Impact of Climate Change on Static Ratings of Overhead Line in Edinburgh

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***Abstract*-Static rating is the most widely used overhead line rating strategy to plan the operation of the overhead transmission system. Usually, the static rating of an overhead line is set with conservation assumptions of the most unfavorable weather condition based on the historical weather records. However, the climate change brings the uncertainties in both the level and frequency of these unfavorable weather conditions. This paper proposed a probability based approach to study the impact of climate change on the static ratings of the overhead lines. Through the thermal model developed based on IEEE Std 738, the static ratings are determined under the future climate conditions in Edinburgh simulated from UKCP09 weather generator with the climate change assumption in IPCC SRES A1FI. The results indicate an average reduction of 6.94% and a maximum reduction of 17.4% in the pre-fault static rating of the Zebra ACSR conductor in the summer of 2080s. It is also found out that the novel Drake ACCR conductor with a high rated operating temperature can be used as a potential solution to mitigate the impact against climate change.**

***Index Terms*—Climate change, Overhead conductor, Static thermal rating, Transmission line, Weather condition.**

I. Introduction

The rating of an overhead line is defined as its maximum current carrying capacity which is limited by the designed rated conductor operating temperature and the ambient weather conditions. The exceedence of this rated temperature will cause an unexpected excessive thermal expansion of the overhead line. This will lead to a decrease of the conductor-ground clearance violating the safety regulations. Static rating, as the most widely used rating strategy in the planning of the of overhead line transmission system operation, is a fixed rating to ensure the lines to work in the safety margin for most of the time. Therefore, the static rating is calculated based on the most unfavourable weather condition observed in the historical weather records which is usually a combination of high air temperature, high solar radiation and low wind speed.

As a result of the development of the global economy and the desire of a cleaner energy source, the demand of electricity is increasing incredibly in the recent years and is expected to keep increasing exponentially in the following decades. In this context, the existing overhead line transmission system has to operate close to the safety margin in the future. As the future climate is believed to be more variable than the existing one, the lines being operated with static rating set based on the historical weather records may be more likely to exceed this safety margin. Therefore, it is of vital importance to study the overhead line static ratings under the future climate conditions.

The key challenge to the ratings of overhead lines is global warming. Caused by the unprecedentedly rate of increase of greenhouse gas (GHG) emissions, global warming is expected to lead an average ground temperature increase from 1.1 ℃ to 6.4 ℃ as indicated in IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report (AR4) issued in 2007 [1]. These predictions of climate change are based on the climate models developed according to the historical climate records and the assumptions of future GHG emission scenarios.

In this paper, the static ratings of two different types of overhead line conductors (Zebra ACSR and Drake ACCR) are recalculated based on the simulated future climate change in Edinburgh. This climate change is obtained through UKCP09 weather generator [2] following the assumption of IPCC SRES (Special Report of Emission Scenarios) A1FI [3]. By comparing static ratings under the future climate condition to the existing ones, the impact of climate change on the overhead line static ratings is quantified.

II. Overhead Line Thermal Model

To investigate the impact of climate change on overhead line static ratings, the overhead line thermal model is utilized to convert the simulated future weather data to the predicted ratings. In this study, the thermal model is developed based on IEEE Std 738 [4]. The process of heat transfer between the overhead line conductor and ambient weather conditions can be presented with the heat balance equation, as shown below

$$I^2R(T_c) + q_s = q_c + q_r. \quad (1)$$

where I is the current flowing through the conductor, $R(T_c)$ is AC resistance at conductor operating temperature T_c, q_s is solar heat gain, q_c and q_r are convection loss and radiated loss respectively.

Under the specified weather condition, the current carrying ability of an overhead line is limited by its maximum allowed conductor operating temperature (T_{max}) which is set in order to minimize sag, line losses, loss of strength, or a combination of the above. Assuming that the conductor is

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operating at T_{max}, the rating of this overhead line can be derived from equation (1) as below.

$$I = \sqrt{\frac{q_c+q_r-q_s}{R(T_{max})}}. \quad (2)$$

A. Solar Heat Gain

The solar heat gain can be affected by the solar radiation and the surface condition of the conductor. In the model presented in this paper, both direct solar radiation immediately from the sun and diffuse solar radiation reflected from cloud, sky and ground are considered. Instead of calculating the total solar radiation roughly based the assumptions provided in IEEE standard, this study uses a more precise method to obtain the solar radiation based on the simulation results from the weather generator which take more weather factors such as rain fall and cloud cover into consideration.

