
Analysis on Ampacity of Overhead Transmission Lines Being Operated

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Abstract

Dynamic thermal rating (DTR) system is an effective method to improve the capacity of existing overhead line. According to the methodology based on CIGRE (International Council on Large Electric systems) standard, ampacity values under steady-state heating balance can be calculated from ambient environmental conditions. In this study, simulation analysis of relations between parameters and ampacity is described as functional dependence, which can provide an effective basis for the design and research of overhead transmission lines. The simulation of ampacity variation in different rating scales is described in this paper, which are determined from real-time meteorological data and conductor state parameters. To test the performance of DTR in different rating scales, capacity improvement and risk level are presented. And the experimental results show that the capacity of transmission line by using DTR has significant improvement, with low probability of risk. The information of this study has an important reference value to the operation management of power grid.

Keywords

Ampacity, Dynamic Thermal Rating, Rating Scales, Risk Level, Transmission Line

1. Introduction

With economic development and the growth in power demand, power transmission lines are often used inefficiently. In order to ensure safe operation and keep the structure of existing transmission line unchanged, it becomes a hot topic to further tap the potential of power grid through the analysis of line capacity [1].

In power system, an important constraint of transmission expansion is the thermal limit of overhead line. The conductor will cause irreparable damage when the heat generated by the current run above the thermal limit. To prevent problems caused by thermal overload, it is necessary to set the maximum current at less risk of overheating in accordance with the carrying capacity. Carrying capacity is the main parameter of the line design and operation, and the static thermal rating (STR) is determined by using the worst set of ambient weather conditions and unified regional standard [2]. This value is the maximum allowable current under the conservative meteorological conditions, which makes lower transmission efficiency of the overhead line.

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The dynamic thermal rating (DTR) was proposed by Davis [3,4], which is based on the study of the transmission capacity in real time. Compared to the STR system, the potential capacity of transmission line can be explored effectively by using real-time weather conditions in DTR system [5]. In DTR system, the measuring devices and monitoring systems have been installed along the lines, which lead real-time measurement of the conductor temperature and meteorological inputs. Sensitivity of the effect of the conductor parameters and meteorological inputs on the line ampacity is analyzed in this study. The information can provide an effective basis for the design and research of overhead transmission lines [6]. This paper makes three contributions. First, we conduct the simulation analysis of relation between relevant parameters and conductor ampacity. Second, we propose the variation range and mean value of ampacity in different rating scales of Weihai by considering key parameters. Third, we test the capacity improvement and risk level of the conductor under the static and dynamic way.

The content of this paper is organized as follows: in Section 2, we review the methodology of conductor ampacity calculation described in CIGRE (International Council on Large Electric systems) standard. Relations between parameters and ampacity, and the capacity of transmission line in different rating scales are described in Sections 3. In Section 4, we present the line capacity improvement and risk tolerance levels in different rating scales, including STR and DTR. Section 5 gives the conclusion and research work that should be carried out in the future.

2. Brief Review of the Line Rating Model

Two representative methods of solving transmission line ampacity are IEEE standard and CIGRE standard. In most cases, the difference between the two standards is less than 1% and the CIGRE standard is more suitable for calculating the ampacity based on real-time environment [7]. In this paper, the calculation and analysis are established on the basis of CIGRE standard.

Assuming that the transmission line is uniform, the steady-state heating balance of the overhead transmission line is described as in the following equation

$$q_1 + q_s = q_c + q_r \quad (1)$$

where q_1 and q_s are, respectively, the heat rate generated by the current and the solar heat rate absorbed by the conductor. q_c is the convective heat loss and q_r is the radiated heat loss. In CIGRE standard, the evaporation heat loss, corona loss and other minor amount are neglected.

The heat generated by the current is the main factor for the temperature rise of the conductor. For conductor containing iron, the joule heat caused by the current is calculated as in the following equation

$$q_1 = I_{dc}^2 R_{dc} [1 + \alpha(T_c - 20)] \quad (2)$$

where I_{dc} is the DC current and R_{dc} is the DC resistance. α is the temperature coefficient of conductor resistance at 20°C and T_c is the conductor temperature.

