Examination of thermal behavior of high voltage conductors

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***Abstract* — Due to the increasing energy demand, new questions raise for engineers such as how to achieve high utilization of the existing transmission system. For this purpose, the investigation of network equipment and elements is indispensable. Dynamic line rating (DLR) is a cost-efficient way to raise the transmission power capacity of the existing high voltage overhead lines. DLR technology is based on the real-time thermal equilibrium of the conductors, which is the basis of the ampacity calculation of the given line. Therefore, the investigation of the thermal behavior of wires is essential to fine tune the existing calculation methodologies.**

The aim of this paper is to present the research regarding to the thermal behavior of high voltage conductors performed in the High Voltage Laboratory of Budapest University of Technology and Economics. In this research the time constant of a wire was determined both in case of different static and dynamic thermal processes, thus the heating and cooling mechanism of the conductor can be described in a more precise way in case of thermal monitoring of the wires.

Keywords — dynamic line rating, DLR, tranmission line, high voltage conductors, thermal process

I. Introduction

In the past, transmission lines were designed at assumption – called static line rating – that the maximum current load was much less than their real thermal limits. Therefore, the likelihood that the high current load would occur simultaneously with high ambient temperature and low wind speed is extremely low. However, due to the persistent increase in electricity consumption and long-lasting investments of new transmission lines, the average current load significantly increased. The power lines are conventionally designed and operated with worst case limitations defined by static ratings [1]. Due the high penetration of intermittent renewable energy sources (IRESs), transmission line currents show large fluctuations and thus significant uncertainty [2], [3].

During the design of new overhead lines, the transmission capacity is normally calculated assuming conservative weather conditions and the maximum allowed conductor temperature [4]. In this case, when high current flows through the wires, it increases the losses in the form of heat known as Joule heating, which results increased conductor temperature. Excessive temperature may result in expansion sag of conductors causing decreased clearance to ground. For the investigation of conductor temperature and sag relationship, a more accurate model of the resistance of the steel-cored conductors operating at high AC current densities has been developed. Additionally, more reliable data on the radial and axial temperature distributions within the conductors are available thanks to various researches [5].

The thermal rating – also referred to as ampacity – of an overhead line is the maximum current that a circuit can carry without exceeding its sag temperature or the annealing onset temperature of the conductor. The sag temperature is the temperature at which the legislated height of the phase conductors above the ground is met the defined values by national laws. The present practice is to monitor the power flow on power lines without the knowledge of the actual conductor temperature or the height of the conductor above ground. There are many variables affecting the conductor temperature, such as wind speed and direction, ambient temperature and solar radiation. As these are difficult to predict, conservative assumptions have been made so far in order to always ensure public safety [6].

Currently several transmission lines need for uprating their transmission capacity in order to increase network reliability, contribute the penetration of renewable energy sources and homogenize the electricity prices in the adjacent markets as the results of the sufficient cross-border power flow. Transmission system operators (TSOs) are usually faced with network reinforcements, but due to their financial and administrative complexity, new solutions such as dynamic line rating should be investigated. The latent transmission capacity made available by DLR technology means the operation time of equipment can be extended, especially in the current power system scenario, where power injections from IRESs put stress on the existing infrastructure. DLR can represent a solution for accommodating higher renewable production whilst minimizing the cost of infrastructural developments [7].

Dynamic line rating is a technology used to increase the ampacity of transmission lines as the function of the rapidly changing environmental parameters. It is based on the observation that the ampacity of an overhead line is determined by its ability to dissipate the heat produced by Joule effect into the environment. This capability depends on environmental conditions – such as ambient temperature, solar radiation, wind speed and direction – and also on the thermal time constant of the applied conductors [8], [9]. With the introduction of thermal

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time constant, the model can be optimized and generalized, thereby making the predictions more reliable. This paper presents the thermal time constant during the heating and cooling effect of Joule heating affects the high voltage conductors.

II. Thermal Time Constant Measurement

A. Thermal time constant

Thermal time constant is the parameter characterizing the thermal response to a step input of a system, which can be calculated according to the temperature difference between the initial and the final thermal states. By definition, the temperature equalization rate of an object is the thermal time constant, denoted by τ. This is the time during the temperature difference between the initial and final state decreases from the original to "e".

The thermal time constant can be calculated for temperature increase and decrease, according to (1).

$$T(\tau) = \frac{T_0 - T_K}{e} + T_K \qquad (1)$$

Where

- $T(\tau)$: the temperature at the thermal time constant [°C],
- τ: thermal time constant [min],
- T_0: initial temperature [°C],
- T_K: final temperature [°C],

B. Measurement arrangement and data collection method

The research was made in the High Voltage Laboratory of Budapest University of Technology and Economics. The measurements were performed for several consecutive days, to ensure that the conductor return its original thermal state between each measurement.

During the measurements three thermocouples were used, whose data was collected with Matlab function in real-time through an NI-9213 temperature input module made by National Instruments [10]. The Matlab function is specially designed for data collection of these thermocouples and a Keysigth multimeter, which measured the current of the conductor.

