RESEARCH REPORT

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Maximising power line transmission capability by employing dynamic line ratings – technical survey and applicability in Finland

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Summary

The power lines are conventionally designed and operated with worst case limitations and static ratings. The power transmission limiting feature on thermally limited lines is the line sag. On maximum sag with prevailing ambient condition, the actual current capability, i.e. ampacity, is most of the time larger than static ratings. This hidden transmission capacity potential could be utilized with dynamic line rating (DLR) monitoring.

Based on literature review, the different commercially available DLR monitoring methods as well as some experiences there has been on DLR monitoring methods and using DLR, are covered in this report. In addition DLR monitoring equipment, other related issues to DLR application are discussed as well.

Fingrid has had one DLR monitoring unit installed in their grid and has some measurement data from it. This data is looked at briefly. The DLR applicability possibilities in Finland is preliminarily analyzed based on the literature review done, as well as providing some guidelines and options especially related to DLR application in context of wind power integration and grid connection.

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Preface

This report has been done as subcontracted work for Fingrid as part of the Smart Grids and Energy Markets (SGEM) project, phase III.

The work steering group consisted of experts at Fingrid: Antero Reilander (contact person), Aki Laurila, Jussi Matilainen, Antti-Juhani Nikkilä, Kaisa Nykänen and Tuomas Rauhala.

The guidance and help of the steering group at Fingrid, and especially Antero Reilander, is greatly acknowledged.

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Espoo 28.2.2013

Sanna Uski-Joutsenvuo

Contents

1 Introduction

Ampacity of an overhead transmission line is the maximum electrical current that a power line can carry without either reducing the tensile strength of the conductor or exceeding the maximum sags beyond which minimum electrical clearances to ground and to objects or other conductors below the line are violated. In practice, to guarantee that the power line material strength or clearances are not jeopardized, the transmission lines are given ratings, i.e. power transmission limits, in the line design procedure. The ratings are determined by the most critical circumstances, and with high reliability level.

There has been development of the dynamic line ratings (DLR) and their determination and measurement over the recent years, even decades, especially related to wind power development issues in constrained networks and in areas where it would be difficult to build new power lines, e.g. Central Europe, UK and USA.

There are different commercial methods available for employing and determining the dynamic power line ratings. The different methods can be based on weather monitoring, line tension metering, monitoring the line frequency spectrum, line temperature etc. Although there is commercial DLR monitoring equipment available, they do not seem to be extensively used or established technology yet.

There have been pilot projects with DLR and different DLR determination methods worldwide in several power systems and geographical locations over the recent years.

2 Goal

Wind power production is highly variable source of power production, and most of the time the power produced by wind farms is lower than the wind farm rated capacity. The needed power transmission capacity for wind power evacuation from the wind farm to the power system is corresponding to wind farm power production.

The power line temperature, and specifically cooling of the power lines (e.g. the ambient temperature and heat transfer by wind) has strong influence on power line transmission loadability. Thus the transmission lines' capacity probably would not need to be dimensioned according to the conservative static line rating criteria and wind farm rated power at all the times throughout the year. And also vice versa, the acceptable wind farm capacity may not be necessary to be limited according to the available transmission capacity defined by conservative static line ratings.

Dynamic power line ratings consider the prevailing weather conditions and enable higher ratings at most times of the year. Employing dynamic power line ratings – while at the same time maintaining high reliability level – might produce savings in time and money as the existing power lines would be used in efficient way. New power line construction and unnecessary over-dimensioning could be avoided.

Employing DLR for "maximizing power line capability" means that the existing transmission connections are used in more efficient way, without actual grid reinforcements (except some investments on DLR monitoring and operation).

This work provides the background information existing today on DLR and DLR use related to wind power integration into power systems. There work done from the perspective of considering the DLR applicability possibilities in Finland related to wind power grid connection. Also other available means to maximize power line capability besides DLR are briefly reviewed in chapter 4.

3 Theory and facts behind power line ratings

The capability of a high voltage power line is usually set by thermal limit for shorter lines and transmission distances (up to 80 km), and longer (80 to 320 km) lines by voltage regulation, and very long lines (> 320 km) by stability issues [1].

The foundation of, and the assumptions related to power line thermal ratings date back to a 1930 study [2], where it is stated e.g. that less than 2 ft/s wind is not to be expected more than 5 % of the time during the summer season and its occurrence with high temperature is even less frequent, thus the change of overheating conductors is practically negligible. The ratings are still commonly defined by these conservative weather assumptions, e.g. simultaneous 40°C ambient temperature, full sun, 2 ft/s wind perpendicular to the conductor [3]. The ratings are determined by the most critical circumstances and with high reliability level in order to guarantee absence of truly hazardous loading of the lines.

Ampacity determination was discussed in early 70's in [4], the days when computer calculations were not used in everyday life. Even before that the power line ratings have been discussed in several papers over the decades, often providing ratings for power lines at different ambient temperatures. Those days there were nomograms made for looking up power line rating at different temperatures.

IEEE Standard 738-2006 for Calculating the Current-Temperature of Bare Overhead Conductors [5] is widely used to calculate the thermal rating of a conductor. CIGRE Working Group 22.12 has also published Thermal Behaviour of Overhead Conductors [6] describing a calculation method for conductor thermal behavior as well as a Guide for Selection of Weather Parameters for Bare Overhead Conductor Ratings [7].

The normal clearances defined e.g. in standards (CENELEC standard EN 50341-3) determine the permissible sag for the line, and thus are defined the limitations for line design. The maximum line temperature is also determined by the maximum sag, but generally there are used standard (design) maximum temperatures, e.g. according to EN 50341-3. Allowed maximum permanent conductor temperatures vary by countries generally between 75 and 90°C [1]. The EN 50341-3 standard has national (differing) requirements for temperature limits and in Finland the highest allowed conductor temperature is 80°C, and 200°C with short-circuit current [8].

As the line sags have not been possible to predict with high accuracy due to inherent error margins and tolerances of conductors and installation, there are commonly used buffers between 0.9…1.2 m on the sag. [9]

The static ratings are determined according to the most critical circumstances, and relying on low probability of this rating being underestimated. This, as well as the actual real-time rating, ampacity, is illustrated in Figure 1.

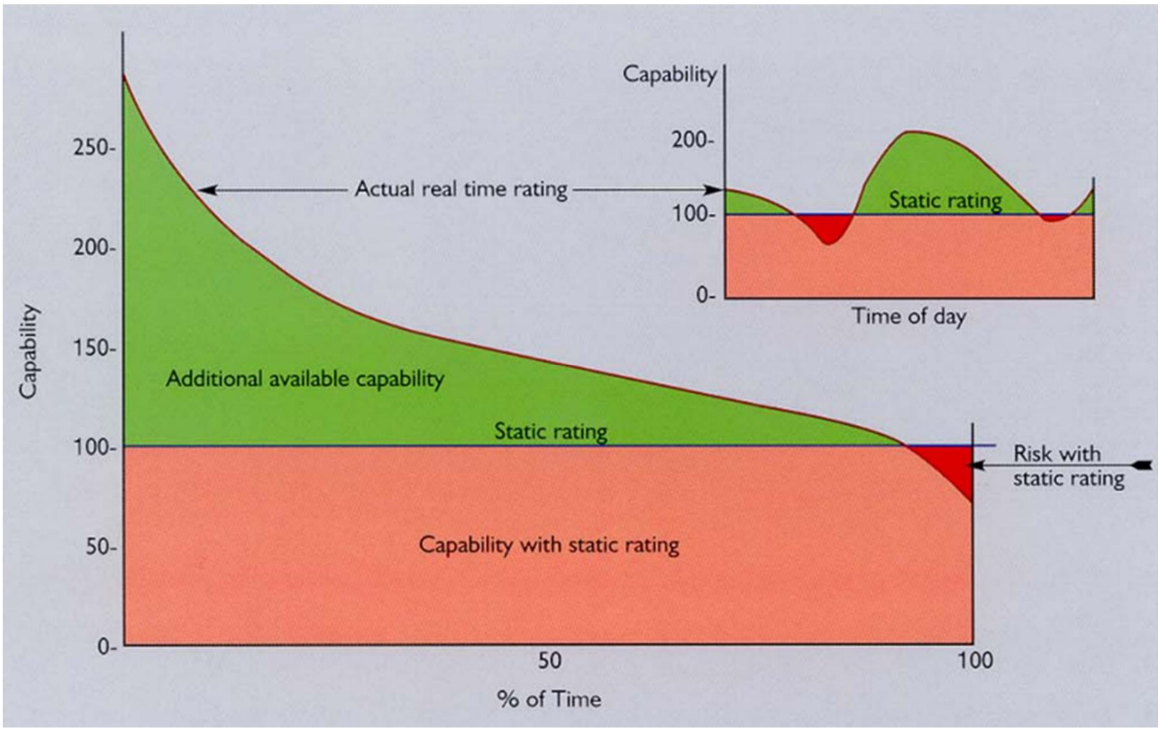

Figure 1. Duration curve of ampacity, i.e. real-time line rating, compared to static rating. Use of dynamic real-time rating would eliminate the risk included in static rating, as well as enable significant amount of additional transmission capacity. [10]

3.1 Traditional design of power lines and line ratings

Power lines are built according to transmission capacity needs. Construction of transmission lines in Finland (110 kV and higher voltage) is subject to law (sähkömarkkinalaki) and approval by regulator (Energy Market Authority / Energiamarkkinavirasto). The application procedure and prerequisites are described e.g. in [11].

Typical implementation period of a 110 kV power line in Finland is 3-5 years starting from the determination of the need for a transmission line, covering the design, environmental impact assessment, approval application and construction phases up to putting the line in operation. The costs for power line investments are dependent on several features, e.g. on the power/energy to be transmitted via the line which in the end determine the technical solutions. The power line investment costs can be expressed in the units EUR/MW,km,a (costs per transmitted MW's per kilometer in a year), and are ranging from appr. 1400 EUR/MW,km,a to several thousand [12].

The power lines are designed according to the standards and when using the static line ratings, the dimensioning is done with conservative assumptions (see Figure 1). This assumption, however, may accept and contain a low probability of rating being over estimated up to a few of percent of the time. E.g. in Germany was done analysis of weather data in context of DLR employment study [13], that showed that the occurrence frequency of individual weather variables is very low (see Figure 2), not to mention the combined occurrence of dimensioning temperature and wind speed values.

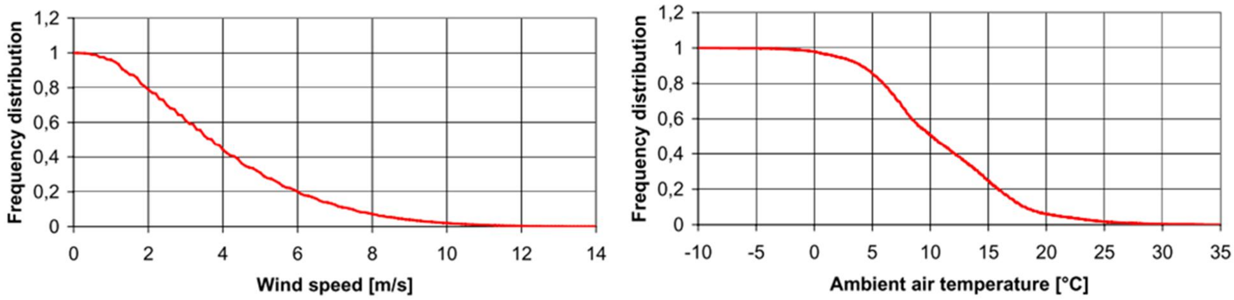

Figure 2. Frequency distribution of measured ambient temperature and wind velocity in northern Germany for one year's period. [13]

In conventional power system operation, the protection relay current settings are normally higher than power line rating in high ambient temperature and settings are static. In emergency situation it might be up to the operation personnel to ensure that the power lines are not being over loaded.

3.2 Actual power line transmission capability – ampacity

The actual limit for transmission line current carrying capability is a combination of the influence of the line heating and cooling. The limiting feature may be either the actual line temperature (conductor material issues), or the decreased conductor clearance from the ground (jeopardized by increased sag due to conductor heat expansion). The more common limiting feature is the sag of the line. Also in Finland on the Fingrid owned lines the limiting feature is the clearance from the ground or objects under the line.

There are several quantities that influence on heating and cooling of power lines (See Figure 3):

- The **current** flowing on the line heats the conductor,
- as well as the **radiation** of the sun and reflections from the surroundings,
- the surrounding air cooling effect, and thus
    - the **air temperature**, and
    - **wind speed** perpendicular to the conductor, as well as
    - **radiation of heat** from the conductor to the surroundings.

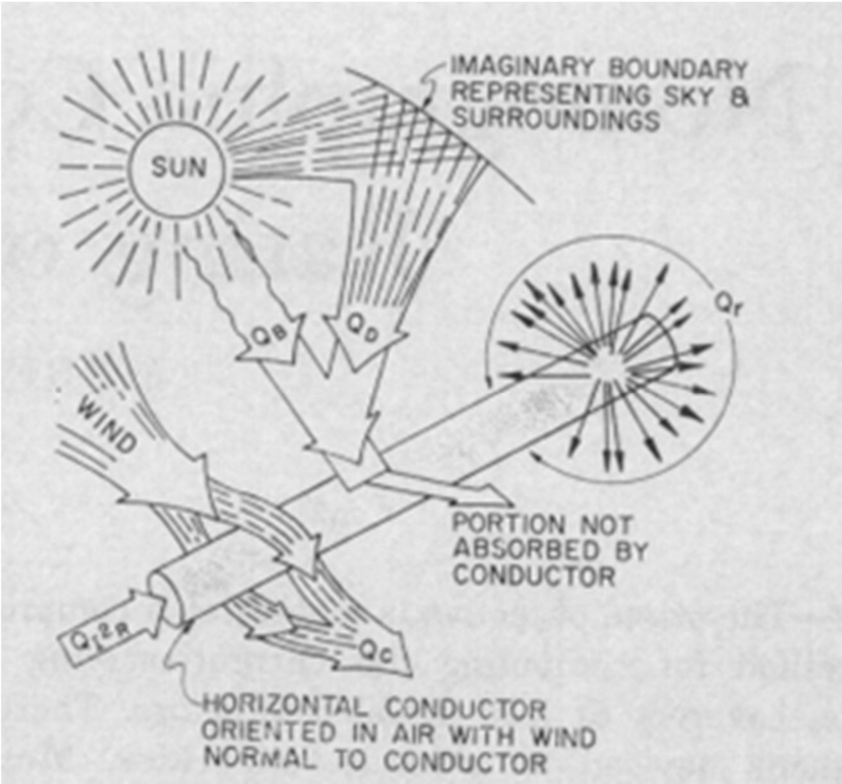

Figure 3. Pictorial diagram quantities heating and cooling a power line.[4]

The above listed quantities are both varying along the transmission line, as well as in time. In addition most of the quantities are difficult to measure, and/or predict with high reliably. This is discussed further in section 6.1.

CIGRE as well as IEEE have published mathematical models or calculation methods for conductor temperature [6], [5].

Wind speed has the most significant influence on the power line ampacity, as shown in Figure 4 with a comparison done by varying single parameters in the mathematical model of overhead conductors (CIGRE model [6]) for Zebra conductor [14].

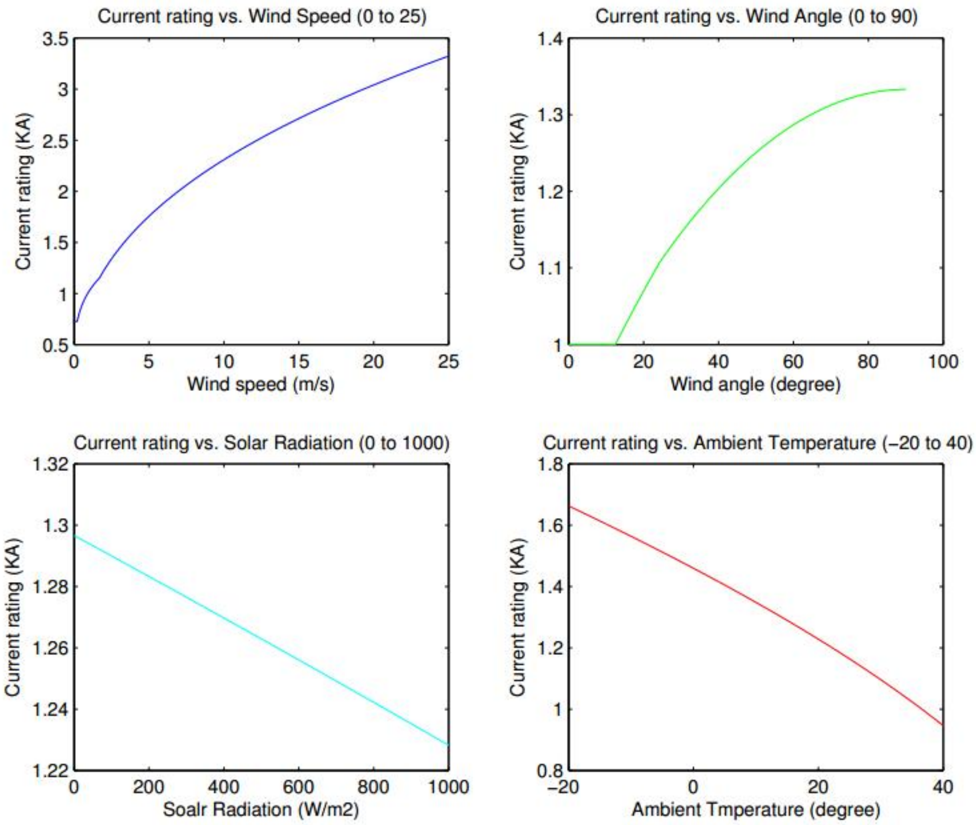

Figure 4. Current rating versus ambient temperature (default ambient condition if not specified: V = 2m/s, δ = 45°, S = 1000 W/m^2, T_a = 20°C). [14]

The Figure 5 illustrates further the influence of combined impact of two variables for the Zebra conductor.

