DYNAMIC RATING OF POWER LINES AND TRANSFORMERS FOR WIND ENERGY INTEGRATION

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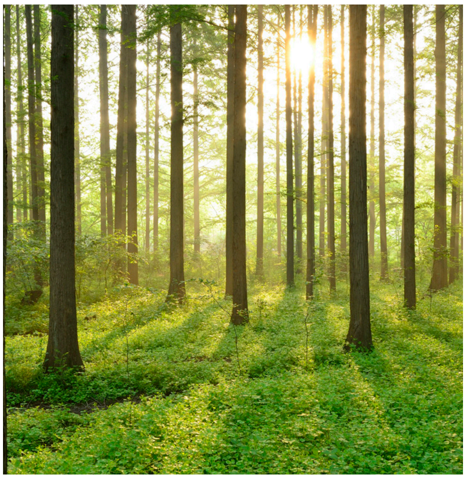

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Dynamic Rating of Power Lines and Transformers for Wind Energy Integration

KATERYNA MOROZOVSKA

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Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Foreword

Med ökad andel förnybar elproduktion ökar också kraven på elnätet. Hur stor effekt kan vi ansluta? Behovet att överföra maximal effekt varierar kraftigt med väder och vind.

Genom att systematiskt undersöka överföringskapaciteten under olika klimatbetingelser ger de här resultaten värdefull information hur man på ett säkert sätt kan tillåta en varierande överföringskapacitet. Det vill säga att tillåta mer effekt när det till exempel är låg temperatur och mycket vind. Att slippa investeringar eller att kunna investera i billigare utrustning är naturligtvis ekonomiskt fördelaktigt både för nätägaren och vindkraftsägaren.

Projektet är en del av Kateryna Morozovskas licentiatsprojekt "Dynamic rating of power lines and transformers with applications to renewable energy and demand response". Det har finansierats av Energiforsk och Energimyndigheten genom Vindforsk.

Projektet har utförts av KTH med Patrik Hilber som projektledare. Referensgrupp har varit RCAM med Dr. Per Westerlund, Dr. Ebrahim Shayesteh och de tidigare medlemmarna Dr. Sajeesh Babu, Niklas Ekstedt, Dr. Carl Johan Wallnerström och Dr. Johanna Rosenlind.

Göran Dalén

Ordförande i Vindforsk

Sammanfattning

Dynamisk belastning (Dynamic Rating - DR) frigör kapacitet hos kraftledningar och transformatorer genom att använda tillgänglig information om väderförhållanden och komponentens skick. Våra studier visar att DR har stor potential för besparingar vid etablerandet av till exempel nya vindkraftparker, där dessa tekniker är speciellt lämpad, särskilt i norden.

Kapaciteten hos de flesta kraftapparater är högst beroende av värmeöverföringsegenskaperna hos materialen som enheterna är tillverkade av. För att säkerställa korrekt effektbegränsningar för utrustningen, måste man inte bara ta effektbelastningen i beaktning, utan även omgivande förhållanden såsom temperatur, vindhastighet, vindriktning, solstrålning, fuktighet, tryck, strålning mot atmosfären, och magnetiska förluster som apparatens skick.

Rapporten är indelad i två områden; DR för luftledningar (DLR) respektive transformatorer (DTR). Detta eftersom dessa två komponenttyper är viktiga för kraftsystemet och att omgivande faktorer har en tydlig inverkan på deras belastbarhet.

Målet för doktorandprojektet "Dynamic rating of power lines and transformers for wind energy integration" är att utforska möjliga vägar att ansluta elkraft genererad av vind till elnätet med hjälp av DR. Resultatet för applicering av DLR för integrering av vindkraftparker i elnätet har visat att tekniken kan användas utan att minska tillgängligheten av elnäten. Rätt använd kan DR snarare höja elnätens tillförlitlighet.

Rapporten presenterar en jämförande studie mellan olika DR tekniker och föreslår en ny klassificering av dem. Denna klassificering är användbar vid bedömning av vilken DR teknik som skall appliceras i enskilda fall.

Studier och experiment har visat att DLR har ett behov av mer detaljerad analys och bättre förståelse av hur konvektivvärmeöverföring fungerar, detta för att kunna modellera DLR mer precist än vad som är möjligt idag.

Analyser av DTR visar på möjligheter att minska transformatorernas storlek utan att kompromissa om tillgänglighet, särskilt I anslutning till vindkraftparker. Detta resulterar i höga ekonomiska nyttor av att applicera DTR på transformatorer jämfört med att använda standard värden.

Summary

Dynamic Rating (DR) unlocks the capacity of power lines and transformers taking into account information on weather and apparatus condition. Our studies show a great potential of Dynamic Rating, the technique can make significant cost savings for new wind power farms, where this technique is very suitable, especially in the Nordic area.

The capacity of the majority of power devices is highly dependent on the heat transfer properties of the materials which the devices are made of. To ensure correct power limits of the equipment, one must take into consideration not only the load, but also ambient conditions, such as: temperature, wind speed, wind direction, solar irradiation, humidity, pressure, radiation into the atmosphere and magnetic losses as well as the general condition of the apparatus.

The report is divided into two topics: Dynamic line rating and Dynamic transformer rating, since these belongs to the more important parts of the power systems and are affected by ambient conditions to a large degree.

The main objective of the doctoral project "Dynamic rating of power lines and transformers for wind energy integration" is on exploring potential ways to connect power generated from wind to the grid with the help of dynamic rating technologies. The outcome of the analysis of DLR application for wind farm integration has shown a potential of using the technique without decreasing reliability of the network. Correctly applied DR can instead increase the reliability of the network.

The report presents comparisons of different line rating methods and proposes a new way of their classification. This classification is useful in the assessment of which DR technique that should be applied.

Studies and experimental evaluation has shown that DLR has a need of more detailed analysis and better understanding of the convective heat transfer mechanism, this in order to enable a more precise DLR.

The dynamic transformer rating application has shown a possibility to decrease the size of the power transformer without shortcomings in component availability for wind power farms. This result in a high economic benefit of a transformer with DTR compared to a standard rated transformer.

List of content

List of Papers

Following publications are included in the thesis:

Paper I

K. Morozovska, P. Hilber, "Study of the Monitoring Systems for Dynamic Line Rating" in : Energy Procedia, 2017

Paper II

K. Morozovska, P. Hilber “Risk analysis of wind farm connection to the existing grid using dynamic line rating”, 2018. Accepted for publication to the 2018 IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS).

Paper III

T. Zarei, **K. Morozovska**, T. Laneryd, P. Hilber, M. Wihlem, O. Hansson “Reliability Considerations and Economic Benefits of Dynamic Transformer Rating for Wind Energy Integration “, 2017. Submitted to the Journal Elsevier Electric Power and Energy Systems and is currently in the first revision stage.

Paper IV

A. Vieira Turnell, N. Tamadon, A. Linnet, **K. Morozovska**, P. Hilber, T. Laneryd, M. Wihlen “Risk and economic analysis of utilizing dynamic thermal rated transformer for wind farm connection” 2017. Accepted for publication to the 2018 IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS).

I am the main author of the Paper I and Paper II. The initial idea described in Paper I belongs to my supervisor Docent Patrik Hilber; I have performed the detailed literature overview and contributed to the development of line rating methods classification. The idea for Paper II has been proposed by me, I have performed the dynamic rating application and risk analysis. The initial idea for the analysis described in Paper III and Paper IV belongs to me. Paper III is based on the Master’s Thesis of my student Tahereh Zarei; Tahereh has conducted the analysis described in Paper II with advisory contributions from Dr. Tor Laneryd and me; I have composed the manuscript and prepared it for publication. Paper IV is the continuation of the analysis described in Paper III and has been written as a part of the course project of Alice Vieira Turnell, Nahal Tamadon and Agnes Linnet; the risk and economic analysis were performed by the students under my supervision. The paper has been composed by the joint effort of myself, Alice Vieira Turnell, Nahal Tamadon and Agnes Linnet.

This paper is not included in the thesis:

O. Giesecke, R. Karlsson, **K. Morozovska**, P. Hilber "Reliability study of two offshore wind farm topologies: Radial and ring connection" in : PROCEEDINGS 15th Wind Integration Workshop: International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Darmstadt, 2016.

1 Introduction

Dynamic rating (DR) names the collection of methods that allow loading power equipment over the nominal rating by building thermal models. Thermal models for dynamic rating take into account available information on system performance, location characteristics and weather parameters. Dynamic rating is applied to key components in the power system such as power transformers, transmission lines and underground cables.

The price per kilometre of transmission line and underground cable is not as high as for a single power transformer, but power lines and cables usually lie for hundreds of kilometres, which makes them good candidates for dynamic rating application. The studies on dynamic rating can be logically divided into: dynamic rating of lines, dynamic rating of transformers and dynamic rating of underground cables. The following study conducts analysis of DR for power lines, - dynamic line rating (DLR) and DR for power transformers, - dynamic transformer rating (DTR).

DLR is done by calculating heat balance of the conductor using collected weather and load data; there exist a number of DLR thermal models for calculation of the heat balance. Depending on the way of data collection, calculated conductor heat balance can have different levels of accuracy.

DTR is applied in a similar manner to DLR; however the construction of transformers is more complicated than of power lines. An important role in transformer operation is devoted to maintaining hot-spot temperature under certain level. The hot-spot temperature has a significant effect on transformer ageing. If the hot-spot temperature crosses nominal critical value, rate of insulation degradation in transformer windings increases; this phenomenon is called accelerated insulation ageing. During accelerated insulation ageing transformer’s loss of life increases dramatically, therefore the additional capacity can affect transformer lifetime.

For better evaluation of the information available in the literature on topics of dynamic line rating and dynamic transformer rating, Table 1 divides information into several key topics: DLR; DTR; monitoring systems; Dynamic Rating application; DR application in wind sector; economy; methods of DR. Given division represents a compressed evaluation of information available in various literature sources.

Table 1 Evaluation of available literature sources on topics of dynamic rating.

