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ScienceDirect
Energy Reports 7 (2021) 242–249
www.elsevier.com/locate/egyr

The 4th International Conference on Electrical Engineering and Green Energy CEEGE 2021, 10–13 June, Munich, Germany

A novel methodology for critical span identification for Dynamic Line Rating system implementation

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Received 19 July 2021; accepted 5 August 2021

Abstract

Nowadays the reliable availability of electricity is expected by both industrial and residential consumers. However, the generation, transmission and distribution all pose engineering challenges in adapting to consumers and sustainable directives while maintaining operational safety. The increasing demand for electricity on the consumer side and the growing number of renewable energy sources (RES) on the generation side are supporting the spread of capacity uprating methods. Dynamic Line Rating (DLR) is a novel, cost-effective line management method with which system operators are able to utilize existing power lines with greater efficiency than with traditional techniques. While the use of DLR has many benefits, there are also challenges that system operators have to cope with at system-level implementation. One of the most significant of these challenges is to find the balance between the required infrastructure for DLR implementation and the reliability of the implemented system. The aim of this article is to present a novel methodology for critical span identification based on which the sensor measurements accurately represent the prevailing conditions along the whole overhead line. Contrary to current methods, the proposed critical span analysis method takes into account the clearance of the conductors, which provides compliance with legal requirements. Furthermore, the uncertainty caused by using weather data to determine local conductor annealing is also eliminated with the recommended method. This way a flexible power system can be created that meets current needs, such as the integration of renewable and distributed energy sources or cross-border energy trade, while at the same time it enhances the operational safety of overhead lines.

Peer-review under responsibility of the scientific committee of the 4th International Conference on Electrical Engineering and Green Energy, CEEGE, 2021.

Keywords: Dynamic line rating; DLR; Overhead lines; Power system; Critical span analysis; Sensor placement strategy; System approach

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https://doi.org/10.1016/j.egyr.2021.08.050

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1. Introduction

Traditionally the so-called static line rating (SLR) calculation method is used to determine the ampere capacity (ampacity) of a power line. The SLR calculation is based on the worst-case environmental scenarios and as a result it is a wasteful method with respect to the utilization of the thermal capacity of the line. However, it is simple and does not require any additional infrastructure or time-consuming mathematical model.

Today's trend among power providers is to utilize the existing infrastructure to the extent that is allowed by the system's physical properties without significant loss of the system's lifetime. Dynamic line rating (DLR) is one of the technologies applied for such optimization, which allows the utilization of overhead lines in a less constrained way. The DLR calculation requires various monitoring equipment to be installed on the overhead line for real-time modelling of the thermal behaviour of the phase conductors. This way, the actual ampacity of the line can be determined based on the heat balance of the conductors, which on average offers a 20 to 40% increase in transmission capacity. Furthermore, the local thermal overload of the conductors is avoidable when the actual weather conditions are less favourable than those used for the SLR computation. With additional methodologies, which require the modelling of the thermal behaviour of the conductors, a complex line management system can be implemented that is able to predict and detect ice accretion and simulate the real-time sag of the conductors [1–6].

As a result of such novel line management systems, there is a demand for measuring devices in the vicinity of the phase conductors. Line rating determination requires the measurement of several environmental parameters, such as the intensity of solar radiation, ambient temperature, precipitation intensity, relative humidity, and wind speed and direction. These measurements can be obtained with the installation of weather stations on the high voltage towers' legs, as close to the bottom phase conductor as possible. Furthermore, there are line monitoring sensors based on different measuring principles that are able to determine the temperature of the conductor, the sag or clearance of the span, the accumulation of an ice layer on the conductors or the actual current load of the line. Different studies showed that the achievable safety level with the weather-based and line-monitoring-sensor-based system is nearly the same, because the temperature of the conductors can be calculated within the range of $\pm$ 2 °C compared to sensor measurements. This is approximately the same level as the measurement uncertainty of the DLR sensors [1,7,8]. Accordingly, the key issue during the establishment of the DLR-based system is the selection of the number and locations of the measuring equipment – weather stations and line monitoring sensors – in order to optimize the investment cost and the reliability of the grid management system. The methodology which determines the required number and installation position of the measuring equipment for a DLR system is called critical span analysis.

