DETERMINATION OF CONSTANT SEASONAL VALUES FOR THE CURRENT RATING OF OVERHEAD LINES IN THE NETWORK PLANNING

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ABSTRACT

This paper presents a new probabilistic approach for optimal planning of high voltage distribution grids, which aims to increase the transmission capacity by considering the environmental and weather conditions. For this purpose, the developed planning method determines admissible values for the current rating of the particular lines for individual seasons of the year. Then, these can be processed in the time-series-based probabilistic network planning in compliance with the (n-1) criterion in order to increase the allowable transmission capacity by optimal utilization of the available grid infrastructure. In addition, the paper shows the synergy effects between the constant current rating values and the use of a dynamic curtailment.

INTRODUCTION

The increase use of renewable energy sources (RES) in the German distribution grids confronts the network operators with new challenges in order to integrate the high installed capacity of decentralized generation plants into the energy grid. As a result, the distribution networks are changing from their traditional passive to an active character [1] and therefore new requirements in the distribution network planning need to be met [1]-[3]. In addition, due to the long planning and approval times for new lines, grid operators have to plan the enhancement of the transmission capacities today already in order to avoid future overloadings caused by the RES. Thus, time-series and probabilistic methods can take into account the uncertainties of RES and are a major objective of these new requirements [4]-[7].

In the high-voltage grids, power is usually transmitted through overhead lines, which are also preferably used to reinforce individual lines when expanding the grid, as these are cheaper than cables. In addition, the thermal limit current of the overhead lines in Germany is determined for a static design case and a maximum allowed conductor temperature according to the installation regulations of DIN EN 30341 [8]. Here a defined scenario is assumed for the environmental influences of midsummer weather conditions, which rarely occur in reality.

In order to increase the transmission capacity and to use more optimally the grid, the environmental influences can be taken into account in a dynamic line rating (DLR) [9]. In this case, the maximum permissible temperature of the conductor must not be exceeded in order to avoid possible damage to the conductor and excessive sags. A project in [10] showed that there is a spatial and temporal correlation between the cooling of the conductors and the feed-in from decentralized generation plants. Other projects were concerned with carrying out (n-1) safety assessments, including additional flexibility options of DLR [11], [12].

In this paper, the developed planning method aims to increase the transmission capacity taking into account the environmental and weather influences. For this purpose, a method is presented first, determining for the considered lines permissible values for the current rating for individual seasons. These are then used in the time-series-based, probabilistic network planning in compliance with the (n-1) criterion and coupled with a dynamic curtailment method. Then, different variants of this planning methodology are applied to a real German high voltage distribution grid. Finally, the benefits of this method is highlighted.

METHOD FOR DETERMINATION OF THE CONSTANT SEASONAL VALUES

In this section, the methodology for the determination of the constant seasonal values is explained. Therefore, the thermal properties of the conductor are modelled first in order to calculate the current rating of the lines. Then, the time-series for the environmental influences are created and finally the seasonal values are determined.

Steady-State Line Heat Balance

To calculate the weather-dependent current rating, a model is required for the heat balance of the overhead lines, in which the heating of the conductor by the current flow and the solar radiation is equal to the cooling by convection and radiation. In the literature, different models exist, among them models according to [9] and [13], which are similar and simulate the heat balance of the conductor.

In this paper, the model according to CIGRE [9] is used and the equation for the heat balance is:

$$P_J + P_S = P_R + P_C \qquad (1)$$

Here, the heating is composed of the Joule heating P_J, which is caused by the current flow and the temperature-dependent AC line resistance $R_{AC}(T)$, and by the solar radiation P_S. The conductor is cooled by the heat radiation P_R, which is due to the difference between the conductor and the ambient temperature, and by the convective cooling P_C, which depends on wind speed and wind angle of attack. The equation for the static heat balance can then be changed for fixed ambient influences and a maximum permitted conductor temperature. Thus, the maximum current rating is calculated as follows:

$$I_{max}(T_{max}) = \sqrt{\frac{P_R(T_{max})+P_C(T_{max})-P_S}{R_{AC}(T_{max})}} \qquad (2)$$