Paper	DLR	DTR	Monitoring Systems	DR Application	Application in wind sector	Economy	Methods
[1]	+/-	-	-	-	-	-	-
[2]	-	-	-	-	-	-	-
[3]	-	-	-	-	-	-	-
[4]	+	-	+	-	-	-	+
[5]	+	-	+	+	-	-	-
[6]	+	-	+	-	-	-	+

Paper	DLR	DTR	Monitoring Systems	DR Application	Application in wind sector	Economy	Methods
[7]	+	-	-	-	+	-	+
[8]	+/-	+/-	+/-	+/-	-	-	+/-
[9]	+	-	-	-	-	-	+
[10]	-	-	-	+	-	-	+
[11]	+	-	-	-	-	-	-
[12]	+	+/-	+/-	+	+/-	+	-
[13]	+/-	-	-	-	-	-	+/-
[14]	+	-	+	+	+	+	-
[15]	+	-	-	-	-	-	+
[16]	+	-	-	+	-	-	+
[17]	+	-	+	-	+	-	-
[18]	+	-	+	+	-	-	-
[19]	-	-	+	+	-	-	-
[20]	-	-	+	-	-	-	-
[21]	-	-	+	-	-	-	-
[22]	-	-	+	-	-	-	-
[23]	-	-	+	-	-	-	-
[24]	+	-	+	+	-	-	-
[25]	+	-	+	+	-	-	+
[26]	+	-	+	-	-	-	+
[27]	-	-	+	+	-	-	+
[28]	+/-	-	+	+	-	-	-
[29]	+	-	+	-	-	-	-
[30]	+/-	-	+	-	-	+	+
[31]	+/-	-	+	+	-	-	-
[32]	+/-	-	+	+	-	+/-	+
[33]	-	-	+	+	-	-	-
[34]	+	-	+	-	-	-	+
[35]	+	-	+	+	-	-	+
[36]	+	-	+	+	-	-	-
[37]	+	-	+	+	-	-	+
[38]	+/-	-	+	+/-	-	-	-
[39]	+	-	+	+	-	-	+
[40]	-	-	+	-	-	-	-
[41]	-	-	+	-	-	-	-
[42]	-	-	+	-	-	-	-
[43]	-	-	+	-	-	-	-
[44]	-	-	+	-	-	-	-
[45]	+	-	+	+/-	-	-	+
[46]	-	+	-	-	-	-	+/-

Paper	DLR	DTR	Monitoring Systems	DR Application	Application in wind sector	Economy	Methods
[47]	-	+	-	-	-	-	+
[48]	-	+	-	+	-		-
[49]	+	-	-	-	+	-	+/-
[50]	+	-	-	-	-	+	+
[51]	-	-	-	-	-	-	-
[52]	-	+	-	-	-	-	+
[53]	+	-	+	+	-	-	+
[54]	+	-	-	-	-	-	+/-
[55]	-	-	+	+	-	-	+
[56]	-	+/-	+/-	-	-	-	+
[57]	+	-	-	+	-	+	-
[58]	+	-	-	-	-	+	+
[59]	+	-	-	-	-	-	-

Evaluating the information from Table 1 it can be concluded that DLR has been more addressed in literature than DTR. Basing on the information from Table 1 it can be stated that dynamic line rating is a more developed technology compared to the dynamic transformer rating. There exist a number of DLR technologies that have different price range and installation complexity; the suitable DLR method should be chosen depending on the type of application. Many studies have been dedicated to the monitoring systems for DLR. The application of DR to the grid is widely addressed in the literature, however only a limited number of sources available describe DR application in the wind energy sector. The economic aspects of dynamic rating application do not have a significant representation in the literature. Methods of dynamic rating application are addressed in many sources, but the number of sources covering this topic is lower than that covering monitoring systems. Most of the sources focusing on monitoring systems, dynamic rating application and economy evaluate dynamic rating of power lines. Literature sources combine several of the mentioned topics, for example dynamic rating and monitoring systems application. This thesis is composed of analysis on different topics lacking representation in the literature from Table 1.

1.1 AIM

The aim of the thesis is to obtain results about risks and benefits of dynamic line rating and dynamic transformer rating application, specifically in wind energy sector. Another objective is to obtain more detailed information on heat transfer processes in power lines and transformers and determine the impact of dynamic rating on the ageing of power components.

1.2 GOALS

The goals of the thesis are:

- to use analysis of the available information on dynamic line rating and dynamic transformer rating to select important areas for future investigation;
- to apply the reliability analysis and risk analysis techniques for studies related to dynamic rating application to power network, both on system and component levels;
- to perform empirical studies of the effect of convective cooling on the overhead line heat balance;
- to perform experiment on effects of moisture on transformer insulation ageing during dynamic load operation.

1.3 RESEARCH AREAS DESCRIBED IN THE THESIS

In the following chapters concepts of dynamic line rating and dynamic transformer rating will be introduced in greater detail. The thesis is divided into three main parts: Dynamic line rating; Dynamic transformer rating; Discussion and conclusion. Chapter 2 is an introduction to Dynamic Line Rating and heat balance models. Chapter 3 addresses the differences in different line rating methods and introduces proposed classification of the above. In Chapter 4 the reader is introduced to the hypothesis and procedure for experimental study of effects of wind on the power line cooling. Chapter5 is referring to the risk analysis on additional wind power connection to the existing line by means of DLR described in Paper II. Chapter 6 is a general introduction to dynamic transformer rating and thermal models for calculation of real transformer ampacity. Chapter 7 is a summary of the studies from Paper III and Paper IV and is devoted to the risk and economic analysis of DTR application in wind energy sector. The results of the studies described in Chapter 7 have become a basis for the experimental testing of transformer insulation for different variable heat frequencies; the experimental hypothesis and introduction to planned experimental set-up are described in Chapter 8. The conclusion is presented in Chapter 9 and future work is organized into Chapter 10.

2 Introduction to Dynamic Line Rating

Dynamic line rating can be described as a collection of procedures that allow overloading power lines over the standard rating while maintaining high reliability and low risk of faults. The DLR is done by employing information about conductor, system and ambient properties to calculate real time heat balance. The capacity of power lines is directly proportional to the ambient weather temperature and wind conditions.

There are a number of models for the calculation of line heat balance for dynamic rating application. IEEE Standard for Calculating the Current-Temperature relationship of bare Overhead Conductors mentions 10 different methods and introduces another one [59]. However, the most popular and utilized standardized models are proposed by IEEE and CIGRE [59] [60]. The heat balance models from IEEE and CIGRE have many similarities; however they differ in the factors that they consider for the heat balance calculation [6]. There are several components that affect the overall heat balance of the overhead line:

P_J is Joule heating of the conductor, $[W \cdot m^{-1}]$;

P_S is solar heating of the conductor, $[W \cdot m^{-1}]$;

P_c is convective cooling of the conductor, $[W \cdot m^{-1}]$;

P_r is radiative cooling of the conductor, $[W \cdot m^{-1}]$;

P_M is magnetic heating, $[W \cdot m^{-1}]$;

P_i is corona heating, $[W \cdot m^{-1}]$;

P_w is evaporative cooling, $[W \cdot m^{-1}]$ [59] [60] [61].

The IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors proposes heat balance equation as presented in (1) [59].

$$P_J + P_S = P_c + P_r \qquad (1)$$

The CIGRE loading guidelines expand the formula (1) by corona heating P_i, magnetic heating P_M and evaporative cooling P_w as shown by (2) [6] [9] [60].

$$P_J + P_S + P_M + P_i = P_c + P_r + P_w \qquad (2)$$

Based on (1) the formula for calculation of the current rating of the conductor (3) is developed.

$$I = \sqrt{\frac{q_r + q_c - q_S}{R(T_{avg})}}, \quad [A] \qquad (3)$$

where q_S is the rate of heating due to Solar irradiation, $[W \cdot m^{-1}]$; q_r is the rate of cooling due to radiation into surrounding medium, $[W \cdot m^{-1}]$; q_c is the rate of cooling due to convective heat transfer, $[W \cdot m^{-1}]$; $R(T_{avg})$ is the conductor resistance at the average temperature T_{avg}, $[\Omega/m]$.

A more detailed overview of P_J, P_S, P_c and P_r is presented further in this section. It has to be mentioned that the effect of evaporative cooling (P_w) is difficult to take into account due to the complications associated with measuring humidity around the overhead line for long distances. Therefore, evaporative cooling component is often excluded from heat balance calculation. For the conductors made of Aluminium alloy the effects of magnetic (P_M) and corona heating (P_i) can be neglected.

2.1 JOULE HEATING

Joule heating can be described as the conductor temperature change due to the current flowing through it. According to CIRGE [60] the Joule heating per unit length can be defined using (4) for DC lines and using (5) for AC lines [60].

$$P_{J_{dc}} = I^2 \cdot R_{dc}, \quad [W \cdot m^{-1}] \qquad (4)$$

where I is the total DC current, $[A]$; R_{dc} is the DC resistance per unit length, $[\Omega/m]$, which depends on the conductor shape and resistivity of the material ρ_T for a specific temperature T as in (7) [60].

$$P_{J_{ac}} = k_{sk} \cdot I^2 \cdot R_{dc}, \quad [W \cdot m^{-1}] \qquad (5)$$

where k_{sk} is the skin effect factor, which can be determined by (6) [60].

$$k_{\text{sk}} = \frac{\mathrm{D}^2 \cdot \pi \cdot (E/I)_R}{4 \cdot \rho} \qquad (6)$$

where E denotes the electric field, $[V \cdot m^{-1}]$; R denotes the resistance per unit length, $[\Omega/m]$; D denotes the circumferential diameter of the conductor, $[m]$; ρ is the resistivity of the material as in (7), $[\Omega/m]$ [60].

$$\rho = \rho_{20} \cdot \left[1 + \alpha_{20} \cdot (T_{avg} - 20) + \zeta_{20} \cdot (T_{avg} - 20)^2\right], \quad [\Omega \cdot m] \qquad (7)$$

where T_{avg} is the mean conductor temperature, [°C]; ρ_{20} is the resistivity of the material at the temperature $T = 20$ °C, $[\Omega \cdot m]$; α_{20} is the linear temperature coefficient of resistance at the temperature $T = 20$ °C, $[K^{-1}]$ and ζ_{20} is the quadratic temperature coefficient of resistance at the temperature $T = 20$ °C, $[K^{-2}]$.

