{RDP}{622} \tag{78}$$

Table 12: Normal insulation life of transformer at the reference temperature of $110°C$ [2]

Basis	Normal insulation life	
	Hours	Years
50% retained tensile strength of insulation	65000	7.42
25% retained tensile strength of insulation	135000	15.41
200 retained degree of polymerization in insulation	150000	17.12
Interpretation of distribution transformer functional life test data	180000	20.55

2.11 Maximum contingency loading

Overloading the transformer is one necessity in liberated electricity market to maximize the profit when the energy price is high. However, the profit from overloading is not without cost. The cost of overloading is loss of life of transformer as a result of increased aging acceleration factor. The maximum contingency loading is defined in [24] as the maximum load so that "the loss of life of transformer over a complete day must not exceed the normal daily loss of life". This value is different for different ambient temperature. To calculate maximum contingency loading, favorable aging factor for entire year is selected. The corresponding hot spot temperature is calculated and it keeps constant value during the year. The variable parameter is ambient temperature which is input and load will be calculated. Figure 3 shows a block diagram representing maximum contingency loading process.

It is important to notice that although it is possible to overload transformer during some period of time when the ambient temperature is low, it is not recommended by standard loading guidelines. The reason is that it may cause some currently unknown electrical and mechanical stress on transformer which may increase the transformer failure risk [41]. Therefore it is important to follow the limitations which is recommended by [1] or [2]. These limitations are shown in Table 13 based on IEC suggestion.

By having ambient temperature forecast for transformer location, the maximum loading can be calculated and based on the maximum contingency loading the optimum transformer size can be selected. Therefore this method is more useful in feasibility study for purchasing a transformer. It also can be used to define maximum loading of transformer for any time step without online monitoring systems.

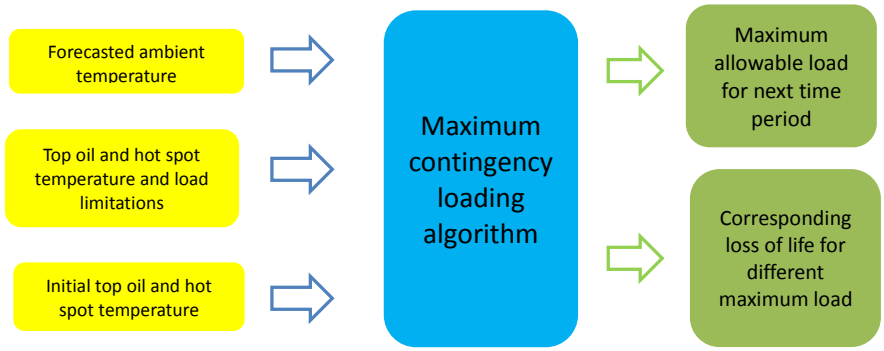

Figure 3: Block diagram representing maximum contingency loading

Table 13: IEC limits for maximum contingency loading

Current and temperature limits for medium power transformer	Normal cyclic loading	Long time emergency	Short time emergency
Current (p.u.)	1.5	1.5	1.8
Winding hot spot temperature and other metallic parts in contact with cellulosic insulation material	120	140	160
Other metallic hot spot temperature	140	160	180
Top oil temperature	105	115	115

3 Model implementation

In this section based on literature review, thermal models are selected to calculate hot spot temperature and corresponding loss of life. Difference equations from IEC and bottom oil model (Annex G) from IEEE are selected to be implemented to calculate hot spot temperature. MATLAB is used to implement models and run the calculations. Having hot spot temperature calculated, loss of life is calculated.

3.1 Transformer specification

In this section hot spot temperatures are calculated using IEC difference equations model and IEEE Annex G model. These models are implemented on a wind farm connected transformer belongs to Ellevio. The data are collected form transformer T1. Table 14 illustrates transformer specifications based on transformer's data sheet and heat run test.

Load and ambient temperature data

Load data is collected for every 5 minutes during 2016. Data are provided by Ellevio. Loads are from primary side, therefore primary rating current is used to calculate per unit load. Minimum load is 0 and maximum is 1.07. Since

Table 14: Transformer specification

Transformer specification			
Power	19400 kVA	Temperature reference	$75°C$
Primary voltage	44000 V	Temperature rise of top oil over ambient	$55.8°C$
Secondary voltage	$22000(11000)\,V$	Temperature rise of average oil	$44.1°C$
Rated HV current	$254.6\,A$	Temperature rise of winding	$63.5°C$
Rated LV current	509.1(1018) A	Hot spot temperature rise of winding	$78.3°C$
Cooling operation	ONAN	Load losses	$137500\,W$
Cold resistance of HV winding	$539\,m\Omega$	No load losses	$7370\,W$
Cold resistance of LV winding	$98.5\,m\Omega$	Rated ambient temperature	$23.9°C$
Hot resistance of HV winding	$679\,m\Omega$	Primary winding hot spot factor	1.16
Hot resistance of LV winding	$123.35\,m\Omega$	Secondary winding hot spot factor	1.21
Mass of core and coil	-	Specific heat of tank	$3.51\,W - min/lb°C$
Mass of tank	-	Specific heat of core	$3.51\,W - min/lb°C$
Mass of oil	-	Specific heat of oil	$13.92\,W - min/lb°C$

the transformer is connected to a wind farm, the load is basically the power generated at the wind farm and is a function of wind speed. Load probability is shown in Figure 4. As it can be seen almost 50% of time load is less than 0.2 per unit.

Hourly ambient temperature data are downloaded from Swedish Meteorological and hydrological Institute (SMHI) [44]. As there is not any weather station to collect temperature data at transformer location, temperature data from nearest weather station is gathered as ambient temperature data. Since time increment is selected to be 0.5 minutes, all data are linearly interpolated to have corresponding data for every 0.5 minutes.

3.2 Thermal model implementation: IEEE Annex G

To run this thermal model following data are acquired from transformer specification:

- Specific heat of core (core assumed to be steel)

$$C_{p,core} = 3.51\,W - min/lb\,°C$$

- Specific heat of oil

$$C_{p,oil} = 13.92\,W - min/lb\,°C$$

- Specific heat of winding (Copper).

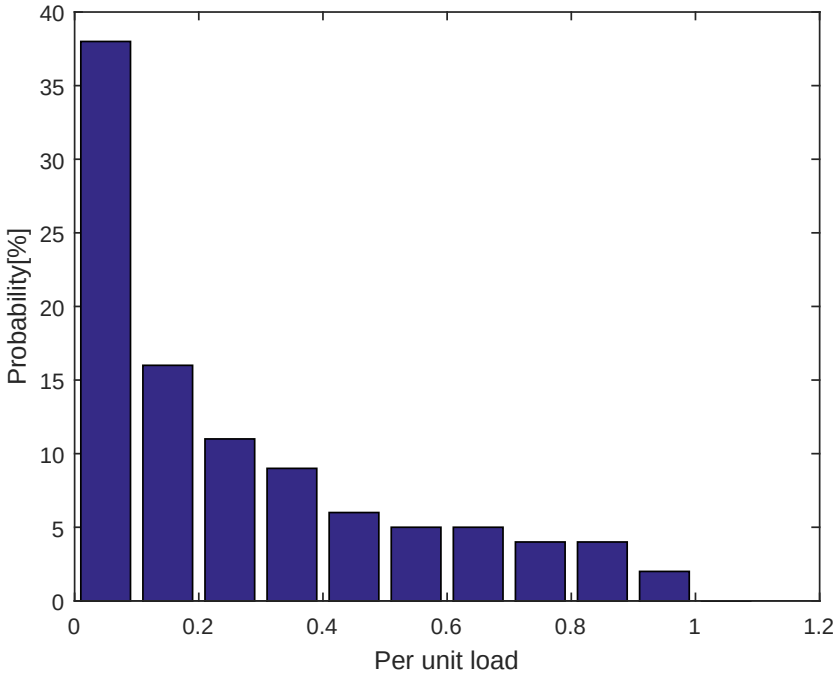

Figure 4: Probability distribution of per unit load during 2016

$$C_{p,w} = 2.91\,W - min/lb\,^{\circ}C$$

- Specific heat of tank (tank assumed to be steel).

$$C_{p,tank} = 3.51\,W - min/lb\,^{\circ}C$$

Following data are required from heat run test:

- Rated average winding rise over ambient: This value is equal to guaranteed value for this parameter.

$$\theta_{KVA2} = 65^{\circ}C$$

- Tested or rated average winding rise over ambient:

$$\Delta\theta_{W,R} = 63^{\circ}$$

- Tested or rated hot spot rise over ambient:

$$\Delta\theta_{H,R} = 78.3^{\circ}$$

- Tested or rated top oil rise over ambient: tested value is used.

$$\Delta\theta_{TO,R} = 55.8^{\circ}$$

.