For the unit length of the conductor, the solar heat gain is calculated as in the following equation

$$q_s = \alpha_s D [I_D (\sin \eta + \frac{\pi}{2} F \sin H_s) + B] \quad (3)$$

where

$$H_s = \arcsin(\sin \phi \sin \delta_s + \cos \phi \cos \delta_s \cos Z) \quad (4)$$

$$I_D = 1280 \sin H_s / (\sin H_s + 0.314) \quad (5)$$

$$\delta_s = 23.4 \sin[360^\circ(284 + N) / 365] \quad (6)$$

$$\eta = \arccos[\cos H_s \cos(\gamma_s - \gamma_c)] \quad (7)$$

$$\gamma_s = \arcsin[\cos \delta_s \sin Z / \cos H_s] \quad (8)$$

$$B = (\pi / 2) I_d (1 + F) \quad (9)$$

where D is the conductor diameter, α_s is the solar absorptivity, H_s is the solar elevation angle, γ_s and γ_c are the solar azimuth and conductor azimuth, respectively, δ_s is the latitude angle, N is the number of days in a year, Z is the solar time division angle, I_D is the direct solar heat, I_d is the solar radiated heat and F is the albedo.

Convection heat loss is divided into two types of forced convection and natural convection [8]. In the case of forced convection, the convective heat loss is calculated as in the following equation

$$q_c = \pi \lambda_f (T_c - T_a) N_u \quad (10)$$

where

$$N_u = B_1 (R_e)^n, \lambda_f = 2.42 \times 10^{-2} + 7.2 \times 10^{-5} T_f \quad (11)$$

$$R_e = D \rho_f V_w / \mu_f, \rho_f = \rho_0 \exp(-1.16 \times 10^{-4} y) \quad (12)$$

$$\mu_f = (1.32 \times 10^{-5} + 9.5 \times 10^{-8} T_f) \rho_0, T_f = 0.5(T_c + T_a) \quad (13)$$

in the above equations, T_a is the ambient temperature, λ_f is the thermal conductivity of air, N_u is the nusselt number, B_1 and n depend on the Reynolds number and the roughness of the surface, ρ_0 is the air density of sea level, y is the altitude.

In the case of natural convection, N_u depends on the Prandtl number (P_r) and Grashof number (G_r). The calculation equation is described as follows

$$N_u = A_2 (G_r P_r)^{m_2} \quad (14)$$

$$P_r = 0.715 - 2.5 \times 10^{-4} T_f, G_r = D^3 \rho_o^2 (T_c - T_a) g / [(T_f + 273) \mu_f^2] \quad (15)$$

Radiated heat loss is influenced by the diameter and the conductor surface. The radiated heat loss is calculated as in the following equation

$$q_r = \pi D \varepsilon \sigma_B [(T_c + 273)^4 - (T_a + 273)^4] \quad (16)$$

in the above equation, ε is the emissivity, σ_B is the Stefan-Boltzmann constant and the value is $5.67 \times 10^{-8} W / (m^2 \cdot K^4)$.

3. Ampacity Analysis under Steady-State Heating Balance

3.1 Parameter Setting

Factors affecting the ampacity of the transmission line are divided into two categories: one is the conductor state parameters, including the conductor diameter, maximum allowable conductor temperature, emissivity and solar absorptivity of conductor, altitude and latitude, the second is environmental parameters, including wind speed, wind angle, the ambient temperature and solar angle [9]. The conductor state parameters and meteorological data are different in various regions. Therefore, the ampacity analysis is based on the actual parameters in each region. In this paper, the research of Weihai city in Shandong province is presented, we select the LGJ-400/50 model of aluminium conductors steel-reinforced (ACSR) and obtain the meteorological data (2011–2015) from the China Meteorological Administration. The relevant parameters are set as follows.

