Application of dynamic rating to improve transportation capability of the power systems connected to wind power plants

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***Abstract*— Transmission and distribution networks are facing major challenges. The change in electricity production and consumption patterns claims for an improved flexibility in the dispatch of energy throughout the grid. Among the different possibilities, Dynamic Line Rating (DLR), is emerging as the most interesting solution from both the economic and technical points of view. The presented Thesis work investigates the performance of DLR from both the theoretical and practical perspectives. IEEE 738 standard analysis highlighted weaknesses on the theoretical approach employed on the forced convective cooling calculation. The results show that an inclined wind-conductor relative direction can have a more important impact on the line rating than foreseen with the IEEE thermal model. The practical side of the work include the performance investigation of DLR as a mean to introduce new wind energy on a pre-existent 130 kV OHL. Results show that wind energy production is often associated with an increased cooling on the line's conductors. For the selected hot-spot, in 2015, DLR would have allowed a transport capability improvement of 69.6% during the summer and of 26.7% during the winter. Overall DLR proved to be the most interesting solution from both the technical and economic points of view.**

Keywords: ***Dynamic line rating, overhead lines, conductor temperature model, wind energy.***

Introduction

Energy has been traditionally supplied by big power stations able to adjust outputs in order to follow the peculiar dynamicity of the demand (e.g. Hydropower, Nuclear, Carbon or oil thermal power plants). Under this assumption, the network has been shaped with the objective to dispatch constant forecastable power flows. These conditions are not longer valid since the renewable energy production share is rising year by year in order to decrease the human impact in the ecosystem. Renewable energy production is characterized essentially by two factors: The distribution of the plants along a spread area in order to exploit the maximum available diffuse resource; and the intermittent production due to the impossibility to precisely foresee the resource availability in time and space. These peculiarities affect dramatically the management of energy flows in the grid. Under these conditions grid owners are struggling in order to face this radical change ensuring minimum expenses in network investments. Among the different possibilities Dynamic Line Rating (DLR) is emerging as the most interesting solution from both the economical and technical points of view. The work is divided in two main parts.

Part one reviews the performed laboratory test. A wind tunnel have been employed to obtain precise measurement on the cooling process of an OHL conductor. The results have been compared with the IEEE thermal model predictions in order to verify if the effect of different wind speed angles is precisely obtained with the cited calculation standard.

Part two reports the work done on a real study case. The favorable wind conditions present in the Southeastern part of Sweden welcomed the installation of several wind farms. New turbines will be erected in the coming future and it is necessary to understand if the present energy grid is ready to accommodate higher energy fluxes due to the wind energy production. The study case concern specifically two OHLs and the installation of a new 27 MW wind farm. A technical and economical investigations are performed in order to understand what is the best adoptable solution for Ellevio AB which is the grid owner.

Wind Tunnel Test

Considering the performed Lab tests as of now, it is possible to recognize how, in the different study cases, attention has been devoted mainly to wind speed cooling magnitude and radial temperature profile of the conductor. Few tests can be found concerning the verification of how different wind flow directions affect the heat transfer process. The hypothesis that justify the performed laboratory is that an OHL conductor shape is not perfectly cylindrical and not a uniform body. This will affect the convective cooling of a real OHL. The experiment aims at increase the reliability of the DLR concept enriching the knowledge on the convective cooling of an OHL.

Methodology

One of the available wind tunnels of KTH aerodynamic department has been employed to simulate the cooling of different pieces of overhead lines under different wind flow conditions. The tunnel section has two wooden windows on the left and right sides. These windows have been replicated and modified. On the window sections different circular holes have been drilled to host two conductive steal junctions.

The junctions are shaped in order to accommodate different conductors' diameter. Junctions are then fixed on different holes present in the windows in order to obtain measurement with different angular position. This configuration avoid the creation of air leakages on the windows. Leakages would disturb the air flow inside the wind tunnel section. The wind is created through a fan placed downstream respect the accessible tunnel section. Wind speed can be adjusted, varying the fan rpm, between 0 and 25 m/s.

