Integration of Monte Carlo methods into ice prevention model

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Abstract — **Dynamic Line Rating (hereinafter referred to as DLR) is a promising method to increase the transfer capacity of high voltage overhead lines. As a result of the increased power, ice prevention could become a promising additional advantage of the whole DLR system.**

Based on the international literature, a hybrid icing model had been developed regarding to high voltage overhead line conductors. The essence of this model is that it can determine, how the current of the power line need to be increased in order to avoid icing problems. The main aim of this article is to present the possible extension of this model by using different distributions for the environmental parameters and Monte Carlo sampling methods. As a result of the extension, a risk factor can also be determined for each circumstance, that could help the system operator in decision-making to prevent icing processes.

Keywords— ***overhead line, combined icing model, Monte Carlo sampling, ice prevention***

I. INTRODUCTION

Ice accretion on overhead lines (hereinafter referred to as OHLs) can cause serious damage that led to the development of different anti-icing and de-icing methods. With the use of anti-icing techniques, the ice accretion process could be prevented, while de-icing methods lead to result when the ice layer is already formed on the conductor. The icing of the OHLs is a complex process that depends on several environmental factors. According to these environmental parameters different types of ice accretions can be distinguished that have different appearance and physical parameters [1][2].

Icing process can be divided into two groups which are the in-cloud icing and precipitation icing. The in-cloud ice formations are the soft rime, hard rime and glaze due to supercooled cloud droplets, while the precipitation icing accretions are the glaze due to freezing rain, wet snow and dry snow. These types of ice accretions form extra load on the conductor, influences its resistance and cause increased sag in each span. Due to surplus torsional forces the high voltage towers could collapse causing serious black-outs in the power system. According to this, in those countries where icing of the OHLs is a real risk, the transmission and distribution system operators (TSOs and DSOs) make great efforts to fight against this process [3].

Nowadays, there is a great demand of increasing OHLs' transfer capacity that leads to the more efficient use of the existing power infrastructure. Dynamic Line Rating (DLR) based on the real-time monitoring of environmental parameters is a method to recalculate the conductor ampacity from time to time. On the other hand, this real-time monitoring system could also be used for anti-icing methods and in the following, a modified DLR model is used for ice prevention [1]-[3].

Figure 1 OTLM DLR sensors installed on conductors [4]

II. ANTI-ICING MODEL

In general, anti-icing techniques can be divided into 4 different groups which are the following [3]:

- passive methods based on natural forces or physical geometry;
- active coatings and devices;
- mechanical methods based on breaking down the ice;
- thermal methods based on ice melting.

The anti-icing method explicated in this article is based on ice melting processes. The steady-state hat balance equation of the conductor is described with Eq. (1) [5]-[7].

$$q_C + q_r = q_s + q_J \tag{1}$$

Where q_c means natural or forced convection, q_r means radiation loss, q_s is the heat gained from solar radiation and q_J is the resistive heating of the conductor. The units of all heat terms in Eq. (1) are [Wm^{-1}]. This Eq. (1) could be completed with the effect of precipitation (q_e), and the final heat balance could be described with Eq. (2) [6].

$$q_C + q_C + q_r = q_s + q_J \tag{2}$$

In Italy, an ice prediction model was investigated for wet-snow, with which an estimation could be provided for the necessary current level in order to avoid ice accretion. Parallel to this, test spans were also installed where snow accretion could be observed in case of different conductors treated with different hydrophobic varnish. Results showed, that these varnishes have poor effect on anti-icing, but the simulated value of melting current was efficient also in case of tests under real circumstances. This article aims to link a model similar to this with Monte Carlo sampling techniques in order to supplement each environmental and load condition with an operational risk factor [7]-[10].

III. Monte Carlo methods

Monte Carlo methods is a collective term for procedures, simulations and sampling processes which are based on random number generation. Initially, Monte Carlo simulations were used by physicians to calculate difficult integrals, but with the increasing computing power over the last few decades, their application became almost indispensable for all areas [11].