The conductor diameter ranges is set according to the diameter variation range of ACSR. The diameter of LGJ-10/2 model and LGJ-800/100 model are 4.50 mm and 38.98 mm respectively, so the range of conductor diameter is 4.50 to 38.98 mm. ACSR of this paper is the LGJ-400/50 model, and the diameter is 27.63 mm. The traditional ampacity is set in accordance with the 40°C air temperature, and considering the maximum allowable temperature of new conductor is above 200°C. Therefore, the allowable conductor temperature is allowed to vary within 40°C to 200°C. The maximum allowable temperature of LGJ-400/50 ACSR model is fixed at 70°C. For bright conductors, the solar absorptivity and emissivity are 0.27, and the industrial weathered conductor is 0.95. For LGJ-400/50 ACSR models, the typical values of solar absorptivity and emissivity are 0.27, 0.5, 0.7, and 0.95. The fixed values of absorptivity and emissivity are set as 0.5 and 0.7, respectively in this study. The altitude range of Weihai City is 0 to 200 m, and Weihai City at 37° north latitude. The latitude angle changes throughout the year, the winter solstice is $-23^\circ 27'$, the summer solstice is $23^\circ 27'$, the vernal equinox and autumnal equinox is 0° . The autumnal equinox is selected for this study. According to the data provided by the China Meteorological Administration, the change range of wind speed in Weihai is 2.5 to 20.3 m/s and the average wind speed data is 6.1 m/s. The range of environmental temperature is $-8.3^\circ C$ to $34.3^\circ C$ and the average ambient temperature is $27.5^\circ C$. In this paper, the mean value of wind speed and temperature is used as the fixed value in sensitivity analysis. The number of days in a year set as the autumnal equinox and this day is 262nd days. The solar time division angle changes from 0° at 12 noon, 15° changes for each hour after 12 noon, and the range is all hours of the day and night.

3.2 Results of Parameters Influence

In this study, we make one of the parameters changes within the range, and other parameters remain fixed value. The influence results of relevant parameters on ampacity are summarized in Table 1. The ampacity difference is calculated as the maximum and minimum values of input. Meteorological inputs,

such as the ambient temperature, wind speed and angle, have very high impact on ampacity. Among conductor state inputs, allowable conductor temperature and conductor diameter have great influence on ampacity. Other parameters with low degree of influence on ampacity, including latitude angle, number of days and altitude [9,10].

Table 1. Influence of parameters on ampacity

Parameter	Fixed value	Range	Ampacity difference (A)	Influence
Allowable conductor temperature (°C)	70	40 to 200	1739.5	
Conductor diameter (mm)	27.63	4.50 to 38.98	619.2	
Wind speed (m/s)	6.1	2.5 to 20.3	538.4	High
Ambient temperature (°C)	27.5	-8.3 to 34.4	482.1	
Wind angle (°)	30	0 to 90	455.7	
Absorptivity	0.5	0.27, 0.5, 0.7, 0.95	86.9	Medium
Emissivity	0.7	0.27, 0.5, 0.7, 0.95	85.0	
Solar time division angle (°)	30	-180 to 180	50.1	
Latitude angle (°)	0	-23°27' to 23°27'	23.8	Low
Number of days in a year	262	1 to 365	7.3	
Altitude (m)	200	0 to 200	6.0	

3.3 Simulation Analysis of the Relation between Parameters and Ampacity

For the purpose of this study, we used MATLAB software to simulate and analyze several parameters which have high level of influence. Maximum allowable conductor temperature has highest impact on ampacity value. This functional relation, for different absorptivity and emissivity values, are captured in Figs. 1 and 2. Ampacity increases obviously with the increase of allowable conductor temperature. When the allowable conductor temperature is increased from 40°C to 100°C, the ampacity rises more rapidly. Ampacity value reaches the maximum when both of absorptivity and emissivity are 0.95 while conductor temperature is fixed value. When the conductor temperature is below 80°C, absorptivity has greater influence than emissivity on ampacity, and emissivity has much more effect while the temperature exceeds 80°C.

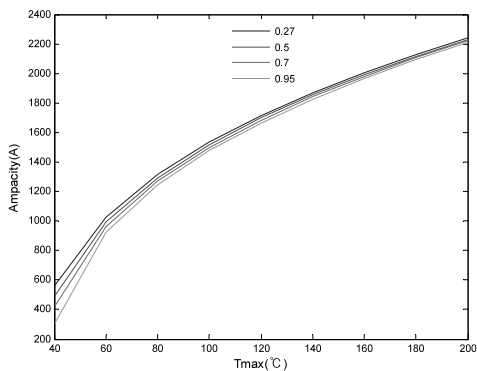


Fig. 1. Relation between conductor temperature and ampacity for various absorptivity.

