

OPERATION AND EFFECTS ANALYSIS OF THE SYSTEM FOR CONDUCTOR TEMPERATURE REMOTE MONITORING AND REAL-TIME AMPACITY FORECAST ON THE OHL 110 KV BANJA LUKA 1 – BANJA LUKA 6/I AFTER FIVE YEARS OF OPERATION

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Abstract: This paper presents architecture of dynamic thermal rate (DTR) system installed on OHL 110 kV Banja Luka 1 – Banja Luka 6/I. The paper presents performance of the system, conductor temperatures reached during the past five years period of exploitation as well as meteorological data from meteorological station in correlation to power consumption data of the area of interest. The critical scenarios in transmission line operation were analysed and conclusions were drawn regarding the justification of the DTR system installation against to a transmission line reconstruction.

Keywords: Conductor temperature performance, Dynamic thermal rate, Ampacity, Overhead line, Reconstruction

INTRODUCTION

The trend of rapid development of generation capacities based on renewable energy sources (RES), primarily wind and solar energy, has caused significant changes of power flows in some areas of the transmission network and has imposed new challenges on transmission system operators (TSOs). Increased generation from RES results in growth of the power flows through transmission lines over short periods of time. As a possible solution for this problem is considered implementation of systems for remote monitoring of conductor temperature and real-time forecasting of the ampacity or current carrying capacity (hereinafter referred as “CCC”) of transmission lines (Dynamic Line Rating – DLR or Dynamic Thermal Rating, hereinafter referred to as the “DTR system”). Opposite to traditional concept of static overload protection this solution is expected to allow increasing of CCC during periods of time with favourable weather conditions for conductor cooling, without exceeding the maximum permanently permitted conductor temperature at relative low investment costs and short period of implementation.

As a possible solution to the overload problem of the 110 kV overhead line Banja Luka 1 – Banja Luka 6/I identified through development plans, Elektroprijenos-Elektroprenos BiH a.d. Banja Luka (TSO of Bosnia and Herzegovina, hereinafter referred as “Elektroprenos BiH”) decided to install a DTR system on this transmission line five years ago.

The authors are familiar with studies [1], [2] that address the theoretical aspects of DTR system implementation, CCC calculation, and the analysis of the justification for installing a DTR system prior to its deployment. However, these studies do not present operational experiences with DTR systems. In some transmission system development studies [3], it can be found that the CCC of an overhead line equipped with a DTR system amounts to 120% of the capacity of a line without a DTR system. It should be noted that such an assumption is adopted for parts of the power system in which critical power flows occur during the operation of wind power plants, where a high probability of favourable conductor cooling conditions can be expected at the time of line load peaks.

The authors’ intention is to analyse the operation of a DTR system on a specific overhead transmission line located in a part of the power system where line load peaks is determined by power consumption. The reliability and security of line operation, as well as the possibilities for relieving line loading under critical operating conditions, are analysed.

The key question addressed in this paper is whether the installation of a DTR system, together with the reduction of transmission line loading under critical operating conditions due to transmission network reconfiguration, ensures reliable and secure operation in the observed part of the power system, and whether additional investments in transmission line reconstruction are required. In addition to the DTR system performance

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indicators, a retrospective analysis was conducted using a dataset of meteorological

conditions collected from the DTR system's meteorological station, as well as transmission line load forecasts based on realized consumption and generation data during past operating period. The objective of this analysis was to verify whether thermal overloading of the transmission line would have occurred during the period of DTR system operation if a critical network outage had taken place at any point in time.

The transmission line load forecast is theoretically based on the DC network model described in the literature [4]. To determine the participation factors of consumption and generation at individual nodes within the part of the network of interest, power flow calculations were performed using the PSS®E software package developed by Siemens PTI, which is widely used for power system analysis and planning through various static and dynamic simulations. Power flow results for the winter and summer peak load models of the Bosnia and Herzegovina power system were obtained using the Newton–Raphson power flow method. The steady-state power flow conditions were simulated with load levels increased by 20% compared to the peak loads recorded in the period 2020–2023 in the network of interest.