2. Review of existing critical span analysis techniques

The basis for critical span analysis is the selection of the spans for sensor placement that most closely represent the prevailing thermal conditions along the line so that thermal overloads and clearance violations can be avoided. The easiest sensor allocation approach is the equidistant placement strategy [9], which places the available number of sensors in equally spaced sections, where the distance of the sensors can be calculated according to (1). While it is simple, the clearance and thermal overload criteria cannot be fulfilled with this method.

$$d_{sensors} = \frac{l_{line}}{n+1} \tag{1}$$

where $d_{sensors}$ [m] is the distance of sensors from each other, l_{line} [m] is the length of the transmission line and n is the available number of sensors.

Two other sophisticated algorithms are available according to the international literature. These algorithms are based on the investigation of weather parameters along the line corridor in order to determine the correlation between line ratings calculated based on data from different locations [9], or to calculate the sag of the span and identify the possible conductor annealing locations [10].

2.1. Environmental factors for critical span identification

From a meteorological point of view, macro- and microclimates can be distinguished. Macroclimate describes the environmental parameters of large geographic zones such as continents and oceans. Therefore, macroclimatic weather models are suitable for global environmental modelling (such a globally applied model is the ECMWF [11]), further refined by national weather agencies according to the specific local microclimatology conditions. During the application of microclimatic weather models, the local specialties of the given area are taken into account. When weather parameters are used as input for DLR calculations it practically means the sheltering effect of objects and vegetation on the line. However, it should be noted that the validating data of the microclimatic models come from weather stations that are in most cases placed in open areas, therefore these data can cause large deviation with regards to sheltered areas such as transmission line corridors. Therefore, the weather parameters along the line can be expected to significantly differ from the weather conditions measured by meteorological stations, especially in the case of wind speed and direction. According to [12] it can be stated, that not only are the variations of weather parameters between the line route and open areas different, but a significant difference can also be observed between the measured parameters by weather stations placed on transmission line towers along a power line.

The most advanced microclimate weather models are able to determine the expected weather conditions by spatially interpolating to the line corridor, with a spatial resolution of around a few hundred metres. Therefore, theoretically such a model can be applied as an input of critical span analysis methods described in [9] and [10]. These weather models are also validated using measurements from meteorological stations mostly placed in open areas, which also causes a significant error in the modelling of the environmental parameters relative to power line sections that are going through sheltered areas.

For the illustration of this deviation, a case study was carried out to determine the correlation between the measured weather parameters on a 110 kV overhead line's tower and the microclimate weather model output for the same coordinates (spatially interpolated weather model) at the same time. The correlation coefficient of two variables can be calculated according to (2).

$$\rho(A, B) = \frac{1}{N-1} \sum_{i=1}^{N} \left(\overline{\frac{A_i - \mu_A}{\sigma_A}} \right) \left(\frac{B_i - \mu_B}{\sigma_B} \right) \tag{2}$$

where A and B are the sets of variables, μ_A and σ_A are the mean and standard deviation of variable A, respectively, and μ_B and σ_B are the mean and standard deviation of variable B.

Fig. 1 shows the correlation between the environmental factors required for determining the conductor temperature – ambient temperature, solar radiation, wind speed and direction – for a one-year period.

