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Estimation method for dynamic line rating potential and economic benefits ☆

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ABSTRACT

The determination of economic benefits of increasing transmission capability by dynamic line ratings is a multifaceted task. In addition, there are many parties concerned within the complex electricity markets. This paper suggests a method for the evaluation of economic feasibility and benefits, as well as for the minimum potential assessment of employing dynamic line ratings. The suggested deterministic method considers very conservative assumptions in order not to compromise the power system reliability, even though the method is intended for the power system planning and not for the operation purposes. The method is applicable for congested transmission connections between electricity market price areas and it is demonstrated with a distinct case study of congestion on the power transmission from Sweden to Finland. Despite the very conservative assumptions used in the ampacity calculation to be on the safe side, the method can clearly point out the motivation to consider the implementation of dynamic line ratings on congested transmission connections in order to relieve bottlenecks and provide benefits for the society.

Introduction

The power lines are conventionally designed and operated with the worst case limitations and static ratings. The power transmission limiting feature on thermally limited lines is typically the line sag. On the maximum sag with prevailing ambient conditions, the actual current capability, i.e., ampacity, is most of the time larger than the static rating. This overlooked transmission capacity potential could be utilized by employing dynamic line ratings (DLR). High reliability would be maintained—and case-specifically even increased—by the transmission line ampacity and state monitoring. There are several technical applications available today for the DLR monitoring.

There exist different calculation standards and methods for the determination of the power line ampacity, e.g., by IEC [1], IEEE [2] and CIGRE [3]. The text books on power line design may present some of the different calculation options, e.g., in [4] the IEC equations are given as one alternative. There may be slight differences between the results obtained by the different calculation methods. The IEEE and CIGRE methods have been compared analytically and even experimentally, e.g., in [5–7].

There has been development of the dynamic line ratings and their determination and measurement over the recent decades, started in the late 1970s [8]. Since then, there has been a great number of publications and discussion on DLR.

However, the economic benefits of the DLR are quite rarely discussed in the publications. Chu presented in [9] a method for the selection of power lines on which the implementation of DLR would have the largest financial return through the savings in fuel costs. Greenwood and Taylor touch the question of the economic benefits of the DLR in [10] in the form of improved and cost-effective utilization of the network assets without compromising the network reliability when employing DLR.

Quite often DLR is studied and implemented in the cases when it is almost the last alternative, e.g., there is no time or possibility to build a new power line to increase the power transmission capacity. However, employing DLR could also be beneficial and bring economic savings in other situations. Usually it may be difficult to calculate the monetary value of employing DLR in the whole for the parties concerned, e.g., for the electricity consumers.

This paper suggests a method for the estimation of the economic feasibility of DLR to be applied in the congested power transmission connections. This method calculates the line ratings as ambient adjusted ratings (the term used and defined, e.g., by CIGRE in [11]). Ambient adjusted ratings are most of the time more conservative than the actual ampacity of the lines. This is because

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the influence of wind, that is significant in increasing ampacity, is ignored. Thus, only some of the potential of DLR is displayed by ambient adjusted ratings with the ambient temperature as the only variable.

The method is demonstrated with the analysis of publicly available data in a distinct case study. In this case study, the costs related to the congestion are easy to determine. The selected demonstration case concentrates on the congestion in the power transmission from Sweden to Finland in the AC connections in the northern parts of the countries. Finland and Sweden are part of the same electricity market, and congestion on the cross-border connections directly affects the electricity prices in the electricity market by creating price areas on either side of the transmission bottleneck. Publicly available data of the temperature, electricity market and system operation of 2011 are used in the demonstration case.

Method description

The estimation method for the dynamic line rating potential and economic benefits is based on the calculation of the hourly ambient adjusted ratings of the power lines for a certain period of time, e.g., a year.

The calculation of the ambient adjusted rating uses a combination of equations as well as some assumptions from a power line design text book [4], IEC [1] and CIGRE [3].

In this method, more conservative assumptions are preferred to be used for the ampacity calculation to be on the safe side.

The hourly ambient adjusted rating data series is calculated with the hourly temperature data series, the ambient temperature being the only variable. The used temperature data series is based on the historical temperature measurement data of multiple locations in the vicinity of the concerned power lines. The calculation for the hourly ambient adjusted ratings is covered more thoroughly in Section 'Ampacity of transmission line'.

For each hour of the year, the highest temperature value of the n different locations is selected for the temperature data series. In addition, a temperature security margin T_{marg} is added to the highest value, as

$$T_{\mathrm{h}} = \max\{T_{1,\mathrm{h}}, T_{2,\mathrm{h}}, \ldots, T_{\mathrm{n,h}}\} + T_{\mathrm{marg}}, \quad h = 1, 2, \ldots, 8760. \tag{1}$$

In the case the temperature data sampling is greater than one per hour, the highest instant value within an hour would be selected.

