Dynamic Line Rating Analysis in Transmission lines: Protection Application

Fatemeh Hajeforosh

Dept. of Engineering Sciences and Mathematics
Luleå University of Technology
Skellefteå, Sweden

Supervisors:

Math H.J. Bollen, Sarah K. Rönnberg

10 November 2020

Abstract

Load growth, addition of renewable sources and increased consumption highlight a significant need to increase the transfer capacity of transmission lines. The final solution is building a new transmission line; however, it takes several years plus huge investment. Dynamic Line rating (DLR) systems appear as an appropriate option to address rapid changes in the loading of the power grid. DLR is the way of determining the line rating by measuring how the weather impacts the thermal behavior of the system. Environmental parameters as well as line characteristics are two key points in the operation of DLR. Traditionally the rating of the line is set based on conservative assumptions, called static line rating (SLR), in weather parameters to make sure that the conductor surface temperature and line sag is below a certain limit even for maximum load. However, with the additional parameters a higher line rating can be accepted. Along with DLR, the rating of thermally limited electrical elements along the line should be considered and their rating may require increase. Next to addressing the rating of other elements, it is also important to consider the protection system that is classically set to remove faults. Taking these as motivations, the purpose of this report is to analyze the benefits and risks of DLR as part of the protection operation. The method described in IEEE 738 standard is used in this report for calculating the line rating of overhead lines.

The overview of dynamic rating in general and the steady-state calculation of the line rating in particular are being studied in Chapter 2. In Chapter 3, we go through the analysis of protection operation in a transmission line and overload protection setting to model an overload protection with DLR. The qualitative description of DLR reliability is provided in Chapter 4. Uncertainty handling in power systems and modelling uncertainty in line rating are the focus of Chapter 5. Grids' hosting capacity provided by DLR is studied in Chapter 6. Chapter 7 is dedicated to findings and discussion and finally the future works and recommendations are the subject of Chapter 8.

Contents

Acknowledgments

This project has been funded by Skellefteå Kraft Elnät, Swedish Energy Agency and Energiforsk and the work has been done at the Power Engineering Group in Luleå University of Technology. The financial support is greatly appreciated and I hope that this report will bring knowledge that is useful for the funders and people interested in the subject given in this thesis. I would like to thank my supervisor Math Bollen. You have provided excellent support and guidance throughout this project which has made this thesis possible. I would also want to thank my colleagues at Electrical Power Engineering Group for answering questions and providing good discussions.

I would like to thank my husband Ali for his unconditional love and support since the beginning of this journey that make it possible for me to follow my ambitions.

Chapter 1

Introduction

1.1 Background

The available transmission line capacity has always been important to maximize the loading of the lines and exploit the most out of existing transmission lines [1]. In addition, the construction of a new transmission line is being constrained by environmental issues and takes several years between realizing that a new line is needed and this line being actually available. But due to growth in consumption and addition of renewable energy resources it becomes necessary to address existing or future congestion problems in the grid. The lead-time at which congestion is expected to occur has become less than the before-mentioned time to have a new transmission line available. Two distinctively different congestion problems occur in the transmission grid; stability limits and thermal limits. Stability limits become relevant for transfer over long distances (in Sweden: between North and South), whereas thermal limits are the dominating issue for shorter lines (in Sweden: the supply into cities). In this report we will only address the thermal limits.

Thermal limits of overhead conductors may cause congestion due to insufficient physical transfer capacity on a transmission line to implement all energy schedules and make balance between generation and demand. Thermal ratings of overhead conductors may not allow system operators to utilize existing transmission capabilities fully. They in most cases cause underestimation of the thermal capability, however, in worse cases they may lead to overestimated rating that may cause damage to the system or dangerous situations due to excessive heating of the conductor. Dynamic line rating (DLR), the rating which accounts for weather conditions and line characteristics at a much shorter timescale (for instance one hour), can be used to increase the line rating up to its physical thermal limit. The (dynamic) line rating is defined as the maximum current that will not result in temperature exceeding the maximum permissible temperature. DLR calculation is explained in more details in Chapter 2.

1.2 Motivation

There are several challenges for DLR implementation. The over utilisation of the existing power system would have an impact on the performance of the overall network. Some of the challenges to be considered are accelerated aging, data uncertainty, and taking measures from protection viewpoints. When applying dynamic rating it is necessary to take into account the other thermal limiting elements of the power system, specifically the protection system of overhead lines [2, 3]. Protection systems should be tuned with the DLR in order not to limit the available capacity and prevent unnecessary measures. DLR protection operation is discussed in Chapter 3.

1.3 Objective and Scope

This report is aimed towards analyzing the benefits and risks of applying DLR in to the protection operation and comparing with classical settings. Some of the objectives are listed as follows:

- Studying DLR applications during the operational planning. Defining critical scenarios for the DLR operation that affect the protection operation (discussed in Paper A).
- Designing and modeling the protection operation and issues concerning dependability and security of the protection (discussed in Paper B).
- Stochastic modeling of the line rating and calculating the probability of overloading in three different case studies (discussed in Paper C).
- Quantifying the potential of DLR during increased consumption, specifically from electric vehicles (EVs) viewpoint (discussed in Paper D).

1.4 Approach

The research that is presented in this work is divided into four sections. Different approaches have been used for different sections:

1. A review of the reliability aspects of dynamic line rating is done focusing on what can constitutes DLR failure. A generic model is also presented containing different types of elements and their failures that have the potential to impact the performance of DLR. The approach used here is a qualitative description to identify different errors in the system.
2. Time-series analysis of DLR is carried out for various scenarios to obtain the probability of overloading. Eight-year data for weather, wind farm, PV production, and consumption is subsequently provided for the analysis. The resolution of the data is one hour. Weather data is obtained from the Swedish Meteorological

and Hydrological Institute (SMHI). Wind farm data is obtained from the distribution network operator and PV the data is obtained from an open access website (www.renewables.ninja) [4, 5], and finally loading data that is obtained from the Swedish Energy Agency publicly available data. Investigating the benefits of DLR in Sweden and estimating the risks this brings by updating other thermal elements along the line.

3. Designing and modeling an overload protection with DLR. The stochastic method for uncertainty handling in weather data is done to address stochasticity in the line rating. The model is based on the probability of overloading and aimed towards making a balance between dependability and security in the overload protection.
4. The potential of implementing DLR based on real data is studied as part of this report. The available transfer capacity of the line (hosting capacity) is estimated to study the maximum load growth of the region, in this case from EVs viewpoint.

1.5 Contribution of the Work

The main contributions of the work are listed as follows:

1. Showing the potential of DLR for allowing additional growth in consumption and production.
2. Describing DLR and especially its failure, in terms of overload protection. This description provides the terminology to make a trade-off between unwanted measures being taken and necessary measures not being taken.
3. A stochastic overload protection scheme for overhead lines, where the probability that the actual instantaneous line rating is less than the current, is used as a decision parameter. Uncertainties in weather parameters and line parameters can be considered in the proposal scheme.
4. A stochastic scheme that can be used during "hour-ahead" or "day-ahead" operational planning.
5. Showing that the acceptable probability of overload has a big impact on the number of times that measures against overloading have to be taken.

1.6 Social Aspects of DLR

The increase in the demand for power leads to an increase in the utilization of the electricity grid. With continuing increase in demand, providing grid access for new users and connections is no longer straightforward and requests for new connections may be denied. The lack of capacity hurts economic development by limiting electrification of transport, establishment of new companies, development of new urban areas, and residential buildings in existing urban areas.

The classical solution has been to build new transmission lines, cables, substations, etc. This will be expensive, but especially it will take a long time. Building a new transmission line will take around ten years according to the Swedish transmission system operator [6]. Alternative solutions have to be found, that are cheaper and especially that are faster and more flexible. Enhancing the use of the existing grid through DLR is one of the alternative solutions to deal with the lack of capacity. The use of DLR makes among others that the available transport capacity of a transmission line increases during cold periods. This is relevant as the typical demand in Nordic countries increases during such cold periods due to heating loads. The potential of this is shown specifically for the expected demand increase due to charging of electric vehicles. In this way, DLR removes a barrier against the electrification of transport.

Another alternative to building transmission lines is to curtail the demand whenever it would result in the transmission-line loading exceeding the line rating. This will allow a certain amount of demand growth, but during certain hours of the year, the higher demand will be curtailed. Using DLR will reduce the number of hours per year that curtailment is needed and thus reduce the social and economic inconveniences due to the curtailment. The DLR protection application, developed in this work, assists the transmission-grid operator to assess the overloading risk of the line prior to the operation and make a better decision to prevent load shedding and reduce the number of interruptions per consumers. It allows a more fair balance between high risk of overloading and unnecessary curtailment of the demand.

Due to fast growth in the renewable energy resources such as wind farms, DLR will further increase social welfare by allowing more accessibility to cheaper and cleaner sources of energy.

1.7 Outline of Half-way Report

This report is divided into seven chapters as follows:

- The first chapter provides the overview of the report; background, motivation, scope, approach, contributions and outline of the report.
- The importance of dynamic component rating, specifically of overhead transmission lines, will be introduced in Chapter 2. The details of the IEEE thermal rating calculation are also included in this chapter.
- In Chapter 3 the details of the overload protection in transmission lines are presented from DLR viewpoints.
- The reliability aspects of DLR is discussed in Chapter 4
- Chapter 5 starts with a brief overview of uncertainty handling and different techniques to cope with that. Following this overview, the proposed stochastic dynamic line rating will be described along with an uncertainty analysis.
- Chapter 6 is about illustrating the potential of DLR application, in particular in Sweden, to prevent overloading of the downstream network when, for instance, EVs are added to the system.

- In Chapter 7 findings are presented with a discussion of them.
- Chapter 8 briefly discusses further studies needed to be done in this research topic.

1.8 Appended Papers

The papers that are included in this report are as follows:

- **Paper A**

  SF. Hajeforosh, M. Bollen, L. Abrahamsson,"Dynamic Line Rating Operational Planning : Issues and Challenges", 25th International Conference on Electricity Distribution (CIRED), 2019.

- **Paper B**

  SF. Hajeforosh, M. Bollen,"Transmission Line Overloading Analysis Using Probabilistic Dynamic Line Rating", 16th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), 2020.

- **Paper C**

  SF. Hajeforosh, M. Bollen,"Uncertainty Analysis of Stochastic Dynamic Line Rating", Submitted and under the second review in Electric Power Systems Research, 2020.

- **Paper D**

  SF. Hajeforosh, M. Bollen,"Increasing the Grid Capacity for Electric Vehicle Charging using Dynamic Rating", To be submitted to the 26th International Conference on Electricity Distribution (CIRED).

The following paper is not included in this report:

- **Paper E**

  SF. Hajeforosh, Z. Nazir, M. Bollen,"Reliability Aspects of Battery Energy Storage in the Power Grid", IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 2020.

Chapter 2

Thermal Rating

2.1 Dynamic Component Rating

The term "dynamic rating" implies that component's rating can be changed or is adaptive. These components are series-connected elements that are thermally limited in the power system: transformers, overhead lines, and underground cables.

Generally, a power transformer is one of the most costly devices in a power system. One way to postpone purchasing a new transformer due to loading constraint is operating the existing transformers beyond their nameplate ratings for a limited number of short periods. However, the insulation deterioration of power transformers is a function of the temperature of the insulation, which in turn is a function of the loading and ambient temperature. Proper combination of these two could safely allow transformer loading to exceed the nameplate rating without an unacceptable amount of aging. There are three determining factors that influence the rating of the transformer; top oil temperature, winding hot spot and ambient temperature. The calculations concerning thermal models for dynamic transformer rating are discussed in the IEEE and IEC loading guidelines for oil-immersed transformers [7, 8].

Likewise, dynamic rating of cables is dealing with loading cables beyond their static rating, depending on ambient temperature and even temporary loading beyond the rated temperature. An iterative method that comprises calculating electrical and thermal parameters is described in the IEC 60287 series [9] and a thermal cable analysis can be made according to the IEC 60853-2 [10]. Soil thermal resistivity and ambient temperature are two parameters that control the rate of heat transferred from the cable. However, the big challenge about applying dynamic cable rating is that soil thermal properties vary with terrain and time and that these properties are often unknown. The weakest parts of a cable are the cable terminations and cable joints; this is where the electric field is highest with highest heat development in the insulator as a consequence. The temperature inside the joint can be much higher than elsewhere along the cable that will lead to increased ageing of cable insulation inside joints or terminations and, in the worst case, to insulation failure [11]. It is worth mentioning that the cost of underground cables are high either for installing new cable or for troubleshooting in case of any failure [12].

