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Dynamic Thermal Rating of Overhead Transmission Lines Based on GRAPES Numerical Weather Forecast

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Abstract

Dynamic thermal rating technology can effectively improve the thermal load capacity of transmission lines. However, its availability is limited by the quantity and high cost of the hardware facilities. This paper proposes a new dynamic thermal rating technology based on global/regional assimilation and prediction system (GRAPES) and geographic information system (GIS). The paper will also explore the method of obtaining any point meteorological data along the transmission line by using GRAPES and GIS, and provide the strategy of extracting and decoding meteorological data. In this paper, the accuracy of numerical weather prediction was verified from the perspective of time and space. Also, the 750-kV transmission line in Shaanxi Province is considered as an example to analyze. The results of the study indicate that dynamic thermal rating based on GRAPES and GIS can fully excavate the line power potential without additional cost on hardware, which saves a lot of investment.

Keywords

Dynamic Thermal Rating, Global/Regional Assimilation and Prediction System (GRAPES), Meteorological Data, Power Grids, Thermal Load Capacity, Transmission Line

1. Introduction

The harsh combination of meteorological parameters is applied to calculate the static thermal rating (STR) of transmission lines, including wind speed of 0.5 m/s and ambient temperature of 40°C. The results are conservative. Meanwhile, the dynamic thermal rating (DTR) technology, obtaining actual environmental meteorological parameters from measuring devices, can achieve line capacity of between 10% and 30%, which is higher than that of the traditional STR [1]. However, to take full advantage of the DTR technology, there is a need for numerous measuring devices throughout lines. In addition, high-level communication technology is necessary to collect parameter information. Owing to these reasons, most of power grids still use the traditional STR technology even though the DTR technology can effectively improve the transmission capacity of overhead transmission lines. Therefore, it is necessary to study the method to reduce the cost of applying DTR.

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Regarding the DTR technology, in 1977, the dynamic load carrying capacity of transmission lines was studied in [2], in which the concept of DTR was put forward. According to the actual weather conditions, including ambient temperature, wind speed and sunshine, DTR can establish the line power transfer capacity. In 1988, the research and practice of DTR were conducted under the auspices of the United States Electric Power Research Institute [3]. In 1996, a small-scale engineering practice was carried out [4]. In the 21st century, the development of smart grid has further promoted the application of DTR. In the western United States, the east, and Texas, in particular, the three major interconnected systems with a total length of 240 000 km use the DTR techniques [5]. Across the United Kingdom, especially in England, Welsh and Scotland, the transmission network with maximum voltage rating of 400 kV, and the distribution network with voltage rating below 132 kV, achieve DTR of the key transmission lines [6]. In China, in the early 21st century, DTR technology was studied and implemented on overhead lines in the eastern and coastal areas [7,8]. In the above study, all the weather parameters are usually obtained by measuring devices located along transmission lines. This has the capability of limiting the development and application of the DTR technique.

To address the above problem, this paper puts forward the application of the numerical weather forecast to obtain the wind speed and ambient temperature data along transmission lines. The maturing global/regional assimilation and prediction system (GRAPES) will be used to study the thermal load capacity of transmission lines. In addition, the DTR will be carried out by means of numerical weather forecast system without the need to install actual meteorological monitoring devices. As well, the DTR of any overhead line can be easily realized and a large number of grid investment can be saved.

The rest of this paper is organized as follows: Section 2 will present the DTR of transmission lines based on IEEE standard thermal balance equation. After that, Section 3 will introduce GRAPES numerical weather forecast and geographic information system (GIS). In Section 4, the paper will give the calculation and analysis of thermal load capability of overhead transmission lines based on GRAPES and GIS. In Section 5, the accuracy of numerical weather forecast in space and time will be verified, and DTR analysis of 750 kV transmission line in Shaanxi Province will be presented as well. Lastly in Section 6, the conclusions will be provided.

