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Study on Thermal Load Capacity of Transmission Line Based on IEEE Standard

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Abstract

With the sustained and rapid development of new energy sources, the demand for electric energy is increasing day by day. However, China's energy distribution is not balanced, and the construction of transmission lines is in a serious lag behind the improvement of generating capacity. So there is an urgent need to increase the utilization of transmission capacity. The transmission capacity is mainly limited by the maximum allowable operating temperature of conductor. At present, the evaluation of transmission capacity mostly adopts the static thermal rating (STR) method under severe environment. Dynamic thermal rating (DTR) technique can improve the utilization of transmission capacity to a certain extent. In this paper, the meteorological parameters affecting the conductor temperature are analyzed with the IEEE standard thermal equivalent equation of overhead transmission lines, and the real load capacity of 220 kV transmission line is calculated with 7-year actual meteorological data in Weihai. Finally, the thermal load capacity of DTR relative to STR under given confidence is analyzed. By identifying the key parameters that affect the thermal rating and analyzing the relevant environmental parameters that affect the conductor temperature, this paper provides a theoretical basis for the wind power grid integration and grid intelligence. The results show that the thermal load potential of transmission lines can be effectively excavated by DTR, which provides a theoretical basis for improving the absorptive capacity of power grid.

Keywords

Dynamic Thermal Rating, Key Parameters, Thermal Equivalent Equation, Thermal Load Capacity, Transmission Line

1. Introduction

As the economy develops rapidly, power energy demand is also rising [1]. According to future energy assessments of China, electric energy demand will reach 7.5 TWh by 2020, and it will reach 9.73 TWh by 2030 [2]. With the continuous increase of energy consumption, carbon dioxide emissions are also increasing, which has a great negative impact on the environment [3]. Traditional energy will gradually dry up and new energy has been rapid development. At the end of 2016, wind power installed capacity is about 1.69 TWh in China. Compared with the rapid growth of new energy, especially due to the uneven

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distribution of energy in China, power grid development is still lagging behind the demand of electricity. Power grid technology and equipment are relatively backward. At the same time, due to the dense population and tight land resources in our country, it is very difficult to open up new transmission lines corridors, which aggravates the burden of the existing power grid. In response to the shortage of load in rush hours in many regional power grids, the power dispatching department usually sacrifices the reliability and safety of power grid equipment to meet the balance between supply and demand in the power market, which cases a huge security risk to the grid operation [4]. In order to meet the balance of supply and demand in the power market, it is necessary to improve the utilization of transmission capacity, making the grid more economical, safer and smooth operation [5].

In addition to thermal limits, the factors that determine the transmission capacity of the transmission components include the static stability and the node voltage level during the operation of the grid system. With the application of flexible alternating current transmission technology, the thermal limit of overhead transmission lines has gradually become a key factor to limit the load capacity of transmission components [6]. The ampacity at the maximum permissible operating temperature is the line thermal load capacity [7]. The factors affecting the thermal load capacity include ambient temperature, wind speed, wind direction, sunshine radiation, wire size and so on. Static thermal rating (STR) is the maximum current carrying value under severe environment such as low wind, high temperature and strong sunlight, and is often used as a standard to measure transmission line transmission capacity [8,9]. However, the probability of this weather condition is low. Generally, the line load is lower than the maximum allowable current, which causes the waste of transmission capacity [10]. As energy shortages become increasingly severe and power supply reliability requirements continue to increase, intelligentization has become an inevitable trend in the development of international power grids, and dynamic thermal rating (DTR) has become an important method to increase the utilization of capacity in smart grid system [11-13]. The DTR technology uses the measuring equipment to monitor the current meteorological parameters along the transmission line to dynamically evaluate the current carrying capacity. When the conductor condition is determined, the maximum transmission capacity is calculated with the real-time meteorological conditions, that is the DTR technology. Compared to STR, DTR is more accurate in estimating the real transmission capacity [14]. Under extreme conditions, DTR can make better use of the line capacity without overestimating transmission capacity [15]. The potential transmission capacity provided by DTR means that it can extend the running time of the equipment, while minimizing or postponing network reinforcement. The integration of DTR into the power system will make a higher penetration rate of renewable energy, reduce greenhouse gas emissions, and increase economic and social benefits [16-19]. The calculation criteria of DTR are CIGRE standard [20], IEEE standard and so on. The literature [21,22] compares the differences between CIGRE and IEEE standards. It is pointed out that the calculation result of IEEE standard is slightly conservative with respect to CIGRE standard, which is more suitable for practical engineering based on simplified parameter monitoring and thermal equivalent equation. The transmission capacity limitation of overhead lines is an important factor affecting the reliability of distribution network. The DTR can effectively increase the utilization of transmission capacity and improve the reliability of distribution network operation [23].