In the IEEE model, the Joule heating is accounted for as the part of steady-state heat balance (8) and (9), for better distinction between parameters in IEEE and CIGRE models the author will use q_x notation, when describing different heating and cooling components of the IEEE model [59].

$$q_c + q_r = q_S + I^2 \cdot R(T_{avg}) \qquad (8)$$

$$P_J => I^2 \cdot R(T_{avg}), \quad [W \cdot m^{-1}] \qquad (9)$$

where, $R(T_{avg})$ is the conductor electrical resistance as the function of average temperature, $[\Omega/m]$ and is calculated by (10) [59].

$$R(T_{avg}) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}}\right] \cdot (T_{high} - T_{low}) + R(T_{low}), \quad [\Omega \backslash m] \qquad (10)$$

where T_{high} is the high average conductor temperature at which AC resistance is specified, [℃] and T_{low} is the low average conductor temperature at which AC resistance is specified, [℃].

2.2 RADIATIVE COOLING AND SOLAR HEATING

One of three main mechanisms of heat transfer is radiative heat transfer. Radiative heat transfer happens by emission of electromagnetic waves to the surrounding medium and/or absorption of the radiation emitted by other objects, in other words named absorption.

A general case of radiative heat transfer is determined by (11) [62].

$$q_{r\_gen} = \varepsilon_S A \sigma_B \cdot (T_s^4 - T_a^4), \quad [\mathrm{W} \cdot m^{-1}] \quad (11)$$

where A is the surface area, $[m^2]$; T_s is the surface temperature, $[K]$; T_a is the temperature of the surrounding medium, $[K]$; ε is the radiative material property called emissivity, which defines how efficiently the surface emits energy relative to the blackbody; values of emissivity are in the range of $0 \leq \varepsilon_S \leq 1$; σ_B is the total emissive intensity of the blackbody over all wavelength and is termed Stefan-Boltzmann constant $\sigma_B = 5.67 \cdot 10^{-8}$, $[W \cdot m^{-2} \cdot K^4]$ [62].

The CIGRE radiative cooling component for the overhead line is presented in (12) [60].

$$P_r = \pi \cdot \mathrm{D} \cdot \sigma_B \cdot \varepsilon \cdot (T_s^4 - T_a^4), \quad [\mathrm{W} \cdot m^{-1}] \quad (12)$$

The IEEE radiative cooling component for the overhead line is defined by (13) [59].

$$q_r = 17.8 \cdot \mathrm{D}_0 \cdot \varepsilon \cdot \left[\left(\frac{T_s}{100}\right)^4 - \left(\frac{T_a}{100}\right)^4\right], \quad [\mathrm{W} \cdot m^{-1}] \quad (13)$$

where D_0 is the conductor outer diameter, $[m]$.

As it can be seen from (12) [60] and (13) [59] both CIGRE and IEEE radiative cooling components incorporate the general formula (11) for radiative heat transfer and use the $A = \pi D \ m^2$ to determine the area of the cylindrical conductor.

Usually objects tend not only to emit, but also to absorb electromagnetic radiation emitted from other objects. Heating due to solar radiation is expressed by (14) for IEEE [59] and by (15) for CIGRE standards [60].

$$q_S = \alpha \cdot \mathrm{Q}_{se} \cdot \sin(\theta) \cdot A', \quad [\mathrm{W} \cdot m^{-1}] \quad (14)$$

where α denotes the absorptivity of material and lies in the range of $0 \leq \alpha \leq 1$; Q_{se} denotes the total solar and sky radiated heat intensity for a specific elevation, $[W \cdot m^{-2}]$; A' is the projected conductor area; θ is the effective angle of the sun rays, $[deg]$ [59].

$$P_S = \alpha \cdot \mathrm{I}_T \cdot D, \quad [\mathrm{W} \cdot m^{-1}] \quad (15)$$

where I_T is the global radiation intensity that can be found as a combination of direct solar radiation on the facing conductor surface and diffuse sky radiation to a horizontal plane, $[W \cdot m^{-2}]$ [60].

In real conditions, solar radiation can be direct or diffuse, depending on the cloud coverage of the sky. Solar radiation can be quite difficult to measure in the real-time, so it is preferred to use solar radiation charts, which are established for different regions.

Absorptivity and emissivity are the material properties that determine the rate of thermal energy gain or loss by means of radiation. Emissivity and absorptivity depend on the properties of conductor material and coating that are used. However, these properties are not constant, they change depending on the temperature, ageing of the conductor and different types of pollution; therefore, when designing appropriate heat balance models, the conditions, affecting the overhead line, should be taken into account [18].

Emission and absorption of heat play an important role in the specification of the conductor rating. When determining critical spans of the long overhead line, parameters associated with terrain should be taken into account. If line passes different terrains, such as forest and open field, solar radiation effect has different impact on the conductor heat balance. When line passes through forest, solar heating is not critical; however, a conductor located at the open field area and constantly exposed to the direct sunlight, can experience faster ageing and more drastic change in emission and absorption coefficients.

IEEE and CIGRE standards for conductor heat balance calculation suggest using table values for emissivity and absorptivity. However, the perfect scenario would be to use an algorithm which will estimate correct emissivity and absorptivity of the conductor depending on the terrain, temperature and solar intensity.

2.3 CONVECTIVE COOLING

One of the main heat transfer processes that influence conductor cooling is convective heat transfer. Convective heat transfer is done by two mechanisms: random molecular motion or diffusion and bulk (macroscopic) fluid motion (advection).

Convection can also be classified in terms of the nature of the fluid as forced or free convection; the overhead line exposed to ambient uncontrolled conditions experiences free convection. Depending on the wind speed both micro and bulk molecular motion will have different impact on the conductor cooling. When the wind speed is low, convection is done mainly by diffusion. In the case of high wind speeds, fluid motion has a much bigger impact on the cooling of the surface due to the bulk molecular motion [62].

The convection from the surface can be describe as the heat flux or heat transfer rate per unit area (16) [62]. The expression (16) is also known as Newton's law of cooling [62].

$$q''_{convection} = h(T_s - T_\infty), \quad [W \cdot m^{-2}] \qquad (16)$$

where T_s is the temperature of solid's surface, $[K]$; T_∞ is the temperature of a fluid, $[K]$; h is convection heat transfer coefficient, $[W \cdot m^{-2} \cdot K]$ [62].

Based on (17) total heat transfer rate can be expressed as (17).

$$q_{convection} = q^{"}_{convection} \cdot \mathrm{A} = \bar{h}A(T_s - T_\infty), \quad [W \cdot m^{-1}] \qquad (17)$$

where A is the surface area, $[m]$; $\bar{h}$ is average convection heat transfer coefficient along the surface, $[W \cdot m^{-2} \cdot K]$.

The expression (17) for convective heat transfer is fairly simple, but the determination of the heat transfer coefficient h is a challenging task. h depends on surface geometry, conditions of the flow and various fluid properties such as viscosity, specific heat, thermal conductivity and density [62]. h can be approximated as a function of Nusselt number (18) [62].

$$h \equiv \frac{Nu \cdot k_f}{L}, \quad [W \cdot m^{-2} \cdot K] \qquad (18)$$

where k_f is the thermal conductivity of the fluid at the average temperature at the boundary layer, $[W \cdot m^{-1} \cdot K]$; Nu is the Nusselt number, which is a dimensionless temperature gradient at the surface and is determined as the function of the Reynolds number Re, the Prandtl number Pr and the dimensionless spatial coordinate x^*, $Nu = f(x^*, Re, Pr)$. Depending on the surface geometry the correlation for Nu determination can be significantly different.

Reynolds number is specified as a ratio of inertia and viscous forces in the fluid and is calculated by using (19) [62].

$$Re = \frac{\rho_f VL}{\mu} = \frac{VL}{\nu} \qquad (19)$$

where ρ_f is the density of the fluid, $[kg/m^3]$; V is the velocity of the fluid with respect to the studied object, $[m/s]$; L is a characteristic linear dimension, $[m]$; μ is the dynamic viscosity of the fluid, $[kg/m \cdot s]$; ν is the kinematic viscosity of the fluid, $[m^2/s]$.

Prandtl number is specified as a ratio of the momentum and thermal diffusivities and is calculated by using (20) [62].

$$Pr = \frac{c_p \mu}{k} = \frac{\nu}{\alpha} \qquad (20)$$

where c_p is the specific heat, $[J/kg \cdot K]$; k is the thermal conductivity, $[W/m \cdot K]$; α is the thermal diffusivity, $[m^2/s]$ [62].

Thermophysical properties of air at atmospheric pressure such as μ, ν, k, c_p, ρ_f and α are table values and are specified in various literature sources [62]. By using the table values of thermophysical properties Re and Pr numbers are calculated. Based on the established values of Re and Pr suitable correlation for calculation of Nusselt number is selected [62].

The IEEE standard proposes following procedure for convective heat transfer calculation: first step is the calculation of the heat loss rates for low and high wind speeds $q_{c_{low}}$ and $q_{c_{high}}$ by (21) and (22) respectively. $q_{c_{low}}$ is a convective heat loss rate for low wind speeds, which are below 5 m/s and $q_{c_{high}}$ is a convective heat loss rate for wind speeds that are above 5 m/s. The IEEE standard recommends calculating q_c using both methods and choosing the larger of two values [59].

$$q_{c_{low}} = K_{angle} \cdot [1.01 + 1.35 N_{Re}^{0.52}] \cdot k_{f_{IEEE}} (T_s - T_a), \quad [W \cdot m^{-1}] \quad (21)$$

$$q_{c_{high}} = K_{angle} \cdot 0.754\, N_{Re}^{0.6} \cdot k_{f_{IEEE}} (T_s - T_a), \quad [W \cdot m^{-1}] \quad (22)$$

where N_{Re} is the dimensionless Reynolds number; $k_{f_{\text{IEEE}}}$ is the thermal conductivity of the fluid at the average temperature at the boundary layer, calculated by (23), $[W \cdot m^{-1} \cdot °C]$; K_{angle} is the wind direction factor, calculated by (25) [59].

$$k_{f_{IEEE}} = 2.424 \cdot 10^{-2} + 7.477 \cdot 10^{-5} \cdot T_f - 4.407 \cdot 10^{-9} \cdot T_f^2, \quad [W \cdot m^{-1} \cdot °C] \quad (23)$$

where T_f is the average fluid temperature at the boundary layer as in (24), [°C] for IEEE [59] and $[K]$ for CIGRE [60].

$$T_f = \frac{T_s + T_a}{2}, \quad [°C] \quad (24)$$

$$K_{angle} = 1.194 - cos(\phi) + 0.194 \cdot cos(2\phi) + 0.368 \cdot sin(2\phi) \quad (25)$$

where ϕ is the angle between the direction of wind flow and the line axis, $[deg]$ [59].

