Paris 2020

D1-108

Evaluation of dynamic loading capability for optimal loading strategies of power transformers

I. LUPANDINA*[1], W. GAWLIK[1], M. SCHRAMMEL[1], A. ILGEVICIUS[2], M.KÜRTEN[1], K. VIERECK[2]
TU Wien[1], Maschinenfabrik Reinhausen GmbH[2]
Austria[1], Germany[2]

SUMMARY

Increasing needs for operational flexibility encourage concepts of using thermal operational limits of grid equipment instead of nominal limits, e.g. "dynamic line rating" for transmission lines. Using the available loading flexibility of complex and valuable power transformers requires a comprehensive approach. The thermal state and condition of a power transformer are among the most the considerable impact factors for planning overload capability and lifetime management in the long-term.

This paper investigates the dynamic loading capability of power transformer by using a dynamically calculated initial thermal state, set thermal limits and a dynamic thermal model proposed in the IEC 60076-7:2017. Different thermal limits can be set depending on the operation state, e.g. long-term emergency or insulation-friendly. The suggested thermal limits also consider ageing and dielectric properties of insulation. Thermal limits of equal ageing velocity for different moisture content in solid insulation can be used to operate the transformer with respect to long-term asset management strategies.

Using the proposed reverse calculation of the thermal model's steady-state loading limits, e.g. nameplate rating, the permissible short-term loading beyond the steady-state limits can be obtained for given timespan. The dependency of the steady-state loading limit from ambient temperature is approximated as a polynomial function with linear, quadratic and cubic components.

For a safe loading of the power transformer the steady-state limits of the subsystems have to be compared. The study shows, that the hot-spot steady-state limits for normal and long-term emergency loading are lower than the top-oil steady-state limits.

Power transformers are usually subject to variations in the loading profile. The current thermal state becomes essential for the estimation of the thermal reserve and loading capability, especially when permissible overloading for a time up to 60 minutes is scheduled. When determining the possible overload for a longer time span, the validity of the results is decreasing due to growing uncertainties. Moreover, the paper proposes a

lupandina@ea.tuwien.ac.at

system to enhance the model by a moisture migration model for mineral-oil-immersed power transformers, decision-making under uncertainties assistance and transformer´s intelligent condition assessment system.

KEYWORDS

Dynamic overload capability - Power transformer - Thermal limits - Security assessment - Loading strategies

1. INTRODUCTION

Growing propagation of distributed and volatile energy resources and increased use of automatic control systems on all voltage levels of the power grid challenge the process of power flow forecasting in power systems. This leads to rising uncertainties and deviations from the calculated prognosis values for the power flow [1], [2]. Therefore, power system components like transmission lines and power transformers increasingly reach their operational limits. This causes the need for preventive re-dispatch as a countermeasure to guarantee a secure operation.

Using the available loading flexibility of complex and valuable power transformers requires a comprehensive approach. Estimation of loading capability needs three main inputs: the initial thermal state, given thermal limits and an appropriate thermal model (TM).

Winding hot-spot and top-oil temperatures are commonly used to describe the thermal state of a power transformer. Besides the limitation of winding hot-spot temperature, the loading capability of power transformer should consider the following restrictions:

- the thermal state of all subsystems, e.g. bushing, core, current transformers, cable-end connection and losses in inactive parts should remain in the limits as well as pressure and expansion of insulation liquid [3], [4];
- the conditions of all subsystems as the cooling system etc. should be taken into account [5],
- the tap-changer should be able to operate under high currents, the bushings and insulation should maintain their dielectric strength etc. [3], [4];
- the model should deliver reliable results even under uncertainties caused by measurements, modelling, deviations from the expected values in the forecasts;
- power system operation limits related to protection settings and thermal reserves for transformers with isolated or resonant grounded neutral in case of earth faults;
- short-term grid operation needs to be coordinated with mid- and long-term asset management strategies.

Thermal stress is a primary cause for major failures of power transformers, as it leads to a deterioration of solid insulation in the long-term and a thermal breakdown in the short-term [3], [6]. The thermal state and condition of the power transformer are among the most the considerable impact factors for planning overload capability and lifetime management.

This paper is focused on developing a dynamic loading capability model for liquid-immersed power transformers that is considering winding hot-spot temperature limits. The limits take into account ageing and dielectric properties of the insulation. The model considers preloading, overloading and post-overloading in the short-term and deals with long-term asset management strategies.

In chapter 3, a methodology to obtain steady-state loading limits and determine permissible short-term loading beyond the limit based on the reverse calculation of the thermal model is introduced. The steady-state loading limits based on hot-spot and top-oil temperature limits are compared. Using iso-lines of permissible duration with an initial hot-spot temperature and an assumed load step above steady-state limits as input values and the resulting dynamic thermal reserve are investigated. In chapter 4, the dielectric response of liquid insulation due to moisture migration at different loading profiles is studied. The models are implemented and evaluated in Matlab® Simulink®.

2. OPERATIONAL THERMAL LIMITS OF POWER TRANSFORMERS

The thermal state of the power transformer and its subsystems e.g. core, bushings etc. can be modelled and simulated using dynamic thermal models (DTM). The dynamic thermal model proposed in the standards, e.g. IEC 60076-7, is a special case of the commonly used thermal-electrical analogy that considers the 3-body model and delivers the winding hot-spot and top-oil temperatures as its output.