Subsequently, the impact of changes in generation and consumption at individual nodes within the analysed network area on the loading of the observed transmission line was examined. This analysis yielded participation coefficients that quantify the effect of consumption and generation power at specific nodes on active power flows along the considered transmission line. After determining these participation coefficients, the transmission line loading was calculated using a custom-developed program written in the MathWorks®MATLAB software package, under the assumption of constant voltage and constant reactive power flows along the transmission line. The line loading calculations were carried out for all 15-minute consumption and generation intervals at the nodes of interest over the period 2020–2023.

For the calculated transmission line loadings under normal operation, critical operating conditions, and after load alleviation, conductor temperatures of the overhead line were simulated. The calculations utilize a set of meteorological data collected from the DTR system's meteorological station over the period 2020–2023, with a sampling interval of 15 minutes. The calculations are based on the CIGRÉ methodology described in the literature [5], for which a dedicated program was also developed using the MathWorks®MATLAB software package.

The difference with respect to the methodology described in [5] lies in the fact that the calculated conductor

temperature as a function of wind speed and wind direction is compared with the temperature calculated for a wind speed of 0.5 m/s perpendicular to the conductor axis, which corresponds to natural convection conditions, and the lower of the two calculated conductor temperatures is adopted. This approach was applied because, when comparing the calculated conductor temperatures with the measured conductor temperatures, it was observed that this correction provides less deviation between simulation results and the measured conductor temperature values. Chapter 1 presents the topology and characteristics of the transmission network in the area of interest, while Chapter 2 describes the characteristics of the 110 kV overhead line Banja Luka 1 – Banja Luka 6/I, including an assessment of additional investments required to improve the security of line operation and to upgrade the DTR system, compared with the costs of transmission line reconstruction. The architecture of the DTR system and its performance indicators over the previous period are presented in Chapter 3. Chapter 4 addresses the thermal calculation of the transmission line conductors under characteristic operating conditions (normal operation, the most unfavourable N-1 contingency, and transmission line load alleviation following the most critical branch outage in the part of the power system under consideration) for 15-minute nodal loadings in the regional transmission network during the period 2020–2023. The conclusions drawn from the conducted analyses are presented in Chapter 5.

1. CHARACTERISTICS OF THE TRANSMISSION NETWORK IN THE AREA OF INTEREST

The 110/35/10 kV Banja Luka 1 substation stands as major node of the 110 kV transmission network, with six overhead line bays through which approximately 50–60% of the electricity demand of the Banja Luka city and the surrounding region is supplied. The substation is equipped with a double-busbar system and a bus coupler bay.

This substation is connected to the 400/110/20 kV Banja Luka 6 substation via two overhead transmission lines: the 110 kV Banja Luka 1 – Banja Luka 6/I line with Al/Steel (hereinafter referred as “ACSR”) 150/25 conductors, and the 110 kV Banja Luka 1 – Banja Luka 6/II line with ACSR 240/40 conductors. The 400/x kV Banja Luka 6 substation is the main supply point from which the Banja Luka city and the wider Banja Luka and Doboj regions are supplied with electrical energy through two 400/110 kV transformers rated at 300 MVA.

A situational layout of the network part under consideration is shown in Figure 1.

In development plans, the 110 kV Banja Luka 1 – Banja Luka 6/I transmission line is identified as one of the facilities

that becomes overloaded in the event of an outage of the 110 kV Banja Luka 1 – Banja Luka 6/II transmission line. To overcome this limitation and taking into account that the ACSR 150/25 conductors on the 110 kV Banja Luka 1 – Banja Luka 6/I line were replaced with new ones in the period from 2000 to 2012, a DTR system was installed on this transmission line. The system was installed in 2018 and has been in stable and reliable operation since 2020.