The temperature security margin has two functions. The first function is to consider a possible higher temperature along the power lines in question. Thus the margin considers a systematic ambient temperature difference between the warmest spot along the line and the temperature measurement data locations. The second function is to consider temperature changes and variations within the temperature data sampling period, e.g., the inter-hour variations in the case of one per hour sampling. As the defined temperature data series is used for the estimation purposes (and not for the actual operation, or definite DLR potential calculations either), the temperature margin can be selected suitably and conservatively by analyzing the available temperature data, or by guessing.

The calculation of transmission capacity continues by determining the Net Transfer Capacity (NTC) hourly data series on the cross-border or between bidding areas. The NTC is calculated by using the same method that is generally used for NTC determination for the interconnection concerned, but now using the individual considered transmission line ambient adjusted rating data series instead of the conventional line ratings.

The historical data series of the power transmission ($P_{\mathrm{x-y}}$) in the connections in question is analyzed on the same time period (e.g., a year), as for which the temperature data based NTC data series is calculated. The relevant transmission congestion situations and hours are identified with the help of the hourly data series of the electricity price SP on the related bidding areas x and y, as well as the transmission capacity $NTC_{\mathrm{x-y}}$ given for the market for each hour. Only the hours on which a transmission bottleneck due to the static transmission line ratings is deemed to be the cause of price areas are considered. Hours with a limited NTC are omitted. I.e., the following conditions are true

$$\begin{cases} SP_{\mathrm{y},0} > SP_{\mathrm{x},0} \\ P_{\mathrm{x-y}} \approx NTC_{\mathrm{x-y,0max}} \end{cases}, \tag{2}$$

where 0 denotes the historical situation and data. The situation and data with NTC based on the calculated ambient adjusted rating is denoted by 1. A transmission bottleneck is assumed to be relieved or possibly even removed if the calculated NTC with the DLR on an hour that is transmission capacity congested, is larger than the NTC in the historical electricity market data, i.e.,

$$NTC_{\mathrm{x-y},1} > NTC_{\mathrm{x-y},0}. \tag{3}$$

The hours on which the NTC increase potential is very small could be neglected in the economic benefit calculation by discretion.

It would be a complex task and require confidential data and information to determine

- how big an increase in the NTC could be allowed (i.e., there may be other constraints that set limits before the NTC based on the calculated ambient adjusted ratings);
- how much additional transmission capacity would be needed to remove the bottleneck, thus resulting a uniform electricity price in both bidding areas;
- and what would be the electricity prices of the bidding or price areas with an increased NTC.

It is clear, however, that the prices with an increased NTC would be between the original area prices

$$SP_{\mathrm{x},0} \leqslant SP_{\mathrm{x},1} \leqslant SP_{\mathrm{y},1} < SP_{\mathrm{y},0}. \tag{4}$$

Without the knowledge of the magnitude of congestion relief and the resulting electricity prices, this method assumes that the electricity price in area y would be the average of the two original area prices. I.e.,

$$SP_{\mathrm{y},1} = (SP_{\mathrm{x},0} + SP_{\mathrm{y},0})/2. \tag{5}$$

In the case an increased NTC would reduce the electricity prices according to Eq. (5), the money saved by consumers SV due to the considered x–y congestion relief under the conditions of Eqs. (2) and (3) would be

$$SV = \sum_{\mathrm{h}=1}^{8760} (SP_{\mathrm{y},1,\mathrm{h}} - SP_{\mathrm{y},0,\mathrm{h}}) P_{\mathrm{x,cons,h}}. \tag{6}$$

It is assumed that the consumption $P_{\mathrm{x,cons,h}}$ would be the same regardless of the electricity price difference.

The method also assumes that a different generation dispatch enabled by an increased NTC at 1 h, does not affect the bids for the following hours the rest of the year. Thus, the historical data series can be used as is. Running the power generation fleet differently could in fact affect, e.g., the water reservoirs, fuel reserves and the value of the fuel reserves that in turn could influence the bids in the future.

Demonstration case: Sweden–Finland congestion

The case of congestion in the power transmission from Sweden to Finland was selected for the demonstration of the method. Despite the relatively good connections between the countries, the transmission constraints in the Nordpool electricity market occasionally cause the bidding areas of Sweden (or north of Sweden) and Finland to become price areas.