According to the CIGRE standard, the convective heat loss can be expressed by (26) [60].

$$P_c = \pi \cdot k_f \cdot (T_s - T_a) \cdot Nu, \quad [W \cdot m^{-1} \cdot °C] \quad (26)$$

where k_f is the thermal conductivity of the fluid at the average temperature at the boundary layer, $[W \cdot m^{-1} \cdot K]$ and is calculated by (27); Nu is the Nusselt number.

$$k_{f_{CIGRE}} = 2.368 \cdot 10^{-2} + 7.23 \cdot 10^{-5} \cdot T_f - 2.763 \cdot 10^{-8} \cdot T_f^2, \quad [W \cdot m^{-1} \cdot °C] \quad (27)$$

A more detailed evaluation of the heat balance calculation can be found in corresponding standards [59] and [60]. The analysis of existing background information about the heat balance calculation for overhead lines has become the basis for a hypothesis described in Chapter 5.

3 Types of Dynamic Line Rating

Line rating can be determined using several different methods. The most commonly used one is calculation of the rating based on the extreme weather conditions and the highest load demand, this type of rating is usually specified in the loading guidelines for power lines. It has become common to employ seasonal rating; seasonal rating is based on the extreme conditions depending on the season, for example, winter and summer rating. The line rating method which is analysed in this manuscript is termed a dynamic rating. DR can be divided into several types, depending on the method of its application. The first step to dynamic line rating is calculation of the line ampacity based on the collected weather data for several years at the location of the line. A more advanced solution is dynamic rating based on weather forecasts. Dynamic rating can also be done using monitoring devices that measure conductor parameters in real time and provide up-to-date information on the ampacity of the line.

In Paper I authors propose a classification of the line rating methods. Proposed categories are organized in alphabetic order depending on the level of complexity, cost and accuracy of DLR:

A - Static rating (STR)

B - Seasonal rating (SER)

C - Weather model (WM)

D - Weather forecast (WF)

E - Conductor temperature evaluation (CTE)

F - Tension monitoring (TM)

G - Line sag measurement (CSM)

H - Clearance-to-ground measurement (CTGM)

I - On-line monitoring of every overhead line segment, or full scale monitoring (FSM).

The term dynamic rating refers to the methods C to I on the list above. It has to be noted that all the DR methods have significant differences in their accuracy and the method of application.

The classification named “Weather model” (WM) refers to DLR algorithm, which is based on the historical weather data from the location of the power line. Weather models do not provide a high accuracy, because they are based on probabilistic studies, but they can be viewed as a good cost effective alternative due to gain of DLR benefits with minimal investment costs.

Weather forecast (WF) is an advanced alternative to Weather model. WF for DLR employ weather forecast from local meteorological stations in order to pro- vide probabilistic forecast of the line ratings with different levels of accuracy, which allows selecting rating based on the level of risk associated with each percentile.

WM and WF can be classified as indirect dynamic rating methods. Direct DR methods involve installation of a measuring device directly at the location of the line span or on the line itself.

CTE is a DR technology that is mainly based on the measurement of conductor temperature in real-time and using this information to calculate ampacity for the next time step.

Tension measurements are usually done by the installation of a tension measuring device directly on the conductor. TM can provide real-time information on the conductor sag as a function of tension.

Line sag measurement or CSM is a technology that uses real-time measuring device of conductor sag. Sag is often measured by installing optical sensors or cameras on the conductor; these sensors are usually accompanied with conductor temperature measuring sensor.

CTGM is a device that is installed under the conductor or directly on the conductor and directly measures distance of the conductor to ground. In theory distance to ground is more robust characteristic of the conductor than sag, because sag measurements do not take into account terrain and surface roughness of the surrounding. However, some CTGM devices have shown to decrease in accuracy in the snow conditions.

FSM would be an ideal case of DR measuring device that will be installed along the line at each span and will provide real-time information for all the locations.

Given classification of methods and monitoring systems provide useful background information for suitable rating method selection. All DLR methods have several advantages and disadvantages. Direct DLR techniques provide higher accuracy and real-time information, but they require higher investment and are more complex in installation. Indirect DLR methods do not provide high accuracy and limit maximum possible rating, but on the other hand do not require high investment and provide software based installation.

4 Experimental Studies of Wind Speed and Direction Effects on Conductor Cooling

4.1 EXPERIMENT HYPOTHESIS

Dynamic rating methods evaluation in Chapter 2 has identified the differences between CIGRE and IEEE standards on conductor thermal balance calculations and conventional heat balance calculation methods. The author proposes an experimental hypothesis for possible improvements of thermal model calculations: wind speed has higher effects on the conductor cooling than it is described by IEEE and CIGRE thermal models due to surface roughness and micro-turbulences close to boundary layer. The experimental analysis aims to test the effect of wind speed and direction on the cooling of the power line, as the convective cooling plays an important role in estimation of correct ampacity values. The models for convective cooling component calculations are different; however, author sees a need in more detailed analysis. There is a possibility to improve the accuracy of the convective cooling calculations by studying the effects of wind speed and direction in better detail. In order to study the effect of convection on conductor heat transfer, the effect of the wind speed should be studied separately in the controlled environment. The experimental analysis described in this section is performed in the wind tunnel, under steady ambient conditions.

4.2 EXPERIMENTAL SET-UP

The experiment was conducted in the wind tunnel facility; the wind tunnel has a $400 \times 500\ mm^2$ cross sectional area and $120\ mm$ length. The wind speed range is variable due to the ambient factors, such as air pressure and temperature, and also roughness and cavities inside the tunnel. The maximum achieved wind speeds were in the range of 24-25 m/s. The overhead lines were tested for wind speeds: $1 - 10\ m/s$, $12\ m/s$, $14\ m/s$, $16\ m/s$, $18\ m/s$, $20\ m/s$, $23\ m/s$, $25\ m/s$.

The tunnel is designed for experiments in fluid dynamics; the tunnel sides are uniform. To perform the test on the constantly heated conductor is a challenge in several ways: a) it is necessary to have a constant supply of current; b) supplied power has to be high in order to heat the piece of an overhead line; c) safety requirements, when using high voltage equipment are high and have to be addressed properly in place which is not designed for high voltage tests.

One of the challenges is to heat an overhead line to high temperatures in the facility which is not suitable for high voltage tests. The decision was made to use a current transformer, connected to power circuit with low current. Using a large number of turns on the primary side and only two turns of copper wires on the secondary side, the load was able to reach around $550\ A$ at low voltage.

The overhead line samples were placed inside the tunnel perpendicular to the wind direction. The test was carried at 22 ± 1 °C. The samples were not exposed to solar radiation. Air pressure was monitored. The sides of the tunnel were sealed in order to decrease the amount of disturbances to the wind flow. Test samples in the study were made of overhead lines. The test samples were heated by high DC current supplied by the current transformer with $1{:}\,275\ A$ ratio. Voltage was kept at $2\ V$. The ends of the test samples were connected to the supply by heat resistant connectors. The connectors were made of stainless steel in order to have low temperature exchange between the test samples and the rest of the circuit but to ensure enough current passage for the sample heating. The schematic experimental arrangement is shown in Figure 1.

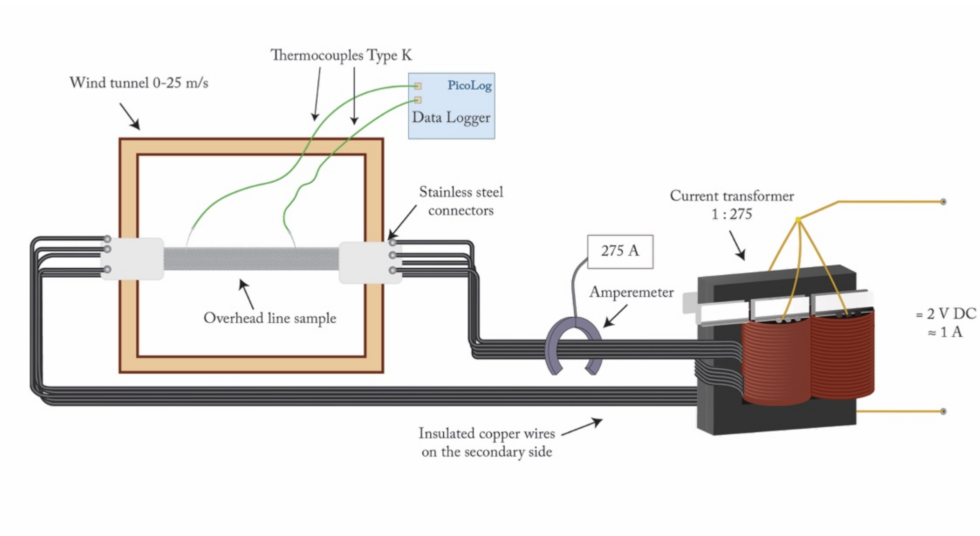

Figure 1 Drawing of the wind tunnel.

The finalized experiment set-up is depicted in Figure 2. Inside of the tunnel is the test sample of the overhead line, from two sides of the tunnel the test sample is connected by two steel pieces to the rest of the circuit.