The Power have been supplied directly from the laboratory electrical grid. Since high current are needed to simulate the real load of OHL a variable and a fixed output transformers have been placed in series. The high final transformer ratio allowed to reach currents up to 600 A. The current has been regulated manually changing the spires ratio of the autotransformer. The variables that have been measured are: wind speed, current and conductor temperature.

- Wind tunnel speed has been regulated through the rpm of the fan. A Pitot tube has been employed to measure the wind speed in front of the conductor.

-The current has been measured through two different current probes applied on the connecting cables.

-Temperature has been measured in different conductor's position through thermocouples applied in small drilled holes filled with thermal paste.

Temperatures have been monitored and processed through PICO software [1]. Wind speed and current have been traced and analyzed employing National Instrument design software called LabVIEW [2].

Ellevio AB provided the OHL piece to be tested. Its characteristics are listed in the following table.

		Stranding and Wire Diameter [mm]			
Code name	**Nominal Area [mm^2]**	**Al**	**Steel**	**Overall Diameter [mm]**	**Resistance [Ω/km]**
Al 59	241	19/4.02	0	20.1	0.1230

Table 1: Tested conductor characteristics.

Results and discussion

The obtained results are presented and discussed. Laboratory measurements are analyzed to understand how the different variables affect the conductors cooling. The results are compared with the developed thermal model. The model calculates the thermal transient of the OHLs pieces taking in consideration Joule heating, convective and irradiation cooling. Overall, the results show a bad match between laboratory and model results. The developed KTH laboratory set-up experienced higher temperature and thermal time constants respect the model forecasts. This could have been a consequence of the system high thermal inertia.

This effect is most probably due to the short pieces length compared to the heavy junctions' dimensions. The following graphs report the results obtained for the Al59 241mm^2 conductor. The graphs show the comparison between the final steady-state temperature for the two different wind angles (90° and 40°); for the test and model cases. The considered wind speeds are 1, 2, 5, 10 and 16 m/s.

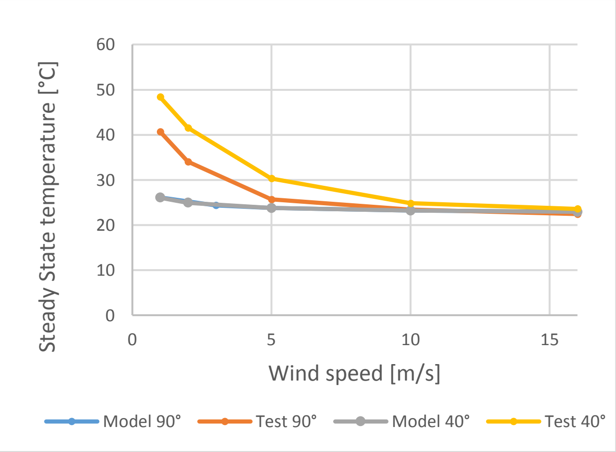

Figure 1: Final steady-state temperatures in the different analyzed cases.

The test equilibrium temperatures are higher for low wind speeds and became similar to the model ones for higher values. The steady state temperature for the 40°, 1 m/s case is 185% the value obtained from the model. While it is possible to notice a substantial difference between the two different directions in the test results (22% higher for the inclined respect the perpendicular direction at 2 m/s), practically no differences are found in the model example.

An aluminum rod has been tested in order to further evaluate the effect of a stranded structure respect a perfect cylindrical conductor. The final steady state temperature is practically the same in the two different cases while the thermal time constants varies considerably for low wind speed. With a wind speed of 1 m/s the rod time constant have been 10 times higher respect the stranded conductor. Increasing the wind speed the difference in the cooling time decreases. With a wind flow of 8 m/s the calculated time for the rod is of 4.5 minutes while for the conductor is 3.83 minutes (circa 20% higher).

It is showed that considering aluminum conductors as cylinders would bring to inexact results. For this reasons results obtained from the CFD simulation employed in [3] should be carefully evaluated.