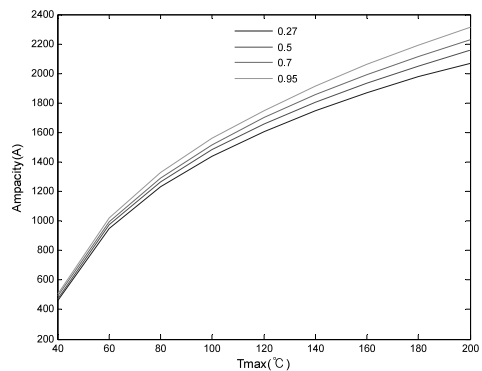


Fig. 2. Relation between conductor temperature and ampacity for various emissivity.

Figs. 3 and 4 show the dependences on wind speed and wind angle, respectively. As observed from two figures, their variation trends are almost similar. The increase of wind speed leads to the rapid increase of ampacity. Difference in ampacity reaches 538 A with wind speed rising from 3 m/s to 20 m/s. In contrast, the influence of wind angle on ampacity is lower. This shows that environment without wind is not conducive to conductor cooling.

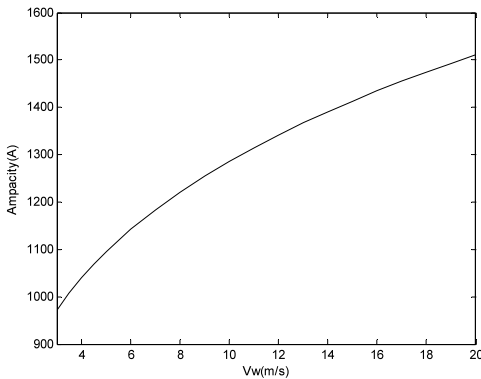


Fig. 3. Impacts of wind speed on ampacity.

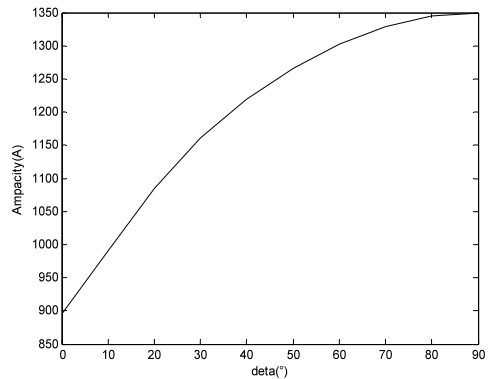


Fig. 4. Impacts of wind angle on ampacity.

Fig. 5 indicates the relation between ampacity and ambient temperature. Ambient temperature is an environmental parameter that must be taken into account, because convective heat loss and radiated heat loss are related to ambient temperature. In the case of higher ambient temperature, the current carrying capacity of transmission line is worse in the case of higher ambient temperature. Ampacity can be increased by about 11% when the ambient temperature drops from 32°C to 22°C, and it can be increased by 20% when the temperature is around 12°C. The relation between ampacity and conductor diameter is depicted in Fig. 6. With the increase of conductor diameter, the ampacity also increases significantly.

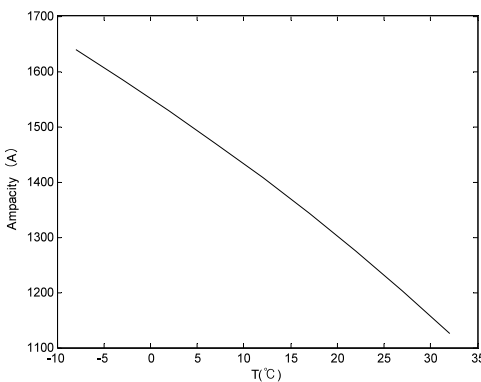


Fig. 1. Relation between conductor temperature and ampacity for various absorptivity.