With respect to transformer dependent factors, using conforming thermal limits along with appropriate dynamic thermal modelling is a key aspect for the safe usage of the power transformer´s thermal reserve.

Loading limits of a power transformer are defined by its thermal limits. The loading guidelines differ between normal cycle, long-term and short-term emergency operation. Furthermore, insulation-friendly operation based on the relative ageing velocity for kraft paper (KP) or thermally upgraded paper (TUP) can be defined. Table I shows the thermal limits recommended in the guidelines for the hot-spot temperature $\theta_{h\ max}$ and top-oil temperature $\theta_{o\ max}$ as well as corresponding ageing acceleration rates for dry and wet solid insulation.

Table I: Thermal limits for hot-spot and top-oil temperatures and relative ageing rate for different operation states according to loading guidelines IEC 60076-7.

Operation state	Thermal limits		Ageing acceleration rate[1]			
	$\theta_{h\ max}$	$\theta_{o\ max}$	KP_{dry}	$KP_{(Cw=1,5\%)}$	TUP_{dry}	$TUP_{(Cw=1,5\%)}$
Normal cycle loading	120 °C	105 °C	12.7	40.2	2.7	3.8
Long-term emergency	140 °C	115 °C	128.0	248.9	17.2	13.3
Short-term emergency (30 min)	160 °C		1290.2	1678.1	92.1	176.8
Insulation-friendly for KP	98 °C		1.00	3.66	0.28	0.78
Insulation-friendly for TUP	110 °C		4.00	13.43	1.00	1.88

Remaining within emergency thermal limits should protect power transformers from thermal breakdown of the insulation while the more strict limits for insulation-friendly operation avoids accelerated ageing of solid insulation.

The risk of thermal breakdown grows with an increasing share of contaminations in the insulation. The water content is highly dependent on temperature and has an essential influence on the dielectric strength of the insulation in two aspects: gas bubbling inception and high moisture relative saturation of liquid insulation, see chapter 4.

As it is already well known in the literature, several conditions contribute to the evolution of gas bubbles on the surface of winding´s solid insulation and increase the risk of breakdown as:

- windings reach bubbling inception temperature that depends on the water content in the paper, the water solubility of insulation liquid, present dissolved gases, external pressure etc.[4],[5], [7]-[9],
- the moisture content of solid insulation in the hot-spot area needs to be sufficiently high to produce required pressure (in [8] at least 2 %),
- the incepted gas bubbles migrate to strong electric stress areas [3], [4],
- temperature gradient exceeds at least 3 K/min [8], to reach the energy density, which is injected into the system to achieve the required pressure to start the inception of bubbles. For instance, for a winding time constant 6 min and ONAN cooling system, the load step must be at least 70 % [10].

An example of using bubbling inception temperature proposed in ANSI 57.91 combined with

[1] The values are calculated in accordance to IEC 60076-7:2017 Annex A with the given $\theta_{h\ max}$.

thermal limits for long-term emergency operation is shown in (solid red line).

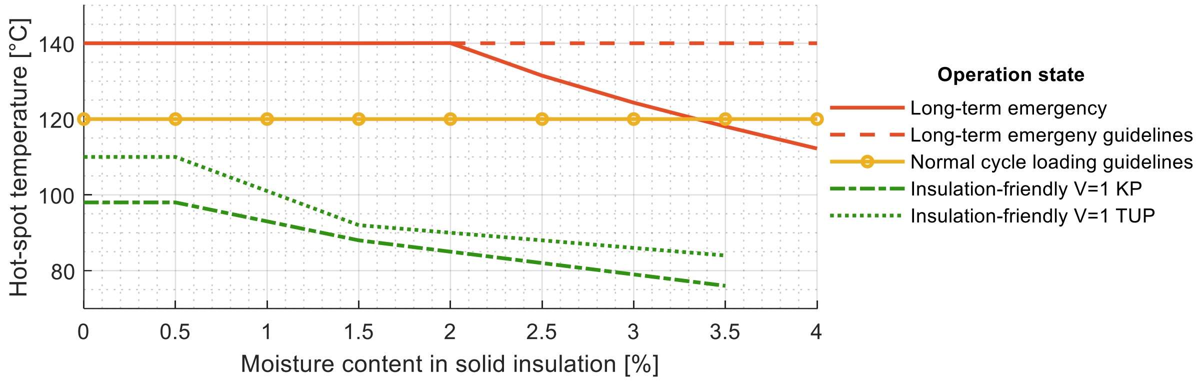

Figure 1: Thermal loading limits depending on moisture content in solid insulation: for recommended and guidelines' proposed long-term emergency operation (solid and dashed red lines respectively), for guidelines' normal cycle loading (marked yellow line), for insulation-friendly operation proposed for KP and TUP (dash-dotted and dotted green lines respectively).

Based on calculation results from Table I, even within normal cycle operation at the limits increases the ageing acceleration rate by a factor of 12.7 for dry KP and 2.7 for dry TUP compared to planned velocity. Additionally, 1.5 % of moisture in paper accelerates the process up to 40.2 times for KP. Lifetime management and planning of overload of the power transformer should not be seen as mutually exclusive.

