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EVALUATION OF THERMAL RATING METHODS BASED ON THE TRANSMISSION LINE MODEL

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Electric power consumption has been growing continuously, especially in the last years. Therefore, implementation of new advanced technologies such as the overhead line thermal monitoring is topical for improvement of the existing transmission line network in order to increase its throughput capacity and reliability of power supply. In general, the real-time thermal monitoring systems are designed based on the existing methods using the limiting conditions for ampacity determination of high-voltage overhead lines. The paper considers commonly used methods for thermal rating estimation which include computation of the conductor temperature and of the conductor sag. Comparative analysis was performed for the measured and calculated steady-state conductor temperatures and line sagging, based on which the thermal rating methods were tested. The experimental measurements were conducted for three cases using special monitoring equipment. The study has been carried out based on the existing line model of the Latvian transmission grid.

Key words: *power transmission line, atmospheric measurements, current measurements, comparative analysis.*

1. INTRODUCTION

Since the existing transmission and distribution systems have to carry ever increasing capacity of the power lines, it is urgent to develop and integrate new technologies into the existing transmission grid [1]. The challenge is to improve the interconnections between neighbouring systems as well as to raise the throughput capacity and technical reliability of a grid. Moreover, the liberalized electrical power market and significant impact of renewable energy producers call for development of a more flexible operational network that would, at the same time, require less investments [2]. The interest has now quickened in the real-time technologies, which thus become an important factor in optimizing diversified technical solutions for adapting the Smart Grid to the existing transmission systems. Some of these solutions are: the dynamic thermal circuit rating (DTCR) [3], the video sagometer [4], the differential global positioning system (GPS) sag monitor for real-time sag measurement [5]; worth mentioning also are: the phasor measurement units (PMU) network [6], which supports the real-time monitoring of operating conditions and automated response to disturbances [7]; the temperature monitoring of overhead lines (OHL) [8]; the OHL rating monitoring [9], etc. Furthermore, these technologies enable the operator to gain intelligence and visibility as to the status of the transmission grid on real-time basis in order to use the existing transmission capacity and energy carrying capability as well as to achieve a bulk transmission system for effective delivery of desired resources on demand [10].

The DTCR software delivers the real-time information about a transmission circuit's operating condition to assist in increasing and optimizing the power flows [11]. Its operational concept is illustrated in Fig. 1 [12]. The software determines the dynamic circuit ratings by evaluating all equipment ratings in a circuit and finding the most limiting ampacity for each rating scenario.

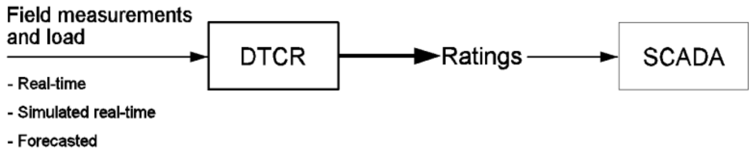

Fig. 1. The concept of DTCR operation.

For implementation of DTCR systems it is necessary to specify the initial operation algorithm based on which a real-time monitoring system can be developed. The choice of calculation methods depends on the type of parameters to be measured or calculated. Thus, a logical chain of operations is to be created for revealing the weaknesses of the selected approach.

In most cases such thermal rating methods as IEEE Std 786-2006 [13], Cigre Brochure [14], IEC 1597 [15], and MT 34-70-037-87 [16] are used to implement monitoring systems. The framework of each method is commonly based on such parameters as the temperature of conductor, its sag, absorptivity and emissivity as well as weather conditions (ambient temperature, wind speed and direction, humidity).

Taking into account the impact of the mentioned parameters on the permissible load current of a particular transmission line (TL) [17], one of the main parameters for the implementation of DTCR systems and the operation of TLs is the conductor temperature. This temperature depends on various parameters of the conductor: its material, diameter, surface conditions, the ability to carry electrical current, and the ambient weather conditions [18]. To ensure reliable and safe TL operation a permissible conductor temperature should exist. Therefore, physical characteristics of a specific conductor (diameter, cross-section area, weight, strength; thermal elongation; electrical resistance) limit its temperature. Typically, the clearance between the energized conductors and other crossed objects does not allow increasing capacity of most existing OHLs. The temperature of the conductor increases with OHL load, causing its elongation – a sag, thereby reducing the clearance. The extent of sagging for a given current loading is directly affected by weather conditions, e.g. the ambient temperature and wind speed [19]. Moreover, a threat arises as to the insulation ruptures and faults due to increased conductor temperature under the impact of electromagnetic field at increasing voltage with the distances between the conductor phases becoming unsafe. As a result, the permissible standard values are exceeded. Therefore, the conductor temperature has to be monitored in order to prevent the excessive conductor sag. Besides, precise estimation of the conductor temperature allows for determination of the power losses and fault location in a TL.