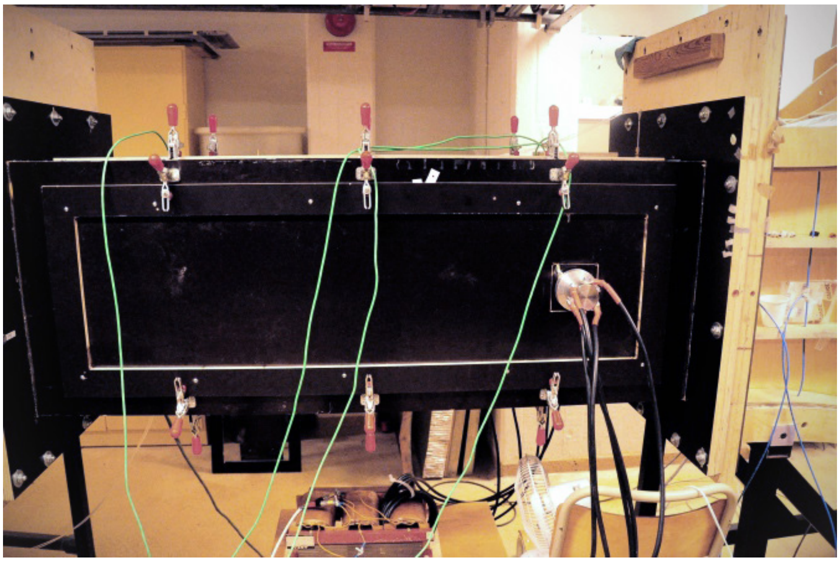

Figure 2 Photo of the wind tunnel lab set-up, for the DLR experiment.

During the experiment several tests were performed on 3 different types of conductors. The properties of test samples are presented in Table 2. The importance of using different types of conductors is motivated by differences that they have in heating-cooling performance, depending on the diameter and material. Overhead line conductors with steel core have a slower rate of heat distribution due to low heat conductivity of steel, however the material properties of stainless steel indicate higher mechanical resistance, preventing line sag during short time overload.

Table 2 Sampled overhead lines used in the test

Code name	Nominal area, [mm²]	Diameter of Al strand, [mm]	Diameter of St strand, [mm]	Total diameter, [mm]	Resistance, [\Omega/km]
Dove	329	26/3.72	7/2.89	23.6	0.1020
Al59	241	19/4.02	0	20.1	0.1230
Al59	593	61/3.52	0	31.7	0.0501

The following experimental tests were performed during wind tunnel sessions:

- testing of temperature response to change in wind speed and respective time to reach steady-state temperature. Conductor was heated up to the same temperature level for each wind speed test. Samples of $Al59$ 241, $AL59$ 593 and $Dove$ ($FeAl$ 329) were tested.
- comparison between temperature response to change in wind speed and respective time to reach steady-state temperature of $AL59$ 241 and solid Aluminium rod of the same diameter. Samples were heated up to the same temperature level for each wind speed test.
- capacity temperature response to the increase in wind speed. Samples of $Al59$ 241 and $Dove$ ($FeAl$ 329) were tested. The procedure for the test was the following:

  1. conductor is heated to the maximum allowable temperature;
  2. wind speed is increased by 1 $[m/s]$;
  3. after reaching steady temperature - conductor temperature is increased to the maximum allowable temperature;
  4. repeat steps 2 and 3.

In the next section a detailed description of one of the performed tests will be given. The preliminary results of the experiment will be presented and discussed.

4.3 ANALYSIS OF MEASURED DATA FROM $AL59$ 241 CONDUCTOR AND SOLID ALUMINIUM ROD OF THE SAME DIAMETER

The test was performed on the sample from $AL59$ 241 conductor and on the Aluminium of the corresponding diameter and cross-sectional area. The comparison between two different shapes of the Aluminium wire was made in order to analyse the physical properties of the convective cooling component and provide improvements to calculations proposed by IEEE and CIGRE standards [59] [60].

The specification of $AL59$ 241 overhead conductor in accordance with the Swedish standard $SS4240814$ is presented in Table 3 [63].

Table 3 $Al59$ 241 parameters according to the Swedish standard $SS4240814$ [63].

Parameters		Value	Units of measure
Nominal area		241.2	mm^2
Strands	Number	19	-----
	Diameter	4.02	mm
Diameter		20.1	mm
Mass per unit length		663	kg/km
DC Resistance		0.123	Ω/km
Rated strength		55.5	kN

There were several types of measurements taken during the experiment: temperature at the surface of the sample; sample core temperature; ambient temperature, wind speed; wind direction, current, voltage. Wind speed was measured by the probe at the entrance of the tunnel, before the wind enters region with test sample, because of the uneven flow distribution after wind passes the conductor. The wind speed generation in the tunnel is highly dependent on the air pressure, therefore the pressure changes were monitored using a barometer. The current was measured by the ampere-meter and recorded with the $LabView$. The temperature was measured by Mantle thermocouple $Type\ K$, 00049205, by Jumo with the parameters listed in Table 4. The readings from the thermocouples were recorded by a logging device $PICO\ TC - 08$.

Table 4 Parameters of the Mantle thermocouple

Element	$Type\ K$
Sheath	$1.5\ mm$
Positioned length	$100\ mm$
Measuring range	$-200 \ldots + 1200$℃
Operating temperature, lead	$-50 \ldots + 180$℃
Lead length	$2.5\ mm$

The comparison between $AL59$ and Aluminium rod samples temperature measurements for different wind speeds can be seen in Figure 1 - Figure 7.

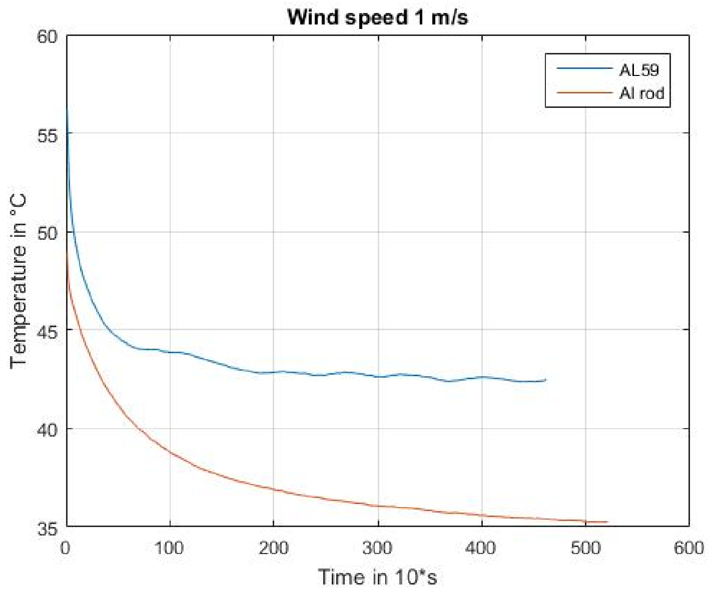

Figure 3 Temperature readings at 1 m/s.

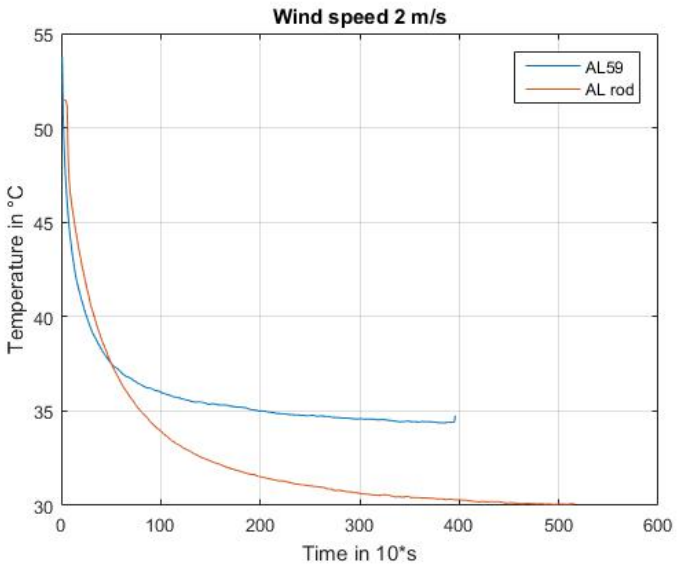

Figure 4 Temperature readings at 2 m/s.

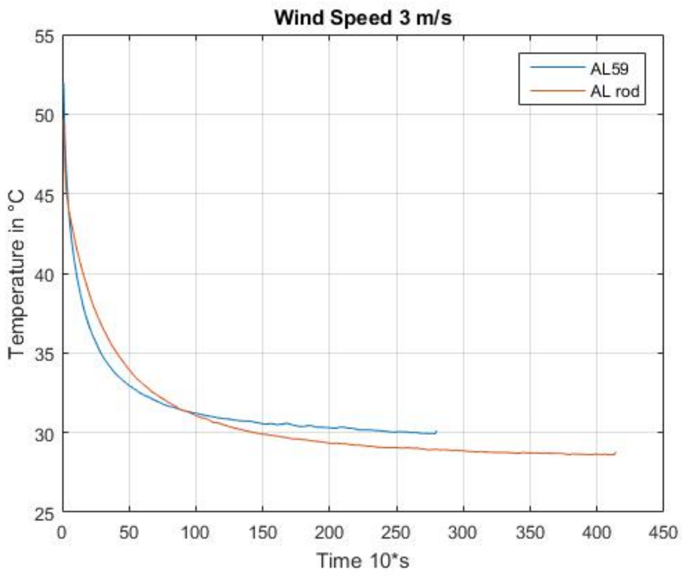

Figure 5 Temperature readings at 3 m/s.

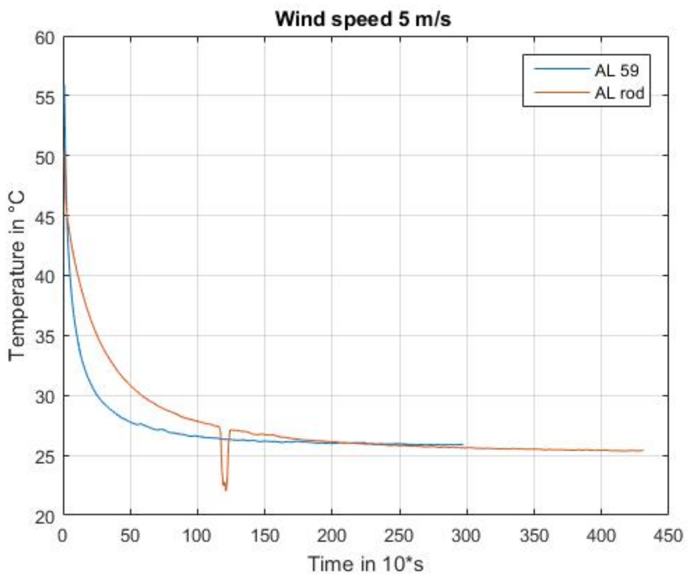

Figure 6 Temperature readings at 5 m/s.