Deterioration of solid insulation driven by pyrolysis, oxidation and hydrolysis is frequently a consequence of end-of-life failures and removal from service of power transformers [3], [6]. Using thermal limits with equal acceleration rates allow operating the power transformer in accordance with the long-term planning strategies. Therefore, the curves of equal relative ageing velocity[2] for KP and TUP for different moisture content in solid insulation for insulation-friendly operation can be used, see Figure 1. Due to set priorities, loading strategies can consider the thermal limits with respect to the lifetime and condition of the power transformer.

Depending on the design of the power transformer, time constants of some subsystems like bushings might be lower than the windings' and are therefore prone to reach their temperature limits more rapidly [3]. Steady-state loading limits, as well as temperature rises of subsystems, should be taken into account and compared with the hot-spot loading limits. Comparison of loading limits of the top-oil and the hot-spot temperature is presented in chapter 3.

A comprehensive approach is needed for the secure use of thermal limits, which could be provided by an intelligent transformers' condition assessment system.

3. USING THERMAL LIMITS IN POWER SYSTEM STUDIES

The thermal limits, when converted to equivalent electrical values, can be used in power system studies. The rated current can be given by nameplate rating or steady-state loading limits. Temporary or permanent loading beyond nameplate rating is permissible in power system studies and in actual operation as long as the current thermal state of power transformer is known and within the permissible range.

3.1 Reverse calculation of the steady-state thermal model

By application of thermo-electrical analogy, the thermal performance of the power

[2] The values are calculated in accordance to IEC 60076-7:2017 Annex A with the given moisture content 0 %, 0,5 %, 1,5 % and 3,5 % free from air, the values between the points are linear approximated.

transformer in steady state is a result of its thermal resistance and applied constant loading. The thermal resistance depends on material properties of the component, cooling system state and ambient conditions.

Thus, when the cooling system state and ambient temperature θ_a are known, the thermal model (TM) is parametrised and hot-spot temperature limit $\theta_{h\,max}$ is predefined, a load factor K can be obtained, which is needed to reach the temperature limit $\theta_{h\,max}$ in steady state for a given timespan.

Based on the following nonlinear steady-state TM[3]

$$\theta_h = K^y \Delta\theta_{hr} + \left[\frac{1+K^y R}{1+R}\right]^x \Delta\theta_{or} + \theta_a \tag{1}$$

The reverse calculation by Newton´s method can be executed on this equation. Based on the equation (1) the created function $f(K)$ is

$$f(K_i) = K_i^{\,y} \Delta\theta_{hr} + \left[\frac{1+K_i^{\,y} R}{1+R}\right]^x \Delta\theta_{or} + \theta_a - \theta_{hmax} \quad i \in \mathbb{N} \tag{2}$$

The function is steady and has only one zero-point in the chosen definition area (3). Besides, the parameter for different transformer types are within the following boundaries: $x \in [0.7, 1.1], y \in [1.1, 2], R > 1$[3].

$$f(K) : (0;2] \rightarrow \Re \tag{3}$$

Therefore, an iterative search using Newton´s method can be applied and returns the steady-state loading limit K_{stat}.

$$K_{i+1} = K_i + \frac{f(K_i)}{f'(K_i)} \tag{4}$$

The first derivative of the function $f(K)$ is

$$f'(K_i) = y\Delta\theta_{hr} K_i^{\,y-1} + x\Delta\theta_{or} \frac{2K_i R}{1+R}\left[\frac{1+K_i^{\,2} R}{1+R}\right]^{x-1} \tag{5}$$

The iterative search is finished, when the function tends to zero

$$|f(K_i)| \le 10^{-3} \rightarrow K_{stat} = K_i \tag{6}$$

Therefore, the steady-state limits can be calculated for a given time, and the dependency between steady-state loading limits and ambient temperature can be obtained.

3.2 Dependence of steady-state loading limits from ambient temperature

The dependence of steady-state loading limits from ambient temperature mentioned above using thermal limits for different operation states for the power transformer with ONAN cooling system is shown in Figure 2. At θ_a =20 °C, the modelled power transformer tolerates an additional +14.5 % loading in normal cycle and +26 % for long-term emergency loading.

[3] Thermal model with parameters $\Delta\theta_{hr}, \Delta\theta_{or}, x, y, R$ are specified in IEC 60076-7:2017

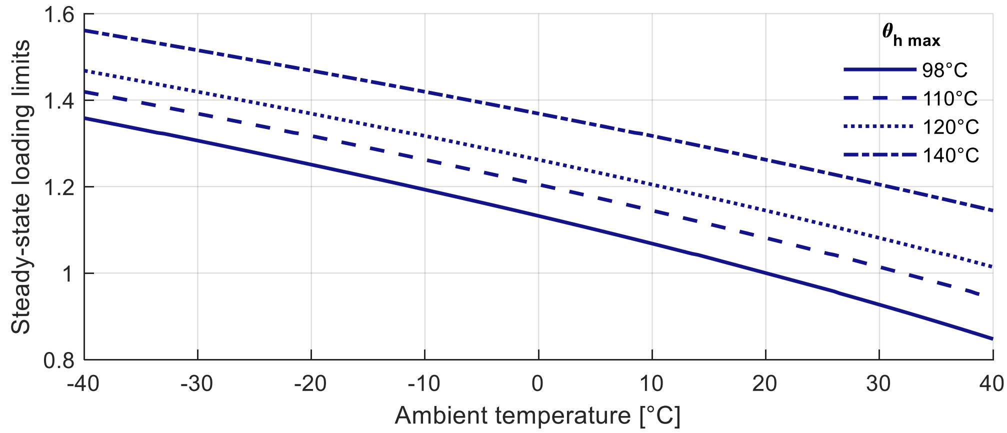

Figure 2: Steady-state loading limits in dependency of ambient temperature for an exemplary power transformer with ONAN cooling system and different hot-spot thermal limits: 98 °C (solid line), 110 °C (dashed line), 120 °C (dotted line), 140 °C (dash-dotted line).

