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Determining the Transmission Capacity of Existing Transmission Lines Under High Wind Generation Conditions

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Summary — Determining the transmission capacity of existing transmission overhead lines (OHL) is primarily defined by conductor ampacity. Transmission OHL needs to be loaded with the currents below their thermal capacity limit to avoid irreparable damage to conductor. The maximum value of current can be determined by the static approach (STR – Static Thermal Rating) or by the dynamic approach (DTR - Dynamic Thermal Rating). STR is defined by simple calculations and often does not change throughout the year while the DTR is calculated in real time taking into account actual atmospheric conditions, weather forecasts and actual conductor current. Most common approach used to calculate conductor temperature is by applying IEEE standard (IEEE 738, 2012) or CIGRE standard (TB601, 2014). During the higher production from wind farms caused by, higher wind speeds, it can be the case that local transmission OHL are loaded up to their limits and congestions can occur. But in case dynamic approach of capacity estimation is used it can show that due to high wind speed and better heat removal conditions the actual capacity of the line might be higher. In this paper, analysis of relation between atmospheric parameters, wind speed, wind direction, ambient temperature and solar insolation, and ampacity is described. Considering historical weather data from meteorological stations, actual atmospheric conditions on transmission OHL corridors and taking into account the frequency of occurrence of individual meteorological variations ampacity of conductor is determined. For determined ampacity the potential variation and uncertainty of estimation is provided through different indicators. The obtained results provide an insight into the change of OHL ampacity based on actual conditions and their potential to be loaded even over their rated ampacity in cases of high engagement of wind power plants.

Key words — capacity of over-head transmission line, conductor ampacity, conductor temperature, meteorological conditions, ACSR conductor (Aluminium Conductor Steel Reinforced), dynamic thermal rating DTR

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I. Introduction

Integration of large number of renewable energy sources into the power system potentially increases loading of some transmission OHL and can cause congestions is specific network segments. To avoid congestions it is necessary to consider possible solutions to increase the capacity of OHL and overall capacity of the transmission system. Construction of new transmission OHL can be challenging and depending on the circumstances can be economically unjustified. Therefore, different solutions to increase the capacity of existing OHLs are being considered. One of the ways to better utilize the existing OHL transmission capacity is to determine its actual, real time, operational ampacity in a certain moment based on measurements and actual weather conditions

OHL ampacity ratings determine the thermal limits of conductor and suspension equipment. During operation, it is necessary to respect the permissible thermal load that the equipment can withstand, to avoid incurring irreparable structural damage and loss of mechanical and electrical properties. In most cases operational ampacity is determined for most unfavorable weather conditions that can be expected on the transmission OHL corridor. This approach is called STR and can be defined for different periods of the year, for example winter and summer periods. Another approach is to determine ampacity limits of OHL in real time using DTR approach where operational ampacity is depending on the current weather conditions, most recent weather forecasts and on the actual status of the line [1], [2], [3].

Based on conducted studies determined operational ampacity highly depends on the speed of the wind and its direction. Wind is considered to be the dominant factor in process of dissipating heat from the conductor [4], [5], [6]. On higher wind speeds (≈ 20 m/s) operational ampacity can theoretically increase up to 4 times compared to low wind conditions [7]. At the same time under the higher wind speed conditions there is a high probability of having a significant production from wind power plants. Applying DTR where OHL have to operate near their operational limits is considered and with different weather conditions is considered [8]. Using DTR involves complex methodologies that need to be investigated separately for each case/corridor and that need to be in accordance with legal and technical requirements [9].

This paper considers influence of weather conditions on capacity/ampacity limits of transmission OHL. Determination of the transmission OHL ampacity is conducted in accordance with the IEEE 736.2012 standard [10]. In section 2 standard models for calculating conductor temperature are presented. Influence of environmental weather parameters is carried out in section 3. For observed case study transmission OHL and historical measured weather parameters analysis of DTR is described in section 4 and conclusion is given in section 5.

II. Current Ampacity of OHL

Calculations of the maximum current can be done using one of the standards (IEEE, CIGRE or IEC) that take into account structure and design of the conductor, the meteorological conditions and the operating conditions of the transmission OHL [11], [12].