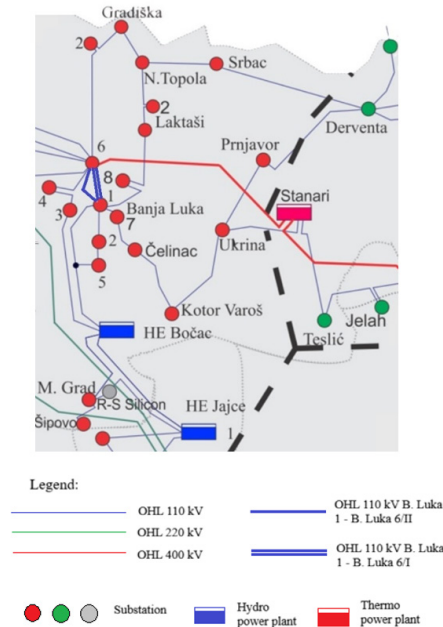


Figure 1: Transmission network in the area of interest

2. CHARACTERISTICS OF THE 110 KV OHL BANJA LUKA 1 – BANJA LUKA 6/I

The 110 kV Banja Luka 1 – Banja Luka 6/I overhead transmission line has a total length of 13.87 km. A section with a length of 11.13 km, equipped with ACSR 150/25 conductors, was constructed in 1962, while on a portion of the route built in 1980 as the connection of the Banja Luka 6 substation to the power system, ACSR 240/40 conductors were installed. The 110 kV Banja Luka 1 – Banja Luka 6/II line is a parallel transmission line equipped with ACSR 240/40 conductors along its entire length and presents the right circuit of the former double-circuit 110 kV Jajce – Zagreb transmission line, constructed in 1957.

For the 110 kV Banja Luka 1 – Banja Luka 6/I transmission line, the standard N-1 planning criterion is not satisfied, since an outage of the 110 kV Banja Luka 1 – Banja Luka 6/II line results in an overload of the Banja Luka 1 – Banja Luka 6/I line beyond its thermal limit of 89 MVA. This limit corresponds to a line current of 468 A, calculated in accordance with IEEE Standard 738 [6], using the following meteorological conditions: ambient air temperature of 35 °C, solar radiation intensity of 850 W/m², and wind speed of 0.6 m/s perpendicular to the conductors (natural cooling conditions).

Given that new conductors were recently installed on the line, a DTR system was implemented as an alternative to full transmission line reconstruction. Prior to the installation of the DTR system, an analysis of ground clearance and safety distances was carried out for the 110 kV Banja Luka 1 – Banja Luka 6/I transmission line. In accordance with the regulations in force at the time of construction, the line was designed to satisfy the required safety clearances at a conductor temperature of 40 °C. The analysis covered 49 control points where the line crosses over roads, low-voltage (LV) or medium-voltage (MV) lines or passes in the vicinity of residential buildings.

Out of the 49 control points, the required safety clearances are not met at three locations at a conductor temperature of 40 °C. Two of these cases involve crossings with LV and 20 kV lines, which require cabling. All structures associated with insufficient safety clearances were constructed after the transmission line had been built. At a conductor temperature of 60 °C, safety clearances are violated at ten control points, while at a conductor temperature of 80 °C, safety clearance violations occur at fourteen control points, as shown in Table III in Annex.

Given that the deviations in safety clearances are relatively small, the considered transmission line could be brought into compliance with safety clearance requirements at a conductor temperature of 80 °C by increasing the heights of towers at critical locations and by installing horizontal insulator strings on the lower phase at suspension towers in the remaining spans. The reliability of the transmission line could be further improved through additional investment in the expansion of the DTR system, including the installation of additional conductor temperature sensors and an additional meteorological station, as well as by increasing conductor safety clearances at critical locations. The estimated cost of these additional measures amounts to approximately EUR 300,000, which corresponds to up to 20% of the current cost of full transmission line reconstruction.

3. DTR SYSTEM ARCHITECTURE AND PERFORMANCE INDICATORS

The DTR system consists of a sensor unit installed on the transmission line conductor and a meteorological station mounted on the tower structure. The sensor unit enables direct measurement of conductor temperature, current, and inclination. The inclination data are used to estimate conductor sag and to indicate ice accretion on the conductor. The meteorological station is equipped with sensors for measuring wind direction and wind speed, ambient air temperature, air humidity, and solar radiation intensity.

