Impact of Weather Conditions on Line Ampacity of Overhead Transmission Lines

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***Abstract*—The weather parameters along the overhead line change significantly and this have a significant effect on the thermal behaviour of the conductors. The thermal behaviour of the conductors is of great importance to the optimization and increase in line ampacity. Calculation of line ampacity of transmission lines helps power system operators to solve specific high demand and emergency situations in the power system network and simultaneously ensuring that the temperature limits and line ampacity of the conductors are not exceeded. In this paper, the line ampacity of an overhead line under different weather conditions is analysed. The results from the case study show that changes of weather conditions along the overhead line have an important impact on the line ampacity.**

***Index Terms*—line ampacity, weather parameters, overhead line, thermal behaviour**

I. Introduction

Overhead line ampacity is traditionally calculated based on worst case limitations and static rating [1]. The increasing integration of renewable energy sources and decentralisation of energy production requires a transmission grid that is versatile [2]. Renewable energy sources are greatly influenced by weather conditions. For example, wind energy production is dependent on wind speed at any given time of day and solar energy production is dependent on the solar irradiance. On the other hand, the line ampacity of overhead lines is dependent on weather parameters. Therefore, the integration of renewable energy source to the transmission grid needs great analysis to balance the energy generation and the line ampacity of the overhead line. To integrate solar and wind power energy into the transmission grid, there is need to understand how solar irradiance and wind speed influence the line ampacity of the overhead line. Commonly, the dynamic line rating (DLR) scheme is used to increase the line ampacity of overhead transmission lines [1], [3]–[6]. The scheme is based on the fact that the line ampacity of overhead lines continuously changes depending on the weather conditions that surround the transmission line.

Different methods have been used to calculate overhead transmission line ampacity. The IEEE and CIGRE methods have been calculated for analytical and experimental comparisons [7], [8]. In South Africa, the CIGRE method is the recommended calculation method for line ampacity. The worst case limitations are considered as the base case for line rating. The line ampacity is mainly dependent on the thermal model of the conductor. Validation of thermal models of conductors is very scarce in the literature. In ref [7] an Aluminium Conductor Steel Reinforced (ACSR) was monitored with controlled temperature and weather conditions and the measured results were found to be in agreement with the modelled results. However, the maximum attained temperature for the experiment was 40^0C. In most cases, power utilities split the year into seasons which have static weather conditions and therefore the line ampacity is static for the respective seasons. This will mean that most of the time during the seasons, the overhead line operates either at lower or higher line ampacity than it could carry. The integration of renewable energy source to the power grid has necessitated the need to increase the line ampacity at different supply points along the transmission line. Since renewable energy sources are intermittent, the voltage and current supply to the grid is not always constant as they are influenced by the weather conditions [9], [10]. It is therefore possible to make use of the remaining current capacity of the existing overhead lines without the need to reconfigure and reinvest in the transmission grid. The DLR scheme can be used to calculate actual line ampacity that is continuously varying depending on real weather conditions. Many power utilities have started programs to implement DLR scheme in their transmission grid.

The static line rating is the most common method used due to its simplicity and easy of implementation [1]. The method is based on historical weather profiles in the areas where the conductors are located. The most conservative weather conditions are used in the calculation of the line ampacity. The main disadvantage of employing this method is that there is a significant risk that the calculated line ampacity might surpass the actual line ampacity of the conductors at some given time of the day. In some cases, it also underestimates the conductor available transfer capacity because the weather conditions are not always as extreme as most weather assumptions. Figure 1 below shows the relationship between static and dynamic line thermal rating. The region indicated as available transfer capacity can be utilised by power system operators as they are able to tap into this unused capacity during peak load time of the day. However, the region indicated as risk of static rating

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can be very catastrophic to the power system network. This can cause forced blackouts due to overcongestion in the power system network.

