Grid Management Technology for The Integration of Renewable Energy Sources into The Transmission System

Levente Rácz
Department of Electric Power Engineering
Budapest University of Technology and Economics
18 Egry József street, Budapest 1111, Hungary
racz.levente@eszk.org

Dávid Szabó
Department of Electric Power Engineering
Budapest University of Technology and Economics
18 Egry József street, Budapest 1111, Hungary
szabo.david@vet.bme.hu

Gábor Göcsei PhD
Department of Electric Power Engineering
Budapest University of Technology and Economics
18 Egry József street, Budapest 1111, Hungary
gocsei.gabor@vet.bme.hu

Bálint Németh PhD
Department of Electric Power Engineering
Budapest University of Technology and Economics
18 Egry József street, Budapest 1111, Hungary
nemeth.balint@vet.bme.hu

Abstract — **One of the key issues during the integration of widely spreading renewable energy sources into the electric transmission system is the management of the generated surplus power. There is a new and cost-effective way to handle this problem, the so-called Dynamic Line Rating (DLR). There are several realization options for system implementation, such as soft-computing methods, physical models or the use of overhead line monitoring systems. The aim of this paper is to demonstrate the advantages of the DLR calculation method in case of using mathematical and numerical techniques to manage the issues caused by renewable energy sources integration into the transmission grid.**

Keywords — dynamic line rating, DLR, renewable energy sources, resource management, system resilience, transmission line, soft computing, neural network

I. Introduction

Nowadays, the key issues of the electrical transmission system are the increasing demand for the electrical energy and the integration of the renewable energy sources, which could cause overload on critical parts of the system, such as the cross-border lines. On the other hand, it is also highly important to maintain the operational safety and continuity of the transmission grid. There are several options to manage the overload of the conductors, such as building of new overhead lines (OHL), reconductoring of existing power lines or the implementation of Dynamic Line Rating system. The main advantages of DLR calculation method are the cost-effective and less legally regulated application and the increased system reliability.

Based on the conventional terminology, a so-called static rating was determined for the limitation of transmission capacity of OHLs, where the worst-case environmental parameters were assumed. On the contrary, DLR system intended to manage the surplus power generated by renewable energy sources by offering a good opportunity to monitor the real-time status of the environmental parameters and the transmission lines. DLR is also usable for the planning of installation of new, renewable power plants in case of fully utilized electricity network.

II. The Renewable energy sources and their integration

A. General trends in Europe

In the last few decades there have been far-reaching changes in the energy sector not just in Europe, but all over the world. In Europe, particular attention has been given to the issues of greenhouse gas emission, renewable energy sources (RES) and energy efficiency in order to reduce the pollution and implement a clean energy strategy. According to the European Union (EU) 2020 climate and energy package, where energy targets had been settled, the member countries of the EU have increased the number of RES in the energy mix year-on-year. As a result of this phenomenon, almost 16.9 % of the used energy was from RES in 2016 in the EU. However, the pace of the RES growth slows down, the number of the renewable energy sources developments will still increase in the near future [1].

B. Integration RES into the existing transmission grid

In Europe hydropower, photovoltaic (PV)/solar power and wind power assume leading role in RES power generation. The number of solar and wind power increases year-by-year,

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meaning that they will represent a significant proportion in the energy mix of the future [1].

However, generating energy is just one segment of the energy sector, integrating them into the existing infrastructural background is also an important process. Almost the half of generated RES energy is renewable electricity, which cause several additional challenges that European countries have to deal with in order to enhance the flexibility and resilience of the transmission system.

