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Risk analysis of wind farm connection to existing grids using dynamic line rating

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Abstract—Dynamic Line Rating (DLR) is a technology that allows extending capacity of existing power lines for transportation higher electrical power capacity from production site to the customer. Environmental conditions such as air temperature and wind speed have significant impact on the heat balance of the power line, therefore by monitoring the weather parameters one can dynamically vary the capacity of power line. Brief analysis of the wind speed and direction effects on the cooling of overhead lines and principles of wind power generation provide a background for the analysis of wind power connection to the existing power lines by means of Dynamic Line Rating.

This paper presents the case study of wind farm connection to the existing power line by application of DLR. Statistical weather data and information about system properties give an input parameters for the risk analysis of the dynamic rating application and highlight benefits of using DLR. The results show a potential to expand the transportation capacity of the line by injecting more wind power. Probabilistic analysis of the historical weather data and reliability analysis of the system show that line capacity can be expanded with more wind power without affecting availability of the connection.

I. INTRODUCTION

Current process of building new wind farms requires a lot of planning and analysis. In addition to it, the connection of new wind farms to the grid is a challenge on its own. Sometimes wind farm owners have to wait for grid connection after construction of the wind farm has been finished. Instead of building new transmission lines, new wind farms can be connected to the existing lines by means of DLR. DLR has a potential to connect new wind farms to the grid faster, by minimizing construction efforts on necessary transmission system [1][2][3].

Dynamic rating allows adding more capacity to the line in operation, when the environmental conditions are favorable. Standard ratings are usually calculated for extreme weather conditions, which is during a hottest summer day with very low wind. By using Dynamic rating it is possible to use capacity of the line more effectively [2][4].

Dynamic rating technology employs information about the overhead conductors heat balance in order to determine their actual ampacity. The main components that contribute to the heat balance of the power line are: convective cooling (cooling due to fluid motion), radiative cooling (emission of the heat from the surface to atmosphere by electromagnetic waves), solar heating (absorption of the electromagnetic radiation from sun and sky by the material) and Joule heating (heating of the

line by electric current) [5][6]. Dynamic line rating can have several levels of accuracy depending on the way it is applied to the system. DLR methods range from algorithmic application of thermal models based on the weather forecast to monitoring devices with various levels of precision that are installed at the power line location [7]. In the further analysis we will consider DLR by application of weather model (WM), which is the simplest DLR method [7]. Dynamic rating by WM technique allows increasing the line capacity by up to 20%, depending on the weather conditions [1][5][6].

There exists a significant number of literature sources that describe possibilities of Dynamic Line Rating application. However, there is a need in more information regarding the risks that DLR brings to the system and analysis of the availability of the line after DLR application.

In the following section we present a case study of the existing power line scenario and possibility to extend its capacity by connecting the wind farm. Each DLR Application has its features, depending on the grid properties and specific ambient conditions at the line location. Therefore, the statistical analysis of the historical weather data is performed. Based on the weather analysis and DLR calculations the reliability analysis is performed. The results provide a reader with information about the risks of DLR application and suggestions on possible improvements.

II. METHODOLOGY AND INITIAL CONDITIONS

To evaluate a potential benefit of the dynamic rating for wind power integration we use a overhead line located in the northwest mainland in Sweden. The line connects a convectional power plant with standard summer rating of 344 A (October – April) and winter rating of 531 A (May–September). The standard winter and summer ratings are designed for the extreme weather conditions. The information about physical properties of the overhead line can be found in Table I.

TABLE I: Conductor specification

Name	Ibis	Emissivity	0,8
Type	ACSR	Absorptivity	0,8
Area, mm ²	234	Voltage, kV	130
Resistance	0.1434	Maximum allowable temperature, °C	50

For the estimation of the correct rating of the conductor we have used IEEE guidelines “IEEE standard for Calculating the

Current-Temperature Relationship of Bare Overhead Conductors” [5]. The rating of an overhead line conductor can be expressed by (1) [5].

$$I = \sqrt{\frac{(q_{conv} + q_{rad} - q_S)}{R(T_C)}}, \quad [A] \quad (1)$$

where q_{conv} is the convectional cooling of the conductor, $[W \cdot m^{-1}]$; q_{rad} is the radiative cooling of the conductor, $[W \cdot m^{-1}]$; q_S is the solar heating of the conductor, $[W \cdot m^{-1}]$; $R(T_C)$ is the specific conductor material resistivity at certain surface temperature, $[\Omega/m]$.