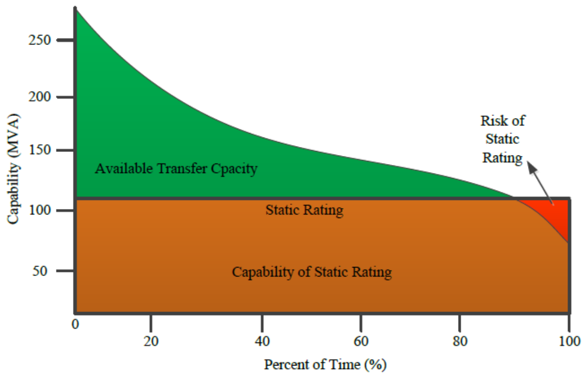

Fig. 1. Static and dynamic thermal rating of overhead line conductor

This paper presents a case study investigating the effect of weather parameters on calculation of line ampacity for a South African transmission grid. The effect of variation of ambient temperature, wind speed and solar irradiance is investigated. For this study, actual local weather conditions are used.

II. Methodology

A. Line Ampacity

Most power utilities calculate line ampacity of overhead lines using the worst case scenario. This will ensure that there is a significant leeway for changing the line ampacity without exceeding the limits of the overhead line during sudden changes of weather and conductor parameters. Two main calculation methods are commonly used by power utilities, namely; CIGRE and IEEE methods. Both methods use the fundamental heat balance equation to derive the line ampacity of the overhead line. The heat balance equations specified by CIGRE and IEEE are given below in Eqs. 2 and 1 respectively [11]–[13].

$$P_c + P_r = P_s + P_j \tag{1}$$

$$P_c + P_r + P_w = P_s + P_j + P_m + P_i \tag{2}$$

P_j - Joule heating; P_m - magnetic heating; P_s - solar heating; P_i - corona heating; P_c - convective cooling; P_r - radiative cooling; P_w - evaporative heating.

The main difference in the equations is that the CIGRE equation include additional parameters to that of the IEEE equation. The additional parameters of corona heating, magnetic heating and evaporative cooling are neglected in the calculation of line ampacity in this paper. The reason for this assumption is for the sake of simplicity and independence of the variables. Using this assumption, the heating by the electric current is given as in Eq. 3 below

$$P_j + P_m = R_{T\ AC}.I^2 \tag{3}$$

$$I_{rat} = \sqrt{(P_r + P_c - P_s)/R_{T\ AC}} \tag{4}$$

The following subsections will give a detailed explanation of how to calculate each term used in the calculation of line ampacity given in Eq. 4 above.

1) Solar heat gain: When overhead lines are exposed to solar radiation they gain some heat energy and this is known as solar heat gain. The degree of heat gain is dependent on the outer diameter of the overhead line conductor (D), global solar irradiance, S_t and the absorptivity of the overhead line conductor surface, α_s.

$$Q_s = \alpha_s.D.S_t \tag{5}$$

The absorptivity of overhead line conductor surface is normally given by the manufacturer and varies from 0.2 - 0.9 depending on the age of the overhead line conductor and the period of exposure to solar radiation. The recommended value of absorptivity for South African conductors is 0.5 [14]. For this reason it is the value that is used in this paper.

The global solar irradiance received by conductors is not always uniform for different locations along the conductor. The important differences may arise as a result of different reflectance from ground, orientation, sheltered places etc. Devices for measuring global solar irradiance are available and can be easily installed in different locations for line monitoring systems. The solar radiation is also dependent on the time of day and year of the respective location. In this paper the global solar irradiance is assumed to be uniform along the entire conductor for the case study location considered.

2) Radiative cooling: Overhead lines radiate heat either to the ground and surroundings or directly into the sky. The total radiated heat from the overhead line is determined using Stefan-Boltzmann law and can be expressed as in Eq. 6 below.

$$Q_r = \pi.D.\epsilon.\delta_B[T_s + 273)^4 - (T_a + 273)^4] \tag{6}$$

ϵ - emissivity of overhead line conductor; δ_B - Stefan Boltzmann constant (5.6697 x 10^-8 W/m^2K^4); T_s - surface temperature of conductor; T_a - ambient temperature

Emissivity value of the conductor varies between 0.23 - 0.95 depending on the period it has been used. Commonly, emissivity value of 0.5 is recommended when calculating the line ampacity. However, in South Africa, the power utility recommends an emissivity value of 0.8 [14]. This is mainly because the existing South African transmission grid conductors are now very old thus a very conservative emissivity value is recommended. It is for this reason that the value of emissivity used in this paper is 0.8.