To sum up, there are many parameters affecting the thermal load capacity, so it is essential to make a quantitative analysis of DTR and its influence factors. At present, most of the literatures only study the impact of single meteorological elements on the current carrying value of overhead transmission lines and conductor temperature, and its practical value is relatively small. In this paper, based on IEEE standard thermal balance equation, we will consider several meteorological environmental factors and identify key parameters in different meteorological environment factor ranges. At the end of this paper, the real-time meteorological data of Weihai area is used to evaluate the actual ampacity and conductor temperature. The relationship between carrying capacity, conductor temperature and meteorological parameters is analyzed. This paper validates the identification correctness of key meteorological environment elements and its practical application value.

This paper is organized as follows: thermal equivalent equation of transmission line under IEEE standard is introduced in Section 2. In Section 3, we give the calculation and analysis of ampacity and conductor temperature, and the influences of ambient temperature, wind speed, wind direction, and sunshine intensity on current carrying capacity are described in detail. Case analysis based on meteorological data for 7 years in Weihai area is presented in Section 4. Conclusions are provided in Section 5.

2. Transmission Line IEEE Standard Thermal Equivalent Equation

The conductor temperature depends mainly on two factors. One is the line ampacity, the other is the surrounding environmental factors including wind speed, wind direction, sunshine intensity, and ambient temperature. In detail, the heat generated by the current passing through the line and absorbed by the sunshine radiation make conductor temperature rise. The wind and radiation due to the difference between conductor temperature and ambient temperature are main factors affecting the heat dissipation. The transient thermal equivalent equation under IEEE standard, as shown in Eq. (1), describes the dynamic change of conductor temperature with the change of ampacity and environment along the line.

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

where q_c is the convection heat dissipation, q_r is the radiation heat dissipation, q_s is the solar radiation absorption, I is the current carrying capacity, T_c is the conductor temperature, $R(T_\mathrm{c})$ is the conductor resistance at the temperature T_c, m is the conductor mass, C_p is the specific heat capacity of the conductor, and t is time. Detailed expressions for parameters in Eq. (1) are presented in [6].

When the current carrying capacity is determined and the surrounding weather is in steady state, heat absorption and heat dissipation will eventually be in equilibrium. The steady-state thermal equivalent equation is shown in Eq. (2).

$$q_\mathrm{c} + q_\mathrm{r} = q_\mathrm{s} + I^2R(T_\mathrm{c}) \tag{2}$$

Actually, because the temperature change of conductor is inconsistent with the ampacity or the ampacity changes abruptly, the transient situation occurs. The focus of this paper is the maximum allowable current carrying capacity with the weather conditions known in the steady state heat equivalent. And under the condition of known environmental meteorological parameters along the transmission line, the conductor operating temperature is considered in steady state heat balance. Therefore, this paper will mainly use the steady-state thermal equivalent equation of overhead transmission lines to analyze the related problems.

3. Calculation and Analysis of Current Carrying Value of Transmission Line

When the type of line and the meteorological parameters are known, the current carrying value can be derived by Eq. (2), as shown in Eq. (3).

$$I=\sqrt{\frac{q_{c}+q_{r}-q_{s}}{R(T_{c})}} \tag{3}$$

When the conductor temperature reaches the maximum permissible temperature (70°C in China), the current carrying value is the maximum. At present, the maximum allowable current carrying value of most overhead transmission lines in China is still obtained by STR. The boundary environmental parameters for the static heat capacity in China are shown in Table 1. Compared with STR, the DTR technology uses the actual meteorological parameters to evaluate the current carrying capacity. The DTR can effectively improve the line ampacity.