Based on the mentioned standards, determining operational ampacity for OHL in operation can be done using either using STR or DTR approaches. Applying STR approach takes into account the most conservative climate and weather conditions for observed OHL. In reality, this approach gives very conservative limits and can lead to lower level of OHL capacity utilization. On the other hand, the dynamic DTR approach takes into account current meteorological conditions (wind speed and wind angle, ambient temperature and solar insolation) at critical and most demanding segments of the OHL corridor and based on them, calculation of operational ampacity is performed. The fundamental principle for determining operational ampacity of a conductor is its heat balance between the heat generation and heat dissipation. For this reason, taking into account current meteorological conditions proves to be a more effective approach for determining OHL ampacity.

Calculating temperature of conductor is possible using several standard, where IEEE and CIGRE standards are the most represented. Both standards apply the heat balance of the conductor to calculate the temperature of the conductor, where the IEEE standard gives more conservative results compared to the CIGRE standard. The same CIGRE standard is more suitable for practical engineering based on simplified online monitoring of OHL parameters [12]. CIGRE transient thermal equation of the conductor (eq. 1) describes the dynamic temperature changes due to changes in conductor current and changes in meteorological conditions along the conductor route. Equation (eq. 1) describes the dynamic change in temperature caused by conductor and meteorological condition changes.

$$q_c + q_r + q_w + mC_p\frac{dT_c}{dt} = q_M + q_C + q_S + I^2R(T_c) \qquad (1)$$

Where q_c marks convective cooling, q_r radiative heat loss, q_w evaporative heat loss, $mC_p\frac{dT_c}{dt}$ heat capacity of the conductor with m being the mass per unit length, c_p specific heat capacity of conductor and T_c the theoretical conductor temperature, q_m magnetic heat, q_c corona heat loss, q_s solar heat and $I^2R(T_c)$ joule heat losses where I^2 being current and $R(T_c)$ conductor resistance at the given temperature.

IEEE standard transient heat equation of the conductor (eq. 2) describes the temperature of the conductor in a simpler form considering that certain effects are not always present and relevant and ultimately their amount does not significantly affect the final temperature of the conductor.

$$q_c + q_r + mC_p\frac{dT_c}{dt} = q_s + I^2R(T_c) \qquad (2)$$

Where again q_r radiative heat loss, q_c corona heat, $mC_p\frac{dT_c}{dt}$ heat capacity of the conductor, q_s solar heat and $I^2R(T_c)$ joule heat losses.

Observing the IEEE heat equation of the conductor it can be concluded that the temperature of the conductor primarily depends on two main factors: 1) the current passing through the conductor; 2) the meteorological conditions around the conductor (wind speed, wind direction, intensity of solar radiation and ambient temperature). Current measurement can be done at the beginning and at the end of the transmission line while measurements of meteorological conditions need to be done on critical segments along the transmission OHL corridor. When all parameters are known and the input parameters do not change, heating and cooling of the conductor are equal, i.e. thermal balance is achieved and previous equation (eq. 2) can be rewritten in simpler form (eq. 3):

$$q_c + q_r = q_s + I^2R(T_c) \qquad (3)$$

From equation above (eq. 3) conductor current can be calculated when all meteorological conditions are known (eq. 4.):

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \qquad (4)$$

By calculating the abovementioned maximal current the operating transmission capacity of OHL can be directly determined. In most cases this DTR approach can lead to higher capacity compared to the STR calculated values, all under the assumption the voltage stability is also satisfied. In today's transmission networks active managing of transmission capacity through the process of determining its thermal limit can provide increased flexibility of operation.

III. Calculation of Maximal Current Using IEEE 738 Standard

3.1. Input parameters

When calculation is performed main parameters that affect conductor temperature can be divided into two groups, conductor parameters (conductor diameter, permissible conductor temperature, emissivity and absorption, altitude and latitude) and weather conditions (wind speed and wind angle, air temperature and insolation). All mentioned parameters depend on the conductor itself, the geographical position of the transmission OHL and meteorological data. Therefore the result of this calculation can differ significantly for each case and an individual analysis determining operational ampacity of conductor for each transmission OHL is necessary.