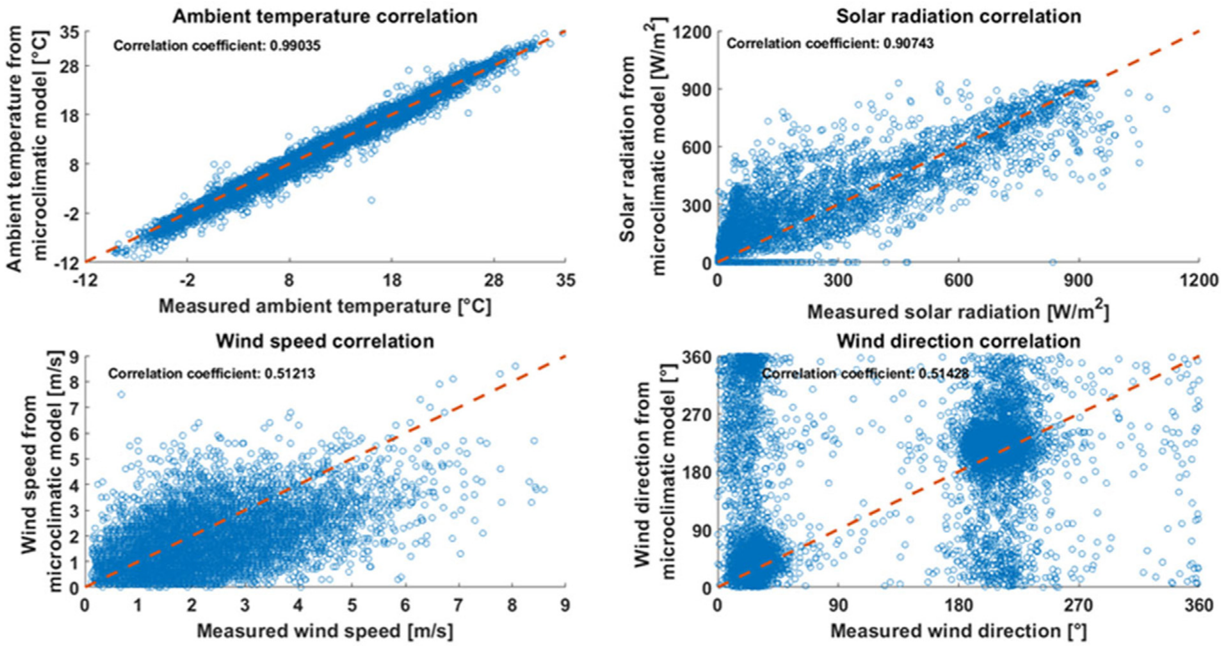

Fig. 1. Correlation between measured and forecasted weather parameters.

Fig. 1 shows, that the correlation between measured and modelled wind speed and direction is around 0.51. Several studies have shown that the thermal modelling of the conductors is the most sensitive to these parameters [13,14], which can cause more than 5 °C variance in conductor temperature resulting from 1 m/s difference in wind speed.

This chapter demonstrated that the equidistant sensor placement strategy does not represent the line rating for the whole line appropriately [9], while the weather-based critical span analysis method provides unreliable data that does not accurately reflect the temperature variability along the line [12]. Furthermore, the accuracy of weather parameters from microclimatological weather models is not satisfactory for critical span identification if conductor annealing is taken into account.

3. Proposed methodology

The challenges discussed in Section 2 provide the motivation for the development of a new critical span analysis method, which is able to determine the most representative locations along a power line for line rating calculations without the use of exact environmental factors.

3.1. Clearance regulations

The most critical factor during the operation of high voltage conductors at their maximal thermal rating is the observation of adequate external clearance limits, which is regulated by EN 50341-1:2012 in the European practice. The external clearance has two parts, the basic electrical clearance and an additional clearance component. The basic electrical clearance component (D_{el}) is intended to prevent the flashover between the energized parts and the earth potential objects in the vicinity of live conductors. The additional clearance component (D_{add}) is intended to avoid the violation of electric distance even in cases where a person or conductive object gets under the line while working or during leisure activities. The D_{e_1} component of the clearance is constant at a given voltage level, while the D_{add} component varies depending on the terrain and objects under the line. The additional clearance component includes normal ground profile, steep slopes, buildings with different roof types, crossing overhead lines, recreational areas, etc. [15].

Transmission and distribution system operators have to meet clearance regulation requirements, which means that the legal component ($D_{el} + D_{add}$) should be kept under all operating conditions. In practice this is accomplished with the consideration of a safety margin.

3.2. Sag-clearance model

The actual sag of a given span depends on the conductor temperature and wind load as varying parameters, while the conductor's technical parameters and the maximal tensile stress can be considered as constant values. The clearance can be derived from a sag model as the minimal distance between the bottom phase conductor and the terrain or any object under the line in each span.