The implementation of DTCR software based on the information from sensors about a transmission line that would provide real-time operation makes it possible to monitor the OHL sag, temperature, and local ambient conditions. For monitoring the conductor temperature two ways are known:

1. Direct monitoring, i.e. measuring directly the conductor temperature, which is inconvenient for the operation of a TL.
2. Indirect monitoring, i.e. thermal rating calculation using the measured key parameters that impact the allowable conductor temperature.

Since the theoretical principles of DTCR are based on several thermal rating determination methods, it is necessary to select a proper accurate approach that would allow doing this not only for the thermal rating of a line but also for the key parameters, e.g. the conductor temperature. Otherwise, the incorrectly calculated ampacity may cause line outages, insufficient operation due to elevated conductor temperature and increased sag.

In general, the procedure for estimation of thermal rating methods can conceptually be presented in four main stages:

1. Knowing the current carried by a conductor and the ambient conditions to calculate the conductor temperature. Since this parameter cannot exceed the permissible value affected by the conductor's physical characteristics, the manufacturer's technical documentation is to be considered.
2. Knowing the conductor temperature to calculate the conductor sag and clearances to the ground or to the crossed objects as well as the parameters of electrical and magnetic fields (which must be in the limits of allowable standard values).
3. Based on the calculated parameters to determine the permissible load current for the conductor.
4. Finally, to correct the operation mode if needed.

The authors of works [20–22] describe the thermal rating estimation methods for different cases and conditions, commonly assuming that such parameters as conductor and ambient temperatures, relevant clearances and climate conditions are known.

This work deals with testing the thermal rating estimation methods based on indirect monitoring of the conductor temperature, which is followed by comparison of the measured and calculated temperatures of the conductor and its sag.

2. EXPERIMENTAL

2.1. General Description

The experimental measurements were conducted for three main cases (A, B, C) using the OHL model of LN-600 line (Fig. 2). The measurements were done for the span between towers No. 1 and No. 2.