This paper considers influence of the meteorological conditions on transmission capacity of the OHL calculated in real time. More specifically the results are observed for specific grid segment in Croatian transmission grid for periods when the production from the surrounding wind farms is the highest. This occurs during summer period under the most unfavorable meteorological conditions. For the meteorological data input, measuring station on the transmission OHL pole at a height of 10 m from the ground was chosen. This specific measuring station is located in the forest basin which represents the most unfavorable meteorological conditions along the corridor. Observed transmission OHL is equipped with one conductor ACSR 240/40 mm^2 with conductor diameter 21,8 mm, ohmic resistance 0,12 Ω/km, emissivity of conductor factor 0,5 and solar absorption factor of 0,5. Maximum permitted temperature of the conductor is determined by national legislation and is equal to 80°C. Some of the manufacturers of the ACSR conductors state that the maximum permitted temperature for their conductor is up to 100°C, but the final value is defined by the customer regarding technical regulations and individual national legislation [13]. According to historical data collected from the selected measuring meteorological station on one-year period the following min and max values where recorded: wind speeds in range from 0 to 13.7 m/s and air temperature in range from -10.3°C to 37.2°C. For calculations, the wind speed and temperature are taken as mean value of 15-minute measured intervals. The insolation angle was divided into time series that changes from 0° at 12 o'clock and 15° for every hour after noon.

3.2 Influence of input parameters on OHL ampacity

Heat generation of conductor is primarily consequence of the current passing through the conductor and solar insolation. Conductor's temperature will be higher than ambient temperature because of those effect so the thermal transmission will always be present between conductor and ambient air. It can be said that environment around conductor is acting like energy sink for generated heat in conductor. Therefore, environmental conditions have a decisive impact on the final temperature of the conductor. Maintaining conductor temperature below permissible thermal limits is the main goal and it is achieved by understanding the thermal balance of the conductor. Main physical processes responsible for the cooling effect are convective and radiative cooling, where convective cooling is provided by air flow (wind) and radiative cooling occurs as a result of heat emission without physical contact caused by temperature difference. In order to understand the influence of the mentioned parameters on the permitted current, calculations were carried out for a selected ACSR 240/40 mm^2 conductor. Initial input data that was taken for test case calculation include ambient (air) temperature 40°C, wind speed 0,6 m/s, wind angle 90° and maximal solar radiation (161th day of the year, at 2 p.m), emissivity and absorption factor 0,5 for the maximal conductor temperature 80°C. Results of conducted calculation are mainly theoretical and can be applied in most cases. Calculation was conducted using the programmed script that was developed based on Annex - A IEEE standard [10].

The convection heat loss of OHL highly depends on the angle and wind speed. Therefore it is represented by a complex calculation for forced cooling with the presence of wind of different speeds compared to the case without the presence of wind where natural cooling is dominant. For calculation based on IEEE standard it is possible to determine the heat transfer for all wind speeds and consequently the conductor current at 80°C. Obtained results for different wind speeds are shown in Figure 1. For increase of wind speed in steps of 2.5 m/s it can be seen that characteristic is not linear and that the most significant maximal current increase is achieved at low wind speeds. For a wind speed from 0 to 5 m/s, there is an increase in the current by 160%, and for an increase in speed from 5 to 20 m/s, there is an increase of the current by additional 51%, while the total increase in the current is 293%. The influence of the wind direction on the allowed current is also shown on Figure 1. Again, a non-linear characteristic is visible. For a wind angle of up to 7° there are no changes/increases, while for a wind angle of 40° there is an increase in the maximal allowed current by 33%. Finally for an additional increase in the wind angle from 40° to 90° there is an increase in the current by another 10%, with the total current increase summing up to 46%.