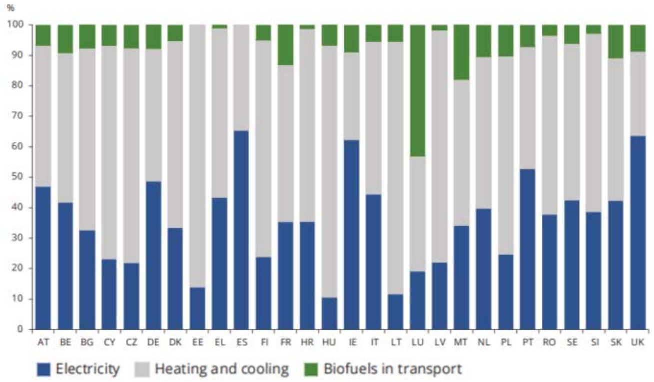

Figure 1 – Shares in 2015 RES consumption of renewable electricity, renewable heating and cooling, and biofuels in transport [1]

It is important to mention that PV and wind power are intermittent energy sources which means they cannot be treated as a constant load for the grid [2]. This is a principal issue in case of the infrastructure of the transmission grid. Due to the RES energy generation, more and more situations occur when the demand for the energy and place of the generation are not the same. According to this, transmission and distribution of energy have become to have vital role in the electricity industry. However, most of the internal and cross-border overhead-lines (OHLs) were not always designed to handle this surplus power which can cause insufficiency in the transmission capacity [3]. Not to mention that the grid density varies from region to region in the EU, making the integration of RES to the continental system to be a difficult achievement. As a result of these phenomena, several OHLs are overloaded, which raises problems to the transmission system operators (TSOs) [4], [5].

C. *Other changes in the electricity issues*

On the other hand, due to the liberalization of the electricity market, the market environment and consumer habits are also changing. In addition, interaction between individual operators is also increasing (demand side management). In order to meet these changes, the system operators need to develop the transmission network to analyze the European power flows significantly influenced by renewable energy sources and to develop the electricity market in order to meet the Internal Electricity Market (IEM) [6]. These processes also require a stable infrastructural background that can handle the dynamic changes in the electrical energy transmission effectively [7], [8], [9], [10].

III. CONCEPT OF DLR

Traditionally the operational limits of transmission lines are specified in a conservative way based on the static rating calculation method. This opportunity is the basis of the idea to use our existing infrastructure more effectively. Nowadays, seasonal line rating (SLR) is a widely applied approach to increase line rating, because no infrastructural modification of the lines is required. SLR rating is typically calculated for summer and winter period of the year, which means notable transmission capacity increment especially in winter period. This method means 15 – 30 % higher ratings in winter than in summer.

Dynamic line rating is state-of-the-art grid management methodology, which can adjust the line rating to the weather and load parameters real-time. This technology can also be utilized to reduce the safety risks of local thermal overloads of the conductors, such as the warming of the wires caused by the surplus power of PV energy sources in case of hot, dry summer weather conditions, or the thermal overloads caused by the low wind speed in sheltered areas in case of high loads. This system is also able to calculate the conductor temperature real-time; therefore, it gives a satisfying information of the actual condition of the conductors to TSOs. Thereby a prevention action can be taken with high certainty to avoid thermal overloads without strict legal processes and social resistance.

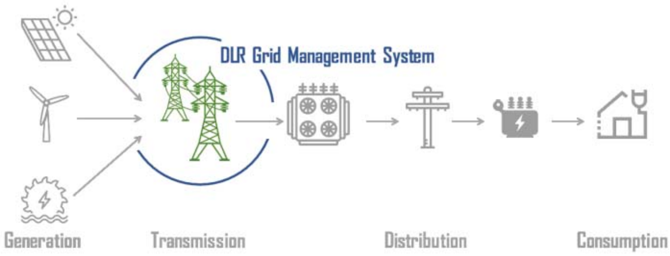

Figure 2 – Schema of DLR grid management system

All in all, DLR grid management system is a new way of transmission lines smart grid, which can be implemented for transmission lines and combines the above-mentioned advantages of line capacity management and methods concern to the increasing of operational safety [11], [12], [13], [14].