Data from the sensor unit are transmitted via a GSM (Global System for Mobile Communications) device to the system server located in the dispatching control centre of

Elektroprenos BiH within the Banja Luka Operational Area. The system is configured to generate two types of alarms based on conductor temperature and, using data from the meteorological station, to display the calculated real-time permitted CCC of the line with respect to a predefined temperature limit. Data from the sensor unit and the meteorological station are transmitted at 15-minute intervals and stored on the server for subsequent analysis and processing.

One sensor unit and one meteorological station are installed on the transmission line, both located on tower No. 5. The appearance of the system installed on the transmission line is shown in Figure 2 and sensor unit is shown in Figure 3. The system was installed in 2018 and, following the completion of the trial operation period, was placed into permanent operation in 2020.

It is important to note that, due to the configuration of the SCADA/EMS system (Supervisory Control and Data Acquisition/Energy Management System) and the protection systems, the DTR system does not provide an automatic trip signal for the transmission line in the event of exceeding the maximum permissible conductor temperature. Instead, the system generates an alarm to the dispatching centre

only, responsible for the necessary line load reductions. The alarm and conductor temperature monitoring functions are integrated into the existing SCADA/EMS system.

The transmission line overload protection is set to generate an alarm at a current of 376 A with a time delay of 20 s, while switching off the transmission line is set at 468 A with an operating time of 20 minutes.

The main performance indicators of the system over the past period are presented in Table I and Table II. During the period 2020–2024, the system recorded an average unavailability of approximately 1.2%, corresponding to an average of about 105 hours per year. It is important to note that this figure also includes periods during which temperature and current data from the sensor unit were not available. This does not necessarily imply unavailability of the DTR system itself but may also include periods when the transmission line was unavailable due to planned outages or similar operational conditions.

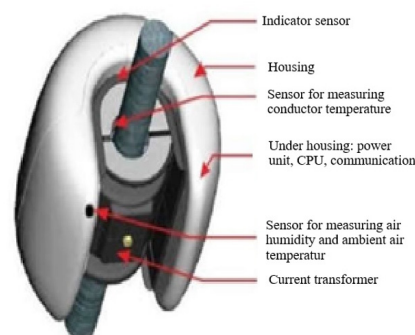
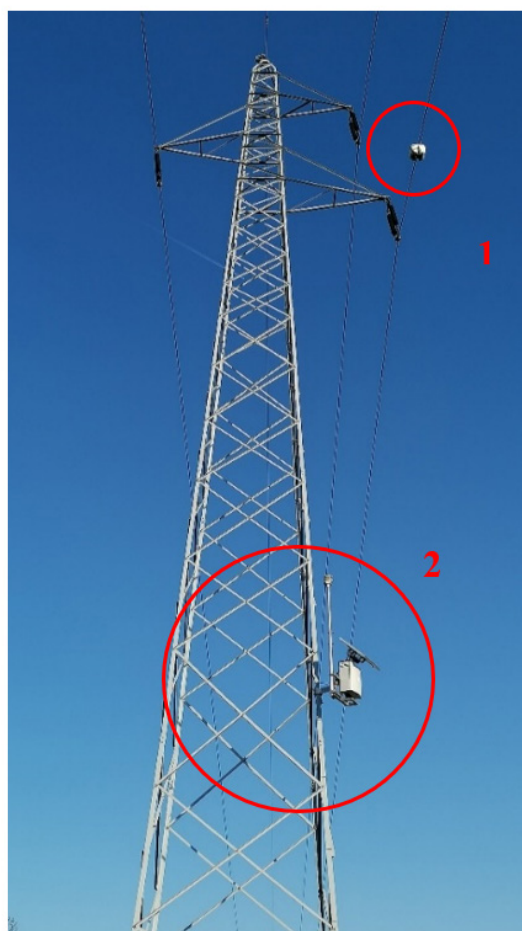


Figure 3: Sensor unit of DTR system



1 – sensor unit
2 – meteorological station

Figure 2: DTR system on tower No. 5 structure

Table I: DTR system unavailability in period 2019-2024

Year	DTR system unavailability*	
	%	h/year
2019	49.84%	4366
2020	1.91%	167
2021	1.23%	108
2022	0.19%	16
2023	0.00%	0
2024	1.58%	139