- Tested or rated bottom oil rise over ambient : This value is not available in heat run test. However, average oil rise over ambient is available using equation below, bottom oil rise can be calculated (using line 1490).

$$\Delta\theta_{AO,R} = \frac{\Delta\theta_{BO,R} + \Delta\theta_{TO,R}}{2} = 44.1°C \tag{79}$$

$$\Delta\theta_{BO,R} = 2\Delta\theta_{AO,R} - \Delta\theta_{TO,R} = 2 \times 44.1 - 55.8 = 32.4 \tag{80}$$

- Rated ambient temperature: This value is the ambient temperature at which aforementioned values are measured:

$$\theta_{A,R} = 23.9°C$$

- Per unit of winding height to hot spot location: This value is

$$H_{HS} = 1.16.$$

- core (no load) losses
- core (no load) losses calculated at rated load:

$$P_C = 7370\,W$$

- Eddy loss of winding: This value is assumed to be zero based on instruction 1 from [2].
- Winding RI^2 losses calculated at rated load:

R is equal to hot resistance calculated in transformer heat run test report which is equal to 0.679Ω. I is rated current.

$$P_{W,ref} = RI^2 = 0.679 \times 254.6^2 = 44013.57W \tag{81}$$

- Load losses calculated at rated load : $137500W$
- Stray loss: Since Eddy loss is zero, stay loss is the difference between load losses and winding RI^2 losses.

$$P_{S,ref} = P_{load,ref} - P_{W,ref} = 93486.43W \tag{82}$$

The losses are measured at reference temperature equals to $75°C$.

$$\theta_{KVA1} = 75°C$$

The following equations are used to calculate losses at ambient temperature.

$$\theta_{wr} = \theta_{A,R} + \theta_{KVA2} = 23.9 + 65 = 88.9°C \tag{83}$$

$$T_{K2} = \frac{T_K + \theta_{wr}}{T_K + \theta_{KVA1}} = 1.04 \tag{84}$$

$$P_W = T_{K2}.P_{W,ref} = 1.04 \times 44013.57 = 45774.11\,W \tag{85}$$

$$P_S = \frac{P_{S,ref}}{T_{K2}} = \frac{93486.43}{1.04} = 89890.80\,W \tag{86}$$

$$P_E = \frac{P_{E,ref}}{T_{K2}} = \frac{0}{1.04} = 0\,W \tag{87}$$

Then total losses would be:

$$P_T = P_W + P_S + P_E + P_C = 143034.91\,W \tag{88}$$

- Winding RI^2 losses at hot spot temperature at rated load can be calculated. To do that, first, correction factor for correction of losses to hot spot temperature is calculated.

$$T_{KH} = \frac{\theta_{H,R} + T_K}{\theta_{wr} + T_K} = \frac{102.2 + 234.5}{88.9 + 234.5} = 1.04$$
$$P_{HS} = P_W.T_{KH} = 47605.07\,W \tag{89}$$

Using these input data, following input data can be calculated:

- Top oil temperature in tank and radiator at rated load:

$$\theta_{TO,R} = \Delta\theta_{TO,R} + \theta_{A,R}\theta_{TO,R} = 79.7°C \tag{90}$$

- Bottom oil temperature at rated load:

$$\theta_{BO,R} = \Delta\theta_{BO,R} + \theta_{A,R} = 56.3°C \tag{91}$$

- Average oil temperature in tank and radiator at rated load:

$$\theta_{AO,R} = \frac{\theta_{BO,R} + \theta_{TO,R}}{2} = 68°C \tag{92}$$

- Average winding temperature at rated load:

$$\theta_{W,R} = \Delta\theta_{W,R} + \theta_{A,R} = 86.9°C \tag{93}$$

- Oil temperature at top of duct at rated load: This temperature is assumed to be equal to top oil temperature at rated oil.

$$\theta_{TDO,R} = \theta_{TO,R}$$

- Average temperature of oil in cooling ducts at rated load: This temperature is assumed to be equal to average oil temperature in tank at rated load.

$$\theta_{DAO,R} = \theta_{AO,R}$$

- Temperature of oil adjacent to winding hot spot at rated load

$$\theta_{WO,R} = H_{HS}(\theta_{TDO,R} - \theta_{BO,R}) - \theta_{BO,R} = 83.44°C \tag{94}$$

- Winding hot spot temperature at rated load:

$$\theta_{H,R} = \Delta\theta_{H,R} + \theta_{A,R} = 102.2°C \tag{95}$$

Table 15: Transformer specification

Parameter	Value	Parameter	Value
M_{CC}	-	P_W	$45774.11\,W$
M_{Tank}	-	$P_{S,ref}$	$93486.43\,W$
V_{Oil}	-	P_S	$89890.80\,W$
ρ_{Oil}	0.0347	P_E	0
M_{Oil}	-	P_T	$143034.91\,W$
C_{Pcore}	$3.51\,W - min/lb$	T_{KH}	1.04
C_{Ptank}	$3.51\,W - min/lb$	P_{HS}	$47605.07\,W$
C_{PW}(Copper)	$2.91\,W - min/lb$	$\theta_{TO,R}$	79.7
C_{Poil}	$13.92\,W - min/lb$	$\theta_{BO,R}$	56.3
θ_{KVA2}	$65°C$	$\theta_{AO,R}$	$68°C$
$\Delta\theta_{W,R}$	$63°C$	$\theta_{W,R}$	$89.9°C$
$\Delta\theta_{H,R}$	$78.3°C$	$\theta_{TDO,R}$	$79.7°C$
$\Delta\theta_{TO,R}$	$55.8°C$	$\theta_{DAO,R}$	$68°C$
$\Delta\theta_{AO,R}$	$44.1°C$	$\theta_{WO,R}$	$83,44°C$
$\Delta\theta_{BO,R}$	$32.4°C$	$\theta_{H,R}$	$102.2°C$
$\theta_{A,R}$	$23.9°C$	x	0.5
H_{HS}	1.16	y	0.8
θ_{KVA1}	$75°C$	z	0.5
$P_{W,ref}$	$44013.57\,W$		

3.3 Initial values

To run the model following initial values are needed. These values are set to be equal to corresponding values at rated load.

- Initial winding hot spot temperature

$$\theta_{H,initial} = \theta_{H,R}$$

- Initial average winding temperature

$$\theta_{W,initial} = \theta_{W,R}$$

- Initial top oil temperature

$$\theta_{TO,initial} = \theta_{TO,R}$$

- Initial top duct oil temperature

$$\theta_{TDO,initial} = \theta_{TDO,R}$$

- Initial bottom oil temperature

$$\theta_{BO,initial} = \theta_{BO,R}$$

3.4 Thermal model implementation: IEC difference equations

Following data are used from transformer specification data to run the IEC differential equations model.

- Ratio of load losses at rated current to no load losses

$$R = \frac{137500}{7370} = 18.66$$

- Top oil temperature rise at rated losses (no-load losses+ load losses)

$$\Delta\theta_{or} = 55.8°C$$

- Hot spot to top oil gradient at rated current

$$\Delta\theta_{hr} = 22.5°C$$

Winding and oil time constant for IEC model

Thermal model constants and winding and oil time constants are selected from [1]. Based on [1], this transformer is a medium power transformer and corresponding constants are presented in Table 16

Table 16: IEC model thermal characteristics [1]

Medium power transformer with ONAN cooling operation	
Oil exponent x	0.8
Winding exponent y	1.3
Constant k_11	0.5
Constant k_21	2
Constant k_22	2
Time constant tau_o	210
Time constant tau_w	10

It is also possible to calculate winding and oil time constant based on following equations from [1].

$$\tau_o = \frac{C.\Delta\theta_{om}.60}{P} \tag{96}$$

Where τ_o is the average oil time constant in minute, $\Delta\theta_{om}$ is the average oil temperature rise over ambient at the load considered and P is supplied loss at load considered. In this report oil time constant is calculated at rated load and assumed constant for any load considered. The thermal capacity, C, for ONAN and ONAF is calculated in equation

$$C = 0.132\, m_A + 0.0882\, m_T + 0.400\, m_O \tag{97}$$

Where m_A, m_T, and m_O are mass of core and coil, tank ,and oil in kilograms, respectively. Using (97) and (96), the calculated oil time constant is 82.79 minutes. The following equation is used to calculate winding time constant in minutes.

$$\tau_w = \frac{m_W.c.g}{60P_W} \tag{98}$$

Where g is the winding to oil temperature gradient at the load considered, m_W is the mass of winding, c is specific heat of conductor and P_W is the winding loss at the load considered. As in oil time constant calculation, winding time constant is calculated as rated load and assumed to be constant for varying load. In this condition, τ_w is 4.97 minutes.