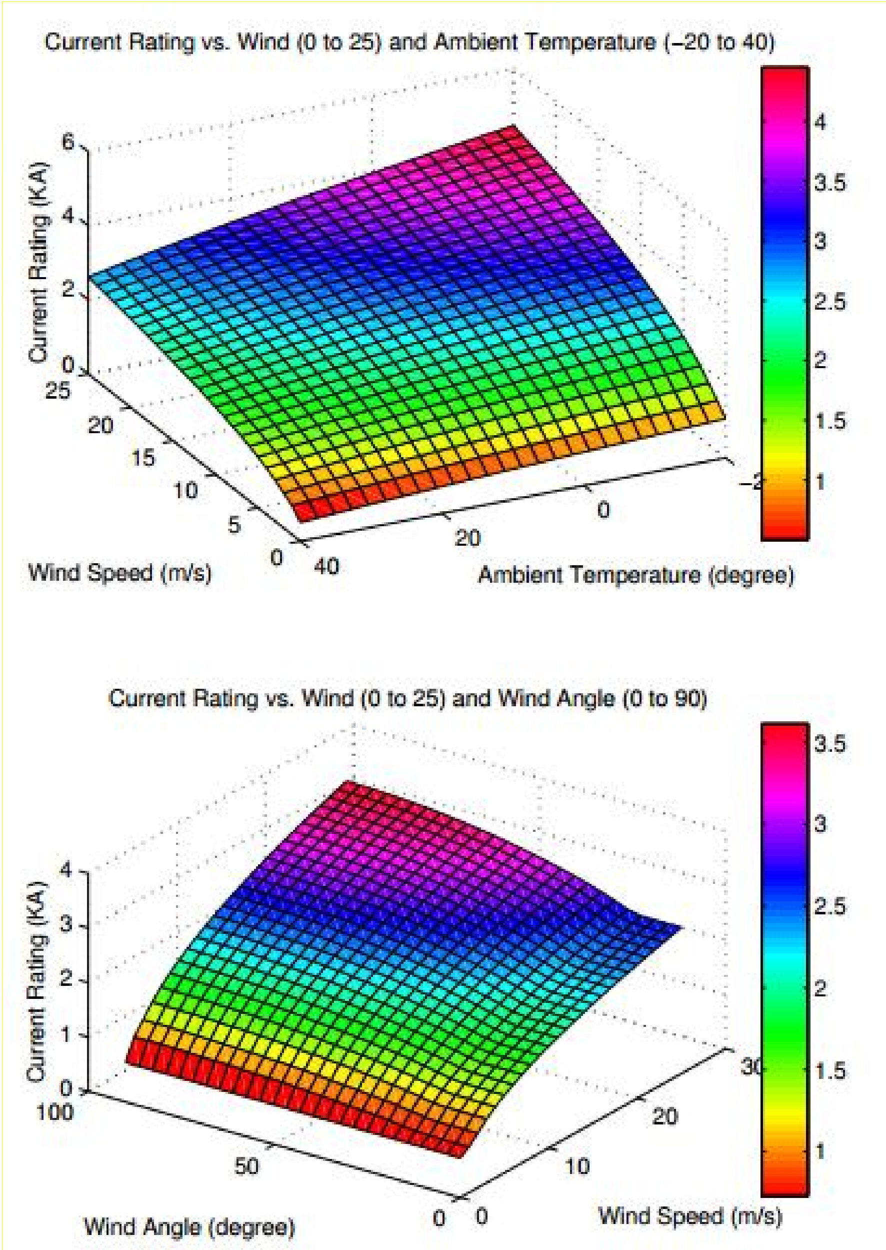

Figure 5. Current rating versus wind attack angle and ambient temperature (V = 5m/s, δ = 0 to 90°, S = 1000 W/m², T_a = -20 to 40°C). [14]

Dynamic line rating is the power line real-time rating based on ampacity under the prevailing circumstances (e.g. weather parameters and other conditions) and considering possible other criteria influencing the line rating, e.g. N-1 contingency criterion. Ampacity can be defined by measurements and line rating theory or models. There are also several other different terms used for actual power line transmission capability in addition to dynamic line rating (DLR), e.g. real-time-rating (RTR), dynamic thermal circuit rating (DTCR), dynamic thermal line rating (DTRL).

Whereas sag is caused by expansion of conductor material, and thus is reversible, creep is permanent elongation of the conductor that happens over time for strained conductor. Creep and annealing caused by loading of the power line lead into conductors experience loss of material strength over time.

4 Possible means and methods for maximizing power line capability

Power line transmission capability can be increased by several different means. It is important to know how much the capability needs to be increased and how often increased capability would be need, i.e. continuously most of the time or the increased need – especially the maximum need – would occur only sometimes. According to the needs, there are different optimal solution alternatives available to be considered.

Different transmission line capacity increase alternatives are looked through e.g. in [15]. Large transmission capacity increase may require replacing the whole transmission line structures and the conductor and increase both the voltage and current. The right-of-way would be the only retained part from the existing line, and this alternative would be more expensive and time consuming. Less dramatic means could be to change the conductor to a type that would allow larger ampacity, e.g. a larger standard conductor or a high temperature low sag (HTLS) conductor (see Appendix 2). For smaller capacity increase need, the conductor re-tensioning or increasing the height of the towers, could be options especially in case the capacity increase should be done economically. In [16] there has been done some economical comparison of different options.

In addition to the structural, material and component changes, there are operation based solution options available for increasing transmission line capability. Instead of using static (absolute or seasonal) line ratings, e.g. ambient adjusted ratings could be used as there seem to be used by ERCOT in Texas, USA [17]. Dynamic line ratings (DLR) would be the way to take more efficiently advantage of the line ampacity.

5 State-of-the-art of dynamic line ratings

Real Time Thermal Rating, i.e. dynamic line rating, was introduced by Murray W. Davis in 1977 in [18]. Even before this, as reported in [18], obeying strict static line ratings was made partial exception of by an electric utility in the 1960’s in terms of a short-duration or unsteady state emergency rating for a river crossing that would be a major interconnection in contingency situation with various outages. The Real Time Thermal Rating was not technologically feasible to implement until in the late 70’s. Development and employment of SCADA and measurement sensor technology brought DLR closer to real life applications.

When using real-time monitoring system for dynamic line rating, it would be possible to utilize the transmission line capacity more efficiently. Figure 6 from the CIGRE State of the Art document (on thermal line ratings in real-time and their application in optimizing power flow [9]) illustrates a line loading distribution, relative to static rating as well as dynamic rating. The dynamic line rating points out an area below the static rating where there could be potential clearance problems with using static rating. This is seen also in Figure 1 with the duration curve of dynamic line rating and static rating over a period of time. Using dynamic real-time line rating, on the other hand, would eliminate this risk, and allow loading the line more towards the actual dynamic rating distribution.

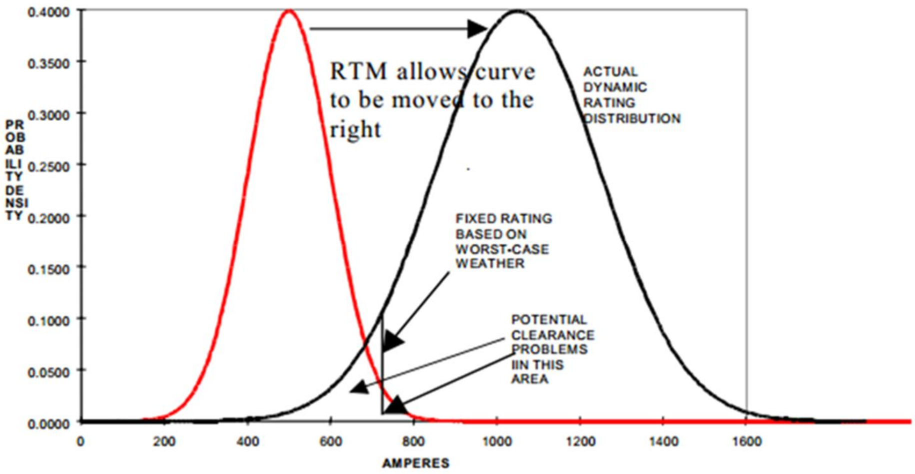

Figure 6. Actual load versus dynamic rating distribution. [9]

Typically the line capabilities can be increased by 10-15 % with relatively minor physical upgrades [16]. Further, employing DLR, 10-15% increase in line capacity can be achieved, resulting in overall 20-35 % increase in capacity with high reliability.

Even if not implementing dynamic line ratings in operation, it could be possible to increase static ratings by running a line rating measurement campaign and studying the measured ampacities in relation to design static ratings [17].

There are several different methods utilized for determining power line ratings today. The dynamic power line ratings are not yet very widely used although there has existed methods and DLR monitoring equipment for a couple of decades already. There have been, and currently are, many studies going on related to DLR, especially as part of research on Smart Grids.

Whereas the general approach to transmission line ratings has been deterministic, the approach in implementing and using dynamic line ratings should be a combination of probabilistic planning approach and a deterministic operation [19] (see Figure 7). CIGRE has published the Guide for Application of Direct Real-Time Monitoring Systems [20] just recently (2012).

According to [20], the sag in direct DLR determination methods can (and must) be determined in the accuracy of ±20cm. Further is specified that the global error margin on real-time rating acceptable for power system operators should be around ±10 % (that could correspond to the ±20cm error in sag, which in turn could correspond approximately 5°C temperature difference for a specific conductor under certain operating and weather circumstances).

In order to be able to plan network operation and have more certainty on the available transmission capacity beforehand (e.g. to be given to the electricity market), DLR forecasting has become a contemporary research topic. Forecasting also has its probabilistic characteristics, and decreasing uncertainty the shorter term ahead the forecasting is done.

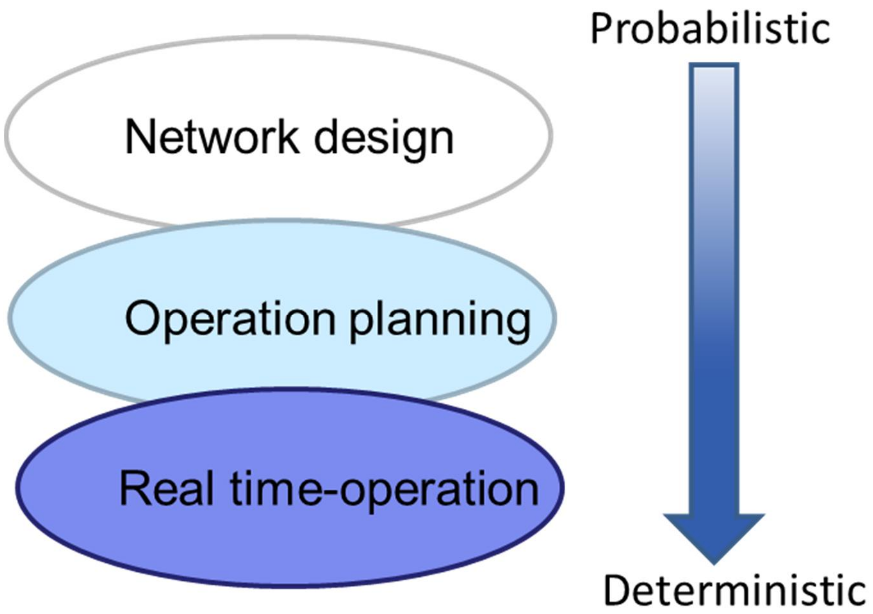

Figure 7. Using DLR would require and enable different approaches from probabilistic network design to deterministic real-time operation.

In [15] there is discussed that there should be formed a common understanding among the different concerns planners, designers, operators and manufacturers. It may well be that the first three mentioned ones are with the TSO, and yet there may be a need to improve the possibilities to get these parties to for a better common understanding on the issue.

Future prospects for the time when static line ratings would be extensively replaced with DLR include several new features, e.g.

- network and power market calculations become more complex compared to the present day, as
  - the line ratings are not constant parameters anymore, but variables with magnitude probability and uncertainty for individual lines as well as combinations for the whole network
- there will be need for DLR forecasting in order to be able to assess the transmission capacities to be provided for the electricity market
- network operation will experience changes, e.g. in terms of
  - possibility to load lines more than planned or forecasted in case needed real-time and ampacity permitting, thus decreasing the need to make corrective actions, e.g. generation redispatch or curtailment
  - occasional need to take actions to change planned load flow situations in case of errors done in DLR forecasting, e.g. by generation redispatch or curtailment
    - these may create costs – and it needs to be defined who covers these
    - there must be defined rules according to which generation is curtailed (if not clear), and how and if these would compensated somehow

- using the existing network assets more efficiently and according to their actual real-time limitations instead of based on conservative design limitations and unnecessary transmission limitations
  - this increases profitability of these network assets.

6 DLR determination methods

Existing dynamic line rating determination methods are generally divided in direct and indirect methods. It depends on the source where the line between direct and indirect methods is drawn: some consider only the sag determination methods as direct methods [21], whereas most consider all the methods monitoring the transmission line characteristics as direct methods. The division can be even further, as in CIGRE guide [20] even line replica method (see section 6.3.1) was considered as direct method, although it does not measure anything of the actual power conductor. The DLR monitoring methods are here divided into three categories (see Figure 8).

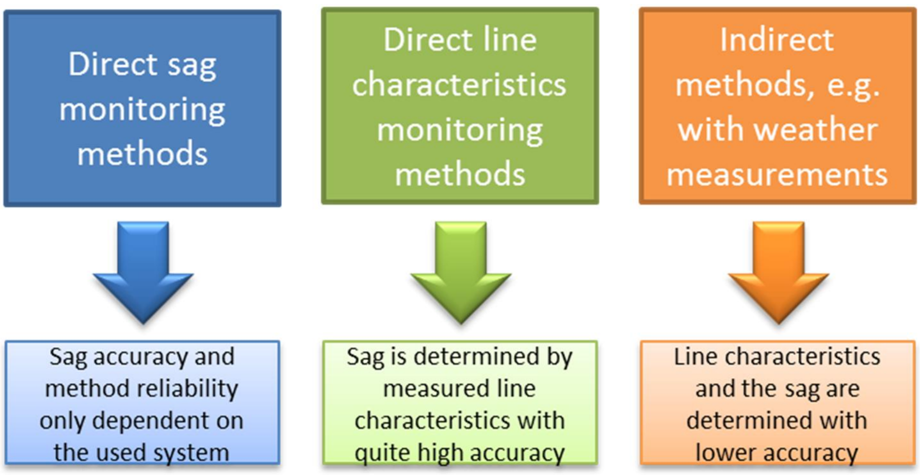

Figure 8. Division of direct and indirect DLR monitoring methods.

The direct methods are based on monitoring and observing the limiting element of a power line, the line sag (or temperature in case it would be the limiting element before the sag). The direct methods monitoring the line characteristics, could be based on e.g. monitoring one or several of the following, the line mechanical tension, the line angle of catenary, the line fundamental frequencies, or line temperature, and based on which the sag is calculated. It should be noted that the measured line temperature is local quantity and temperature can vary along the line even on short distances (see section 6.1).

The direct sag monitoring method accuracy and the method reliability are only dependent on the actual method used. Usually the direct methods measuring some characteristic of the line to determine the sag, are very accurate due to strong dependency of the monitored feature with the sag. Accuracy of the different methods is discussed in context of each method in sections 6.2 and 6.3.

The indirect methods rely on monitoring e.g. ambient weather, and based on which method the line temperature and sag are determined indirectly by theoretical models and calculations. Therefore these methods may have more uncertainty involved (e.g. due to varying nature of the weather quantities along the monitored line, described in more detail in section 6.1) than the direct methods that are monitoring the line characteristics that have strong dependency with the sag.

Determining the actual state of the monitored line (e.g. the sag) is one of the key points in determining and using DLR. However, DLR itself cannot be measured, but it is always derived from the actual line loading and line status (e.g. the sag). Many of the DLR determination methods determine the DLR more accurately, the higher – or more closer to the DLR – the line loading is.