Assuming that the sag of the conductor depends on the average conductor temperature of the given span [16] and the difference in conductor temperature within a span is negligible in short transmission lines where DLR can be applied effectively [17], (3) describes the basic formula of the catenary curve calculation.

$$y = \frac{\sigma_h}{\gamma} \cdot \frac{e^{\frac{x\cdot\gamma}{\sigma_h}} + e^{-\frac{x\cdot\gamma}{\sigma_h}}}{2} \tag{3}$$

where, σ_h is the horizontal component of tensile stress [kg/mm^2] and γ is the specific gravity of the conductor [kg/cm^3].

During the calculation of the catenary curve of the conductors, straight and oblique spans are distinguished. In the latter case, the calculated catenary curve should be corrected with a skewness factor described by (4).

$$f = \frac{a'}{a} \tag{4}$$

where a' is the oblique distance of suspension points [m] and a is the horizontal distance of suspension points [m].

In addition, the formula is able to calculate the position of the conductors with catenary curve by taking into account the terrain conditions, the unequally distributed extra mechanical load and the wind load on the conductors [18].

3.3. Investigation of the accuracy of the sag-clearance model

In order to investigate if the mathematical model described in Section 3.2 is accurate enough to determine the sag and clearance along a power line, a model validation was performed. During the validation process, field measurements were carried out to determine the position of the bottom phase conductor of a 110 kV single circuit overhead line located on a hilly terrain in Central-Europe. During the measurement a Leica theodolite was used to determine the position of the bottom phase conductor. Two measurements were made, one in June and one in November to obtain data under two different conductor temperature conditions. The average conductor temperature was 26.8 °C in June, and it was 4.2 °C in November. Fig. 2 shows the sag simulation results compared to the field measurements. An average deviation of less than 20 cm was found between the simulation and the field measurements, which can be attributed to conductor ageing, measurement error and the difference between the available and real conductor parameters.

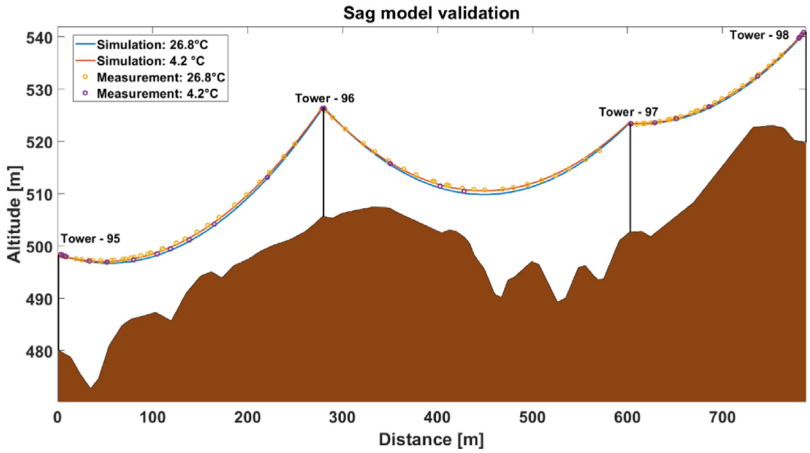

Fig. 2. Sag-clearance model validation on a 110 kV power line.

It is also important to mention, that the investigated tension span contains straight (between tower 96 and tower 97) and oblique spans (both terminal spans). Therefore, the validation of the skewness correction factor described by (4) is also carried out. International sag models, such as the sag model described in [10], can lead to around 10% deviation in oblique spans relative to actual circumstances, therefore, these models can only be used in straight spans for critical span analysis purposes. Based on this case study it can be stated that the presented sag-clearance model is appropriate for the critical span analysis method along the whole line route including both straight and oblique spans.