DLR on the other hand employs a time-varying current capacity dependent on the actual weather conditions and line characteristics [13]. DLR allows exploiting more of the hidden transport capacity of the line and operating the line much closer to its maximum physical capacity. The limiting factor in calculating DLR is the clearing of the line to the surface. This clearing will reduces with increasing conductor temperature. Reduced clearing increases the risk of phase to ground faults, but is also endangers living species and valuable assets under the line. An additional risk with excessive heating of the conductor is that it will cause annealing by reducing the tensile strength of the conductor [14, 15, 16]. A reduced tensile strength is permanent and it makes that the conductor has a higher sag, especially for heavy ice or snow load. This further increases the risk for species and assets below the line. The basics of DLR calculation are explained in the following section.

2.2 Line Rating Calculation

In this section, the calculation of the steady-state thermal rating given a maximum allowable conductor temperature, weather conditions, and conductor characteristics is explained comprehensively. The definition of the line rating in the IEEE standard [17] has proven the capability of using DLR system in the power system. However, not all transmission lines are operated using the DLR. In other words, the line rating of a transmission line can still be defined as either static or dynamic. The equations given below not only can be used for dynamic rating over different time scales, but also for static or for seasonal rating.

2.2.1 The IEEE and CIGRE Standard

The IEEE standard 738 and the CIGRE technical brochure both describe the calculation of a bare overhead conductor line rating [17, 18]. Although both documents use the heat balance concept for the calculation, their approaches to the problem are slightly different. In [19] a comprehensive comparison is carried out to investigate and compare these two standards. The results point out that there are only a few differences between the two and it is up to the user to select which standard to use. In this report, we apply the IEEE model for further studies.

The Heat Balance Equation

Heat balance is an equilibrium between the amount of heat dissipated from the bare overhead conductor and the heat absorbed by that conductor (2.1),

$$q_c + q_r = q_s + q_j \tag{2.1}$$

Where q_c and q_r are convective and radiative cooling, respectively. And q_s and q_j describe the solar heat gain and joule heating of the conductor. In the following, the details of each term will be examined.

The Elements of IEEE Heat Balance Equation

In this part the description of convective cooling, radiative cooling, solar heating, and joule heating is presented.

Convective Cooling

The convection cooling of a conductor consists of two parts; forced and natural cooling. Forced cooling refers to the impact of a wind on the surface of the conductor and natural cooling is about the usual heat transfer to the surrounding air. The former can be determined by either one of the following equations (2.2) and (2.3),

$$q_{c1} = k_{angle}\, k_f \left[1.01 + 0.0372 \left(\frac{V_w D \rho_f}{\mu_f}\right)^{0.52}\right] (T_c - T_a) \tag{2.2}$$

In general, q_{c1} is valid during low wind speed and q_{c2} is used during high wind speed when the impact of the wind is dominant. The IEEE standard recommends calculating convective cooling with both equations and using the larger of the two at any wind speed .

$$q_{c2} = k_{angle}\, k_f \left[0.0119 \left(\frac{V_w D \rho_f}{\mu_f}\right)^{0.6}\right] (T_c - T_a) \tag{2.3}$$

In case of zero wind speed natural convection is used and defined by (2.4). The IEEE recommendation is choosing the larger of the forced and natural convection cooling at low wind as a conservative condition.

$$q_{cn} = 0.0205\, \rho_f^{0.5}\, D^{0.75}\, (T_c - T_a)^{1.25} \tag{2.4}$$

In above equations, D is the conductor diameter, ρ_f is the density of air, V_w is the wind velocity, μ_f is the dynamic viscosity of air, k_f is the thermal conductivity of air close to the conductor. The temperature of the thermal conductivity (so called "film temperature", T_{film}) is according to the IEEE recommendation assumed to be equal to the average of conductor temperature, T_c, and ambient temperature, T_a. k_{angle} is also the wind direction factor and derived from (2.5),

$$k_{angle} = 1.194 - \cos(\phi) + 0.194\, \cos(2\phi) + 0.368\, \sin(2\phi) \tag{2.5}$$

In which ϕ is the angle between the wind direction and the conductor axis.

Radiative Cooling

Radiative cooling is due to the transmitted energy to the surrounding when the conductor temperature is higher than the temperature of its surroundings. This transmitted energy depends on ϵ, the emissivity of the conductor, conductor diameter, ambient temperature and conductor temperature. Equation (2.6) describes the amount of radiative cooling,

$$q_r = 0.0178\, D\, \epsilon \left[\left(\frac{T_c + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right] \tag{2.6}$$

Solar Heat Gain

The solar radiation heat gain is the amount of heat energy provided by the sun to the conductor. Its value is obtained from equation (2.7),

$$q_s = \alpha\, Q_{se}\, A'\, \sin(\theta) \tag{2.7}$$

Where α is the solar absorptivity of the conductor surface, A$'$ is the area of the conductor per unit length, θ is the angle between the incident ray and the conductor and Q_{se} is the corrected heat flux rate. The Q_{se} is also dependent on K_{solar}, solar altitude correction factor, and Q_s, total solar and sky radiated heat flux rate, and is described by equation (2.8),

$$Q_{se} = K_{solar}\, Q_s \tag{2.8}$$

The value of the Q_s is based on the clarity of the atmosphere and K_{solar} is dependent on the H_e that is the elevation from the sea level. Respectively, they are calculated from (2.9) and (2.10),

$$Q_s = A_Q + B_Q\, H_c + C_Q\, H_c^2 + D_Q\, H_c^3 + E_Q\, H_c^4 + F_Q\, H_c^5 + G_Q\, H_c^6 \tag{2.9}$$

$$K_{solar} = A_k + B_k\, H_e + C_k\, H_e^2 \tag{2.10}$$

The constants in (2.9) are polynomial coefficients for solar heat intensity as a function of solar altitude. It should be noted that the impact of cloud coverage is neglected in IEEE standard and the calculation is confined either to clear or industrial sky by changing the constants in the equation. The coefficients in (2.10) represent the solar flux altitude correction. Calculating the H_c, altitude of the sun , is done through (2.11),

$$H_c = \arcsin\left[\cos(\psi)\cos(\omega)\cos(\delta) + \sin(\psi)\sin(\delta)\right] \tag{2.11}$$

Where ψ is the geographical latitude of the conductor location, ω is the "hour angle" and represents the number of hours from local noon times 15 ° C. δ is the solar declination that is based on the day of the year, N, and is calculated by (2.12)

$$\delta = 23.4583\, \sin\left(\frac{284 + N}{365}\, 360 \right) \tag{2.12}$$

θ is also given by (2.13), in which Z_c and Z_l are showing the azimuth of the sun and the line accordingly.

$$\theta = \arccos\left(\cos(H_c)\cos(Z_c - Z_l)\right) \tag{2.13}$$

Furthermore Z_c is given by (2.14), where χ, solar azimuth variable, is also determined according to (2.15)

$$Z_c = C_Z + \arctan(\chi) \tag{2.14}$$

$$\chi = \frac{\sin(\omega)}{\sin(\psi)\cos(\omega) - \cos(\psi)\tan(\sigma)} \tag{2.15}$$

The solar azimuth constant, C_{Z_c} (in degrees), is a function of the "hour angle,", ω, and the solar azimuth variable, χ.

Joule Heating

According to the IEEE standard, the joule heat gain of a bare stranded (homogeneous) conductor is given by (2.16),

$$q_j = R(T_{avg})\, I_{ac}^2 \tag{2.16}$$

Where T_{avg} is the average operating temperature of the overhead conductor, I_{ac} is the conductor RMS current, and $R(T_{avg})$ is the resistivity of the conductor against current flow at the operating temperature. The resistivity of the conductor is calculated through equation (2.17),

$$R(T_{avg}) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}}\right](T_{avg} - T_{low}) + R\left(T_{low}\right) \tag{2.17}$$

The T_{high} and T_{low} are high and low temperature of the conductor. $R(T_{high})$ and $R(T_{low})$ are the AC resistance of the conductor at high and low temperature. It should also be noted that (2.17) considers the skin effects for all types of homogeneous conductors and it assumes a linear relation between conductor resistance and conductor temperature.

Thermal Rating

Finally according to aforementioned definitions, the dynamic conductor rating is calculated by equation (2.18)

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \tag{2.18}$$

Equation (2.18) is in fact a reformulation of the steady -state heat balance corresponding to the conductor current (I) that produces a conductor temperature (T_c) under certain weather conditions. This calculation can be done for any initial conductor temperature at any weather conditions for which the heat transfer model is valid. From now on in this report line rating calculation refers to the steady-state heat balance described in (2.18).

Table 2.1: Conductor data

Name	*Drake*	**Emissivity**	*0.6*
Type	*ACSR*	**Absorptivity**	*0.6*
Conductor Temperature	$75\,^{\circ}C$	**Diameter**	$281\ mm^2$

2.2.2 The Prospect for Dynamic Line Rating

Fig 2.1 shows the various types of rating calculated from equation (2.18) for a specific conductor and compared to each other. The conductor data can be found in Table 2.1. The yellow dashed line represents the fixed or static rating. Fixed or static rating here refers to the worst weather conditions that are typically used in dimensioning of a line for a given maximum load demand. The orange line shows a seasonal rating in the region in northern Sweden. To calculate the seasonal rating worst weather conditions during summer and winter were calculated over an eight-year period. The data for this calculation was obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The blue solid line is a monthly rating calculated in a same way as the seasonal rating. Finally, the purple line represents the hourly rating that in this report we refer to this as a dynamic line rating and it is the base of our further discussion.

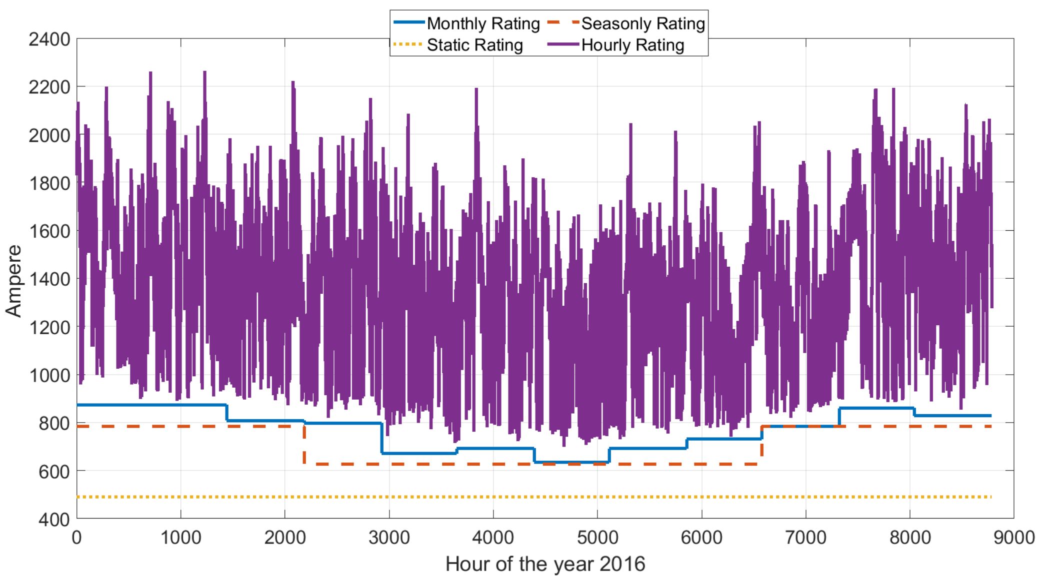

Figure 2.1: Comparing different types of line rating for the same line

In the steady state heat balance, there are several variables determining the rating. Most important weather variables are ambient temperature, wind speed, wind angle attack, and the position of the sun in the sky. Among the line characteristics, emissivity and absorptivity are important in determining the line rating. Besides, conductors' size and resistivity influence the rating but their impact is limited compared to other parameters. Table 2.2 illustrates dynamic rating compared with static rating as base case; 490 (A), 40 °C, 0 m/s, sunny midday, emissivity and absorptivity equal to 0.6. For the sake of sensitivity analysis, we assume one variable changing at a time to see its impact on the rating. The analysis shows that 20 ° drop in temperature will increase the rating by 46% and if this temperature drops another 20 ° to 0 ° we see 82% increment in rating. At the same condition but at midnight there would be a 33% increment in rating comparing to midday with full and direct sunshine. Certainly, the most significant impact is going for the wind speed changes in which with only 1 m/s increment from zero we see a considerable change in a range of 57 to 70 percent in the rating depending on the direction of the wind.