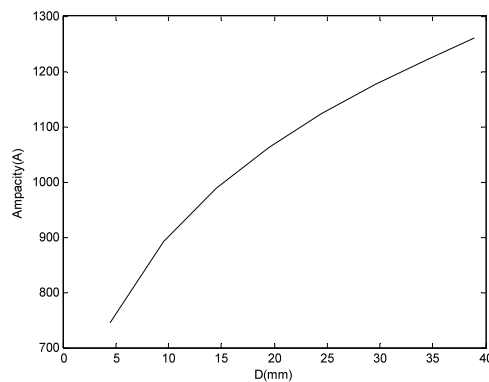


Fig. 2. Relation between conductor temperature and ampacity for various emissivity.

The functional relations of other parameters with low influence, solar time division angle, latitude angle, annual sunshine days and altitude, are not described. Among them, the function image of solar

time division angle is symmetric about 12 noon. For overhead transmission lines in Weihai, influence of the rest parameters can be neglected [10].

3.4 Comparison of Ampacity in Different Rating Scales

The ampacity value depends on the environmental conditions when the conductor body is determined as a certain model. The environmental conditions, however, are quite varied at different times of the year. Therefore, this section studies the effectiveness and practicability of DTR by analyzing the ampacity in different rating scales.

First of all, two kind of commonly used static thermal rating are given for comparison: nominal static thermal rating (STR_{nom}) and conservative static thermal rating (STR_{con}) [11].

- The STR_{nom} depends only on the type of conductor and is defined by the manufacturer. This rating is usually provided for the ambient temperature of 25°C, the conductor temperature of 75°C, the wind speed of 0.5 m/s and coefficient of emissivity and absorptivity is 0.5. The nominal rating value of the LGJ-400/50 conductor is calculated to be 1093.7 A.
- The STR_{con} is obtained by selecting conservative values in the worst-case scenario for the ambient temperature, solar radiation, and wind speed. These values are then used in steady state calculations to determine the current that yields the maximum allowable conductor temperature. This rating is provided for the ambient temperature of 33°C, the conductor temperature of 70°C, the wind speed of 5 m/s. The emissivity varies from 0.1 to 0.5, and the absorptivity from 0.1 to 0.6, for bright conductors. This rating value of the LGJ-400/50 conductor is 1045.2 A.

The meteorological data of Weihai from 2011 to 2015 are selected to calculate the ampacity values. And the variation range and mean value of ampacity in different rating scales are presented in this study, which are determined from real-time meteorological data. From the previous section, function relations between ampacity and key parameters including wind speed, wind angle and ambient temperature are almost linear. Therefore, the ampacity values of conductor reach the maximum when the key parameters in extreme values. Fig. 7 depicts the maximum and minimum values of ampacity during the four seasons of the year. Environmental differences in different seasons lead to a great change in ampacity of each season [10]. As can be observed, capacity of the overhead line is much higher during the winter with lower ambient temperature and greater wind speed. At the same time, STR_{nom} and STR_{con} are calculated under the condition that ambient temperature is higher than most time in a year [11]. So the rated capacities of STR_{nom} and STR_{con} within a year are generally less than the actual transmission capacity of lines. Compared with nominal value, the maximum value of ampacity even has 70% improvement in winter, which fully reveals that the transmission potential of lines is great.

The calculated ranges of monthly, weekly and daily ampacity are demonstrated in Figs. 8–10. As can be seen, transmission capacities determined by these rating scales are also significantly greater than the nominal value and conservative value. In practical applications, complex monitoring devices and communication systems are often required to determine the ampacity in hourly rating or daily rating [12]. For these reasons, a possible alternative is to implement weekly or monthly and even seasonal DTR system, rather than the hourly DTR with a heavy cost. For example, environment conditions in January are conducive to the heat dissipation of the wire, which can provide favorable external conditions for the improvement of transmission capacity in January.