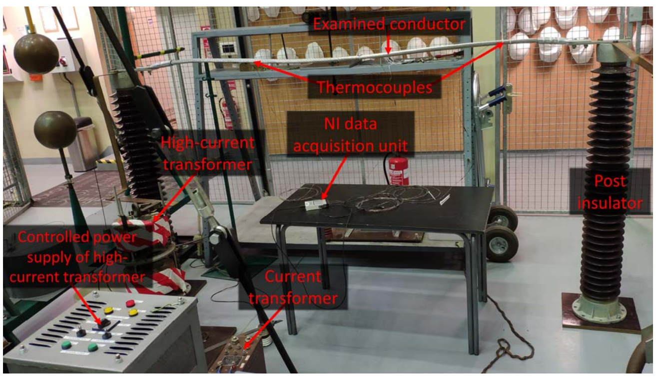

Fig. 1. Measurement arrangement

The current was provided by a high-current transformer controlled through a toroidal transformer. The two post insulators held the specimen, which in this case was a 2-meter-long ACSR 240/40 mm^2 conductor. The thermocouples were attached to this conductor as shown in Fig. 1. The signals of the thermocouples were received by the data acquisition computer together with the current measured by the precision multimeter, which arrived at the instrument via a current transformer, thus forming a ratio of 1: 600. The computer ran a Matlab code that collected the incoming current and temperature data, and measured the time elapsed during the measurement, and visualized the received values in real-time.

III. Measurement's results

Two different measurement methods were used during the investigations to get a comprehensive picture of the thermal behavior of the investigated conductor.

A. Static method

The first was the static technique, where the initial temperature of the conductor was the ambient temperature. Then a current step was applied to heat the conductor, after the thermal balance was reached then the current was terminated according to the following current step functions:

- 0 A – 600 A – 0 A
- 0 A – 900 A – 0 A
- 0 A – 1200 A – 0 A

During the static measurement the warming and the cooling curves were specified separately. In order to the higher accuracy, the three thermocouples data was averaged, thus the impact of measurement noise and other distorting effects was reduced.

Fig. 2 shows the results of the measurement of thermal time constant with static method, when 900 A load was used to heat the conductor.

The measured conductor temperature values in Fig. 2 are plotted as the averaged values of the three thermocouple's measurement results. Then an exponential curve was fitted to the measurement points, on which based the final temperature can be defined in an accurate way. After that, the temperature at the thermal time constant can be calculated, thus the thermal time constant can be determined.

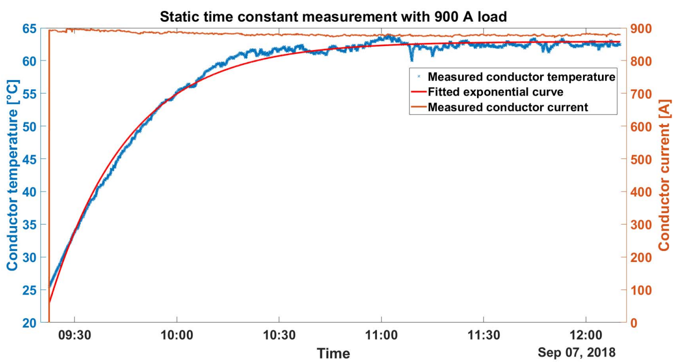

Fig. 2. Thermal time constant measurement with 900 A load

TABLE I. RESULTS OF STATIC METHOD

Para-meter	Maximal current / Heat transfer cycle					
	600 A		900 A		1200 A	
	Warming	*Cooling*	*Warming*	*Cooling*	*Warming*	*Cooling*
T_0 [°C]	25.62	44.19	24.98	65.10	25.34	91.58
T_k [°C]	44.25	25.93	65.91	26.09	94.57	26.64
T_τ [°C]	37.40	32.65	50.85	40.44	69.10	50.53
τ [min]	38.29	38.71	35.65	35.03	32.35	31.21

The results of the thermal time constant measurements by static method are summarized in TABLE I. , on which basis the dependence on the current step change range can be determined.

TABLE I. shows that the thermal time constant was in good approximation in the warming and cooling phases, and it shows a current load dependence. In case of increasing current load, the time constant decreased, approximately 300 A increment in current load resulted 3 min decrease in time constant. As the results show, higher current decreases time constant, thus the smallest time constant realized at the 1200 A case. This experiment should be taken into consideration during the calculation of emergency ratings, when extensive load permitted for a short time period.

B. Dynamic method

The other method to determine thermal time constant is dynamic measurement, when the current load steps change from time to time during the measurements, as in field conditions. In this case the current changed in six steps as described below:

- 0 A – 600 A – 900 A – 1200 A –
  – 900 A – 600 A – 0 A

In this method, only the initial temperature was the same as the ambient temperature. In the other steps, current step function was applied after the temperature of the conductor reached the equilibrium state.

In the dynamic case the conductor could not cool down to the ambient temperature, because the increase in the current values occurred in several steps as it can be seen in Fig. 3.