Table 2.2: Rating Compared to Base Case

Name	Increased Rate	New Rating
Temperature		
20 ° C (Summer)	*46%*	*718 (A)*
0 ° C (Winter)	*82%*	*896 (A)*
Midnight	*33%*	*654 (A)*
1 m/s Wind		
45°	*57%*	*770 (A)*
90°	*70%*	*834 (A)*
Emissivity		
0.9	*16%*	*573 (A)*
0.2	*-28%*	*352 (A)*
Absorptivity		
0.9	*-21%*	*384 (A)*
0.2	*23%*	*605 (A)*

The amount of heat radiated from the conductor to the surrounding is dependent on the emissivity of that conductor and the level of absorbed heat energy depends on the absorptivity of the conductor. For new installations, these values are at their lowest, around 0.2. During operation these values increase up to 0.9 depending on how old the conductor is and how much it is exposed to dust or pollution. Based on the data from table 2.2, with lower emissivity, we face reduction in the rating. The opposite is the case for the absorptivity. The highest rating is obtained when the emissivity is highest and absorptivity is lowest.

2.3 Challenges with DLR Implementation

While there are advantages in utilizing DLR, it is not as easy to implement as may have been concluded from the previous section. Some of the challenges are discussed as follows:

- Uncertainty in weather parameters (day ahead planning or during and/or close to operation).
- Uncertainty in emissivity and absorptivity. These values are changing but the rate of change is not known and should be measured through the conductor in different terrains.
- The link between overload protection and short-circuit protection through overcurrent relays could interfere with DLR. This will be taken up in chapter3.
- Measuring of temperature and comparing with a threshold temperature would be a good way of avoiding line overloading, but is difficult and not always possible. In this report we are not going into details of the technical challenges, but we briefly explain two areas where direct temperature measurement is not applicable;
  - During day-ahead planning, as part of market settlements or to get input to the required volume of the flexibility market.
  - When assessing if the N-1 criterion holds. The measured/estimated ambient temperature and the effective wind speed can be used to calculate the line rating. Knowing the rating and the power flow, verifies if the N-1 criterion holds. The effective wind speed is the wind that for the measured current, ambient temperature and solar radiation results in the measured conductor temperature. [20].

Chapter 3

Protection Operation

3.1 Protection of Overhead Lines

Overhead lines are the least protected part of the power system from the geographical and environmental prospective. Overhead lines are directly exposed to weather and other external influences. The number of line failures is therefore higher than the number of failures in other parts of the system [21]. Hence, the protection of overhead line ("line protection") is one of the most important tasks for the protection system in the power system. The main task of the protection is to protect the overhead lines against overloading, short circuits, and earth faults. Emphasis in the literature and in setting of the protection has classically always been on protecting the lines and other power-system equipment against the adverse consequences of faults on overhead lines. Overloading will result in overheating of the conductors, and decreasing the clearance to ground, objects and vegetation. The kind of protection used for overloading is mainly overcurrent protection with different setting for different line ratings. Overcurrent protection is the main protection against faults for voltage levels below 70 kV but for higher voltage levels it is the distance protection that provides the primary protection [21]. Occasionally differential protection is used for the protection of overhead lines [22, 23, 24, 25]. In the two latter cases, overcurrent will operate as a back-up.

Protection relays must have a very low probability of fail-to-trip, i.e. it must be close to certain that a fault is removed by the protection. Their most significant function, traditionally, has been to initiate the disconnection of the line in case of a short circuit or an earth-fault. The failure to remove such a fault should be very much avoided, which is one of the reasons for the use of often multi-layer back-up protection. Overload protection would be treated differently and the design of the system was such that overloads would normally not occur. (The maximum load demand would be kept below the line rating). The reliability of the protection system includes not only the ability to clear faults but also to prevent undesired trip (both under normal and under faulted operating conditions). The former is referred to as "dependability" and the latter is called "security".

Dependability and security are to some extent complementary and reducing the other often results in an increase of the other. The classical trade-off between the two is almost exclusively based on the need for protection against faults. The trade-off is also often different for primary and for secondary protection. For primary protection keeping the probability of mal-trip low is somewhat prioritized, whereas for back-up protection it is extremely important to have a very low probability of fail-to-trip. Inherently, protection setting is based on achieving a high dependability even if this goes at the expense of the security; the consequences of any assets' failure are higher than the consequences of an outage of the electricity supply. With overload protection, especially DLR based in the modern grid, the situation is different. The trade-off between dependability and security could become rather different. This will be discussed further in the forthcoming sections.

3.2 Overload Protection Setting

Overload of an overhead line is a situation in which there is a current exceeding the line rating (an overcurrent), when there is no fault in the system. An overload occurs when the sizing of the conductor is not sufficient for the supplied load [26]. Some kind of protection must be provided to remove any overload before the temperature of the line conductor gets too high. Protection against overloads can be provided by fuses, or overcurrent relays in combination with circuit breakers. Alternatively, and used at transmission level and in industrial installations, the overload situation will be reported to a control room, where a decision is made about which actions to be taken. A short-circuit or earth fault also results in an overcurrent, but this one is typically much higher and of shorter duration, because it is tripped fast by the protection. Protection devices must be provided to limit and break the short-circuit currents before their thermal effects, heating of the conductors, and mechanical effects damage equipment. Likewise, protection against faults can be provided by circuit breakers and overcurrent relays. In low and medium-voltage networks, protection against faults can also be provided by fuses.

3.3 Overcurrent Protection against Overload and Faults

In classical protection the maximum load current, I_c, must not exceed the protection setting, I_s, and I_s must be less than the maximum rating of the conductor (rated current), I_r. (This process is referred to as "protection coordination".) The rated current on an overhead line is determined for selected values of the weather parameters, including ambient temperature and wind speed, without exceeding the maximum allowable temperature of the conductor. A time-dependent relay characteristic, able to remove overloads as well as faults, is shown in Fig 3.1. For currents exceeding the rated current, the lower operating time is achieved for higher values of current. In other words, the more the rated current is exceeded, the faster the relays generates a tripping signal. For faults, the currents are very high, the rated current is exceeded a lot, and the circuit breaker clear the fault very quickly.

$$I_c \leq I_s \leq I_r R \tag{3.1}$$

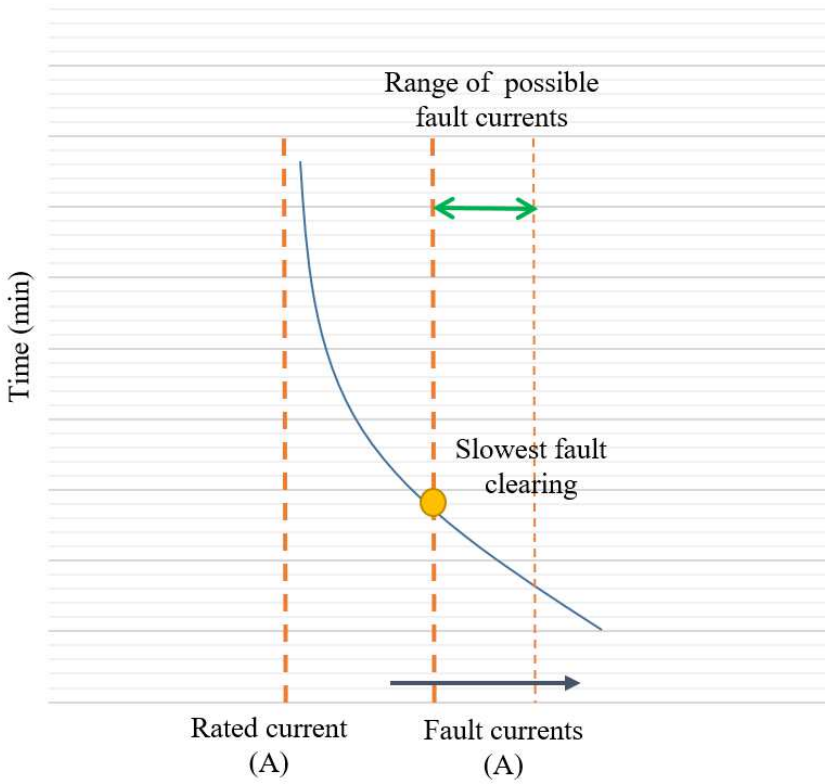

Figure 3.1: Time-dependent characteristic of the classical overload protection

In which R is the result of design differences between the protective devices and between the standards used to determine their rated currents. Classical overload protection is based on a calculation of the rated current using the thermal heat balance, equation (2.18), for a fixed set of weather parameters, typically close to worst-case values. This results in a fixed line rating and fixed setting of the protection. In order to provide adequate thermal protection without limiting the line loadability, thermal rating will need to be adjusted for varying weather conditions [27]. This is what is called "dynamic line rating".

An important decision to make for DLR-based protection is which parameter is determining if a line is overloaded; conductor temperature or current compared to the rating. There are disadvantages with both choices. The problem with using the rating is that it is based on a calculation model including assumptions about the conductor temperature if these assumptions do not hold the results will change significantly. On the other hand,

spots, availability of the sensors, and etc. are some of the issues. Also, there is much more practical experiences with using current compared with a rating, which will make such a method easier to accept. Therefore, in this report we are including the dynamic rating in the protection setting rather than directly using conductor temperature.
The influence of changes in the setting of the protection is presented in Fig 3.2 with two different relay characteristics; summer and winter rating. The principle for each of the curves is the same as aforementioned, however for the winter rating, the rated current is higher and the curve is shifted to the right. The minimum fault current is not season-dependent. As a result of the increase in rated current, a fault with the same fault current will take longer to be cleared. This does not have to be an issue, but it should certainly be checked to avoid that certain faults are not removed by the overcurrent protection. What is shown here for two settings, gets even more complicated when there is a large range in settings, as when for example DLR with hourly settings is used. A maximum-permitted fault clearing time sets a limit on the setting of the overload protection. This in turns put an upper limit to the current that can be transported over the line, even if the thermal limit would allow a higher current .

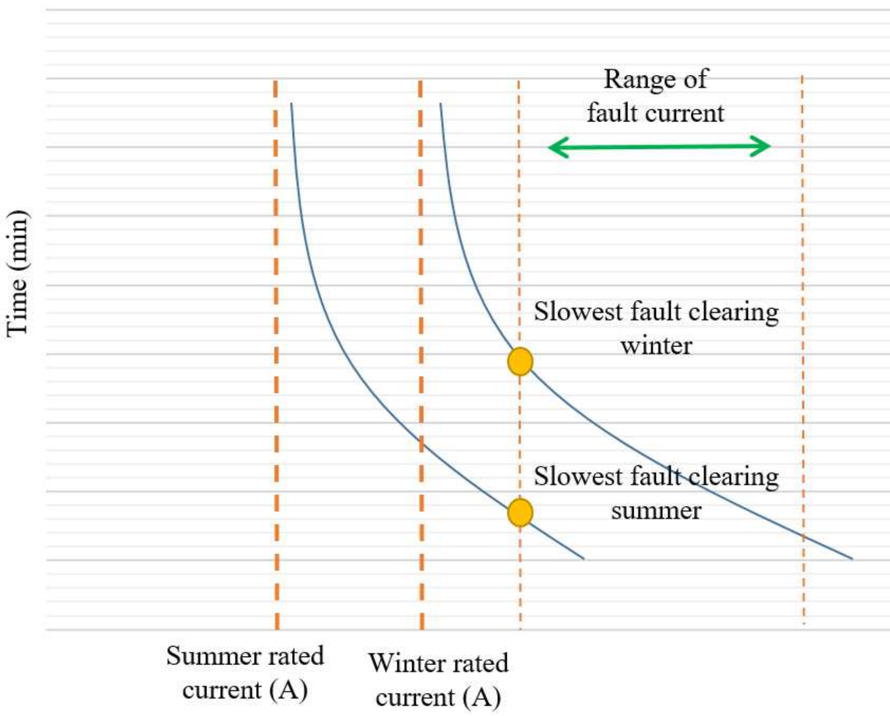

Figure 3.2: Time-dependent characteristic of the overload protection for two different rated current

3.4 DLR Protection Scheme

This part briefly explains the DLR overload protection. With DLR there would be an increase in the security and it is regarded as an advantage to efficiently utilize the additional capacity. However, dependability may be reduced. The details of the protection model with illustrative examples are broadly discussed in papers B, C and Chapter 4. Fig. 3.3 shows the overall scheme of DLR overload protection.