The TM is parametrized to have a 100 % steady-state loading K_{stat}=100 % with a hot-spot thermal limit $\theta_{h\,max}$ =98 °C and ambient temperature θ_a =20 °C. The values should be scaled to rated current by using of nameplate rating.

As long as the parameters of the TM remain constant, an approximated function of the dependence can be parametrised by applying the least square method. Using 3rd-degree polynomial equation (7) the coefficients of a_0, a_1, a_2, a_3 can be estimated.

$$K_{stat}(\theta_a) = a_0 + a_1\theta_a + a_2\theta_a^{\ 2} + a_3\theta_a^{\ 3} \tag{7}$$

The calculated dependencies for the power transformers with ONAN and OD cooling systems by $\theta_{h\,max}$ =98 °C have been fitted with a linear, quadratic and cubic polynomial part. The residuals and the polynomial coefficients are represented in Table II. The input ambient temperature varies gradually by 0.5 °C in the range between -10 °C and 50 °C.

Table II: Polynomial coefficients by the linear, quadratic and cubic fitting of dependency between steady-state loading limits and ambient temperature for power transformer with ONAN and OD cooling systems by $\theta_{h\,max}$ =98 °C.

	ONAN $\theta_{h\,max}$ =98 °C			OD $\theta_{h\,max}$ =98 °C		
	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic
a_0	1.184	1.182	1.181	1.135	1.132	1.132
a_1	$-9.8\cdot10^{-3}$	$-8.6\cdot10^{-3}$	$-8.7\cdot10^{-3}$	$-7\cdot10^{-3}$	$-6\cdot10^{-3}$	$-6\cdot10^{-3}$
a_2	0	$-2.6\cdot10^{-5}$	$-1.5\cdot10^{-5}$	0	$2.6\cdot10^{-5}$	$-1.5\cdot10^{-5}$
a_3	0	0	$-2\cdot10^{-7}$	0	0	$-2\cdot10^{-7}$
RMSE	$7.2\cdot10^{-3}$	$7.95\cdot10^{-4}$	$1.15\cdot10^{-4}$	$7.2\cdot10^{-3}$	$8.26\cdot10^{-4}$	$1.14\cdot10^{-4}$
R-square	0.998	1.000	1.000	0.996	1.000	1.000

The quadratic and cubic fitting is applicable having insignificant residuals, although the cubic fitting is better suited when stronger non-linear dependencies are recognized. By estimating coefficients through field measurements, the ambient temperature range is determined by the selection of fitting type [5], [11].

Varying thermal resistance has an influence when the insulation liquid changes properties due to a change of the cooling system state or influence of low temperatures, so the parameters of the TM will change and the approximated functions as well.

3.3 Steady-state loading limits of different systems and subsystems

Different thermal behaviour, functions and properties of subsystems as windings, bushings, core, insulation liquid require using different thermal models and thermal limits [3], [12]. This becomes an essential issue by selection of steady-state loading limits.

The method above allows calculating the loading limits for normal and emergency long-term operation state for hot-spot and top-oil temperatures based on corresponding limits from Table I and TM[4] that are shown in Figure 3.

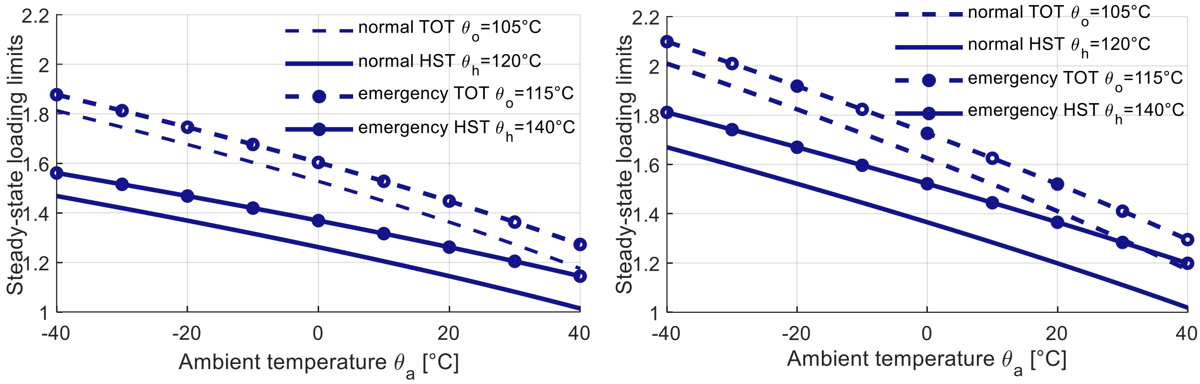

Figure 3: Dependency of steady-state loading limits from ambient temperature based on hot-spot and top-oil temperature limits (solid and dashed lines respectively) for power transformer with ONAN (left) and OD (right) cooling systems.