There are two 400 kV connections (assumingly 2-Finch) and one 220 kV connection (assumingly 1-Condor) between the countries in the north, in addition to the HVDC connection(s) between the south of Finland and central Sweden. In addition to the congestion between the countries, there are also internal transmission constraints between north and south in each country.

From 2009 onwards, the operating range and transmission limitations of the Finnish power system are defined by the Transmission System Operator (TSO) Fingrid in [12]. According to Fingrid, the transmission limitations from Sweden to Finland are partly determined by the current carrying capacity of the lines. The maximum transmission capacity in the AC connections in the north (called RAC) is 1500 MW according to Fingrid [12].

The demonstration case described in this paper concentrates only on the congestion in the power transmission from Sweden to Finland with the maximum NTC value of 1500 MW. These situations are assumed to be due to the thermal constraints of the transmission line capacity.

There are also other non-thermal constraints that could be setting limitations for the power transmission. In the case that the Sweden–Finland NTC could be increased from 1500 MW based on the calculation results, it is not known what would be the following transmission limiting feature. Moreover, neither is it known at which value this feature would limit the NTC.

Ampacity of transmission line

The power line rating and ampacity calculation is reviewed here as it forms the backbone for the topic. The calculation method selection as well as the assumptions and parameters that are used, influence greatly the calculation results. To a quite large extent, the equations, parameter values and assumptions are matters of choice. For the sake of simplicity, in the method described in this paper, the steady-state heat balance of a conductor is considered in conjunction with favoring conservative calculation alternatives and assumptions.

CIGRE presents in [3] the heat balance of the conductor in the steady state as an equilibrium between the heat gain and heat loss with

$$q_J + q_M + q_S + q_i = q_c + q_r + q_w, \tag{7}$$

where the specifications are as follows

- q_J – Joule heating;
- q_M – magnetic heating, that can be neglected with non-ferrous conductors but could be significant with steel-cored conductors;
- q_S – solar heating;
- q_i – corona heating, that can be neglected;
- q_c – convective cooling;
- q_r – radiative cooling;
- q_w – evaporative cooling, that can be neglected.

The Joule heating, magnetic heating and skin effects together form the current heating according to [3].

In the following subsections, the calculation of each term in Eq. (7) is explained more thoroughly, as well as mentioned the parameters and assumptions that are used in the calculations in this paper. Some variables have more influence on the heat balance than others, wind being the most significant variable [13]. Thus, the assumptions related to the different quantities of Eq. (7) and physical variables, possess a different importance.

Especially for the convective cooling, there are several different calculation alternatives available. In addition, the calculation equations or parameters may depend on the variable values (e.g., the wind speed or a calculated variable like the Reynolds number). The equations used in this paper for the ampacity calculation are from [4] and in correspondence to the IEC 61597 standard [1] unless specified otherwise. The reason for selecting these equations to be used, is the sake of simplicity and the independence of the variable values.

Ampacity is deliberately calculated with rather conservative assumptions for the method described in this paper. This is done in order to obtain the minimum dynamic ampacity values with even a higher reliability than the reliability associated with the transmission lines (and their static ratings) designed in the conventional manner.

Solar radiation

The conductor heating due to the solar radiation is calculated by

$$q_S = \alpha S D, \tag{8}$$

where α is the absorptivity, S the solar radiation and D the diameter of the conductor.

The typical absorptivity for the conductors is $0.23, \ldots, 0.95$ according to CIGRE [3], and generally the value 0.5 can be used. Several conductor manufacturers also give value 0.5 for the conductor absorptivity. The absorptivity of the new conductors is smaller, and larger on the older weathered conductors. For the method in this paper, the maximum value of 0.95 for the absorptivity is used.

The solar radiation depends on the geographical location and the time (the time of the year as well as the time of the day) in addition to the weather. For the sake of simplicity, in this paper the approximate maximum value of $S = 1.366$ kW/m^2 is assumed. This value corresponds to the solar radiation coming perpendicularly to the target at brightest—all the time.

The conductor diameter is calculated as an average of several conductor manufacturer datasheets for the conductor types in question. E.g., for a Finch conductor $D = 0.032285$ m and a Condor $D = 0.027108$ m.

Convective cooling

The convective cooling can be based on natural convection, i.e., the wind speed is zero and the cooling occurs by colder air moving to replace the heated air, or the forced convection as air moves due to wind (i.e. wind speed differs from zero).

Generally in the power line rating calculations, a forced convection is assumed typically with 0.6 m/s (or 2 ft/s) wind speed perpendicular to the conductor. This is originally based on a study conducted in the 1930s defining that this value of wind speed is safe enough an assumption for determining the (static) thermal line ratings. The study by Schurig and Frick [14] concluded that 0.6 m/s wind is not to be expected more than 5% of the time during the summer season and its occurrence with a high temperature is even less frequent, and thus the chance of overheating the conductors is practically negligible.