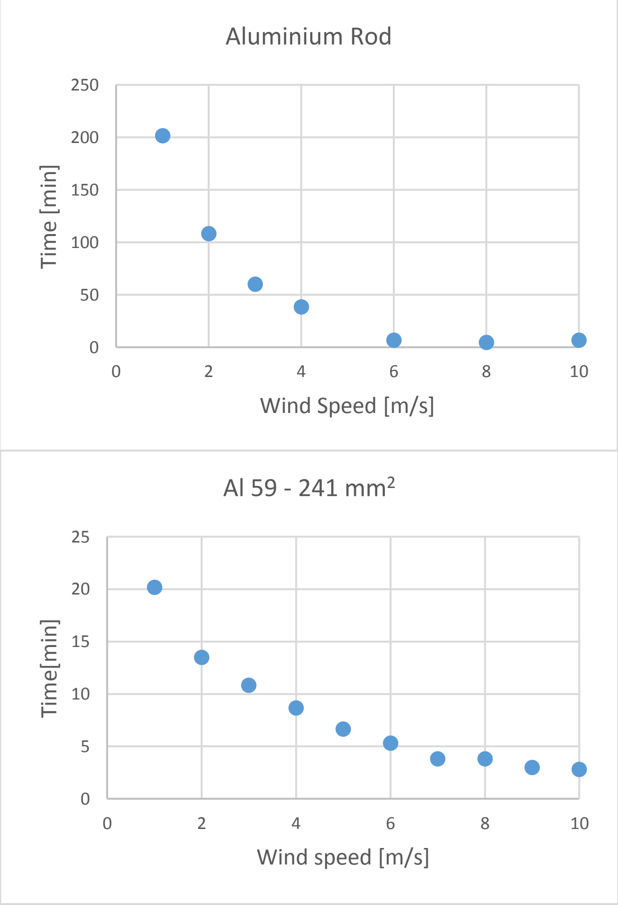

Figure 2: Results comparison between aluminum rod and same diameter dimension aluminum stranded conductor.

Conclusion and Future Works

The performed laboratory at KTH has been the first of a series of tests aiming at simulate OHLs conditions employing a closed wind tunnel. The laboratory results show that the effect of a change in the wind angle has a higher magnitude respect the one foreseen by the IEEE thermal model. This, preliminary, confirm the stated hypothesis. However, due to the high difference between test and model results it is not possible to understand in what extent the set up imprecision affected the obtained measurements.

Different imprecisions derived from the simplicity of the used set-up. In order to obtain sensible data useful to find a precise answer to the initial objectives it is necessary to increase the precision of the laboratory equipment.

Specifically difficulties have been experienced in the following procedures:

- Regulation of the current. Since no automatic control on the current has been employed, to maintain a constant value along all the measurements has been nearly impossible. The current decrease is related to the change of the conductor and copper cables resistance with the increase and decrease of the temperature. The same phenomena has been experienced in [4].

- Thermocouples precise installation. Differences of millimeters in the thermocouples positioning caused important differences in the results. It is suggested to carefully plan the sensors' position and to glow them directly on the conductor since wind flow, causing oscillations, affect the obtained results. An example of good placement of the couple can be found in [5].The thermocouples were mounted in stainless steel sheaths, and attached to the conductor surface with aluminum tape.

- Precise Regulation of wind speed. Wind speed has been regulated manually changing the fan rpm. This system proved to be quite accurate.

Another important factor to consider is the consideration of the conductor Tension. As reported in [6],[7] tension has a relevant influence on the conductor radial temperature distribution. Future experiments should aim at the inclusion of load cells in order to simulate real line conditions.

Study-case

Swedish installed wind power is expected to reach 6466 MW by the end of 2016 [8]. This power will be supplied by 3382 turbines spread on the Swedish territory [8]. Favorable wind conditions are found mostly in the southern part of the country [9]. Värmland region is located in the South-West area. Ellevio AB owns different lines located in this territory and will need to face the installation of new wind power capacity in the coming future. Two sensible OHLs will be analyzed to estimate the impact of DLR installation as a mean to accommodate higher current levels in pre-existing networks. These two OHLs are in this article named line A and line B.