3) Convective cooling: Overhead line conductors can be cooled either through natural or forced convention. Natural convention is as a result of natural flow of air and the wind speed is considered to be zero. In forced convention, flow of air around the conductor is as a result of wind thus in this case the wind speed is not zero. Commonly, forced convection is assumed when calculating the line ampacity of overhead lines. Typical wind speed of 0.6m/s perpendicular to the conductor is normally considered in line ampacity calculation. The variability of wind is dependent on the location of the overhead lines and also the season of the year. Therefore, when calculating the line ampacity of the overhead line it is important to take into account the effect of wind variability. The standard wind speed for calculation of line ampacity in South Africa is 0.6m/s perpendicular to the overhead line.

Convective heat loss from a conductor is expressed as in Eq. 7 below.

$$Q_c = \pi.\lambda.I.Nu.(T_s - T_a) \tag{7}$$

λ - thermal conductivity of air (W/K.m) that surround the conductor surface; T_s - conductor surface temperature; Nu - Nusselt number. The thermal conductivity of air is normally given for each specific discrete temperature value. However, in this paper, the thermal conductivity of film air around the conductor is inter- and extrapolated with temperature values from 0^oC and 300^oC as in Eq. 8 below

$$\lambda = 2.368x10^{-2} + 7.23x10^{-5}.T_f - 2.763x10^{-8}.T_f^2 \tag{8}$$

The air temperature that surrounds the conductor surface is given as in Eq. 9 below.

$$T_f = 0.5(T_s + T_a) \tag{9}$$

The Nusselt number can be calculated from Eq. 10 and 11 below

$$Nu = 0.65Re^{0.2} + 0.23Re^{0.61} \tag{10}$$

$$Re = 1.644x10^9.V.D(T_a + 273 + 0.5(T_s - T_a))^{-1.78}.A \tag{11}$$

Re - Reynolds number; V - wind speed.

The value of A is dependent on the angle between the overhead line and the wind direction. Eqs. 12 and 13 below are used to determine the value of A for the different angles.

$$A = 0.42 + 0.68(Sin\phi)^{1.08} \qquad \phi < 24^o \tag{12}$$

$$A = 0.42 + 0.58(Sin\phi)^{0.9} \qquad \phi > 24^o \tag{13}$$

ϕ - angle between conductor and wind direction.

The surface and core temperatures of a conductor determines the cooling and sagging of the conductor respectively. The interdependence of these two conductor temperatures have a great effect on the thermal cooling and resistance of the conductor. To determine the resistance of the conductor, the average temperature of the conductor is used. CIGRE standards recommends that the average and surface temperature of the conductor can be assumed to be the same. This is because the difference between the two temperatures is considered to be very small between 0.5^oC and 7^oC. The design temperature of the conductor is provided by the manufacturer and typically varies between 75^oC and 90^oC. The maximum temperature considered in South Afican standards is 80^oC [14]. In this paper, it is assumed that $T_s = T_{av} = T_c$ i.e. the average temperature is assumed to be 80^oC.

TABLE I
PARAMETERS OF THE OVERHEAD TRANSMISSION LINE

Parameter	***value***
Rope diameter	28.62 mm
Resistance (DC)	6.74 x $10^{-5}/m$ @ 20^oC
Resistance (AC)	8.21 x $10^{-5}/m$ @ 75^oC

[a]Zebra cable parameters

III. Case Study

In order to investigate the variation of line ampacity with weather conditions an aluminium steel standard cable has been selected. The Zebra type cable is used in the South African grid at transmission level. The dimensions and characteristics of the conductor type are as shown in Table I below.

The weather data was taken from ref. [14] for the period of one year - December 2017 to Decemeber 2018. All the above data was analysed using MATLAB software to generate the simulated line ampacity of the conductor. The line ampacity was analysed using two time resolutions i.e. one minute and hourly resolutions. Two case studies were considered in the analysis and actual measured data for each time resolution was used. Three parameters were considered in each analysis, namely; ambient temperature, solar irradiance and wind speed. A specific day for summer and winter seasons was chosen for each case study.