The absorptivity is the key factor which is used to describe the surface condition of the conductor during the calculation of the solar heat gain. Theoretically, the higher the absorptivity is, the larger the solar heat gain. Although the absorptivity can be changed as a result of aging, shading and pollution, it varies only in a small range for the specified type of conductor [5]. Moreover, the solar heat gain is a minority part of the total conductor heat gain comparing to the Joule heat gain caused by the current. Therefore, the variation of the absorptivity is ignored in this study and a suggested value in the standard of 0.5 is used in the calculation [4].

B. Convection Loss

The convection loss is determined by two factors: wind speed and wind direction. Three equations are given in IEEE standard to calculate the convection losses for different levels of wind speed including high, low and zero. In static rating calculation, the wind speed (V_w) is assumed as 0.5 m/s and the angle ($\emptyset$) between wind direction and the conductor axis is assumed to be 12.5° for conservative consideration. The equation to calculate the convection loss caused by low wind speed is therefore used and it is described as the equation below.

$$q_c = \left[0.0119\left(\frac{D\rho_f V_w}{\mu_f}\right)^{0.6} k_f K_{angle}(T_c - T_a)\right]. \quad (3)$$

where D is conductor diameter, ρ_f is air density, μ_f is dynamic viscosity of air, k_f is thermal conductivity of air, K_{angle} is wind direction factor calculated as below

$$K_{angle} = 1.194 - \cos\emptyset + 0.194\cos 2\emptyset + 0.368\sin 2\emptyset. \quad (4)$$

C. Radiated Loss

The equation for the calculation of radiated loss is given below as

$$q_r = 0.0178D\varepsilon\left[\left(\frac{T_c+273}{100}\right)^4 - \left(\frac{T_a+273}{100}\right)^4\right]. \quad (5)$$

where ε is conductor emissivity.

It can be observed that the radiated loss of a conductor depends on its diameter and emissivity. The latter is various based on the conductor surface condition. Similar to the absorptivity, it also varies in a small range for the specified type of conductor [5]. In this paper, the emissivity is assumed as 0.5 as suggested in IEEE standard [4].

III. Weather Data Simulation

The weather parameters required by the IEEE thermal model to calculate the ratings of an overhead line include air temperature, solar radiation, wind speed and wind direction. For the calculation of the static ratings, the wind speed and wind direction are assumed as the constants for conservative consideration. Hence, the variables input to the model are air temperature and solar radiation.

Fig. 1 illustrates the process of the weather data simulation. The weather generator is trained with the historical weather record to simulate the weather conditions in a synthetic time series at the selected location based on the existing climate. By introducing the UK climate projections obtained from the running of climate model as the change factors, the weather generator can produce the simulated future climate with the weather variables required by the overhead line thermal model (i.e. air temperature and solar radiation). The details are discussed in this section.

A. Climate Model

The climate change information comes from the simulation results of the climate model. The modeling of the future climate change requires an estimation of the future levels of emissions of GHG. In theory, a greater climate change is expected to take place with a higher GHG emission scenario. According to the different assumptions of the future pathways of economic and social change, a series of future GHG emission scenarios were published in the IPCC Special Report on Emissions Scenarios [3] in 2000. To investigate the limitation of the overhead line static rating under an unfavorable great climate change, a relative high emission scenario is studied in this paper. This emission scenario, labeled as A1FI scenario, describes a storyline which is a case of rapid economic growth, global population that peaks in mid-century the declines, and widely introduction of new and more efficient technologies [3].

The climate model consists of two layers: GCM (global circulation model) and RCM (regional climate model). GCM gives the future climate change information covering the entire global. Based on the outputs of GCM, RCM simulates the regional climate with a finer resolution. In such way, UK climate projections (UKCP09) [6] are gained by running 17 Hadley Centre RCMs.

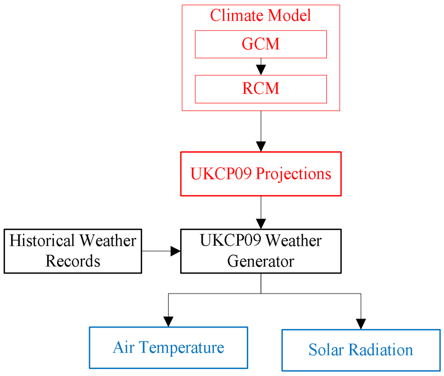

Fig. 1 Illustration of the weather data simulation process

B. UKCP09 Weather Generator

To investigate the climate change at the selected location, UKCP09 weather generator [2] is developed to downscale the UK climate projections to the grids with a resolution of 5 km. This weather generator is trained by the historical weather record observed between 1961 and 1995. By introducing the UKCP projections, the weather generator can generate a synthetic time series of hourly future weather data including air temperature, direct solar radiation, and diffuse solar radiation, etc.