The steady-state loading limits based on hot-spot temperature limits for both operation states are lower than the limits based on top-oil temperature. Moreover, the winding time constant is significantly smaller than the oil time constant. Consequently, hot-spot temperature limits are appropriate because the hot-spot temperature tends to exceed its limits faster than top-oil temperature. In the same manner, the steady-state limits of other subsystems must be proved.

3.4 Loading beyond nameplate rating

The loading guidelines suggest using permissible duration curves to receive allowable loading above the nameplate rating with an electrical preloading value as input parameter [4].

However, power transformers are usually subject to variations in the loading profile. In addition, the large thermal capacitance of the significant quantities of insulation liquid leads to growing deviations between the current temperatures and those steady-state temperatures, which would build up if the current loading would be maintained indefinitely. This may lead to underestimation or overestimation of the loading capability of the power transformer.

Therefore, the current thermal state (i.e. the hot-spot temperature) for a given time should be used as initial value and be assumed as quasi-stationary. The dynamic loading capability model [10], [13] supposes using two equally parameterized DTM to receive current hot-spot temperature and to estimate the current loading capability:

- A basic model to consider hot-spot temperature for a given time that uses the current or forecasted ambient temperature and loading profile as main inputs,
- A scenario model, which is using the current hot-spot temperature as input parameter and calculates permissible duties of the applied loading scenario.

[4] The values are calculated based on proposed in IEC 60076-7:2017 TMs for steady state

Figure 4 is representing the iso-lines of permissible duration when a constant load above the nameplate rating is applied and the current hot-spot temperature is set as initial value. The reverse calculation of the DTM in exponential form[5] is similar to the approach for the calculation of steady-state loading limits, but using the regula falsi 1. order method (Secant approximation method) instead of Newton's method. Accordingly, the permissible load for the predefined duration can be achieved and vice versa.

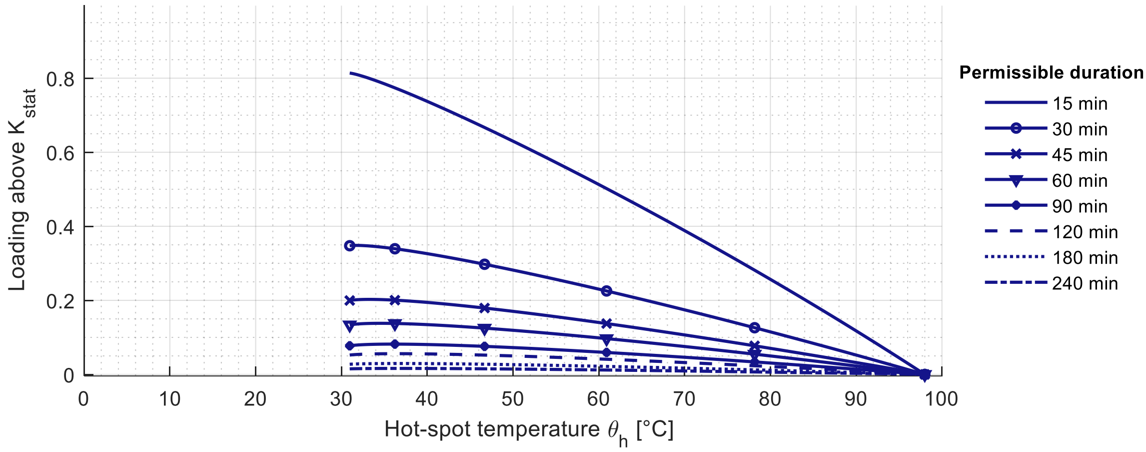

Figure 4: Iso-lines of permissible duration for values between 15 min and 240 min with initial hot-spot temperatures and predefined load steps as inputs for power transformer with ONAN cooling system by $\theta_{h\,max}$ =98 °C and θ_a =20 °C.

The difference between the thermal limit $\theta_{h\,max}$ =98 °C and the no-load hot-spot temperature of 31 °C is proportional to the maximal thermal reserve at the current ambient temperature θ_a =20 °C.

The short-term loading capability up to 60 minutes in the study depends mostly on the current thermal reserve, e.g. the difference of the current hot-spot temperature to the maximum allowable one. With growing permissible duration, the initial values are getting more and more irrelevant and the permissible load steps depend primarily on current steady-state loading limits. Taking into account,

- the duration above 1 hr,
- the permissible load step $\Delta K_{permissible}$ < 10 %,
- and varying ambient temperature and load profile,

the validity of the results is decreasing due to growing uncertainties. At the same time, an estimation error of steady-state loading limits can lead to an overestimation of the loading limits. Thus, the thermal reserve will be used up with the velocity that is proportional to the error. This issue has to be considered when using long-term emergency limits for operation.

Figure 5 shows curves of equal permissible duration for 30 minutes when different thermal limits are applied under different ambient conditions.

Using different operational thermal limits affects the calculation of the loading capability of power transformers as well. Compared to an insulation-friendly operation, the use of the limits for a normal cycle or a long-term emergency operation increases the permissible loading of about 11 % and 20 % respectively at an initial hot-spot temperature of 80 °C.