IV. Results

The results of the static and DLR for the two case studies are presented from Fig 2 - 9 below. Differences with respect to the time resolution and season are analysed. The results show that during winter season, the DLR is very high compared to

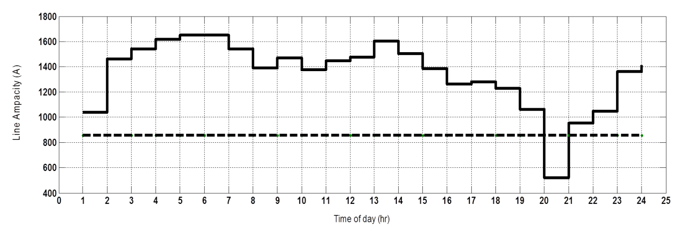

Fig. 2. Summer static and DLR on hourly weather condition data: UNV

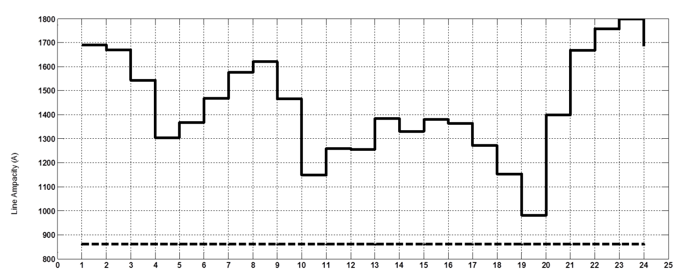

Fig. 3. Winter static and DLR on hourly weather condition data: UNV

the static line ampacity rating. This is mainly because of the cooler temperatures and thus despite the heat generated by the conductor the temperature of the conductor remain low and thus result in the increase of line amperage. During summer season, the line ampacity increases during the night when temperature is reduced. During the day when temperature

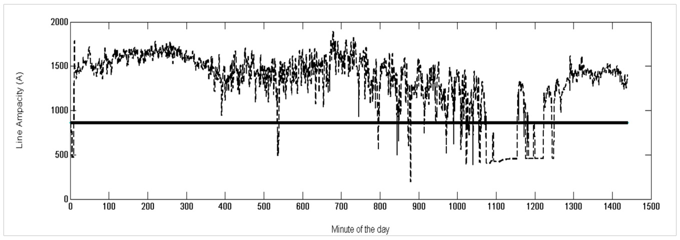

Fig. 4. Summer static and DLR on minutely weather condition data: UNV

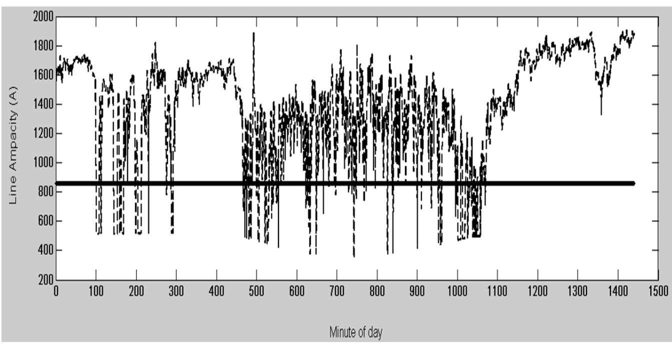

Fig. 5. Winter static and DLR on minutely weather condition data: UNV

is very high, the line ampacity is reduced. In some instances, the line ampacity is reduced below the static line ampacity especially when when a higher time resolution is used. This shows the need for high time resolution data analysis of line ampacity in order to avoid catastrophic blackouts in the power system when the conductor line ampacity is exceeded in the power system network especially during peak hours.