According to [8], the nominal current rating for the Al/St conductors used in this paper is determined for fixed environmental influences and a maximum conductor temperature of 80 °C. The reference environmental influences for these conductors are an ambient temperature of 35 °C, a solar radiation at 900 W/m², a wind speed of 0.6 m/s and a wind angle of attack of 90°. This standard line design will be used later in this paper to evaluate the benefits of using seasonal values for the current rating.

In [9], [11] and [12] the influence of weather conditions is analyzed more precisely. It was shown that the wind has the strongest influence on the increase of the current rating. The ambient temperature has only little and the solar radiation the slightest influence.

Modelling the Environmental Influences

In the area of the considered high-voltage grid, time-series with 15 minutes time resolution are generated from a climate model for one year for modelling the ambient temperature, solar radiation and wind speed. The used climate model has a geographical resolution for the individual regional areas of 0.1° in horizontal and vertical direction [13]. In addition, the time-series are average values in the individual areas of the climate model.

Figure 1 shows a small number of spatially resolved areas to improve the representability of the climate model. In addition, an exemplary course of an overhead line between two substations that runs through several regions is depicted.

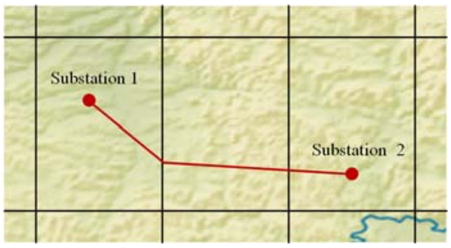

Fig. 1: Schematic representation of the spatially resolved climate model and an overhead line course

Risks and Potentials of Dynamic Current Rating

For an overhead line, the dynamic current rating for an Al/St line is calculated using the time-series of the environmental influences of any selected region and the thermal model of the overhead line. Since the thermal model also considers the wind angle of attack, a worst-case scenario of the angle of attack of 0° is assumed in this paper. According to [9], the current rating of the lines is the lowest at this angle and can occur under unfavorable conditions in real operation.

The dynamic current rating calculated in this way is normalized to the current value of the design case. This and the nominal current rating are shown as an ascending annual duration line in Figure 2. The figure shows that in more than 50 % of all simulation times the current rating is over 140 % of the nominal value, which means that the potential for increasing the transmission capacity is considerable. However, it is also evident that due to unfavorable weather conditions such as calm and high temperatures, the current rating in the simulation is 1.5 % of the times below the nominal rating. This would result in an operational risk in the case of real application due to possible conductor damage to the network operators.

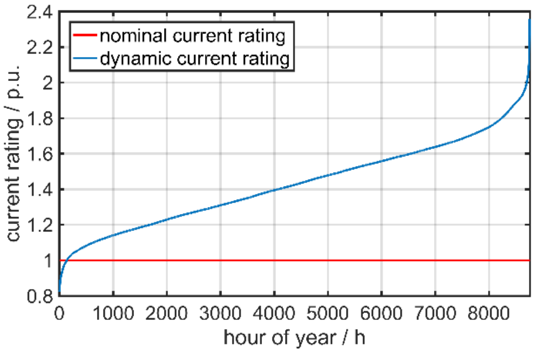

Fig. 2: Annual duration line of the current rating of an overhead line for different design cases

Determination of the Constant Seasonal Values for the Current Rating

An overview of the process of determining the constant seasonal values for the current rating can be seen in Fig. 3. At the beginning, the described structure of the thermal model of the overhead line according to [9] as well as the identification of all required parameters of the model takes place. These parameters include, among others, the diameter of the rope, the steel core and the aluminium wire, the temperature-dependent resistance value and the thermal conductivity for the overhead line.