One of the major advantages of Monte Carlo simulations is that distributions are in use for the different parameters instead of exact values. According to this, a wide range of possible outcomes can be simulated that can give a more accurate picture of the real progress of each process. In connection with this, different risk calculations and assessments are also an important field of the usage of these simulations [11].

In case of real-time transmission capacity calculation and icing phenomenon, the forecast of the environmental parameters is essential. For these predictions a special type of Monte Carlo simulation, the so-called Markov Chain Monte Carlo (MCMC) simulation could be useful and could provide accurate forecast in the vicinity of the OHL. The essence of this method is to build up time-series models for each environmental factor and to define different parameters that determine these models. If the prior distribution is available for these parameters (which are available thanks to sensor measurements), then the posterior distribution of each parameter could be estimated. In these MCMC simulations the aim is to build up a Markov Chain that has a stationary distribution close to the desired posterior distribution. In this way, an accurate forecast could be implemented with the necessary spatial and time resolution [11][12].

IV. Hybrid anti-icing model

A. *The aim of the model*

The main aim of the hybrid anti-icing model is to completely prevent the ice accretion on the conductors. To achieve this, the conductor temperature is required to be above a certain value for that time when the national environment agency gives a clear icing warning. This value based on the theoretical knowledge and the practice of the Italian model should be 2°C, and it means that if the conductor temperature exceeds this value, ice layer cannot be formed on the wire [7].

In this model it is assumed that the conductor temperature and weather parameters are known in real-time, and there is also available weather forecast for the near future. The inputs of the model are the forecasted weather parameters and the actual load of the OHL. For each environmental parameter different distributions are used which are presented in detail in Table 1 [11]-[13].

Table 1 The environmental parameters and the distribution applied for them [11]-[13]

Environmental parameters		
1	Wind speed	Weibull distribution
2	Wind direction	von Mises distribution
3	Ambient temperature	Normal distribution
4	Solar radiation	Normal distribution
5	Precipitation	Normal distribution

The actual load of the conductor is an exact value measured by the SCADA system. The conductor temperature functions as the output of the model which can be calculated based on Eq. (3) [6][7].

$$T = T_{init} + \frac{q_s + q_J - (q_e + q_C + q_r)}{c_p m} dt \qquad (3)$$

Where T_{init} [°C] is the initial temperature value of the conductor, c_p [$Jkg^{-1}K^{-1}$] is the heat capacity of the conductor, m [kgm^{-1}] is the mass of the conductor and dt [s] is the time for the temperature change.

B. *Monte Carlo sampling*

This calculation is executed by several times due to the inputs are not exact values but different distributions. This is the step where Monte Carlo simulation is used, due to this method is applied for sampling from each of the available distribution. The advantage of this Monte Carlo sampling is that values which are more likely to occur are sampled more frequently. In this way, the result for the conductor temperature is also a distribution that forms the basis for the introduction of an operational risk factor [11][12].

C. *Operational risk factor*

The goal is to exceed the 2°C limit temperature of the conductor. Each simulated conductor temperature value which is higher than the limit represents a possible source for operational risk. Eq. (4) shows how the risk factor could be determined easily from the results of the simulation steps [11][12].

$$P(\theta_c < \theta_{min}) = \frac{N_e}{N} \qquad (4)$$

Where P ($\theta_c < \theta_{min}$) [-] is the probability of ice accretion risk, N_e [-] is the number of cases when the conductor temperature does not exceed 2°C and N [-] represents all of the cases.

However, under real circumstances the system operator needs to declare the required safety level. According to this, if the safety level of the simulation result is not satisfactory it could be controlled with the change of the input current. In this way, it is possible to determine the current required to prevent icing at a pre-set safety level [11].