Table II: conductor performance indicators

Year	Time with conductor temperature exceeding +40°C	
	%	h/year
2019	---	---
2020	1.09%	96
2021	3.96%	347
2022	1.79%	157
2023	0.00%	0
2024	1.58%	139

An overview of the maximum values of the observed time-dependent parameters is presented in Table IV in Annex. Regarding the transmission line current loading and the maximum conductor temperature, it can be seen that the current loading remained below settings of the overload protection. During the observed period, the conductor temperature also remained below 60 °C; consequently, no high-temperature conductor alarms were activated.

It is noteworthy that, at the maximum conductor temperature reached in each of the observed years, none of the meteorological parameters attained their extreme values—neither maximum values (ambient air temperature, solar radiation) nor minimum values (wind speed and wind direction). Therefore, in all cases, a certain, at least minimal, thermal margin with respect to conductor current loading was available.

Maximum thermal loading of transmission line conductors typically occurs during the summer months, when transmission line loadings are relatively high. Therefore, this period requires particular attention when planning transmission line operation.

Based on a more detailed analysis of meteorological parameters, the presentation of which is beyond the scope of this paper, it can be concluded that the spring period and warmer days during winter are the most favourable for planning works on nearby facilities, due to relatively low transmission line loadings, lower ambient temperatures, and a higher frequency of wind occurrence. On the other hand, warmer days during the autumn period may also be critical for transmission line operation, owing to relatively high ambient temperatures, relatively high solar radiation intensity, and a lower frequency and intensity of wind.

Based on the data collected from the meteorological station, it can be concluded that favourable conditions include the relatively high frequency of wind occurrence and the fact that the dominant wind directions are approximately perpendicular to the transmission line route. Based on the processed data, it can be concluded that, with regard to load forecasting and potential seasonal adjustment of protection settings, the spring and autumn periods should be treated in the same manner as the summer period, due to the possibility of relatively high ambient temperatures and solar radiation intensities that are comparable to those observed in summer.

A limitation of the system lies in the fact that measurements are performed at one location only. The manufacturer's recommendation was to install conductor temperature sensor units at three locations along the transmission line and meteorological stations at two locations.

In Chapter 4 of this paper, system limitations were analysed by calculating conductor temperatures in all tension spans equipped with Al/Steel (ACSR) 150/25 conductors, under the assumption that ambient air temperature, solar

radiation, wind speed, and wind direction are uniform along the transmission line route. Summary results of conductor temperature calculation are presented in Table VII and Table VIII in Annex, showing maximal and average calculated values of conductor temperature in normal operating state, after outage of critical OHL 110 kV Banja Luka 1 – Banja Luka 6/II and following busbar splitting in the SS Banja Luka 1 after critical outage, all compared with values measured with DTR system. The maximum annual deviations of conductor temperature along the transmission line, resulting from different angles between the wind direction and the conductor axis and calculated according to the methodology described in Chapter 5, amount to 9.3 °C–11.09 °C under normal operating conditions. In the event of an outage of the 110 kV Banja Luka 1 – Banja Luka 6/II line, these deviations increase to as much as 34.97 °C–44.27 °C, while after transmission line load alleviation they range between 20.28 °C and 25.27 °C. The probability that, under operating conditions recorded during the period 2020–2023, the difference in conductor temperature of the ACSR 150/25 conductors along the transmission line route exceeds 20 °C in the event of a critical outage and following appropriate load reduction is approximately 0.78%, without taking into account the probability of occurrence of the critical fault state itself. This practically means that a DTR system configured in this manner and set with an alarm threshold at 60 °C should, in most cases, ensure that the conductor temperature does not exceed the maximum continuous permitted temperature of 80 °C for ACSR conductors, provided that line load reduction is performed sufficiently quickly.