Average wind measurements are available from both the vicinity of the farm (Årjäng at 100 m height) and of the OHLs (Arvika at 10 m height). The two sites are approximately 40 km far from each other. In order to understand the relation between wind energy supply and OHL cooling magnitude, data from the two locations are compared to analyze the correlation between the wind condition in the different locations. The results are depicted in the following figure.

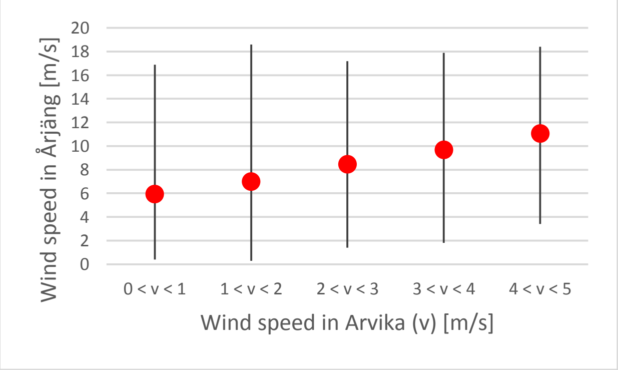

Figure 3: Correlation between the wind speeds measurements in Årjäng (hub turbine's height) and Arvika (10 m) during 2015. The red points represent the average speed and the vertical lines the whole correlation range.

An average good correlation is present also if several possible risky conditions have been registered along the year. A wind speed of 16.9 m/s, enough to fully power a standard wind turbine, co-existed with moments of still wind conditions at the OHL location. In these instances, the increase in the line current, is not correlated with an increase conductor cooling. Thus, during these periods, overloads of lines are possible and this remind how important is the monitoring of the network conditions. Considering that these critical events have been recorded only during few occasions it is possible to suppose that generally a higher wind energy supply coincide with an increased cooling capacity. In addition, the thermal effect due to an increased wind power supply is not directly proportional to the effect of the increase wind convective cooling.

It is important to notice that, as it has been demonstrated by the experiment, the difference between a wind speed of 0 and 1 m/s would incur in an important increase of the cooling capacity. Also, the difference between a perpendicular or parallel direction respect wind and conductor has a substantial impact on the overall cooling process. Employing the IEEE thermal model standard the following results are found.

An "Ibis" ACSR conductor in an ambient temperature of 22 °C is considered. The increase of the wind speed from 0 to 1 m/s make the cooling capacity grows from 5.8 W/m to 44.489 W/m (almost 7 times higher) increasing the current rating of 265 A. For a wind speed of 1 m/s, the calculated convective cooling capacity of a perpendicular and parallel wind directions is of 44.49 W/m and 17.26 W/m respectively (2.5 times lower). This reduce the current rating of 170 A.

Analyzing the lines' profile it is possible to notice how a small part of line B is in West-East direction. This means that the wind will flow parallel to this span for the majority of the time. Forests are present in the area. The presence of high trees creates wind shadowing effects on the line reducing the effective wind speed hitting the conductor. Ellevio AB identified this location as one of the hottest sections of the line, i.e. a critical span, which is likely to limit the ampacity of the whole circuit.

To understand how the span behaves in different climate conditions line and weather data have been precisely monitored and analyzed along the entire 2015 year.

The collected data include:

- Line current. The data is obtained from active power measurements on lines A and B.

- Three hours interval weather data. Temperature, wind speed and direction have been retrieved from Arvika SMHI weather station [10]. The weather station is 18 km far from the hotspot.

- Conductor characteristics. The employed conductor is called Ibis. It is an ACSR conductor with an overall area of 234 mm^2.

The temperature ranged between 30 and -20 °C with an average of 6.63 °C. The registered medium wind speed is 1.5m/s. It reached peaks of 7.5 m/s. In Figure 4 it is possible to notice that there is not an evident correlation between air temperature and wind speed during the selected period.