The DLR monitoring equipment is installed somewhere (single or multiple locations) on, or along the monitored line. A single transmission line may be several tens (or even hundred(s)) of kilometers long, and may pass different kinds of terrain, geographical locations, vegetation and varying weather circumstances along the line. The selected location(s) for the DLR monitoring device should be the most critical location(s) along the transmission line, so that in case the line is secured on this location, it is secure also elsewhere along the line at all times. Regardless of the DLR monitoring method used, usually the whole line and all of its sections are not, or cannot be monitored. The selection of monitoring equipment locations is of paramount importance. The variability degree of these circumstances along a transmission line, as well as DLR monitoring equipment location selection, are discussed further in detail in section 6.1.

The existing direct methods are introduced in section 6.2 and the indirect methods in 6.3 based on literature review and other gathered information.

6.1 Variables along the line and measuring these quantities

The power line ampacity is dependent on several features and measurable quantities (as described in chapter 3) and the quantity cumulative impacts throughout the spans. The power line ampacity is determined by the most limited section on the whole line length. Below the different variables and features having impact on line rating, are discussed.

Current

The current flowing on the line is well known by monitoring the transmission connections. Its magnitude is somewhat uniform along the whole line, except for small decrease as part of transmitted power is lost in the line resistance as losses, thus heating the conductor. The line current is the variable that is attempted to define the limiting value (ampacity, DLR) while all the other aspect set the limitations.

Wind speed and direction

Whereas the wind has most significant impact [14] on power line cooling, and thus power line ampacity, it has most variability both in time as well as location along the line, e.g. as illustrated in [22] for wind measurement locations on a transmission line 1.5 kilometers apart from each other. Thus DLR determination method measuring and utilizing wind speed has rather high uncertainty.

Radiation
The solar radiation from the sun and reflections from the clouds and surroundings warm the conductor. The conductor also radiates heat back to the surroundings. The radiation has smaller impact on the conductor heating (see section 3.2), and it is relatively difficult to measure reliably covering the whole line. For solar radiation can be determined quite easily the absolute varying maximum values dependent on the diurnal variation (guaranteed absence of the sun) based on geographical location, the date and the time of the day.

Line temperature
The line temperature is a result of cooling and heating of the line, and it causes prolongation of the line and thus the line sagging. Whereas the cooling of the line e.g. due to convection caused by wind and heat radiation to the surroundings, is very variable spatially, so varies the actual line temperature spatially. Spatial line temperature variation on a single span can be significant as shown by field measurements (e.g. 10-20°C) [19] and test site measurements (up to 29°C) [23].

The line temperature could be the limiting feature for power line rating, but usually it is the line clearance from the ground or objects below the line. Thus the temperature would be used to determine the sag of the line. According to the tests reported in [23], monitoring of the line temperature in a few discrete locations of a line would lead in severe over- or underestimations of actual power line ratings.

Line tension
According to overhead power line design theory ([1], p.547-548]) instead of assuming rigid attachment points in each span, more precise approximation is to consider equal tensile forces and mechanical loadings on all *n* spans of a tensioning section. Based on this assumption, the equivalent span, or ruling span of a tensioning section, is defined. The sags in the individual spans can thus be determined under the assumption of equal conductor tensile forces on all spans within tensioning section. The sag itself is determined by catenary equations.

In [24] is brought into attention that the ruling span approximation may not be accurate enough to analyze the operation of a line, although it was used for the design of the line especially in case there is a need to operate the line above the original design temperature (> 100°C). Also issues preventing full tension equalization, e.g. angle suspension insulators, large-weight span suspension, suspension insulator flexibility, short insulator string etc., may cause errors when using ruling span method. On a tensioning section, the error magnitude in sag calculation for different span lengths vary, e.g. shorter spans are more sensitive to temperature changes than long spans.

Equalization of the tension along the tensioning section is illustrated in Figure 9. The ruling span method is applicable with acceptable error margins for lines operated below 100°C, with relatively equal length and near level spans, and with suspension structures allowing rather free movement.

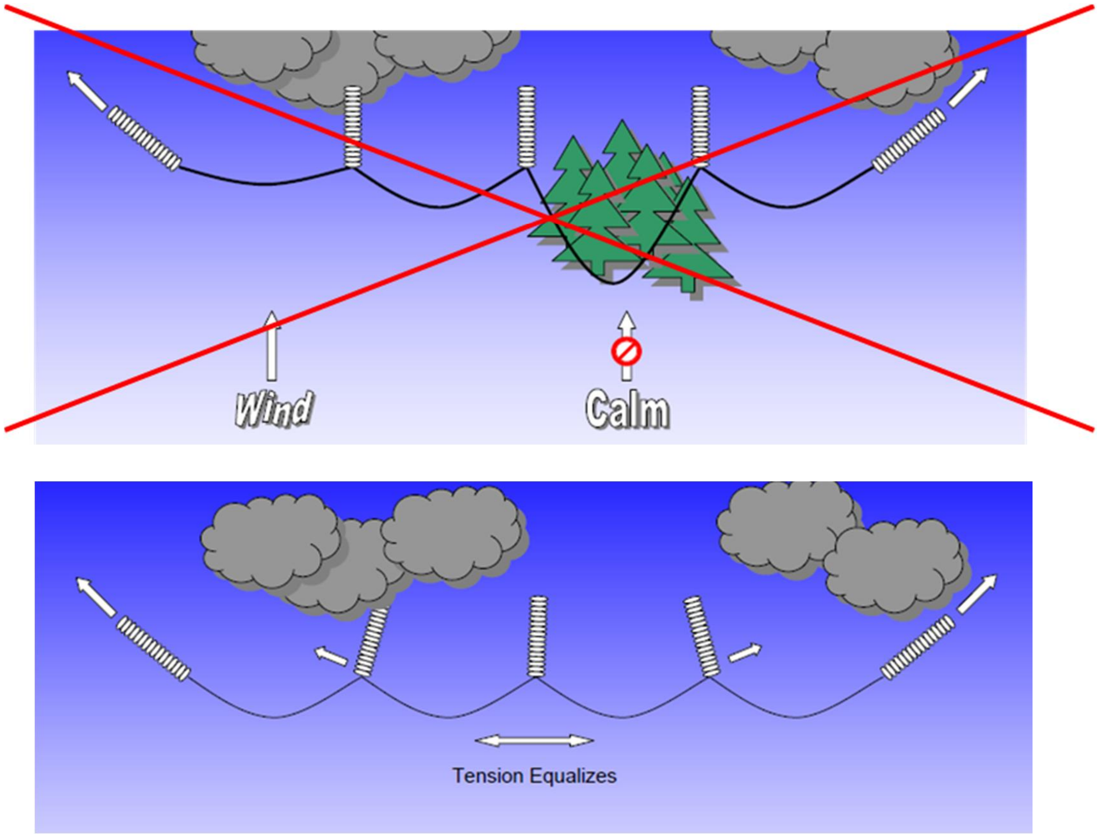

Figure 9. Suspension insulator strings swing to equalize horizontal conductor tension along the tensioning section of the line. [25]

Critical sag on the whole line length

Due to fact that the line tension equalizes between two dead-ends (see above), the sagging between these dead-ends is equalized into certain extent. The tension and sagging is governed by the average temperature along the line between the dead-ends, and thus the critical span is not necessarily the one with highest (local) line temperature. The line temperature on the span (between the dead-ends) on which the sag could be critical, may not even exceed the critical line temperature, as explained e.g. in [19]. Critical span can also be a span on which security of people is of importance, e.g. crossing roads or surroundings of settlements, i.e. places where people could be in danger in case of conductors sagging too low.

Generally, applicable to all the direct DLR monitoring methods is that a critical span or section of a line needs to be determined for maximum sag (i.e. minimum clearance marginal to the ground / objects under the line) or the maximum conductor temperature – whichever comes first – and the monitoring equipment would be installed on this span or tensioning section.

Trials carried out on the same transmission line at the two ends of the line show the correlation of tensions (the sag is correlated to, and can be calculated from tension values) along the whole line [19]. These trials on the 20 km Inkoo-Virkkala 110 kV line show how that the tensions measured at the two ends of the line track each other showing similar sagging behavior along the whole line, including simultaneously occurring low tension readings, as well as high tension readings.

In the Smart Grid Demonstration Program (SGDP) currently going on in Oncor network in Texas, USA, the selection of location for monitoring equipment is studied at from both geographic and quantity perspective (i.e. how many monitoring equipment is required, their spacing and geographical locations) [17]. The issue is also discussed in [20], and concluded that a monitoring device every 3 km would be good, depending also on the terrain.

6.2 Direct DLR methods

The first real-time rating system (RTTRS developed by Murray W. Davies [18]) consisted of conductor temperature sensor-transmitter-receiver, weather station, SCADA and thermal rating computer programs. Since then, there have become several commercial DLR monitoring equipment available that are based on quite many different characteristics. The different direct commercial DLR monitoring methods available today are described in brief in the following sections in the order of their appearance/development.

For all the overhead line monitoring equipment, even those to be installed on the line, live-line installation can be done if live-line work is allowed. There seems not to be too much difference in the installation time or requirements (interruption etc.), so the installation features are not discussed further in the following sections.

6.2.1 Power Donut2™ by USi

Background [26] [27]:
Power Donut was developed by Nitech Inc. The first generation of Power Donut™ was in 1988-2004, the second generation Power Donut2, PD2™, in 2004-2011, and the third generation Power Donut3, PD3™, is presently in development and initial field testing.

According to USi, there have been more than 1000 Power Donuts installed between 1988 and 2012.

Method is based on [28],[27],[29]:
The Power Donut monitors e.g. the current, line-to-ground voltage, conductor temperature, conductor angle of inclination (catenary parameters). The Power Donut can be used also for line sag and tension monitoring (apparently it was initially intended for line temperature monitoring). See Figure 10 for installed Power Donut equipment.

The Power Donut DLR calculation is based on IEEE 738 Weather Model, with adaptation that cross calculates the convection heat flow using the conductor current and temperature readings as inputs.

The equipment temperature sensor is outside the donut, and thus thermally insulated from the shell. A lot of R&D has been done to ensure that the shell does not influence the conductor temperature readings.

According to USi the Power Donut measures conductor surface temperature with an accuracy of ±1°C. The ambient temperature is approximately in the same accuracy range. The line sag accuracy has been validated as 5 inches in 30 feet by autorobotic theodolites.

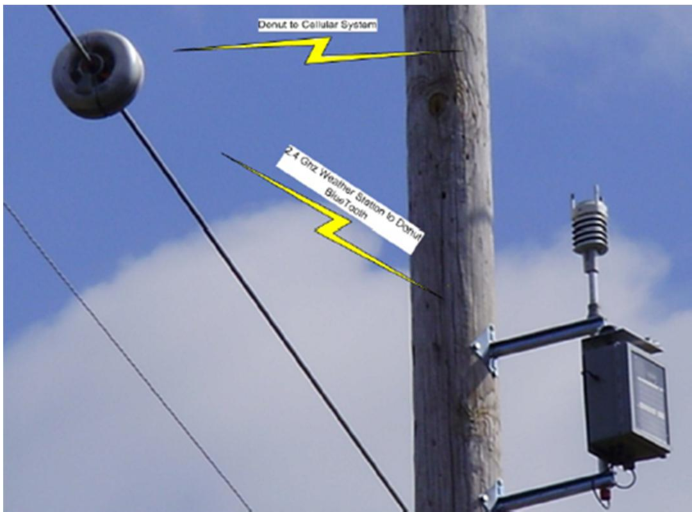

Figure 10. Power Donut mounted on a conductor and a weather station near-by the Power Donut. [27]

<u>Price [29]:</u>
The price of Power Donut technology depends on the system configuration and architecture. A complete system for one location would be in the range of $40.000…80.000 US.

<u>Application, installation, user interface etc.:</u>
The equipment is powered directly from the monitored conductor via electromagnetic field, it contains also a lithium battery to maintain operation also at low line loading (i.e. current < 50 A, charged when current > 130 A) up to 1 hours.

Communication is done via GSM network.

<u>Pros & Cons:</u>
Powered directly from the measured conductor.

6.2.2 CAT-1 by Nexans, former Valley Group

<u>Background [30]:</u>
The CAT-1 method is developed by Tapani Seppä (Seppa) who founded the Valley Group in 1990. Currently the Valley Group is under Nexans. The method is patented.

The first CAT-1 Transmission Line Monitoring System was installed in Virginia Power in 1991. According to Nexans, there are over 300 Transmission Line Monitoring Systems installed by over 100 utilities in more than 20 countries on 5 continents. Over two thirds of the 30 largest utilities in North America have CAT-1 systems, and over half of those utilities operate CAT-1 systems in real-time to provide accurate real-time ratings to utilities' EMS/SCADA.

Method is based on:
The CAT-1 load cells are installed at the dead-end structure of a power line and they measure tension of the line suspension section. The sag on the suspension section spans is determined by the conductor tension once the installed equipment is calibrated.

DLR is determined based on IEEE and optionally the CIGRE methods.

Figure 11. CAT-1 measurement unit in Lappeenranta, Simolantie.[31]

Price:
Typical cost level of tension-based monitoring system has been (year 2000) around $ 1500 to $ 3000 per circuit-km [16].

The price for a single tower CAT-1 DLR instrumentation, i.e. 2 load cells, one in each direction, is about 40 000 €. The fully integrated and operational setup is in the range of 2500 – 3000 € per circuit-km. Wide deployment reduces the price because the costs for the equipment and software in the control center is only needed once. [32]

Application, installation, user interface etc.:
The CAT-1 DLR monitoring system communication solution is shown in Figure 12.

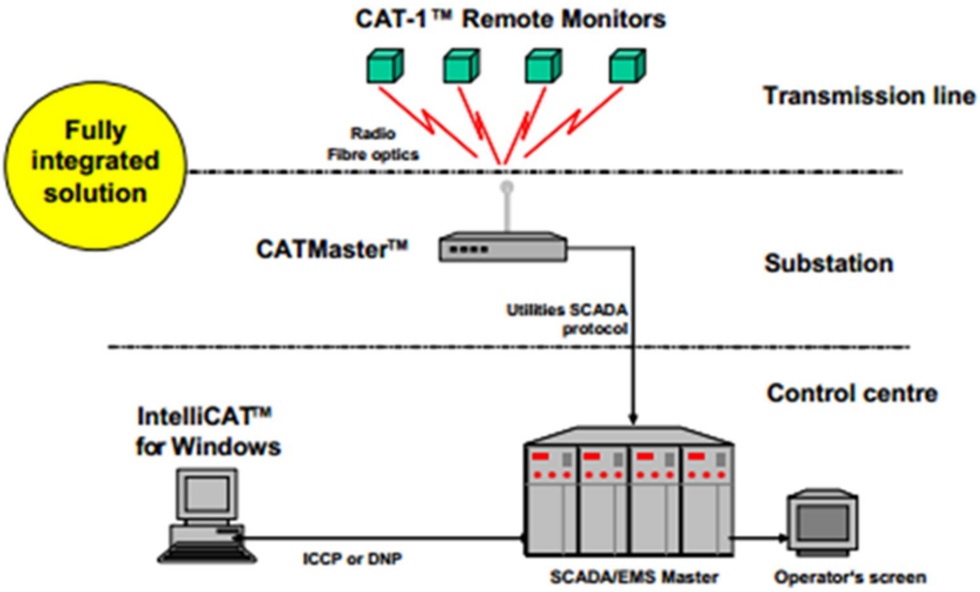

Figure 12. CAT-1 DLR monitoring system communication solution flow chart. [25]

<u>Pros & Cons [33]:</u>
Requires for ruling span method to apply [34] and thus requirements for the monitored span are:

- the span lengths in the ruling span section should not differ greatly
- the insulator string should be relatively long
- most suspension structures of the line should not be angles
- structure should be rigid

6.2.3 Sagometer by Avistar, EDM International Inc.

<u>Background [35],[17]:</u>
The Sagometer line rating system technology was developed by Electric Power Research Institute (EPRI) and sponsoring utilities in 1997. The first utility system unit was installed in 1999. The Sagometer is marketed by Avistar, EDM International, Inc.

According to Avistar, there are over 80 units installed throughout North America.

<u>Method is based on [35]:</u>
The method is using a "smart" machine-vision camera that captures image on target attached to the conductor, and calculates and reports the ground clearance or sag. The camera works also at night due to near-infrared laser illumination. The equipment is shown in Figure 13.

Figure 13. Sagometer camera mounted on a tower (left) and the target mounted on the power line (right). [36], [37]

According to Avistar, the method accuracy for sag is ±15mm.

Price:
(The price for the method was not found out.)

Application, installation, user interface etc. [35]:
The unit is powered by a self-contained photovoltaic system.

The communication system could be selected among a variety of options, e.g. CDMA or GMS network, local radio transceiver, or fiber optic.

GridWatchRT (by EDM) is a web-based data service that can be used for line rating analysis. The Sagometer can also be integrated with EPRI's DTCR package or PLS-CADD.

Pros & Cons [35]:
Extreme weather conditions, such as fog or heavy snow, may compromise the target image clarity and unit operation.

6.2.4 Ampacimon SA

Background [38]:
The Ampacimon company and its DLR monitoring equipment is a spin-off from the University of Liége in 2010. The Ampacimon DLR solution was patented in 2006. The method has been tested and piloted in collaboration with ELIA and RTE in 2008-2010.