Table 1. Boundary environment parameters

Parameter	Value
Ambient temperature (℃)	40
Wind speed (m/s)	0.5
Wind direction (°)	90
Radiation coefficient	0.9
Absorption coefficient	0.9
Sunshine intensity (W/m^2)	1,000
Maximum operating temperature (℃)	70

It is worth mentioning that the conductor temperature in thermal balance state is calculated under known line current and ambient weather conditions, and it cannot be expressed as an explicit function by IEEE thermal equivalent equation. It can only be expressed as an implicit function, and solved by iterative method.

Now choose the steel core aluminum wire LGJ-400/50. The conductor diameter is 27.63 mm. The resistance temperature coefficient is 0.0039/°C (20°C). Select the geographical location of Weihai. Average altitude is 250 m. Latitude is 37.15°. The STR is 592 A. Then, according to the variation of meteorological conditions, the carrying capacity is analyzed.

3.1 Influence of Wind Speed on the Line Current Carrying Capacity

Wind speed is the main factor influencing the convection cooling. Under the condition that the other parameters keep the boundary environmental condition, the range of the wind speed change is supposed to be 0–20 m/s, and the influence of the wind speed on the carrying capacity is shown in Fig. 1.

As seen in Fig. 1, in the wind speed of 0–5 m/s section, as the wind speed increases, the ampacity increases significantly from 368 A up to 1,252 A. Relative to the wind speed of 0 m/s, the carrying capacity increased by 240%. While in the wind of 5–20 m/s section, carrying capacity increases from 1,252 A to

1,926 A. Compared with the wind speed of 5 m/s, the ampacity increased by 53.8%. The influence is declining when compared with the wind speed of 0–5 m/s. In summary, the wind speed has a great influence on the current carrying capacity.

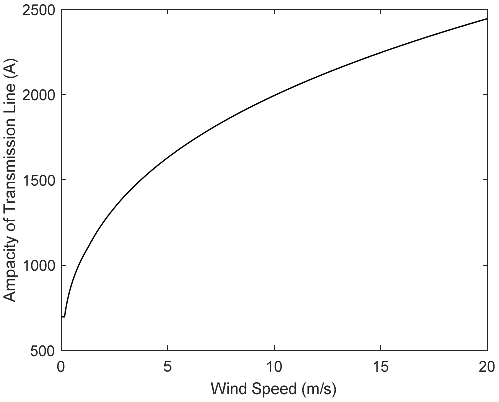

Fig. 1. Influence of wind speed on ampacity of transmission line.

3.2 Influence of Wind Direction on the Line Current Carrying Capacity

Wind direction is the influence factor on the convective cooling of the overhead transmission line. Under the condition that the other parameters keep the boundary environmental condition, the wind incidence angle along the line direction is 0°–90°, and the influence of the wind direction on the current carrying capacity is shown in Fig. 2.

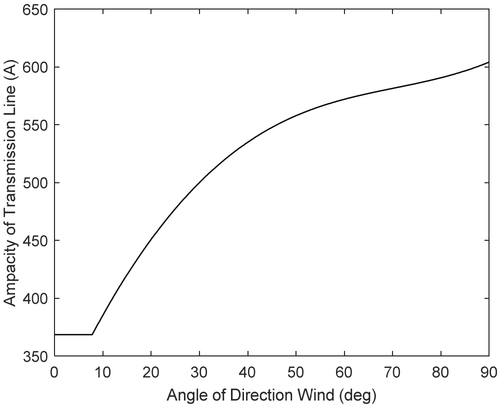

Fig. 2. Influence of wind direction on ampacity of transmission line.

By analysis of Fig. 2, it can be drawn that the transmission line capacity is fixed to a constant 368.4 A in the wind direction angle of 0°–7.8° section. The reason is that when the wind speed is 0.5 m/s, the wind incidence angle is too small, so that the effective value of wind speed is approximately 0. So only the natural convection is considered. In the wind angle of 7.8°–45°, with the increase of the angle, the carrying capacity increases obviously, from 368.4 A to 547.6 A. Compared with the wind angle of 7.8°, the carrying capacity increased by 48.64%. In the wind angle of 45°–90° section, with the angle increases, the load increases from 547.6 A up to 604.2 A. The carrying capacity increased by 10.34% with respect to the wind angle of 45°. In summary, the wind incidence angle has a great influence on the current carrying capacity.

