Determination of Overhead Power Lines Ampacity Based on CIGRE 207 Brochure

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Abstract — **With increasing consumption of electricity, the need for its production naturally rises as well. Thus, it is important to know if it's still possible to use existing overhead power lines or if it's necessary to replace or extend them. Ampacity, or current-carrying capacity, is defined as maximum amount of current that can flow through power line without damaging the conductor. It depends primarily on the electrical and mechanical properties of the conductor, their ability to spread generated heat and the ambient weather conditions. Design of power lines as any electrical device is subject to the valid standards. In general, the environmental conditions are not constant over time. They depend on the climatic conditions of the country, area, that are different climatic nature. Each manufacturer is providing the maximum allowable current load of the conductors so that its maximum operating temperature does not exceed the maximum safe value. This article is dealing with confirmation of maximal allowable current that is resulting maximal operating temperature provided by manufacturer of the conductor. For that purpose, designing and assembling a measuring apparatus to determine ampacity in overhead power lines were realized. The measurements and calculations based on standard CIGRE brochure 207, were made. The measured results were compared with calculation. It was proven that standard CIGRE brochure 207 has sufficient accuracy for the use in practice.**

Keywords: ampacity; overhead power line; current-carrying capacity; ACSR conductor

I. INTRODUCTION

Power system consists of electric power components, which are used for generation, transformation and electricity transmission. For transmission of electricity, we distinguish the transmission and distribution power lines. A transmission lines are representing at ultra-high voltage system, which provide a transmission of power from sources to the three local areas of distribution system. Also cross-border power lines belong to the transmission system of power lines [1] [2].

Current capacity of every power lines depends on their constructions and used types of the conductor. Manufacturer of the conductors specified maximal allowable temperature for the operation of the power line. With maximal allowable temperature is related a current that can flow through the conductor and leads to achieve maximum operating temperature [3]. A maximal current value that flow through the conductors by not excited allowable temperature is marked as capacity of power lines or ampacity of power lines [3].

Capacity of the power lines depends on the electrical and mechanical features, thermal features of the conductor insulation and ambient conditions [3].

Every construction of electricity facilities is subject to the standard. This standard described methods for construction these facilities and to determination of maximum allowable conditions, that are non-destructive for their operation.

During a preparing of project to construction of power lines it is necessary to determine a capacity of power lines. For determining a capacity of power lines exist a standard EN 50341 where are defined ambient conditions, that have main influence on the value of maximal current.

II. DEFINING RESEARCH PROBLEMS

1) *Current capacity*

Current capacity of the power lines means a current value that can be transmitted through a power line without destroying conductors. For this state deals steady state equation, which depends on determinants that represents the produced and consumed heat (1) [5] [6].

$$P_Z + P_S = P_k + P_r \qquad (1)$$

Where:

P_Z is heating the conductor due to current flow,

P_S is heating the conductor due to solar radiation,

P_k is cooling the conductor due to forced convection,

P_r is cooling the conductor due to natural convection.

By substitution equation above, we obtained a following expression for determining current capacity [5] [6]:

$$I = \sqrt{\frac{P_r + P_k - P_S}{R_{ac}}} \qquad (2)$$

Where:

R_{ac} *is* the ac resistance of the conductor at 20 °C in Ω.

For the design of power lines is currently applicable standard EN 50341 where are defined ambient conditions for calculation of maximum allowable current value. This standard recommended maximum operating temperature 70°C of conductor [7].

Ambient conditions for calculation of maximum allowable current value of conductor according to the standard are:

- The ambient temperature is 35 °C,
- Wind speed is 0.5 $m.s^{-1}$ at 45° angle of impact,
- Solar irradiance is 1000 $W.m^{-2}$,
- Absorption coefficient is 0.5,
- Emissivity coefficient of 0.5 [7].

It is necessary to say that conditions given by a standard are the worst case of ambient conditions, which is rarely found.

For determining current capacity standard CIGRE Technical Brochure 207 describes equations for calculation based on the climatic conditions and temperature of conductor. [8]

Based on this hypothesis, we compare temperature of conductor during a heating by nominal current value and calculated temperature for examined conductor.

2) *Construction of ultra high voltage power lines*

In practical terms, for the line of 400 kV voltage level are used trunked conductors where one phase consists of three conductors each and electrically connected at a distance, thereby enhanced radius of the conductor of one phase [9].