According to Ampacimon, there are 35 monitoring sets installed in 5 countries worldwide today.

Method is based on [39],[40],[41]:
Ampacimon smart sensor module is attached directly to an overhead power line (Figure 14), anywhere on the span. It analyses conductor vibrations and detects fundamental frequencies of the span. The sag can be determined from the fundamental frequency with gravity (constant) being the only additional needed

parameter. The accelerometers detect even a slight movement of 1 mm at the lowest frequency for a typical span (e.g. 0.15 Hz).

The Ampacimon equipment determines the line ampacity based on thermal models in accordance with the IEEE and CIGRE recommendations.

Accuracy of the determination is within 20 cm marginal. The verification of method accuracy was done by land surveyor measurements over 4 days on 5 spans with the Ampacimon equipment installed.

Figure 14.Ampacimon sensor installed on the line (with armour rods). [42]

<u>Price:</u>
Ampacimon offers [43] different kind of packages, e.g.

- Module: 20.000 € including configuration but installation done by customer personnel.
- Server: 40.000 € plus 10.000 € per line for real-time measurement and 20.000 € plus 10.000 € per line extra if you want forecasted values. Setup is 10.000 €.
- Hosted service: You can select this option if you do not wish to host the server yourself (quicker and less impact on internal IT org.). 30.000 € per year (including setup) for a project with less than 5 modules, 50.000 € for a project with up to 10 modules.

<u>Application, installation, user interface etc.:</u>
The equipment takes the power needed for operation from the line by means of a current transformer and thus does not require additional power source. Ampacimon has its own predictive model for short term ampacity prediction up to 4 hours (and day-ahead forecasting under development) [44]. See also chapter 7.

Data is initially processed by a data signal processor (DSP) before being sent via GSM/GPRS to a remote server, where it is collated and analyzed to give the appropriate readings for DLR.

<u>Pros & Cons [45]:</u>
The advantages of the Ampacimon equipment are:

- there is no need for calibration
- the equipment does not require external power source

- no need for multiple parameters or variables in addition to conductor vibration frequencies measurement[1]

The Ampacimon equipment requires:
- minimum level of current (> 80 A) flowing on the line in order to operate (however, on low current i.e. low loading of line, usually there is no need for DLR)
- movement of the line (minimum acceleration 100μG corresponding to e.g. 1 mm amplitude at 0.15 Hz)

6.2.5 RT-TLM by Promethean Devices Inc.

Background: [46],[47]:
The Promethean Devices RT-TLM system has been developed by Steven J. Syracuse over the last several years. Over a dozen years ago, Syracuse had developed a conductor temperature sensor for overhead transmission lines and bus bars. That system consisted of hardware and reporting software. Whereas the temperature sensor had to be installed on the conductor or bus bar, the RT-TLM system is totally non-contact, ground-based monitoring system.

Method is based on [48],[46]:
Sensor is placed under ground below the monitored line. However, the exact location of the sensor unit is not critical (within 100 ft. from the cable span nadir). The installation options for the RT-TLM system are shown in Figure 15.

Ampacity estimation of the equipment is consistent with the IEEE Standard 738-1993.

Clearance is determined by ±0.20 % accuracy (e.g. ±4 cm at 18.5 meter phase-to-ground clearance), temperature by ±4.5°C, and phase currents by ±1.0 % (e.g. 8.5 A rms at 1000 A per phase) accuracy.

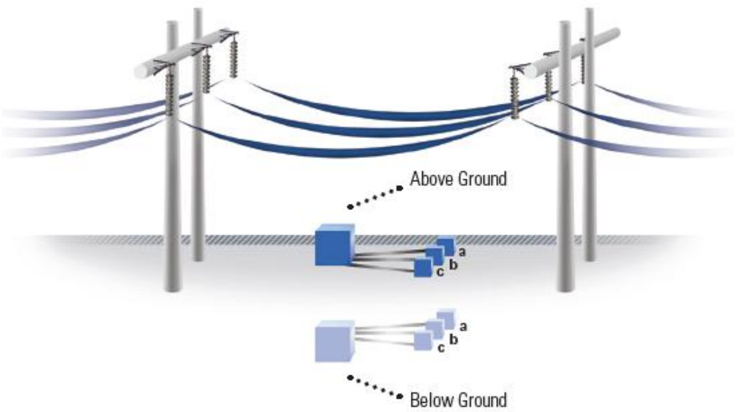

Figure 15. Promethean RT-TLM system installation options. [49]

[1] e.g. even parameters generally considered as being well known may be erroneous, e.g. span length has been measured (155 m) to differ from overhead line plan (162 m) by several meters [39]

Price:
The price for the equipment was not publicly available. The company claims in [50] that “Ground-based system is far less expensive (in terms of total installed/operational cost) than existing, commercial transmission line monitoring and rating products.”

Application, installation, user interface etc.:
Solar powered with battery backup. Communication is done by wireless EVDO (cell-phone) network link.

Pros & Cons [50]:
• Entirely non-contact and non-invasive installation, calibration, and operation.
• Fully secure, real-time communication of data.
• Solar powered with battery backup.
• Remote, autonomous, reliable field-and-forget operation.
• Does not require utility field crew for installation and calibration.
• Does not require outages for installation, calibration, & maintenance.
• Operation and accuracy not affected by rain, wind, fog, smoke, hail, snow and ice.
• Direct burial allows physically secure, subsurface operation.

Requires using land on the right-of-way under the transmission line. Monitoring power lines with multiple circuits and different conductor spatial arrangements complicate the monitoring.

6.2.6 LIOS Technology GmbH

The LIOS real-time thermal rating system is an application for power cables (underground or submarine) and is based on temperature measurement of the cable with distributed temperature sensing (DTS) along the whole cable length [51].

6.2.7 Other methods

There are also other possibilities for implementing direct DLR monitoring, e.g. DGPS [52], [20] or Distributed Temperature Sensors (see section 6.4.7) on overhead lines, but these methods apparently do not have commercial DLR applications available yet.

6.3 Indirect DLR methods

The indirect methods are based on determining the transmission line sag by other means but measurements of the line itself (e.g. sag or temperature). The weather station based methods are indirect methods, but these methods do not seem to be commercialized, or they are related to other means (e.g. see section 6.3.2). Thus weather stations themselves are not covered here.

6.3.1 ThermalRate™ by Pike

The ThermalRate method is based on conductor replicas and determines the line capacity by measuring how the weather conditions heat and cool the conductor ([53],[3]). The replicas are of the same material as the actual conductor, and they are placed close and parallel to the line so that they would experience the same weather conditions as the conductor. One of the replicas is heated with approximately constant wattage to increase the replica temperature. Comparing the temperatures of the heated and unheated replicas, the line capacity is calculated. The method uses Standard IEEE-738 equations. The method has been laboratory tested and the ratings appeared to be conservative in almost all the cases, reducing the risk of overestimation of the rating [54].

Figure 16. ThermalRate equipment. [53]

<u>Price:</u>
(The price for the method was not found out.)

<u>Application, installation, user interface etc.[53]:</u>
ThermalRate Monitor includes a spread-spectrum radio to communicate with SCADA without software changes needed.

<u>Pros & Cons [53]:</u>
With ThermalRate method, the line rating can be determined independently of the actual line loading (which the line tension, sag and temperature monitoring methods do not do at low line loading). This could be useful for estimating N-1 contingency situations, and/or for offline rating analysis.

The method does not measure the line quantities and thus there is no actual verification of the line state. In addition the method is local, i.e. it does not consider the whole line span (combined/equivalent/average) circumstances.

6.3.2 Alstom DLR P341 relay (formerly AREVA) [55],[56]

Alstom P341 relay employs weather station data in determining ampacity or DLR, and is used as a back-up protection for possible line over-loading (line loading exceeding the determined ampacity) in context of wind power integration. In case of line loading exceeding the power line ampacity, the relay can act by reducing the wind farm power output in order to maintain the transmission line loading below ampacity level and maintain transmission reliability or even trip off the wind farm.

Price of DLR relay unit is not much different from typical relay units.

6.4 DLR experiences and research

Over the couple of last decades, there has been research, testing, pilots, demos, and actual use of DLR monitoring and DLR in several locations with a number of commercial methods and equipment. In the following sections, there are gathered brief descriptions of the experiences (attempted to present in chronological order). The coverage is not fully extensive including only publically available information and the emphasis is put on wind power integration related and higher quality cases. In the last section there are gathered and described in a few words additional cases for reference.

The figures quoted by the DLR monitoring equipment suppliers (see sections 6.2 and 6.3) imply that there are numerous more users of DLR and DLR monitoring equipment. However, there may not be (publically) available information on the use of DLR monitoring equipment in these locations/companies, and at least in some cases it may be that the equipment is not actually used for DLR.

It ought to be noted, that there are different kinds of applications of DLR, based on different DLR determination methods. The method accuracies vary and there are different levels of uncertainties involved. Especially in the weather measurement based methods there are large uncertainties involved, and thus often conservative assumptions as well as safety marginals used. It may well be, that the actual ampacity, if possible to be measured (or in case used a more accurate and extensive measurement system), could be even bigger. Therefore the results of different experiences are not directly comparable.

6.4.1 San Diego Gas and Electric, California [57]

Feasibility and reliability of using real-time line ratings were tested in California in the late 1990’s. A CAT-1 unit was installed on one key 230 kV transmission line that limits import capability into the San Diego Gas and Electric (SDG&E) system. The monitoring data was passed to SDG&E energy management system (EMS) as information for the system operator and to be used in operation decision making.

The test project indicated that the monitored line could have 40-80 % more power transfer when using real-time transmission line ratings instead of static ratings. It was also concluded that implementation of real-time transmission line ratings could result in significant capital cost savings in deferred transmission line projects and improved usage of existing generation resources.

6.4.2 Eon Central Networks UK, Skegness-Boston [58],[59],[60],[61]

In the Skegness area in North-East of England, there are several wind farms currently existing as well as planned. The area is connected via a 132 kV dual-circuit 40 km connection to Boston. The connection was originally designed to supply relatively small load in the area, but the wind power production is expected to cause large reverse power flows.

Since fall 2008 Eon Central Networks UK is using automatic calculation based on CIGRE 207 [6] of the Skegness-Boston dynamic line rating based on local weather measurements. There are two weather stations connected to the Skegness line end, and one weather station located at the Boston line end. All the weather stations feed into the load management system. Due to the varying wind direction, a conservative assumption of 20° angle between the wind direction and the line is assumed. In addition there is also a safety margin used in order to take all ambient condition uncertainties into consideration (i.e. the relay ampacity is lower than actual determined ampacity).

Additionally there are four Power Donut™ units (see section 6.2.1) in three locations on the line for direct monitoring of the line temperature.

The system takes actions in two levels as needed to secure operation:
1. when line current reaches certain percentage (e.g. 95 %) of dynamically calculated ampacity, a signal is sent by the load management system to the wind farm generators to reduce power
2. as back-up, in case the wind farm output power is not reduced, the protection relay (by AREVA, currently Alstom, see section 6.3.2) will trip a wind farm after a time-delay

The line temperature measurements have been used for comparison of line temperatures based on the calculations from weather measurements, and they have been reported to have rather good correspondence with each other.

According to [58] the employed DLR monitoring on the Skegness-Boston line enables 20-50 % more wind generation to be connected to the grid.

6.4.3 Elia, Belgium [62],[63]

The Belgian TSO Elia has implemented DLR analysis on its 70 kV network in South-East Belgium using the Ampacimon DLR monitoring devices (see section 6.2.4) in order to allow more distributed generation to be connected in the region, and minimize the curtailment of the wind farms and other distributed generation production.

Calculating the available connection capacity in this area in the traditional way, the transmission capacity is fully utilized and there is no room to connect new wind power plants, for which there are significant amount of connection applications. Refusing connection is not an options and grid reinforcements are not possible in the timeframe and budget in question. The existing distributed generation has firm connection contracts, and cannot be contractually curtailed.

The new wind farms would be connected to the grid with the right for the TSO to curtail wind power production via Active Network Management (ANM) as needed and automatically to guarantee safe network operations at all times. The suggested/applied ANM solution is described in more detail in [63].

The Principles of Access (PoA) would define the rules according which DG units having conditional access to the network will be curtailed, when there is a need to decide among the units which unit would be curtailed. The possibilities are:

- Last In First Off (LIFO): the last unit connected, would be the first one to be curtailed or tripped off;
- Technical optimization: generators are curtailed for their output to be compliant with network constraints and minimize or maximize a given parameter (e.g. injected energy);
- Shared percentage: generators are curtailed the same percentage e.g. of their installed capacity.

The curtailment method to be used will probably be according to the shared percentage method proportional to the output power at the time of the transmission is constrained.

An Ampacimon device installed on an ELIA 400 kV line and measuring from July 2008 to November 2009, shows that the actual ampacity was much higher than the static rating, most of the time even by 25 % [41] (see also. Figure 17). The ELIA lines with Ampacimon devices have been pilot cases in the EU Twenties Transmitting Wind research project [64]. Also the French TSO RTE has been involved in similar case studies with Ampacimon equipment installed in Bretagne, costal region of west of France.

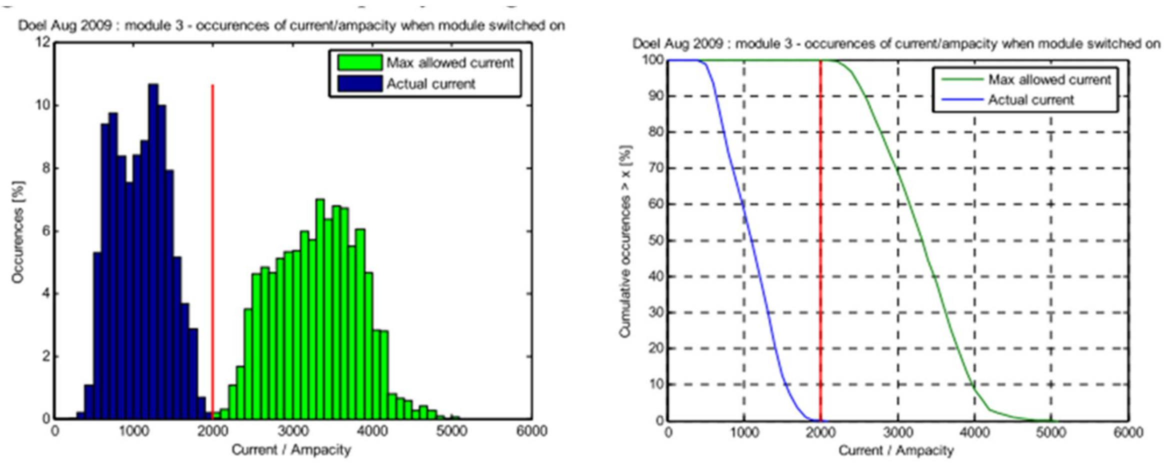

Figure 17. Ampacity histogram of ELIA 400 kV (twin bundle) line during August 2009, and cumulative occurrences of actual current and available capacity.[41]

6.4.4 Germany

A German TSO Amprion GmbH (operating on the western parts of the country) carried out a pilot study on DLR by two separate DLR determination methods based on measuring conductor surface temperature and weather station measurements [65]. Statistical data analysis of almost two years of measurements showed that on the measured lines, the conductor temperature was 30 % of the time below 10°C, and only 10 % of the time over 30°C. The conductor temperatures varied between -10°C and 50°C covering the whole allowed current range between 0…100 %. The common conductor temperatures are thus far below the permissible limit of 80°C, and there is potential for increasing ampacity by overhead line monitoring.

There were defined the necessary measures to be taken in order to increase the transmission capability of grid part in question in the German study. The workflow is shown in Figure 18.

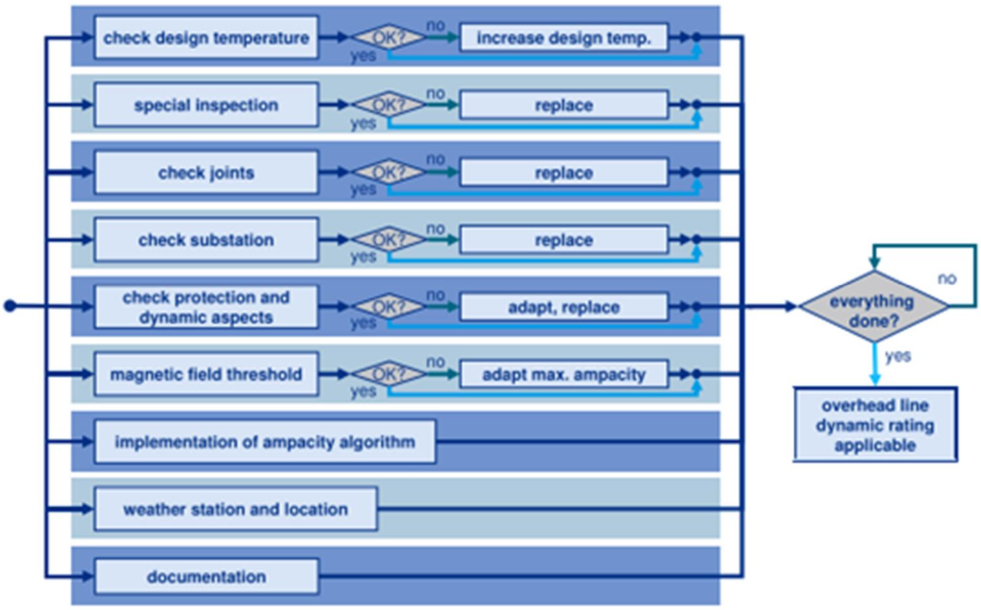

Figure 18. Workflow of necessary measures for dynamic line rating implementation. [65]

There is a need for transmission capacity increase in the North-South 380 kV connections between Hamburg and Frankfurt (see Figure 19) to 3150 A. Based on weather data measurements, duration curve of available ampacity is plotted in Figure 19, and it shows that 3150 A transmission is possible 80 % of the time.