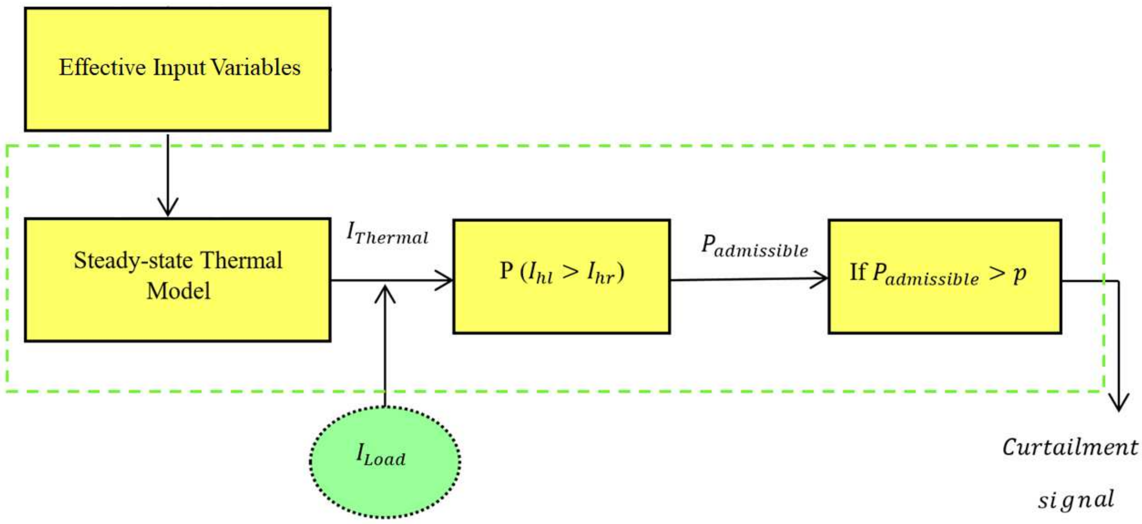

Figure 3.3: Protection Scheme with DLR

The steps to reach the aforementioned model are as follows:

1. The initial step is identifying the effective input variables involved in the calculation. These variables might be weather parameters and line characteristics that are measured, predicted, and/or estimated through numerical models, probabilistic estimation etc. These parameters and characteristics are fed into the thermal model (2.18). This process is repeated for each set of input variables (randomly selected from the probability distribution function) leading to a collection of different values of the rating for each 1-h period, forming the overhead lines' rating distribution.

2. Meanwhile, the load current is assumed to be known prior to the operation and is measured and/or estimated for each 1-h period.

3. For the decision making process the first step is comparing the thermal rating distribution with the current during every 1-h period. The probability $P(I_{current} > I_{rating})$ is an indicator of the risk of overloading, associated with this situation of the weather, the line and its loading. This probability is obtained as the fraction

of simulations resulting $I_{current}$ greater than I_{rating} as equation (3.2),

$$P(I_{current} > I_{rating}) = \frac{N_{overload}}{N_{total}} \tag{3.2}$$

where $N_{overload}$ is the number of simulations which obtain a current greater than the rated current; N_{total} is the total number of simulations for 1-h period.

4. The second step in the decision making process and final step in the protection operation is introducing the acceptable risk $P_{admissible}$ to set the limit for overloading level. This parameter allows choosing between operations when intervention is needed, dependable operation, and avoiding unnecessary operation, secure operation. A discussion about selecting this parameter can be found in Chapter 5.

Chapter 4

Reliability of DLR

4.1 Failure of DLR

One of the first questions to ask when studying the reliability of a system is: " what is the aim of the system". For this chapter the question is: "what is the aim of DLR" or, formulated in a negative way, "what constitutes a failure of DLR". By realizing that DLR and overload protection are closely linked, the two basic aims of DLR become easily clear:

- Measures should be taken when otherwise the line would get overloaded.
- No measures should be taken when the line, even when those measures were not taken, would not get overloaded.

The two failure modes follow from this and they can be formulated as follows:

- No measures or insufficient measures are taken and the line gets overloaded.
- Measures are taken when the line, even when those measures were not taken, would not get overloaded.

In the more classical approach to overload protection, typically referred to as "static rating", the main effort for the protection setting was towards limiting the probability if the first failure mode occurring. Limiting the probability of the second failure mode occurring was part of the system design, where the maximum load demand was kept the static rating.

4.2 Generic DLR Reliability Model

Study the reliability of DLR is not only the issue of having a highly accurate and reliable method of calculating the line rating but it is also a matter of reliability of various measurement devices, sensors, communication, protection, calculation and prediction models.

Fig 4.1 shows a generic model of DLR, where the intention is to cover both operational planning (for identifying market barriers) and use during operation (for protection). This generic model will next be used to look at reliability from two different viewpoints: error and failures of each of the elements in the system that would affect the DLR calculation; and the impact of a DLR failure on the power system. Dashed lines representing the communication channel between two blocks.

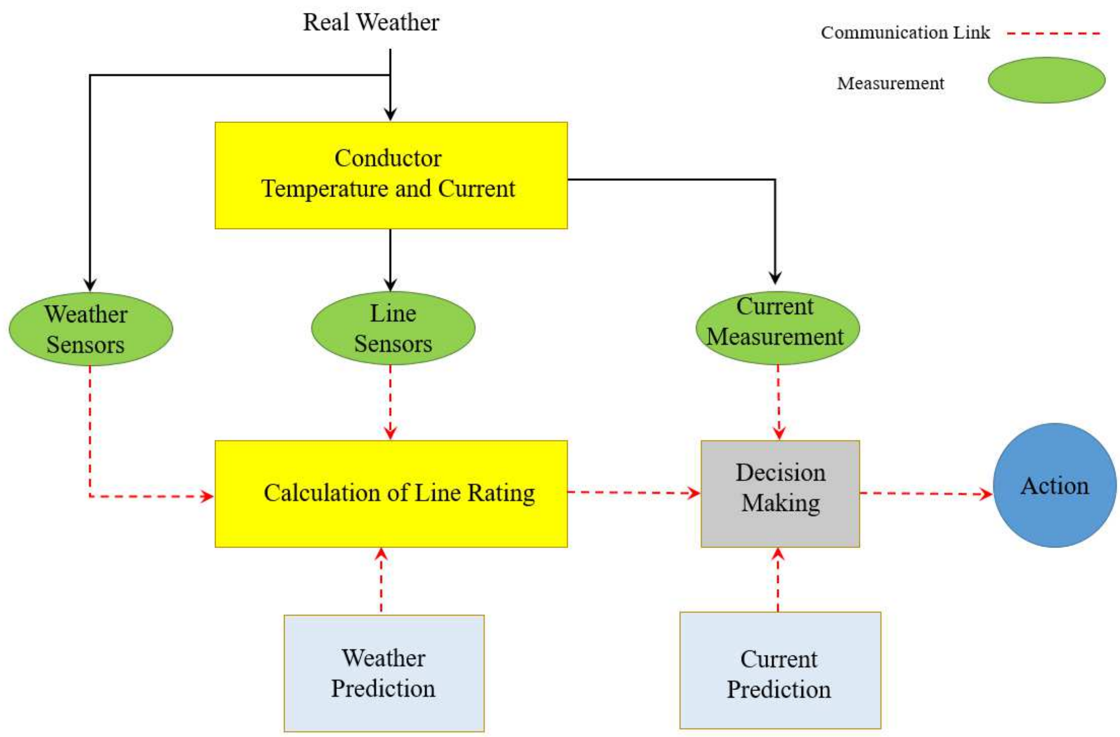

Figure 4.1: Generic model of dynamic line rating (DLR) in the grid

4.3 Components Failure

The generic model in Fig 4.1 contains different types of elements that are all part of DLR including measuring devices, communication channels, models and algorithms for predicting and calculating line rating, weather prediction and decision making blocks for deciding about actions to be taken. Failures in any of these elements have the potential to impact the performance of the DLR and consequently of the power system. Input to the algorithms comes in some DLR systems also from prediction done elsewhere: prediction of weather parameters; prediction of line currents. Errors and failure may occur in those predictions, resulting in incorrect values being provided to the algorithm calculating rating or conductor temperature.

4.3.1 Failures of Measurement Devices

Measurement devices are essential for enabling the DLR technology. Different types of measurement devices are needed, as shown in Fig 4.1. Line sensors are located in direct contact or very close to the line; some of them are mounted on the line and energized by induction from the line current. Examples of line sensors are those measuring conductor temperature, clearance to ground, and conductor tension [28, 29, 30]. These sensors are often novel designs without long records of practical use. The reliability of the sensors is a general concern and something that needs to be considered in the design of a complete DLR system. A specific issue is the powering of the sensors; inductive energy transfer from the line current to the sensor is an option, but special care should be taken for low line currents when the sensor may not receive sufficient energy. Next to complete failure of the sensor (no value of an obviously incorrect value), the accuracy of the measurement (a value that deviates from the actual value but cannot be distinguished from the actual value) should be considered as well. A second group of sensors is those collecting the weather data at specific locations along a transmission line. Calculating conductor temperature or line rating from measured weather parameters is known as the indirect method [31, 32]. In either cases the collected data are exposed to measurement inaccuracies. In the following several possible failure states of the weather measurement are explained:

- Regular measurement errors regarding the accuracy of the measurement devices and the location of the devices. Devices that, for example, measure temperature are generally of high accuracy. The concern is however mostly in the relevance of the measurement for the conductor heat balance; a temperature sensor that is exposed to direct sunlight will overestimate the air temperature; a wind-speed sensor may overestimate or underestimate the speed of the air passing the line conductors; etc. Weather parameters will also vary along the line, which is another source of errors.
- Wrong setting may cause larger errors as they may be originated from, for instance, human errors and they are difficult to detect. The example might be not converting dimensions in the right way: degrees Fahrenheit instead in Centigrade; miles per hour instead of meters per second.
- Another issue that may cause errors of the increasing inaccuracy is errors of devices due to their aging. This can be a complete loss of function or a large error, but it can also be a slowly increase in systematic or random error with time. Especially the slow increase in error will be hard to detect.
- Failure of sensors is another type of component failure that should be included in DLR reliability study. Two types of sensor failure can be considered:
  - Not sending any signal, so that the algorithm will lack input data. This will be immediately detected by the algorithm, which means that a back-up plan can be easily activated, assuming such a plan exists.
  - Sending wrong values that have a large deviation from the actual value. This is not immediately detected, but a reality-check can be included in the algorithm

to detect unrealistic values.

– Sending wrong values that have a lesser deviation from the actual value. Detecting such errors will be very difficult and in practice impossible.

The third type of sensor is the measurement of the line current. This is a classical, well-developed, commonly used instrument transformer with a high reliability and a high accuracy.

4.3.2 Communication Failure

As shown in Fig 4.1 communication is an indispensable part the power system when DLR is included [33]. The successful implementation of DLR depends on the reliability of communication networks, wired as well as wireless communication channels. These communication channels enable interaction amongst devices to the transmission of line rating information to the control room or protection/curtailment devices that enable the recreation of appropriate line current [34], i.e. a current below the rating. Investigating the reliability of wired communication in a traditional network is more straightforward since they are mostly located in the local area with short distances and are less prone to external influences like adverse weather. Wireless communication channels, typically radio links, are more prone to external influence. Adverse weather conditions may however result in a high failure rate of communication equipment, both for wireless and wired communication. Any weather influence is very important here because it could result in common-mode effects. A high unavailability of communication channels during weather that results in low values of line rating would result in a high probability that an overload is not detected. The other way around, a high unavailability during weather that results in high values of line rating would result in a high probability than unnecessary measures are taken.