The assumption that meteorological conditions are uniform along the transmission line route can be considered approximately valid with respect to ambient air temperature and solar radiation intensity; however, it is questionable in the case of wind speed and wind direction due to varying terrain topography along the route, and it cannot be verified or quantified without the installation of additional measurement devices. For this reason, the paper also considers the additional costs associated with upgrading the DTR system by installing two additional conductor temperature measurement systems and one additional meteorological station, as well as the costs of increasing safety clearances at critical locations, as described in Chapter 2, in order to enable the transmission line to meet safety criteria at conductor temperatures of up to 80 °C. For current DTR system configuration, yearly time with potential violating temperature limits in conductors is shown in Table IX in Annex. Between 2020 and 2023, there was a 1.5% probability that the conductor temperature would exceed its maximum continuous limit of 80°C. This condition applies during a critical outage before a busbar split, with a maximum annual duration of 220.3 hours. After busbar split in substation Banja Luka 1 following the critical outage, probability of violating alarm temperature setting of 60°C was 0.77% in period 2020–2023, with maximal yearly duration of 116h.

4. CONDUCTOR TEMPERATURE CALCULATION IN CRITICAL OPERATING CONDITIONS

In certain circumstances, when an outage or switch off the 110 kV Banja Luka 1 – Banja Luka 6/II transmission line occurs, current loadings are high; therefore, an additional conductor temperature calculation was performed. The calculation was carried out under the assumption of actual transformer substation loadings recorded during the period 2020–2023 and measured meteorological parameters over the same period. It was assumed that the outage could occur in any 15-minute interval, and the steady-state conductor temperature was calculated for the meteorological parameters and the estimated line current loading corresponding to that interval. Furthermore, the analysis considered different conductor position for each tension section, and the maximum conductor temperature was estimated under the assumption that wind speed and wind direction are uniform along the entire transmission line route.

The transmission line current loading was determined by estimating the line loading based on transformer substation loadings in the area of interest for each 15-minute interval, using equations (1) and (2). For the purposes of the calculation, participation factors of individual transformer substations in the transmission line loading were determined from the summer peak and winter peak operating conditions. The total transmission line loading was then calculated as:

$$P(j) = \sum_{i=1}^n k(j)_i \cdot P_i + P(j)_0 \quad (1)$$

Where:

$$k(j)_i = \frac{\partial P(j)}{\partial P_i} \quad (2)$$

-participation coefficient of transformer station or power plant with index i ,

P_i —active power consumption or generation in node i , and $P(j)_0$ is calculated as a difference between active power flow along the line out from peak load model in PSS®E and sum $\sum_{i=1}^n k(j)_i \cdot P_i$ for corresponding operating conditions presented in Table V in Annex.

For simplicity, and due to the observed minimal variations of $P(j)_0$, an average value was adopted for the corresponding switching state. Index $j=1$ corresponds to the normal operating state, $j=2$ corresponds to an outage of the 110 kV Banja Luka 1 – Banja Luka 6/II line, and $j=3$

corresponds to busbar splitting in the Banja Luka 1 substation following the outage of the 110 kV Banja Luka 1 – Banja Luka 6/II line. Average values were also adopted for $Q(j)$ and $U(j)$ for each respective switching state.

Finally, the phase conductor current was calculated using the following equation:

$$I(j) = \frac{\sqrt{P(j)^2 + Q(j)^2}}{\sqrt{3}U(j)} \quad (3)$$

Characteristic values of the modelled current loading of the 110 kV Banja Luka 1 – Banja Luka 6/II transmission line are presented in Tables V and VI in Annex.

Based on the calculated conductor current loadings and the environmental parameters recorded at the DTR system meteorological station, the conductor surface temperature T_s was calculated for each tension section using the methodology described in [5] and Equation (4).

$$P_g + P_s = P_{conv} + P_{rad} \quad (4)$$

Where:

- P_g – Joule loss power generated in the conductor, which depends on the conductor current and temperature;
- P_s – absorbed solar radiation heat power, which depends on the solar radiation intensity and the absorption coefficient of the conductor surface;
- P_{conv} – convective heat loss power, which depends in a complex manner on wind speed and wind direction, ambient temperature, and conductor diameter;
- P_{rad} – radiative heat loss power, proportional to the fourth power of the conductor temperature and to the emissivity coefficient of the conductor.

$$T_c - T_s = \frac{P_g + P_s}{2\pi\lambda} \cdot \left[\frac{1}{2} - \frac{d^2}{D^2 - d^2} \cdot \ln\left(\frac{D}{d}\right) \right] \quad (5)$$

Where:

- T_s – conductor surface temperature;
- T_c – temperature at the hottest spot of the conductor;
- λ – effective radial thermal conductivity of the conductor, assumed to be 2 W/m·K;
- d – diameter of the conductor core;
- D – outer diameter of the conductor.