Essentially, the weather generator is a stochastic model parameterized by a variety of variants. UKCP09 weather generator provides 10,000 such variants. Each run of weather generator is based on one of these variants to produce one possible climate projections at the selected location. A sufficient number of runs are required to gain a range of climate change and the probabilities of the change at the certain levels. In this study, 1000 variants are used to simulate the future climate in three 30-year time frames which are 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099).

IV. Conversion from Simulated Weather Data to Static Rating

A. Pre-fault Rating and Post-fault Rating

As the weather condition is dynamic, the rating of an overhead line varies as a function of time. The most conservative static rating is defined as the lowest rating over the specific period to maintain the operation of an overhead line under all the weather conditions. This lowest rating, however, only has to be used in an extreme unfavorable weather condition (i.e. high air temperature and high solar radiation) with a minor probability. For most of the time, the actual thermal rating is higher than this lowest rating. This means that an excessively conservative static rating will limit the efficient use of an overhead line. Therefore, instead of using the lowest rating as the static rating, the utilities set different tolerance risk levels based on the probability of the overhead line conductor exceeds its rated temperature to determine a more flexible static rating. Pre-fault rating and post-fault rating are two of these static ratings widely used by utilities.

Both pre-fault rating and post-fault rating are used to scheme the operation of the lines. The pre-fault rating is set to ensure a very low risk of exceeding the conductor's rated temperature. When the overhead line has to operate above the pre-fault rating, the post-fault is used until pre-fault requirements can be restored. The period of the use of the post-fault rating should not exceed 24 hours and will normally be tolerable within 24 hours. Based on a statistical analysis of conductor temperatures calculated from weather data recorded over several years, the pre-fault rating is set to ensure that the probability of exceedence of the conductor's rated temperature is below 0.1%. The post-fault rating is the static rating with a higher risk level which allows the conductor exceeds its rated temperature for 12% of the time.

B. Determination of Static Rating from Simulated Weather Data

The simulated future weather data from the weather generator is given in the form of a time series of 30-year hourly air temperature and solar radiation. To determine pre-fault and post-fault ratings from the simulated weather data, the maximum rating which can be carried by the overhead line conductor in each hour is calculated through the thermal model. Then all of these hourly ratings are placed into a cumulative probability distribution as shown in Figure 2. The pre-fault and post-fault ratings can be determined by applying the different risk levels to this distribution. For example, by using $I_{pre\text{-}fault}$ corresponding to a probability level of 0.1% as the pre-fault rating, it ensures that the overhead line conductor's current carrying capacity is expected to be below $I_{pre\text{-}fault}$ for only 0.1% of the time without exceeding the rated temperature. During the 0.1% of low current carrying period, the overhead line has to exceed the rated temperature to maintain a minimum current of $I_{pre\text{-}fault}$ that can be delivered to the customer through the line. Furthermore, the post-fault rating is determined in the same way as the pre-fault rating with a probability level of 12%.

C. Probability Distribution of Static Ratings

As introduced in the previous section, each run of weather generator parameterized by a set of variants provides one possible climate projection. Therefore, a pair of pre-fault rating and post-fault ratings can be calculated from each run of weather generator. To estimate a more precise prediction of static ratings, 1000 such pairs are gained through the simulated weather data from 1000 runs of weather generator. Then the future pre-fault and post fault rating are predicted based on the probability distribution of these 1000 pairs of static ratings.

An example of the prediction process of the post-fault rating Zebra ACSR overhead line under the climate in Edinburgh in the summer of 2020s is shown in Fig. 3 and 4. Fig. 3 illustrates the post-fault ratings determined by five runs of weather generator. Given the simulated data from 1000 runs of weather generator, the 1000 post-fault ratings form a distribution shown in Fig. 4. The range of the post-fault rating can then be gained between lowest rating and highest rating among these 1000 post-fault ratings. The mean values of these ratings are considered as the average summer post-fault rating of Zebra. Furthermore, the deviation can be also worked out to calculate a likely occurrence range of ratings.