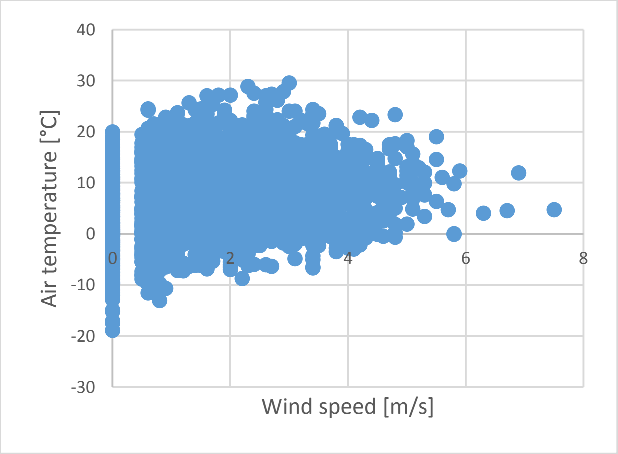

Figure 4: Correlation between ambient temperature and wind speed at Arvika weather station.

It is important to notice that clouds effect is not taken in account. Due to the high variability that the cloudiness level has, direct radiation is calculated all along the year without considering the clouds shadowing effect. This choice ensure that the obtained results are conservative.

An Excel and Matlab models have been developed in order to estimate the line temperature during the selected period. Differently from the model developed for the laboratory analysis, the latter calculates the current rating in steady state conditions.

The thermal heat rate exchange has been calculated following the IEEE 738 standard. The allowed maximum current is calculated through the following formula:

$$I_{MAX} = \sqrt{\frac{Pc+Pr-Ps}{R}} \qquad (1)$$

Where P_c and P_r are convective and radiative cooling, P_s is the solar heating and R the resistance of the conductor. To calculate the rating it is necessary to decide the maximum temperature that the conductor can withstand without incurring in annealing or clearance to ground issues.

For the selected line 50 °C is taken as the maximum allowed temperature. The selected line is rated with the SLR method. Two different limits are present, one summer and one winter rating. The maximum ampacities obtained for the two different periods are reported in the following table.

	Ambient temperature [°C]	**Wind speed [m/s]**	**Ampacity [A]**	**Period of validity**
Summer	30	0.6	**344**	1st of May to 30th of September
Winter	10	0.6	**531**	Rest of the year

Table 2: Summer and winter static line ratings.

DLR and SLR amapacities are compared along 2015. SLR is calculated considering the conditions reported in table 2. It can be noticed that that the model prediction crosses different times the SLR limits. This is an important result since SLR ampacities would cause conductor overheating in many different occasions.

The registered current along the year however, has been way lower respect the static rating constraints. The current never went over the limits imposed by both SLR and DLR. In average the DLR current value has been 550 A higher respect the actual flowing current and 183 A higher respect the SLR. This means that there is extensive room for the inclusion of new energy fluxes in the grid.

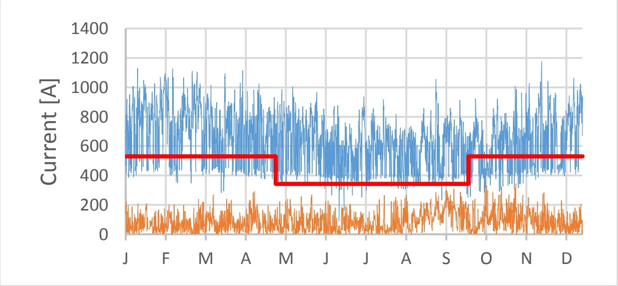

Figure 5: SLR (Red), DLR (Blue) and actual flowing current (orange) on the selected hotspot.

DLR is compared with the static ampacities for the two different seasons. It is observed that the ampacity is underestimated for most of the time. The following table reports the resulting values that can be resumed from Figure 5.

	Time DLR > SLR	**Medium ampacity improvement**
Summer	96.5%	69.6%
Winter	68.0%	26.7%

Table 3: Uprating margin results for 2015.