IV. PREPARATION FOR THE CALCULATION

It is important to note that DLR can only be applied for transmission lines when the load capacity of the conductor is the so-called weak point of the system, i.e. other devices are capable of safe operation, even at increased transmission load. In cases where the transformer, voltage and current transformers or other constituents are not designed to handle surplus power above static load capacity, DLR technology cannot be applied effectively. It is also important to note that the spatial extent of the transmission lines is relatively large (hundreds of kilometers), therefore the environmental parameters may vary depending on the extension and location. This can be eliminated if DLR calculation is preceded by a critical span analysis, which determines the critical points of the transmission line considering the clearances and the topography conditions. Hereinafter, these critical towers represent the whole transmission line for the calculations. These two steps do not form an integral part of the models, so that the analyses of the critical spans are already assumed to be.

V. BME's EXTENDED WHITE BOX MODEL

A. *Aspects of physical DLR models*

The literature outlined two physical models for DLR calculation, which are called IEEE [15] and Cigré [16] method. These methodologies are based on the thermal equilibrium of the conductors, which means that the actual line temperature can be calculated using concrete weather parameters and load. These models use the ambient temperature, wind speed, direction, and solar radiation as weather parameters, which are measured by weather stations installed on the towers. DLR value can be calculated with the knowing of heating and cooling effects which affect the conductor through these ambient variables. Budapest University of Technology and Economics' (BME) extended white box model is designed to enhance the operational safety earned by the using of DLR grid management technology through the clarification of the international physical models.

B. *Extended model*

The main concept of BME's extended white box model is to make a decision-support process for system operators, which can be practically applied and is based on the experiments gained during sensitive analysis of several years of weather data.

Sensitivity analysis showed that wind speed is the most significant parameter during DLR computation and the wind direction is stochastic in case of wind speeds lower than 5 m/s. Physical models do not include practical instructions how to take the wind into consideration. On the contrary, BME's white box model separates the line into several sections along the bends of the line and the wind direction is handled separately in each section, therefore the thermal state of the conductors can be defined in a more precise way along the line. Another advantage of this methodology is that the local thermal overloads can be avoided, because always the worst-case line rating value is used as the DLR value for the whole line.

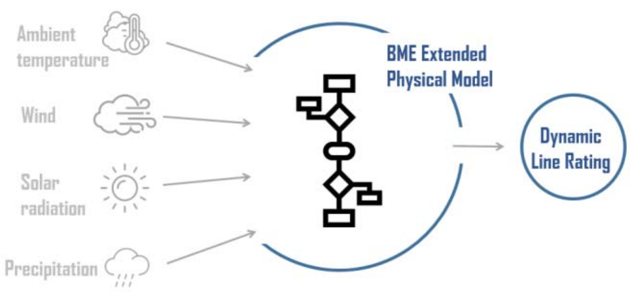

Figure 3 – Schema of BME Extended Physical model

Conventional physical models neglect the cooling effect of the precipitation during the calculations. BME's model also takes the heat loss caused by evaporation [17] into account. Thereby 6-8 % extra load capacity can be achieved during an average rainfall intensity, which means 4 to 8 mm/h precipitation in practice.

DLR method can be utilized for planning generation schedules also, but in this case the expected line rating values should be calculated. For this purpose, weather forecast shall be applied, but its accuracy highly depends on the forecasted weather parameters, which are becoming more and more inaccurate as time goes by. These quantities usually offer only 1-3 hours' time resolution, which is unsatisfactory for DLR calculation. Accordingly, BME's extended white box model have an improved data processing module, which increases the time resolution of the forecasted weather parameters by using miscellaneous interpolation technics adjusted to each weather variable, thereby the accuracy of predetermined line rating can be refined [18].