In addition, the environmental influences are modelled as time-series based on a climate model. This climate model is also used to calculate the feed-in time-series of the photovoltaics and wind power plants for the regions according to the methodology from [15]. This results in a high spatial and temporal correlation. Thus, a high wind speed leads to a high feed-in, which can overload the lines, but at the same time the transmission capacity can be increased by the wind cooling.

As shown in Figure 1, the overhead lines can pass through several regions of the climate model. In order to calculate the minimum seasonal current rating of an overhead line between substations, the regions crossed by the overhead line must be determined. For this purpose, the geographical coordinates of the grid of the climate model are necessary. On the other hand, the grid model to be investigated must be analyzed in order to determine the relevant overhead lines for the use of dynamic current ratings. For these lines, the coordinates of the substations are required, to which the lines are connected. In addition, the coordinates for the overhead line towers must be known. By assuming a wind angle of attack of 0°, only a part is necessary, so that the calculation time can be minimized. These data can then be used to determine the affected regions.

The time-series for the current rating of the affected regions are then calculated for each line according to its rope type using the thermal model and the ambient conditions. If two or more overhead lines of different types run through one region, separate time-series are created for each overhead line section of particular type.

Finally, each time-series is divided into the individual subsets related to the seasons of the year, like summer, winter and transition time. These subsets are then searched for the minimum current rating for each overhead line section, since this is the limiting factor for the maximal allowable current. Thus, the constant seasonal values for the current rating have been determined.

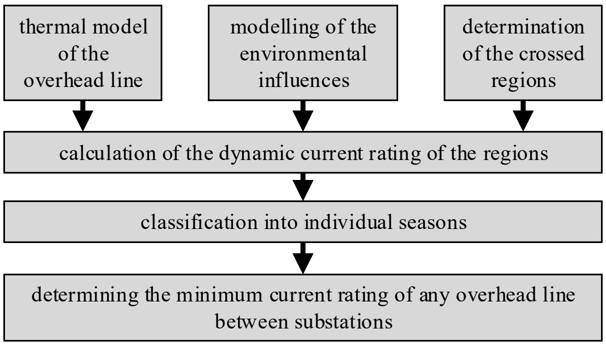

Fig. 3: Simulation sequence for determining the constant seasonal values for the current rating

Figure 4 shows as an example a section of the normalized duration curves of the calculated dynamic current ratings for the individual seasons summer, winter and transition period for a region. During the transition period the value is below the rated current for 20 hours, while in the summer, this is the case for 118 hours per year. Only in winter, the line for the load capacity is above the rated current in each time points. This also shows that, apart from a few points in time, there is potential for increasing the transmission capacity in all seasons.

When determining the minimum current rating for each season and overhead line, the first value of the duration lines shown in Fig. 4 is used. These results in a seasonal value of 103 % for the winter, which ensures that at all times the mechanical stability of the conductors is maintained in winter. In addition, the maximum sag is not exceeded. The minimum values for the transition period and summer are below the nominal value, so their use would lead to a reduction in transmission capacity. The overhead lines in operation in Germany are designed in accordance with [8] and operated with the nominal current rating. In order to consider these operating modes, the seasonal current ratings are finally set to 100 %, if the individual values are below the design case. Thus, the minimum values for summer and transition time from Fig. 4 are changed to 100 %.