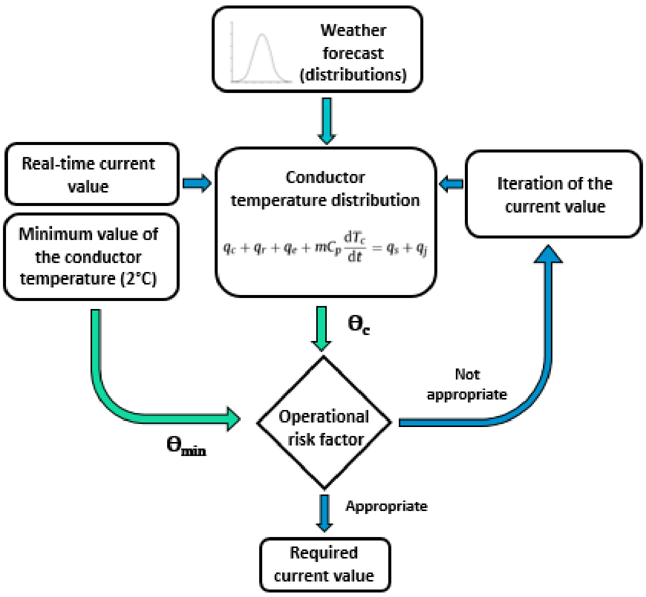

Figure 2 Operation of the hybrid anti-icing model

The required safety level could vary depend on the importance of each line. In case of an indispensable OHL this factor needs to be over 99% while in case of less important lines the safety factor could be set to 95%.

D. *The advantage of real-time transfer capacity calculation*

According to the conventional calculation of the transmission capacity if the calculated current needs for the icing prevention is higher than the static line rating of the OHL, the icing process cannot be prevented. However, with the calculation of DLR, it is possible to exceed this limit if the thermal overload of the conductor is not in danger. The only factor that needs to be considered in this case is that whether the other parts of the OHL such as current transformers etc. are designed for the higher current value. If not, the icing prevention cannot be successful with thermal method and other anti-icing technics need to be applied.

V. CASE STUDY

A. *General information*

In order to demonstrate how this hybrid anti-icing model operates a case study is presented within the framework of a DLR pilot project. The aim of this case study is to determine the required current value with the operational safety factor of 95% to avoid wet snow accretion on the conductor. For this study a 110 kV Central European OHL has been chosen on which sensors and weather stations are installed and icing forecast is available from the national environment agency. The main parameters of the OHL is described in Table 2 [11].

Table 2 Main parameters of the observed OHL

Conductor	
Material	ACSR
Strand diameter	3.5 mm
Overall diameter	21.9 mm
Number of outer strands	16
Coeff. of emissivity	0.55
Coeff. of absorption	0.55
Resistance @ 25°C	$1.2009 \cdot 10^{-4}\ \Omega m^{-1}$
Resistance @ 75°C	$1.4371 \cdot 10^{-4}\ \Omega m^{-1}$
Line	
Altitude	544 m
Maximum temperature	40 °C
Static line rating	530 A

The applied sensor installed on the phase conductor requires direct contact to measure conductor temperature. The operating range of the sensor is between –40.0°C and +85.0°C and the measurement resolution is 0.5°C. The device is supplied by a current transformer and the measurement deviation is within ±2.0°C in the operational range [11].

B. *Icing occasion*

On February 1, 2019, wet snow was predicted at dawn on a part of the power line by the environment agency. At 1 AM the conductor temperature was -0.3°C according to the measurement of the installed sensor while the ambient temperature was measured to be -3°C.

Figure 3 Landscape of the OHL a day before the forecasted icing [14]

Based on the weather forecast shown in Table 3 there was a high possibility to appear ca. few mm wet snow on the observed part of the OHL.

Table 3 The expected values of the environmental parameters

Weather forecast	
Ambient temperature	-2.3°C
Solar radiation	$0\ Wm^{-2}$
Wind speed	$1.5\ ms^{-1}$
Wind direction	24°
Precipitation	$0.3\ mmh^{-1}$
Relative humidity	98%

According to the long-term environment and load forecasts this wet snow layer could have increased significantly by 2 PM. This occasion was the basis of the following case study.

C. *Validation of the model*

Due to the OHL is equipped with sensors, there is a possibility to validate conductor temperature calculation part of the Monte Carlo based anti-icing model. At 2 AM the sensor measured -0.4°C conductor temperature with the pointing error mentioned earlier at the effect of 68 A load. Using the known model types, parameters and the uncertainties of the forecast, approximate distributions were generated in Matlab for all environmental parameters.