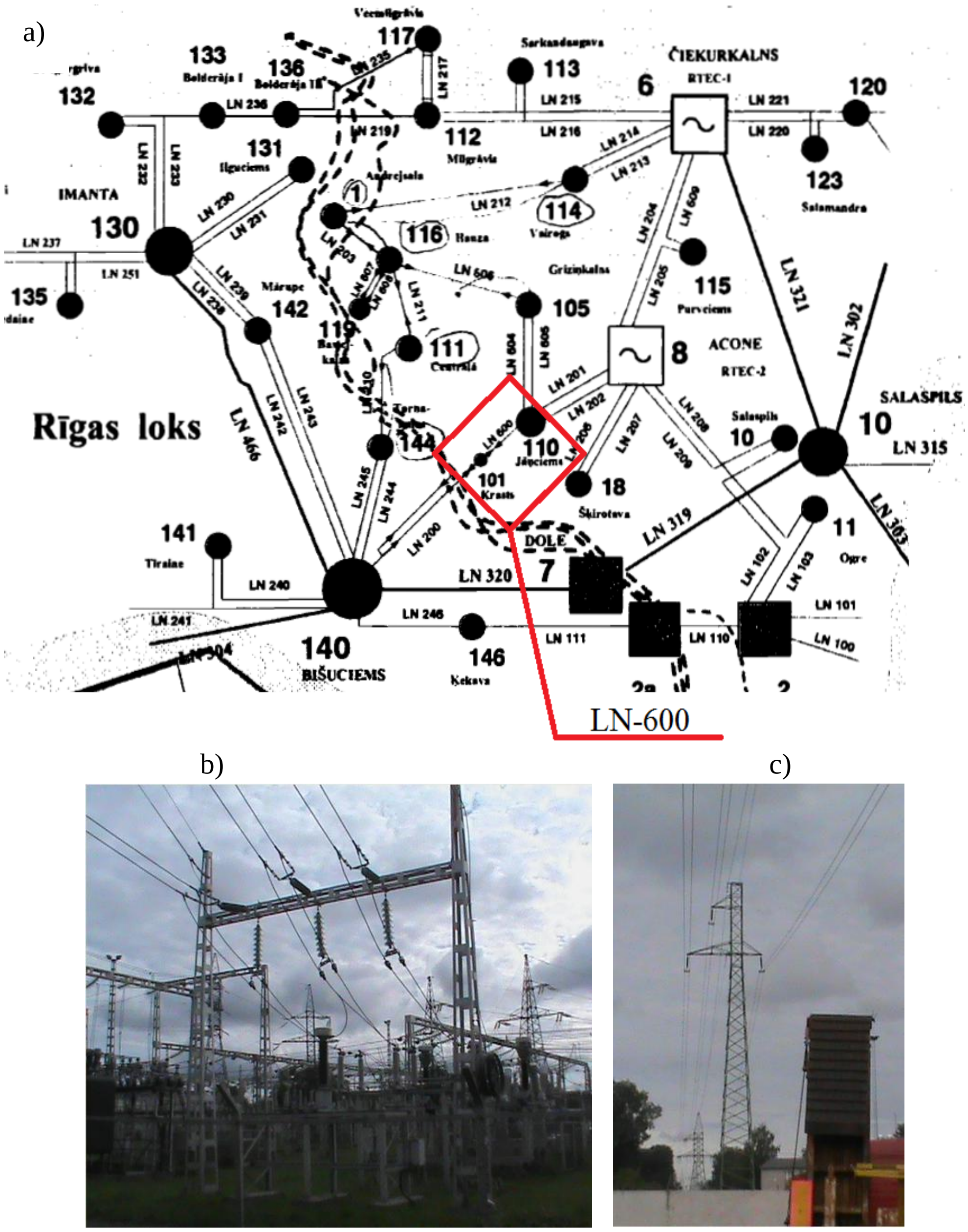

Fig. 2. Partial electrical diagram of power line LN-600 (*a*); part of tower No. 1 – substation "Janciems" span (*b*); part of the span between towers No. 1 and No. 2 (*c*).

The power line LN-600 is a single-circuit line with traditional AS-240/32 conductor having two wires per phase.

2.2. Experimental equipment

The setup for measuring the parameters of transmission line LN-600 is shown in Fig. 3. In this study it was necessary to obtain the results of measuring the conductor & ambient temperatures, humidity and wind speed. For the measurements the following special monitoring equipment was used:

a) for the conductor temperature – a special thermovision device (FLIR ThermaCAM P65, Fig. 3*a*) [23];
b) for the ambient temperature and humidity – a thermohygrometer (Testo 635-1, Fig. 3*b*);
c) for wind speed – a pocket weather tracker (Kestrel 4000” in Fig. 3*c*).

Fig. 3. The monitoring equipment: thermovision device (*a*); thermohygrometer (*b*); pocket weather tracker (*c*).

3. RESULTS AND DISCUSSION

3.1. Experimental results

The results of measuring weather parameters (ambient temperature, wind speed, humidity) as well as thermal (conductor temperature) and electrical (load current, voltage) parameters are shown in Table 1 for operating line LN-600, cases A, B, and C. Concerning the validation of the electrical and magnetic fields, these parameters had been tested before.

As seen from Table 1, the wire temperature of phase in some cases is lower than the ambient temperature, which is wrong and probably occurred due to measurement equipment error. However, since this is within the permissible limits of ±2 °C, for each case the highest wire temperature of the relevant phase is taken as the initial parameter for testing the thermal rating methods.