2. Dynamic Thermal Rating of Transmission Lines

The DTR of overhead transmission lines is determined by the surrounding weather conditions, such as wind speed, wind direction, sunshine intensity and ambient temperature. Among these conditions, the main factors that affect DTR are the Joule heat caused by the current passing through the line, the heat absorbed by the sunshine, the convection heat dissipated by wind and the radiation heat as a result of the difference between conductor temperature and ambient temperature. Transmission lines are assumed to be uniform conductors. According to the IEEE standard, neglecting the small amount of heat balance equation such as evaporation heat and corona loss, the ampacity of overhead transmission lines can be established by the transient-state thermal balance equation, as shown in Eq. (1).

$$mC_{\mathrm{p}}\frac{\mathrm{d}T_{\mathrm{c}}}{\mathrm{d}t} = I^2 R(T_{\mathrm{c}}) - Q_{\mathrm{c}} - Q_{\mathrm{r}} + Q_{\mathrm{s}} \tag{1}$$

where, I represents the current through the conductor; $R(T_c)$ represents the conductor resistance when the conductor temperature is T_c; $I^2R(T_c)$ is the heat generated by the current; Q_s represents the heat absorbed by the sunshine effect; and Q_c and Q_r are the heat dissipated by radiation and convection, respectively.

Detailed expression of the above three parameters are illustrated in [9], where m is the mass of per unit length, kg/m and C_p is the specific heat capacity of a conductor material, J/kg·°C.

When the surrounding weather conditions are in a steady state and the carrying current is determined, the heat absorption and heat dissipation can eventually be in balance. The differential term is zero in Eq. (1). Meanwhile, Eq. (2) shows the steady-state thermal equivalent equation.

$$I^2R(T_c)+Q_s=Q_r+Q_c \tag{2}$$

Given the actual ambient meteorological parameters and the conductor type of transmission lines, assuming that the conductor temperature reaches the maximum permissible temperature, such as 70°C in China, the DTR of transmission lines in thermal balance state can be calculated using Eq. (3).

$$I=\sqrt{\frac{Q_r+Q_c-Q_s}{R\left(T_c\right)}} \tag{3}$$

3. GRAPES Numerical Weather Forecast and GIS Geographic Information System

On the basis if the current atmosphere state, numerical weather forecast is a technique used to predict the weather for a certain period in future by solving the physical equations. According to the atmosphere mathematical model, the appropriate initial and boundary conditions are set up, and a large amount of meteorological information data is computed using large-scale computers.

3.1 GRAPES Numerical Weather Forecast

GRAPES is currently developed by China. As a new generation of China's numerical forecast system, GRAPES is dominantly studied by the China Meteorological Administration in 2000 [10]. In addition, the high performance computer technology related to numerical forecast system has developed rapidly over the years. Also, it plays a fundamental role in the high-resolution, high-precision numerical weather forecast model, and provides a reliable, stable and fast calculation requirement for numerical weather forecast [11,12]. As at now, GRAPES has put forward the development plan for 2020–2040. The horizontal resolution will be 5 km in the global assimilation forecast system model, and will be 1 km in the area model [13]. Also, the fine forecasting system developed based on GRAPES will further expand its application scopes [14].

The data source of this paper is the large data platform of China meteorological data network, which is the East Asian regional forecast product generated by GRAPES. The forecast frequency for this product is twice a day (00:00/12:00). The forecast for the next 72 hours will be delivered after every 3 hours. The spatial level resolution is 0.09°×0.09°, which is a grid data of 10 km×10 km. In addition, data is stored in a GRIB2 encoding format. Some of the forecast elements include ambient temperature: *U* component of wind speed, and *V* component of wind speed, pressure, and precipitation. Fig. 1 shows the data lattices of numerical weather forecast. The wind speed and ambient temperature information are vital in the calculation of the DTR of overhead transmission lines.

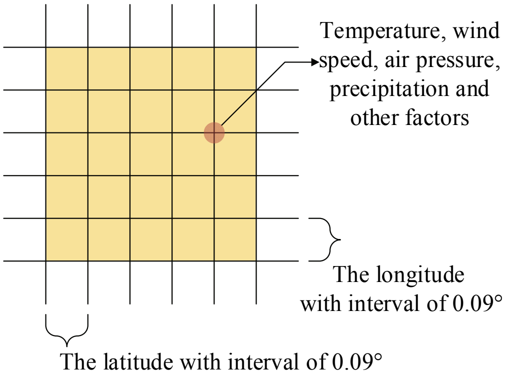

Fig. 1. Data lattices of numerical weather forecast.