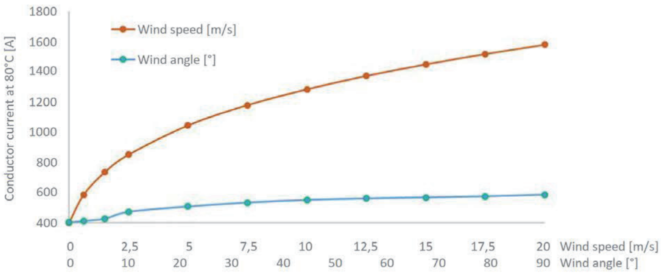

Fig. 1. Conductor allowed current at 80°C depending on different wind speeds and wind angles

Conducting heat from conductor to the environment is mainly influenced by the temperature of the surrounding air. The lower air temperature and consequently greater temperature difference between conductor and surrounding air leads to better convection and radiation of heat. Figure 2 shows the influence of temperature of the surrounding air on the maximal allowed current, where for the observed air temperature range is 0°C to 40°C. From the Figure 2 it can be seen that the curve is approximately linear. For the observed temperature range of surrounding air (0°C – 40°C), the current is reduced by 52% at 40°C compared to current 0°C.

The calculation of solar heat (insolation) influence on conductor temperature was also considered. With an increase of insolation in range from 0 to 1000 W/m^2, conductor absorbs more energy that contributes to an increase in its temperature. Influence of insolation on conductor temperature is shown on Figure 2. It is evident that, as is the case of an increase of temperature, that the function is dominantly linear. For the selected sunniest hour of the year (161st day of the year at 14 hours), which corresponds to the maximum radiation, a reduction of the permitted current load of 8% can be expected compared to the case of solar radiation intensity of 0 W/m^2

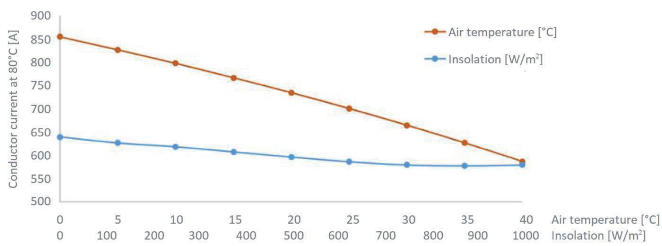

Fig. 2. Conductor allowed current at 80 °C dependence on air temperature and insolation

Conducted calculations were done separately for each parameter that was changed while the other parameters were constant (Ceteris paribus approach). In real operation this is not the case. In section 4 analysis for real conditions will be conducted taking into account changeable weather condition. Conducted calculation shows that wind speeds have dominant influence on conductor temperature and due to wind characteristics often demonstrating rapid changes permissible current can be significantly affected. Wind angle has similar characteristic like wind speed with rapid changes in while ambient temperature is relatively stable with slower changes throughout the course of the day. Insolation usually has similar characteristic like temperature demonstrating gradual changes, but can also have steeper changes due to sudden appearance of clouds or storms. Through presented analysis of Section 3 from all the input parameters analyzed wind speed and angle have been concluded to have dominant influence with air temperature and insolation influence being less impactful.

IV. Calculating Dynamic Transmission Capacity of an OHL

For the described calculations in this Chapter 4, conductor is defined by its final and unchanged model and conductor current depends primarily on the weather conditions. Atmospheric and meteorological conditions are different throughout the year and it is desirable to determine a characteristic for each period that is observed. In conducted analysis both STR and DTR approach were used where STR values are defined for unfavorable atmospheric conditions where ambient (air) temperature is 40°C, a wind speed of 0.6 m/s, maximum solar heat and maximum conductor temperature of 80°C. For presented conditions calculated STR approach maximal current is 605 A.

In the process of calculating currents with DTR approach, available real time measured meteorological data is necessary, as well as forecasted values for corridor segments not covered by installed measurement devices. In the previous chapter influence of various atmospheric conditions were presented where highest ampacity was achieved for higher wind speed values that appear just in a small number of hours for the observed period and are therefore not realistic for practical use. Differences in environmental conditions change significantly throughout the year where higher transmission capacity of OHL are achieved in winter, when the ambient temperature and solar radiation are the lowest and the wind intensity is statistically the highest. In order to get a realistic insight into the ampacity of OHL analysis was performed for time period of high air temperatures, high solar radiation and high wind, consequently also high production from the surrounding wind farms. Third week in June (from June 16, 2021 until June 2021) was selected. Based on presented calculation in section 2 conductor current (at conductor temperature 80°C) were calculated for each 15-min interval and the results are shown on Figure 3.