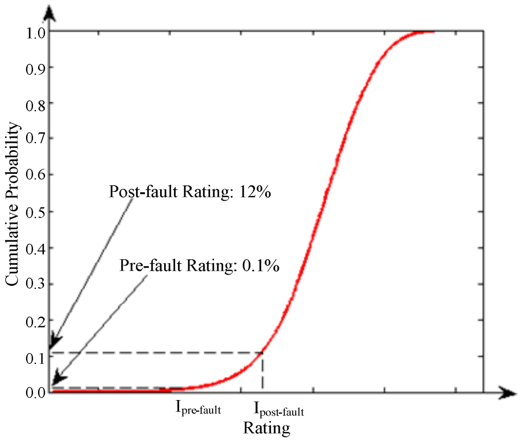

Fig. 2 Determination of pre-fault and post fault ratings

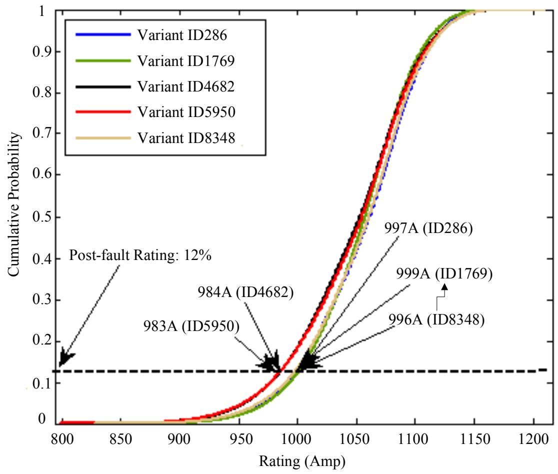

Fig. 3 Determination the post-fault rating base on the simulated weather data with different variants

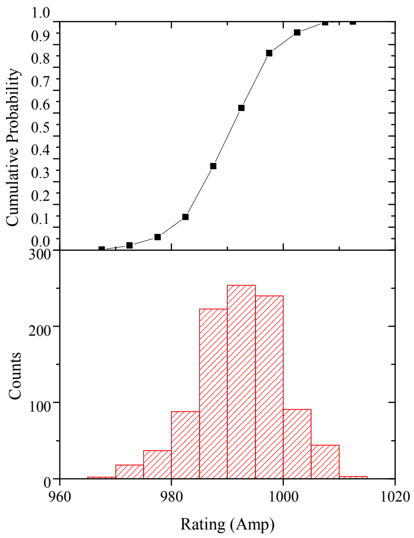

Fig.4 Cumulative probability distribution of the 1000 post-fault ratings calculated from the simulated weather data

V. Results

In this paper, the Zebra ACSR conductor and Drake ACCS conductor are selected as the examples to demonstrate the impact of climate change on the overhead line's static ratings. The simulated future weather data in Edinburgh is used as the basis for the determination of the pre-fault and post-fault ratings. As climate in different seasons can be quite different, three seasonal static ratings are calculated and analyzed. The summer months are from May to August; the winter are from December to February; the rest months in a year is defined as the spring (or autumn) months.

A. Predicted Static Ratings of Zebra ACSR Conductor

The static ratings of Zebra ACSR conductor calculated from the simulated weather data is shown in Table I. The baseline ratings are calculated based on the existing climate condition which is observed between 1961 and 1995. The future weather data in 2020s, 2050s and 2080s are simulated based on the assumption of A1FI emission scenario. The result shows the different levels of reduction in the both pre-fault ratings and post-fault ratings.

Taking the baseline static ratings as the references, the percentage of the de-ratings are gained and shown in Table II. It can be observed that from 2020 to 2050 and to 2080, the de-rating of both the pre-fault and post-fault in different seasons all goes up since the level of climate change gradually increases with time. Furthermore, the summer ratings are challenged by the greatest reductions whilst the winter ratings have the least reductions. The maximum de-ratings are expected to take place in the summer of 2080s with the reductions of 6.94% and 5.04% for pre-fault rating and post-fault rating respectively. It can also be observed that

TABLE I
PRE-FAULT AND POST-FAULT RATINGS FOR ZEBRA ACSR CONDUCTOR IN EDINBURGH (UNIT: AMP)

	Season	Baseline	2020s	2050s	2080s
Pre-fault	Summer	896	878	858	834
	Spring	961	944	930	908
	Winter	1046	1030	1021	1009
Post-fault	Summer	1007	992	976	956
	Spring	1064	1051	1041	1026
	Winter	1115	1107	1099	1089

TABLE II
PERCENTAGE OF DE-RATINGS IN PRE-FAULT AND POST-FAULT FOR ZEBRA ACSR CONDUCTOR IN EDINBURGH

	Season	2020s	2050s	2080s
Pre-fault	Summer	2.04%	4.24%	6.94%
	Spring	1.78%	3.28%	5.49%
	Winter	1.47%	2.37%	3.52%
Post-fault	Summer	1.46%	3.06%	5.04%
	Spring	1.21%	2.16%	3.57%
	Winter	0.66%	1.42%	2.35%

at a certain time frame, the de-ratings of post-fault ratings are less than those of pre-fault ratings in each season. This indicates that the climate change has more impact on the pre-fault ratings with the increasing extreme weather conditions in the future.