Wind is highly variable in terms of the spatial location, direction relative to the power line, and time, as stated also in [7]. Therefore considering the cooling of wind brings high uncertainty in a calculated ampacity almost regardless of the used wind speed value.

Although the most conservative assumption would be to assume a zero wind speed and natural convection, the wind speed 0.6 m/s perpendicular to the conductor is considered conservative enough an assumption for the method presented in this paper.

The forced convective cooling

$$q_c = \pi\lambda \cdot Nu \cdot (T_s - T_{amb}), \tag{9}$$

where λ is the thermal conductivity, Nu the Nusselt number, T_s the surface temperature of the conductor and T_{amb} the ambient air temperature.

Thermal conductivity is given as table values for discrete temperatures. In the calculations for this paper, the conductivity is inter- or extrapolated with the values for temperatures 0 °C and 40 °C as

$$\lambda = 0.0243 + T_{amb}(0.0272 - 0.0243)/(40 - 0). \tag{10}$$

The Nusselt number can be calculated as

$$Nu = 0.65Re^{0.2} + 0.23Re^{0.61}, \tag{11}$$

for which the Reynolds number is calculated as

$$Re = 1.644 \cdot 10^9 \cdot VD(T_{amb} + 0.5(T_s - T_{amb}))^{-1.78}, \tag{12}$$

where V is the wind velocity.

The surface temperature of a conductor has a significant role in the calculations of the conductor cooling, the conductor core temperature on the other hand determines the conductor sag, and the average conductor temperature determines the conductor temperature dependent resistance [3]. According to CIGRE [3], the difference of the conductor core and surface temperature is between 0.5 and 7 °C, and thus it is generally acceptable to assume for the average temperature $T_{av} = T_s$.

The design temperature, i.e., the maximum temperature, of the power lines may be determined by standards, and typically is between 75 and 90 °C in different countries [4]. In Finland, the standard [15] determines the maximum temperature to be 80 °C. In the calculations presented in this paper, is assumed $T_s = T_{av} = T_c$, i.e., the 80 °C is used as the conductor uniform radial temperature distribution from the core (T_c) to the surface (T_s).

Radiative cooling

The radiative cooling of a conductor

$$q_r = \pi D\varepsilon\sigma_B((T_s + 273)^4 - (T_{amb} + 273)^4), \tag{13}$$

where ε is the emissivity and σ_B the Stefan–Boltzmann constant $5.67 \cdot 10^{-8}$ W/m^2 K^4.

The emissivity value typically varies from 0.23 for the new conductors to 0.95 for the old conductors. CIGRE recommends the value of 0.5 in [3]. In this paper, the recommended value of 0.5 for the emissivity is used as this value seems to be quite conservative for the older conductors. Considering also that a higher and more conservative absorptivity value was selected to be used, this assumption is justified.

Electrical conductor heating and maximum current

The heating by the electrical current

$$q_J + q_M = R'_{T\,AC} \cdot I^2, \tag{14}$$

where $R'_{T\,AC}$ is the AC resistance of the conductor calculated as in [4] and I the current flowing on the conductor.

For the determination of the line rating for a conductor, i.e., the maximum current, Eq. (14) is solved for I_{rat} with the results of Eqs. (7), (8), (9) and (13), as

$$I_{rat} = \sqrt{(q_R + q_C - q_S)/R'_{TAC}}. \tag{15}$$

Weather data

The weather data used for the demonstration case in this paper is from the National Climatic Data Center (NCDC) archive of NOAA.[1] There is data available of a few locations within the area of the cross-border RAC transmission connections between Finland and Sweden. Data from three locations is used. The Ajos, Haaparanta and Meltosjärvi data sites form a triangle. Ajos and Haaparanta are on the coast, south of the cross-border connections over 30 km apart from each other. Meltosjärvi is inland, over 80 km from Haaparanta and over 90 km from Ajos, and to the north from the cross-border connections.

Temperature data analysis

The temperature data of the three locations was first checked for consistency and the temperature variation was analyzed briefly in respect to the geographical location and time (i.e. between the hours).

Of the year 2011 temperature data consistency was found the following

- Ajos: some 1–2 h gaps (some 3 h gaps), total of 132 data points missing;
- Haaparanta: 1–2 h gaps, total of 23 data points missing;
- Meltosjärvi: 1–2 h gaps (some 3 h gaps and about 24 h missing in two occasions), total of 113 h data points missing;
- the gaps coincide quite often in the Ajos and Meltosjärvi data, and the only simultaneous gap in all three datasets is not significant in this study, as it is not a Sweden–Finland congestion hour.