3.3 Influence of Sunshine Intensity on the Line Current Carrying Capacity

Sunshine intensity is the influence factor on solar absorption of overhead transmission line. Under the condition that the other parameters keep the boundary environmental condition, select the sunshine intensity change range of 0–1,000 W/m^2 and the influence of sunshine intensity on current carrying capacity is shown in Fig. 3.

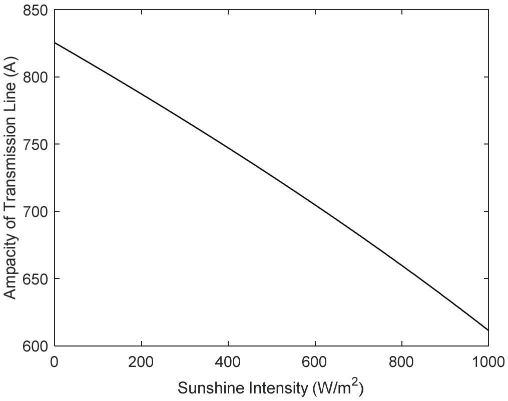

Fig. 3. Influence of sunshine intensity on ampacity of transmission line.

Fig. 3 shows that the effect of sunshine intensity on current carrying capacity is approximately linear. With the increase of the sunshine intensity, the solar absorption of the transmission line increases and the carrying capacity decreases from 825.4 A to 611.4 A. Relative to the sunshine intensity of 0 W/m^2, the carrying capacity decreased by 25.9%. In summary, the change of sunshine intensity has relatively small effect on current carrying capacity.

3.4 Influence of Ambient Temperature on the Line Current Carrying Capacity

The ambient temperature is the influence factor on the radiation dissipation. Under the condition that the other parameters keep the boundary environmental condition, the variation range of the ambient temperature is 0°C–40°C, and the effect of the ambient temperature is analyzed in Fig. 4.

Fig. 4 shows that the influence of ambient temperature on the line ampacity is approximately linearly reduced. As the ambient temperature rises from 0°C to 40°C, the difference between the conductor temperature and the ambient temperature decreases. The radiation cooling is reduced, so that the current carrying value is reduced from 1,021 A to 604.2 A. The carrying capacity is reduced by 40.8% relative to the temperature of 0°C. In summary, the ambient temperature also has a great influence on current carrying capacity.

The effects of wind speed, wind direction, sunshine intensity and ambient temperature on ampacity of transmission line are compared and quantified. Table 2 shows the difference in the carrying capacity of different environmental parameters in descending order.

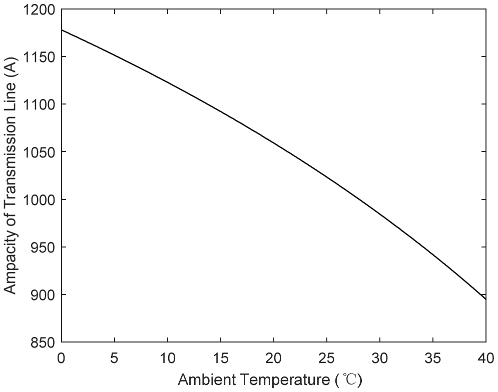

Fig. 4. Influence of ambient temperature on ampacity of transmission line.

Table 2. Influence of different environment parameters on current carrying capacity

Meteorological parameters	Parameter range of change	Current carrying difference (A)
Wind speed (m/s)	0–20	1,557.5
Ambient temperature (℃)	0–40	406.5
Wind direction (°)	0–90	235.8
Sunshine intensity (W/m^2)	0–1,000	213.9

When one meteorological parameter is studied, other parameters are maintained as the values under the boundary conditions in Table 1. The influence of wind speed on the current carrying capacity is the greatest, followed by ambient temperature, wind direction and sunshine intensity, respectively. The randomness of the wind speed is relatively large, and the distribution of the ambient temperature is relatively regular. All in all, wind speed and ambient temperature are the key parameters that affect the line ampacity.