Conducted calculation for the mentioned period shows an average increase in transmission capacity of OHL by 9%, while the recorded maximum increase was 45% compared to STR values. Also using DTR there were periods with lower values of transmission capacity with recorded minimum of 25% smaller capacity compared to STR calculated limit due to low wind speed and bad wind angle. From Figure 3, where the curve of the calculated maximum current is shown for both approaches, it is also evident that the lowest values were achieved when the wind speed and consequently production from wind farms were the lowest. For these specified hours where DTR current value is lower than STR an additional analysis is required to determine the influence of atmospheric parameters contribution to lower ampacity result.

For the intervals where the DTR current values were calculated below the STR value analysis was made for wind speed and wind direction as limiting input parameters. In relation to the STR calculation of the current, which assumes a wind speed of 0,6 m/s and a wind angle of 90°, a total of 186 15-minute intervals (out of a total of 672 intervals) were recorded in which the calculated current was lower than the nominal STR value.

Table 1 shows the distribution of recorded 15-min intervals (for different groups of calculated current I_{Cal} where I_N represent the nominal STR value. The main causes for smaller value of I_{Cal} compared to I_N are the differences in wind angle and wind speed. Based on the results from Table 1, it can be concluded that the wind speed significantly affects the lower values of the I_{Cal} ($I_{Cal} < 0{,}9\ I_N$), while the wind angle is significant in all calculation of the I_{Cal}. The main causes of the lower value I_{Cal} compared to I_N comes from the fact that I_N was calculated for wind speed 0,6 m/s and wind angle of 90° where in reality there were period with lower speed (below 0,6m/s) or without wind and with lower wind at lower angle.

Table 1. The distribution of intervals for which is $I_N > I_{Cal}$

I_{Cal} [A]	Intervals		
	$I_N > I_{Cal}$	Wind speed <0,5 m/s	Wind angle <60°
$0{,}7\ I_N < I_{Cal} < 0{,}8\ I_N$	5	60%	100%
$0{,}8\ I_N < I_{Cal} < 0{,}9\ I_N$	58	45%	95%
$0{,}9\ I_N < I_{Cal} < I_N$	123	20%	86%

Additional analysis also considers conductor temperature for the most unfavorable case recorded where $I_{Cal} < I_N$ and with input