The gaps in the data series are left as are. As calculating the temperature differences between the locations, the difference is neglected in case data is missing from either location. Also when calculating the temperature change between the hours, the difference is calculated only between those hours for which data is available.

The maximum difference between the consecutive temperature data samples (i.e., hours) in the data series is 9.2 °C, and over 5 °C in 29 instants (of total of about 8760 h of the yearly data series). The standard deviation is about 1 °C (mean 0 °C).

The mean temperature difference between the different locations is 0–1 °C, standard deviation 2.1–3.4 °C and maximum difference between two locations 14.8 °C (see Table 1 and Fig. 1).

Temperature data series for line rating calculations

The absolute maximum temperature during an hour (from on-the-hour h to $h + 1$), would be the ideal temperature data to be used in the analysis discussed in this paper. As a simple approach, the temperature value of the hour h is used to represent the temperature of during-the-hour between h and $h + 1$. This approach is taken because the transmission and electricity market data are presented by the during-the-hour $h, \ldots, h + 1$values.

For the line rating calculations, the largest temperature value of the three locations is selected for each hour (i.e., the temperature value of hour h corresponding to the during-the-hour $h, \ldots, h + 1$ in the power system data). Furthermore, 5 °C security margin is added to this largest temperature value each hour in order to

[1] http://www.ncdc.noaa.gov/ (last accessed on 17/10/2013).

Table 1
The temperature data differences between the measurement data locations and data sampling.

Temperature difference between locations	>5 °C	>10 °C	Standard deviation (°C)
Ajos and Meltosjärvi	1257 h	126 h	3.4
	14%	1%	
Ajos and Haaparanta	355 h	10 h	2.6
	4%	<1%	
Haaparanta and Meltosjärvi	618 h	0	2.1
	7%	0%	
Temperature difference between hours	**>5 °C**	**>10 °C**	**Standard deviation (°C)**
Ajos	5 h	–	0.8
Haaparanta	9 h	–	0.9
Meltosjärvi	29 h	–	1.1

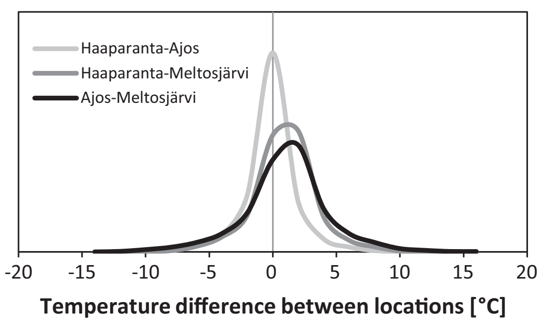

Fig. 1. Frequency distribution of the temperature differences between the measurement data locations.

consider uncertainties. The value is an estimate and supported by the data analysis results described above.

Historical electricity market and transmission data

The economic impacts of an increased cross-border capacity can be assessed by the analysis of the calculated thermally limited NTC data series, and the historical electricity market and power transmission data related to congestion in RAC cross-border for 2011.

The transmission capacities provided to the market, actual commercial power exchange on the cross-borders (i.e., including Elspot and Elbas market transactions), as well as measured physical power transmission on the cross-borders, are available as historical time series data on Fingrid website.[2] In addition, Nordpool Spot provides the transmission capacity and power exchange data on their website.[3] The Fingrid data on the power transmission and capacities is primarily used here and completed with the Nordpool data.

The following data series were calculated or screened to be used:

- the price differences, i.e. if the price is higher in Finland than in northern Sweden, signifying that there is congestion in RAC;
- the actual power transmission in RAC in a Sweden–Finland congestion situation (calculated only for the congestion cases when the price is higher in Finland than in northern Sweden);
- the Elspot transmission capacity in RAC (calculated only for the congestion cases in which the price is higher in Finland than in northern Sweden).

The electricity market and power transmission data was synchronized with the NOAA temperature data to be used for calculating the NTC data series for the analysis.

Power rating calculation for RAC

The hourly transmission capacities with thermal transmission limits for the individual connection lines are calculated first. The cross-border transmission capacity is calculated based on the individual line calculation results, and considering the $N-1$ contingency as well as the NTC calculation principles used by the TSO.

Individual line rating

The transmission line capacity is calculated for the two conductor types and power lines, 400 kV 2-Finch and 220 kV 1-Condor lines.

The conductor or power line rating is determined as the maximum current that is allowed to flow on the line and it is calculated by Eq. (15). For the electricity market, the transmission capacity is given as active power in megawatts. The power rating in a three phase system with rated current is

$$P_{\text{rat}} = \sqrt{3}\cos\varphi U I_{\text{rat}}, \qquad (16)$$

where $\cos\varphi$ is the power factor determining the active power of the total apparent power, and U the phase to phase voltage.