3.4. Conductor annealing

Another important limitation during the thermal utilization of overhead line conductors is the lasting degradation called annealing. Annealing is the reduction of tensile strength of aluminium strands when the sustained temperature exceeds the annealing temperature of the conductor material for a considerable amount of time. Contrary to sag modelling, the determining factor of annealing is the local temperature of the conductors, especially the hot spots. According to [12], local hot spots change along the line in time, therefore, their accurate detection requires conductor temperature measurement in every tension span. Consequently, critical tension spans cannot be determined based on conductor annealing as in this case every tension span is critical.

3.5. Proposed methodology for the determination of critical spans based on clearance simulation

Based on Sections 3.1 and 3.2 it can be stated that the largest longitudinal unit that properly represents the thermal conditions of the conductors is a tension span, especially in the case of sag determination, where the average temperature is appropriate for the calculations in case of each tension span [16]. Therefore, the proposed methodology is based on only the clearance modelling of transmission lines, while in order to avoid the annealing of the conductors, all of the tension spans should be covered with sensors or weather stations.

To determine the safety level of the selected span, an auxiliary variable should be introduced, named safety reserve. Accordingly, Eqs. (5) and (6) present an optimization problem whose solution provides the set of critical tension spans.

$$C(S_t) = \min_{\forall i \in S_t} \sum_{i=1}^{N^{S_t}} m_i$$
$$\left(sr_i^{S_t} = c_i^{S_t} - c_{legal}^{S} \right) \geq \varepsilon \tag{5}$$

where

- $C(S_t)$ is the set of critical spans,
- S_t is the set of tension spans,
- sr_i is the safety reserve of i^{th} tension span in [m],
- c_i is the simulated clearance of i^{th} tension span at maximal continuous operating temperature [m],
- c_{legal} is the simulated legal part of clearance in the i^{th} tension span [m],
- ε is the required safety reserved by TSO in [m] and

$$m_i = \left\{ \begin{array}{c} 1, if\ sensor\ is\ installed\ in\ tension\ span\ i \\ 0, \quad otherwise \end{array} \right\} \tag{6}$$

It is important to note, that c_{legal} depends on objects potentially located under a given span (such as overhead line crossings, railways, buildings, recreational areas, etc.), as it influences the D_{add} component of the legal part of the clearance described in EN 50341-1:2012 in the European practice. With the proposed methodology not only can the distance-to-ground clearance be fulfilled as in international models available so far, but also every other clearance type is fulfilled. The article clearly demonstrated that weather parameters cause high uncertainty during the determination of the critical spans. Therefore, the proposed methodology uses only technical parameters thereby eliminating the precarious conductor annealing condition of the existing models.

3.6. A case study with the proposed methodology

To illustrate the application of the proposed methodology, a case study is presented here, which was carried out in the FARCROSS project framework. The critical span analysis with the recommended approach was performed in a single-circuit transmission line located in Central-Europe.

In the first step of the evaluation, the sag-clearance simulation was carried out for all line spans. The clearance values for a randomly selected tension span with ten spans are shown in Fig. 3. The sum of the height of the light blue and orange bars shows the ground clearance of each span from which the legally required ground clearance is marked with light blue, which is 8 m. Accordingly, the orange bars are visually showing the safety reserve of the ground clearance. In the case of spans with obstacles under the line another bar is showing the clearance from the obstacle (Sample span #2, #3 and #8). Fig. 3 shows that there is a road crossing under sample span #3. In this case, the legally required clearance limit is 9 m, marked with dark blue in the image, while the safety reserve is marked with red. In addition, there are two medium voltage line crossings under the presented tension span in sample span #3 and sample span #8. In these cases, the legal clearance limit is 5 m, marked with dark blue. The safety reserve is marked with red in these spans, which is under 10 cm in the case of sample span #8. Correspondingly, the lowest safety reserve in the presented tension span occurs in sample span #8, where a medium-voltage line crossing is located under the evaluated line.

In the case of $\varepsilon = 0.75$ m required safety reserve, the proposed methodology provides two critical spans, while the existing methods identify only the span with the lowest ground clearance value in the arrangement presented in the case study. The comparison of the proposed model with the existing methods is summarized in Table 1.

Taken together, the case study demonstrated that more unfavourable clearance conditions could be identified with the proposed methodology than the existing ones, which provides a more reliable technique for critical span identification from the clearance reserve point of view.