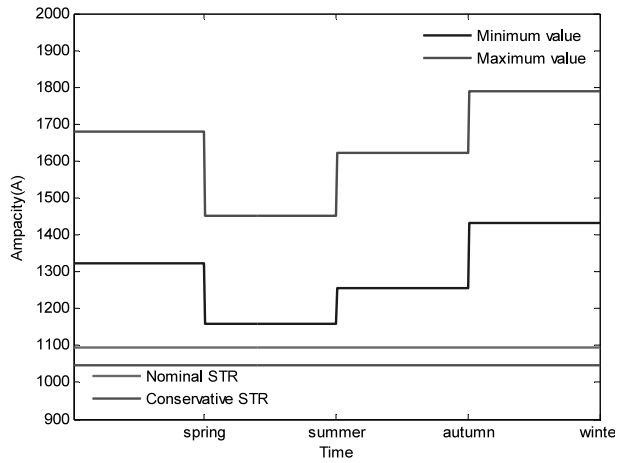


Fig. 7. Variation range of ampacity in seasonal rating.

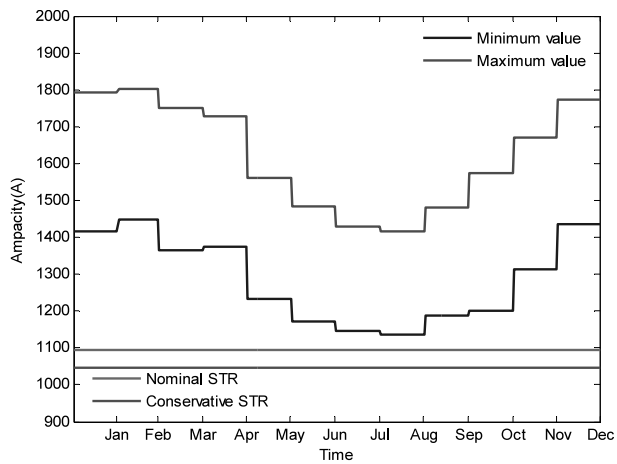


Fig. 8. Variation range of ampacity in monthly rating.

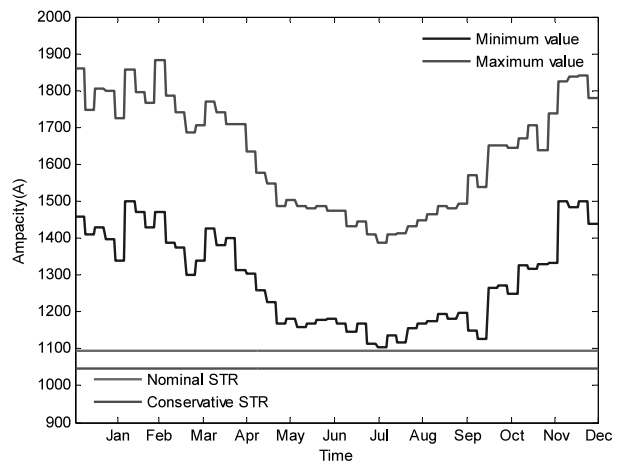


Fig. 9. Variation range of ampacity in weekly rating.

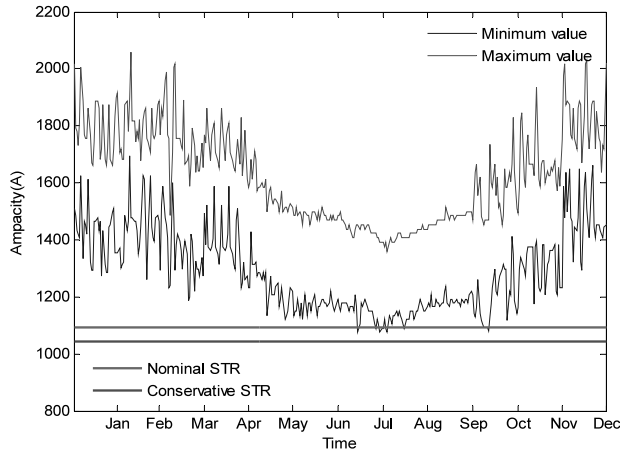


Fig. 10. Variation range of ampacity in daily rating.