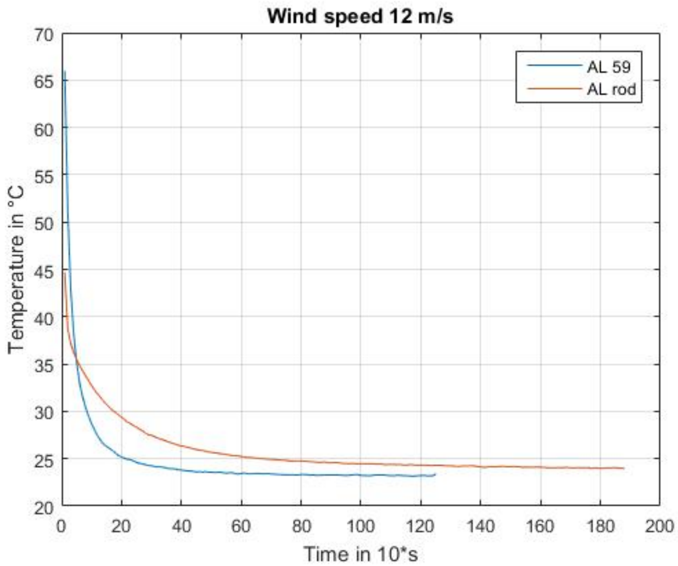

Figure 7 Temperature readings at 12 m/s.

The preliminary analysis of the measured data gives a distinct difference in the cooling patterns of two samples. As all the other conditions differ in very small amounts for two samples, it can be pointed out that the shape of the surface has quite a big influence on the speed and curvature of the convective cooling for $AL59$ stranded conductor and Aluminium rod with a smooth surface. The Aluminium rod temperature decreases faster for the speeds $0 - 3\ m/s$, but after for wind speeds higher than 5 m/s it can be seen that the $AL59$ stranded conductor has higher heat dissipation. The different cooling patterns can be explained by higher natural cooling of the smooth cylinder, but faster cooling of the stranded conductor during higher wind speeds. Better cooling of the stranded conductor under higher wind speeds can be explained by more turbulence that occurs around the surface curvatures.

Future work on the experimental data will continue in the following way:

- the measured data will be used for building heat balance model for the experimentally tested sample and isolating the convective cooling effect;
- the convective cooling component in the heat balance model will be studied in order to provide more suitable correlation for the Nusselt number and more accurate calculation of convective heat transfer coefficient h;
- the effect of wind angle on conductor heating-cooling operation will be investigated;
- the effects of wind speed on cooling of the steel reinforced conductors will also be studied.

The author thinks that based on the preliminary overview of the measured data it will be possible to improve the methods for convective cooling calculation of the power lines. The author believes that the convective heat transfer component has s higher effect on the conductor cooling than the existing standards suggest due to micro-turbulences occurring near the surface boundary layer between strands.

Thermal models accuracy is important for DLR application, because application of DLR to new power networks requires reliable predictions on the risks associated with the dynamic capacity.

5 Dynamic Line Rating for Wind Energy Applications

Wind power is one of the main renewable energy sources worldwide. Wind energy production is growing each year, especially across Europe, and this growth creates more challenges in terms of stressing the power grid. According to the GWEC 'Global Status Overview' [64], in 2014 the annual wind energy market grew by 44 % and for the first time in history passed the point of 50 GW of yearly installed capacity. At the end of 2014 the global total installed capacity equalled 369.6 GW [64]. In order to accommodate the capacity from new wind power plants power networks should be significantly expanded, which means building new substations and power lines.

Dynamic Rating can be a good solution for monitoring and facilitating the power coming from renewable energy sources. Whereas high wind speed conditions DR can provide more transmission capacity due to the cooling effect that high wind speeds have on overhead lines [7] [17] [50] [51].

A clear disadvantage of this approach is that overhead lines usually travel long distances and weather conditions and terrain can have a distinct difference from the wind farm area. In this case it is necessary to investigate the difference between power production at the wind site and the measurements applied for the time- dependent Dynamic Rating for the overhead lines [50].

In Paper II a case study of a DLR application for connection of more renewable energy to the grid is analysed. The case study investigates a possible connection of new wind farm to the existing power line. The power line is used for transmission of power from conventional power plant to the grid. The proposed wind farm has a rated power of 36 MW.

In order to determine the line thermal rating the heat balance was calculated and fitted to the cumulative probability distribution of the wind speed and ambient temperature at the location of the line. The results of the analysis are partially shown in Figure 8 and Figure 9 for month of July and January respectively.

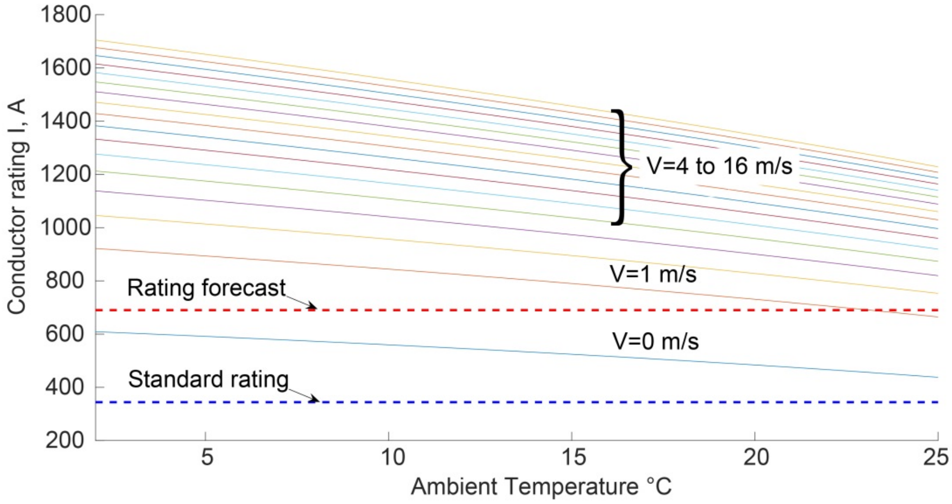

Figure 8 Comparison of the standard rating and real ampacity of the line at different wind speeds during July. Ambient temperature range is $0 - 25$ ℃ .

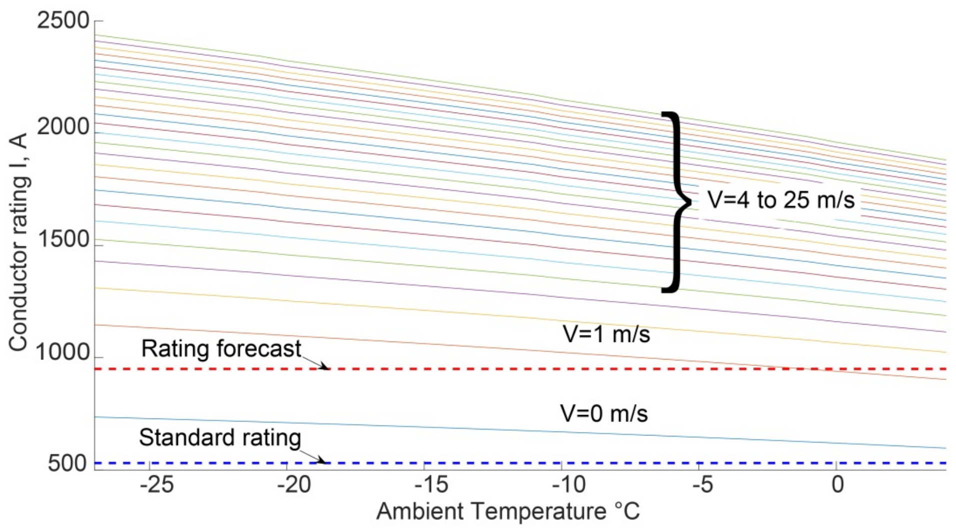

Figure 9 Comparison of the standard rating and real ampacity of the line at different wind speeds during January. Ambient temperature range is $-27 - 5$ ℃.

The average values of the line ampacity and proposed dynamic rating are compared to the standard rating in Figure 10. It is possible to conclude that power line is not being efficiently utilized and has a potential to be expanded by additional inclusion of wind energy.

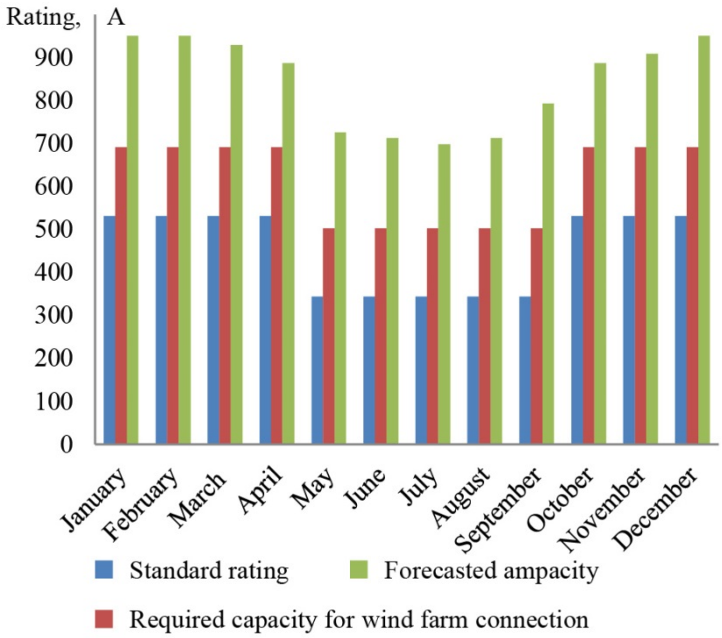

Figure 10 Comparison of average line ampacity with DLR and standard rating of the line.

The analysis of lines for DLR application is usually performed depending on each specific case. One of the future plans of the study includes the investigation of possible ways to identify critical lines and lines with higher transmission capacity in the grid using unified procedure.