Measurements from transformer

The transformer has an installed equipment called $PT100$ which measures the winding average temperature. This equipment is basically a current transformer located in top of the tank. The current goes through the device is proportional to current goes trough the windings. The current factor is β. Therefore, the following equation can be used to estimate the top oil temperature measurements.

$$\theta_{PT} = \theta_{TO} + \theta_{Loss} \tag{99}$$

In this equation, θ_{PT} is the temperature that the device shows, θ_{TO} is the top oil temperature and θ_{Loss} is the temperature rise in the device as a result of heat generated by electrical losses.

$$Q_{Loss} = R_{PT}(\beta I)^2 \tag{100}$$

$$\theta_{Loss} = k(Q_{Loss})^n \tag{101}$$

$$\theta_{Loss} = kR_{PT}^n \beta^{2n} I^{2n} \tag{102}$$

In (102), I is per unit load and θ_{Loss} is a function of I and $kR_{PT}\beta$ is constant which can be calculated using (99) and (102) for rated current. Also, n is selected as oil exponent and is equal to 0.8.

$$\theta_{Loss,R} = 7.7°C \tag{103}$$

$$\theta_{Loss,R} = kR_{PT}^n \beta^{2n} I_R^{2n} \tag{104}$$

$$kR_{PT}^n \beta^{2n} = \frac{\theta_{Loss,R}}{I_R^{2n}} = 7.7 \tag{105}$$

It is assumed that $kR_{PT}^n \beta^{2n}$ remains constant for variable load. Having calculated θ_{PT}, θ_{TO} can be calculated. This value is an estimation of top oil temperature measurement.

4 Results and discussion

In this section results from simulations are illustrated and discussed. After calculating hot spot temperature, the loss of life is calculated using (74). Using calculated hot spot temperature, maximum contingency loading for the transformer is calculated for three cases. Moreover, some applications for utilizing hot spot temperature for transformer dynamic rating are presented and the risk of overloading the transformer by implementing dynamic rating is calculated. Finally, based on findings on loss of life calculated for the investigated transformer, suggestions for new wind farm planning and also currently installed transformers are proposed.

4.1 IEEE Annex G

After running the model, top oil, bottom oil and hot spot temperatures are calculated for every 0.5 minutes. Figure 5 - 8 show hot spot temperature calculated for four sample days.

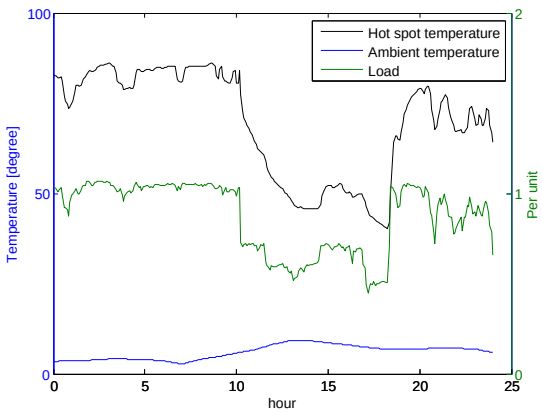

Figure 5: Hot spot temperature calculated using IEEE model 2016-10-29

As it can be seen in these figures load variations do not follow a cyclic pattern.

Loss of life is calculated using hot spot calculation results. After one year operating the loss of life would be 0.22 $[day/year]$ which means at the end of 2016, the transformer has lost 0.22 $[day/year]$ or 5.3 $[hour/year]$ of its expected life and the equivalent aging factor for the entire year is 0.00059.

Critical days

In this report, we define critical days as days with highest loss of life. In Figure 9, these days are referred to the points with the sharpest slope. Table 17 illustrates these days based on IEEE model calculations.

As it is shown in Table 17 , 50% of loss of life which is equal to 0.113 $[day/year]$ occurs in first 17 days of the table and 80% of total loss of life occurs in just 30 days of the year.

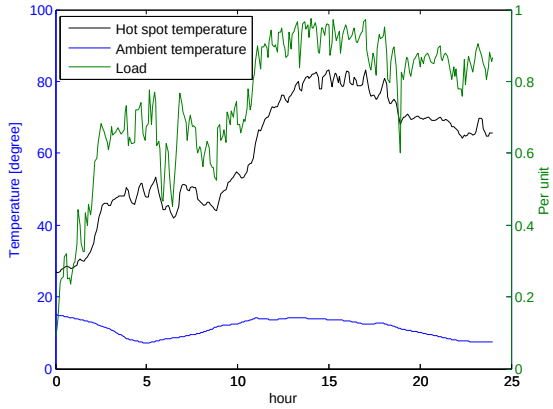

Figure 6: Hot spot temperature calculated using IEEE model 2016-06-08

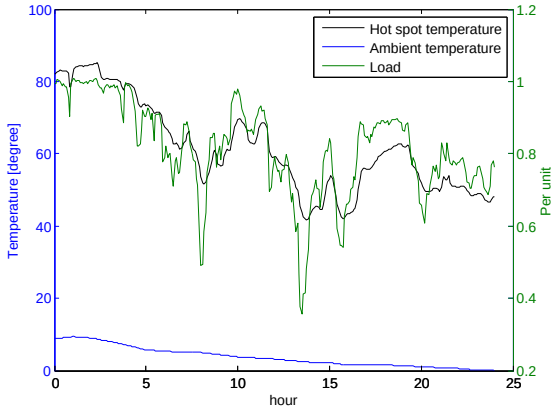

Figure 7: Hot spot temperature calculated using IEEE model 2016-12-05

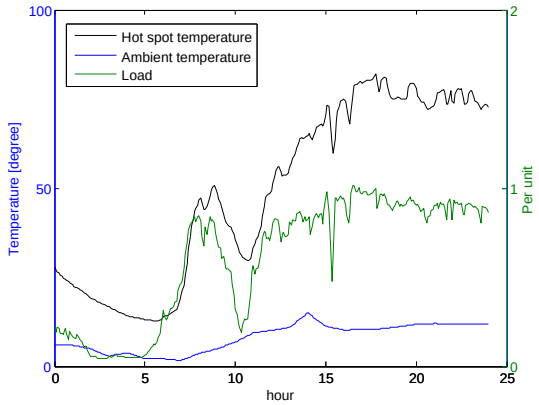

Figure 8: Hot spot temperature calculated using IEEE model 2016-09-29

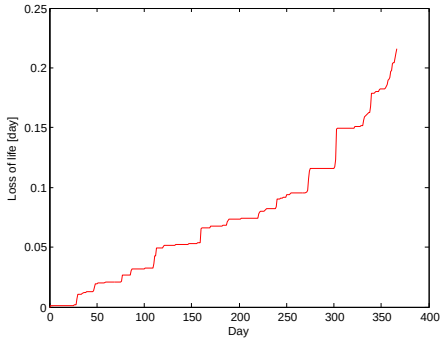

Figure 9: Daily loss of life calculated by IEEE thermal model

It can be seen in these graphs that hot spot temperature mainly follows the load.

Table 17: Critical days based on IEEE thermal model

Date	**Loss of life per day [day]**	**cumulative loss of life [day]**
2016-10-29	0.025448024	0.025448024
2016-06-08	0.011754016	0.03720204
2016-12-05	0.01124573	0.04844777
2016-09-29	0.009521834	0.057969604
2016-12-30	0.007682119	0.065651723
2016-04-20	0.006843155	0.072494878
2016-04-22	0.006613888	0.079108766
2016-09-30	0.006433407	0.085542173
2016-10-28	0.006317261	0.091859434
2016-08-27	0.006286864	0.098146299
2016-02-17	0.005845971	0.10399227
2016-12-27	0.005839025	0.109831295
2016-12-04	0.005377456	0.115208751
2016-03-17	0.005090561	0.120299311
2016-12-25	0.004654155	0.124953467
2016-01-29	0.004592317	0.129545784
2016-11-26	0.004174574	0.133720358
2016-01-30	0.004036978	0.137757335
2016-04-19	0.003814936	0.141572271
2016-08-08	0.00378588	0.145358152
2016-12-31	0.003754634	0.149112786
2016-12-22	0.003667691	0.152780477
2016-07-06	0.00317182	0.155952297
2016-03-26	0.003130227	0.159082525
2016-11-27	0.003050101	0.162132626
2016-10-01	0.002492263	0.164624889
2016-12-21	0.001964348	0.166589237
2016-03-27	0.001903337	0.168492574
2016-07-07	0.001851033	0.170343607
2016-09-06	0.001779103	0.17212271

4.2 IEC model

Top oil and hot spot temperatures are also calculated using IEC model for every half a minute for entire 2016. In Figure 10 - Figure 13 hot spot temperature calculated for the same days that it is calculated using IEEE model are shown. Then in Figure 14 - 17 hot spot temperature calculated using IEEE and IEC models are shown in one graph for the same four sample days.