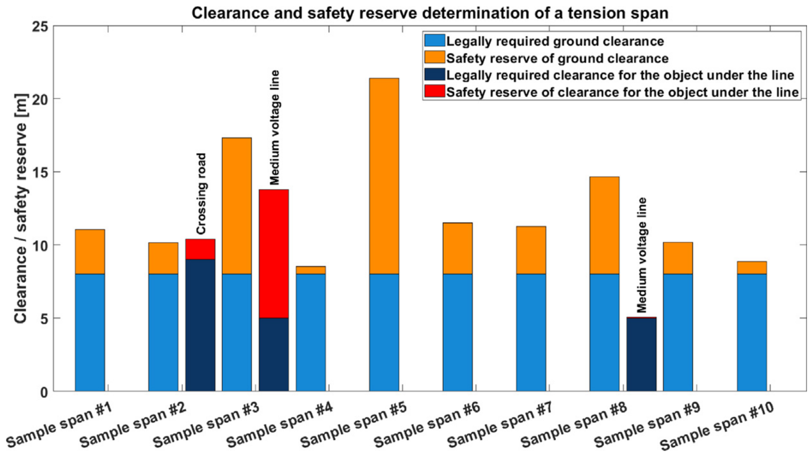

Fig. 3. Clearance and safety reserve determination with the proposed methodology. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1. Selected spans for critical span analysis in case of $\varepsilon = 0.75$ m required safety reserve.

Method	Span no.	Safety reserve [m]	Limiting factor
Proposed methodology	8	0.08	Clearance to medium voltage line crossing
	4	0.53	Ground clearance
Existing methods	4	0.53	Ground clearance

4. Conclusion

The application of dynamic line rating methodology is assisting in a more efficient utilization of power lines, which in turn supports the incorporation of renewable energy sources in the electrical power grid and the establishment of market connections through cross-border lines. During the implementation of such a system the optimal placement of line monitoring sensors and weather stations has a central role in balancing the reliability of the line management technology and the return on investment. The so far known algorithms for critical span identification are based on the analysis of prevailing environmental conditions along a given line. According to the comparison of measured weather parameters and microclimatic environmental factors, only the weather parameters measured along the line corridor are appropriate for the thermal modelling of the phase conductors.

Based on these results, a new critical span identification method is proposed, which only takes into account the technical parameters of a given line. The proposed methodology is based on the simulation of sag-clearance of each tension span, where the oblique spans are corrected with a skewness factor in order to provide more accurate results. Moreover, the suggested approach considers the objects located under the line in the D_{add} clearance component. Accordingly, the determined locations for sensor installation offer the possibility for compliance with EN 50341-1:2012 during a DLR system implementation. The validation of the proposed sag simulation model was performed to achieve compliance with regulation EN 50341-1:2012. This way, the modelling of conductor annealing is eliminated while compliance with clearance regulations is incorporated into the proposed calculation method (in addition to the distance-to-ground clearance), which leads to a more reliable method for the implementation of a DLR-based line management system. A case study was also presented to demonstrate the operation of the algorithm. Through this case study it was shown that spans with lower clearance safety reserve can be identified with the suggested method, which promotes the avoidance of possible clearance violations where objects are located under the power line.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been developed in the High Voltage Laboratory of Budapest University of Technology and Economics within the boundaries of FARCROSS GA No 864274 project funded by Horizon 2020. The project aims to connect major stakeholders of the energy value chain and demonstrate integrated hardware and software solutions that will facilitate the "unlocking" of the resources for the cross-border electricity flows and regional cooperation.

FARCROSS European Commission Horizon 2020 European Union funding for Research & Innovation

References

[1] Levente Rácz, Dávid Szabó, Gábor Göcsei, Bálint Németh. Grid management technology for the integration of renewable energy sources into the transmission system. In: 2018 7th international conference on renewable energy research and applications. Paris: 2018. p. 612–7. http://dx.doi.org/10.1109/ICRERA.2018.8566852.