As conductors of transmission lines are used aluminum cables with steel core. Their advantage is greater mechanical strength, which allows its use for large distance. Among their other advantages include greater flexibility, more uniform structure. When wires material mistake can degrade the whole wire, but with ACSR ropes, tearing of one wire not damage the whole conductor [9].

ACSR rope used in high voltage grid was used to investigate due to limited conditions in the laboratory.

A rope 24-AL1/4-ST1A was chosen for research with following parameters:

Table 1 Parameters of 24-AL1/4-ST1A

Conductor type		24-AL1/4-ST1A
Cross section (mm^2)	AL	23,64
	ST	3,94
	Overall	27,58
Number of wires	AL	6
	ST	1
Diameter of wires (mm)	AL	2,24
	ST	2,24
Rope diameter (mm)	Inner section	2,24
	Overall	6,72

Table 2 Electromechanical specifications of 24-AL1/4-ST1A

Nominal weight ($kg.km^{-1}$)	95,46
Nominal strength (kN)	8,87
Maximum DC resistance at 20 °C ($Ω.km^{-1}$)	1,1823
Final modulus of elasticity (MPa)	79 000
Coefficient of thermal expansion (10^{-5} K^{-1})	1,86
Current load capacity (A)	125,9

III. The design and assembling of measuring apparatus to determine ampacity in overhead power lines

Basic hypothesis for this article is verification of proposed mathematical model. It was determined based on empirical equations of current-carrying capacity of conductors under the influence of ambient conditions according to CIGRE standard. Main element for the investigation was ACSR conductor troughs which was flowing electric current.

This electric current is causing conductor warming caused by Joule losses neglecting ambient conditions. Based on theoretical knowledge, two main elements have influence at conductor warming, ambient temperature (which also contributes in Joule losses) and intensity of solar radiation. In contrast, when conductor is being cooled the main influence has temperature drop caused by forced convection and temperature drop forced by natural convection.

Another essential element for measuring apparatus is transformer. With the transformer it is possible to continuously regulate the value of the electric current until desired value is reached (current load capacity of examined conductor).

Temperature probes are part of the measurement. They are measuring temperature of conductor surface.

Based on theoretical analysis for measuring apparatus, laboratory measuring site was compiled.

Block diagram is shown in Figure 1. At the input of measuring site is three phase power supply SST 250/20 with voltage regulation 0 – 250V and electric current regulation 0 – 20A.

Power supply SST250/20 is exciting large current transformer (TR) in the range 0 – 1000A.

Between SST250/20 and large current transformer was connected device WPQT1H. WPQT1H is primary intended for testing the electrical protection. In measuring apparatus its protection functions are used for protection against TR damage. On the secondary side of TR is connected examined ACSR rope with temperature probes.

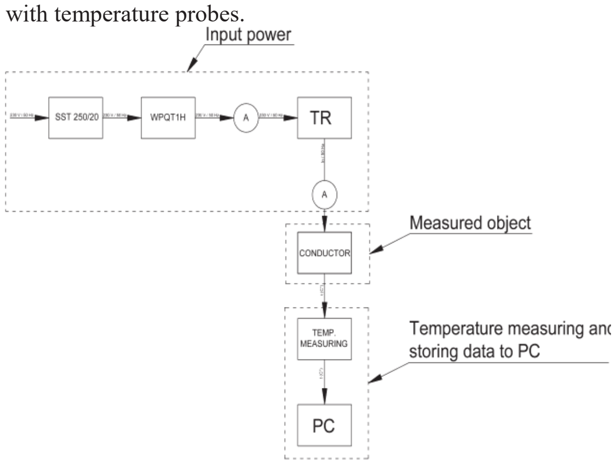

Figure 1 Block diagram of measuring apparatus

Based on measured temperature of the conductor, when the maximal allowable current is flowing through, the maximal allowable conductor temperature can be determined.