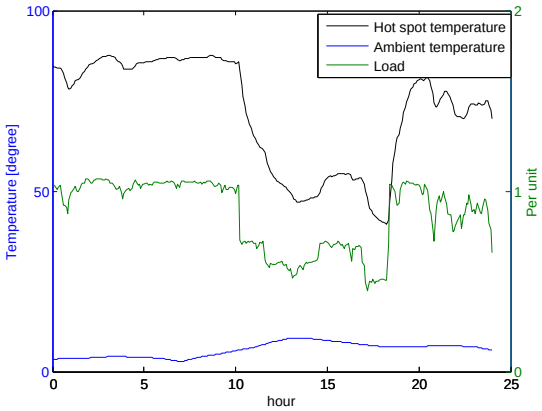

Figure 10: Hot spot temperature calculated using IEC model- 2016-10-29

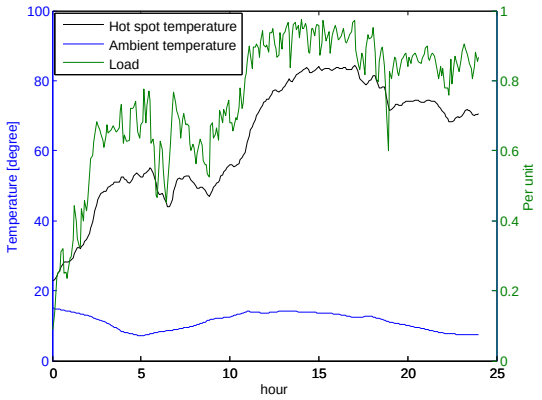

Figure 11: Hot spot temperature calculated using IEC model- 2016-06-08

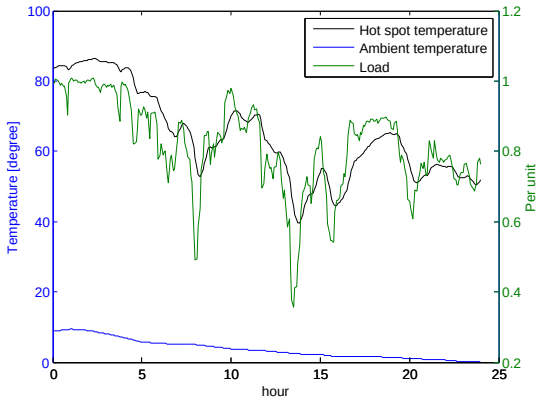

Figure 12: Hot spot temperature calculated using IEC model- 2016-12-05

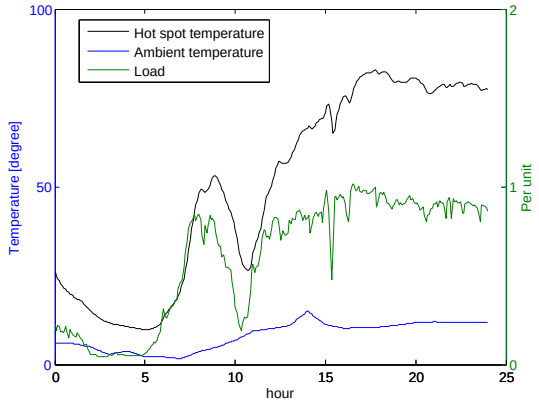

Figure 13: Hot spot temperature calculated using IEC model 2016-09-29

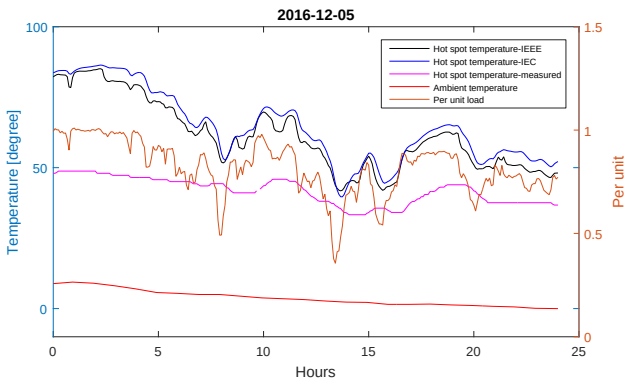

Figure 14: Hot spot temperature calculated using IEEE annex G and IEC difference equation - 2016-12-05

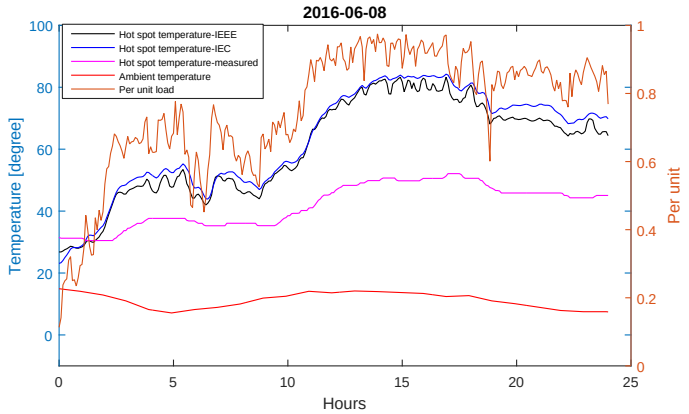

Figure 15: Hot spot temperature calculated using IEEE annex G and IEC difference equations - 2016-06-08

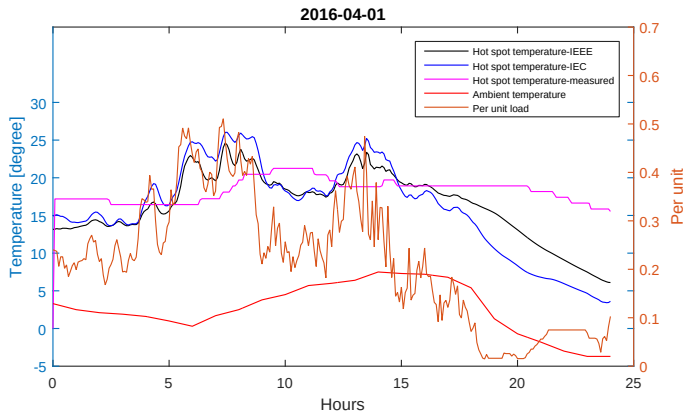

Figure 16: Hot spot temperature calculated using IEEE annex G and IEC difference equations - 2016-04-01

It can be seen that hot spot temperatures calculated using IEC and IEEE models have almost the same value while measured values from PT100 are not in the same range as calculated hot spot temperatures. The measurements are not adequately sensitive to load and ambient temperature changes. Old technology used in PT100 could be one reason to that problem. Besides technical problem, the difference may also caused by the difference between ambient temperature at the transformer location and the ones in model from nearest weather station. Figure 18 illustrates the loss of life calculated by IEC model which uses oil and winding time constants from Table 16 and the one uses calculated time constants.