4. Case Analysis

Through above analysis, it can be concluded that wind speed and ambient temperature are the key meteorological parameters. The real-time key meteorological parameters are from Shandong University (Weihai) observatory, from January 1, 2009 to December 31, 2015, with the interval of 10 minutes and 363,737 sets of continuous data. Moreover, the wind incidence angle is fixed at 45° and the sunshine intensity is calculated by the IEEE standard formula. The type of transmission line is ACSR-400/50 in Weihai city. Regardless of the transient temperature change process of lines, the ampacity and the conductor temperature are analyzed in the steady state.

4.1 Analysis of Thermal Load Capability

According to the calculation and analysis of the above method, corresponding to 10 minutes interval for the 7 years meteorological data, using the IEEE standard thermal equivalent equation, current carrying value of 363,737 groups can calculate. The scatter diagram is shown in Fig. 5.

Fig. 5 shows that the distribution of dynamic current carrying value of overhead transmission lines has obvious seasonal characteristics. Especially the current carrying value is high in winter and is low in summer, which is consistent with the ambient temperature distribution of meteorological elements, low temperature in winter, and high temperature in summer. As can be seen from Fig. 5, the ampacity of 363,737 groups is negatively correlated with the temperature, and the lower the temperature, the higher the current carrying value. The maximum value of transmission line current carrying capacity appears in winter, and the maximum value is 2,758 A. The minimum value appears in summer, and the minimum value is 534 A. The average current carrying capacity is 1,721 A and the standard deviation is 307.56. The data points in the scatter plot have very few points below the static load rating of 592 A. The data of the 363,737 groups' DTR is only a few arrays below the STR, which verifies that DTR can effectively improve the utilization of transmission capacity. Fig. 6 is the frequency distribution of 363,737 groups' DTR. The distribution range and operational risk of DTR values are analyzed deeply.

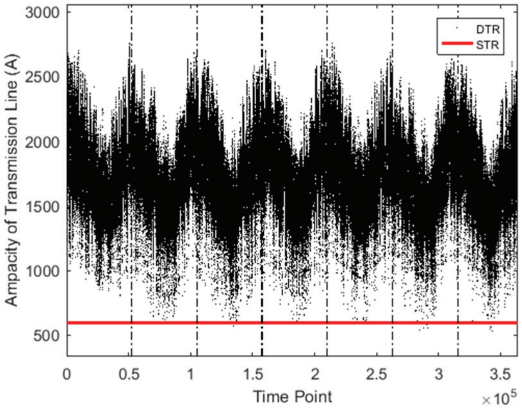

Fig. 5. Carrying current value based on seven years of meteorological data.

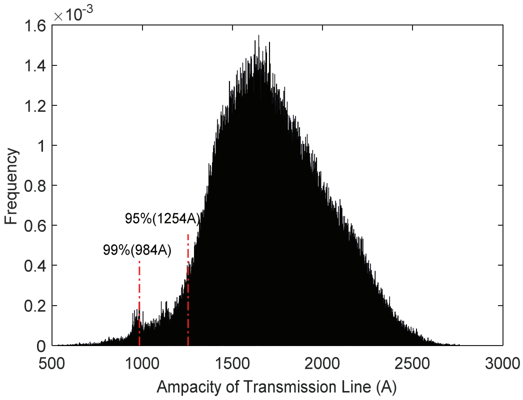

Fig. 6. Frequency distribution of current carrying values in 7 years.

As shown in Fig. 6, 99% (984 A) represents the frequency sum of data greater than 984 A is 99%, and 95% (1,254 A) represents the frequency sum of data greater than 1,254 A is 95%. In addition, the confidence interval for the transmission line current carrying capacity at 99% is [985, 2426], and the minimum value under the confidence interval is 985 A with the maximum being 2,426 A. The confidence interval for line carrying capacity at 95% is [1254, 2249]. The minimum value under the confidence interval is 1,254 A and the maximum is 2,249 A. Therefore, when the current value is 984 A and 1,254 A, the operation risk is 1% and 5%, respectively. Compared with STR, the dynamic carrying capacity increased by 66.2% and 111.8%, respectively. The results show that STR is a relatively conservative method, while DTR can effectively improve the utilization of transmission capacity.