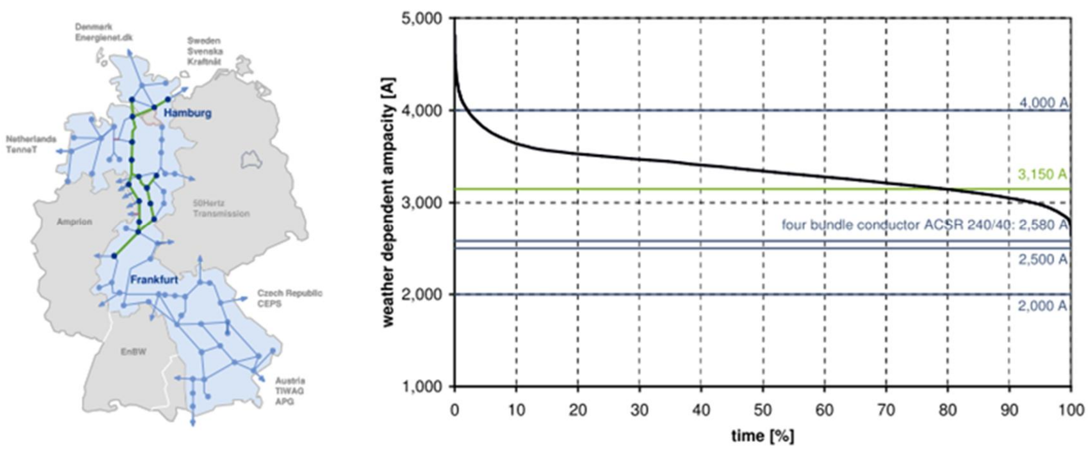

Figure 19. Important North-to-South connections on a German TSO TenneT grid between Hamburg and Frankfurt that are aimed to be utilized more efficiently before building new lines. The duration curve shows the available ampacity with DLR based on weather data assessment. [65]

6.4.5 New York Power Authority and EPRI, New York [37],[66]

In a project initiated in 2010 between New York Power Authority (NYPA) and EPRI (Electric Power Research Institute), the effects Dynamic Thermal Circuit Ratings (DLTR) are demonstrated. Use of real-time thermal rating measurements were used to analyze increased transmission capacity availability to increased wind power generation.

DLR was implemented on three 230 kV transmission lines using four different technologies

- EPRI's Conductor Temperature and Load Sensors (EPRI Sensors) for conductor temperature and current measurement
- ThermalRate systems (see section 6.3.1)
- Sagometers (see section 6.2.3)
- Weather stations to monitor relevant weather variables

The project has ended in 2012, but apparently the final report is not available yet.

6.4.6 Oncor, Texas [67],[68]

The Oncor Electric Delivery Company in Texas, USA, is conducting an extensive Smart Grid Demonstration Program (SGDP) aiming at removing constraints that prevent utilities from using dynamic line rating (DLR) technology. Reliability is the paramount to the control rooms, regardless of the economic values. In order to get control rooms use DLR system, it must be reliable, accurate and logical.

The project has started in 2010 and the will be completed in March 2013. A technical performance report has been published in the end of 2011, in which the information of the project (and results) described here is based.

DLR technology was installed to provide dynamic rating on eight transmission lines in central Texas where there are constraints in North to South power transmission. 19 CAT-1 load cells were installed on 345 kV lines and 26 load cells on 138 kV lines on the total of 8 lines. The ample monitoring will be used to determine optimum deployment of instrumentation.

Validation and accuracy assessment of the DLR technology is part of the project. Therefore secondary monitoring systems are installed parallel to the primary CAT-1 units. Two different technologies are used as secondary units, the Sagometer^{TM} (see section 6.2.3) and RTTLMS by Promethean (see section 6.2.5).

One of the concerns in DLR is about persistence of DLR, i.e. how long the increased rating would be available, e.g. only a few minutes or several hours. A longer duration lower DLR value is more valuable than a higher short duration DLR peak value. The study is looking also at DLR persistence.

In order to evaluate the economic benefits of utilizing DLR, various measureable quantities would be used (see Figure 20).

Metrics Derivation

Real-time Measurements:	Line Tension	
	↓	
Real-time Parameters Derived:	Conductor Temperature → Sag → Real-time Ground Clearance	
	↓	
Real-time Line Rating:	MW	[Load to Match Minimum Clearance]
Constraint:	Baseline Rating exceeded by actual loading or n-1 contingency load	
Transmission Constraint Relief:	MW -	Real-time Rating – Baseline Rating
	t -	Duration of increased capacity
	Mw-hr -	Mw x t
	↓	
Economic Relief	$^{1}	Mw-hrs x Congestion Shadow Price

Figure 20. Metrics Derivation for various measureable quantities to define the benefits derived from dynamic line rating. [17]

6.4.7 Other studies and experiences

In the mid-1990's Hydro Tasmania used a self-made and harsh system for dynamic line rating to maximize N-1 transfer capability of some circuits [69]. This procedure led further installing CAT-1 units on several circuits, and also using regional weather stations to determine ambient conditions and thus line rating.

A Brazilian utility CEMIG (power producer and electricity distribution company) has compared the CAT-1 (see section 6.2.2), Power Donut (see section 6.2.1) and Sonar technologies [70],[20].

The Portuguese TSO Rede Eléctrica Nacional, S.A. (REN) has tested CAT-1 system (see section 6.2.2) starting in 2004/2005, and in 2010 the FiberSensing System that monitors the line temperature (see Figure 21) [71]. The FiberSensing System was giving lower temperature values than actual temperatures.

Figure 21. FibreSensing system installed [71].

The Spanish TSO Red Eléctrica de España REE and IBERDROLA have made studies on how to implement real-time thermal ratings in 400 kV Spanish transmission network by means of weather stations [72].

As part of the TWENTIES project, requirements for design, construction and implementation for a new Real Time Thermal Rating (RTTR) system, based on Distributed Temperature Sensors (DTS), were defined [73], [74]. The system measures line thermal behavior over the complete line instead of single point, and calculates the maximum load that could be transmitted through the line. The study perspective is RTTR and its mitigation impact on evacuating wind power production.

Vattenfall experimented weather station based line rating method on two 130 kV lines in southern Sweden in 2010-2011 and it was reported in a Master Thesis [75]. The measurements included also line temperature and sag measurements. The research for real-time monitoring was to continue in 2011.

DLR monitoring has been implemented also e.g. in Denmark (by ELTRA), Colorado, USA (New Century Energies, Inc.), Portland, USA (Portland General Electric) and New Zealand [16].

7 Forecasting DLR

Having a reliable DLR monitoring and determination method installed on the critical power lines, the power system operator is able to monitor that the specific power line is actually operating within safety limits in real-time. It may, however, be essential to know beforehand how much power flow can be allowed on certain connections, e.g. to provide transmission capacity to the power market in advance and identify transmission constraints and bottle necks. Therefore forecasting DLR becomes an important issue.

DLR forecasting was discussed already in early 1990's [76]. The method in question consisted of ambient temperature forecasting, which alone can bring considerable increase in transmission line ampacity. There was identified that the forecasting should have the following qualities

- 24 hours ahead prediction with high certainty
- thermal limits must not be exceeded
- automatic update of ampacities in hourly bases
- forecasted ampacities printable on a single page
- user friendly, high reliability system that is menu driven.

The Ampacimon DLR system includes also forecasting of the DLR in short term (i.e. a few minutes to few hours) using historical records. Also long term forecast (up to 2 days) is possible by using machine learning algorithms to analyze historical records and weather forecast. [42]

In the TWENTIES project Demo case was concluded that the probability for the wind speed perpendicular to the inland power line being < 2 m/s in case the wind speed in offshore wind farm is > 10 m/s, is very small (5 %). [44]

The forecast errors of short term DLR forecasting (1h/4h) of Ampacimon system DLR demo in Elia grid in Belgium (in Twenties research project) are given in [42]. The DLR forecasting in short-term 1h/4h was on the safe side (i.e. underestimated the DLR) 98 % of the time with maximum error of 10 % (of the static limit) in the line rating. Only 2 % of the time the forecast overestimated DLR (i.e. could lead into unacceptable rating of a line) with up to 20 % of static limit.

In (long term) DLR forecasting, the final objective is not to forecast weather variables, but to make a wise use of them to predict a highly useable ampacity one-day ahead. It is essential to know when to trust the prediction and when not to trust it. If the prediction has a high uncertainty, it is possible for TSO to choose to plan its operation in the most conservative way using static security limits. [42]

CAT-1 by Nexans also has forecasting included in short-term, as well as possibility for longer term (e.g. day-ahead) forecasting, but there are no publications available on this.

DLR forecasting itself and forecasting errors, do not jeopardize the power system operation reliability. It allows the power system operator to have estimation of the available ampacity on certain power lines at certain time ahead. The physical power flows, or the intended power flows, may not approach the forecasted ampacity at all times, but only sometimes. There should always be the DLR monitoring system on the lines using DLR, based on which measurements the lines in the end are operated and thus maintaining the system operation reliability. At times, in case of errors made in the DLR forecast in optimistic line ampacity direction and high power transfers coinciding, the need to curtail and/or redispatch power transfer and generation is faced.

8 Requirements for and impacts of employing DLR

There may be economic, technical, authority and society impacts and requirements involved when discussing about maximizing power line capability by employing dynamic line ratings. These issues are discussed in the following sections.

8.1 Requirements and laying prerequisites

One of the contributing factors in the 2003 North American blackout, was the fact that wind did not blow as assumed by the defined static ratings, and the risk involved in the static ratings (see Figure 1) became real [77]. Since 2003, the reliability rules of system operation in North America have been substantially tightened [20] and NERC (North American Electric Reliability Corporation) rules specifically allow use of real-time ratings.

Generally the time it takes to build new power lines is rather long – although in Finland not quite long yet as in densely populated Central Europe (where it may take 5-20 years to build a transmission line starting from identification of the need for the line). Building high voltage power transmission lines is subjected to permit application for specific power line and approval by authorities. Even in Finland, there have been signs lately of decreasing public acceptance towards new power lines [8]. Appeals may prolong power line building processes. Adapting DLR as a means of employing existing power transmission assets more efficiently – and maintaining high reliability or even increasing it – could serve also as a way to enhance public image. Using DLR would also reflect the essence of the idea of Smart Grids.

8.2 Economic impacts

In [16] there was pointed out that traditionally transmission line investment were done in a straight forward way: the generation and power marketing were part of the same integrated system as transmission ownership, and thus the grid reinforcements were done in economical way. The lifetime of the need for transmission line was possible to be assumed to be approximately the same as the lifetime of the line itself. Today a major difficulty related to transmission line decisions is uncertainty of load flows, as power generation and marketing entities are different from power transmission infrastructure owners. The lines with physical lifetime of over 50 years may now be invested on and operated under (guaranteed/reliable) economic horizon of only a couple of years.

Something similar related to this has happened also in Finland: the transmission lines on which Fingrid has the CAT-1 units, were earlier more loaded (the reason for installing the CAT-1 units there), but today the power flows on those connections are rather low due to changed power flows as there was built new parallel transmission connection.

Transmission line investments are generally long-term and permanent investments (i.e. several decades, the transmission line structures e.g. 50 years, the right-of-ways even longer). Power lines are rarely dismantled. DLR monitoring equipment is less expensive investment, and it can be moved to another location in case becoming obsolete on certain lines.

In operation of DLR there can be expenses in terms of increased work for the operating personnel compared to the use of static ratings. In addition, DLR forecasting could create expenses, in case forecasting is found necessary.

DLR forecasting is used to avoid situations when actions need to be taken i.e. to reduce power flows, redispatch generation or curtail (wind) power production. In case or errors in DLR forecast, these situations may occur at times, and have a price. It needs to be defined who covers these costs under what conditions.

8.2.1 Savings and benefits

Power line design and investment planning contains also economic considerations in order to minimize the (foreseen) transmission costs. These are generally expressed for transmitted MWh over a distance (e.g. 100 km) [1]. There are used several figures and terms, e.g.

- fixed annual costs in EUR/km,year
- power losses (kW/km) and related costs in EUR/km,year
- annual utilization period (quotient of the total energy transported during a year).

Using DLR might result in that less new power lines would need to be built [57]. These savings could be considered as improving the existing power line infrastructure efficiency and profitability figures (see above). It would also result in savings in the land area and thus also decrease environmental impact or power lines. According to [57] the power line right-of-way for a typical 500 kV transmission line corresponds 24 acres of land per mile (appr. 25 are per km).

In [16] there was done some comparison of the cost of employing DLR with tension based DLR monitoring method compared to other alternatives (e.g. upgrading connections). Often reasonable amount of increased transmission capacity could be achieved by using dynamic line rating, and it would pay off with a few hundred hours of increased line capacity use.

8.2.2 Costs and drawbacks

Using DLR and loading the lines more, may result in the lines aging a bit faster. Already Davies considered the line thermal history on the line lifetime in context of loading the lines according to their real-time ratings [18].

When monitoring the DLR, and the line rating allowing more power be transmitted, other network components (e.g. breakers, transformers) may become the transmission limiting factors before the line ampacity. Possible limitations of these other components must be checked and there may be a need to consider if these other network components would be ungraded.

Outages for DLR monitoring equipment installation usually is very short (up to few hours) and most of the installations are possible to do as live-line installations. Upgrading other line components to be enable increased loading of the line, may cause short interruptions.

Using DLR may result that the lines are used more often closer to the actual limits, and closer to the conductor maximum temperature (e.g. 80°C, defined by standards). Temperature increase of the conductor does not have very significant impact on the losses of power transmission in normal operating temperatures (see Appendix 1), so the transmission increased losses are mainly influenced by the current (not that much by increased line resistance). Also many HTLS conductors have quite similar resistance over the same temperature range of the regular (e.g. ACSR conductor) and the resistance increase due to temperature takes place at higher temperature. Therefore, in case the line capacity is limited by N-1 criterion and there is a need for increased capacity, the possible losses may not be significant issue when comparing different alternatives (i.e. the higher temperature operation would take place only rarely in N-1 situation).

In terms of losses the different options for increasing transmission capacity could be compared (see Figure 22), i) using static ratings and building a new line, ii) re-conductoring the line with HTLS conductor (increased resistance at high temperature operation range) and iii) the original power line with DLR (provided that DLR is used and satisfies the increased need for transmission capacity).

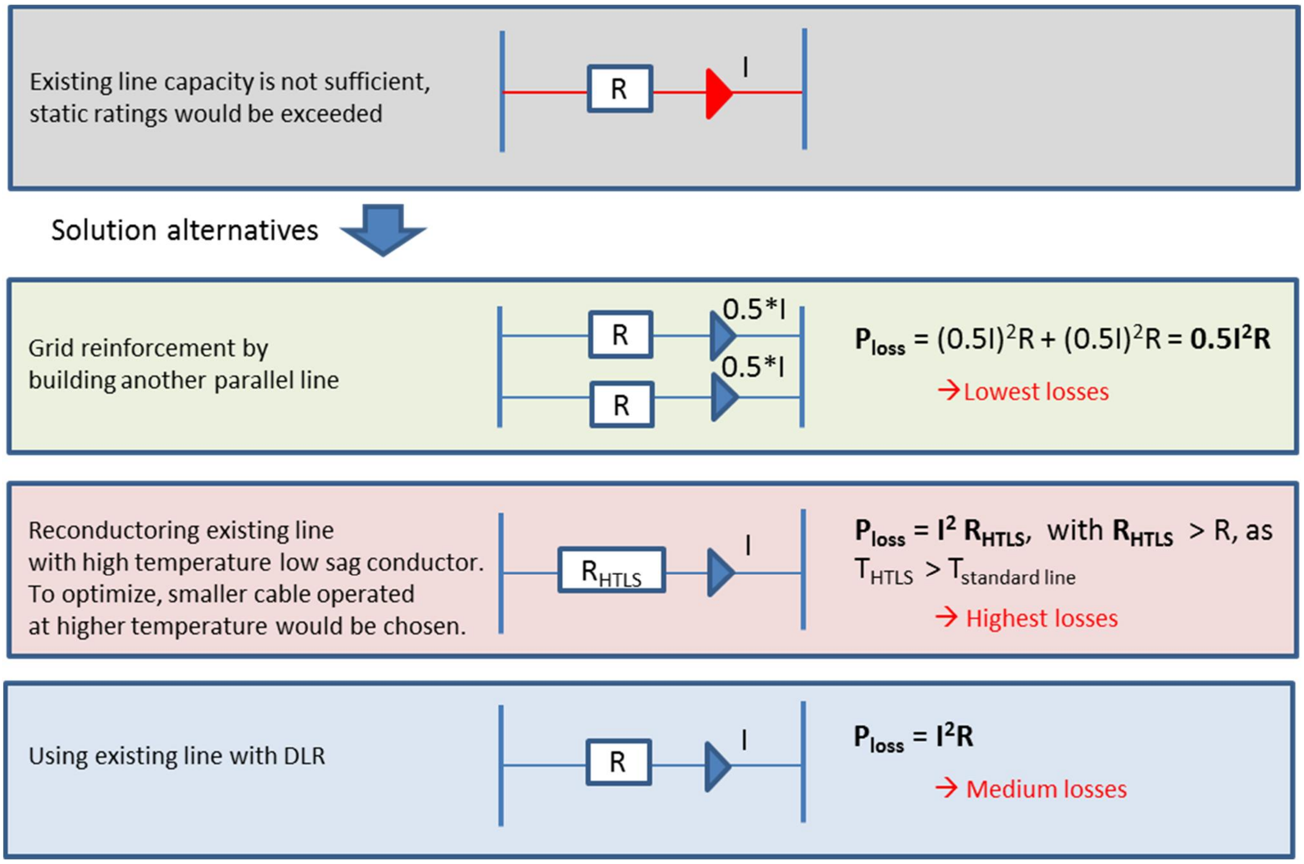

Figure 22. Comparing losses of different options increasing transmission capacity in normal operating states with N-1 limitations.