Figure 18 shows the effect of winding and oil time constants on loss of life. This also indicates the importance of using accurate time constants in the model. In the rest of the report, results are shown from the model using time constants

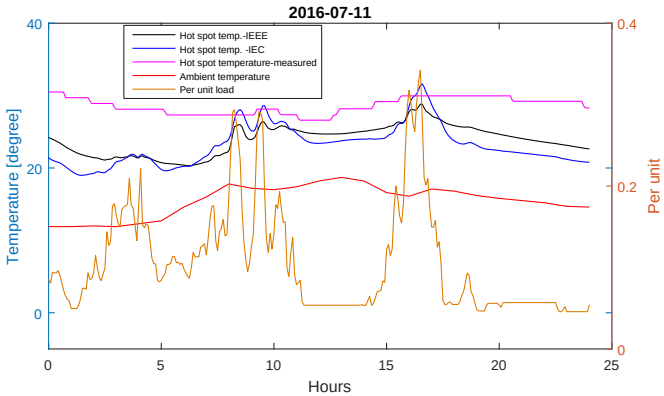

Figure 17: Hot spot temperature calculated using IEEE annex G and IEC difference equations - 2016-07-11

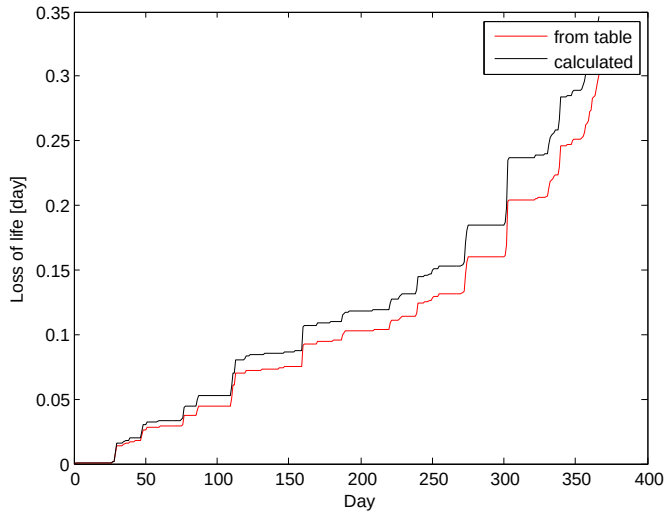

Figure 18: Loss of life calculation in IEC model using standard and calculated time constants

from Table 16. The loss of life at the end of 2016 is 0.3 $[day/year]$.

Critical days

As in IEEE model, critical days are defined as days with highest loss of life during the year. Table 18 depicts the critical days based on IEC model calculations.

During first 12 days from Table 18 50% of entire loss of life during 2016 occurs and the 30 days mentioned in this table accounts for 80% of yearly loss of life. If one wants to control loss of life, these days are the ones to be monitored and controlled.

Table 18: Critical days based on IEC thermal model

Date	Loss of life per day	Cumulative loss of life
2016-10-29	0.033512528	0.033512528
2016-06-08	0.01620571	0.049718239
2016-12-05	0.015940455	0.065658694
2016-09-29	0.013087361	0.078746055
2016-12-30	0.011366308	0.090112363
2016-04-20	0.01033228	0.100444643
2016-09-30	0.009464655	0.109909298
2016-04-22	0.009129297	0.119038595
2016-12-27	0.008790809	0.127829404
2016-02-17	0.008551924	0.136381328
2016-10-28	0.007969884	0.144351212
2016-08-27	0.007736027	0.15208724
2016-12-25	0.007064135	0.159151375
2016-03-17	0.006894734	0.166046109
2016-12-04	0.006634213	0.172680322
2016-01-30	0.006436599	0.179116921
2016-11-26	0.006371105	0.185488026
2016-01-29	0.006313645	0.191801671
2016-12-31	0.005874962	0.197676633
2016-12-22	0.005581843	0.203258476
2016-04-19	0.00533175	0.208590226
2016-11-27	0.005171163	0.213761389
2016-08-08	0.004963911	0.2187253
2016-07-06	0.004406858	0.223132158
2016-03-26	0.004293468	0.227425626
2016-10-01	0.003570594	0.23099622
2016-12-21	0.003073223	0.234069444
2016-03-27	0.002917956	0.2369874
2016-09-06	0.002461411	0.239448811
2016-07-07	0.002400372	0.241849182

Comparing calculated hot spot temperature and measurements

Results from IEEE model and IEC model are in the same range while there is a considerable difference between calculated results and output of PT100. Hot spot temperature measurements from PT100 are not measurements from direct techniques in which fiber optic is used to measure hot spot temperature directly. The measurements done by PT100 are as a result of a simplified thermal model. This thermal model is different from standard thermal models which are used to calculate hot spot temperature in this report. Therefore, the reliability of the results from PT100 needs to be investigated. The method used in this device is old and there is a need to use more advance measurements device such as fiber optic or device which uses standard thermal models to calculate hot spot temperature.

4.3 Decreasing loss of life by controlling load in critical days

In previous section it was shown that there are some days, which we named as "critical days", that have a considerable effect on loss of life. If one wants to decrease the loss of life at the end of the year, one way is to reduce load in these days. Figure 19 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 at the other days remain unchanged. On October 29th, if the load decreases by 10% the loss of life would become 0.28 $[day/year]$ and if the load cuts off to zero, the loss of life would be 0.27 $[day/year]$. In Figure 19 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 is needed to be calculated. First we need to find the rate of loss

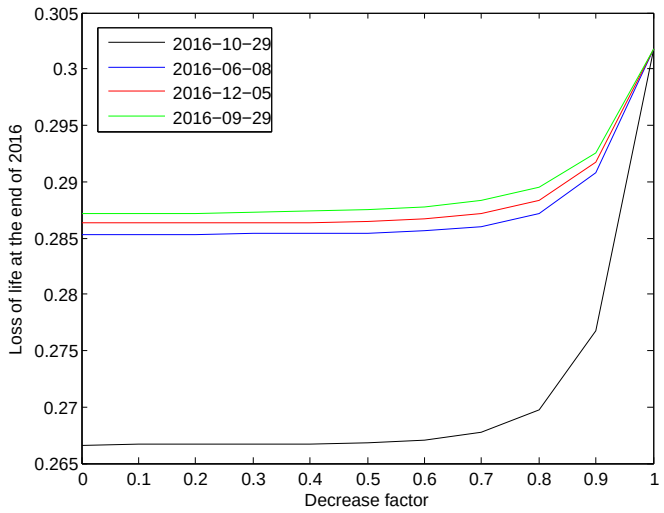

Figure 19: Loss of life calculation in IEC model for decreased load at critical days

of life reduction per each 10% of load reduction in these four critical days. As it can be seen in Figure 19, the important factor is not the absolute value of loss of life after load reduction but the rate of loss of life reduction. The rate of loss of life reduction for each 0.1 decreasing factor is the slope of the curves in Figure 19. Considering percent of reduction as the only influencing criterion, the most influential reductions are listed based on their rank on Table 19. Therefore, the first action to decrease loss of life is reducing load at October 29th by 10%. If one needs more reduction in loss of life, the next step would be reducing load at June 8th by 10% followed by December 5th and so on.

In reality, decision on factor of load decrease during these days is a trade-off between increasing the remaining life of transformer and decreasing income as a result of reduction in energy production at wind farm during these days.

Table 19: Load reduction prioritisation

Load reduction [%]	**Load factor [%]**	**Date**
10	90	2016-10-29
10	90	2016-06-08
10	90	2016-12-05
10	90	2016-09-29
20	80	2016-10-29
20	80	2016-06-08
20	80	2016-12-05
20	80	2016-09-29
30	70	2016-10-29
30	70	2016-06-08
30	70	2016-12-05
30	70	2016-09-29

Moreover, during these days the electricity prices are not the same which makes electricity price an influential factor.

4.4 Safety margin in loss of life calculations

As it can be seen in (74) loss of life is highly sensitive to 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 $[day/year]$ to 0.82 $[day/year]$.

4.5 Impact of loss of life calculations on investment decision making

As we have seen in the previous section, the loss of life after one calender year operation is just 0.3 $[day/year]$ and 0.8 $[day/year]$ without and with safety margin consideration. If this transformer works under similar conditions, and accepting normal life of transformer to be 150000 hours, then the life expectancy of the transformer would be 20800 and 7800 years for loss of life calculations without and with margin. It seems that this transformer is over designed for this application. Definitely, this transformer will not be in service for this long period. To have life expectancy in a reasonable range, either the ambient temperature or per unit load should increase. Increasing the ambient temperature if possible does not bring any benefit to transformer owner. However increasing per unit load is desirable. Per unit load is calculated using (106) in which I is actual load and I_{rated} is rated current.

$$I_{pu} = \frac{I}{I_{rated}} \tag{106}$$

Per unit load can be increased either by increasing actual load or decreasing rated load. Decreasing rated load means decreasing size of the transformer.