It can be seen from the above analysis that the dynamic carrying value has obvious seasonal distribution characteristics. The typical weather conditions of the summer solstice and the winter solstice will be selected. Then, the ampacity and conductor temperature will be analyzed. Static weather conditions of the boundary environment meteorological conditions occur in the summer. Fig. 7 shows the dynamic ampacity for three consecutive days by using the actual meteorological data in Weihai on June 21, 2014 and the days before and after the summer solstice.

In theory, the winter weather conditions are more suitable for improving the ampacity than other seasons. Fig. 8 shows the dynamic ampacity for three consecutive days by using the actual meteorological data in Weihai on December 22, 2014 and the days before and after the winter solstice.

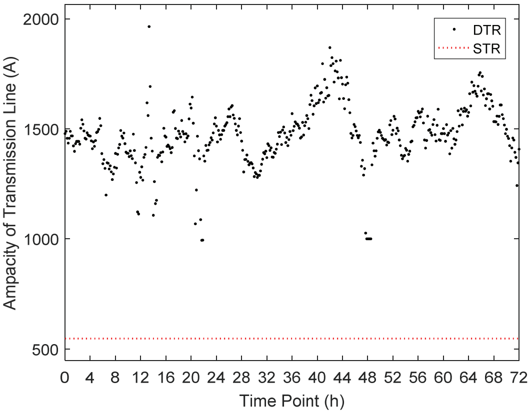

Fig. 7. Analysis of dynamic carrying capacity in summer solstice.

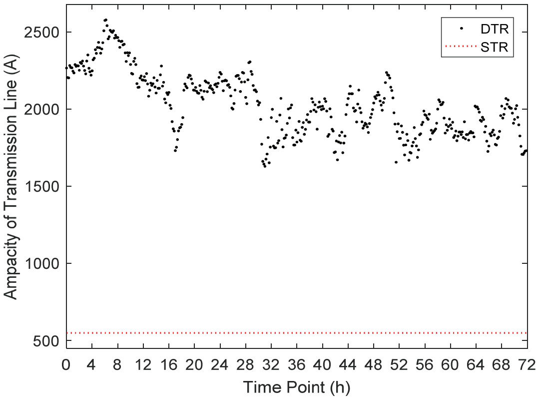

Fig. 8. Analysis of dynamic carrying capacity in winter solstice.

As can be seen from Figs. 7 and 8, the dynamic ampacity is greater than the STR of 592 A. In summer solstice, the maximum carrying capacity is 1,965 A of the 72 sets data, and the minimum value is 994 A. The average value is 1,472 A and the standard deviation is 138.85. In winter solstice, the maximum carrying capacity of 72 sets data is 2,577 A, and the minimum value is 1,628 A. The average value is 2,029 A and the standard deviation is 202.84. The whole winter dynamic current carrying value is significantly higher than that in summer. Parts of Weihai have wind farms and the application of DTR technology can provide transmission lines with higher ampacity, increase the utilization of wind power in the electricity market as well as improve the utilization of clean energy.

4.2 Analysis of Conductor Temperature

The conductor temperature under steady-state conditions is analyzed using the actual weather data of Weihai on June 21, 2014, along with the summer solstice before and after 2 days, a total of 3 consecutive days. In addition, the relationship among the conductor temperature, ambient temperature and wind speed is analyzed. The results are shown in Fig. 9. Similarly, the conductor temperature and their relationship are analyzed using the actual weather data on December 22, 2014, along with the winter solstice before and after 2 days, a total of 3 consecutive days. The results are shown in Fig. 10.