8.3 Electro-technical and operational impacts

The DLR monitoring method needs to be selected carefully according to the method quality, as well as considering the method applicability, communication and monitoring interface in the power system control room.

8.3.1 Selecting the DLR monitoring method

The different DLR monitoring methods may have different accuracies, and thus e.g. the indirect methods may have larger safety marginal in the defined DLR due to higher uncertainty. Bigger marginals also limit the increased capacity to lower level, and thus benefits are may be smaller than with higher accuracy methods.

The DLR monitoring systems and units – even the more expensive ones – are not really expensive and their pay back themselves quite fast when the investments are correct. Therefore the comparison of the method and equipment to be selected could be done more based on the technical and operational aspects.

Clearly it might be good to use the selected technology solution in all DLR monitoring locations instead of mixing different equipment technologies. In addition the staff being obliged to master more than one technology, there might be compatibility problems with multiple interfaces and communication systems etc. It may be far-sightedly wise to select a method or equipment supplier in the first place that easily enable a change to another DLR monitoring method/supplier later on (for any imaginable reason) and maintaining system compatibility.

Easy to use, low maintenance, high reliability, reliable communication system, easy to use and clear user interface to control room are some of the features to value in method selection.

8.3.2 Contingency criteria

Often when transmission is getting limited on a power line by line ratings, there is N-1 contingency criterion involved. It means that the line rating is not being approached by the actual power flow on the line in a normal transmission situation, but in case of an N-1 contingency situation (e.g. loss of parallel connection) line loading would be increased so that the rating would be exceeded.

The line power flow is limited to a lower level for N-1 security reasons, taking into account that the line rating would not be violated in case of an N-1 contingency situation. This procedure may require some action to reduce the line loading in normal operation state.

With DLR monitoring, the actual line rating could be known, and it may well be that it is higher than the static rating. Thus the operator can avoid being forced to take corrective actions (compared to the case when relying only on static “book” ratings) and only take them in actual need (by monitoring actual ratings).

As stated in [16], a thermal contingency situation is real only if
i) the limiting cooling conditions exist simultaneously
ii) at the same time the contingency happens, and

iii) the contingency lasts long enough for the conductor to reach high enough temperature to cause (a threat of) clearance violation.

There are low combined probabilities involved (i, ii and iii above individually), as well as time (iii above). Thus the TSO using DLR on transmission connections used for wind power evacuation, can soften the wind farm connection criteria, and limit the wind farm power injection by N-situation instead of N-1 criterion [62]. In case of a contingency incident, curtailment could take place by using Active Network Management (ANM). This procedure could alone increase the available connection capacity by nearly 75 %.

The different aspects, the capacities and time, related to potential line rating use are gathered in Figure 23.

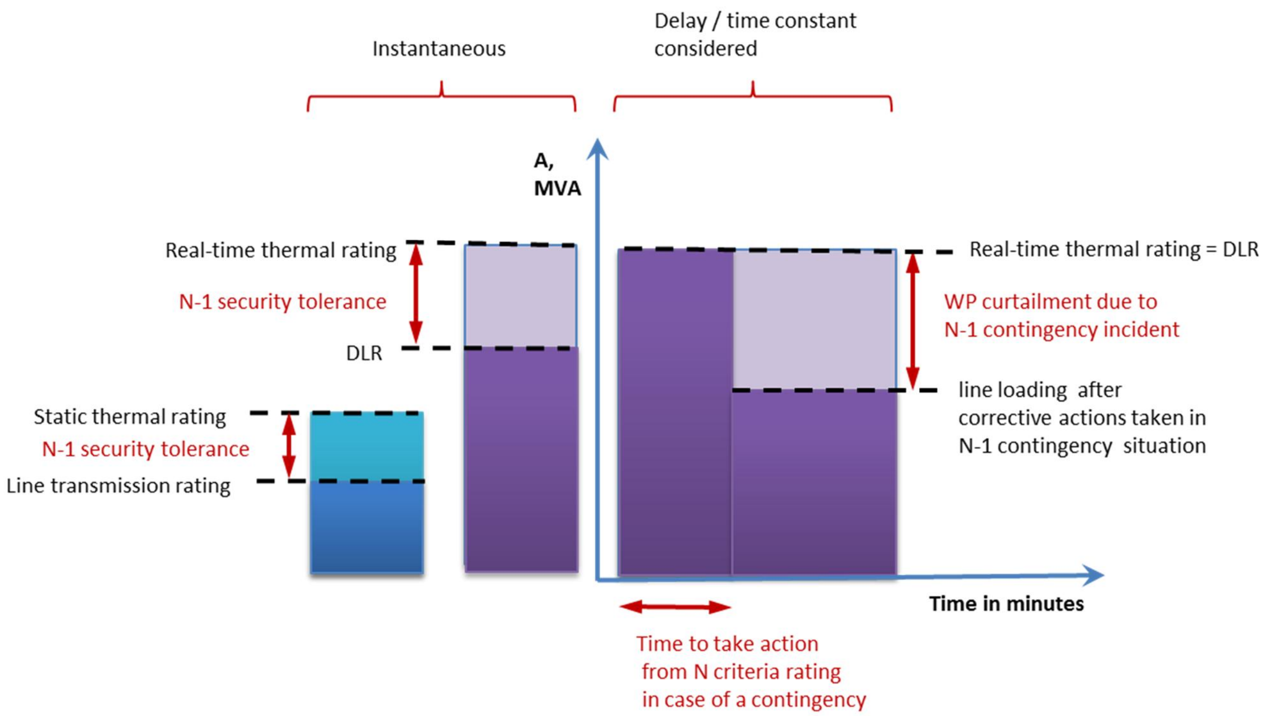

Figure 23. Schematic comparison of traditional static line ratings combined with N-1 -security criterion to ways of utilizing DLR i) in static/instantaneous mode, as well as ii) N-security mode with action to be taken within time constant limits in a contingency situation.

Many of the DLR monitoring methods do not give accurate estimation for DLR in case of low loading of the monitored line – generally, the higher the line loading, or closer to the DLR the line is loaded, the more accurate DLR value is. Normally this should not be problematic, i.e. at low load there is no risk of overloading the line. However, there could be a special situation in case of an N-1 contingency, when this low loaded line would get highly loaded, and it would be essential to be aware of the post contingency (N-1) ampacity for this particular line.

8.3.3 Impacts on stability and grid strength

Adding power transmission lines into the transmission system benefits more or less the whole system and improves its reliability in many ways. Therefore the benefits an added individual power line – especially the lines in the meshed grid – cannot only be evaluated by its impact on power transmission capacity between points A and B. Increasing power transmission capacity between these points A and B by DLR on the existing connections without building new lines may lack these other benefits.

In case there is a need for more transmission capacity for a connection, and the options are i) grid reinforcements and ii) increasing the existing transmission line capacity with DLR, stability issues may also play a role in decision making. [65] In case the DLR option is chosen and exploited, it means that the system angle stability (or generator rotor angle stability) limit is approached, and the stability simulations may need to be run to check stability.

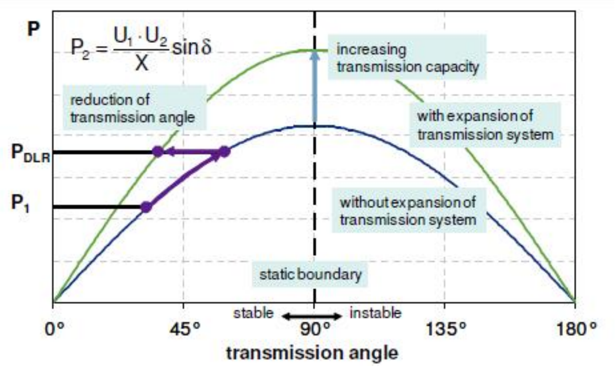

Figure 24.Transmission angle as a function of the transmission capacity (DLR – Dynamic Line Rating) Where P_1 is the feeding power and P_2 is the load power, P_{DLR} is the increased feeding power using dynamic line rating, U_1 and U_2 are the voltages at the beginning and the end of the line, and δ is the angle between current and voltage. [65]

9 DLR and wind power integration – implementation in practice

The transmission line capacity theory and DLR determination methods are one thing, and actual practical application of DLR and running a power system in real-time with high reliability, is another thing. When there is also a power production unit (e.g. wind farm) and thus another power system actor in addition to the grid operator involved, there are many variables that must be made to work together seamlessly. In [19] is stated that probabilistic planning combined with deterministic operations, can increase transmission capabilities by 20-30 % with 99 % availability and 100 % safety. Using DLR may not only make planning and operation more complicated, but also increase safety and awareness, in addition to intensifying the existing grid asset use.

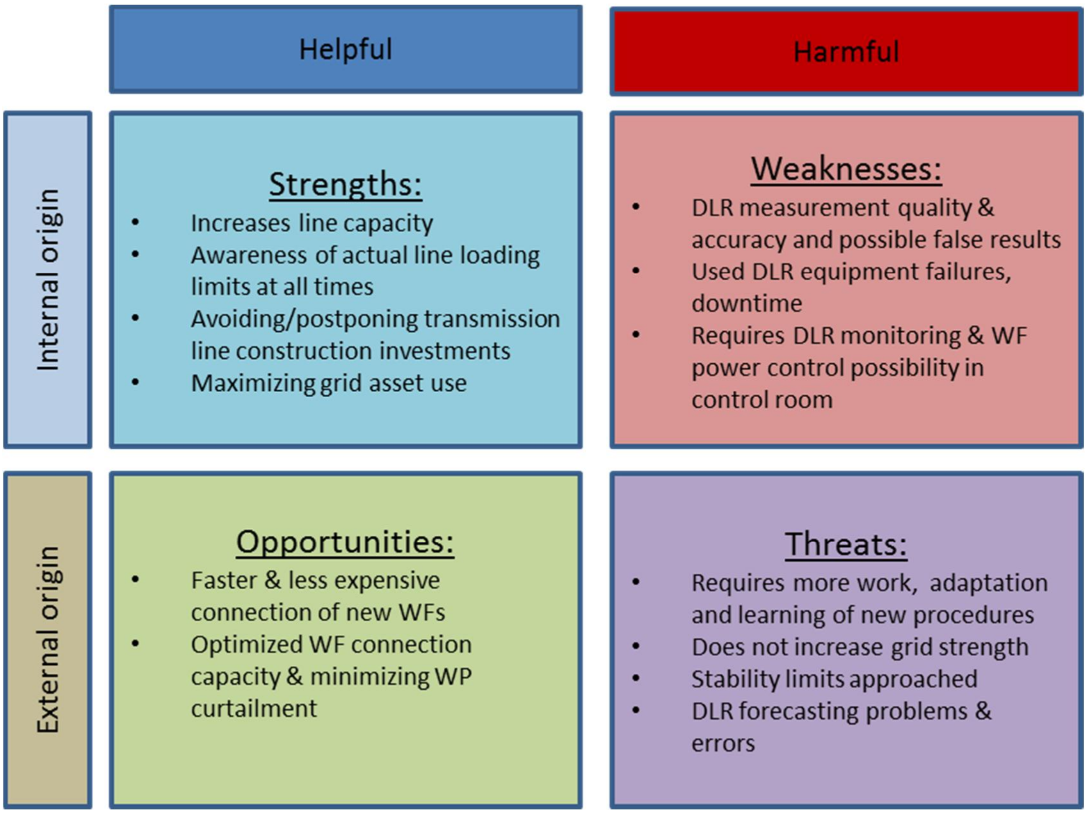

Figure 25. SWOT-analysis for DLR monitoring and utilization related to wind power connection to power system.

For the TSO operating the meshed grid, the cases depicted in Figure 26 could be relevant to consider related to wind power grid connection and operation with employing DLR to maximize power line capability.

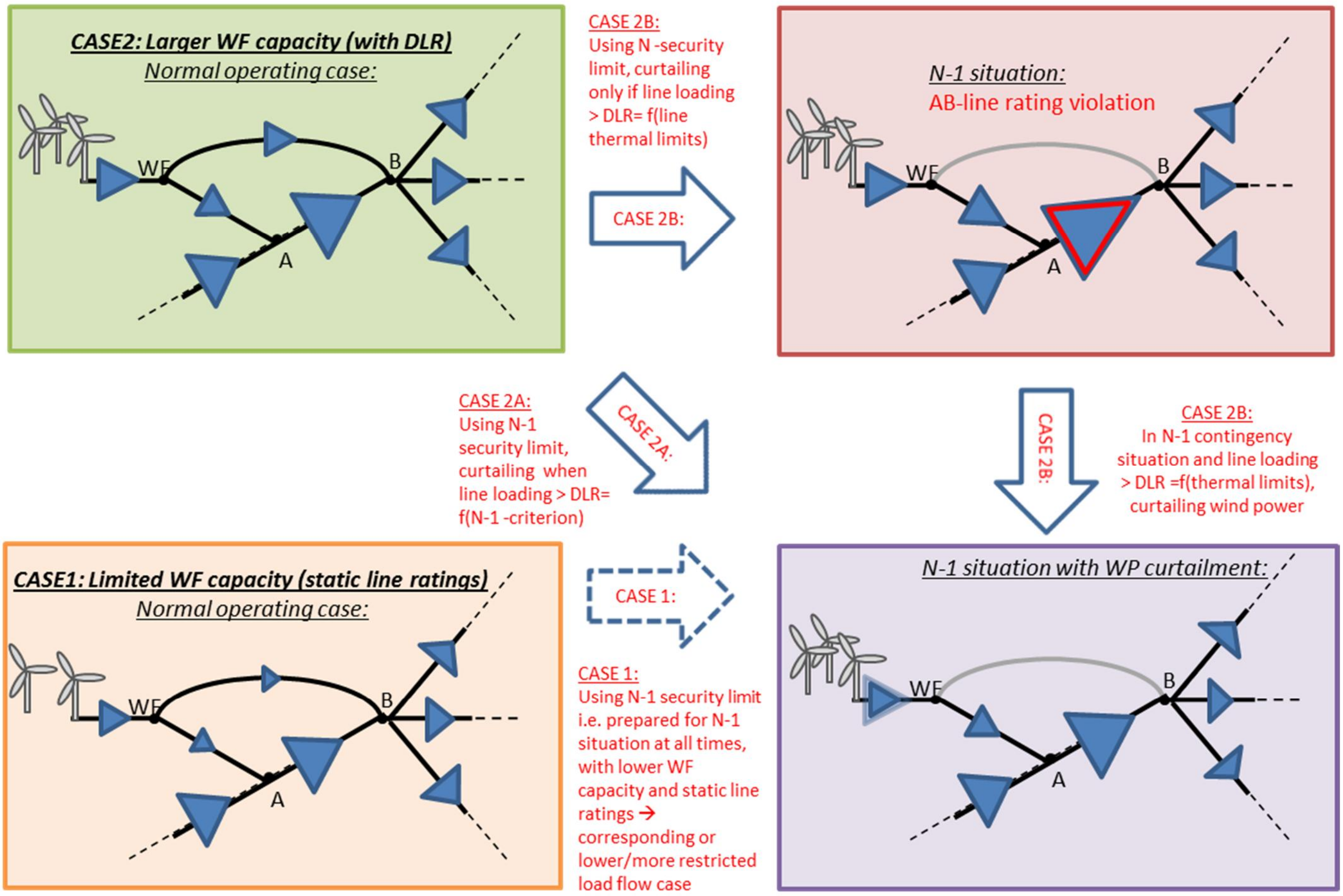

Figure 26. Wind farm grid connection options (in terms of capacity and connection rules), DLR in terms of N and N-1 criterion and wind power curtailment compressed in a diagram depicting important load flow situations.