Table 20: Comparing results for two transformer sizes

Transformer size	**16 MVA**	**20 MVA**
Loss of life [hour]	135.84	7.2
Loss of life [day]	5.66	0.3
Life expectancy [year]	1104	20833
Investment cost [SEK]	4,500,000	5,500,000

Weather and load estimations can be used to calculate dynamic rating and consequently size of a transformer based on desired loss of life. This approach can be used to utilize dynamic rating to unlock transformer available capacity and therefore decreasing transformer size. It is mainly beneficial for renewable connected transformers which experience high load fluctuations. For example, for studied wind farm connected transformer, the maximum hot spot temperature is $87.63°C$. This temperature happens when the load is 1.07 per unit. As the hot spot temperature is below the limit mentioned in Table 13, the per unit load can be even higher. This can happen by increasing the actual load or decreasing transformer size. By selecting smaller size transformer, the new per unit load will be calculated and then for new per unit load hot spot temperature will be calculated. We will decrease the size of transformer until one of the limitations mentioned in Table 13 breaches. The smaller the size of transformer is, the lower the initial cost of transformer will be. This way, the most suitable size of transformer will be selected. This approach is applicable in designing phase of transformer where the utility or manufacturer wants to determine the most efficient size of transformer based on load and ambient temperature forecasts and expected life of transformer. For currently installed transformer, transformer size is unchangeable and applying dynamic rating can be helpful on wind farm expansion plans. We have seen that the studied transformer can tolerate higher per unit load. In the second approach we increase the nominator in (106), which means increasing wind farm power generation.

4.6 Decreasing transformer size

In this section, we want to investigate what would be the best transformer size for this wind farm. IEC model is implemented for A 16 MVA transformer. All transformer specification data are assumed to be similar to the 19.4 MVA transformer except for the rated load. Therefore the only change in the model is in per unit load. Table 20 compares results based on IEC model for these transformers.

Even with the smaller size, the transformer always operates safely without breaching any limits while having lower investment cost. It is shown that by applying dynamic rating in designing phase we can select the optimum transformer suitable for considered application. To select the most efficient transformer, load profile and ambient temperature forecasts are needed to run the thermal model for different scenario based on transformer size. The scenario with lower transformer size which does not breach any limit suggested by standard, will be selected. Comparing these scenario from Table 20 for existing load and ambient temperature data, it can be concluded that the smaller transformer can satisfy the expectations for this application with lower investment cost.

4.7 Increasing load

In this section load is increased by constant factor to evaluate the effect of increasing the wind farm power generation on transformer loss of life. Figure 20 shows the loss of life at the end of year for varying increasing factor, n. It can be

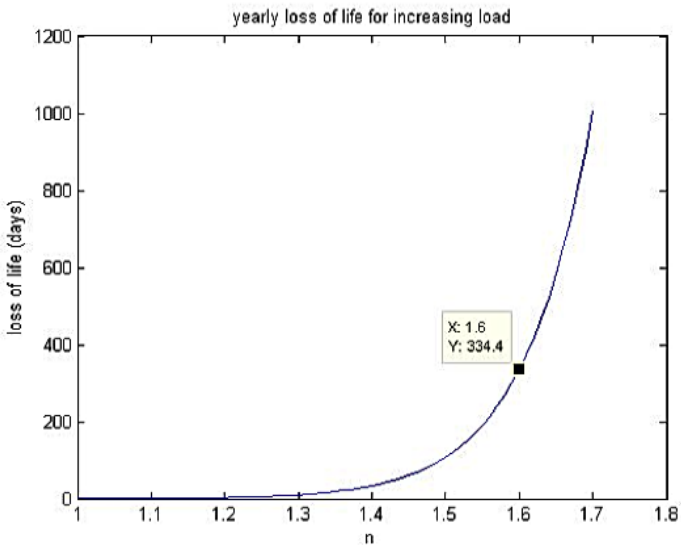

Figure 20: Loss of life calculation in IEC model for increasing load

seen that if the wind farm expands by 60% the loss of life is nearly 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 curve slope in this figure increase dramatically as the increase factor, n, increase from 1.4. To have life expectancy equal to 40 years,as requested by Ellevio, the wind farm can be expanded by 53%.

As the loss of life is highly dependent of hot spot temperature, a safety margin equal to $8°C$ is added to hot spot temperature calculated by the model. The value for safety margin is the absolute maximum difference between hot spot temperature calculated using IEC model and IEEE model. Other curves in the figure shows results for safety margin. Curve corresponding to loss of life calculation considering safety margin equal to $8°C$ is selected for further analysis. Table 21 shows yearly loss of life for different wind farm expansion plans. If the life of transformer is expected to be 40 years, then the wind farm should be expanded by 47%. This means that this transformer is suitable for a wind farm which is 47% bigger than the existing one.

4.8 Economic analysis

In this section of the report a simple economic analysis will be conducted to determine the size of wind farm expansion. By increasing the number of wind turbines the wind farm electricity generation will be increased which results in increase in revenue. However, the costs will be increased accordingly. Costs are as following:

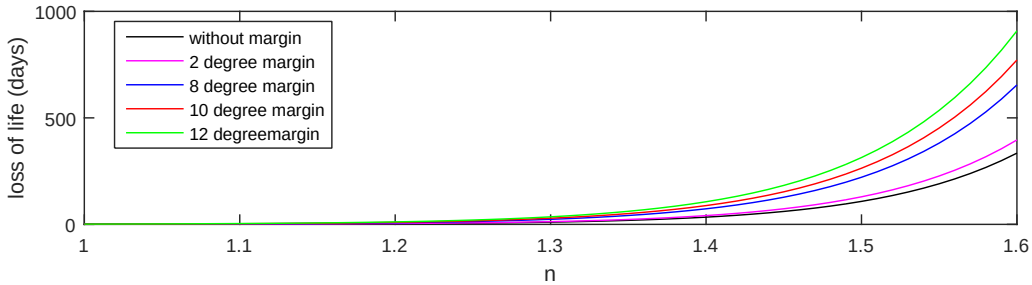

Figure 21: Loss of life calculation for increasing load and considering margins for hot spot

Table 21: Yearly loss of life for different load increasing factor considering $8°C$ safety margin

Increasing factor	**Loss of life/year [day]**
1	0.82
1.05	1.41
1.1	2.48
1.15	4.36
1.2	7.67
1.25	13.51
1.3	23.78
1.35	41.76
1.4	73.11
1.45	127.5
1.5	221.1
1.55	381.6
1.6	654.5

- Transformer loss of life
- Operation cost
- Investment cost

As it seems, it is an optimization problem in which the net income as objective function should be maximized. To have realistic optimization problem limitations such as land area and grid integration should be taken into accounts. However, in this report, it is assumed that there is not any limitation to expand the wind farm. To solve this problem, purchasing and installation cost for each wind turbine and operation cos and electricity price t for each kW power generated are needed. Electricity price is gathered from [45]and elcertificat which is a support scheme in Sweden to increase the share of renewable energy is added [46]. Based on existing power generation and electricity price, the revenue in this wind farm is 18.9 million SEK and the loss of life is 0.3 day which costs 264.06 SEK yearly. By increasing wind farm by 50% the revenue will increase by 50% as well and reaches 28.4 million SEK. In this case the loss

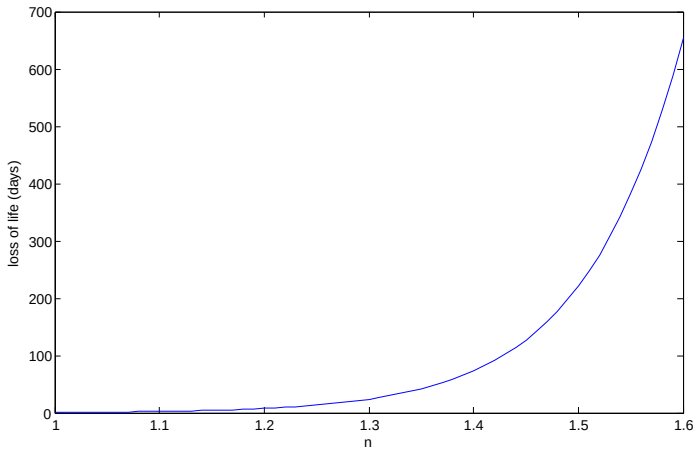

Figure 22: Loss of life for different increasing factor by considering $8°C$ safety margin

of life will be 107 $[day/year]$ which means the cost corresponding to transformer will be increased to 94181.2 SEK. There are also other costs regarding operation cost and investment cost of new wind turbines which are neglected in this report. If the wind farm had the smaller size transformer ($16\,MVA$), to have expected life equal to 40 years, wind farm could have been increased by 20%. In this case, the revenue and the cost of loss of life would be 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 transformer are depreciated for 40 years, regardless of the actual age of transformer and life expectancy, the cost of loss of life is not an effective factor. This cost is not a accountable cost and it is calculated based on transformer investment. However, transformer investment cost is different for different size of transformer. Therefore, for the existing wind farm size it is better to select the smaller size transformer. 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 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. The bigger the wind farm size, the more investment is needed for the wind turbine. In this report investment costs are neglected but one can compare these scenario 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 $16\,MVA$ 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 is 20 MVA and will be depreciated after 40 years.