Table 1

Results of measuring the parameters of LN-600 line

Parameters / Measurement data	LN-600		
	Case A	Case B	Case C
	Towers No. 1 – No. 2		
Voltage, kV	115	115	117
Load current, A	37	162	73
Active power of load, MW	2	31	7
Reactive power of load, MVar	7	9	13
Wire temperature of phase 1 (AR01), °C	17	25.6	3.9
Wire temperature of phase 2 (AR01), °C	–	–	–
Wire temperature of phase 3 (AR01), °C	14.7	25.8	3.5
Ambient temperature, °C	17	21	3
Wind speed, m/s	2–5	1–2	3–5
Wind direction	West	West	South
Weather conditions	partially cloudy	sunny	cloudy
Conductor type	2xAS-240/32		
Allowable load current at ambient temperature			
+20°C	1271 A	1271 A	
+5°C			1452 A
Line loading, %	3	13	5

3.2. Computation results

The computation results of the conductor temperature as well as conductor sag for three general cases are presented in Table 2.

Table 2

Computation results based on the experimental data

Thermal rating method / Calculated parameters		LN-600								
		Case A				Case B		Case C		
		Towers No. 1 – No. 2								
Measured wind speed, m/s		*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
IEEE Std 786-2006	Conductor temperature, ºC	23.4	22.3	21.6	21.2	35.0	31.4	8.9	8.1	7.6
	Conductor sag, m	3.8	3.7	3.7	3.7	4.0	3.9	3.5	3.5	3.4
IEC 1597	Conductor temperature, ºC	20.3	19.7	19.3	19.0	27.1	25.3	5.7	5.3	5.0
	Conductor sag, m	3.7	3.7	3.7	3.7	3.8	3.8	3.4	3.4	3.4
MT 34-70-037-87	Conductor temperature, ºC	17.1	17.1	17.1	17.1	25.1	22.2	3.2	3.2	3.2
	Conductor sag, m	3.6	3.6	3.6	3.6	3.8	3.7	3.3	3.3	3.3

3.3. Comparison of the results

Tables 1 and 2 present the obtained experimental and computational results for the examined cases A, B, C and different weather and line load conditions.

In this study, the model for estimation of the thermal ratings was elaborated in three general stages. First, an existing overhead line was chosen, for which the initial parameters (physical, mechanical and electrical) were determined. Second, the necessary weather parameters under the chosen conditions were measured or assumed according to the local data. In this case, the ambient temperature, wind speed, wind direction and humidity were measured using special equipment, whereas the global solar radiation was assumed. In the third stage, the estimation of thermal ratings taking into account the measured weather parameters was done based on the calculated conductor temperature and sag. For the computation, mathematical equations of the IEEE Std 786-2006, IEC 1597 and MT 34-70-037-87 methods were taken.

The results obtained for the measured conductor temperatures have been compared with the computed conductor temperatures for different weather conditions and used for estimation of the selected thermal rating methods taking into account the difference in the conductor temperature values.

Figure 4*a* presents comparison of the steady-state conductor temperatures – both measured and calculated for several wind speeds (case B). Here the measured conductor temperature T_m = 25.8 °C (the highest wire temperature of phase 3), is compared with the calculated conductor temperatures (T_c) according to the examined thermal rating method. The diagram shows that the largest difference in the measured and calculated conductor temperature values is for the IEEE Std 738-2006 method (T_c = 35.0 °C), then the IEC1597 approach follows: T_c = 27.1 °C, (a lower difference percentage), and the last one is the MT 34-70-037-87 method with T_c = 25.1 °C (i.e. almost identical to the measured temperature at a wind speed of 1 m/s). At the same time, for the wind speed of 2 m/s the situation is somewhat different: for the IEC1597 method T_c = 25.3 °C – practically the same as the measured conductor temperature, while for the MT 34-70-037-87 approach it is less than T_m (T_c = 22.2 °C). Moreover, it is observed that the conductor temperature values are decreasing under the impact of wind (the higher the wind speed, the higher the convection heat loss).

Besides, it should be noted that measured current I_m in case B is 162 A, so the line loading in our example (the conductor type AS-240/32, two wires per phase, the allowable conductor current of 1271 A at +20°C) is only 13 %.

Nevertheless, not only the thermal limitation such as conductor temperature can be one of the general criteria for the estimation of thermal rating methods; also the mechanical limitation such as conductor sag is among the key influential parameters by which the so-called ground clearing distance and clearing distance to the crossed objects are determined.