The iso-lines for different ambient temperatures are showing a similar trend at elevated initial hot-spot temperatures. The variation of an otherwise similar trend is increasing for shorter permissible durations.

---

[5] The DTM is proposed in IEC 60076-7:2017

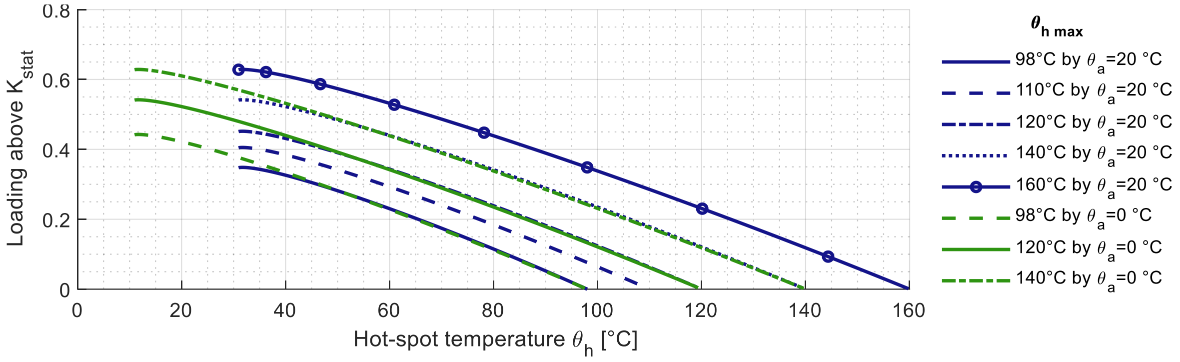

Figure 5: Iso-lines of permissible duration for 30 minutes for different $\theta_{h\ max}$ and θ_a.

An example of the applied method for converting thermal limits in electrical limits values during a day is shown in Figure 6.

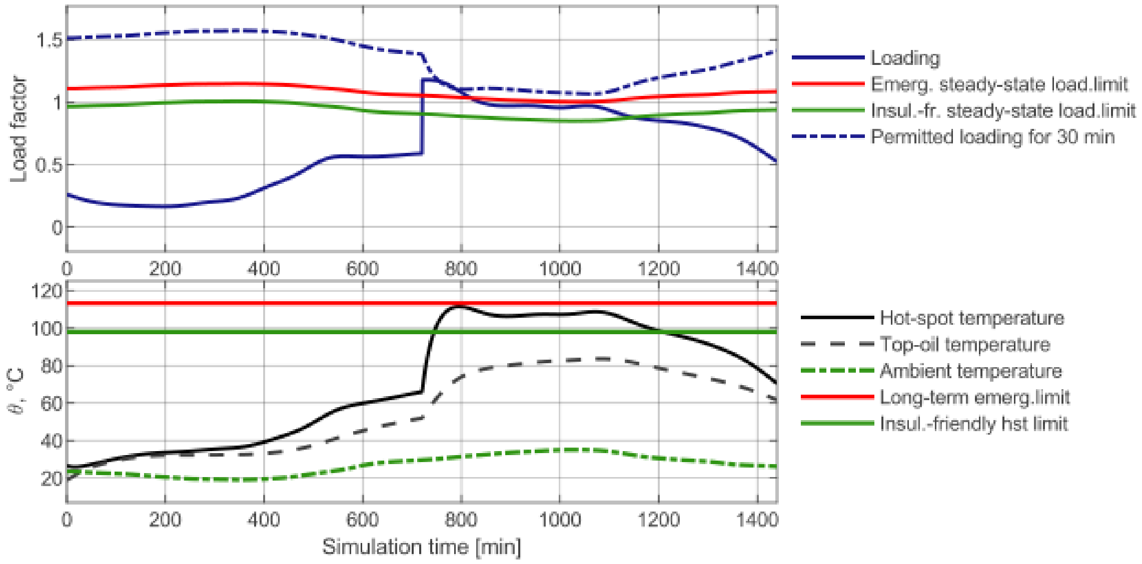

Figure 6: Simulation of thermal performance (bottom) and loading limits (top) of a power transformer for given load and ambient temperature profiles.

Steady-state loading limits vary with ambient temperature. The difference between hot-spot temperature and the applied thermal limit influences the permissible loading above current steady-state limit for 30 min. This is an indicator for the remaining thermal reserve of a power transformer. At simulation time 750 min, the loading step cases the load factor to exceed steady-state limits, and without reaching thermal limits, the loading drops below the steady-state limit again. During that phase, the thermal reserve starts to build-up again.

4. LIMITATIONS OF USING THERMAL OPERATIONAL LIMITS DUE TO INFLUENCE TO DIELECTRIC PROPERTIES OF THE INSULATION LIQUID

A simplified analytical dynamic moisture migration model for short-term view is developed to investigate the influence of the loading dynamic on the relative saturation of insulation liquids.

4.1 Model description

The modelling of solid insulation is confined to hot-thin structures that approximately have winding temperature and amount to approximately 38 % of solid insulation area. The structures are figured as 3 mm thick sheets with 470 m² area according to [14], that has direct contact with the insulation liquid and has linear dispersed winding temperature from bottom to the top of power transformer. Moisture migration between inner layers of solid insulation, the influence of thin and thick cold structures are neglected.