3.2. Decoding Method of GRIB2

China meteorological data network uses the GRIB2 as its data data storage format, which is encoded by the form-driven code. The form-driven code, proposed by the World Meteorological Organization (WMO), is a common format for meteorological data. Multi-dimensional grid data can be described by GRIB2 in time and space. In addition, GRIB2 is mainly utilized to represent product information of numerical weather analysis and forecast [15]. Fig. 2 shows the GRIB2 coding format.

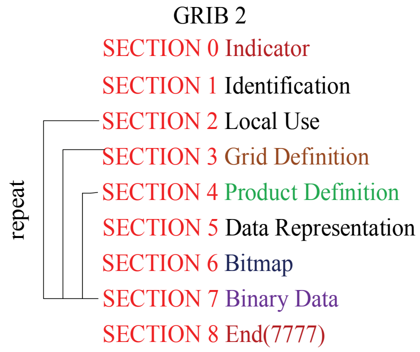

Fig. 2. GRIB2 encoding format.

Since the GRIB2 encoded format is not explicitly displayed, it is necessary to decode the GRIB2 data file to obtain the ambient temperature and wind speed information. The ambient temperature and wind speed information are extracted and saved into the data files of txt or dat format, which are applicable in this paper. We will use the weather professional mapping software, OpenGrads, to decode GRIB2 format file. The decoded core commands are as follows:

```
!g2ctl d:/grib/multi.grib > d:/grib/multi.ctl
!gribmap -v -i d:/grib/multi.ctl > d:/grib/multi.txt
```

The following batch command outputs the extracted data information to the txt data file, which is directly readable by the MATLAB software:

```
'reinit'
'open d:/grib/GRMC91618000.ctl'
'set gxout print'
'd VGRDprs'
file='d:/grib/GRMC91618000.txt'
rc=write(file,result)
rc=close(file)
```

3.3 Geographic Information System

On the basis of the geospatial database, GIS is a geography model analysis method that can be used to provide a variety of spatial and dynamic geographic information. GIS can also provide services for geography research and geographic decision-making. It integrates the functions of acquiring storage, querying, analyzing and displaying geospatial data of the computer information system.

Presently, as an important technical support means of digital power grid, GIS has developed rapidly both in domestic and international power enterprises. At present, GIS is mainly used in the three major fields of power transmission, transformation and distribution. The power transmission GIS is founded on the geographical map. It carries out GIS management of the tower parameters, power equipment information and geographic information. Fig. 3 summarizes the specific application of GIS.

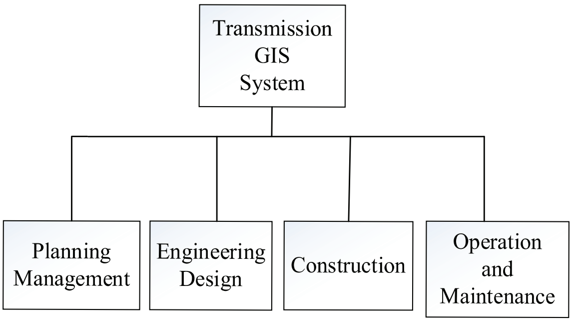

Fig. 3. Transmission GIS system function.

Planning management is mainly used in the planning stage of power grids, counting related economic and technical indicators. The engineering design is to perfect the spatial database based on planning management. Data can be compiled into data collection during the construction phase. Besides, the operation and maintenance functions can be used to manage and analyze the operation of the grid as per the actual geographical location, the device parameter database, as well as the relevant technical standards.

This paper applies GIS to obtain ambient temperature and wind speed as per the geospatial information along transmission lines. The line DTR and the operating temperature are analyzed or predicted in the planning management, operation and maintenance phase. As a powerful large-scale GIS product, ArcGIS is also widely used as the mostly developed platform of China's GIS applications. In this line, this paper will use ArcGIS as a GIS application tool.