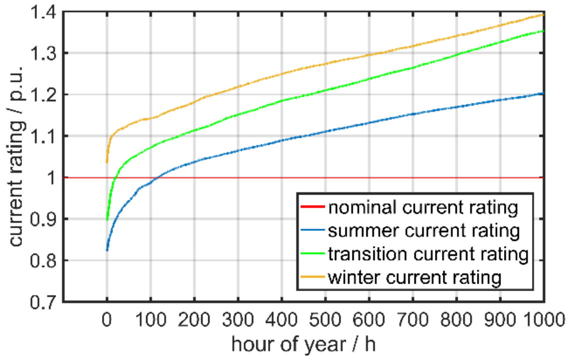

Fig. 4: Duration curve of the current rating for different seasons

APPLICATION OF THE SEASONAL VALUES IN THE NETWORK PLANNING

Based on a planning study on a real 110 kV grid in the south of Germany, the constant seasonal values are applied. These are used in a probabilistic, time-series based load flow calculation and contingency analysis to determine the (n-1)-criterion that must be met according to the valid planning guidelines for high-voltage grids. In the following, the input data and the procedure of the simulations as well as the results of the planning study are described.

Generation of the Input Data

The model from [15] is used to model the profiles for the exchange power with the medium-voltage network. In contrast to [15], this planning study does not assume an increase in the load, but only an increase in the installed capacity of RES. This increase and the maximum load for the year 2030 is shown in table 1. Thus, it can be expected that at certain times overhead lines can be overloaded due to the high feed-in of the RES into the high-voltage grid.

Table 1: Forecast data for the planning study

	Year 2016	**Year 2030**	**Increase to**
Installed PV-Power	479 MW	895 MW	187 %
Installed Wind-Power	204 MW	619 MW	303 %
Maximum Load	634 MW	634 MW	100 %
Annual RES Energy feed-in	901 GWh	2312 GWh	257 %

Planning Methodology

Figure 5 shows the sequence of the simulations for the developed planning methodology. First, the input data for the simulations are modeled according to [15]. For a comparability of the results, the same data are used for a consideration with and without seasonal values as well as a coupling with a curtailment method.

The constant seasonal values for the current rating are determined according to the method in Fig. 3. These can then be used directly in the time-series-based load flow calculation. However, the increase in the transmission capacity can result in a remaining overload of the lines can due to the high penetration of RES.

By coupling the previous planning method with a dynamic curtailment according to [16]-[18], the line utilization can be limited below the technical limit of 100 %. By using the seasonal values, the boundary conditions for the maximum line load are adjusted accordingly in the optimization problem used here. The power to be curtailed is then determined individually at each generation plant at the respective times in order to prevent line overloads.

Finally, a linearized load flow calculation and failure analysis according to [18]-[20] is carried out for each variant and the obtained results are analyzed below.

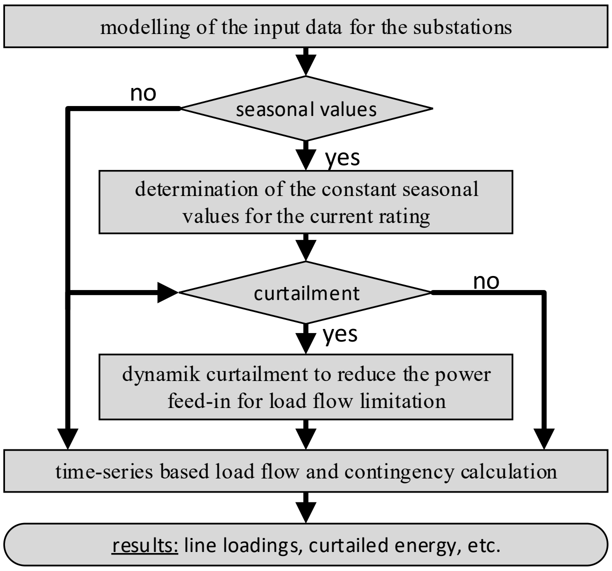

Fig. 5: Simulation process for the application of constant seasonal values for the current rating

Comparison of the Line Loadings

Table 2 shows a comparison of the seasonal values for current rating for the four most overloaded lines of the research network. This shows that it is not possible to increase the transmission capacity in the entire grid during the summer and the transition period. The values for the winter differ up to 2 % from each other and are attributable to the different environmental influences in the extended grid.