Reactive power transmission is tried to be minimized within the limits of other power system operation features and requirements. E.g., 1500 MW active power transmission with a power factor of 0.98 and reactive power transmission of 300 MVar would require 1530 MV A apparent power. In this paper it is considered reasonable to assume minimal, close to zero, reactive power on the cross-border connection lines and approximate the transmission line rating by assuming $\cos\varphi = 1$.

In Finland, the actual voltage of the lines at each operating instant can vary under the normal conditions within the range 215, ..., 245 kV on 220 kV lines, and within the range 395, ..., 420 kV on 400 kV lines with 400, ..., 416 kV being the optimal operation range. Thus, on the determined current rating, the corresponding power rating can vary due to the operating voltage. In the calculations described in this paper the lowest normal operating voltages (215 kV and 395 kV), giving the lowest power rating values, are used in order to obtain conservative results.

Cross-border NTC

There are total of three power lines for the RAC cross-border power transmission. The most significant $N-1$ contingency to be considered for the calculation of the RAC transmission capacity would be the loss of one of the two 2-Finch transmission lines.

The *NTC* that is also provided for the electricity market, is calculated by

$$NTC = TTC - TRM \qquad (17)$$

[2] http://www.fingrid.fi/ (last accessed on 17/10/2013).
[3] http://www.nordpoolspot.com/ (last accessed on 17/10/2013).

where *TTC* is the Total Transfer Capacity and *TRM* is the Transmission Reliability Margin. The *TTC* is determined by defined transmission capacity of the power lines and considering the $N-1$ criterion, and the value of *TRM* in Finland is 100 MW according to Fingrid [12].

Thus, the ambient temperature adjusted transmission capacity on the RAC interconnections from Sweden to Finland is

$$NTC_{1,h} = P_{\text{rat-2-Finch,h}} + P_{\text{rat-1-Condor,h}} - TRM, \quad h = 1, \ldots, 8760. \qquad (18)$$

Demonstration case results

The method described in Section 'Method description' is applied for the demonstration case by calculating first the minimum potential of increasing the NTC for Sweden–Finland transmission. The economic benefits of the increased NTC for Sweden–Finland transmission by using the DLR to relieve bottlenecks and bring savings for the electricity consumers in Finland are assessed also.

Potential to increase NTC by using DLR

The calculated NTC values based on the temperature data and assumptions described in this paper are shown in Fig. 2 as an hourly data series, as well as a duration curve. For comparison, there is also plotted the present maximum NTC value of 1500 MW for the power transmission from Sweden to Finland.

Fig. 2 shows that the present NTC maximum value is quite appropriate considering reliability with the static line ratings. The results also prove the reasonability of the assumptions made in this paper related to the RAC connection lines. Both of these conclusions are supported by the fact that at lowest, the calculated NTC value comes close (only 1% above) to the TSO defined NTC maximum value.

Examining the results and Fig. 2 further, it is evident that even with the conservative calculation assumptions and considering the ambient temperature as the only variable, the increase in NTC could be almost up to 80%. However, these very high values most likely are not acceptable on Sweden–Finland power transmission. Presumably there are other constraints that set limitations at lower value from this calculated NTC with the DLR., e.g., internal north to south transmission limitations (presently 2000 MW) in Finland, stability or voltage issues, or other network component loading limitations.

It is to be remarked that 97% of the time during the whole year of 2011 the calculated NTC—with ambient adjusted line ratings by temperature measurement data—is at least 20% higher than the NTC maximum with static line ratings. This corresponds to 300 MW more transmission capacity most of the time.

The analysis of the calculated NTC data series and historical electricity market and power transmission data shows that there were total of 500 h on which an increased NTC could bring relief for congestion in Sweden to Finland power transmission in 2011. On 432 h of these, the calculated NTC increase potential to the present NTC based on static power line ratings is at least 300 MW. The minimum increase potential of the studied congestion hours is 140 MW.

Economic impacts of increased NTC

The situations eligible for using increased NTC and considered for economic benefit assessment, were the hours when

- the electricity market price was higher in Finland than northern Sweden, i.e., there was congestion on the RAC, and
- the RAC transmission capacity was limited to approximately 1500 MW, i.e., including only the "normal" transmission situations.

Increase potential of NTC in all studied hours—i.e., 140 MW at minimum, and over 200 MW in 99% of the studied hours—can be considered significant. Thus all the considered congestions hours are taken into account for the calculation of the economic benefits.