Of particular interest for further analysis is the maximum estimated temperature along the entire transmission line. The applied methodology is valid for the determination of both the conductor surface temperature and the internal conductor temperature. The parameter of interest is the maximum internal conductor temperature, which, however, does not differ significantly from the calculated conductor surface temperature. The summarized results of the conductor temperature calculations are presented in Tables VII and VIII in Annex.

In Table IX in Annex is shown cumulative time during a year with possibility of exceeding temperature limits of conductors along the OH 110 kV Banja Luka 1 – Banja Luka 6/II.

5. CONCLUSION

The installed DTR system has proven to be highly reliable and enables effective management of the loading of

the 110 kV Banja Luka 1 – Banja Luka 6/I transmission line, ensuring that the conductor temperature remains below the maximum continuous permitted temperature of 80°C for this conductor type in most critical operating conditions. Power flow analysis under a violated N-2 criterion identified a single case with reduced possibilities for transmission line load decrease.

Based on the performed analyses, it can be concluded that these criteria are expected to be satisfied in the forthcoming period as well; therefore, the authors' position is that reconstruction of the considered transmission line is not necessary. The reliability of the line can be further improved through investments that do not exceed 20% of the transmission line reconstruction costs. Given the high expected current loading and the importance of both lines for the security of supply of the wider Banja Luka area, the 110 kV Banja Luka 1 – Banja Luka 6/I and Banja Luka 1 – Banja Luka 6/II transmission lines require enhanced maintenance measures, including thermographic inspections, more frequent vegetation clearing, and prompt overhauling of any detected conductor damage. In transmission line load management, load reduction is achieved by splitting the load of the Banja Luka 1 substation into two busbar systems via the bus coupler bay. This solution provides a higher level of supply security and reliability for the regional load compared to previously applied dispatching actions. Since an outage of the 110 kV Banja Luka 1 – Banja Luka 6/II line may result in high line

loadings and high conductor temperatures up to 107.3°C, as shown in Table V and table VII in Annex, rapid response in implementing transmission line load reduction measures is required in order to keep conductor temperature under maximum continuous conductor temperature of 80°C. As can be seen in Table VII maximal calculated temperature of conductor, following critical outage and load reduction measures for observed period is 78.9°C and does not exceed maximum continuous conductor temperature. As presented in Table IX, yearly time with potential violating maximum continuous conductor temperature of 80°C during critical outage and before busbar split in substation Banja Luka 1 was about 1,5% of period 2020-2023. After busbar split in substation Banja Luka 1 following the critical outage, the time with potential violating alarm temperature setting of 60°C is reduced to 0,77% of period 2020-2023. These results support the thesis that the installation of the DTR system combined with busbar split measures was the right decision.

Seasonal adjustment of overcurrent protection settings should also be considered, such that during the winter period (e.g., from 01 December to 28 February) the overcurrent protection is set to 640 A, while the existing overcurrent protection settings are maintained during the remainder of the year, as discussed in Chapter 3. The operating time of the overcurrent protection must be coordinated with the time required to implement transmission line load reduction actions.