The process in a wireless communication starts from collecting data from sensors and sending them to the control units of the DLR to gather all data from different parts of the transmission line. Through communication channels these data are then forwarded to small gateways and subsequently to the data aggregator units to form a wide area network (WAN) containing all the data from devices [35]. Based on the input data, an algorithm is used to calculate, for example, the line rating. This calculation is being done in a data management center, which may be close to the line (in one of the substations connected by the line) or in a central control room. Based on the outcome of the algorithm, either the network operator or an automatic relay, makes a decision on how to avoid overloading or (as will be the case most often) take no action at all. The elements involving in the measurement, calculation and decision process are interconnected and failure of any communication channel may lead to failure of the DLR system.

Failures of the communication can also be classified as functional failures and network failures. The former includes any failures of communication elements, however in the latter type of failures all the elements remain functional but a failure occurs at processing commands because of the failure in other parts of the network as a whole. Studies show that the failure of communication channels can significantly degrade the reliability of a power system including DLR [34]. The same distinction that was made for failures of measurement devices (no signal, a large error in value, a minor error in value) should also be made for failure of the communication. With modern digital communication systems, the probability of a minor value in error seems to be small.

4.3.3 Model Inaccuracy

Model inaccuracy is defined as an incorrect calculation and/or prediction of line rating or conductor temperature. This will include for instance inaccuracy in the mathematics of the model. Some of the factors that should be considered as part as model inaccuracy are:

- The line parameters can be wrong. For instance, Aluminium is used in the line conductor while the resistivity for copper is used in the model. Similarly, an incorrect conductor area can be used. These are the systematic errors that are difficult to detect.
- There could be something wrong in coding of the DLR algorithm.
- Some errors might occur while defining the algorithm by itself or during the modeling. Some examples: the model for convective cooling is known to be approximation; the resistive heating is calculated neglecting harmonics; the radiative model assumes that the radiation temperature is the same as the ambient temperature; cloud cover is not considered.
- Long sampling times for weather data may cause a significant difference between the actual weather parameters and the ones used in the algorithm. The assumption of stationarity does not hold during fast changes in weather.
- Certain model limitation and errors are intentionally accepted during the design of the algorithm. Such modelling errors (uncertainties is a term more commonly used in this context) are very common and incorrect decision due to them are avoided by introducing some safety margin between the real time rating obtained from the algorithm and the one that is used for the decision. This will keep the probability of overload low, but it will increase the probability that unnecessary measures are taken.
- When the current (related to the rating) is used to detect overloading, short-duration exceeding of the rating is acceptable. The relation between acceptable time of overloading and current compared to rated current should be based on the thermal model of the line. Also here assumption are made, resulting in additional model inaccuracy.

4.3.4 Control System Failure

Decision-making and actions are the two final stages of the DLR system. Combined together, this is where the system decides whether to fully utilize the transfer capacity of the transmission line or corridor or if some level of mitigation line curtailment is needed. After analyzing the data, for example by comparing the load current and rating or by comparing conductor temperature and maximum-permissible temperature, there would be different failures that can occur even at this stage:

- The signal for curtailment or tripping command is send while the decision parameter is below the threshold.
- The decision parameter is above the threshold but no signal is sent.
- A signal is sent for the tripping or curtailment, but no action or insufficient actions are taken.
- The algorithm results in the need for a certain amount of curtailed power, but more curtailment is applied to the system.

Each of the aforementioned issues could impact the functionality of DLR and subsequently prevent the suitable operation that DLR is designed for.

4.4 Impact of DLR Failure

In the previous sections, different kinds of component failure and errors (for example in measurements and in calculations) have been discussed. All these errors and failure may affect the reliability of DLR. Note that, in this chapter, we only consider the performance of the whole DLR system: where the aim is to take action (against overload) when needed and to refrain from action when not needed. An alternative approach towards reliability would have been to compare the predicted or calculated line rating or conductor temperature with the actual rating or temperature. Such an approach would have resulted in a measure of accuracy of the DLR, somewhat independent of the line current. From a power system, such a measure would be of less use as it does not related to the need for overload protection. In this section, the performance (and failure) of the DLR system will be placed in the perspective of its application and its impact on the performance of the power-system as a whole. In the following some of the applications are presented and the way they may be impacted by DLR failure. Seen from the power system, the following kinds of DLR failures can occur, where the two types of failures from Section 4.1 are used as a starting point again.

- The current is somewhat below the actual line rating, but due to various uncertainties, unnecessary measures are taken.

- The current is somewhat above the actual line rating, but due to various uncertainties, necessary measures are not taken.

- The current is a lot below the actual line rating, but due to various failures and uncertainties, unnecessary measures are taken.

- The current is a lot above the actual line rating, but due to various failures and uncertainties, necessary measures are not taken.

The first two types of failures are typically due to random errors in predictions, measurements and calculations. The result of those is that for example the calculated conductor temperature deviated from the actual value. This inaccuracy is normally taken care of by adding a safety margin between the calculated value and the threshold at which action is taken. As long as the aim of the DLR system is to avoid overload (i.e. to take action when needed), such an approach is suitable. However, this approach will come at the expense of an increased probability of taking unnecessary action. The original aim of introducing DLR has been to avoid setting limits to the line current when not needed, so that this is something that should be seriously considered in the implementation of DLR. In Chapter 5, a probabilistic approach to DLR is introduced, that allows for a better trade-off between the two probabilities. The last two kinds of failures in the above-mentioned bullet list are more “classical failures” where typically a major component failure results in an erroneous decision by the DLR system.

4.4.1 Impact on the Power System

When DLR is used in the line, it increases transmission line capacity and thus relieves the congestions to some extent, during those hours that congestion exists. However, the presence of the rather complicated DLR system also increases the risks to power system operation because of the risk of error in its calculation and an increased risk of unnecessary operation and lack of action when needed. This increase in risk is always present, also during the hours that there is no need for DLR (i.e. when the line current is below the static rating). Here a distinction should again be made between “fail to take action” and “unnecessary action ”.

Fail to Take Action

When a line is overloaded and no action is taken, this can have a number of consequences. The first impact will be that the conductor temperature will rise above its permissible value and the conductor sag will become higher than acceptable. This is safety issue for buildings and persons residing below the line. It also increases the risk of the line “sagging into vegetation” with a fault as a result. Such a fault will occur when the line is already (too) heavily loaded and the impact of it will thus be more severe. In a radial system, the loss of a heavily loaded line with result in a large loss of load. In a meshed system, the load of this line will be taken over by other (parallel) lines. These lines in turn might get overloaded. As this occurs during a heavy-load situation, there is even a risk of instability and a large-scale blackout. During the fault, the conductor temperature will increase even more, possibly resulting in annealing [36, 37, 14], in which the conductor material weakens. When the line rating is calculated correctly, but for some reason no action (like curtailment) is taken, a back-up protection could take action and trip the line. This will have the same impact on the system as a fault, but it will avoid the risk to buildings and persons and it will avoid annealing.

Unnecessary Action

The other type of failure, taking action when not needed, will have an immediate impact, either on the customers or on the system. The removal of the line will again risk of overloading and instability, as described before. The difference with the previous case is that the line itself is not overloaded and could well be very lightly loaded. The impact of the loss of the line will thus be less. In a meshed system, the loss of a line should normally not result in a major system failure, the so-called (N-1) criterion. Unnecessary curtailment will have an impact, typically economically, on the customers being curtailed. If such unnecessary curtailment happens regularly, this impact may become unacceptable. Action due to overload (either real overload of an erroneously detected overload) may also consist of services being bought by the network operator. This may be in the form of gas turbines starting up. The unnecessary action will have an economic impact on the network operator, depending strongly on market mechanisms and tariff regulations being in place.

4.5 Common-Mode Failures

The term "common-mode failure" refers to the loss of multiple components in a system, for example, multiple transmission lines, because of a single underlying failure. The collapse of a transmission tower carrying multiple circuits is an example of an important common-mode failure. Common-mode failure are especially important to consider in meshed systems, because they can overrule the operational security achieved by the (N-1) criterion. There is very limited information available on the risk of common-mode failures when DLR is implemented on multiple lines. It is however, according to the reasoning above, important to study this.

Some possible examples of phenomena that may lead to common-mode failures or an increase in probability of two lines being lost together are given below.

- The weather parameters are an important input for many DLR algorithms. When the measurements or predictions have large errors, multiple lines in the same geographical area will be affected.
- The loss of a communication channel may affect the DLR system for multiple lines.
- Some failure probabilities increase when a line is heavily loaded. Multiple lines, for example supplying a city, will in that case likely all be heavily loaded. The risk of losing multiple lines, exactly when they are really needed, could become unacceptably high.

Chapter 5

Stochastic Dynamic Line Rating

5.1 Uncertainty Handling

The uncertainty handling is one of the main concerns in the final decision making process that is part of the DLR system (see for example Fig. 4.1). Most of the decisions are subject to a certain level of input data uncertainty. There are several developed methods to deal with uncertain parameters.

5.1.1 Different Methods

Generally speaking, the main difference between different methods is the applied technique for describing the uncertainty of input parameters. For example, a fuzzy method uses membership functions for describing an uncertain parameter while stochastic methods use probability density functions. The similarity between the methods is that all of them quantify the effect of uncertainty in input parameters on model's outputs. In the following we briefly review these approaches [38]:

- *Probabilistic approach:* In this approach it is assumed that the input parameters of the model are random variables with known probability density functions (PDF).
- *Possibilistic approach:* The input parameters of the model are described using the membership function of input parameters.
- *Hybrid possibilistic–probabilistic approach:* This approach uses both random and possibilistic parameters in the model.
- *Information gap decision theory:* In this approach, no PDF or membership function is available for the input parameters. Instead it is based on the difference between what is known and what is vital to be known by quantification of any severe lack of information in the decision making process.

- *Robust optimization:* The uncertainty sets are used for describing the uncertainty of input parameters. Using this approach, the obtained decisions remain optimal for the worst-case realization of the uncertain parameter within a given set.
- *Interval analysis:* In this approach it is assumed that the uncertain parameters are taking values from a known interval. This approach is somehow similar to the probabilistic modeling with a uniform PDF and results in the upper and lower bounds of output variables.

Each of the aforementioned approaches results in several modeling techniques that can be applied to a specific system with uncertainty. Based on the characteristics of the available data and the accuracy level needed for the study a certain approach can be selected. In this report a probabilistic approach is applied to quantify uncertainties in input parameters. A general overview of different techniques that can be used as part of a probabilistic approach is provided in Fig. 5.1

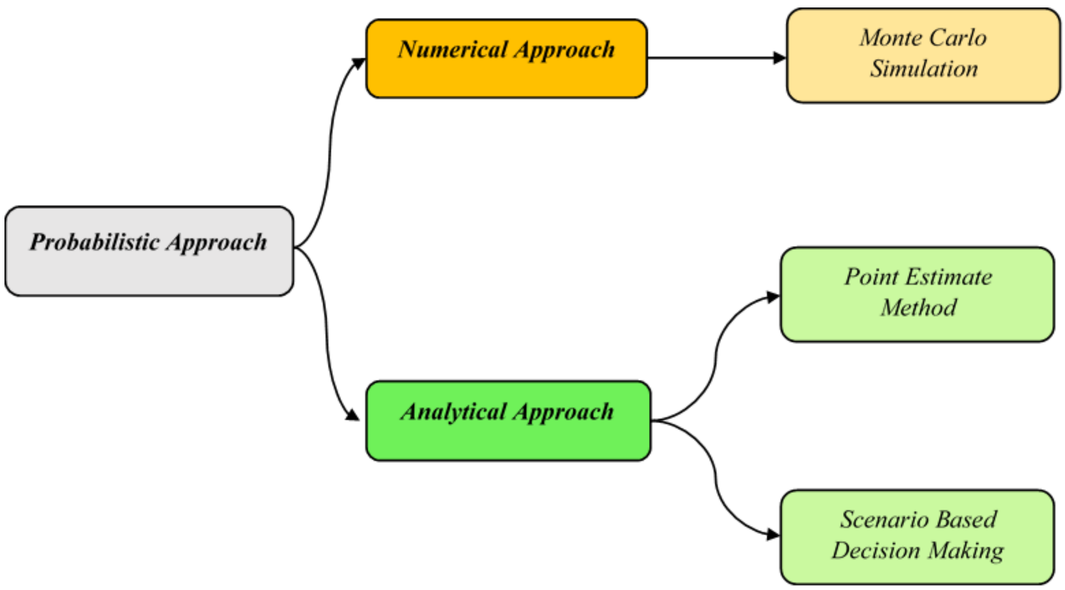

Figure 5.1: Probabilistic Approach Classification

5.1.2 Monte Carlo simulation

A Monte Carlo (MC) simulation is one of the methods for modelling of probabilistic uncertainty used to predict the probability of different outcomes in the presence of random variables. Monte-Carlo simulation is capable of quantifying the impact of risk and uncertainty in probabilistic models. The basis of any MC simulation involves assigning multiple values to an uncertain variable to achieve multiple results. Pseudo-random number generators are used to randomly generate different sets of input variables and calculating a value of each outcome variable for each set. By repeating the generation of input variables many times, a large number of random values for the output variables are obtained. These can next be used to obtain PDFs of the output variables.