Figure 4*b* displays the comparison of conductor sag values based on the calculated conductor temperatures for the given comparative methods. The diagram shows that the maximum conductor sag – up to 4.0 m – is observed in the case of the IEEE Std 738-2006 method due to higher calculated conductor temperatures;

by contrast, the smallest conductor sag, 3.7 m, is observed for the MT 34-70-037-87 thermal rating method. It is obvious that the difference of conductor sag is here quite small – only up to 30 cm – despite a noticeable difference in the conductor temperatures (up to 10ºC, see Fig. 4*a*).

Cases A and C obey the same concept of comparison as case B (Fig. 4*a*,*b*) but with different obtained results due to dissimilar weather conditions (see Table 2).

In case A, the T_m of 17.0 °C (the highest wire temperature of phase 1) is compared with T_c according to the IEEE Std 738-2006 method (T_c = 23.4 °C), then the IEC1597 approach follows (T_c = 20.3 °C), and the last one is the MT 34-70-037-87 method (T_c = 17.1 °C) at the wind speed of 2 m/s. It is worth noting that T_c of 17.1 °C at all wind speeds for the MT 34-70-037-87 thermal rating method is practically the same as the measured conductor temperature (T_m = 17 °C); thus, it can be inferred that this estimation is quite accurate (the difference between the measured and calculated conductor temperature values is negligible). In addition, despite the difference between the measured and calculated conductor temperatures – up to 6.3 ºC – the conductor sag in different methods is quite similar, with the maximum value of 3.8 m in the case of MT 34-70-037-87 method and of 3.7 m in the IEC1597 method. Such a result can also be due to low line loading (only 3% at such weather case, when the measured load current is 37 A).

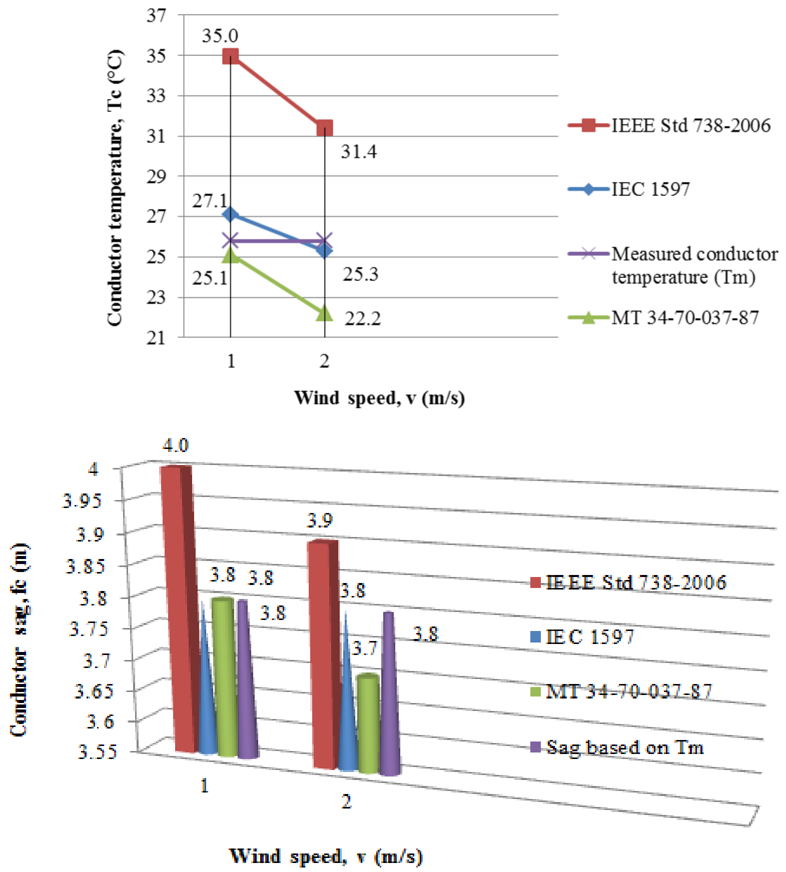

Fig. 4. The computation results based on the experimental data for LN-600 line, case B: *a*) steady-state conductor temperature; *b*) conductor sag.

Analysing the results obtained for case C, the same tendency as for case A could be seen – yet with a smaller difference in values between the estimated conductor temperatures for all the presented thermal rating calculation methods, and with smaller conductor sags.