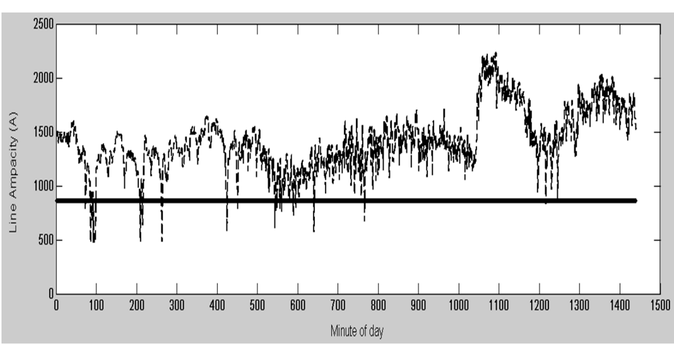

Fig. 6. Summer static and DLR on hourly weather condition data: CSIR

The use of lower time resolution e.g. month, season or year, would have a great impact on the power system network and in most cases it would either under estimate or over estimate the line ampacity of the transmission line. The increase in

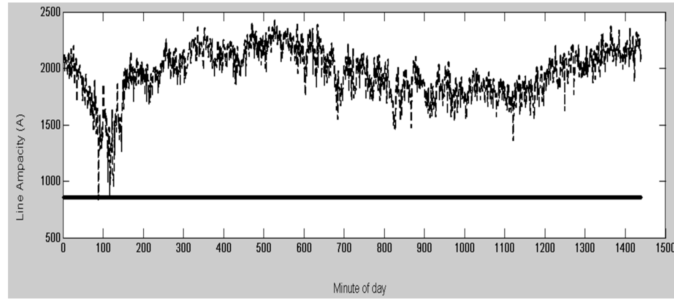

Fig. 7. Winter static and DLR on hourly weather condition data: CSIR

use of electronic measurement instruments for smart grids has necessitated the need to have higher time resolution for measurements of line ampacity. This will aid in reducing the need for refurbishment and construction of new transmission lines in areas where renewable energy sources are connected to the grid. The available transfer capacity can be used for renewable energy sources to feed into the existing grid without the need to construct any new power lines.

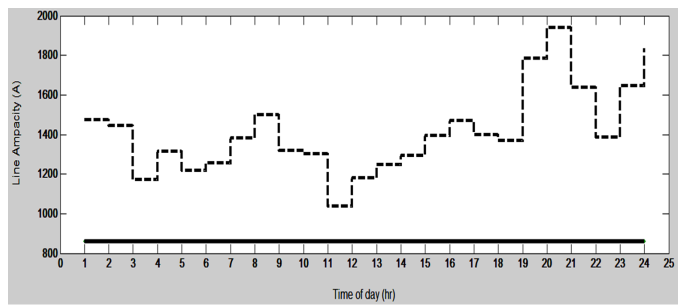

Fig. 8. Summer static and DLR on minutely weather condition data: CSIR

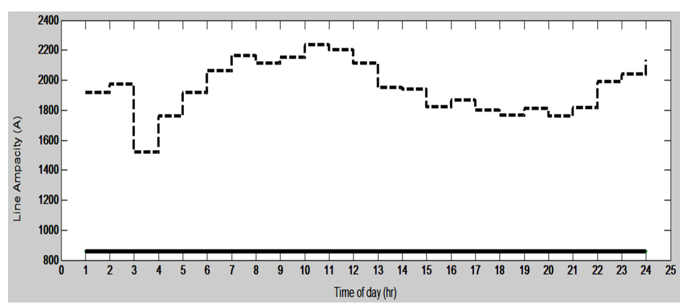

Fig. 9. Winter static and DLR on minutely weather condition data: CSIR

V. Conclusion

The variation of line ampacity of overhead line is of great importance especially now due to an increase in integration of renewable energy sources into the conventional transmission grid. Both power generated from renewable energy sources and the line ampacity is dependent on weather conditions. It is therefore important to know how line ampacity of conductors vary in order for recommendation of refurbishment and correct use of the transmission line when renewable energy sources are connected. This paper presents results from analysis of overhead conductor under different real weather conditions in South Africa. The results show that the weather parameters have a great influence on line ampacity of the overhead line. The study also show that it is important to consider higher time resolution of the weather parameters in calculation of conductor line ampacity.

The MATLAB program developed under this analysis can be used in conjunction with real time sensors to calculate the real time line ampacity and this would help optimise the operation of the transmission grid. In future, the impact of a varying line ampacity on reliability of a power system network will be investigated.

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