The convective cooling q_{conv} for low wind speeds is calculated using (2) and for high wind speeds using (3). However, IEEE guidelines recommend calculating both variables q_{c1} and q_{c2} for each wind speed and using higher of two values [5].

$$q_{c1} = \left[1.01 + 0.0372 \left(\frac{D \rho_f V_w}{\mu_f} \right)^{0.52} \right] \cdot k_f K_{angle} (T_C - T_A), \quad [W \cdot m^{-1}] \quad (2)$$

$$q_{c2} = \left[0.0119 \frac{D \rho_f V_w^{0.6}}{\mu_f} \right] k_f K_{angle} (T_C - T_A), \quad [W \cdot m^{-1}] \quad (3)$$

where D is the conductor diameter, $[m]$; ρ_f is the air density, $[kg/m^3]$; V_w is the wind speed, $[m/s]$; μ_f is the dynamic viscosity of the air, $[kg/m \cdot s]$; k_f is the thermal conductivity of the air at average temperature $(T_C + T_A)/2$, $[W \cdot m^{-1} \cdot K]$; T_C is the conductor surface temperature, $[^\circ C]$; T_A is the ambient temperature, $[^\circ C]$; K_{angle} is the wind angle coefficient, which is calculated by (4) [5].

$$K_{angle} = 1.194 - \cos(\phi) + 0.194 \cos(2\phi) + 0.368 \sin(2\phi) \quad (4)$$

where ϕ is the angle between the overhead line conductor and the wind direction, $[deg]$ [5].

For the future analysis angle coefficient is assumed to be equal to $K_{angle} = 1$ or $\phi = 90^\circ$ during 100% of the time. It is hard to estimate the exact angle between the power line and the wind flow direction, because power lines travel for 10th of kilometers and tend to turn several times along the distance. Preliminary analysis of the line heat balance shows that for the wind temperatures lower or equal to $-5^\circ C$ provide enough power line cooling to host additional power at any wind speed. The following analysis considers constant rate for solar heating and radiation, which corresponds to the highest level during the midday in the summer. The radiative cooling component q_{rad} and solar heating component q_S are obtained using IEEE guidelines assuming east-west direction and azimuth of line equal to $Zl = 90^\circ$. The value of q_S was calculated for mid day, in order to account for the highest possible value of the solar heating [5]. For simplification of the analysis value of q_S is kept constant, considering the maximum possible q_S value for the hottest afternoon of month July for a given latitude.

The information on weather conditions at the location are collected from a weather station in the close proximity; the historical weather data for the course of 10 years is available at SHMI [8]. The weather information consists of wind speed and air temperature measurements; collected data points represent

5 minute average values. General weather conditions in the region can be considered continental. Peak high temperature is $+26^\circ C$, peak low is $-27^\circ C$. Peak wind speed is 29 m/s. Wind conditions in the area a changing and the average wind speed is 6.5 m/s [7].

The following study will explore the possibility to connect an on-shore wind farm consisting of 10 wind turbines 3.6 MW each, total nominal power of 36 MW. The wind farm will be joined to the overhead line that connects conventional power plant to the grid by application of Dynamic Line Rating.

The wind farm requires additional capacity of 160 A, when the production is at nominal power level. However, wind turbine generation is determined by the power curve and depends on the wind speed in the area. Wind farm does not operate with the wind speeds below 3 m/s and higher than 25 m/s. Using the open source power curves the approximate power production of each turbine under different wind conditions was calculated. Wind direction was not taken into account in the analysis. It has to be mentioned, that power output of the wind park strongly depends on the roughness of terrain in the area and turbulence created by turbines, shading one another. The required ampacity for each additional level of wind power generation depending on the wind speed is presented in Table II.

TABLE II: Power production for each turbine for different wind speeds based on the power curve for 3.6 MW wind turbine.

Wind speed, m/s	1 turbine power production, kW	Wind farm power out, MW	Wind farm rating for each wind speed, A
0-3	0	0	0
4	200	2	9
5	450	4,5	20
6	700	7	31,5
7	1050	10,5	47
8	1600	16	71,5
9	2250	22,5	100
10	2900	29	129
11	3350	33,5	149
12-25	3600	36	160
>25	0	0	0

Based on give initial conditions the analysis aims to: determine wind farm availability, considering fault rate and weather conditions; explore the possibility of increasing production from conventional power plant during the summer period. Statistical analysis of historical weather data is used for the estimation of possible line ratings for each month.

III. RISK ASSESSMENT

To identify the possible risks of Dynamic line rating application it is necessary to analyze the weather parameters in the area. Statistical analysis of the 10 year 5 minute average weather data have been performed; Figure 1 shows the frequency of different wind speeds occurring (step=1 m/s) as a share of total cumulative factor of 1.

Considering the dependence of wind power generation on wind conditions, we can approximate probability of having

certain power production from the wind farm in question; the frequency distribution for each month is shown in Figure 2.

Fig. 1: Frequency of different wind speeds occurring during each month based on the statistical weather data analysis.

Fig. 2: Frequency distribution wind power generation for each month considering historical wind statistics.