4. CONCLUSIONS

The comparative assessment of the IEEE Std 738-2006, IEC1597 and MT 34-70-037-87 steady-state thermal rating methods was based on experimental and computational results.

The experimental results reflect the actual values of such important parameters as the conductor temperature, ambient temperature, humidity, and wind speed and direction, obtained using special monitoring equipment.

The computation results show the estimated values of the conductor temperatures and sags obtained by measurements.

The difference between the measured and the calculated conductor temperatures and conductor sags for the mentioned methods can be explained as follows.

1. The estimated conductor temperature values depend on the wind speed, yet to a different extent; thus, each example needs to be reviewed and discussed.
2. The line loading should be considered and estimated both for normal and faulty operation in order to moderate the current limitations at line loading being very small; or, by contrast, to make the adjusted limitations stricter at a significant percentage of line loading (adaptation for actual line loading is to be taken into account). Besides, the higher the loading percentage of a line, the bigger the difference between the ambient and the conductor temperatures; it does not matter whether the conductor temperature is measured or calculated.
3. The percentage of reserve accounting for the conductor temperature rise (found in the thermal rating estimation methods) plus additional resistive losses are to be revealed and taken into account, since the load current value has been forcibly reduced due to an additional conservative limitation by this percentage.
4. Different empirical techniques of the examined calculation methods as well as the complexity of these methods have to be taken into account.

Despite the difference in the measured and the calculated conductor temperatures for cases A, B, and C, all the estimation methods under consideration are quite accurate; this fact is confirmed by the results obtained for the conductor sags, where the maximum difference is only 30 cm.

The higher loading of a line is usually possible if real measured weather parameters are known; unfortunately, traditional static ratings are overly conservative, since they are based on the worst-case weather assumptions: for example, when the calculated conductor temperatures are far below the maximum allowable conductor temperature, the line is insufficiently loaded; besides, the allowable conductor temperature defined by the manufacturer cannot be exceeded.

However, knowing the real conductor temperature data makes it possible to control the thermal rating of the line in a more flexible way using special monitoring systems relied on a highly precise method for determination of the maximum real-time TL rating.

This study focuses on the selection of the most appropriate method for calculating the ampacity of a line, based on which the real-time thermal monitoring systems can be developed for best practices of integrating the remote sensor data into the utility communication and energy management; therefore, it is necessary to carefully study the theoretical approach of a selected method, along with the use of experimental measurements based on simple monitoring equipment.

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TERMISKO JAUDAS METOŽU NOVĒRTĒJUMS, BALSTOTIES UZ ESOŠO ELEKTROPĀRVADES LĪNIJAS MODELI

S. Berjozkina, A. Sauhats, A. Banga, I. Jakuševičs

K o p s a v i l k u m s

Elektroenerģijas patēriņš nepārtraukti pieaug, īpaši šī tendence novērojama pēdējos gados. Tādējādi jaunu progresīvu tehnoloģiju ieviešana, piemēram, tādu kā elektropārvades līnijas termiskās monitoringa sistēmas, ir viens no aktuāliem risinājumiem, kas ļautu uzlabot esošo pārvades tīklu, palielinot tā caurlaides spēju, kā arī elektroapgādes drošumu. Vispārējā gadījumā reālā laika režīma monitoringa sistēmas balstās uz pastāvošajām metodēm, izmantojot ierobežojošos nosacījumus jaudas noteikšanai augstsprieguma gaisvadu līnijām. Līdz ar to visbiežāk izmantojamo termisko jaudas metožu novērtējums, kas ietver vada temperatūras un nokares aprēķinu, ir diezgan aktuāls jautājums, kas jāizskata detalizētāk. Darbs atspoguļo izmērītās un aprēķinātās vada temperatūras un nokares salīdzinošo analīzi, balsoties uz kurām tika veikta termisko jaudas metožu testēšana. Turklāt ir vērts atzīmēt, ka eksperimentālie mērījumi tika veikti, izmantojot speciālas monitoringa iekārtas, izpētot trīs galvenos gadījumus “A”, “B” un “C”. Eksperimentālie un skaitļošanas pētījuma rezultāti parādīti rakstā, balstoties uz esošo līnijas modeli Latvijas pārvades tīklā.

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