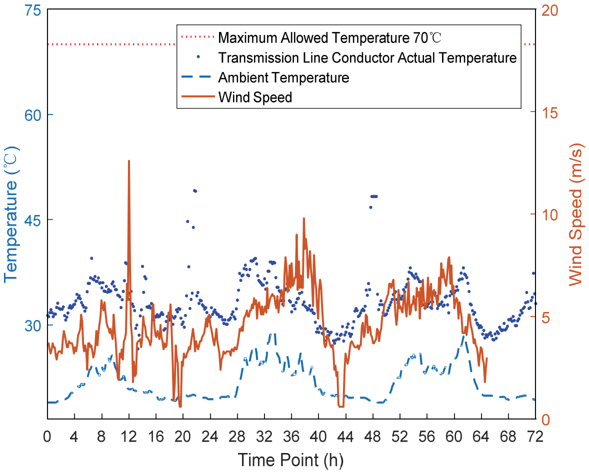

Fig. 9. Analysis of conductor temperature in summer solstice.

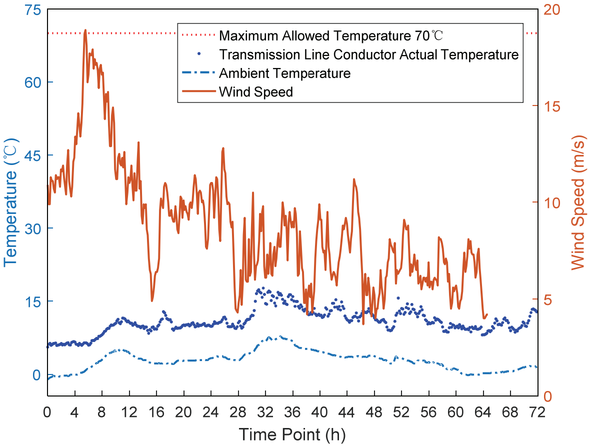

Fig. 10. Analysis of conductor temperature in winter solstice.

It can be drawn from Figs. 9 and 10 that when the ampacity is 592 A, the conductor temperature is much smaller than the maximum allowed temperature of 70°C. The conductor temperature is about 15°C in winter, while it is about 40°C in summer. Overall, the winter and summer transmission line conductor operating temperature trend is basically consistent with the ambient temperature trend. The environment temperature is relatively high in summer, and the summer wind speed is relatively lower than winter. Come to the conclusion that if the wind speed is small the conductor temperature is relatively high. The winter environment temperature is lower, but the wind speed is mostly more than 5m/s. Therefore, the conductor operating temperature relative to the summer, there are not many isolated conductor high temperature points. The above results well validate that transmission line conductor operating temperature and ambient temperature is a positive correlation, but with the size of the wind speed is negatively correlated, which is consistent with the principle of heat absorption and heat dissipation of the transmission line. In summary, the conductor operating temperature for overhead transmission lines has a great safety margin and the use of dynamic current carrying value will be able to effectively tap the thermal load potential of transmission lines.

5. Conclusion

In this paper, first, we introduce the IEEE standard steady-state thermal equivalent equation of transmission lines, and analyze the main factors influencing the transmission line conductor. We study the method of calculating the current carrying value by using the IEEE thermal equivalent equation and the transmission line conductor operating temperature under the given meteorological parameters. Secondly, we analyze separately the ambient temperature, wind speed, wind incidence angle, and sunshine intensity which effect the line ampacity. The key meteorological factors are found as wind speed and ambient temperature. Then this paper analyzes the actual ampacity of 220 kV overhead transmission lines in Weihai area, and analyzes the thermal load capacity of DTR relative to STR under given confidence interval. Finally, the actual ampacity on summer solstice day and winter solstice day in 2014 as well as the transmission line conductor operating temperature are analyzed correspondingly. The results show that the carrying current capacity of overhead transmission line in Weihai area is too conservative under STR, and DTR can effectively excavated the thermal load potential of transmission lines. Dynamic current carrying capacity can better reflect the transmission capacity. The DTR is affected by many uncertain factors. In future work, it will be devoted to studying the uncertainty of conductor temperature, the uncertainty of system power flow and the operation risk of grid capacity increase. By combining the analysis method of this paper, dispatchers are provided with operational risk information of transmission line, and combined with load forecasting technology, intelligent load dispatching can be carried out better.

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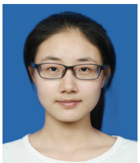

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