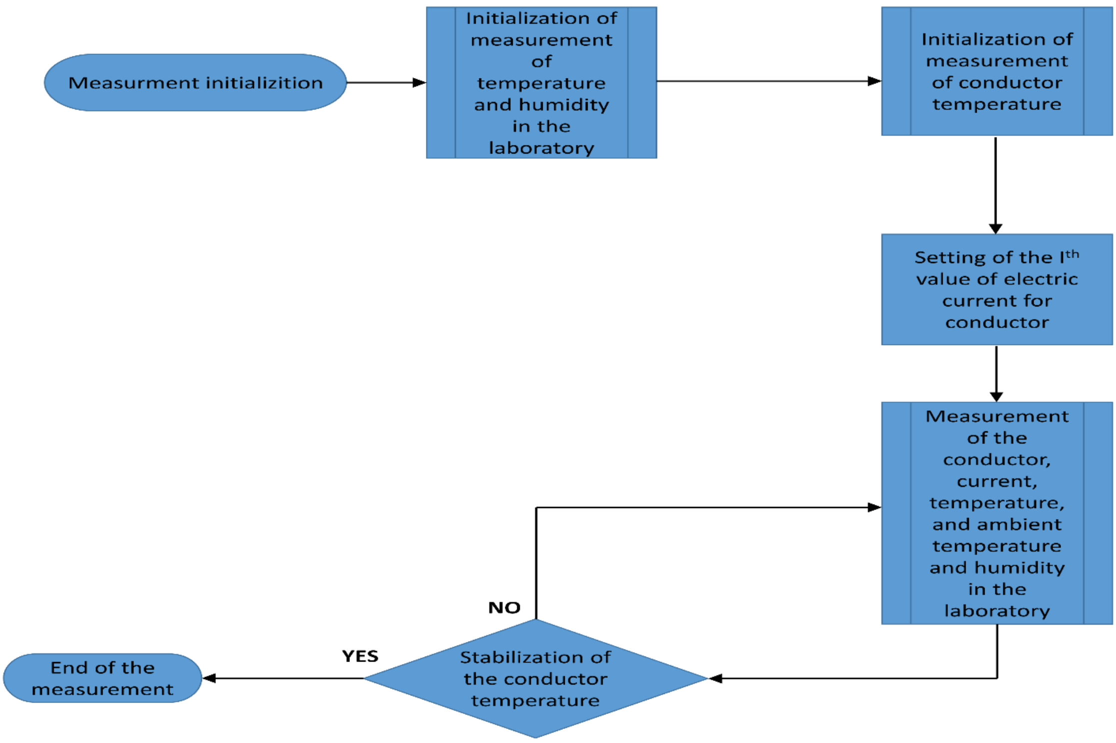

Figure 2 Flow chart of measurement

Measurement method in form of flow chart is shown in Figure 2.

After measurement initialization of ampacity is concurrently started measurement of temperature and humidity in laboratory. Subsequently with using of voltage source is current set to nominal value. To end the measurement, temperature of conductor has to be in steady state, i.e. it has not upward or downward trend.

IV. Measuring of ambient temperature influence on ampacity of 24-AL1/4-ST1A conductor

To determine the influence of ambient temperature on ampacity of conductors was based on proposed experimental measuring apparatus and measuring flow chart (Figure 2) carried out experiment.

Due to technical and security restrictions in laboratory were experiment carried out on ACSR ropes used in high voltage level.

From the point of view of ensuring credibility of measurements were individual measurements repeated 10 times.

The measurement procedure was based on a flowchart shown in Figure 2. Measured temperature was arithmetically averaged.

The ambient conditions were as follows:

- Ambient temperature $T_a = 27^{\circ}C$,
- Wind speed $v = 0$ m.s^{-1}, i.e. windlessness / wind speed $v = 3$ m.s^{-1},
- Intensity of solar radiation $I_s = 0$ W.m^{-2}.

In the process of verification of the mathematical model, measurements were made on the basis of the proposed experimental set-up and technological procedure for the measurement of overhead power lines.

In Figure 3 is shown time course of measured temperature of 24-AL1/4-ST1A conductor in a step load of nominal current.

As shown in the Figure 3, temperature of conductor was measured in advance, i.e. before switching on the measuring circuit.

The temperature measurement time for unloaded ACSR rope was 10 minutes. The measuring circuit was turned on in 10th minute. The set current value was almost nominal, equal to 125A.

There was a sharp rise in driver temperature between 00:10:00 and 00:20:00. From a conductor temperature of 25-27 ° C at 10 repeat measurements, the temperature increased from 73 to 85 °C. For averaged conductor temperature, this meant a temperature rise from 26.2 ° C to 80.5 ° C.