The model is represented by a function of n random variables, $Y = f(X_1, X_2, .., X_n)$ where X_n denotes the n-th probabilistic uncertain variable with PDF, $P(X_n)$. MC simulation is independent of the system size and is used when the system is highly nonlinear, complicated, or has many uncertain variables. MC simulation also supports all PDF types and is relatively easy to implement.

5.2 Modelling Uncertainty Aspects of Line Rating

From the description of the IEEE thermal rating model in Chapter 2, it is concluded that there are several uncertainties that affects the final estimation of the line rating. The most obvious uncertainties are due to uncertainties in weather parameters. In order to study and quantify the risks brought by uncertainties in DLR, it is essential to include these uncertainties and their randomness in the line rating estimation. In this chapter the PDF of input variables are assumed to be known. Ambient temperature, wind speed and wind angle attack are modeled by Gaussian, Weibull and von Mises PDFs, respectively. We assigned the number of sample in the MC simulation, n, equal to 10,000 and the iteration was repeated every hour during an eight year period of data availability. A total of 10,000 random values of the line rating for each hour are obtained. These values are then used for an estimation of the PDF of the line rating. The approach can be expressed as equation (5.1).

$$P(overloading) = Prob(I_{rating} < I_{current}) \tag{5.1}$$

Using the approach proposed in Paper C, there is no longer a defined value for the line rating, not even a real-time value. Instead $P_{overloading}$ represents a measure of stochastic line rating, I_{rating}, under a known loading of the line, $I_{current}$. The aim of the approach is not estimating the exact rating but finding the probability of overloading (as defined in this report and in PaperC) for various events even those that are unlikely to happen but if they occur they significantly impact the performance of the protection operation. Further details of the uncertainty analysis can be found in Paper C.

The measured weather parameters, for each hour during the eight-year period, are used as expected values for each PDF during that specific hour. Getting a suitable value for the standard deviation is less trivial. There is a lack of data regarding errors in measured or predicted data. It is also not generally applicable to measure the weather parameters in each location, at all possibly critical spans. We therefore assume a certain level of error, a fixed error, between the actual weather parameters and the parameters used in the algorithm to calculate the line rating.

5.3 Comparison of Settings

Following the stochastic DLR and based on the protection operation explained earlier in Chapter 3, this section briefly presents the main results derived from the simulations in paper C. Fig 5.2 (a) describes the operation of the DLR protection for a certain winter day in 2018 when the line is heavily loaded. The case that the line rating is less than the line current is defined as an overload and we consider different acceptable risks as a percentage of the $P_{overloading}$. The black dashed line is the overload protection set according to the static rating, which is assumed to be fixed for the whole year. The classical setting of the overload protection with static rating leads to many hours of exceeding the line rating and activating actions, like generation of a curtailment signal.

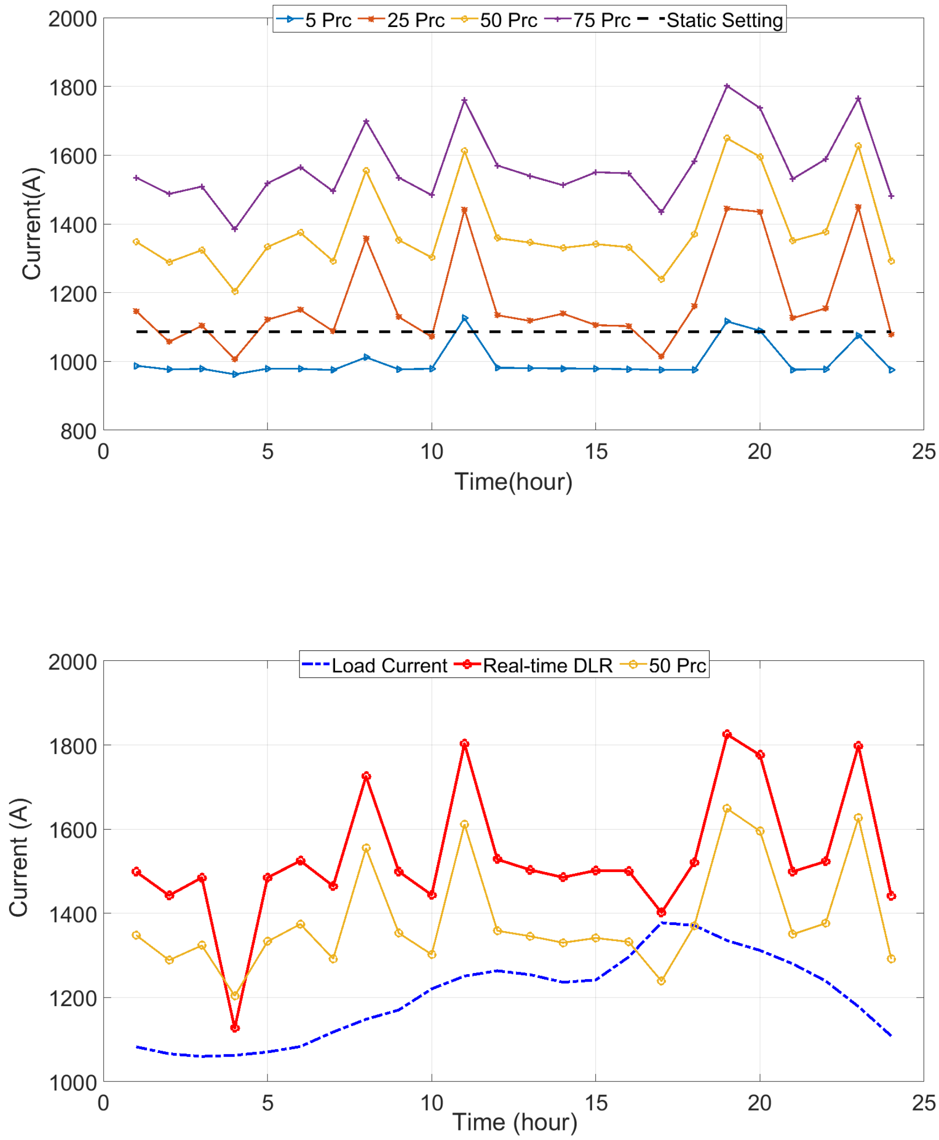

Figure 5.2: Applying probabilistic DLR with 5, 25, 50, 75 percentiles as an acceptable risks (a), comparing real-time DLR and Current(b), in a winter day 2018

With the probabilistic rating approach, the number of hours during which action is needed, depends on the acceptable risk. If we accept 5% as an acceptable risk, this as a threshold for the operation of the protection (generation of curtailment signal), during most hours of the selected day the (stochastic) dynamic rating becomes less than the static rating. Even for a 25% threshold, the dynamic rating is occasionally less than the static rating. By accepting 50% and 75% threshold, the dynamic rating would always be higher than the static rating. This figure shows that selecting any of the thresholds as a basis for the protection operation may increase either the dependability or the security of the DLR-base overload protection (Chapters 3 and 4).

Fig 5.2 (b) shows the variation with time of the load current (dashed blue line), real-time line rating (red line) and 50% threshold (orange line), during the selected day. Comparing current and real-time line rating, there would be a critical hour at 5 p.m. where rating and line current are very close. By taking 50% probability as a threshold, between 4 p.m. and 6 p.m. the line is considered to have a too high risk of being overloaded and the protection should operate. Another observation obtained by comparing (a) and (b) is that in case of having a 75% threshold, no actions will be taken, resulting in a high security but a low dependability.

The consequences of unnecessary action and fail to take action, are often strongly changing with time. The trade-off between dependability and security will change as well. It is therefore suggested that instead of having a fixed acceptable risk, this risk threshold should also change based on the estimated loading profile, the costs or consequences of curtailment, and the rating for each hour. The results shown in the figure are based on a certain day but the methodology behind can be applied any time.

To show the curtailment behavior of the overload protection, for the same day and current as in the previous figure, Fig 5.3 is plotted considering 50% as an acceptable risk. The reason behind choosing 50% is that it gives an equal dependability and security. The probability of failing to curtail when not taking action and unnecessary curtailment when taking action are added always equal to one. Meanwhile, the intention of the protection has traditionally always been increasing the dependability while with the inclusion of DLR it has shifted towards increasing the security as well. However, the increase in one of them results in the decrease of the other and is not possible to get low values for both of them. Here we take 50% as the basis of the further estimation to keep the trade-off between dependability and security.

5.4 Probability of Overloading

The probability of overloading has been calculated for each hour during the eight-year period for which data was available. The PDF of the line rating was calculated for each hour as explained earlier. Time-series for the line current were used to obtain the probability of overloading (the probability that the rating is less than the current) for each hour. In Fig. 5.4 the probability of overloading for each hour is plotted against the difference between the line current and the deterministic dynamic line rating ($I_{current} - I_{rating}$). The deterministic line rating is the value calculated for every hour from the measured

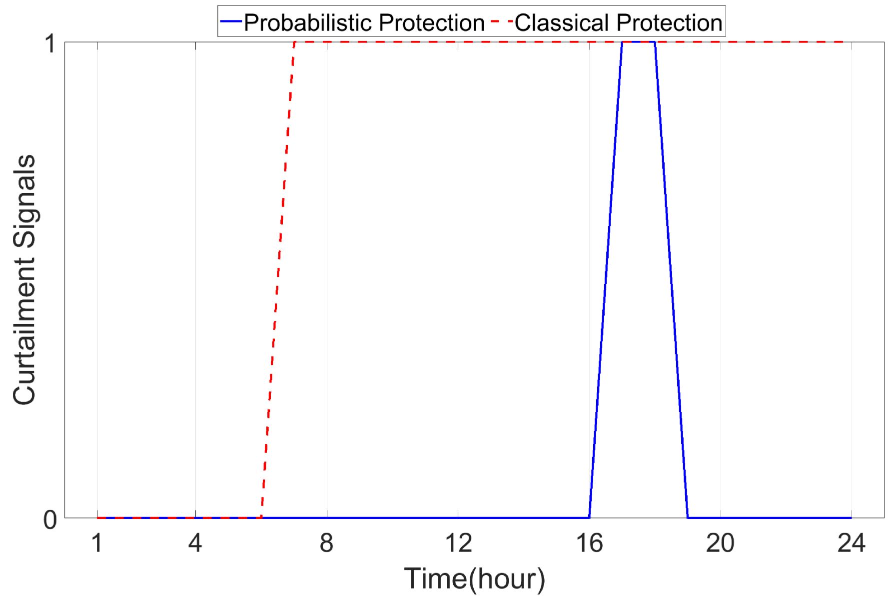

Figure 5.3: curtailment action as part of overload protection with the 50% threshold for a winter day 2018

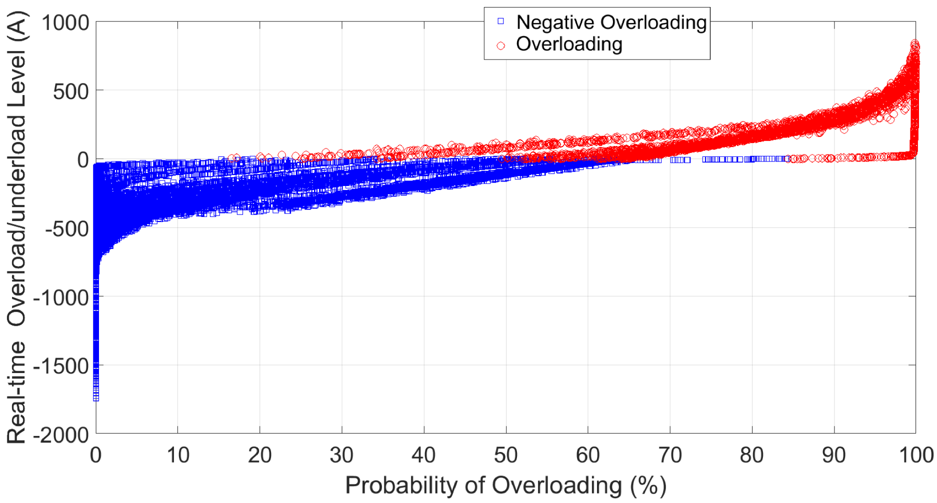

Figure 5.4: Probabilistic overloading versus the time-series overloading analysis

weather data. The probability of overload and the margin have been calculated for a total of 70128 hours during the eight-year period. The red circles in the figure indicate overloading (current exceeds the deterministic rating), and the blue circles indicate underloading (current is less than the deterministic rating).