During the coldest months, as it can be noticed in Figure 6, DLR have been lower respect the SLR for 32% of the time. This value is of concern since, if the load would reach the static maximum level, overheating issues would appear for a third of the total season length. The winter wind speed cumulative probability is reported in Figure 7. The wind speed is lower than 0.6 m/s (Value estimated with SLR approach) is 30%. This suggests that the SLR wind speed choice is not conservative and remind the importance of the convective cooling component in the overall conductor thermal behavior.

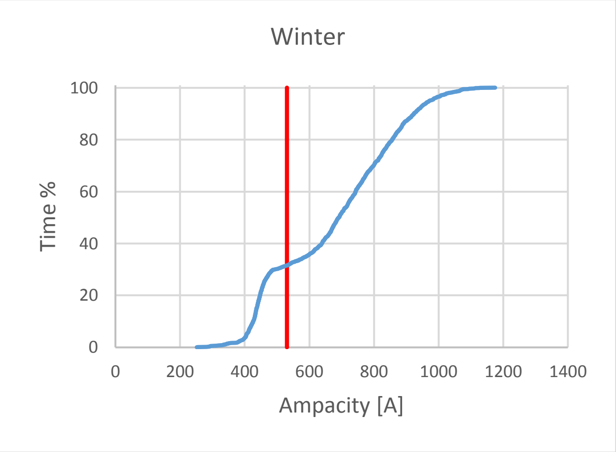

Figure 6: Winter ampacity probability distribution.

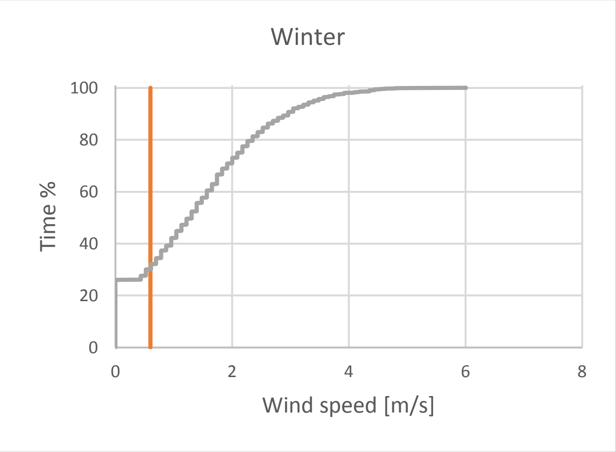

Figure 7: Winter wind speed probability distribution.

Consequences on sag

In order to evaluate the SLR ampacity overestimation drawbacks the transient IEEE thermal model is employed to simulate the conductor temperature response to an excessive current. The maximum difference between SLR and DLR along 2015 has been of 275 A. This happened in the morning of the 2nd of October. Table 4 depicts the climate conditions present at that time. SLR overestimation is due to the presence of a lower wind speed and a higher air temperature respect the considered winter worst scenario.

It is assumed that the initial conductor temperature is 50°C. The transient is evaluated for 10 minutes. The results are depicted in Figure 8.

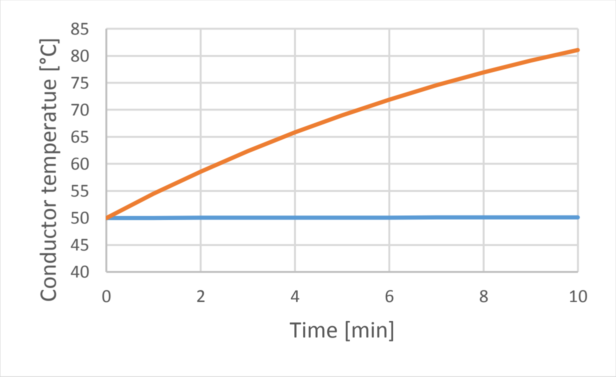

Figure 8: 10 minutes conductor thermal transient difference between SLR (531 A) and DLR (256 A) on the morning of the 2nd of October 2015.

If the temperature/sag trend found in [11] is considered valid for the hotspot span, the line would sag 1.15 m more than expected at the end of the 10 minutes. This value can become dangerous in case of the presence of public roads or other obstacles under the OHL.