A dampened increase in driver temperature was recorded from 00:20:00. In the case of individual measurements, the temperature rises of the conductor at 00:20:00 for individual measurements ranged from 77 °C to 85 °C until 00:50:00 from 77 °C to 90 °C. For average temperatures, an increase from 80.5 ° C to 85 ° C was recorded.

At Figure 3 is possible to observe, that in case of sub-measurements 1 – 10, was temperature increase different, however characteristic of partial temperature increases were almost identical.

This state was caused by the inconsistency of the surrounding conditions. In the laboratory was recorded 1.3 ˚C difference in temperature.

The temperature of the conductor is also influenced by its surface treatment.

In the manufacture process of these ropes they are treated against oxidation in air to maintain their mechanical properties.

To verify the proposed mathematical model for the determination of the static and dynamic part, a calculation was made for determining the temperature of the conductor in the dynamic and static parts. From a solution point of view, the determined steady-state conductor temperature was then compared to the average conductor temperature obtained on the basis of the repeat measurement.

The following ambient conditions were used to determine the static temperature:

- Ambient temperature T_a = 27˚C,
- Room temperature was between 25 – 27 ˚C, however in calculation is necessary taken in to account higher one.
- Intensity of solar radiation I_S = 0 W.m^{-2},
- Wind speed, windlessness v = 0,2 m.s^{-1}.
  - Beaufort's wind force scale defines windlessness at a speed interval 0,0 until 0,2 m.s^{-1}. Given that it was not possible to achieve 0.0 m.s^{-1} in the laboratory; higher wind value is considered.
- Nominal current I = 125 A.

By gradual adjustment of the conductor temperature by the iteration method, the determined conductor temperature was T_S = 74.6 ° C. The factors involved in heating and cooling the conductor was equal to:

- Warming due to current flow P_J = 22,88 W.m^{-1},
- Warming due to solar irradiation P_S = 0 W.m^{-1},
- Cooling due to forced convection P_C = 19,01 W.m^{-1},
- Cooling due to natural convection P_r = 3,88 W.m^{-1},
- Difference ΔP is equal to -0,01 W.m^{-1}.

The dynamic value of the conductor temperature is the conductor temperature that changes over time after the conductor current change or when the ambient conditions suddenly change.

To calculate the conductor temperature at a jump load by the nominal current value, it starts from the static conductor temperature obtained by the calculation in the previous subchapter. It is equal to θ_m = 74.6 ˚C. This temperature represents the steady-state conductor temperature after a step change in current or ambient conditions. The overall time course of temperature after a step change in the current that flowed through the investigator and the comparison is shown in Table 3.

Table 3 Comparison of calculated and measured values for 24-AL1/4-ST1A conductor

Measured average temperature of conductor (˚C)	Calculated temperature of conductor (˚C)	Difference (˚C)	Difference (%)
26,2	35,5	9,3	26,13
67,9	42,4	25,5	60,04
80,5	48,1	32,4	67,19
84,3	52,9	31,4	59,50
85,8	56,7	29,1	51,27
85,8	59,9	25,9	43,24
85,7	62,5	23,2	37,09
86	64,7	21,3	32,99
85,2	66,4	18,8	28,25
85,2	67,9	17,3	25,51
85,2	69,1	16,1	23,34
85,2	70,1	15,1	21,61
85,2	70,9	14,3	20,22
85,2	71,5	13,7	19,11
85,2	72,1	13,1	18,21
85,2	72,5	12,7	17,47
85,2	72,9	12,3	16,88
85,2	73,2	12,0	16,40
85,2	73,4	11,8	16,00
85,2	73,7	11,5	15,68
85,2	73,8	11,4	15,41
85,2	74,0	11,2	15,20
85,2	74,1	11,1	15,02
85,2	74,2	11,0	14,88
85,2	74,2	11,0	14,76
85,2	74,3	10,9	14,66
85,2	74,4	10,8	14,58
85,2	74,4	10,8	14,51
85,2	74,4	10,8	14,46
85,2	74,5	10,7	14,41
85,2	74,5	10,7	14,38
85,2	74,5	10,7	14,35
85,2	74,5	10,7	14,32
85,2	74,6	10,6	14,21