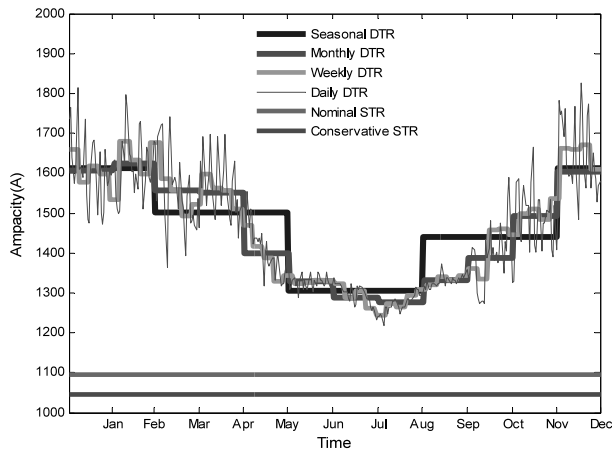


Fig. 11. Mean values of ampacity in different rating scales.

Fig. 11 shows that the value differences of transmission capacity in different rating scales. The capacity values of different months in a year are not same, and the difference reaches about 800 A in the most extreme case. In addition, the ampacity values at the same time in different rating scales are also varied. As it can be seen, ampacity values reach the peak in January and December, and the values at lowest point in June and July. Hence, the carrying capacity can be improved at the peak of the ampacity by using appropriate rating. However, it also brings a significant risk of thermal load, such as reduction of conductor strength, increase of sag and heat of hard wares. To solve these problems, real-time monitoring equipment and temperature measurement system of the line can be used to minimize the risk tolerance levels [5].

4. Capacity Improvements and Risk Levels

The results of ratings comparison show that the conductor carrying capacity is largely limited by the STR_{nom} and STR_{con} . In this section, we discuss the way to improve the capacity of transmission line,

including the static and dynamic way to improve the capacity. To reduce the risks caused by overload, the further analysis of capacity improvement and acceptable risk tolerance levels are performed in this section. Both the static and dynamic way are expected to improve transmission capacity, and increased ampacity value is calculated using the line rating model in different rating schemes [12,13]. To quantify the risk level of the STR and DTR schemes in each rating scale, the risk tolerance level is calculated as in (17)

$$R_l = \frac{X_{(I-I_a)}}{X_I} \quad (17)$$

where X_I is the number of days in a certain rating scale, $X_{(I-I_a)}$ is the number of excessive days which ampacity in a certain rating scale is greater than daily rating.

4.1 Analysis of STR

The ampacity values, capacity improvements and risk level of the conductor by using STR are shown in Table 2. To verify the function of STR system, each rating scale is selected as a single ampacity value for the full year to calculate the increased capacity and risk level based on STR. The carrying capacity, determined by STR_{nom} , is approximately 94% of the minimum seasonal ampacity, and 85% of the average seasonal ampacity. Comparing the seasonal ampacity to STR_{con} , the differences in capacity are even greater. As can be seen from Table 2, the implement of monthly rating increases the average capacity by 8%, and reaches 23% by using the mean value of monthly ampacity, compared to the capacity of STR_{con} . Similarly, the use of weekly rating also has a significant capacity increase effect. However, for the seasonal rating, the risk level is more than 10%, and the risk tolerance level of conductor is less than 5% in general. Thus, the risk of thermal overload may be triggered by using seasonal rating. At this point, the aging of line, the increase of line sag and other security problems must be considered in the operation of transmission lines [13,14].

Table 2. Performance of system by using STR

Rating scheme	Seasonal rating	Month rating	Week rating	Day rating
Minimum value (A)	1159.9	1135.6	1103.2	1074.6
Mean value (A)	1293.5	1284.3	1288.0	1288.0
Minimum value capacity increase (% of STR_{nom})	6.1	3.8	0.8	0.5
Minimum value capacity increase (% of STR_{con})	11.0	8.6	5.5	5.2
Mean value capacity increase (% of STR_{nom})	18.3	17.4	17.8	17.8
Mean value capacity increase (% of STR_{con})	23.8	22.9	23.2	23.2
Minimum value risk level (% of time)	1.1	0.6	0	0
Mean value risk level (% of time)	12.1	9.1	11.5	11.5