Air Temperature [°C]	Wind speed [m/s]	Qs [W/m]	SLR [A]	DLR [A]	Sag difference [m]
11.1	0	12.98	531	256	**1.15**

Table 41: Climate parameters and calculate additional sag in the morning of the 2nd of October 2015.

In the reality any issue have been registered on the line since the current level was low at the same time (3.26 A).

Since the calculations have been performed for the maximum registered overcurrent, the sag excess would have been less than 1.15 m along the rest of the year (considering a maximum thermal transient duration of 10 minutes).

K_{angle} Effect

The first part of the Thesis project aimed at the verification of the coefficient K_{angle}. This parameter is employed in the forced convective cooling calculation of the IEEE standard. The laboratory imprecisions did not allow to have a precise understanding of the parameter accuracy. The following sensitivity study has been conducted In order to estimate the influence magnitude of K_{angle} on the conductor cooling. Results shows that the coefficient substantially influence the conductor's rating. The graph in Figure 9 depicts the effect on the calculated DLR with a +/- 10% change of K_{angle} value.

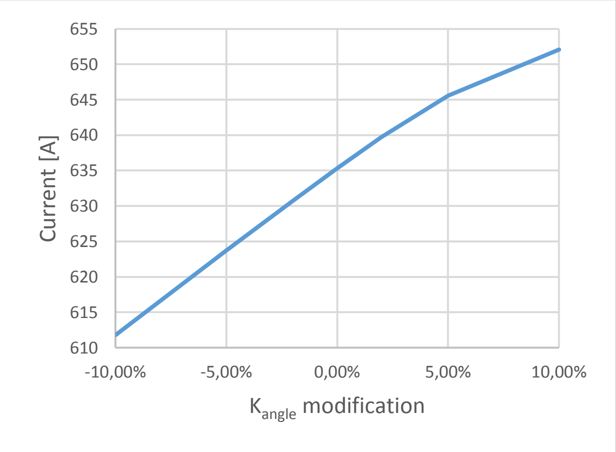

Figure 9: average ampacity rating modification due to a decrease or increase of Kangle.

A 20 % increase of K_{angle} make the average ampacity increase of 40 A circa (that for the investigated OHL corresponds to an increase of 9MW in the allowed power transmission). It is concluded that the effect of K_{angle} can have an important role on OHLs rating and further investigations should be conducted in order to better estimate the conductor conditions when the wind does not flow in perpendicular direction.

New Wind Farm Installations

As it has been noticed previously, the current flowing on line B does not represent a risk for the conductor itself since both DLR and SLR are respected. The situation could change if new wind power will be installed in the area. In order to evaluate this hypothesis, the installation of nine new wind turbines will be evaluated. The selected wind turbine type is Vestas 112. This wind turbine has a nominal power output of 3.075 MW.

The total yearly production is of about 87 GWh with a resulting Capacity factor (Cp) of 35.9%. This data is even higher respect the prospected from the wind farm owner (75 GWh) due to the high average wind speed registered during 2015 at the turbines location (7.25 m/s). It is assumed that in average 60% of the produced wind power will flow in line B. With this assumption it is calculated that, in average, line B current increased of 26.5 A respect the load without the new wind farm. Despite the new installed power, also in this case, the actual current is always lower than DLR limits. This means that the installation of the wind farm would have not incurred in any overheating issues along 2015 .This also means that no energy curtailment would have been necessary, allowing the complete exploitation of the renewable resource. The same was not true if the SLR approach would have been adopted. The current went over the limit for a total of 12h hours causing the necessary curtailment of 37.41 MWh of wind energy.

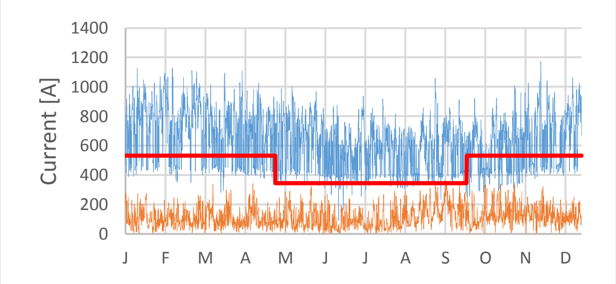

Figure 10: Updated current supply with the inclusion of nine new wind turbines.