VI. BME's BLACK BOX MODEL

A. *The main purpose of the black mox model*

The main purpose of the development of this model was to decrease the neglections of the existing DLR algorithms, such as IEEE or CIGRE models. In these models the heat loss from precipitation had been omitted and the surplus load was significantly different when the wind velocity had a higher value than 5 m/s. However, BME's black box model approaches DLR calculation in a different way than before. This model is based on a soft computing method called neural network which means that in this case an adaptive system is applied. This system is able to recognize patterns and relationships between weather parameters and the actual load state of the conductor. The information flows between neurons which represent the smallest unit of the developed system. Their state is described by an activation function that can vary from model to model. These neurons forms layers, and these layers – also the neurons in them – are connected to each other. By setting the free parameters of the model correctly, an output for a given input data can be calculated more and more precisely. However, this model requires a large number of training data which needs to be valid and uniformly dispersed in real time. According to this, there are sensors installed on the conductor to provide a realistic picture about the load condition and the weather parameters of the monitored line [19], [20].

B. Determination of conductor temperature

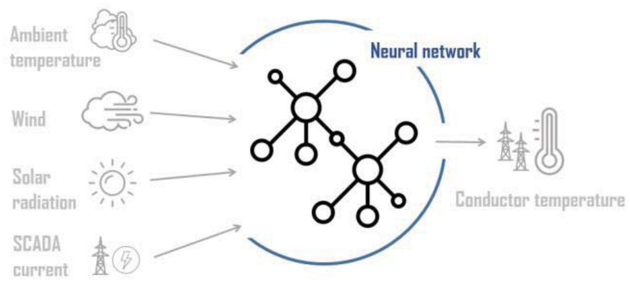

Figure 4 – Schema of the black box model

BME's black box model uses two steps to calculate the real-time ampacity of the transmission lines. In the first step, a neural network calculates the actual temperature of the conductor, which represents the output of this network.

During the investigation, several different network structures were tested and the maximum and average error were examined to find the best solution. Different training methods and network parameters were also inspected. As the result of the research 5 input parameters were defined: ambient temperature, solar radiation, wind speed, wind direction and the current load of the conductor. In order to avoid overfitting, the training period were monitored and validation data were set. The output of the model is the temperature of the conductor, which was the data measured by the sensor in the training method [19].

C. Calculation of DLR value

In the second step the DLR value can be determined from the conductor temperature. Because all of the weather parameters have ongoing effect on the conductor temperature measured by the installed sensor, the conductor temperature determined in the first step also contains the combined effects of the weather parameters.

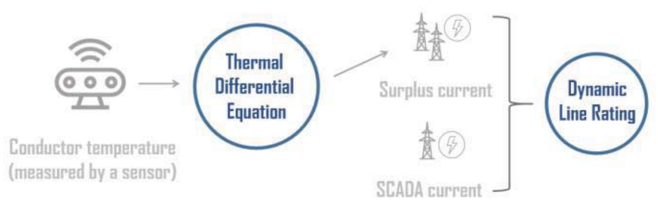

Figure 5 – DLR calculation from conductor temperature in case of neural network

On the other hand, all of the transmission lines have a maximum allowed temperature which cannot been exceeded in order to keep the safety clearances declared by the laws. The difference of these temperatures is the potential that the DLR could exploit. For each moment this difference heat can be generated by a surplus current by surplus Joule-heating. With the knowledge of the exact parameters of the conductor and its time-constant, this extra current can be determined by a differential equation. The increased ampacity, which is actually the DLR value of the line, is the sum of the real-time measured current of the conductor and the calculated surplus current. The major advantage of this model is the lack of neglections of any weather parameters [19].