The parameters for insulation liquids (natural ester and mineral oil) are taken from [15]. It is assumed that the liquid has no further contaminations that can bind water in the oil.

Following assumptions and dependencies are used in the model:

- The dynamic thermal model suggested in IEC 60076-7 and a thermal diagram for calculation of winding and insulation liquid temperatures along a transformer winding high,
- Temperature-dependent saturation solubility of water in liquid insulation,
- Sorption isotherms of solid insulating materials [14],
- Mean water migration distance based on Fick's law, proposed in [16].

The liquid is fully mixed at the top of the tank and motion of liquid is assumed as constant. Contribution of cold thin structures to moisture migration is not taken into account in the model. The relative saturation of the bottom oil is calculated to recognize the risk of breakdown.

4.2 Simulation results

The initial moisture content of the solid insulation amounts to 2 %. It is assumed, that the risk of breakdown increases unallowable, when the relative saturation exceeds 60 %. DTM parameters are taken from IEC 60076-6 for a power transformer with ONAN cooling system.

The influence of repeated overloading of the power transformer for 30 minutes up to 50% above the stationary limit with 20°C ambient temperature without exceeding thermal limits is presented in Figure 7. Such overloading profiles are permissible from the thermal point of view. However, they may not be permissible with regard to the relative saturation.

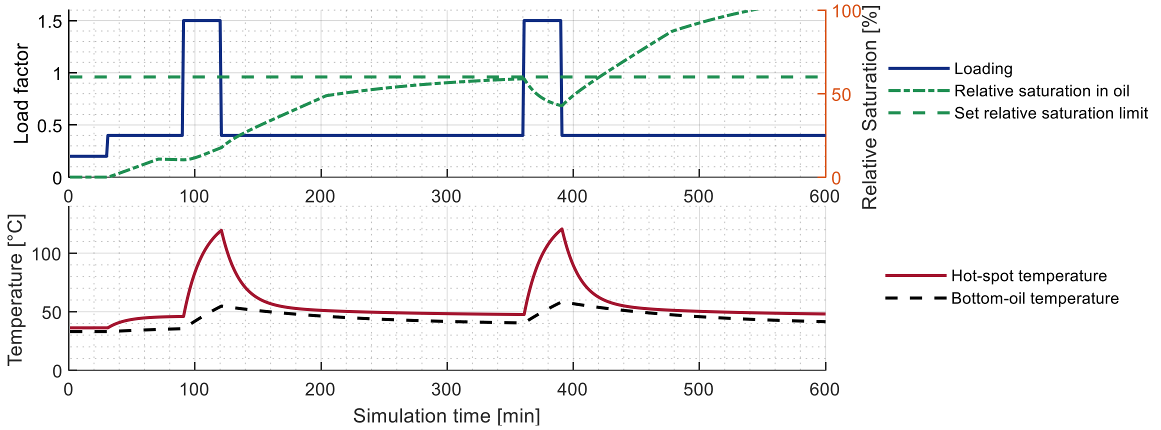

Figure 7 : Relative moisture saturation of bottom oil under influence of specified load profile (top), hot-spot and bottom-oil temperatures (bottom).

Heated up windings drive the process of diffusion of water into the oil. After overloading the cooling down oil temperature influences relative saturation stronger, than occurring diffusion towards solid insulation. In the simulation repeated overloading after 4 hours leads to an inadmissible increase of relative saturation of bottom-oil after 30 min of overloading. The post-overloading period becomes a major issue when mineral oil is used.

Figure 8 shows the influence of post-overloading behaviour (K_{beyond}=0.2 and K_{beyond}=0.8) on relative saturation of bottom oil for two types of insulation liquids, e.g. mineral oil and natural ester. The post-loading of a mineral-oil-filled power transformer at a lower value can lead to high risk of insulation breakdown as it is shown in Figure 8. Additionally, low ambient temperatures and high water content in transformer enhance the effect. The relative saturation of natural ester remains within applicable limits, since the water solubility of natural ester is significantly higher that of mineral oil [15]

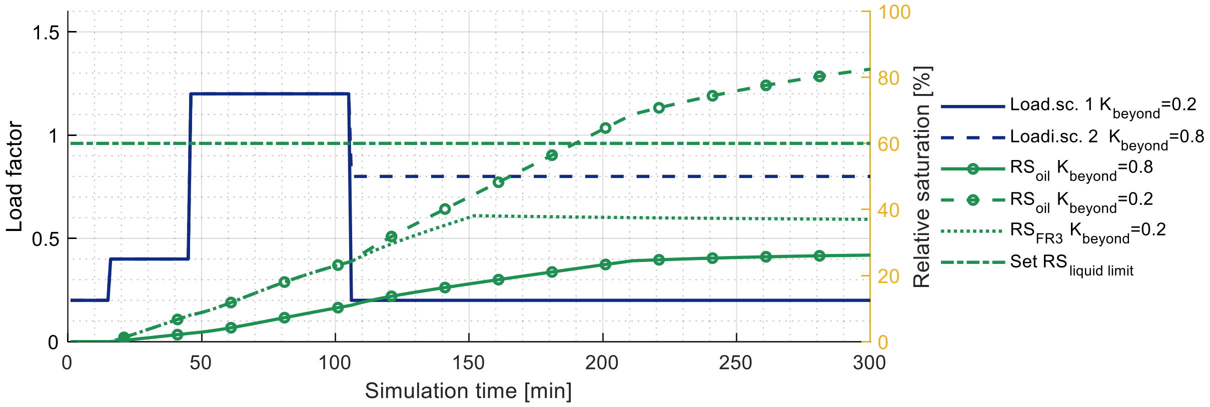

Figure 8: Relative moisture saturation of bottom oil for natural ester and mineral oil by different post-overload loading.