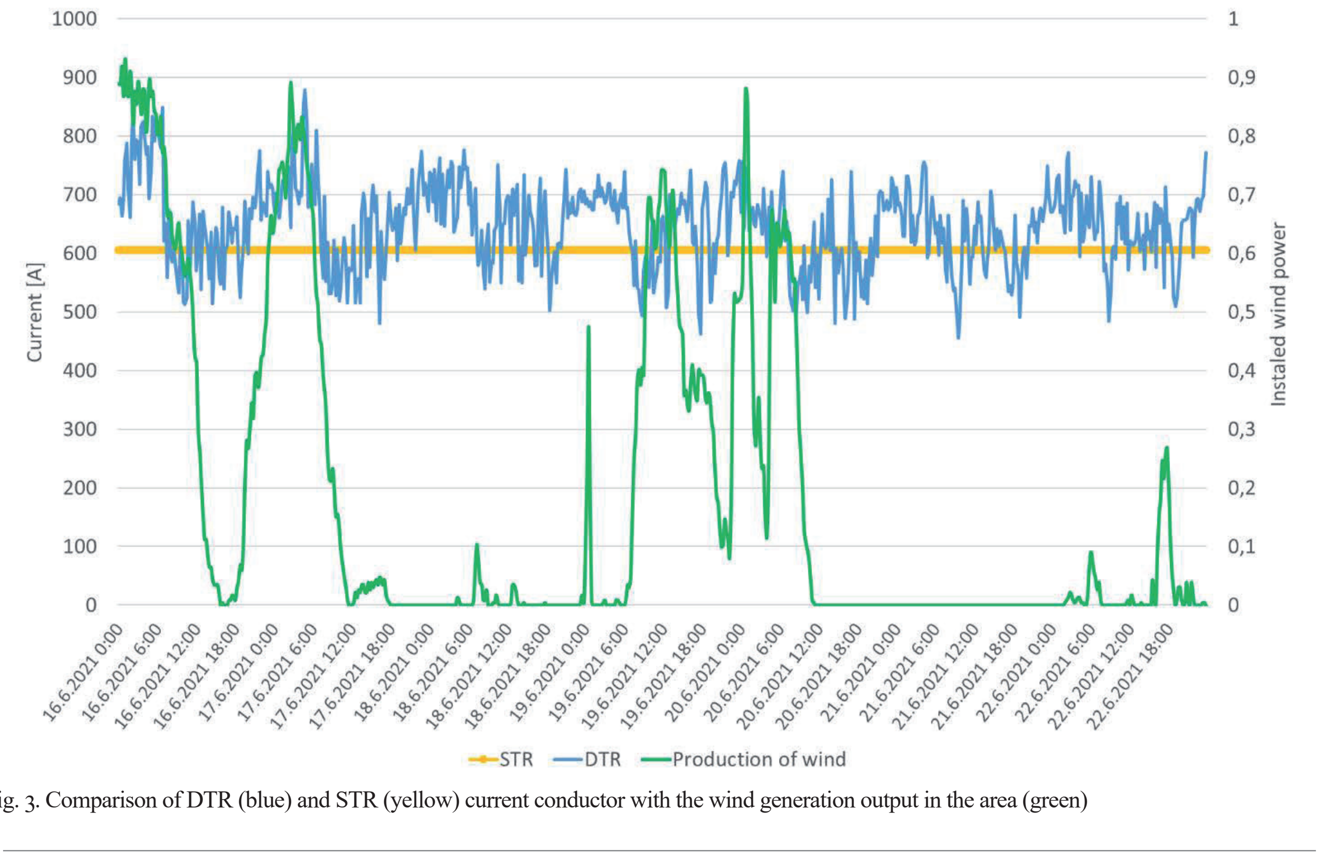

Fig. 3. Comparison of DTR (blue) and STR (yellow) current conductor with the wind generation output in the area (green)

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data: wind speed 0.3 m/s, air temp. 28°C, wind angle 16° at 9 am. For these conditions calculated conductor temperature was 99.7°C. Taking into account the recommendations of the conductor manufactures for the permanent temperature of the ACSR conductor (up to 100°C) [13] without loss of mechanical properties, it can be concluded that the design current values were not exceeded at any time for observed period.

Finally, it can be concluded that during high wind generation the transmission capacity of OHL is increased compared to the nominal STR values. The increased values directly depend on the current meteorological conditions on the transmission OHL and the location of the transmission OHL in geographical place in relation to the wind power plants. In the moments when lower transmission capacity of transmission OHL compared to STR values was recorded, no significant production from wind farms was present due to lower wind speed which makes the lower ampacity result less impactful. On the other hand, during high production of wind when high loading of the grid is expected the DTR calculated ampacity is higher which can significantly impact the power flows and transmission system operation.

V. Conclusion

In process of determining transmission capacity of OHL various methods can be used to calculate maximum current. OHL ampacity in real time can be done using different standards where IEEE and CIGRE are most represented. Calculations of OHL maximal current are highly influenced by atmospheric parameters. It can be expected that similar atmospheric condition are presented on local geographical area and in the case of higher wind generation transmission capacity of OHL can significantly depend on wind speed and angle. The results show that STR approach is conservative and applying DTR can effectively increase OHL capacity, especially during times of high wind and consequently high wind production. Presented calculation of OHL ampacity by DTR approach compared to STR values were made for most unfavorable week in year and still the conclusion drawn was that there is a high correlation between the need for higher OHL capacity due to higher wind generation evacuation and simultaneously higher calculated DTR capacity at these moments.

In future work, the uncertainty of system power flow analysis and the operational risk of transmission capacity will be investigated. Also, in that regard conducted analysis shows promising results since it could provide more efficient process for determining transmission capacity and can be applied in the business processes of planning and management of the transmission grid.

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