VII. CASE STUDY

A. General information about the data

In order to present the results of the two different BME DLR models, a case study had been investigated. In this case study data came from a 110 kV European transmission line with 240/40 mm^2 ACSR conductor. The training data set for the neural network was provided by an OTLM sensor installed on the conductor. This sensor could measure not just the environmental parameters, but the load of the line and also the temperature of the conductor. The temperature measurement deviation is ± 2 °C and the minimum required load for the measurement is 60 A on the line. After the measurement of the parameters in every 10 minutes, the sensor sends data to a central server wireless. For this case study half year of data were available, so the conductor temperature and also DLR calculation simulations were carried out. Because of the frequent sensor measurements, more than 21000 pairs of data were available for the neural network. These data were separated into training, validation and testing groups without mixing the data in them. This means, the testing data and results shown below were not used in the training mechanism of the network. To give a general view of the investigation, 3 different days were chosen from 3 different seasons. The lack of data about the winter period was the reason why there is no winter day in the research [20], [21].

B. Determination of the conductor temperature

Conductor temperature have been calculated for 3 different days, such as 13 May, 14 July and 16 September. Figure 6 shows the calculated conductor temperature values compared to the temperature values measured by the line monitoring sensor. All of the data came from 2017.

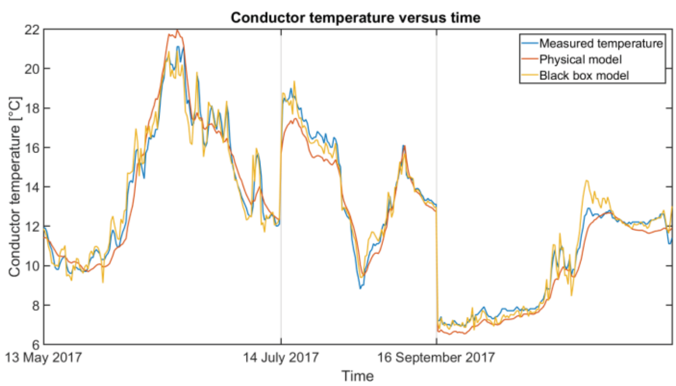

Figure 6 – Conductor temperature calculation results

Box plot diagrams were created for the illustration of the signed deviation of the calculated temperature values from the measurement.

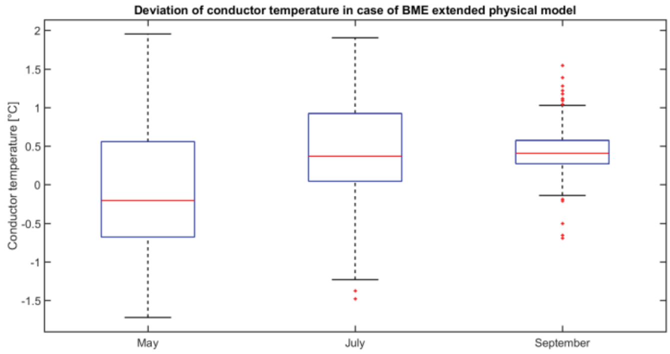

Figure 7 – Deviation of conductor temperature (physical model)

Figure 7 shows that the conductor temperature deviation of the physical model never exceeds the measurement deviation of the sensor in case of this case study. The deviation is mostly positive in case of physical model, which means a safety factor, because the conductor temperature is high end estimated. The absolute of median values of the deviation is lower than 0.5 °C.

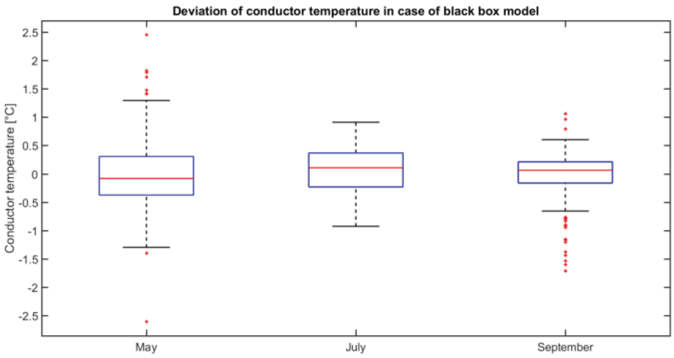

Figure 8 – Deviation of conductor temperature (black box model)

Figure 8 shows that the maximal deviation of the model is -2.6 °C and +2.4 °C, which values are near to the measurement deviation of the sensor. The variance of black box model is lower than in case of the physical model, and the absolute median values are less than 0.2 °C in this case.