Table 2: Seasonal values for the current rating of several lines

	winter	transition	summer
line 1	1,03 p.u.	1 p.u.	1 p.u.
line 2	1,04 p.u.	1 p.u.	1 p.u.
line 3	1,02 p.u.	1 p.u.	1 p.u.
line 4	1,04 p.u.	1 p.u.	1 p.u.

According to Table 2, there is a potential for the constant current ratings only in winter, the line loadings are only compared for this time of the year. Thus, Fig. 6 shows the line loadings in the (n-1)-state for the most overloaded lines. The left box plots show the line loadings without using the constant seasonal values, which is overloaded due to the high increase of the installed RES. The box plots on the right show the results using the seasonal values.

The method reduces the line loading according to the constant current rating only slightly in the winter. In addition, according to table 1, it can also be expected that higher loadings will be caused by the higher installed PV-capacity in summer.

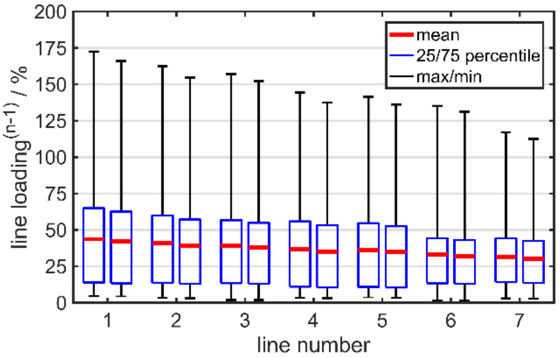

Fig. 6: Comparison of the line loading in the winter for the (n-1)-condition (left box plot: without constant seasonal values, right box plot: with seasonal values)

Comparison of the Curtailed Energy

With the aid of curtailment, the line loading from Fig. 6 can be reduced to a permitted limit with and without the consideration of the seasonal values. For these two variants, Figure 7 shows a comparison of the curtailed energies for some of the generators and substations. With the application of the seasonal values, a reduction of the curtailed energy can be achieved for a large part of the plants. For the entire grid, there is a reduction of 1.81 % without and of 1.73 % with the application of the seasonal values. This reduction is small, but for the grid operators this means a saving in the regulation costs and thus increases their economic efficiency. This shows that the aforementioned two methods are complementary to each other and that the existing grid is thereby used more optimally.

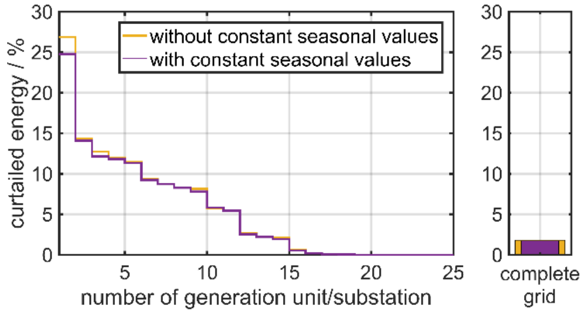

Fig. 7: Comparison of the curtailed energy of the generation units and substations

CONCLUSION

In this publication the determination and application of constant seasonal values for the current rating of overhead lines in the time-series-based, probabilistic network planning was carried out. A climate model and a thermal model of the lines are used to determine the values. In addition, a coupling with the dynamic curtailment and a calculation for the contingency analysis were carried out.

With this method, an increase in the transmission power can only be achieved in winter. In combination with the curtailment, the compliance with the (n-1)-criterion and a reduction of the curtailed energy can be achieved. For grid operators, this method offers the advantage, since it can be easily used in their grid planning. In addition, it is easy to take into account the constant current rating in the network operation, since the values only have to be changed in the grid protection system during the transition periods.

In order to reduce the disadvantage of the small increase in the transmission capacity, a further step in this research will be to integrate the dynamic current rating into the time-series-based network planning. In combination with the dynamic curtailment, this method aims to create synergy effects in order to reduce the curtailed energy as well as the necessary grid expansion.

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