[2] Yunxin Liu, Yao Liangzhong, Liao Siyang, Xu Jian, Wu Di, Tang Wei, et al. The voltage regulation control strategy with distributed photovoltaic participation under serious failure based on transient voltage margin. In: E3S web conf., vol. 186, 2020, p. 01002. http://dx.doi.org/10.1051/e3sconf/202018601002.

[3] Dávid Szabó, Levente Rácz, Gábor Göcsei, Báint Németh. DLR-based ice prevention method. In: 18th international workshop on atmospheric icing of structures. 2019. Reykjavík, Iceland.

[4] Yu Hou, Wei Wang, Zheng Wei, Xiaojun Deng, Qiuhua Ji, Tong Wang, et al. Research and application of dynamic line rating technology. Energy Rep 2020;6:716–30. http://dx.doi.org/10.1016/j.egyr.2020.11.140.

[5] Faizan Afzal, Muhammad S Virk. Review of icing effects on wind turbine in cold regions. In: E3S web conf., vol. 72, 2018, p. 01007. http://dx.doi.org/10.1051/e3sconf/20187201007.

[6] Dávid Szabó, Bálint Németh, Gábor Göcsei, Viktor Lovrenčić, Nenad Gubeljak, Ursula Krisper, et al. Icing analysis of Kleče-Logatec transmission line with two-level icing model. In: Németh B, Ekonomou L, editors. Flexitranstore. Lecture notes in electrical engineering, vol. 610, Cham: Springer; 2019, http://dx.doi.org/10.1007/978-3-030-37818-9_10.

[7] Bálint Németh, Gábor Göcsei, Dávid Szabó, Levente Rácz. Comparison of physical and analytical methods for Dynamic Line Rating (DLR) calculations. In: CIGRE – IEC 2019 Conference on EHV and UHV (AC & DC). Hakodate, Japan. 2019.

[8] Lilik J Awalin, Rahmat M Khairil. A recent development of monitoring devices on smart grid. In: E3S web conf., vol. 186, 2020, p. 02004. http://dx.doi.org/10.1051/e3sconf/202018602004.

[9] Marcelo Matus, Doris Saez, Mark Favley, Carlos Suazo-Martinez, José Moya, Guillermo Jimeneze-Estevez, et al. Identification of critical spans for monitoring systems in dynamic thermal rating. IEEE Trans Power Deliv 2012;27(2):1002–9. http://dx.doi.org/10.1109/TPWRD.2012.2185254.

[10] Jiashan Teh. Analysis of dynamic thermal rating system of transmission lines [Thesis], The University of Manchester; 2016.

[11] ECMW weather model, https://www.ecmwf.int/en/about.

[12] Dávid Szabó, Levente Rácz, Göcsei Gábor. A novel approach of critical span analysis. In: Németh B, editor. Proceedings of the 21st international symposium on high voltage engineering. Lecture notes in electrical engineering, vol. 598, Cham: Springer; 2020, http://dx.doi.org/10.1007/978-3-030-31676-1_96.

[13] Dávid Szabó, Gábor Göcsei, Németh B. Development of physical DLR calculation method. In: 2019 7th international youth conference on energy. Bled, Slovenia: 2019. p. 1–6. http://dx.doi.org/10.1109/IYCE45807.2019.8991598.

[14] Jerrell JW, Black WZ, Thomas J. Parker critical span analysis of overhead conductors. IEEE Trans Power Deliv 1988;3(4):1942–50. http://dx.doi.org/10.1109/61.194004.

[15] Friederich Kiessling, Peter Nefzger, Nolasco Joao F, Kaintzyk Ulf. Overhead power lines. 2003, http://dx.doi.org/10.1007/978-3-642-97879-1.

[16] CIGRE WG B212, TB299. Guide for the selection of weather parameters for bare overhead conductor ratings. 2006.

[17] Electric Power Research Institute. Demonstration of advanced conductors for overhead transmission lines. 2008.

[18] Géza Perneczky. Szabadvezetékek feszítése (Tension of OHLs). Budapest, Hungary Műszaki Könyvkiadó; 1968 [in Hungarian].