ANNEX

Table III: Results of safety clearances calculations

Control point	Span	Control point in urban area	Type of obstacle	Necessary safety clearance (m)	Safety clearance at +40°C (m)	Safety clearance at +60°C (m)	Safety clearance at +80°C (m)
15	6-7	Yes	OHL 20 kV	2.50	2.13	1.47	0.96
15B	7-8	Yes	local road	7.00	7.34	6.99	6.66
15C	7-8	Yes	local road	7.00	6.77	6.35	5.96
18	10-11	Yes	LV line	2.50	3.07	2.63	2.21
19	10-11	Yes	field	7.00	7.31	6.95	6.61
29	18-19	Yes	NNL	2.50	1.83	1.18	0.51
34	22-23	Yes	meadow	7.00	7.18	6.66	6.16
36	25-26	No	forest road	6.00	6.01	5.17	4.34
38	27-28	Yes	yard	7.00	7.89	7.29	6.71
42	31-32	No	meadow	6.00	6.74	6.01	5.31
43	32-33	No	orchard	6.00	6.36	5.94	5.53
44	33-34	No	meadow	6.00	6.21	5.68	5.17
45	35-36	No	local road	7.00	7.21	6.79	6.37
46	35-36	No	orchard	6.00	6.55	6.15	5.77

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Table IV: indicators of current and thermal load measured in period 2019-2024

Year	Max. conductor temperature (°C)	Max. conductor current (A)	Weather conditions and current load at maximum conductor temperature					
			interval	Current (A)	Solar radiation (W/m ²)	Ambient temp. (°C)	Wind velocity (m/s)	Wind direction (°)
2019	---	---	---	---	---	---	---	---
2020	51.10	442	22.09.2020 11:15	439	474	22.6	0.67	121.7
2021	51.75	378	24.06.2021 16:45	325	531	38.0	0.82	51.9
2022	48.60	404	23.07.2022 15:45	263	700	38.9	1.07	210.3
2023	48.60	371	24.07.2023 15:45	264	687	37.1	1.06	268.0
2024	49.23	412	19.06.2024 14:30	286	838	35.9	1.25	287.7

Table V: Maximal values of measured and calculated current load (A)

Year	2020	2021	2022	2023
DTR system -measured	441.5	377.7	404.0	370.7
I1 (normal operating state)	338.6	343.2	330.4	327.9
I2 (N-1, outage of OHL 110 Banja Luka 1 – Banja Luka 6/II)	607.3	615.6	593.4	587.4
I3 (N-1, following busbar splitting in the SS Banja Luka 1)	492.9	497.8	483.6	476.7

Table VI: Average values of measured and calculated current load (A)

Year	2020	2021	2022	2023
DTR system -measured	197.7	202.2	207.5	177.3
I1 (normal operating state)	225.0	231.2	234.1	215.7
I2 (N-1, outage of OHL 110 Banja Luka 1 – Banja Luka 6/II)	402.3	415.6	420.6	387.8
I3 (N-1, following busbar splitting in the SS Banja Luka 1)	300.6	310.5	317.2	287.4

Table VII: Maximal values of conductor temperature (°C)

Year	2020	2021	2022	2023
DTR system -measured	51.1	51.8	48.6	48.6
I1 (normal operating state)	51.5	58.1	57.2	58.1
I2 (N-1, outage of OHL 110 Banja Luka 1 – Banja Luka 6/II)	95.5	104.9	103.8	107.3
I3 (N-1, following busbar splitting in the SS Banja Luka 1)	64.6	73.9	73.5	78.9

Table VIII: Average values of conductor temperature (°C)

Year	2020	2021	2022	2023
DTR system -measured	19.6	19.3	20.2	19.2
I1 (normal operating state)	22.2	22.6	23.7	22.5
I2 (N-1, outage of OHL 110 Banja Luka 1 – Banja Luka 6/II)	45.6	47.4	49.5	43.3
I3 (N-1, following busbar splitting in the SS Banja Luka 1)	30.2	30.9	32.8	29.4

Table IX: Yearly time with potential violating temperature limits in conductors

Year	2020	2021	2022	2023
$T_c > +80^{\circ}\text{C}$ outage of OHL 110 Banja Luka 1 – Banja Luka 6/II	53.3	201.5	220.3	63.0
$T_c > +60^{\circ}\text{C}$ outage of OHL 110 Banja Luka 1 – Banja Luka 6/II following busbar splitting in the SS Banja Luka 1	13.8	116.0	99.0	41.0

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