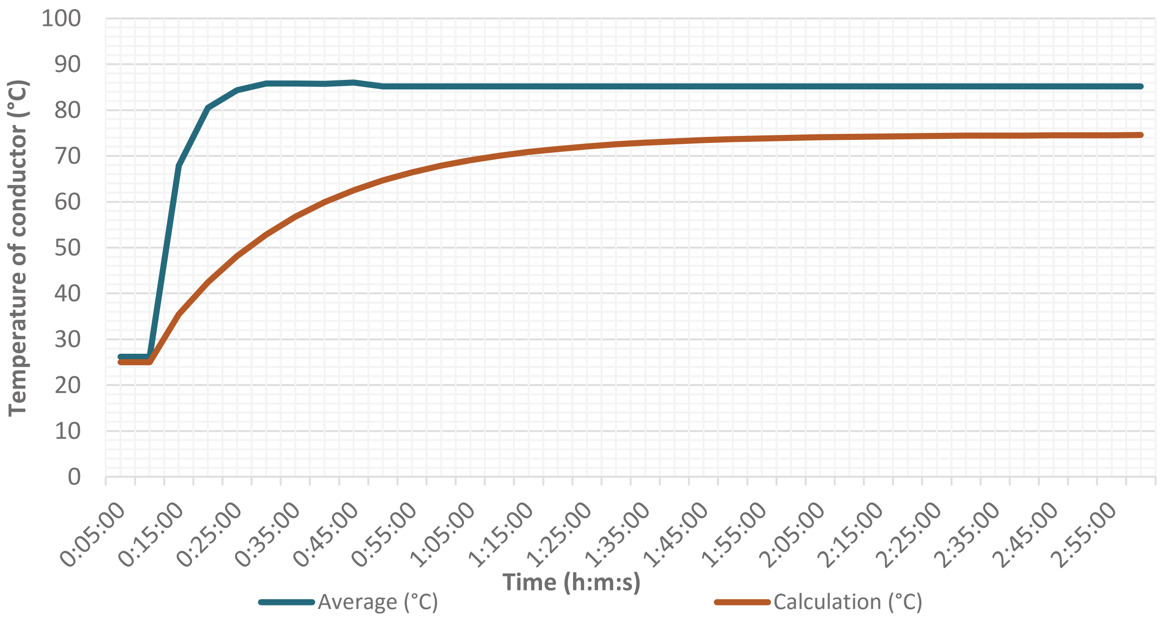

Figure 2 Graphical comparison for 24-AL1/4-ST1A conductor

As can be seen from the Table 3, when comparing the average conductor temperature obtained from 10 measurements and the calculated conductor temperature, there is a significant difference between these temperatures.

The biggest difference was in the first points of measurement, when the difference was up to 67.19%.

With increasing time of measurement and calculation, the difference between the measured temperature and the calculated temperature decreased to 14.21%.

The CIGRE Technical Brochure 207 standard defines a temperature difference up to 20% for smaller wind speeds of 0.5 $m.s^{-1}$.

Measurement uncertainty also has a significant impact. When comparing the driver's static temperature values, this difference is up to 20% by standard.

Due to the low wind speed, the convection is mixed, which is not taken into account by the conductor temperature calculation standard.

The graphical representation of the comparison is shown in the Figure 4.

V. Conclusion

Power lines are one of the most important part of power system. Temperature of the conductor is function of the current value, ambient conditions, type of used conductor and their properties.

Ambient conditions have most influence on the actual value of current capacity. If it is possible to accurately determine the ambient conditions in real time, current capacity can be determined under these terms and adapted on operation of power system or power lines. Increasing current capacity of existing power lines is one of the way how to operate power system in the short term. On the other side, is necessary to build, expand with new power lines which is however time-consuming and economically demanding.

For the static part, i.e. steady-state conductor temperature at rated electric current was found to be 14.21% difference for 24-AL1/4-ST1A. In point of view of such a high difference in measurement and calculation temperatures, the CIGRE 207 standard defines a situation where the air flow rate is less than 0.5 $m.s^{-1}$. In this case difference is up to 20%. In our case, considering the combined measurement uncertainty, this result is excessively accurate.

In the dynamic part, i.e. after switching the measuring circuit, when the nominal current flowed through the conductor, the difference was significantly higher at 67.19% for the 24-AL1 / 4-ST1A rope.

These differences in temperature are beyond the explanation in CIGRE 207. The problem with these parts of the results and its verification is that the CIGRE 207 methodology does not specify a sufficiently accurate calculation option for a state where the wind speed is below 0.5 $m.s^{-1}$ in the dynamic part of the load.

The missing parameter is the effect of mixed convection.

VI. Acknowledgment

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