4. Analysis of Dynamic Thermal Rating of Overhead Transmission Lines Based on GRAPES and GIS

In this paper, ArcGIS is used to model the geographic coordinate system of Shaanxi Province grid. After that, the numerical weather forecast value of the corresponding geographical location will be extracted to evaluate the thermal load capacity. Fig. 4 shows the specific design.

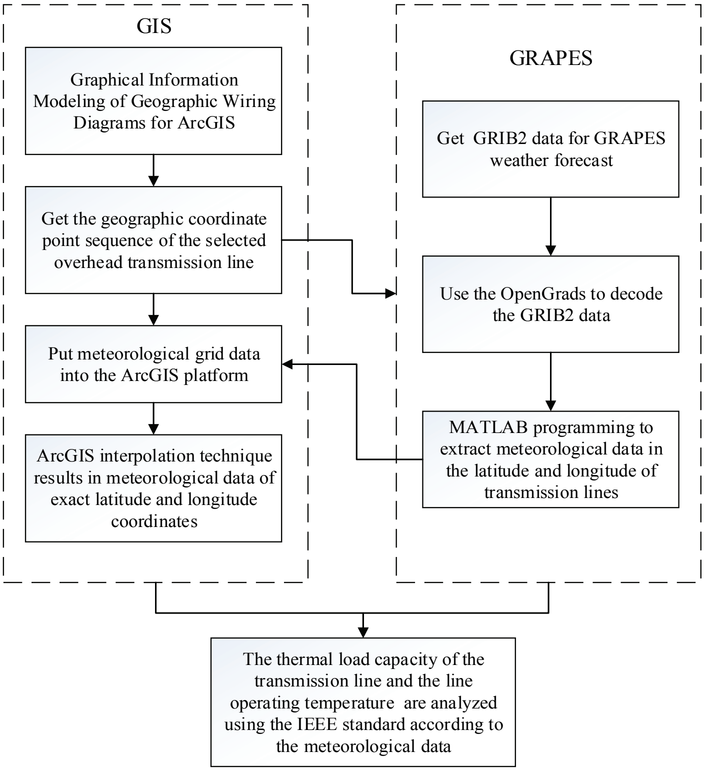

Fig. 4. GIS and GRAPES evaluation of thermal capacity of overhead transmission lines.

In Fig. 4, the evaluation of thermal capacity of overhead transmission lines based on GIS and GRAPES involves three distinct steps:

- GIS application program: Firstly, the geotechnical wiring diagram of Shaanxi Province is imported into the ArcGIS and the precise geographical coordinate system map of Shaanxi power grid is formed through vectorization and geographical registration of the geologic wiring diagram of power grid. After that, ArcGIS's query function can be utilized to extract the latitude and longitude geographic coordinate sequence along the selected transmission line. The GRAPES meteorological grid data of the extracted Shaanxi area is then imported into the ArcGIS platform. Through the use of the spatial interpolation technique of ArcGIS, the meteorological data information at the geographical coordinates sequence can be obtained with the inverse distance weight interpolation.

- GRAPES numerical weather forecast data processing: This involves the step of obtaining the numerical weather forecast data of the specified forecast time. Through the use of the meteorological drawing software OpenGrads, the obtained GRIB2 format numerical weather forecast data can be decoded to get txt format files. Subsequently, the meteorological data information of designated geographic range can be extracted using MATLAB.
- DTR processing: Based on the obtained meteorological data information at the geographical coordinates sequence along the transmission line, and according to the IEEE standard thermal equilibrium equation, the DTR of selected transmission line can be analyzed. At the same time, according to the IEEE 738 standard, the conductor operating temperature can be calculated with the obtained weather data information by the use of the thermal balance equation.

The proposed scheme in this section can be applied to the forecasting of the thermal load capacity of the transmission lines in operation. In addition, it can also be used in the analysis of the thermal load capacity of transmission lines under design.

5. Case Study

To use the data of the GRAPES numerical weather forecast in place of the measurement data of the actual monitoring equipment, it is necessary to verify the validity and accuracy of the numerical weather forecast data. Taking the local weather station temperature as a reference, we can test the temperature forecast accuracy of GRAPES numerical weather forecast.