The method assumes an increased NTC to reduce the electricity price to the level that is average of the area prices on the both sides of the bottleneck (i.e., Finland and northern Sweden). This is very rough, but simple assumption. The uncertainty of the assumption is how well the average of the prices approximates the electricity price the consumers in Finland would have paid in the case of transmission congestion relief. The hourly electricity prices in the 500 h of the study case are shown in Fig. 3 by comparing the calculated price to the historical area price in Finland.

Most of the calculated prices are quite close to the original historical area price in Finland, as seen in Fig. 3. There are some individual hours when the price is reduced significantly, even by 19.3 euros per megawatt-hour and the largest percentage decrease is 40.8%. The average decrease in price is 4.7 euros per megawatt-hour, and 9.4% decrease on average in hourly electricity price. Thus, the method assumptions seem quite reasonable in this case study with the data used for the calculation of an estimate for the economic benefits of employing DLR in order to relieve transmission congestion.

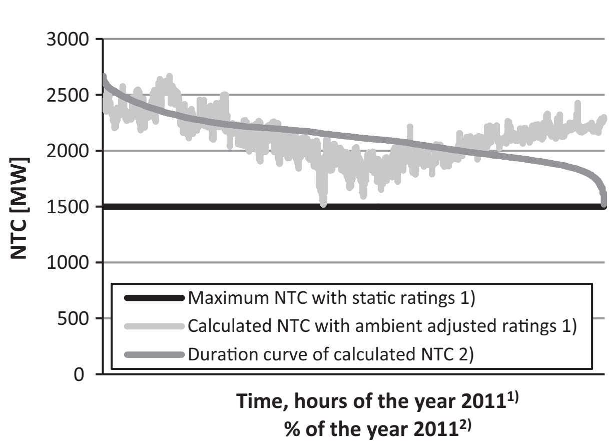

Fig. 2. Calculated NTC as a data series and a duration curve, compared to the present maximum NTC value with static line ratings.

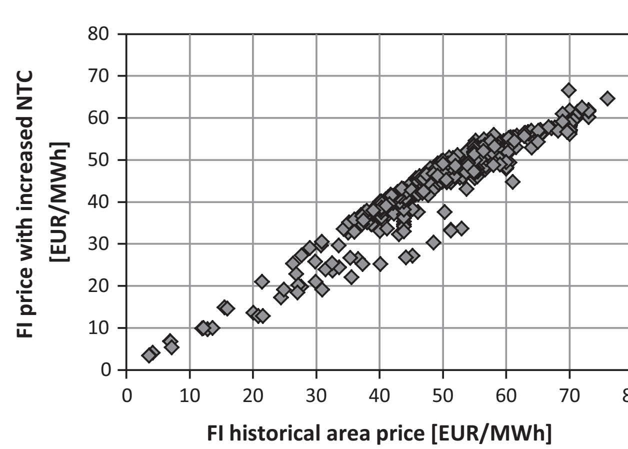

Fig. 3. The calculated electricity prices (as an average of the historical area prices of the bottleneck ends) with an increased NTC as a function of the historical area price in Finland.

Congestion due to the NTC in the Sweden–Finland transmission has an impact on the whole electricity consumption and all the consumers in Finland through the electricity prices in Finland. The calculation method and the historical electricity market and power system data series of 2011 indicate that the consumers in Finland could save the total of about 21.1 million euros (9.6% of total electricity costs paid for these hours) if NTC could be increased by the DLR in the RAC transmission lines.

For comparison, the TSOs of Finland and Sweden have received of these studied 500 congestions hours about 6.8 million euros of bottleneck income. According to the EU regulations the bottleneck income is to be used, e.g., for increasing transmission capacity in the congested interconnections.

These presented figures are the sum of the screened 500 congestion hours for this distinct case study only. There may be more congestion hours and situations that could increase the actual benefits of the DLR. Such cases could be, e.g., the hours when the NTC was limited below the maximum or there was transmission congestion from Finland to Sweden.

The application of the DLR—including the upgrade of the relevant grid components—and the implementation of a monitoring system for the DLR in the congested transmission connections, should be covered by the bottleneck income and be economically feasible considering the potential savings for the consumers.

Conclusions

This paper introduced a method for assessing the potential and economic benefits of employing dynamic line ratings in congested connections due to thermal transmission limitations. The method is applicable with publicly available data and uses conservative deterministic ampacity calculation assumptions for ambient adjusted ratings in order to not compromise power system security by any degree.

There have been no established methods available yet for assessing the potential economic benefits of DLR for the consumers, as it is a multifaceted and difficult topic. This method can be used for preliminary assessment of the benefits, as well as to rationalize the application of DLR in certain transmission interconnections.