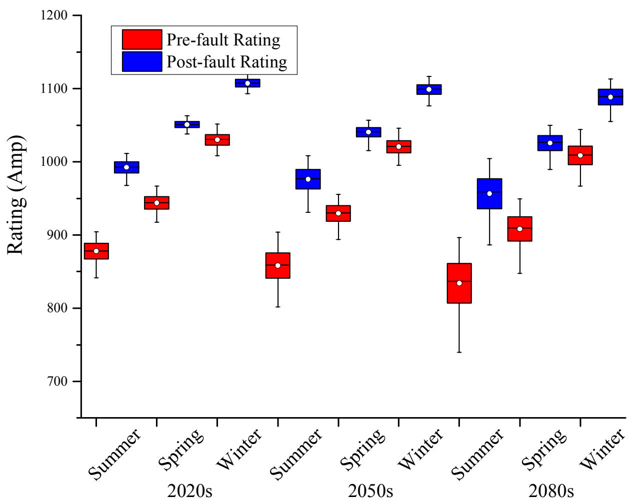

Fig. 5 Ranges of pre-fault and post-fault ratings of Zebra ACSR conductor in Edinburgh in 2020s, 2050s and 2080s

The ranges of the pre-fault and post-ratings are presented in Fig. 5. The upper limits and lower limits are determined by the maximum and minimum ratings in each season of the timeframe. The likely occurrence ranges of these ratings are shown in the form of boxes with a standard deviation coefficient of 1 which covers ratings in 66.7% of the possible climate projections. Moreover, the mean values of the ratings are presented as the white dots inside the boxes. It can be found that the pre-fault rating can be as low as 740 A in the worst climate projection in the summer of 2080s. Comparing to that calculated from the baseline climate, the pre-fault rating is reduced by 17.4%. The reduction of post-fault rating in such case is 12.02%. The likely occurrence ranges of pre-fault ratings (807A to 861A) and post-faults (936A to 977A) indicate the de-ratings up to 9.93% and 7.05% respectively in the summer of 2080s.

B. *Predicted Static Ratings of Drake ACCR Conductor*

The ACCR conductor is a novel all-aluminium-based conductor designed to increase the overhead line transmission capacity by operating with a much higher rated temperature than the traditional conductors. To compare its performance under the future climate conditions to that of the Zebra ACSR conductor, the de-ratings of ACCR conductor are examined. This ACCR conductor is profiled with a maximum rated temperature of 240 °C and the same conductor diameter as that of Zebra ACSR conductor.

As shown in Table III, the maximum de-rating of Drake ACCR conductor is only 1.09% even in the worst weather scenario, i.e. the summer in 2080s. Comparing to Zebra ACSR conductor, Drake ACCR conductor shows an excellent performance against the climate change. This is because that ACCR can gain more cooling benefiting from its higher rated temperature. It can be explained by equation 3 and equation 5 that both convection cooling and radiation cooling can be enhanced by increasing the temperature different between the conductor and ambient air temperature.

TABLE III
COMPARISON OF THE PERCENTAGE OF DE-RATINGS IN PRE-FAULT AND POST-FAULT BETWEEN ZEBRA ACSR CONDUCTOR AND DRAKE ACCR CONDUCTOR IN EDINBURGH IN 2080S

	Season	Zebra ACSR	Drake ACCR
Pre-fault	Summer	6.94%	1.09%
	Spring	5.49%	0.96%
	Winter	3.52%	0.69%
Post-fault	Summer	5.04%	0.96%
	Spring	3.57%	0.74%
	Winter	2.35%	0.52%

VI. CONCLUSIONS

In this paper, a method to investigate the overhead line static rating under the future climatic conditions is proposed. The results demonstrate significant reductions in both pre-fault and post-fault ratings of overhead line with the simulation weather data based on the A1F1 emission scenario. At the same time, it is also shown that the de-ratings of the conductor start to take place in 2020s and become more serious in 2050s and 2080s. In the summer of 2080s, the rating reduction of Zebra ACSR conductor is 6.94% as average and can be as high as 17.4% under the worst climate projection. This indicates that the measures are required to enhance the overhead lines' ratings to maintain the power transmission capacity against the climate change. Furthermore, this paper also proves a potential solution to mitigate the impact of climate change by replacing the traditional conductors with high rated temperature novel conductors.

The static rating assessment approach introduced in this study can also be applied to other types of overhead lines conductors and assumptions of climate change levels at different locations. These predicted future overhead line static ratings can be used as the guidance for the plan of operation and development of the future power system to enhance the capacity and reliability of the future system.

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