5.1 Accuracy Verification of GRAPES Weather Forecast

5.1.1 Verify the accuracy of GRAPES in space

There are 88 meteorological stations in Shaanxi Province lying in latitude span of 31.54°–39.01° and in longitude span of 106.09°–111.00°. When the interpolation technique is utilized to calculate the temperature information of the meteorological stations, the latitude and longitude of the numerical weather forecast lattice ought to be larger than the meteorological stations. In this paper, the latitude and longitude coordinates of the numerical weather forecast lattice are 31.0°–39.5° and 105.5°–111.5°, respectively. Also, the weather station data and numerical weather forecast data at 9:00 on March 9, 2017 were selected for comparative analysis. The data source was the large data platform of China meteorological data network, where the meteorological grid data of the numerical weather forecast at the 88 meteorological stations were obtained using the interpolation techniques. Fig. 5 illustrates the comparison of the data obtained from the numerical weather forecast and the local weather stations.

According to the analysis drawn from Fig. 5, in general, the temperatures of the numerical forecast coincide with the temperatures published by local meteorological stations. The average error is 2.48°C and the minimum difference is 0.1°C. Comparing the temperature data obtained by GRAPES and local station at the 88 locations, we can well verify the accuracy of GRAPES in space.

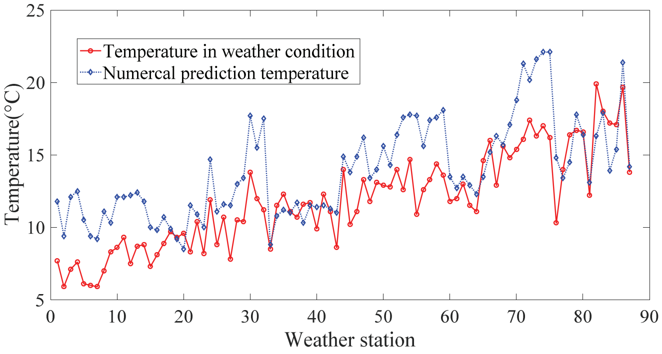

Fig. 5. Verify the accuracy of GRAPES in space.

5.1.2 Verify the accuracy of GRAPES in time

5.1.2.1 Daily maximum temperature

The numerical weather forecast for the whole month of June 2016 was compared with the daily maximum temperature at the Luochuan meteorological station. Fig. 6 shows the results.

Fig. 6 indicates that the overall trend of the numerical weather forecast in the daily maximum temperature forecast is line with the trend of the local meteorological station, with a maximum temperature difference of 4.5°C, and an average temperature difference of 1.6°C. At the same time, the error of the forecast is within a relatively small range. This confirms that the numerical weather forecasting of daily maximum temperature is accurate.

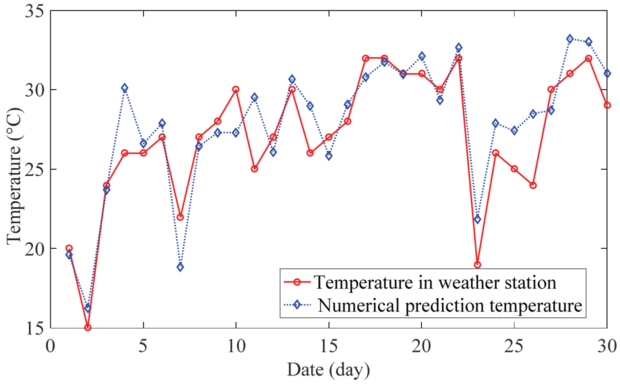

Fig. 6. Verify the accuracy of daily maximum temperature.

5.1.2.2 24-hour temperature forecast over the next 1 day

The temperature value of the numerical weather forecast in Luochuan area from March 27, 2017 to April 2, 2017 was further compared with the hourly temperature value published by the local meteorological station. Fig. 7 shows the results.

Fig. 7 indicates that the temperature of numerical weather forecast is consistent with the temperature issued by local meteorological station. The maximum temperature difference is 2.15°C in the high temperature period, experienced at 14:00 in March 29, 2017. In the low temperature period, the maximum temperature difference is 5.4°C. Therefore, the overall average temperature difference is 1.5°C. Overall, numerical weather prediction is valuable for the 24-hour temperature prediction over the next 1 day.