The selection of the DLR monitoring method should be given consideration from several perspectives. The method accuracy (in case evaluating the direct methods with each other) may not be the most significant feature, whereas most of the methods are within the same accuracy range.

For the application of DLR, a detailed procedure guidelines, connection rules and conditions for the wind farms (including curtailment option and conditions) need to prepared and defined. The procedure should be automated as far as possible.

The different TSO departments must be involved, e.g. planning, design and operation room. It has to be clear that if you have a DLR monitoring system, you know the system accuracy and are able to trust it. But e.g. in case there is no signal, the DLR system fails in any other way, or the operator suspects something, there is option to have a relay as back-up to trip wind farm, and even always possibility to plan to switch on the static rating in real-time operation.

DLR monitoring equipment is a grid component whereas any other grid monitoring device. Its failure consequences should be treated similarly.

10 Analysis of the Fingrid CAT-1 measurement data

About a decade ago, Fingrid has installed a CAT-1 measurement unit (2 load cells) in Lappeenranta Simolantie (see Figure 11 and Figure 27) for a horizontal twin conductor in two phases of a double circuit line. The objective was to monitor the lines more carefully in case one of the lines is off due to maintenance work or contingency. In this kind of situation, the remaining line could have been operating close to static ratings.

Figure 27. CAT-1 load cells installed between the tower structure and the insulator strings on the further-most phases of the two circuits. Simolantie, Lappeenranta.[31]

There have been done changes in the structures in late 2000's and the loading of the lines has decreased as well due to new parallel transmission connection. There has been measurement data available again for the full year 2012. The CAT-1 supplier Nexans analyzed the Fingrid CAT-1 measurement units' data now briefly for this report.

There is measurement data available for several shorter time periods between the years of 2001 and 2004. The monitored line sections have not been calibrated[2] at that time. Thus the CAT-1 did not determine ampacities or DLR.

Calibration for the data ought to be done separately for 2001-2004 and 2012 due to changes in line structures done between these measurement data periods. The measurement data show that between 2001-2004 and 2012 data, the tension has changed in each of the two monitored line sections and also the tension difference between the two monitored sections has increased. The tension readings as function of net radiation temperature (NRT[3]) of 2001-2004 data are plotted in Figure 28, and of 2012 data in Figure 29.

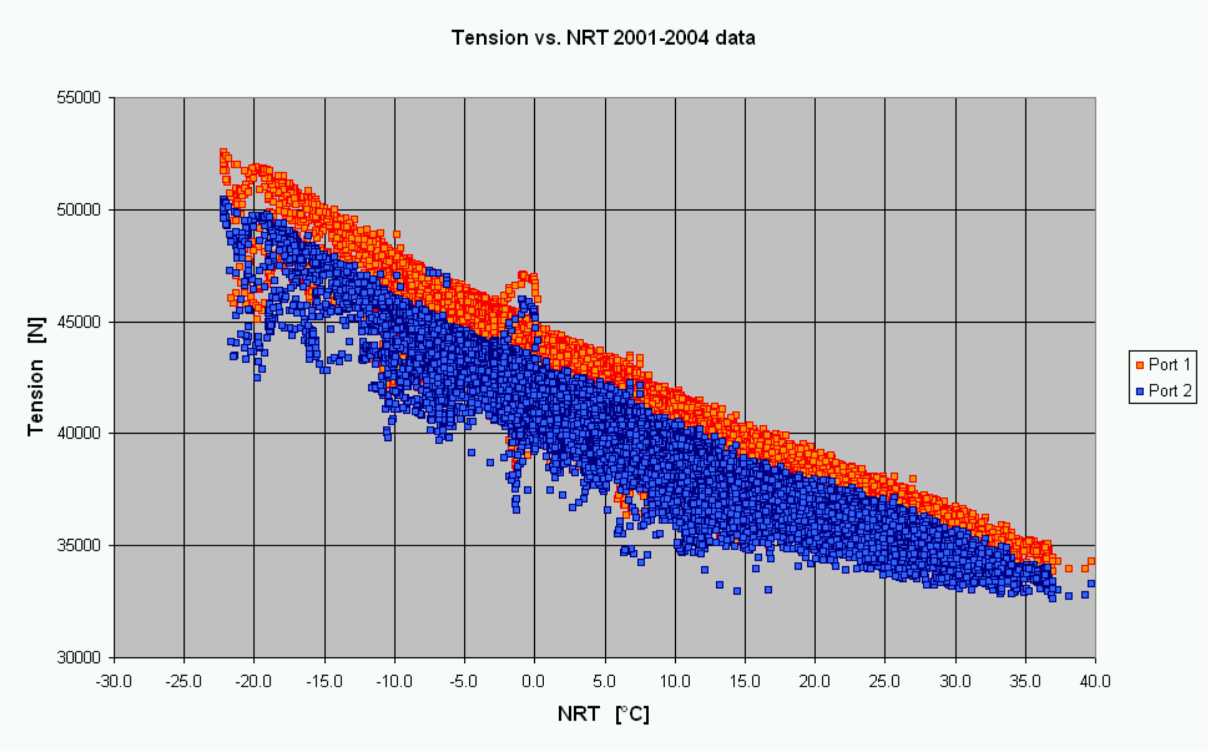

Figure 28. 2001-2004 CAT-1 measurement tension data as function of net radiation temperature data on two parallel lines (Port 1 and Port 2) at Simolantie measurement location.

[2] I.e. the as-built relationship between conductor temperature and mechanical tension was not known and the calculations were based on the well-known theoretical formula. It is known from many projects and practical experience that there could be a huge discrepancy between the theoretical and real relationship between these two parameters and consequently in the conductor temperature and thermal capacity of the line. CIGRE has recommended in [20] to adjust the theoretical relationship of conductor tension and temperature by field measurements. The sag of the ruling span can directly be calculated based on the tensions measured by CAT-1 so that minimum clearance can be maintained at all times.

[3] Net Radiation Temperature, also called Solar Temperature, is the temperature of the conductor when it carries no electrical current. During the summer, solar temperature may exceed the air temperature by 5°C to 10°C depending on the wind conditions and the conductor emissivity and absorbtivity. [20]

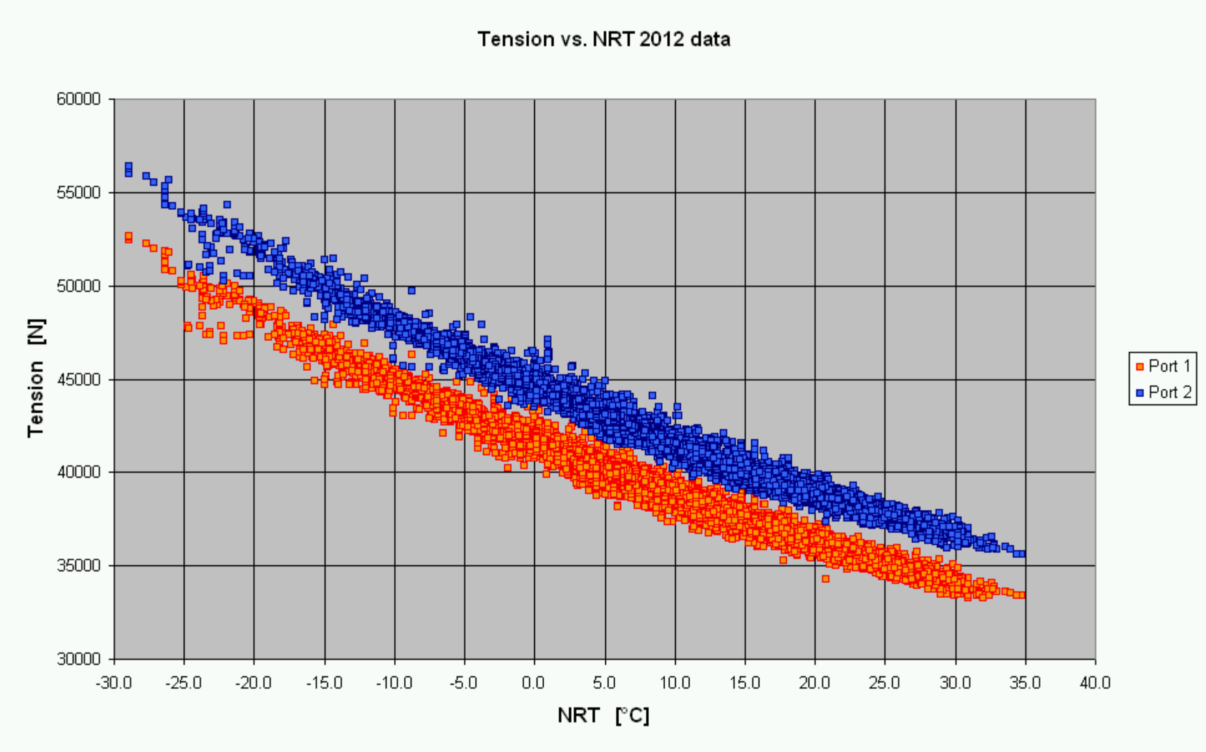

Figure 29. 2012 CAT-1 measurement tension data as function of net radiation temperature data on two parallel lines (Port 1 and Port 2) at Simolantie measurement location.

For calibration some additional information is needed that was not available for this data analysis, and in Figure 30 is shown only an estimated calibration curve for 2001-2004 data. The calibration curve, i.e. the conductor state equation curve, is at the upper boundary of the data point clouds.

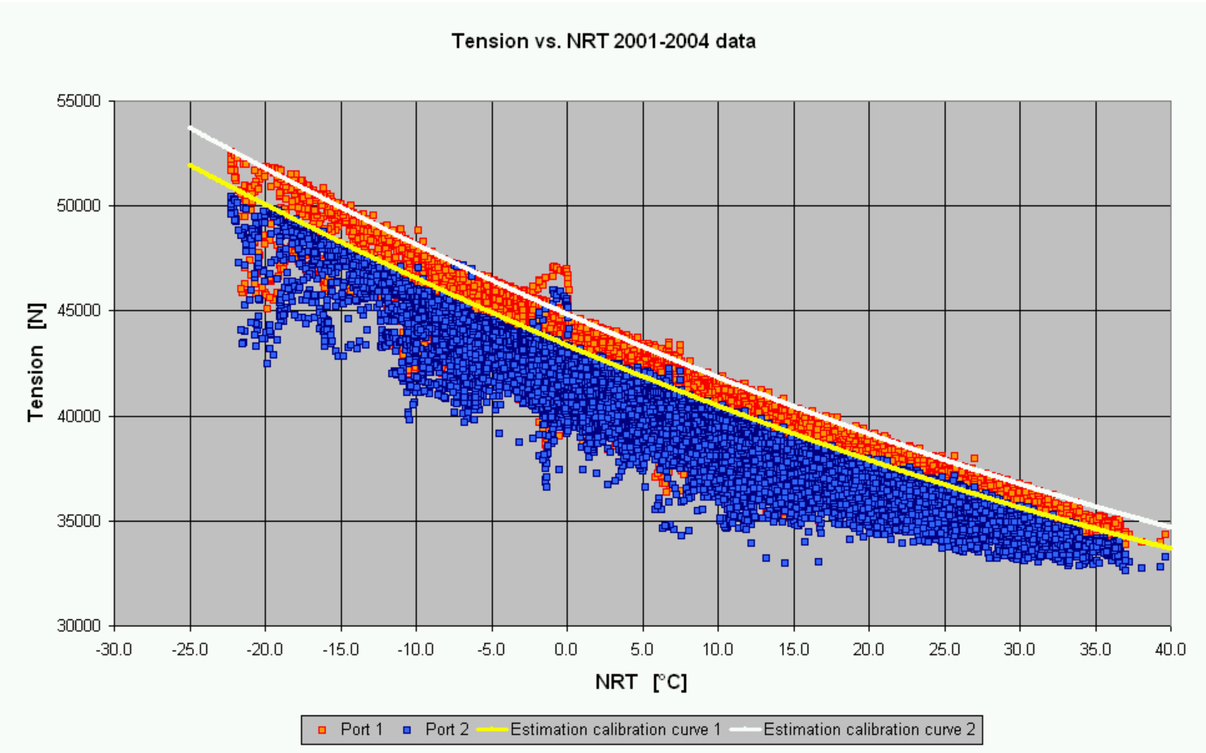

Figure 30. 2001-2004 CAT-1 measurement estimated calibration curves for the two parallel lines.

There are some outlier points above the calibration curve, however. These points represent situations when there has been ice on the conductors (the peaks around 0°C), or there has occurred very strong wind or heavy rain (points located up to 1% above calibration curve) influencing the conductor tension.

The two circuits and phase conductors are running parallel the tower structure with CAT-1 installed. However, the next tower structure is different, and the two monitored conductors are at different levels in this tower structure, and therefore the tensions are different. The changes done in the structure are the probable cause for the differences in 2001-2004 and 2012 data.

Impact of tension difference on sag is illustrated in Figure 31. CAT-1 measures the tension of the twin horizontal bundle conductor. The calculations done for this graph are based on difference in tension in a single conductor between the two monitored parallel phases. Figure 28 and Figure 29 show a tension difference in the range of 1000-3000N for the bundle so that the difference for a single conductor is between 500-1500N. Depending on the Ruling Span (RS) length this causes a sag difference of 3-33cm. It ought to be noted that this calculation is only meaningful if the tension difference is caused by a physical reason and not by wrong offset settings.

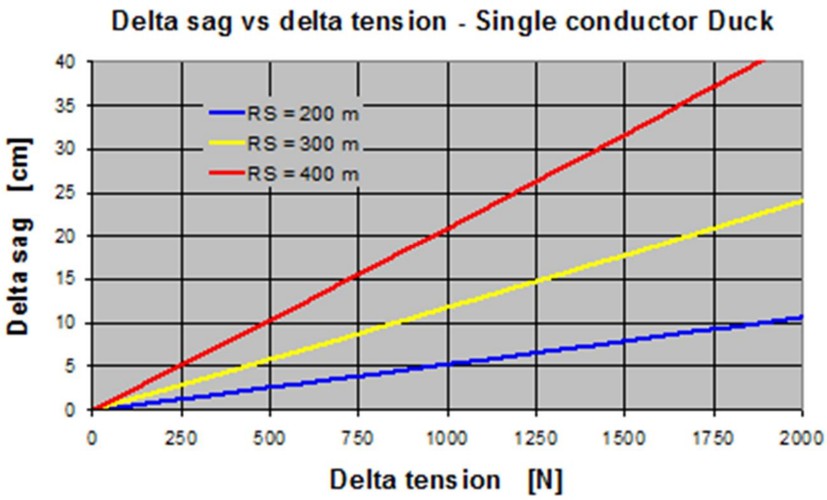

Figure 31. Impact of tension difference on sag.

In both data sets and figures above the CAT-1 readings form data point clouds are partly overlapping. The data point cloud is a bit wider in the 2001-2004 data and narrower in the 2012 data. Wider cloud signifies higher line loading. During an outage when the line carries no current the data point will be more or less following the calibration curves.

The calibration process for the line sections is a difficult and complex procedure. It can be done best based on measurements during “low load conditions” or an outage when the current on the line causes no or only small increase in conductor temperature. Once the calibration curve has been found, the average conductor temperature can directly be determined from the tension readings.

The ampacity, i.e. dynamic line rating, in CAT-1 method is based on IEEE model [5]. The higher the actual load on the line, the more accurate the ampacity calculation will be (i.e. in case the line is very lightly loaded, the determined ampacity value is not quite as accurate).

11 Conclusions

11.1 General conclusions – DLR monitoring

The easiest, i.e. requiring less line construction or renewal work, and most profitable means to increase power line capability without compromising reliability, seems to be utilizing real-time power line ratings (i.e. dynamic line ratings). This could be advantageous especially related to wind power integration and grid connection.

The existing power lines, traditionally designed with worst case situation limitations for reliability reasons, contain even remarkable unused transmission capacity at most times. This capacity could be utilized with transmission line real-time monitoring. In addition, monitoring would provide the system operator better awareness or the power lines' status in real-time at all times, which also would enhance the already high reliability level.

There are several commercially available dynamic line rating (DLR) monitoring technologies based on different means to determine the power line actual state – usually the conductor sag, that is the limiting feature – in real-time. The power line ampacity, and dynamic line rating in the different technologies is usually determined quite similarly using the acknowledged theory.

Based on the literature review done of different available DLR monitoring technologies and of the experiences (research studies, testing, pilots, demos, and actual use), DLR has been proved to increase actual power line capacity at most times by a significant amount, and/or providing the relief that was needed. The methods have proven to be reliable in DLR determination. However, different methods (i.e. especially direct vs. indirect) have different accuracies, but the system reliability is aimed to be secured always. Compensating for inaccuracies and uncertainties involved with assumptions used, the provided DLR value may still be somewhat lower than considering the actual ampacity of the line. More accurate DLR method could provide more additional power line capacity (i.e. higher DLR) with high reliability level.