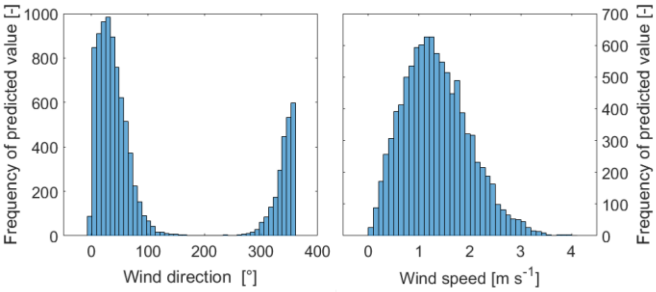

Figure 4 Distribution of the predicted wind direction and wind speed

Due to the need for reducing computation time all generated distributions consist of 10,000 points, from which 2000 are selected during the Monte Carlo sampling.

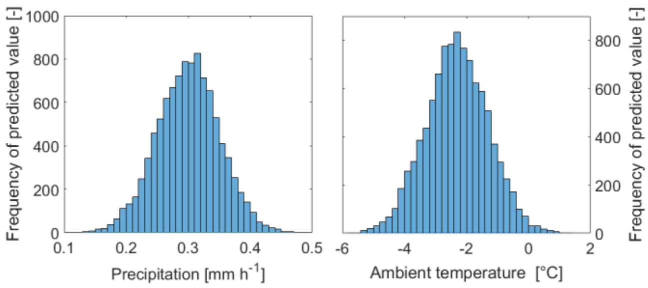

Figure 5 Distribution of the predicted precipitation and ambient temperature

In Figure 6 can be seen the conductor temperature distribution as a result of the validation simulation.

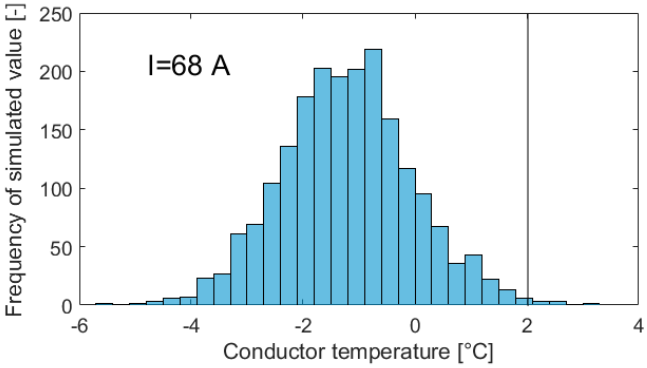

Figure 6 The distribution of the simulated conductor temperature at 68 A

Take into consideration that the expected value of the simulation is around -1.4°C, the simulation result and real-time measurement are consistent with each other. One reason for the difference is that the inaccuracy of the sensor measurement is about 2°C. With the improvement of the model and the measuring accuracy this difference could be decreased significantly.

D. Determination of the anti-icing current

AccordingFigure 6, the conductor temperature was higher than the 2°C limit value only in 10 cases. Based on Eq. (4) this means that the risk of the ice accretion is 99.5 % at 68 A which represents only 0.5 % security level.

However, the aim of this case study is to determine the current necessary to prevent icing with the safety level of 95%. The second simulation was carried out to to find out this reqiured current value.

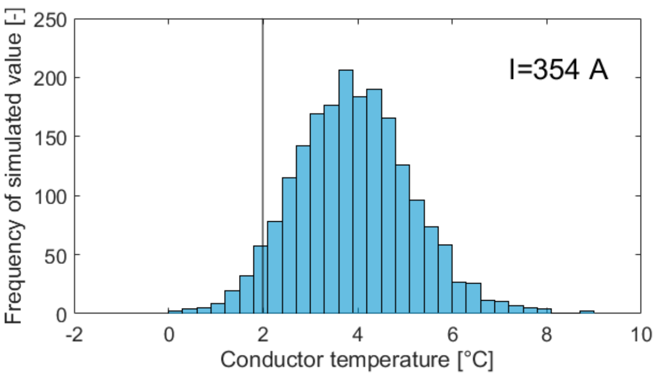

Figure 7 The distribution of the simulated conductor temperature at 354 A

By iterating the current values, it was found that 354 A is the current level that is required to heat the wire up to 2°C in order to avoid ice accretion at a safety level 95%. The static line rating of the OHL is 530 A which means that in this case this limit value is not exceeded so that further inquiries for the other parts pf the OHL are not needed.