The risk analysis of DLR application shows that given line has a potential to be expanded by wind power addition while keeping a high availability of the connection. DLR can improve the process of wind farm connection to the grid by employing the information on the weather data in the area to expand existing power lines.

6 Introduction to Dynamic Transformer Rating

Dynamic Transformer Rating is a method that allows transporting higher capacity through power transformers, by monitoring ambient and system conditions. While the capacity of the power line is directly dependent on the heating and cooling conditions, the transformer ampacity is also dependent on several limiting factors such as: hot-spot temperature; bottom oil transient temperature; maximum contingency loading. According to "C57.91-2011 - IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators" [65] the transformer hot-spot temperature evaluation and the transient temperature of the bottom oil are key parameters that limit the transformer capacity.

The hot-spot temperature of the transformer winding can be calculated using (28).

$$\theta_h = \theta_a + \Delta\theta_{br}\left[\frac{1+NK^2}{1+N}\right]^x + 2[\Delta\theta_{tr} - \Delta\theta_{br}]K^y + Hq_rK^y, \quad [°C] \qquad (28)$$

where θ_a is the air ambient temperature, [°C]; $\Delta\theta_{br}$ is the temperature rise in the bottom oil, [°C]; $\Delta\theta_{tr}$ is the temperature rise of the winding as the winding average, [°C]; N is the ratio between nominal load losses and no-load losses; K is the load current, [pu] and y is the winding index [48].

The transient temperature is calculated by (29) [48].

$$\Delta\theta_{bt} = \Delta\theta_{\mathrm{bi}} + (\Delta\theta_{\mathrm{bu}} - \Delta\theta_{\mathrm{bi}})(1 - \mathrm{e}^{-\frac{\mathrm{t}}{\tau_0}}), \quad [°C] \qquad (29)$$

where $\Delta\theta_{bi}$ is the bottom oil temperature rise at the beginning,[°C]; $\Delta\theta_{bu}$ is the bottom oil temperature rise after the load application, [°C]; τ_0 is the winding time constant, [h].

The rating of the transformer is specified by two limits: the **nameplate rating** and **emergency loading** (emergency rating). The **nameplate rating** is the design parameter that determines the transformer lifetime. The **emergency loading** of the transformer is the shorter period rating that reduces the transformer lifetime, depending on its duration emergency loading can be subdivided into: short time emergency loading and long-time emergency loading.

Transformer oil plays an important role in the heat transfer, at low temperatures heat transfer through oil is much slower than at higher temperatures [47]. The C57.91-2011 IEEE Guide recommends for transformer oil hot-spot to be kept under 110 °C with the maximum ambient temperature of 40 °C and maximum daily average ambient temperature of 30 °C [65] [66].

The constant loading of the transformer provides higher security of supply and ensures longer lifetime. At the same time the static ratings limit the efficient utilization of the power equipment and are not suitable for renewable energy applications. If the transformer hot-spot temperature is constantly maintained under 110 °C, the transformer lifetime is expected to exceed 40 $years$.

The transformer hot-spot temperature is harder to predict than the ampacity of the line. However, the real time data monitoring is easier for power transformers than for the overhead lines. The measurement of top oil can be connected through $SCADA$ system to check, if active cooling of the system works properly. The monitoring of real time data is done in the substation with the easy access and under high safety conditions. The hot-spot temperature can be mathematically estimated from the measured top oil temperature [8].

DTR is a balance between the increasing efficiency of equipment utilization and maintaining high reliability of the grid. The overloading of transformers can have a significant impact on the transformer loss of life. Overloading of transformer above hot-spot temperatures of 110 ℃ accelerates the insulation ageing. If the overloading continues and reaches higher hot-spot temperatures, the formation of bubbles in the oil may occur and therefore, decrease in the transformer dielectric strength [67]. The decreased dielectric strength results in higher failure risks of transformer; the thermal rating of the transformer provides valuable information on the transformer overloading over the critical temperatures and increases reliability [68].

In the following chapter the analysis of the effect of DTR application on the transformer reliability and transformer ageing will be discussed, followed by the economic analysis of the benefits of DTR application.

7 Dynamic Transformer Rating Application in the Wind Energy Sector. Reliability Analysis and Economic Benefits

This chapter provides the reader with the background information and evaluates main findings described in Paper III and Paper IV. The main goal of the study on DTR from Paper III and Paper IV was to investigate the effects of dynamic rating on the transformer lifetime and how the connection of the transformer to the variable load can influence the ageing of the transformer. The results illustrate a comparison between a real transformer, which is connected to a wind power plant, and a smaller size transformer with DTR. The transformer under investigation is 19.4 MVA power transformer connected to the wind farm and is currently in use.

The first part of the analysis is focused on building thermal models for DTR based on the IEC and IEEE loading guidelines for oil-immersed transformers [65] [69]. The next step is a comparison between calculated hot-spot temperature and hot-spot temperature value acquired from information on real-time top-oil temperature measurement.

DTR reliability analysis is based on gathering information about trans- former loss of life and definition of the critical days. Critical days of the trans- former operation are the days when the transformer loss of life is disproportionally high; critical days occur when transformer is being overloaded. The transformer loss of life can be calculated by (30).

$$LOL = \int_{t_1}^{t_2} F_{AA}\, dt, \quad [h] \qquad (30)$$

where F_{AA} is the relative ageing factor or ageing acceleration factor that is calculated by (31) [46] [65]; t_1 and t_2 are time periods when loss of life occurs, $[hours]$.

$$\mathrm{F_{AA}} = \mathrm{e}^{\frac{1500}{110+273}-\frac{1500}{\theta_H+273}}, \quad [h] \qquad (31)$$

where θ_H is the actual dimensionless hot-spot temperature,[℃].

The analysis of the critical days in Paper III shows that 80 % of the transformer loss of life occurs during 30 $days$ through one year. The cumulative loss of life for the 17 $days$, which account for 50 % of the yearly loss of life, is equal to $LOL_{sum} = 0.113\ [days/year]$. The value of loss of life shows that the transformer is not being utilized to its full potential.

The studies on the loss of life have shown the possibility to downsize the transformer for this application or to increase the transformer transmission capacity by expanding the wind farm.

The 19.4 MVA transformer can be replaced with a 16 MVA transformer. In Paper IV a detailed risk assessment and economic analysis of replacing 19.4 MVA transformer with a 16 MVA transformer is presented. The outcome of the analysis shows that if the transformer for current application was replaced with a 16 MVA

transformer with DTR, this application will result in saving on investment at the specification stage. Therefore, it can be concluded that 16 MVA transformer with DR is more economically beneficial for this case study than 19.4 MVA transformer.

Through the course of the DTR reliability analysis the authors noticed a need in more detailed investigation of the effect of variable loading on the transformer insulation ageing. The following questions have initiated the experimental investigation of transformer insulation ageing for operation under variable load conditions described in Chapter 8.

DTR application is highly dependent on the hot-spot temperature, which can be either monitored or calculated using thermal models. The lifetime of a transformer and transformer's loss of life determine its capacity potential. The information on LOL and available DTR methods provides a possibility to choose a more economically beneficial transformer at the specification stage. Economic analysis in Paper III supports author's claim regarding DTR impact on the decrease of investment costs for transformer purchase.

8 Experimental Analysis of the Moisture Effect on Insulation Paper Degradation during Transformer Dynamic Operation

8.1 EXPERIMENT HYPOTHESIS

The experimental studies of transformer dynamic operation were performed on the basis of Master's degree project in cooperation with Corporate Research unit at ABB AB, Västerås, Sweden.

The main aim of the study is to investigate the influence of moisture on the transformer paper degradation under dynamic operation. In the original set-up, when transformers are loaded with constant power, oil characteristics have very little influence on the degree of paper polymerization. However, DTR brings new perspective into transformer loss of life studies. The hypothesis outlines the possibility that moisture content in the mineral oil can have different effect on paper ageing, depending on the heating operation the transformer is subjected to. The authors predict higher a heating-cooling frequency of the transformer to decrease the degree of polymerization in paper and oil.

8.2 BUILDING THE EXPERIMENT

The laboratory experiment is designed to be run through a period of 5 to 9 $months$. During this period of time samples of transformer paper will be attached to a heating component and immersed into the mineral oil as shown in Figure 11. The samples will be placed in glass vessels and sealed. The moisture content in all the samples will be controlled to be at the same level at the beginning of the experiment by drying the test samples in the oil vessels in a vacuum oven and impregnating the samples while they are inside. The mineral oil will be degassed and dried prior to impregnation. The seal will protect the tube from additional moisture during the experiment. Glass vessels will be placed into Aluminium blocks for faster heat dissipation and equal temperature distribution.

The schematic plan of the experimental arrangement is shown in Figure 12. The glass vessels with the same heating curve are placed on equal distance from each other. Each of the glass vessels is identical to the one shown in Figure 11.

The heating cycle will be achieved by using cartridge heaters. The insulation paper will be mounted on the cartridge heater; cartridge heaters will then be placed inside the test tubes and immersed with mineral oil. During the experiment temperature of the cartridge heaters will be a controlling variable, current and voltage parameters will be held constant.

The temperature measurements are done by the set of thermocouples that are attached to heating cartridges and logged by using PXI data acquisition unit. PXI is connected to a stationary computer and communicates output and input signals generated in $LabView$. $LabView$ sends a Pulse Width Modulation (PWM) signal to control the input current to cartridge heaters. The samples are divided into three groups depending on the frequency of heating-cooling operation, the heating-cooling curves for all the operation modes are shown in Figure 13.

To measure the DP of the paper, a small sample of the test subject should be taken for analysis; this is done by analysing samples of oil and paper during the course of the experiment.