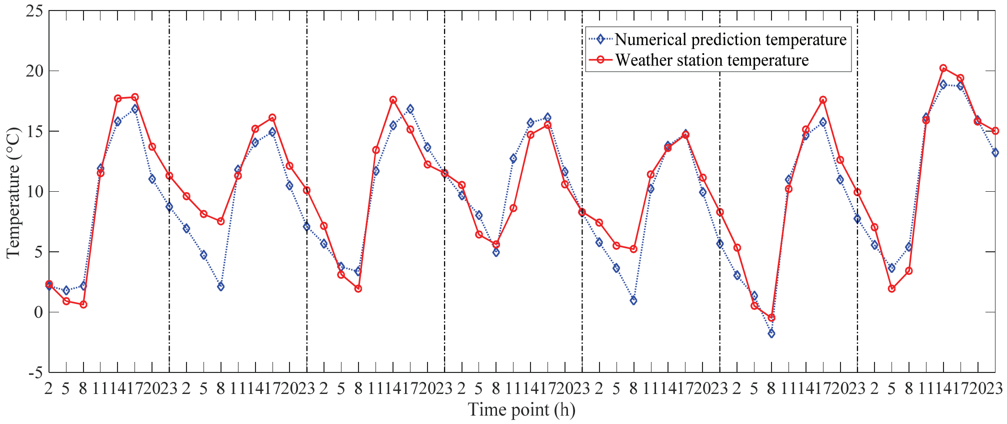

Fig. 7. Verify the accuracy of 24h temperature prediction over the next 1 day.

5.2 Analysis of Specific Transmission Line

In this paper, the GRAPES and GIS are used in the study of the application of DTR of the 750 kV high voltage transmission line in Shaanxi Province. The geographical span of the line starts from Yuheng, through Luochuan, and finally to Xinyi, which is a total length of nearly 400 km. Fig. 8 shows the geographic information in ArcGIS of the specific line.

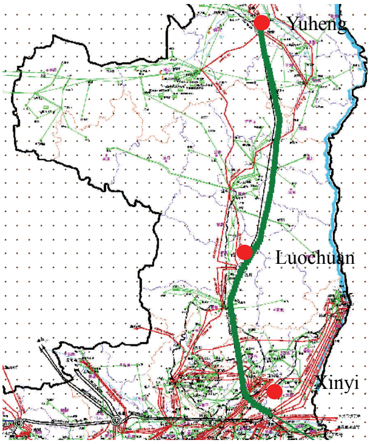

Fig. 8. A 750-kV AC transmission line in Shaanxi Province.

The type of overhead transmission line is 6 × LGJ-400/50. Meanwhile, the average elevation in Shaanxi is 1,027 m and the average latitude is 35.775°. In addition, the traditional STR of the line is 3552 A at ambient temperature of 40°C and wind speed of 0.5 m/s. Also, the GRAPES forecast data at 14:00 on June 21, 2016 (summer solstice) and December 21, 2016 (winter solstice), were used to analyze the DTR of the 750 kV transmission line.

Regarding the DTR measurement equipment, the spatial interval was generally 3–4 km. Drawing from this, the spatial step distance of the latitude and longitude along the line was selected. Also, the coordinate point sequences along the transmission line obtained by ArcGIS were 118 pairs. According to the meteorological information provided by numerical weather forecast, the DTR is calculated by using the thermal balance equation in IEEE 738 standard. The conductor temperature of the transmission line was also included in the research content.

5.2.1 Dynamic current analysis of transmission line

Fig. 9 shows the DTR forecast of the line according to the weather data of the numerical weather forecast along the overhead transmission line.

Fig. 9 indicates that the DTR on winter solstice is greater than that on summer solstice. On winter solstice, the ambient temperature is relatively low, while the wind speed is high. The DTR of the whole line is 7800 A, which is established by the minimum value in the coordinate sequences. On summer solstice, the DTR of the two locations at point 104 and 105 is significantly lower than 3552 A. By checking the actual meteorological data source, we realize that the wind speed and wind direction at two locations are too small. Therefore, we conclude that since DTR is based on actual weather condition, it may be higher than STR, or lower than STR. From different experiments in this paper, we confirm that DTR is higher than STR in most of the locations and for most of the time. Therefore, application of DTR technique can fully excavate transmission potential of transmission lines. In addition, the DTR is more suitable for the actual operation. As well, we concluded that not only the current carrying capacity of the line is excavated for most of the time, but the thermal overload that caused by STR is also avoided. Thus, the security of line operation is improved.