Fig. 5.4 shows that the same margin (difference between current and rating) can have rather different values of the probability of overloading. For example, a margin of 250 A may correspond to a probability anywhere between zero and 40%. The figure can be used to relate acceptable probability of overloading to margin. Choosing the acceptable risk 20%, would require a margin of around 400 A. This would result in a very low risk of overloading probability below 20%. However, this would decrease the security of the protection operation (increase unnecessary curtailment). In fact, for many of the hours with less than 400 A margin, the probability of overloading is less than 20%, so that no measures or less measures are needed.

When security is prioritized (the probability of unnecessary action should be small), we should look at cases with high probability of overloading (small probability of no overload). Choosing 15% as the acceptable probability of unnecessary action, would require a margin of about 250 A, but now above the deterministic rating. For such a fixed margin, there will be cases when insufficient curtailment is taking place.

Chapter 6

Application of DLR during EV Overloading

6.1 Impact of Electric Vehicle on Power System

Due to the oncoming large penetration of plug-in electrical vehicles (EVs), it is necessary to provide sufficient capacity to meet the integration of EV charging into the electrical network. Increased consumption, in this case due to EV charging, necessitates an increase in generation that will together result in increased loading of transmission lines. As many transmission lines in Sweden are already close to their secure transfer capacity, overloading is likely a consequence of this. This is where DLR can be used to increase the amount of power that can be transferred through the line. This in turn increases the hosting capacity of the grid for EV charging [28].

6.1.1 Hosting Capacity

The hosting capacity is the maximum amount of new consumption or production that can be connected to the electrical network without endangering the reliability of the supply [39, 40]. DLR makes it possible to produce more power and provide it to the growing demand by allowing more transfer capacity [41]; see Chapter 2 for more details. With increasing demand due to EV penetration, public charging stations for EVs will become more common. Some of the challenges concerning the integration of EV charging are: where and when will the charging take place. More likely there will be a high charging demand at the same time for some hours during the day and that could lead to the power system becoming overloaded [42]. In this section, the analysis is done to find out the firm hosting capacity and show how many cars can get connected to the network without causing overload. The detailed discussion with calculation can be found in paper D.

6.1.2 Dynamic Line Rating and Electric Vehicle Charging

For the purpose of the study, the hosting capacity is defined as the number of vehicles that can be charged from a distribution network at the same time without causing overloading in the upstream network.

There are some reasons why DLR may be a suitable method to increase the hosting capacity of the grid for EV charging. One of those has to do with curtailment, which is a suitable method of load control in combination with DLR. Charging of an EV requires a certain duration and a certain power. Often it is possible to reduce the power demand without severe adverse impact for the EV owner. Charging of EVs, especially large-power charging, takes often place via dedicated installations (charging powers) equipped with communication, control and monitoring that allow the implementation of curtailment (or equivalent measures like flexibility markets) without much additional costs. Another reason is that growth in charging demand is expected to be fast, but details on growth rate and geographical differences are very much unknown. Traditional solutions (mainly, building more transmission lines) have a long lead time and the different unknowns are associated with a high risk of stranded assets.

To show the potential of DLR, the model proposed in Chapter 3 is applied to estimate the maximum hosting capacity. Fig. 6.1 illustrates the approximate number of EVs in three different charging powers; 3.7 kW, 7 kW and 22 kW that can charge at the same time. The hosting capacity has been calculated for a given 30 kV sub-transmission line in the following way:

- The hourly consumption has been scaled such that the peak consumption, over the eight-year period, is equal to the static rating of the line. When scaling the number of cars in the city in the same way, the consumption corresponds to a city with about 30,000 passenger cars.
- Weather data is obtained from a weather station close to the city, over the same eight-year period.
- The line rating is calculated for each hour, using the weather data.
- For each hour the margin is calculated between the line rating and the consumption. This margin is the maximum amount of additional load, for example in the form of EV charging, that the line can cope with during each hour.
- The hosting capacity for "week nights" is obtained as the lowest margin 7 pm to 7 am for all weekdays during the eight-year period.
- The hosting capacity for "weekend nights", "week days", and "weekend days" is obtained in a similar way.

From Fig. 6.1 and over the eight-year period, it is derived that more cars can get charged at the same time during the night hours than during the day hours. There is no considerable difference regarding providing higher transfer capacity between week days

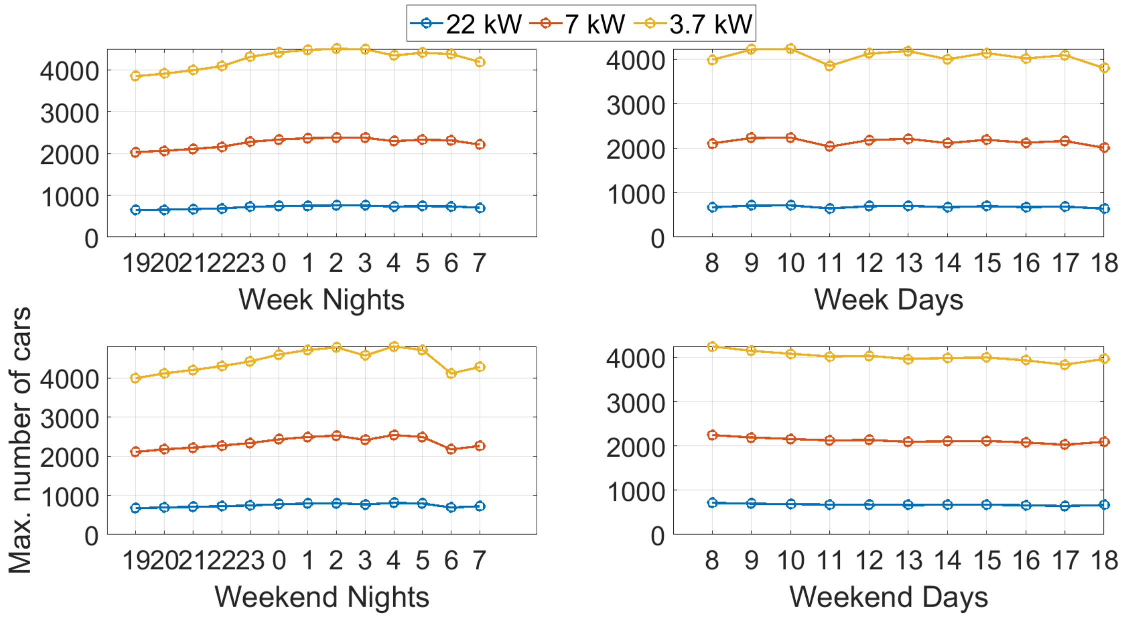

Figure 6.1: Firm hosting capacity during the period 2011 to 2018 for four status; week nights, week days, weekend nights, and weekend days

and weekends. Foe example, during the week the hosting capacity is lowest at 11 a.m. and it is slightly higher between midnight and 6 a.m. During the weekend, however, the lowest hosting capacity occurs at 5 p.m and the highest 2-5 a.m. But overall results show that maximum number of cars (indicating the firm hosting capacity) do not vary considerably hour by hour for each charging station for a specific status.

Referring to the stochastic method introduced in Chapters 3 and 4, probabilistic DLR with different acceptable risks is applied to the line, for 3.7 kW charging power per car during working days Fig. 6.2. Solid blue, red and yellow lines represent 5^{th}, 50^{th} and 95^{th} percentile of the probability of overloading. The results highlight that using real-time dynamic rating can allow charging of much more cars than static rating (SLR in the figure). Using real-time DLR, 3,000 more cars can be charged at the same time without measures haven to be taken. The hosting capacity, assuming static rating, drops to zero for 5-7 p.m. This is due to the scaling method used, where the highest consumption was made equal to the static rating.

Probabilistic approach shows an even bigger potential to increase the transfer capacity, compared to real-time rating. During certain hours of the day, different DLR settings give about the same hosting capacity. For other hours (like 5-6 a.m and 7-9 p.m) the difference is significant. However, If we accept, for instance, "95 prc" (percentile) the hosting capacity increases too much in several hours but at the expense of the dependability.

As mentioned before, the consumption pattern used for this study corresponds to a city with 30,000 passenger cars. Using SLR, there is no firm capacity for charging any of them. Curtailment will be needed. Using real-time DLR, at least 3,750 cars (12.5%) can be charged at the same time, without having to make any major investments in the

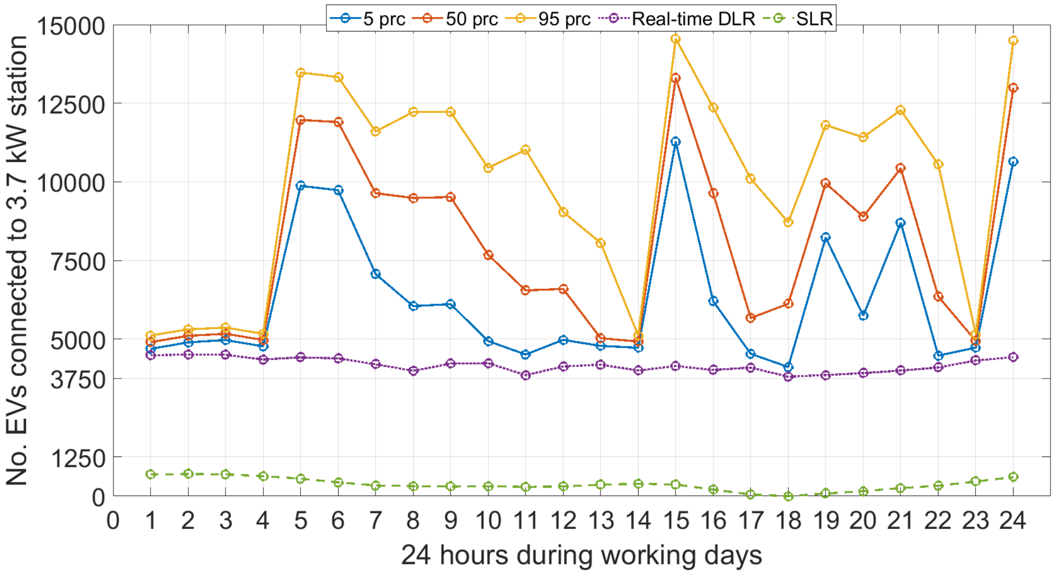

Figure 6.2: Number of cars as a function of the probabilistic rating 5, 50 and 95 percentiles for 3.7 kW charging per car

grid. It is also noted that due to lack of data for charging pattern of the drivers, in this report peak hours are defined when there is a high consumption in local area and drivers connect their cars to the charging power.

Chapter 7

Findings & Discussion

According to the material presented in this report, some of the findings are presented below, together with a discussion around those findings.

1. There is a great potential in the studied region to increase the transfer capacity of the regional network by utilizing a DLR system. Increasing grids' hosting capacity with DLR will allow us adding more loads such as new industrial connections, or electric vehicle charging. For Swedish cities in general, with the peak load related to electric heating, there is a large potential for DLR, even without the need for any curtailment. For a city in Northern Sweden, it is shown that the consumption can be increased by 14 MW (every hour of the year) without overloading the line, by using dynamic instead of static rating (about 40 MW) [43].

2. In the literature on power-system protection there is an excessive emphasis on protection against faults, at the expense of overload protection. For the study of DLR, more knowledge on overload protection is needed. As shown in (Chapter 3), there is a limited attention in the literature of describing the role of DLR in overload protection. There are clear advantages in considering DLR as part of the overload protection, for example in addressing its reliability (Chapter 4) and for a trade-off between taking measures and not taking measures (Chapter 5).