The method application for the demonstration case shows the potential and significance of increasing the power transmission capacity and ratings between Sweden and Finland, and especially related to the power transmission congestion from Sweden to Finland.

The potential of DLR based on actual real time ampacity is deliberately underestimated with the ambient adjusted ratings when using the proposed method. This is in order to be able to give clear proof of the potential of increasing NTC on the cross-border in order to relieve congestion and provide savings for the consumers while maintaining reliability at the same level as with the static line ratings.

Discussion

The deterministic method presented in this paper gives rough estimates with conservative assumptions. The results obtained using this method could pinpoint the cases that ought to be studied further for DLR implementation and evaluate possible benefits that the DLR could provide. Although the dynamic ampacity potential in the power lines in most of the power systems is significant, still the vast majority of power system operators persist in using static line ratings for the sake of power system reliability.

Even with confidence in local weather or temperature measurement data, the NTCs calculated using these very conservative assumptions may not be reliable enough for the power system operation in real time. Furthermore, this method is not intended to be applied in the power system operation with the DLR. In order to employ increased power line ratings effectively, the application of an appropriate transmission line monitoring method and well defined DLR operation procedure would be required to maintain a high power system operational reliability and security at all times. This would also enable the utilization of the very significant potential of wind for cooling that is now ignored.

Although the power system security would be maintained and guaranteed by DRL and transmission line real time monitoring, the transmission capacity information must be announced for the electricity market usually the day-ahead, e.g., 12–36 h before the operation-hour. It may be necessary to use DLR forecasting for the assessment of the transmission capacity to be provided for the electricity market. This day-ahead forecasted capacity could be considered with confidence margins. The forecast could be revised after this until the operation-hour, and electricity market actions and cross-border transmission be dealt with on the short-term market, i.e., Elbas in Nordpool.

There exist needs to develop methods for further analysis both in an academic, as well as a case, power system and electricity market specific purposes. There is also a need to study further and define the optimal procedures, on the first hand in handling the power system security, and on the other hand, making the decisions that are economically the most beneficial for the society.

References

[1] IEC 61597. Overhead line electrical conductors – calculation methods for stranded bare conductors. Geneva: IEC; 1995.

[2] IEEE standard for calculating the current-temperature of bare overhead conductors. IEEE Std 738-2006 (revision of IEEE Std 738-1993); January 2007.

[3] Thermal behaviour of overhead conductors. CIGRE working group 22.12; August 2002.

[4] Kiessling F, Nefzger P, Nolasco JF, Kaintzyk U. Overhead power lines, planning design construction. Springer; 2003. p. 224–8.

[5] Schmidt NP. Comparison between IEEE and Cigré Ampacity Standards. IEEE Trans Power Delivery 1999;14(4):1555–62.

[6] Abbott S, Abdelkader S, Bryans L, Flynn D. Experimental validation and comparison of IEEE and CIGRE dynamic line models. In: 45th International universities' power engineering conference (UPEC); August–September 2010. p. 1–5.

[7] Simms M, Meegahapola L. Comparative analysis of dynamic line rating models and feasibility to minimize energy losses in wind rich power networks. Energy Convers Manage 2013;75(November):11–20.

[8] Davis MW. A new thermal rating approach: the real time thermal rating system for strategic overhead conductor transmission lines – Part I – General description and justification of the real time thermal rating system. IEEE Trans Power Apparat Syst 1977;PAS-96(3):803–9.

[9] Chu RF. On selecting transmission lines for dynamic thermal line rating system implementation. Trans Power Syst 1992;7(2):612–9.

[10] Greenwood DM, Taylor PC. Investigating the impact of real-time thermal ratings on power network reliability. IEEE Trans Power Syst 2014;29(5):2460–8.

[11] Guide for selection of weather parameters for bare overhead conductor ratings. In: CIGRE working group B2.12; August 2006.

[12] Determining the transmission capacity, Fingrid; October 2009 <http://www.fingrid.fi/fi/sahkomarkkinat/markkinaliitteet/Rajakapasiteetit%20ja%20siirrot/transmission_capacity.pdf> [last accessed on 17/10/13].

[13] Foss SD, Maraio RA. Dynamic line rating in the operating environment. IEEE Trans Power Delivery 1990;5(2).

[14] Schurig OR, Frick CW. Heating and current-carrying capacity of bare conductors for outdoor service. Gener Electr Rev 1930;33(3):141–57.

[15] Overhead electrical lines exceeding AC 45 kV. Part 3–7: National normative aspects for Finland. CENELEC standard SFS-EN 50341-3-7; August 2010.