It is possible to notice in Figure 11 that the difference between the two approaches is clear. Energy would be curtailed employing DLR starting from the installation of 27 new wind turbines (41.07 MWh). In the extreme situation of 54 new installed wind turbines the energy curtailment due to SLR would be 8.65 times higher respect the needed 2.56 GWh with DLR. The following graph depicts the case of the installation of 54 new Vestas 112 wind turbines.

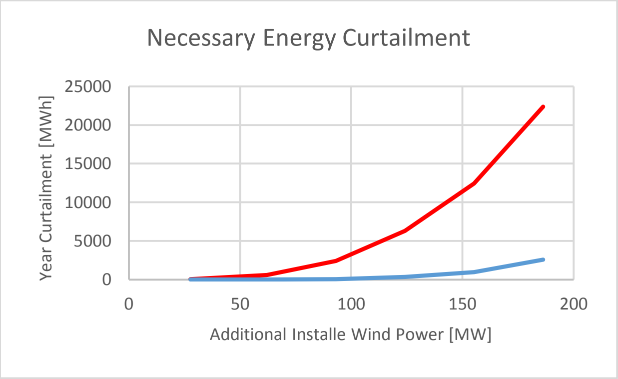

Figure 11: Increase in the necessary energy curtailment due to the installation of new wind turbines. The analysis ranges between 9 and 54 new turbines.

Conclusion

The performed investigation proved that DLR is the best mean to introduce new wind farms in the network. When the wind farm energy supply does not vary substantially the previous grid load, a dynamic monitoring of the OHLs ensure important ampacities improvements without the need of expensive grid up-ratings, as the construction of a new line.

The monitoring of the lines is necessary to avoid annealing or clearance to ground issues caused by conductors overheating. The different field climate data are analyzed in order to obtain the conductor temperature. This calculation can be performed using different conductor thermal models. To ensure a safe operation of the OHLs with a DLR approach it is necessary to certify the accuracy of the cited models and verify their effectiveness. Small error can incur in important consequences.

IEEE calculation standard has been analyzed and weaknesses have been found on the theoretical approach employed for the forced convective cooling calculation. Specifically the wind direction effect is estimated as the conductor was a perfect cylinder. A wind tunnel test have been performed in order to verify the effect of the conductor's strands on the total thermal equilibrium.

The results show that an inclined wind-conductor relative direction can have a more important impact on the line rating than foreseen with the IEEE 738 standard. Because of different laboratory deficiencies the obtained results have not been accurate enough to further investigate the precision level of the analyzed standard. The laboratory set-up precision and control should be improved in future projects in order to have a correct estimation of the conductor heat transients.

The test however confirmed the important influence that forced convective cooling has on the overall conductor thermal balance and proved that stranded conductors cannot be exactly compared with perfect cylinders.

The literature contains several investigation of the methods, both from a practical and a theoretical point of view. Theoretically different weakness in the methods are reported. Field-test experiences on the contrary show that the present precision level is accurate enough to utilize DLR on a larger scale. It is also true that, in Europe, the 15 TSOs that use DLR nowadays does not utilize it as an automatic answer to overload issues. This suggest that even if the employed devices are reliable, a wider field experience is needed to reach higher confidence level with the innovative technology.

Ellevio AB supplied the possibility to investigate the potential benefits of DLR on two weak OHLs in Värmland; a region located in the Southeast of Sweden.

The region has a high wind resource potential. For this reason wind farm owners want to increase the total wind power installed in the area. Specifically the work analyses the impact of the introduction of a 27 MW wind farm on a sensible grid. Two 130 kV OHLs are investigated and results show that, not only DLR would allow a full exploitation of the wind farm, but would also protect it from possible overheating contingencies due to SLR ampacities overestimations.

DLR is particularly suggested in the area because the same favorable wind conditions that power the wind turbines are capable of cooling down the OHL conductors allowing higher currents to be transferred.

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