All turbines are in radial connection and have a separate disconnectors. If one turbine fails, other turbines stay unaffected.

The wind turbine failure rate is not a constant value and it varies depending on manufacturer, age, turbulence etc. In the literature there exist multiple number of suggested failure rates, the authors use failure rates suggest in [9] as a reference. Wind turbine failure rate is assumed to be equal to $\lambda = 0.154$ failures/year with mean down time $MDT = 123$ hours/failure on average [9]. By using failure rate and MDT we can estimate the mean time to failure (MTTF), availability (A) and unavailability (U) of one wind turbine by (5), (6), and (7) accordingly.

$$MTTF = \frac{1}{\lambda} 8760, \quad [hours] \quad (5)$$

$$A = \frac{MTTF}{(MTTF + MDT)} = 0.9978 \quad (6)$$

$$U = 1 - A = 0.0022 \quad (7)$$

From the reliability calculations for various number of failed wind turbines the conclusion is that with the $A = 1$ wind farm can guarantee having 50% of turbines under operation. The highest probability is of getting one turbine fail or 2-3 turbines fail simultaneously, however the probability of having more than one turbine fail at the same time period is low. The probability for number of wind turbines to fail simultaneously is shown in Table IV.

TABLE III: Turbine failures.

Number of failed turbines	failure rate, [failures/year]	Availability per state	Unavailability per state
1	0,15400	0,9979	0,0021
2	0,02372	1	4,57E-06
3	0,00365	1	9,89E-09
4	0,00056	1	2,14E-11
5	0,00009	1	4,63E-14
6	0,00001	1	1E-16
7	0,0000	1	2,16E-19
8	0,0000	1	4,68E-22
9	0,0000	1	1,01E-24
10	0,0000	1	2,19E-27

After the analysis of turbine failures it is necessary to take into account probability that undesirable wind conditions will occur. The undesirable wind speeds are below cut in wind speed of 0 – 3 m/s and above > 25 m/s, the wind farm does not operate outside the 3 – 25 m/s wind speed diapason. The cumulative probability of having undesirable wind conditions is $p_{no_operation} = 0,232077$, or approximately 84 days per year; it can be also expressed in terms of unavailability $U_{due_to_wind} = 0,232077$ and $A_{of_wind} = 0,7679$.

Figure 3 is build for graphical representation of the system for future calculation of the wind park reliability. Total wind park availability can be calculated by using reliability block diagram from Figure 3. The probability of each failure type from Figure 3 is summarized in Table IV.

Fig. 3: Reliability block diagram for wind farm connection to the grid with dynamic rating. Where: 1-10 are wind turbines; C is a power plant; W refers to the wind park; P is production site; L is a power line and D is DLR forecast.

TABLE IV: Probability of failure of system components

Turbine	0,0022
Wind farm wind conditions	0,232
Convectional power plant	0,01
Line faults	0,01
DLR	0,01

Based on the probability of failure for different components in Table IV, total failure probability can be calculated by (8).

$$p_{tot} = \sum p_{comp_{failure}} = 0,02232 * 100\% = 2,232\% \quad (8)$$

where $p_{comp_{failure}}$ is the failure probability of each component in Figure 3.

IV. RESULTS AND DISCUSSION

The resulting dynamic ratings for the month January and July are shown in Figure 4 and Figure 5. January and July are chosen as two month with the most extreme weather conditions.

Fig. 4: Comparison of the standard rating and real ampacity of the line at different wind speeds during January. Ambient temperature range is -27-5 °C

Fig. 5: Comparison of the standard rating and real ampacity of the line at different wind speeds during July. Ambient temperature range is 0-25 °C.

As represented in Figure 4 and Figure 5 the rating communicated to the system is 20% lower than the real calculated rating for the lowest wind speed and highest possible ambient temperature.

In Figure 6 calculation of fitting wind farm to the existing overhead line for each month considering predicted rating with 20% margin is shown. Figure 6 shows that after the Dynamic Rating application the line is able to fit both the wind farm and the convectional power plant capacity.

Fig. 6: Comparison of average line ampacity with DLR and standard rating of the line.

Taking into account the results from Figure 6, we can conclude that during May-September the probability of having wind speed higher than 10 m/s is around 12%, therefore there is room for exploring the possibility of connecting more renewable sources to the power line.

V. CONCLUSION

Results of the case study show that Dynamic Line Rating has a potential to provide new wind farms with fast grid connection by employing the information on the weather data in the area. Risk analysis of the DLR application has shown the possibility to increase the transmission capacity of the power lines when connecting wind generation. The wind power production and line capacity are highly dependent on the wind conditions in the area. When winds speeds are high the generation from wind increases, in the similar way the power line ampacity also increases; the extra ampacity can be used to fit the power generated from wind to the power network.

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