There are not significant differences (e.g. in time, costs, interruptions, effort) in installation of the DLR measurement equipment apart from installation on the line (all these equipment installations are possible for energized line in case live-line work is allowed) or no required line installations. User and system interface of the method, method applicability in different power system management systems, DLR equipment communication, and equipment operational reliability or life-time have not been studied here thoroughly, nor have these issues been discussed in depth in the available reporting of DLR experiences.

The different features (e.g. those listed above) should be evaluated carefully when considering application of DLR monitoring, and in selection of the equipment supplier and method to be used. The initial decision may have impact on both future perspective as well as the system-wide perspective in case DLR monitoring would be implemented in wider scale later on (or leading to discarding DLR application and utilization of existing "hidden" power line capacity potential).

The investment costs of DLR monitoring units and other cost related to DLR monitoring generally are very competitive with other options for increasing power line capacity, and the payback time is short. Also the implementation time is short compared to other options.

The experiences publically reported of using DLR or testing it for potential DLR application by TSOs or in TSO networks, generally show that there is potential for utilizing hidden transmission capacity to be released by DLR monitoring. However, although the potential is discovered, and the method reliability is proven, it still seems to be a big step to be taken before the DLR would actually be used by the TSOs. Those TSOs that utilize DLR and have publically reported about it, seem to have good experiences (e.g. Eon Central Networks, UK).

However, the experiences seem to be reported on quite rarely. Having found a solution for power line capability problem is the task completed for the TSO, not necessarily sharing this with the public through publications. It is likely that negative experiences, tests and trials, could tend to be left unreported as well. In this review work there was not found out that employing DLR would have caused any problems or negative impacts, e.g. a false DRL leading to line or system failures.

Unfortunately, the reporting on the experiences of DLR related to wind power integration did not either contain information of possibly occurred wind power curtailment, or wind power cut-off even in those cases these are options in case of low DLR incidents or as back-up.

There seems to be a need for an extensive survey study to find out and gather together the experiences of actual DLR applications the grid companies have.

11.2 General conclusions – DLR application

In DLR utilization there is more to be considered than purely the DLR monitoring installation on certain power lines. In the end, DLR monitoring tells the actual line loading situation and related DLR.

For DLR implementation, the analysis of DLR profitability and potential could be evaluated based on statistical and probabilistic analysis of offline DLR measurements. The DLR implementation ought to proceed from probabilistic design to deterministic operation.

There may be different DLR application approaches used related to different kinds of needs for increasing transmission line ratings. E.g. wind power integration, with variable production and below nominal capacity most of the time, brings different kind of freedom as well as benefits combined with DLR application. High wind power production means higher winds, that also quite likely provide cooling for the lines. In addition power production curtailment under critical circumstances could be easily applied.

Conventionally the N-1 criterion has been used throughout the power system design and operation. With DLR in certain situations, e.g. related to wind power grid connection, N-0 criterion could be an option to be used with curtailment taking place in N-1 situation if needed.

The N-1 or N-0 criterion determining the DLR monitored power line dynamic line rating may also play a role e.g. in selecting the DLR monitoring method. Generally the direct DLR methods determine the DLR value more accurately when the loading of the line is high (and closer to ampacity) instead of low loading. Generally this should not be an issue from perspective of DLR application needs. However, in case the line and its DLR is N-1 limited, the line loading in normal situation may be low compared to line ampacity or thermal limit. Determining DLR accurately at lower actual line loading and considering N-1 situation may be challenging for some of the leading technologies. Indirect methods could be competitive in these DLR application cases.

In DLR applications on connections that may be significant in terms of power markets (e.g. connections on possible bottlenecks), it is significant to know the DLR beforehand. I.e. in order to able to know the transmission capacity possible to be given to the power market. DLR real-time monitoring and system operator actions to be taken due to critical DLR forecast errors would guarantee the power system operational security ultimately.

Different DLR application procedures would require various rules to be defined. The rules should consider technical, economic and liability aspects under different DLR applications, e.g. related to wind power curtailment due to DLR, and bottleneck corrective action impacts caused by DLR forecast errors. The benefits and costs of DLR implementation and utilization need to be defined, as well as deciding to whom these costs and profits are directed. Extensive utilization of DLR may bring complexity to power system planning, operation planning and real-time operation, as costs for using the power line assets more efficiently and enhancing system state awareness.

11.3 DLR applicability in Finland

Fingrid has had a CAT-1 measurement equipment on their power lines. These experiences, data and the equipment itself could be utilized to study and examine further DLR application in Finland.

Among all the currently available commercial DLR methods and reviewed in this report, the CAT-1 and Ampacimon methods seem to stand out as having the most potential for further consideration. Also the PowerDonut could be considered.

The CAT-1 method has a relatively long history behind, a large number of units installed world-wide, and thus significant amount of operational hours compared to other DLR methods. The method is based on the obvious sag-tension correlation and the ruling span theory that are used already in transmission line designing. The equipment is not attached to the conductor, yet it directly measures the power line.

The Ampacimon method, although being relatively new, has already been piloted and operational in a few TSO networks. The method is very straightforward, as it relies on rather simple equation behind accurate theory of conductor physical vibration. It does not require any additional input parameters of the line, external power source for operation, or even calibration. Installation is on the conductor of an existing high voltage power line.

Both the CAT-1 and Ampacimon methods determine the conductor sag – the power line rating limiting feature – as directly as possible and both methods are patented. They contain short-term (i.e. a few hours ahead) DLR prediction, and for both methods there is longer term (i.e. in day-ahead scale) forecast application option available and under development.

Application of DLR in real-time operation would require integration of the DLR monitoring system to the power system management system in the control room. Apparently this is possible with most DLR monitoring methods. The actions to be taken for DLR should be automatized as far as possible and the operation personnel would need to be educated for DRL operation supervision and in case unexpected critical emergency situations.

It could be a softer start to begin already early on with rather small scale, well defined, “safe” DLR applications in transmission system integrated all the way to the power system operation room. DLR is truly Smart Grid technology and it is very possible that DLR will become more commonly used, or even required technology.

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Temperature–resistivity relationship of conductors

Maximum temperature of the power line is one limiting factor how much specific line can be loaded with power (e.g. specified by standards). Resistance of power lines is dependent on the temperature. It is evaluated here if existing information about voltages and currents could be used to calculate resistance of the power line and more specifically change that results from change in operating temperature – i.e. furthermore if this information could be used for determining the conductor status and ampacity. Key factor is the accuracy requirement for measurement to have meaningful results in temperature calculation.

AC resistance can be calculated if power loss and rms value of the current is known.

$$R = \frac{avg\ power\ loss}{I^2}\ \Omega$$

For small changes in temperature, change in resistance can be calculated as follows,

$$R_{T2} - R_{T1} = R_{T1} \cdot \propto (T1) \cdot dT)$$

Coefficients of temperature depend on material of the conductors. For example value for change of resistivity for draka ACSR 305/39 “duck” is 0.00403 1/Celsius.[1]

Therefore to calculate change of one degree of temperature in resistance of duck conductor [1] with resistance of 0.20878 Ω is,

$$dR = 0.20878 \cdot 0.000403 \cdot 1 = 8.414e^{-5}\Omega$$

(AC resistance is assumed to be close to value of DC resistance)

This change in value is very small. Accuracy requirement for power loss measurement can be calculated with the first equation,

$$dR \cdot I^2 = dP_{loss}$$

ACSR 305/39 “duck” has maximum current rating of 845 A. For 800 A power loss measurement accuracy need to notice 1 degree Celsius change in conductor is,

$dP_{loss} = 8.414e^{-5}\Omega \cdot 800^2$=54 W. Similarly 540 W for 10 Celsius change in temperature.

Power on ACSR 305/39 “duck” loaded with 800 A is (power factor 1.0 for simplification)

$$P = \sqrt{3} \cdot 110kV \cdot \frac{800A}{3} = 51\ \text{MW}$$

540 W of 51 MW is about 0.00106% which is clearly too small to be able to be measured by any device. Therefore relation between resistivity and temperature cannot be used to approximate temperature of overhead line conductor.

In addition it can be concluded that the conductor resistance due to temperature changes within normal allowed operating temperatures has moderate influence on the losses.

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High temperature conductors for increased current capacity

High temperature low-sag conductors, HTLS are developed to withstand temperatures from 150 °C up to 220 °C. HTLS conductors also have lower sag; they expand less with temperature. These two factors enable higher Ampere capacity on overhead power lines. Some manufacturers state 100% increase in Ampere capacity when traditional aluminium conductor is replaced with HTLS conductor. [1], [2] . Figure 1 represents sag comparison of standard aluminium conductor and HTLS conductor.

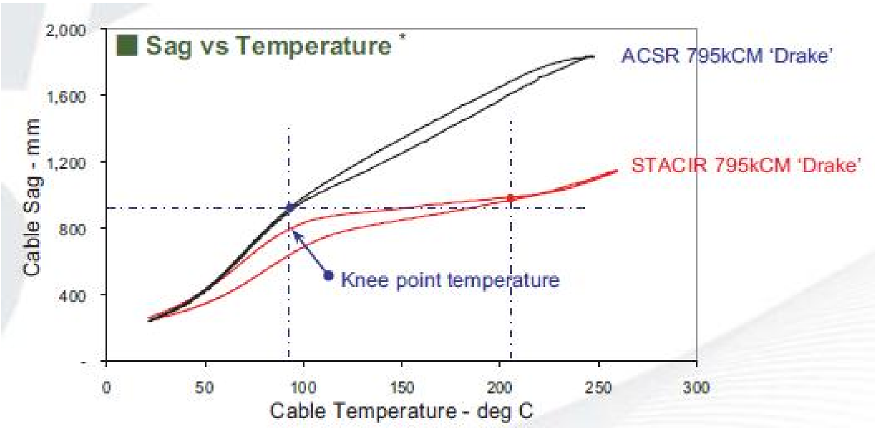

Figure 1. Sag comparison respect to temperature of HTLS conductor and standard aluminium conductor. [2]

When compared to building new parallel transmission line, replacing standard conductor on existing gives savings when new tower and foundations are needed but also in energy costs as installation time is shorter. Also when planning on entirely new line, choosing HTSL conductor will result to savings in tower costs as weight of the wire per current capacity is lower.

Drawback of HTSL conductor is higher power losses on line due higher resistance compared to two parallel lines. When using resistance value of 0.145 Ω for standard conductor with current capacity of 1.0x and 0.215 Ω for HTLS conductor with current capacity of 2.0x, power losses can be about 200% higher compared to two traditional parallel standard conductor lines. [Zamora 2001] This can be calculated with following equation,

$$Power\ loss\ ratio = \frac{R_{HTLS} \cdot (2I)^2}{2 \cdot R_{std\_Al} \cdot (I)^2} = \frac{0.215 \cdot (2I)^2}{2 \cdot 0.145 \cdot (I)^2} = \frac{2 \cdot 0.215}{0.145} = 2.97$$

Although losses and price of the cable are higher, total savings of 47% over investment time of 30 years are presented in [2]. HTLS conductors have many benefits, but the profitability of using them depends on what the actual case is and importantly how much new capacity is needed.

The basic construction of HTLS conductor is made so that the core holds the line mechanically with low sag and the outer part is used to conduct electricity. Profiles of metal matrix and carbon composite core HTLS conductors are presented in figure 2.

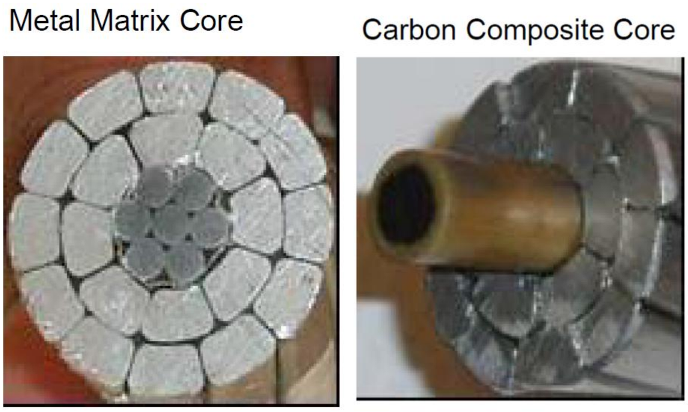

Figure 2. Profiles of metal matrix core and carbon composite core HTLS conductors.[3]

Metal matrix core type conductor was found more resistant to reduction of tensile strength in elevated temperature in [3]. Carbon composite core was found to lose 26% of the strength in elevated temperature in same test. Also temperature gradients are smaller in metal matrix core. Even temperature distribution is good for conductor but also makes modelling of the temperature easier. Temperature model is needed so that conductor can be used at optimum dynamic capacity in different conditions but certainly is not required to get the most of the benefit of HTLS conductors.

Presentation slides from manufactures Sterlite and Metal Link state that ACSS type conductor can be the most economic option. Profile of ACSS is on the left side of figure 2. Comparison chart made by Metal link is presented in table 1.

Table 1. HTLS conductor comparison by Metal link. [4]

Conductor Type	Maximum Continuous Temp. (℃)	Maximum Emergency Temp. (℃)	Relative resistance per unit length	Thermal Rating at Max Cont. Temp. (A)	Relative cost per unit length
ACSR	• 100	• 125	• 1.00	• 990	• 1.0
ACSS	• 200	• 230	• 0.98	• 1570	• 1.1 – 1.5
ACSS/TW	• 200	• 230	• 0.90	• 1745	• 1.2 – 1.5
TACIR	• 150	• 180	• 1.00	• 1325	• 3
ZTACIR (STACIR)	• 210	• 240	• 1.00	• 1615	• 5
GTACSR(GAP)	• 150	• 180	• 0.95	• 1315	• 3
ACCFR	• 210	• 240	• 0.90	• 1640	• >10
ACSS/TW-HMS	•200	•230	• 0.85	• 1832	• 2.5

Power transfer capacity chart by Sterlite is presented in figure 3.[5]

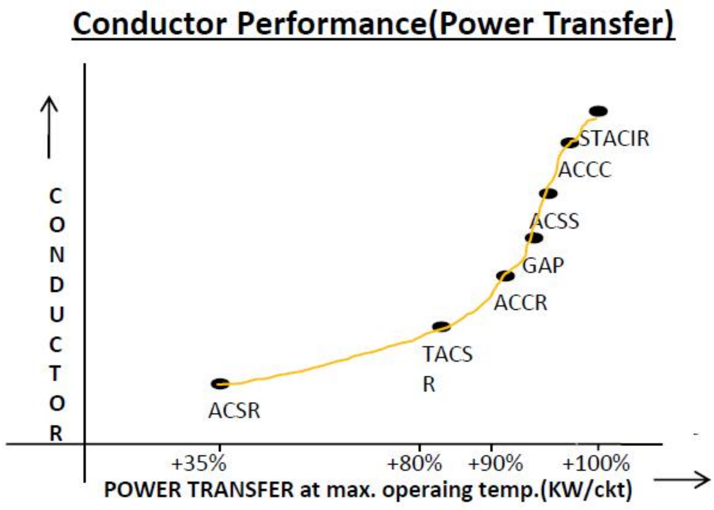

Figure 3. HTLS power transfer capacity presentation.[5]

Power losses are the only major weak point of the ACSS conductor. This can be seen on power line loss chart in figure 4. [5]

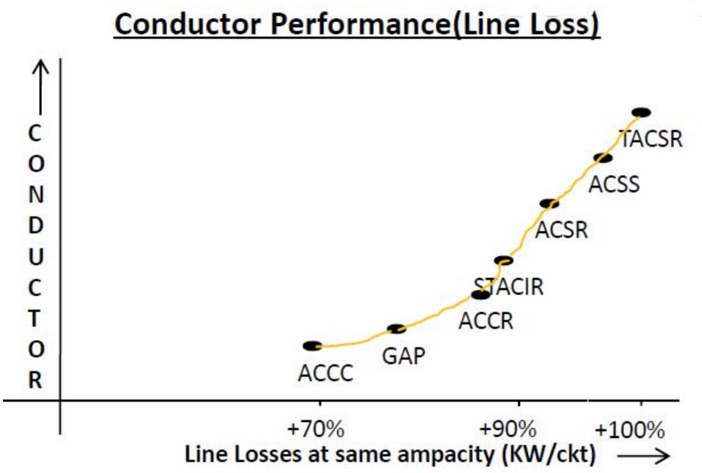

Figure 4. Line power loss comparison. [5]

List of HTLS conductor manufacturers

Following list covers some of the HTLS conductor manufacturers.

Ampar. http://www.apar.com/html/conductors.html

3M. http://www.3m.com

Ohm Tekmin. http://www.ohmtekmin.com/ingles/whoweare.htm

Southwire. http://www.southwire.com/

Sterlite. http://www.sterlitetechnologies.com/

J-Power. http://www.jpowers.co.jp/english/product/oerhead_alum.html

LS Cable. http://www.lscable.com/

CTC. http://www.ctcglobal.com/

GPIL. http://www.guptapower.com

Metal link. http://www.metallink.co.kr

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