Although the model is relatively simple and has to be proven by measurements, it lets us draw some conclusions regarding using of thermal reserve of mineral oil-filled wet power transformers:

- The overload scenarios models should take into account the moisture migration,
- A cooling system control method should be adopted to the post-overloading period,
- Using online drying systems for insulation liquids in aged transformers can influence the process.

5. CONCLUSION

The dynamic loading capability of power transformers for optimal loading strategies has been investigated in this paper. The paper shows that the safe usage of dynamic thermal limits and thermal reserve for power transformers can be applied for power system studies and in actual operation. However, appropriate dynamic thermal modelling of active parts and subsystems, verification of its steady-state thermal limits and dynamic thermal responses, a moisture migration model for mineral-oil-immersed power transformers, decision-making under uncertainties assistance and a transformer´s intelligent condition assessment system are needed.

Depending on the priority set, be it operational power system flexibility or long-term asset management strategies, different thermal limits for hot-spot temperature can be used in the proposed methodology. The moisture depended thermal limits of equal ageing velocity are proposed.

Reverse calculation of the TM allows determining the steady-state loading limits, and short-term permissible loading beyond the limit that can be used in short-term planning and online assessment of power systems. Comparison of steady-state loading limits for hot-spot and top-oil temperature limits shows that top-oil temperature limits can be neglected for the determination of the loading capability if the model provides the hot-spot temperature.

Due to growing variability of the load profiles of power transformers, using a dynamically calculated hot-spot temperature as initial value for assessment of the thermal reserve and loading capability, particularly concerning permissible duration under 60 minutes, are suggested.

Reduction of dielectric strength of the insulation liquid due to moisture migration caused by intensive loading, especially in cases of repeated overloading and reduced insulation liquid temperatures after loading should be taken into account.

BIBLIOGRAPHY

[1] T. Dethlefs, T. Preisler and W. Renz, "An architecture for a distributed smart grid registry system," IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, 2015, pp. 001234-001239.

[2] Kok J.K., Scheepers M.J.J., Kamphuis I.G. (2010) Intelligence in Electricity Networks for Embedding Renewables and Distributed Generation. In: Negenborn R., Lukszo Z., Hellendoorn H. (eds) Intelligent Infrastructures. Intelligent Systems, Control and Automation: Science and Engineering, vol 42. Springer, Dordrecht

[3] IEC International Electrotechnical Commission, "IEC60076-7 Power transformers - Part 7: Loading guide for mineral-oil-immersed power transformers," 2017.

[4] ANSI American National Standard C57.91, "IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators", 2011.

[5] Djamali, Mohammad. Thermal Monitoring of Power Transformers. sierke Verlag, 2018.

[6] Brochure 642 CIGRE. "Transformer Reliability Survey". (2011) 1-57.

[7] Oommen, T. V., and S. R. Lindgren. "Bubble evolution from transformer overload." 2001 IEEE/PES Transmission and Distribution Conference and Exposition. Developing New Perspectives (Cat. No. 01CH37294). Vol. 1. IEEE, 2001.

[8] Koch, M., and S. Tenbohlen. "Evolution of bubbles in oil–paper insulation influenced by material quality and ageing." IET electric power applications 5.1 (2011): 168-174.

[9] Perkasa, C. Y., et al. "Moisture-bubbling of vegetable oil impregnated paper at transformer overload temperatures." 2015 IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM). IEEE, 2015.

[10] I. Lupandina, M. Schrammel, W. Hofbauer, K. Viereck, W. Gawlik: "Dynamische Belastbarkeit von Leistungstransformatoren mit der Auswirkung auf die Versorgungszuverlässigkeit";
Poster: FNN-Fachtagung Schutz- und Leittechnik, Berlin, Germany; Feb. 2018.

[11] Brochure 659 CIGRE. "Transformer Thermal Modelling". (2016): 1-197.

[12] Brochure 755 CIGRE. "Transformer Bushings Reliability". (2019): 1-127.

[13] Viereck, K., M. Heger, I. Lupandina, and E. Herold. "Verbesserung der dynamischen Überlastfähigkeit von Netztransformatoren durch Netzwerkprognosedaten." Stuttgarter Hochspannungssymposium (2020).

[14] Brochure 349 CIGRE. "Moisture equilibrium and moisture migration within transformer insulation systems". (2008): 1-53.

[15] Tenbohlen, Stefan, et al. "Water saturation limits and moisture equilibrium curves of alternative insulation systems." (2011).

[16] Mukherjee, M., and S. Chakravorti. "Assessment of moisture diffusion distance in pressboard insulation within transformer using Fick's law." 2014 Eighteenth National Power Systems Conference (NPSC). IEEE, 2014.