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

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. Besides, when hot spot temperature exceeds $120°C$ the risk of gas formation in oil increase which in return increase the transformer failure which is not desired. Therefore this value is selected as hot spot threshold. 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 figures 23 and 24 for different wind farm expansion plans.

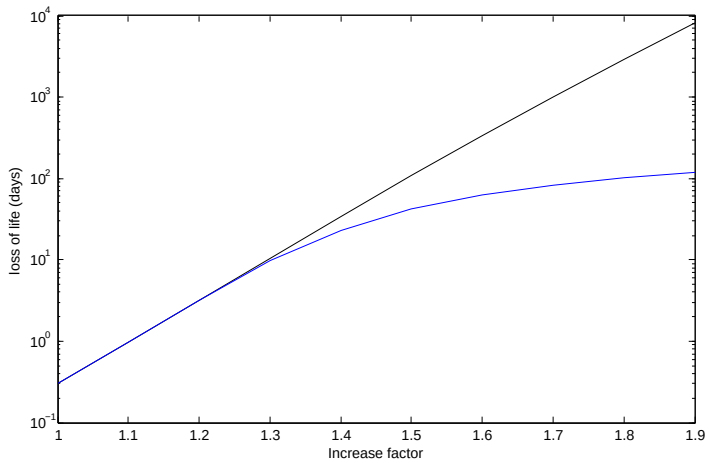

Figure 23: Loss of life calculation for increased load with and without hot spot temperature limitation

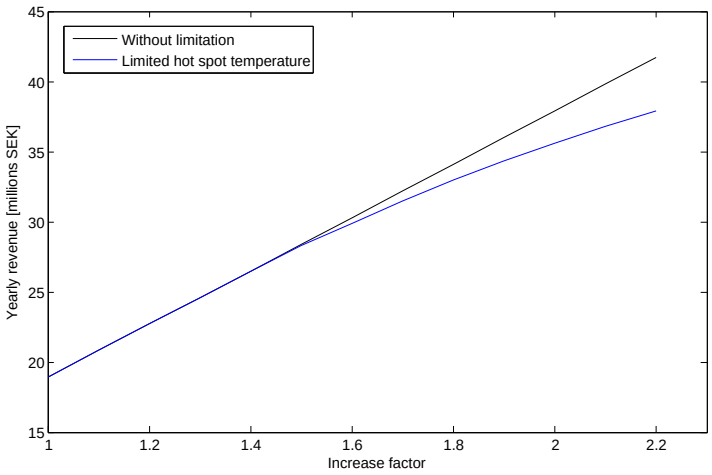

Figure 24: Revenue comparison for increased load with and without limited hot spot temperature

4.9 Maximum contingency loading

The IEC thermal model is used to calculate maximum contingency load at each time interval. Results are shown in figures and for aging acceleration factors equal to 1 and 0.48 respectively.

As Ellevio's transformers are mainly depreciated during 40 years, aging factor equal to 0.428 is selected which means this transformer can tolerate continuous hot spot temperature equal to $102°C$ for 40 years. Maximum contingency loading is calculated for every 30 seconds for 2016. Results for some example days are shown in figures

Having weather forecast and by applying this model for 40 years life expectancy, the transformer capacity increases by 15% compared to static rating. It should be considered that static rating is calculated for 17 years continuous working with hot spot temperature equal to $110°C$ while for 40 years working the hot spot temperature is kept constant at $102°C$. A better comparison is when the hot spot temperature is kept constant at $110°C$. In this case the available capacity of transformer increases 22%.

4.10 Maximum contingency loading for next time period

Having top oil temperature either from sensors or calculations, hot spot temperature from calculation, and ambient temperature forecast for next time step, the maximum load during next time period without exceeding any limit can be calculated. This way, we can indicate how much the transformer can be loaded for next time period considering current situation. This method is currently used for 50 transformers in New Zealand [10]. This method is applied for $T1$ transformer and maximum load for next 5 minutes at each time spot during 2016 is calculated. It is seen that this transformer with existing load profile and ambient temperature data, can be loaded up to $1.5\,p.u.$ during next 5 minutes at any time spot. Figure 28 shows the block diagram representing this model.

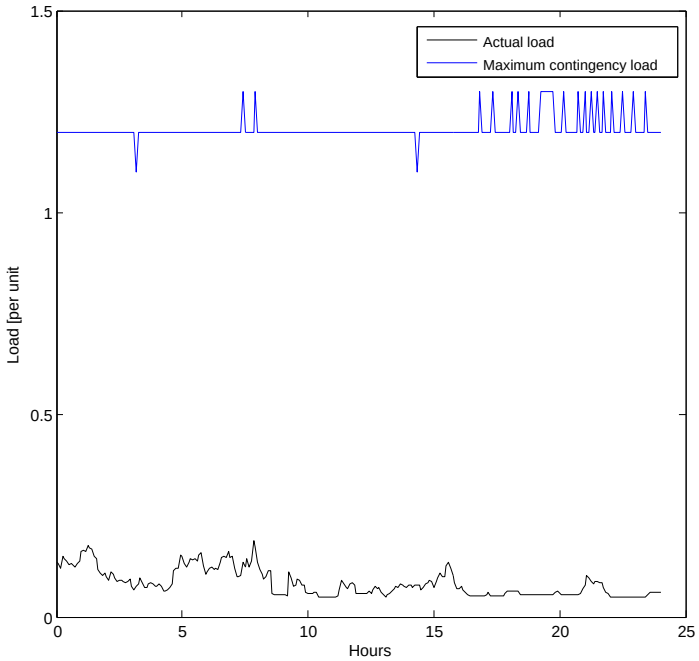

Figure 25: Maximum contingency loading calculated for 40 years life expectancy - 2016/11/03

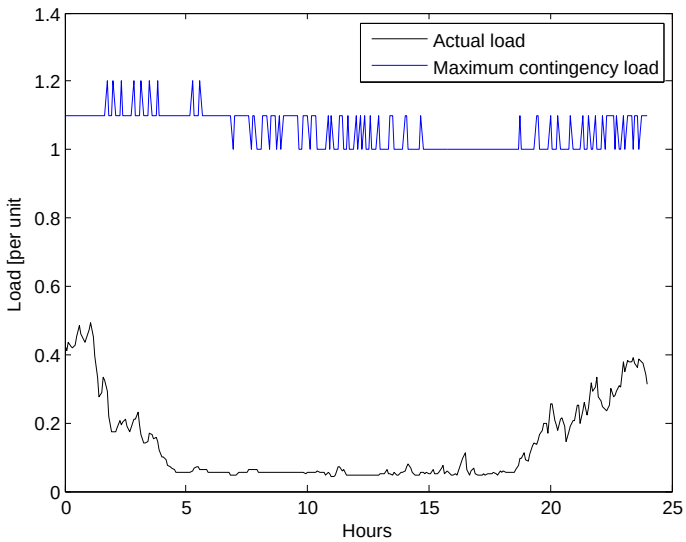

Figure 26: Maximum contingency loading calculated for 40 years life expectancy - 2016/06/23

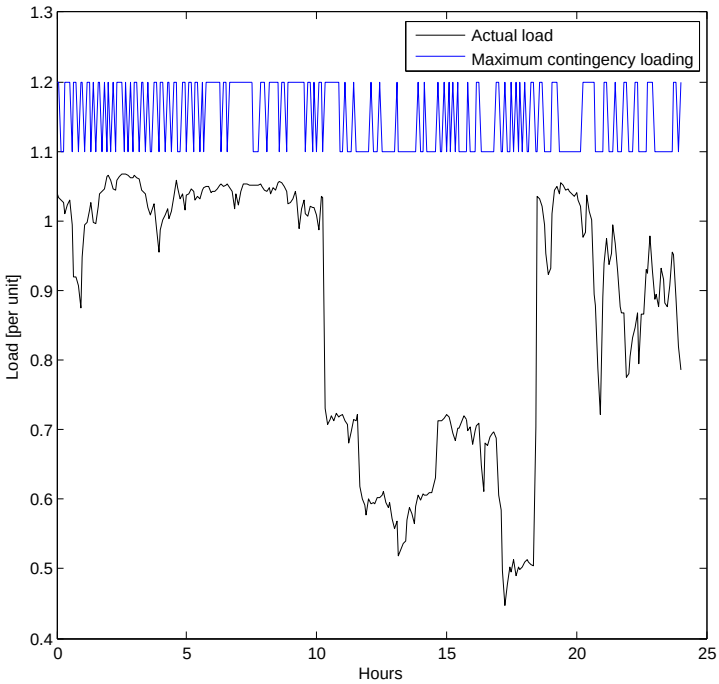

Figure 27: Maximum contingency loading calculated for 40 years life expectancy - 2016/10/29