C. *Calculation of the DLR value*

During the calculation of dynamic line rating, the two models calculates in different ways. The physical model uses a method which describes the cooling and heating environmental factors. Contrarily, black box model originates from the conductor temperature and calculates with the temperature difference between the maximal and actual temperature of the wires. Therefore, the black box model gives less variable DLR values, than the physical model, because the conductor temperature varies in smaller range, than the environmental parameters – as it shown in Figure 9.

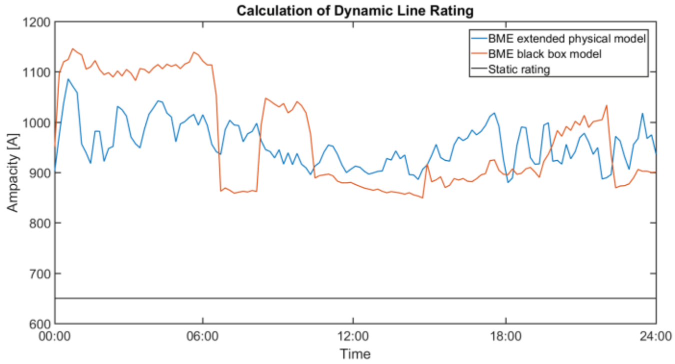

Figure 9 – DLR calculation

The static rating of the examined line is 650 A, and the dynamic rating was never less than 800 A, which means a high potential to a better exploitation of the line. In this case the dynamic line rating value is 40% higher in average, than the static rating of the line.

VIII. Conclusion

All in all, it is considered, that RES will be playing a vital role in the energy-mix of the future. According to this, the transmission system should be prepared for these intermittent energy sources and the generated surplus power varying in time. So that European countries and TSOs have to deal with different challenges to integrate them properly into the existing system while the flexibility and resilience of the transmission system cannot be deteriorated.

DLR seems to be a promising method to exploit the real capacity of the existing transmission line, which means that the maximum allowed ampacity also could be increased. The major advantages of DLR are cost-efficiency, quick implementation and increased power flow on the critical lines. BME has developed two different DLR calculation methods: BME's white box model and BME's black box model. The former model is based on Cigré model, but it is extended with the heat loss of the precipitation, the separation of the line and improved data processing module. The latter model is based on neural networks, which requires installed sensors on the conductor measuring the environmental parameters real-time. From the aspect of the calculation of conductor temperature, it can be considered, that both of the models give similar results. As in this case there were real-time measurement, these results could be compared to the sensor measurement, and the average error was lower than 1 °C.

In case of DLR calculation the results of the models were different but were in the same range. Due to the lack of real-time DLR data, these results cannot be compared and validated, yet. The maximum allowed transmission capacity was significantly higher than the static rating of the line, which is promising from the aspect of the practical implementation of this research. To sum up, both of the BME models are able to calculate not just conductor temperature, but also DLR value, however, there are still possibilities to make them more precise in order to get more accurate results.

IX. ACKNOWLEDGEMENT

This work has been being developed in the High Voltage Laboratory of Budapest University of Technology and Economics within the boundaries of FLEXITRANSTORE project, which is an international project. FLEXITRANSTORE (An Integrated Platform for Increased FLEXIbility in smart TRANSmission grids with STORage Entities and large penetration of Renewable Energy Sources) aims to contibute to the evolution towards a pan-European transmission network with high flexinilty and high interconnection levels.

REFERENCES

[1] EEA Report, “Renewable energy in Europe – 2017 Update, Recent growth and knock-on effects”, 2017

[2] S. S. Dash, "Tutorial 1: Opportunities and challenges of integrating renewable energy sources in smart," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, CA, 2017, pp. 19-23.