E. Application of DLR in the anti-icing model

In the presented case, the specified current value does not exceed the value of the SLR, but this is not always the case. On the same transmission line, there may be a combination of environmental parameters where the SLR is not sufficient to heat the wire up to 2°C with a safety level 95%. Table 4 shows a possible combination for the expected values of the environmental parameters. It is important to mention, that for this possible simulation not necessarily wet snow is the type of ice accretion.

Table 4 A possible environmental forecast for the environmental parameters

Possible weather forecast	
Ambient temperature	-7°C
Solar radiation	0 Wm^{-2}
Wind speed	5.2 ms^{-1}
Wind direction	204°
Precipitation	0.9 mmh^{-1}
Relative humidity	98 %

Figure 8 represents the result of the conductor temperature simulation in case of these possible input values.

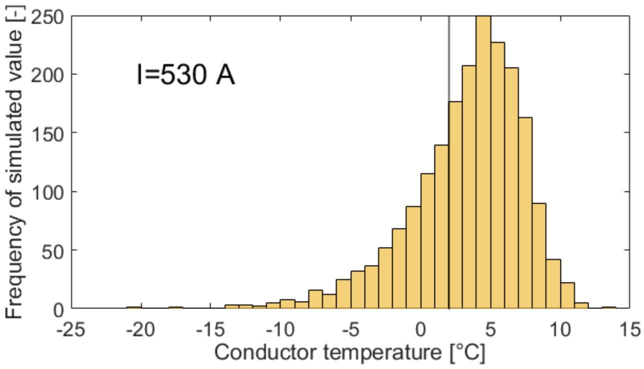

Figure 8 The distribution of the simulated conductor temperature at 530 A for different input parameters

It can be seen in Figure 8 that for this input combination at 530 A the risk factor is around 30%. Theoretically, according to the conventional transfer capacity calculation the ice prevention by melting cannot be possible in this case with the necessary safety level. In this case, the application of DLR method could lead to result. By applying DLR there is a chance to increase the transfer capacity limit due to the thermal safety is not in danger, so that there is a chance to avoid conductor icing. To do this, at first it is necessary to examine all the elements of the transmission line that can withstand the calculated current value. However, for this power line, this condition does not form a problem, so the current can be increased up to reach the appropriate safety level. Thus, icing prevention can also be a potential application for DLR in the future.

VI. Conclusion

Ice accretion on the OHLs can cause serious technical and economic damage, so that TSOs and DSOs in cooperation with industrial partners developed different techniques to avoid such cases. In this article a hybrid anti-icing method based on Monte Carlo sampling is shown with which it is possible to assign a risk or safety factor to each circumstance. A possible application of Dynamic Line Rating in anti-icing is also presented, with which the application limits of the anti-icing models based on ice melting could be increased.

The basis of the hybrid anti-icing method is the thermal balance of the conductor which is also completed with the effect of precipitation. The environmental inputs of the model are distribution forecasts for the weather parameters. Another input is the real-time value of the current and the output is the conductor temperature. From the input distributions an algorithm samples values based on Monte Carlo method and in this way the result will be also a distribution. The aim is to keep the conductor temperature over 2°C. By counting the conductor temperature results that does not exceed this limit temperature a risk factor can be determined. With the iteration of the input current the required safety factor could be reached.

To show the operation of the model a case study is presented where simulations are carried out on an existing Central European OHL. At the end of the case study a case is presented when the calculated melting current exceeds the SLR value of the OHL. With the application of DLR method, the current limit of the OHL can be extended and this makes possible to apply the mentioned model. In this way, a possible future application of DLR method is also presented.

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