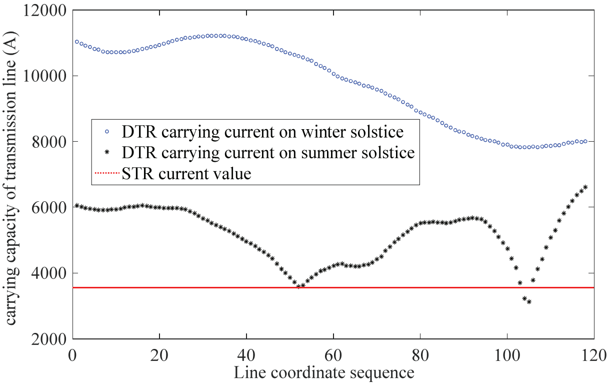

Fig. 9. Dynamic thermal rating of the line.

5.2.2 Analysis of operating temperature of transmission line

Fig. 10 shows the the conductor operating temperature of the transmission line based on the numerical weather forecast when the current of the overhead transmission line is 3552 A.

From Fig. 10, we can conclude that the conductor operating temperature of the transmission line on the winter solstice is lower than that of the summer solstice. We can also infer that the conductor temperature of most of the coordinate points is lower than boundary temperature of 70°C. On summer solstice, in particular, due to the low wind speed and wind direction, the conductor temperature of two locations at point 104 and 105 is higher than 70°C. In addition, the temperature at point 105 reaches 73°C. But on winter solstice, conductor temperature is basically lower than 23°C. In brief, we conclude that the conductor temperature is lower than 70°C for most points and for most of the time. The conductor operating temperature in winter has a greater safety margin than that in the summer.

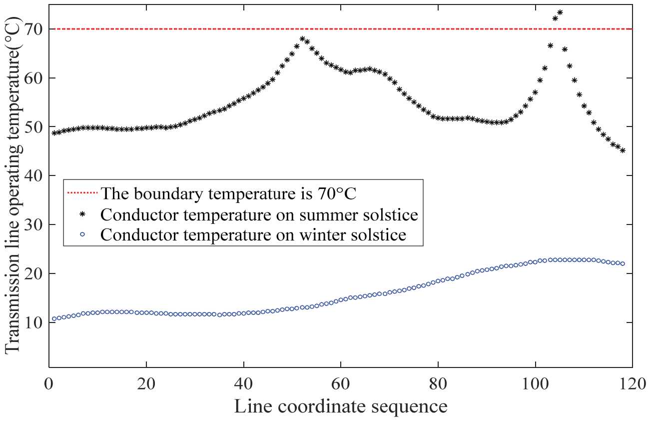

Fig. 10. Analysis of conductor temperature under current carrying of 3552 A on the summer solstice.

6. Conclusion

In this paper, we proposed the DTR of overhead lines based on GRAPES. The acquisition of forecast data, the extraction and decoding of useful information were analyzed. The accuracy of the numerical weather forecast was also verified. By using ArcGIS and GRAPES, the ambient temperature and wind speed were obtained under precise latitude and longitude coordinates. After that, the accurate DTR of the specified overhead transmission line was conducted. Through the analysis of 750 kV transmission line in Shaanxi Province, we concluded that the thermal load capacity of overhead transmission lines is constrained by conservative STRs. We also deduced that DTR can effectively tap the transmission potential of transmission lines. DTR based on GRAPES and ArcGIS can fully excavate transmission potential of transmission lines and save a great deal of hardware investment. However, the deterministic analysis of DTR was not accurate enough. In the future, taking into account the randomness of weather condition, the uncertainty of DTR based on GRAPES need to be studied in detail. In addition, to ensure that transmission network gets a safer operating environment in the condition of DTR, the effect of higher thermal rating on the aging of conductors should be studied in detail.

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