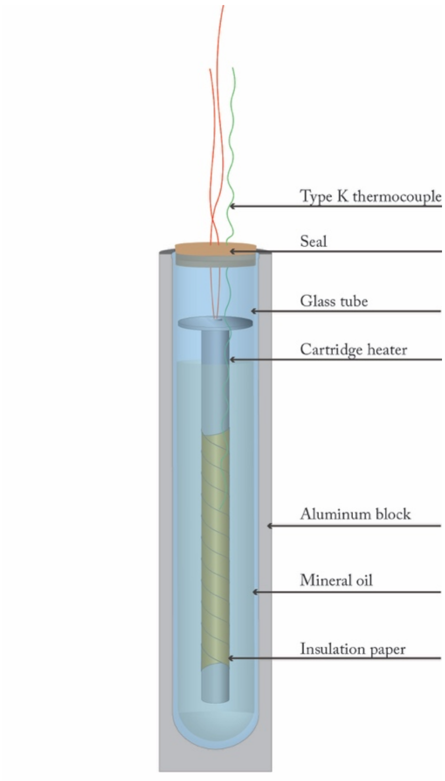

Figure 11 The test paper wrapped around the cartridge heater and impregnated with mineral oil. The cartridge is placed inside a glass tube. The glass tube is fitted into round shaped Aluminium block.

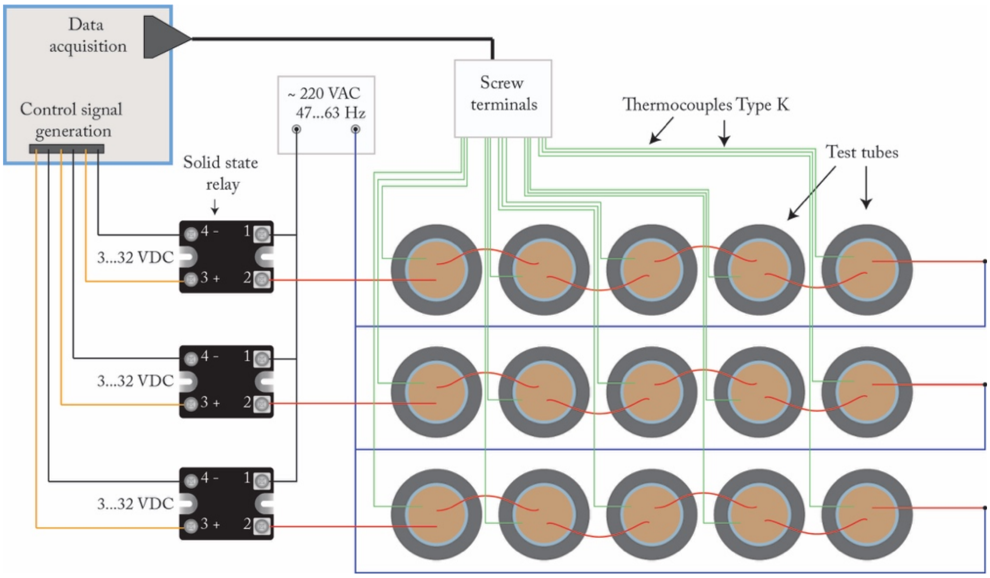

Figure 12 Schematic arrangement of the test tubes and the control sequence.

The author and the team, which is working on the experiment, expect to see differences in the degree of polymerization and the level of ageing in mineral oil and paper. The results from the experiment are important for better understanding of variable loading of power transformers and for development of DTR.

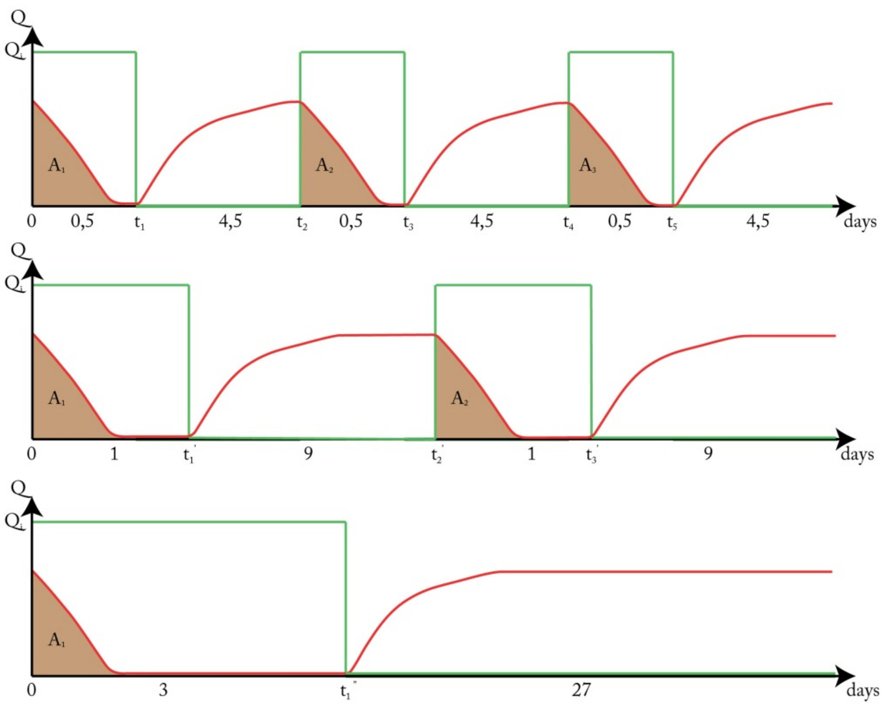

Figure 13 Control cycles of 3 different heating-cooling frequencies for loading cartridge heaters.

9 Conclusion

In the preceding Chapters the main goals and research findings of the project are described in detail.

Literature analysis on the topic of DLR in Chapter 1 shows that significant amount of studies have been done on the topic of DLR application to the grid, but there is not enough information on the economic influence of DLR and DLR application in the wind industry. Literature overview on the topics of DLR has shown that the development of thermal models for DLR has not been a popular topic over previous years.

Part 1 introduces the concept of Dynamic Line Rating. The calculation of the conductor heat balance is a key component in the development of the DLR, current methods for calculation of conductor heat balance provide a detailed instruction for its calculation, but do employ some simplifications compared to conventional methods of heat transfer analysis. The research has questioned the accuracy of the available methods for conductor heat balance calculation. When comparing the methods described in the standards with conventional heat transfer calculation methods, certain uncertainties in convective cooling calculations have been found and are proposed to be addressed by means of experimental analysis. Chapter 1 describes an experimental study that performs an investigation of the wind speed effect on cooling of a piece of an overhead line in the controlled environment.

The experimental study of the convective heat transfer component was developed and performed at KTH. The preliminary results of the testing show the basis for future detailed analysis and investigation of the mechanism in detail. The brief comparison of measurements from the samples with different surface roughness identifies the need in more complex method for convection heat transfer coefficient calculation. Therefore, the development of a more accurate convective heat transfer calculation method is one of the goals of future work.

Chapter 3 is addressing the differences between different ways of Dynamic Line Rating application to the power system. The proposed classification of power line rating methods provides a useful scale that is based on the accuracy of rating, complexity of methods implementation and costs associated with their application.

The risk analysis of DLR application for connection of wind power plant to the existing overhead line is addressed in Chapter 5. The risk analysis shows that the line in Chapter 5 can be safely expanded with additional wind power inclusion. This expansion is motivated by the cooling effect of wind speed on the overhead line, which increases the capacity. Another influential factor is the dependence of the wind power production on the wind conditions in the area.

Literature analysis on the topic of DTR in Chapter 1 shows the lack of studies dedicated to Dynamic Transformer Rating in general. Therefore, Part 2 of the thesis is addressing the study of Dynamic Transformer Rating and the analysis of its application. The analysis of the transformer loss of life after the application of DTR from the Paper III has shown high economic benefits compared to a standardly rated transformer. In Paper III the models for conductor thermal balance calculations are compared and evaluated.

The analysis from Paper III was expanded with a more detailed risk and economic analysis in Paper IV. In Paper IV authors compare the advantages and disadvantages of replacing the transformer of 19.4 MVA with a dynamically rated 16 MVA transformer.

Based on the evaluation of thermal models and transformer ageing during variable loading, the need in a detailed study of the transformer insulation ageing during dynamic loading and short and long time overload conditions has been identified. The hypothesis for the experimental study of the insulation ageing under dynamic heat operation is outlined in Chapter 8.

Dynamic Line Rating and Dynamic Transformer Rating have a potential to provide a better utilization of equipment and minimize the investment costs for connecting renewable energy generation to the power network.

Power transformers and lines are costly equipment and the selection of the dynamically rated lines and transformers at the specification stage can lead to high investment savings. Another application of the DR technologies is expansion of the existing transmission grid with connection of additional wind power generation units. Fast integration of renewable energy is an important topic nowadays and DR can be viewed as an alternative approach to fast integration of renewable energy to the grid, as it cuts down the time for building network connection.

10 Future Work

The future scope of the project includes several research areas to be investigated in the near future:

- reliability analysis of the DLR technologies and evaluation of their suitability for different types of applications;
- studies of the forecasting for DLR, analysis of risk and economic influence of DLR forecast on the reliability of the line and power network;
- detailed analysis of the convective cooling effect on the heat balance of the power line based on the experimental results;
- analysis of the effects of moisture on the transformer insulation degradation under dynamic operation conditions;
- development of power network DR application algorithm, including DLR and DTR for better utilization of the power equipment;
- minimization of risks associated with the application of Dynamic Rating algorithms to power systems;
- minimization of the rating constraints of power components in demand response optimization by application of DR.

Future findings are planned to be presented at conferences, published in scientific journals and discussed in the final doctoral thesis.

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DYNAMIC RATING OF POWER LINES AND TRANSFORMERS FOR WIND ENERGY INTEGRATIONS

Dynamic Rating unlocks the capacity of power lines and transformers taking into account information on weather and apparatus condition. Dynamic Rating can make significant cost savings for new wind power farms, where this technique is very suitable, especially in the Nordic area.

The capacity of the majority of power devices is highly dependent on the heat transfer properties of the materials which the devices are made of. To ensure correct power limits of the equipment, one must take into consideration not only the load, but also ambient conditions, such as: temperature, wind speed, wind direction, solar irradiation, humidity, pressure, radiation into the atmosphere and magnetic losses as well as the general condition of the apparatus.

The dynamic transformer rating application has shown a possibility to decrease the size of the power transformer without shortcomings in component availability for wind power farms. This result in a high economic benefit of a transformer with DTR compared to a standard rated transformer.

Energiforsk is the Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy smarter! Vindforsk is operated in cooperation with the Swedish Energy Agency.