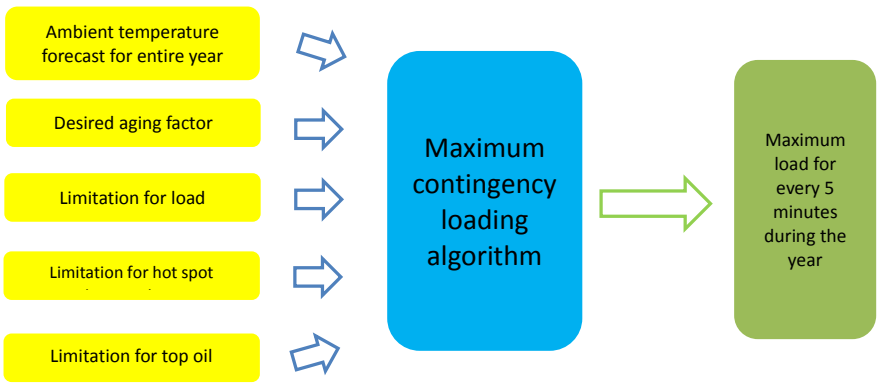

Figure 28: Block diagram representing maximum contingency loading for next time step

4.11 Load versus loss of life

In many occasions it is desired to know the risk of overloading the transformer for a specific period. The risk of overloading can be quantified as transformer loss of life. It is obvious that higher load results in higher hot spot temperature which in

turn leads to higher loss of life. As it is mentioned before, hot spot temperature is not only a function of load. It is also affected by ambient temperature and initial top oil and hot spot temperatures. Therefore, there is not a single graph that can show the relation between loss of life and load. This graph can be plotted for every time spot with known hot spot temperature (or per unit load) and temperature. This graph is plotted for two time spot in 2016. Figures and show loss of life as a function of load during next 30 minutes on 2016/10/29 at 2 : 50 and 2016/05/18 at 12 : 30. The difference in load effect on loss of life for these days is because of different initial state. On 2016/10/29 at 2 : 50 load is $1.06\,p.u$ and hot spot temperature is $87°C$. Therefore any increase in load results in hot spot temperature higher than $87°C$. This leads to increase in aging acceleration factor with higher rate. While on 2016/05/18 at 12 : 30 load is $0.07\,p.u.$ and hot spot temperature is $15°C$. The lower initial hot spot temperature leaves enough space for increase in hot spot temperature as result of overloading.

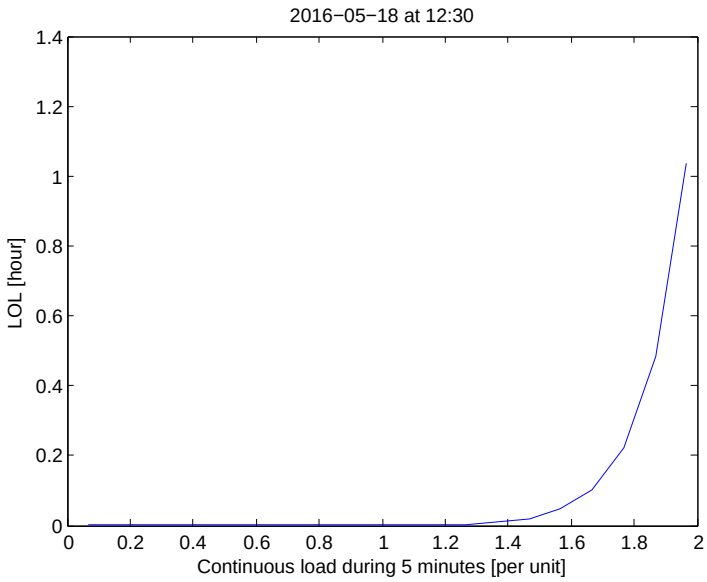

Figure 29: Loss of life for continuous load during next 30 minutes-2016/05/18 at 12:30

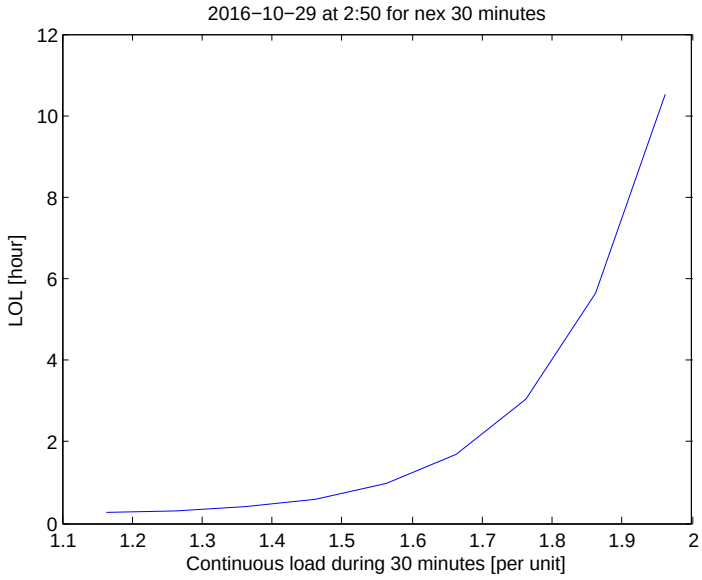

Figure 30: Loss of life for continuous load during next 30 minutes-2016/10/29 at 2:50

5 Conclusion and future works

With higher penetration of renewable energies in future, power transmission systems with higher capacity are needed. Dynamic thermal rating can help to unlock the network capacity and utilize existing components more efficiently. To apply dynamic rating, a first step is to monitor hot spot temperature in transformer either by fiber optic or thermal models. Thermal models from standard guidelines are selected for this purpose. By monitoring transformer loss of life we can determine if it is used to its full potential. As for the studied transformer it seems to be over-dimensioned for this application. It is investigated in this report how dynamic rating can be applied to prevent over-dimensioned transformer in designing phase. Suggestions in terms of wind farm expansion are proposed in order to take advantage of hidden capacity of transformer which can be unlocked by dynamic rating. The transformer investigated in this project is a wind farm connected transformer and therefore there is not any conventional cyclic load defined for this kind of application. While both IEC and IEEE standards are mainly developed for cyclic loads and emergency loading. The proliferation of renewable energy installations increases the need for developing thermal models tailored for unpredictable load profiles. The other characteristic of renewable energy source connected transformer is severe fluctuations in load profile which results in high variations in hot spot temperature. This can cause considerable electrical and mechanical pressure on transformer. The effect of hot spot fluctuations on loss of life calculations needs to be studied in further researches. However, in this report as a result of unavailability of these models, the conventional models are used. The other issue was unavailability of measured hot spot or top oil temperature from the studied transformer. Such

data could be used to compare results from different thermal models in order to evaluate their performance. In this report the effect of hot spot temperature is only studied on winding insulation, while it is also needed to investigate its impact on bushing and tap changer as well. The effect of moisture in oil is not studied here. As the impact is not negligible, this parameter should be taken into consideration in further studies in this field.

Transformer dynamic rating can be used in designing phase of transformer to select the most proper transformer size. This method can help utility owners to reduce investment cost. Manufacturer also can benefit by providing more attractive prices for the same performance. Furthermore, it may have impact on society economically. As transformers account for considerable part of investment in power systems, by extracting all available capacity of transformers, the need for new investment can be deferred which in return can affect the electricity price. Reducing electricity price by cutting investment cost can increase social welfare. Moreover, it helps environment by utilizing less material with higher efficiency. Applying dynamic thermal rating studies for transformers connected to renewable energy is more important as reducing investment cost is a crucial factor for renewable energy generation.

Moreover, as there are many parameters involved in the thermal models used for hot spot calculation, a sensitivity analysis is suggested to be done to determine influential factors in standard thermal models in order to improve them in future works.

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