[3] B. Hartmann, D. Divényi, I. Vokony, “Evaluation of business possibilities of energy storage at commercial and industrial consumers – A case study”, Applied Energy Volume 222, 15 July 2018, Pages 59-66

[4] T.R.Ayodele, A.A. Jimoh, J.L. Munda, J.T Agee, “Challenges of grid integration of wind power on power system grid integrity: A review”, International Journal of Renewable Energy Research, Vol.2, No.4

[5] M. Garba, M. A. Tankari and G. Lefebvre, "Using of distributed energy ressources for microgrid resilience achieving," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, CA, 2017, pp. 659-663.

[6] A. Alzahrani, P. Shamsi, M. Ferdowsi and C. Dagli, "Modeling and simulation of a microgrid using feedforward neural networks," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, CA, 2017, pp. 1001-1006.

[7] N. Kumar, U. K. Sinha, S. P. Sharma, Y. K. Nayak, “Prediction of daily global solar radiation using neural networks with improved gain factors and RBF networks”, International Journal of Renewable Energy Research, Vol.7, No.3

[8] M. Mana, M. Burlando. C. Meißner, “Evaluation of two ANN approaches for the wind forecast in a mountainous site”, International Journal of Renewable Energy Research, Vol.7, No.4

[9] O. Noureldeen, A. M. A. Ibrahim, “Performance analysis of grid connected PV/wind hybrid power system during variations of encironmental conditions and load”, International Journal of Renewable Energy Research, Vol.8, No.1

[10] A. Allik and A. Annuk, "Interpolation of intra-hourly electricity consumption and production data," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, CA, 2017, pp. 131-136.

[11] B. Sinkovics, B. Hartmann, “Analysing effect of solar photovoltaic production on load curves and their forecasting”, International Conference on Renewable Energy and Power Quality: ICREPQ'18, Spain, European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ), 2018. pp. 1-6.

[12] K.S. Sambaiah, “A review on optimal allocation and sizing techniques for DG in distribution systems”, International Journal of Renewable Energy Research, Vol.8, No.3

[13] R. R. A. Galvão, R. H. A. Gonzalez, T. J. L. França and B. C. Pinheiro, "Monitoring and control system for distributed energy generation plants," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, CA, 2017, pp. 833-838.

[14] Electric Power Research Institue, “Evaluation of Instrumentation and Dynamic Thermal Ratings for Overhead Lines”, 2013

[15] IEEE “Standard for Calculating the Current Temperature of Bare Overhead Conductors”, Transmission and distribution committee of the IEEE Power Engineering Society IEEE Std 738-2006

[16] Cigré Working Group B2.43, “Guide for Thermal Rating Calculations of Overhead Lines”, 2014.

[17] Pytlak, P., Musilek, P., Lozowski, E., Toth J., “Modelling precipitation cooling of overhead conductors”, Electric Power Systems Research 81 (2011) 2147-2154

[18] Halász B. G., Németh B., Rácz L., Szabó D., Göcsei G., “Monitoring of Actual Thermal Condition of High Voltage Overhead Lines”, 9th Advanced Doctoral Conference on Computing, Electrical and Industrial Systems, 2018

[19] Rácz L., Németh B., “Investigation of Dynamic Line Rating Based on Neural Networks”, 15th International Conference of Young Scientist on Energy Issues, 23-28 May 2018, Kaunas, Lithuania

[20] Haykin, S., “Neural Networks, A Comprehensive Foundation”, Hamilton, Person Education, 1999. 823 p.

[21] Lovrencic, V., Gabrovsek, M., Kovac, M., Gubeljak, N., Šojat, Z., “The contribution of conductor temperature and sag monitoring to increased ampacities of overhead lines (OHLs)”, DEMSEE'15 10th International Conference on Deregulated Electricity Market Issues in South Eastern Europe. 24-25 September 2015, Budapest, Hungary