Table 3. Performance of seasonal rating scheme by using DTR

Seasonal rating	Spring rating	Summer rating	Autumn rating	Winter rating
Minimum value (A)	1324.5	1159.9	1256.1	1433.5
Mean value (A)	1502.7	1306.0	1439.2	1611.6
Minimum value capacity increase (% of STR_{nom})	21.1	6.1	14.9	31.1
Minimum value capacity increase (% of STR_{con})	26.7	11.0	20.2	37.2
Mean value capacity increase (% of STR_{nom})	37.4	19.4	31.6	47.4
Mean value capacity increase (% of STR_{con})	43.8	25.0	37.7	54.2
Minimum value risk level (% of time)	4.4	1.1	0	1.1
Mean value risk level (% of time)	48.4	49.4	72.5	52.7

4.2 Analysis of DTR

According to the values illustrated in Fig. 7 and Fig. 11, minimum and mean value of ampacity are used as each season rating under the condition of DTR. And the increased capacity and risk level by considering seasonal minimum ampacity with the DTR are presented in Table 3. As can be observed, the use of minimum ampacity with the DTR is ideal for both the capacity improvement and risk reduction. The capacity improvement, provided by seasonal rating with the DTR, reaches at 10% to 37%. At the same time, the risk tolerance level of conductor is controlled within a reasonable range of 5%. In contrast, the risk level of average ampacity is beyond the normal range, which compromises the safety of line operation. Among these ratings, the capacity in winter by using winter rating has greatest improvement when DTR is applied. Therefore, it is feasible to determine the conductor ampacity based on the minimum value of seasonal rating with the DTR.

As observed from Tables 2 and 3, it is feasible to determine the transmission capacity of line by using the minimum ampacity in different rating scales. Table 4 shows the capacity improvement and risk level by using monthly minimum ampacity with the DTR system. Under the condition of DTR, the transmission capacity of overhead line has significant improvement of each month, and with low degree of risk. As shown in Table 4, there is no risk of thermal overload in most months, and the capacity improvements of most months reach about 20%.

Table 4. Performance of monthly rating by using DTR

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Minimum value (A)	1416.9	1448.0	1363.6	1375.9	1233.9	1171.4	1146.2	1135.6	1186.6	1200.2	1312.0	1435.7
Capacity increase (% of STR_{nom})	29.6	32.4	24.7	25.8	12.8	7.1	4.8	3.8	8.5	9.7	20	31.3
Capacity increase (% of STR_{con})	35.6	38.5	30.5	31.6	18.1	12.1	9.7	8.6	13.5	14.8	25.5	37.4
Risk level (% of time)	3.2	0	0	3.3	0	0	0	0	0	0	3.3	3.2

The effect of increasing capacity and degree of risk level can be used to evaluate the performance of the STR and DTR system [10]. Compared to the STR system, conductor ampacity is divided more detailed by using DTR, according to the actual transmission capacity of each month. Thus, the effect of capacity increase by considering DTR is more significant than the STR system, and the DTR system has more safety performance. However, the complexity of the DTR system is also different in different rating scales. When the rating scale of the DTR is divided fine enough, the monitoring equipment has to become extremely complex while the current carrying capacity is greatly improved [15]. When the STR is considered to determine the ampacity, the potential capacity of conductor will not be fully excavated [13]. All factors affecting the rating implementation, including the regional environment, the economy of line operation and the complexity of monitoring system, should be considered in the practical application. By this way, the economic and practical rating scheme is selected to determine the line ampacity [15,16].

5. Conclusion and Future Work

In this paper, we have constructed a sensitivity simulator to analyze the relations between inputs and conductor ampacity. The presented results show that wind speed and ambient temperature have great influence on the carrying capacity of conductor. According to the change of the key meteorological inputs, the simulation of ampacity variation in different rating scales is obtained. This information can effectively help improve the transmission capacity of existing overhead lines. By this way, the STR and DTR systems are compared in the aspects of capacity enlargement and risk tolerance level. The obtained results indicate that the method based on the DTR systems possesses higher security and better improvement than the STR method. The DTR systems can be used for the operation of power system and prolonging the service life of the transmission line.

In the future work, we intend to establish the probability model of regional environment parameters with time varying. By this work, we can forecast the tendency of conductor current carrying capacity by predicting the trend of meteorological data in short time. This can be used to improve the line throughput without affecting the line safe operation, and provide time for monitoring and scheduling in an emergency.

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