3. Protection, combined with curtailment, has a significant effect on the short-term operation and helps improving the performance of the electricity network. Weather-dependent protection, based on DLR, would be an alternative to classical overload protection. Using DLR allows for estimating a time-dependent line rating that considerably improves the security. It is important to consider both dependability and security, when designing and implementing DLR systems. When using DLR, the rating of the line and thus the setting of the overload protection change with time. When overcurrent protection is used both for overload and fault protection, the fault-clearing time increases with higher line rating. A maximum-permissible fault-clearing time sets an upper limit to the line rating.

4. A trade-off has to be made between dependability and security, where the balance between the two will in most cases change with time. This balance cannot be made in the design or parameter setting stage, but needs to be done during operational planning or operation of the system.

5. Deterministic DLR, based on assumed perfect knowledge of all parameters, is associated with a high probability of overload not being removed. A stochastic DLR, where the probability of overload is used as a decision criterion, has advantages above deterministic DLR. It will allow for a continuous trade-off between failure to take measures and unnecessary measures. Therefore, it is recommended to apply DLR overload protection as an alarm system that tracks both the dynamic rating and the line current. The proposed stochastic scheme can be used during "hour-ahead", which is mainly discussed in this report referring to hour-by-hour operation. It can also be applied to the "day-ahead" operational planning.

6. There are several uncertainties in calculating DLR, incorrectly estimating each of them may change the final result. This is especially important for the performance of the protection operation. Overestimating or underestimating DLR means increasing the risk of failure to take measures or unnecessary measures. So it is essential to identify the influential parameters in the calculation and provide accurate models for estimating them.

7. The acceptable probability of overload has a big impact on the number of times that measures against overloading have to be taken. It would give a good approximation of how much increment in rating is safe and avoid the need for unnecessary redispatching (like curtailment or starting of production units).

8. Despite the proven benefits brought by DLR, there are still only a few research studies working on the risk and reliability issues that DLR brings into the power system. In this report, a generic model is provided to describe qualitatively errors and failures in each of the elements affecting DLR calculation such as measurement devices, or communication channels. The existing research literature lacks an integrated study on the performance and reliability of the DLR system as a whole. The concepts dependability and security form a suitable framework for describing the reliability of DLR schemes.

Chapter 8

Future Work

Several open ends appeared during the studies presented in this report, some of which were already mentioned in these chapters or in the "Findings and Discussion". Some of the future work that remains to be covered to close these open ends is summarized below.

- The work in this report is based on one set of time series (current and weather data) for one location. The work should be extended to other locations (in Sweden and elsewhere) to verify the generality of the results. Another extension of the work would be to use randomly-generated time series, using methods like Markov Chain Monte Carlo [44]. These methods can be used to generate time series for new consumption like EV charging, but also to generate different time series of line current from other types of consumption for the same location. In this way, it is possible to obtain probability distributions of, for example, the number of hours during which curtailment is needed.

- The studies in this report considered one line equipped with DLR. Studies should be done for systems where multiple lines are equipped with DLR, this holds both for the protection and for the reliability aspects.

- There should be more emphasis on overload protection in research and in education. To understand the potential and challenges related to DLR more knowledge on overload protection of overhead lines is needed. It is especially important to develop protection schemes that separate overload protection and fault protection.

- The acceptable risk introduced in this report is defined as a probability of overloading. Future work is needed towards methods to make the trade-off between different risks involved in overload protection and to decide, either automatically or in the control room, when action should be taken.

- The study on reliability aspects did not specifically consider human errors. It is important to consider these separately in reliability studies and to design DLR schemes where human errors (which are unavoidable) do not have any major impact on the reliability of the power system. This holds for dependability as well as security.

- Studies are needed to find out to which extent the probabilistic DLR method proposed in this work can be applied to cables and transformers as well.

REFERENCES

[1] K Adachi, T Kumeda, and K Nagano. A method for expanding the current capacity of overhead transmission lines. In *Cigre session*, volume 2, 2004.

[2] Juliano SA Carneiro and Luca Ferrarini. Analysis and design of overload protections for hv lines with a probabilistic approach. In *Proceedings of the 10th International Conference on Probablistic Methods Applied to Power Systems*, pages 1–6. IEEE, 2008.

[3] Juliano SA Carneiro and Luca Ferrarini. A probabilistic protection against thermal overloads of transmission lines. *Electric power systems research*, 81(10):1874–1880, 2011.

[4] Stefan Pfenninger and Iain Staffell. Long-term patterns of european pv output using 30 years of validated hourly reanalysis and satellite data. *Energy*, 114:1251–1265, 2016.

[5] Iain Staffell and Stefan Pfenninger. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy*, 114:1224–1239, 2016.

[6] Göran Ericsson. Research plans and needs for the nordic transmission-system operators. *IEEE Sweden Meeting, LuleåUniversity of technology*, 11 November 2020.

[7] IEEE Xplore. Ieee standard for general requirements for liquid-immersed distribution, power, and regulating transformers. *IEEE Std C571200-2010 (Revision of IEEE Std C571200-2006)*, 2010.

[8] IEC. 60076-7, loading guide for oil-immersed power transformers. *Geneva, Switzerland: IEC*, 2005.

[9] Standar Internasional. Iec 60287-1-1 ed2. 0; electric cables–calculation of the current rating–part 1–1: Current rating equations (100% load factor) and calculation of losses–general. copyright© international electrotechnical commission (iec) geneva, switzerland.

[10] IEC Standard. 60853-2,“calculation of the cyclic and emergency current ratings of cables. *Part*, 2:853–2.

[11] Xiang Dong, Yanling Yuan, Zhongqiang Gao, Chengke Zhou, Peter Wallace, Babakalli Alkali, Bojie Sheng, and Hao Zhou. Analysis of cable failure modes and cable joint failure detection via sheath circulating current. In *2014 IEEE Electrical Insulation Conference (EIC)*, pages 294–298. IEEE, 2014.

[12] Peter H Larsen. A method to estimate the costs and benefits of undergrounding electricity transmission and distribution lines. *Energy Economics*, 60:47–61, 2016.

[13] Soheila Karimi, Petr Musilek, and Andrew M Knight. Dynamic thermal rating of transmission lines: A review. *Renewable and Sustainable Energy Reviews*, 91:600–612, 2018.

[14] Don Orest Koval and Roy Billinton. Determination of transmission line ampacities by probability and numerical methods. *IEEE Transactions on Power apparatus and systems*, (7):1485–1492, 1970.

[15] Vincent T Morgan. The loss of tensile strength of hard-drawn conductors by annealing in services. *IEEE Transactions on power apparatus and systems*, (3):700–709, 1979.

[16] Vincent T Morgan. Effect of elevated temperature operation on the tensile strength of overhead conductors. *IEEE transactions on power delivery*, 11(1):345–352, 1996.

[17] Transmission, Distribution Committee, et al. of the ieee power engineering society,"ieee standard for calculating the current-temperature relationship of bare overhead conductors", institute of electrical and electronics engineers standard# 738, 1993, calculation module 23. *IEEE Corporate Office*.

[18] TB Cigré. 601. *Guide for Thermal Rating Calculations of Overhead Lines, Working group B*, 2:43, 2014.

[19] Alberto Arroyo, Pablo Castro, Raquel Martinez, Mario Manana, Alfredo Madrazo, Ramón Lecuna, and Antonio Gonzalez. Comparison between ieee and cigre thermal behaviour standards and measured temperature on a 132-kv overhead power line. *Energies*, 8(12):13660–13671, 2015.

[20] E Fernandez, I Albizu, MT Bedialauneta, AJ Mazon, and PT Leite. Review of dynamic line rating systems for wind power integration. *Renewable and Sustainable Energy Reviews*, 53:80–92, 2016.

[21] ABB Switchgear. Protection application handbook, 1999.

[22] Hank Miller, John Burger, Normann Fischer, and Bogdan Kasztenny. Modern line current differential protection solutions. In *2010 63rd Annual Conference for Protective Relay Engineers*, pages 1–25. IEEE, 2010.

[23] Z Gajić, I Brnčić, and F Rios. Multi-terminal line differential protection with innovative charging current compensation algorithm. In *10th IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change*, pages 1–5. IET, 2010.

[24] Niclas Johannesson and Staffan Norrga. Longitudinal differential protection based on the universal line model. In *IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society*, pages 001091–001096. IEEE, 2015.

[25] Felipe V Lopes, Caio MS Ribeiro, João Paulo G Ribeiro, and Eduardo Jorge S Leite. Performance evaluation of the travelling wave-based differential protection when applied on hybrid transmission lines. *The Journal of Engineering*, 2018(15):1114–1119, 2018.

[26] Yeshwant G Paithankar and SR Bhide. *Fundamentals of power system protection*. PHI Learning Pvt. Ltd., 2011.

[27] GW Swift, ES Zocholl, M Bajpai, JF Burger, CH Castro, SR Chano, F Cobelo, P De Sa, EC Fennell, JG Gilbert, et al. Adaptive transformer thermal overload protection. *IEEE Transactions on Power Delivery*, 16(4):516–521, 2001.

[28] Clifton R Black and William A Chisholm. Key considerations for the selection of dynamic thermal line rating systems. *IEEE Transactions on Power Delivery*, 30(5):2154–2162, 2014.

[29] TO Seppa, HW Adams, DA Douglass, N Coad, A Edris, P Olivier, and FR Thrash. Use of on-line tension monitoring for real-time thermal ratings, ice loads, and other environmental effects. In *CIGRÉ Session*, pages 22–102, 1998.

[30] John Engelhardt. Dynamic line rating system with real-time tracking of conductor creep to establish the maximum allowable conductor loading as limited by clearance, March 17 2009. US Patent 7,504,819.

[31] HJ Dräger, D Hussels, and R Puffer. Development and implementation of a monitoring-system to increase the capacity of overhead lines. In *Cigré Session*, 2008.

[32] TO Seppa and A Salehian. Guide for selection of weather parameters for bare overhead conductor ratings. *CIGRE WG B*, 2, 2006.

[33] Inger Anne Tøndel, Jørn Foros, Stine Skaufel Kilskar, Per Hokstad, and Martin Gilje Jaatun. Interdependencies and reliability in the combined ict and power system: An overview of current research. *Applied computing and informatics*, 14(1):17–27, 2018.

[34] Jiashen Teh and Ching-Ming Lai. Reliability impacts of the dynamic thermal rating system on smart grids considering wireless communications. *IEEE Access*, 7:41625–41635, 2019.

[35] Emilio Ancillotti, Raffaele Bruno, and Marco Conti. The role of communication systems in smart grids: Architectures, technical solutions and research challenges. *Computer Communications*, 36(17-18):1665–1697, 2013.

[36] BS Howington and GJ Ramon. Dynamic thermal line rating summary and status of the state-of-the-art technology. *IEEE Transactions on Power Delivery*, 2(3):851–858, 1987.

[37] JS Engelhardt and SP Basu. Design, installation, and field experience with an overhead transmission dynamic line rating system. In *Proceedings of 1996 transmission and distribution conference and exposition*, pages 366–370. IEEE, 1996.

[38] Alireza Soroudi. Taxonomy of uncertainty modeling techniques in renewable energy system studies. In *Large scale renewable power generation*, pages 1–17. Springer, 2014.

[39] Math Bollen and Mats Häger. Power quality: interactions between distributed energy resources, the grid, and other customers. *Leonardo Energy*, 2005.

[40] Warren Wang and Sarah Pinter. Dynamic line rating systems for transmission lines. *US DOE*, 2014.

[41] Math HJ Bollen and Fainan Hassan. *Integration of distributed generation in the power system*, volume 80. John wiley & sons, 2011.

[42] Yue Cao, Tong Wang, Omprakash Kaiwartya, Geyong Min, Naveed Ahmad, and Abdul Hanan Abdullah. An ev charging management system concerning drivers' trip duration and mobility uncertainty. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 48(4):596–607, 2016.

[43] SF Hajeforosh and Math HJ Bollen. Increasing the grid capacity for electric vehicle charging using dynamic rating. In *CIRED*, pages 1–5.

[44] Yue Wang and David Infield. Markov chain monte carlo simulation of electric vehicle use for network integration studies. *International Journal of Electrical Power & Energy Systems*, 99:85–94, 2018.