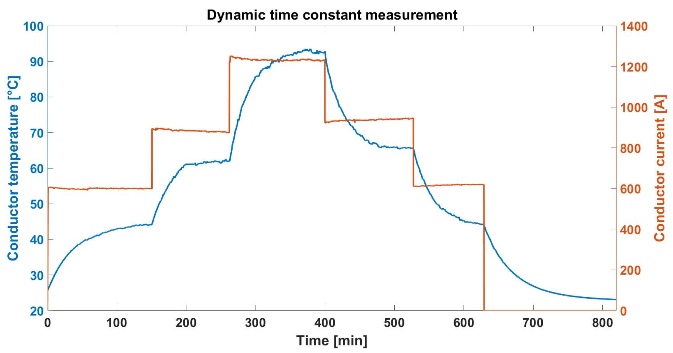

Fig. 3. Thermal time constant measurement with dynamic method

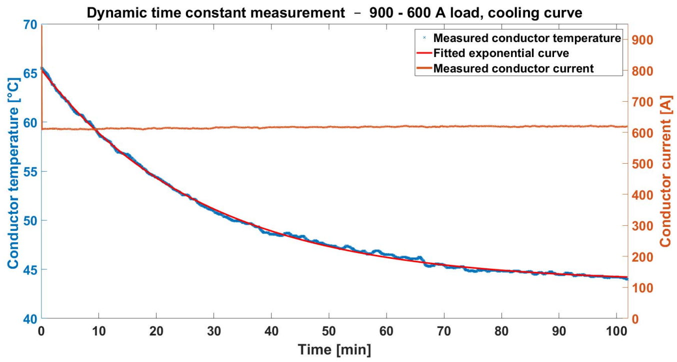

Fig. 4. Thermal time constant measurement with dynamic method – cooling curve

During the evaluation, the individual current load values were taken separately according to the warming and cooling phases, as it described during static method. It is demonstrated in Fig. 4 to a cooling curve when the current load decreased to 600 A from 900 A.

TABLE II. summarizes the measurement results in case of dynamic methodology.

As TABLE II. shows, the first warming phase was almost the same, as in the static case. It is the consequence that the ambient temperature was almost the same, and in both cases the current load was 600 A. The other values are different, because in these cases the conductor could not cool down to the ambient temperature, it always had previous thermal state, contrary during in static method.

According to the analyzation of the results, it can be concluded that, besides the change in the current of 300 A, the time constant was shaped around 25-28 minutes. When 600 A current load staps was applied, the warm-up time constant was 38.2 min, while the cooling down time constant was 41.1 min. Altogether, the dynamic thermal time constant measurements show a higher deviation, accordingly to the broader applied current load steps.

TABLE II. RESULTS OF DYNAMIC METHOD

Heat transfer cycle	Parameter				
	Current [A]	T_0 [°C]	T_k [°C]	T_τ [°C]	τ [min]
Warming	0-600	25.64	44.34	37.43	38.29
	600-900	44.34	61.80	55.84	25.65
	900-1200	61.80	93.67	81.95	28.39
Cooling	1200-900	93.67	65.20	74.40	26.11
	900-600	65.20	43.88	51.85	27.27
	600-0	43.88	23.03	30.71	41.17

C. Comparison of results

In case of static method, the results show more consistency, thus the current load dependence of the time constant can be determined in a precise way. Contrarily, during dynamic approach, the data showed a slightly higher deviation, accordingly to the several different temperature changes, the wire had various preliminary states. The great dependence of the time constant on the previous states – not only the magnitude of the applied current step – is a good basis for the further investigations. Therefore, the dynamic method is able to give a comprehensive picture of the time constant measured more current steps, and different time intervals.

IV. Conclusion

Due to the requirements of a sustainable energy use, new questions are raising for engineers such as how to achieve high utilization of the existing transmission system. For this purpose, the investigation of network equipment and elements is indispensable. Dynamic line rating (DLR) is a cost-efficient way to increase the transmission power capacity of the existing high voltage overhead lines. DLR technology is based on the real-time thermal equilibrium of the conductors, which is the basis of the ampacity calculation of the given line.

The research regarding to the thermal behavior of high voltage conductors was performed in the High Voltage Laboratory of Budapest University of Technology and Economics. In this research the time constant of a 240/40 mm2 conductor was determined both in static and dynamic thermal processes. In case of static method, the results show consistent results in the function of the applied current step load, thus the current load dependence of the time constant can be determined in a precise way. Contrarily, during dynamic approach the data showed a slightly higher deviation, accordingly to the several different temperature changes, by reason of the wire had various preliminary states. Based on the results it can be concluded that the dynamic method is able to give a more comprehensive picture of the time constant, accordingly to the measurements performed with more current load steps and different time intervals in comparison with the static method. Consequences gained during dynamic measurement are more similar to field experiments than static technique, therefore while the presented results are good basis for the further results, these measurements should be proceeded with all-round time steps and current step changes applied on several conductors to get a more comprehensive picture of the thermal behavior of high voltage conductors.

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