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Power Cable Ampacity and Influential Factors Analysis under Operation

Qiang Tong*, Jianping Qi*, Yanling Wang*, Likai Liang*, Xiangxing Meng**, and Qiang Zhang***

Abstract

With the increasing of urban electricity demand, making the most use of the power cable carrying capacity has become an important task in power grid system. Contrary to the rated ampacity obtained under extremely conservative conditions, this paper presents the various steady value of cable ampacity by using the changing surrounding parameters under operation, which is based on cable ampacity calculation equation under the IEC-60287 standard. To some degree, the cable ampacity analysis of actual surroundings improves the transmission capacity of cables. This paper reveals the factors that influence cable ampacity such as insulating layer thickness, allowable long-term conductor temperature, the ambient temperature, soil thermal resistance coefficient, and so on, then gives the class of the influence of these parameters on the ampacity, which plays a great role in accurately calculating the real-time ampacity and improving the utilization rate of cable in the complex external environment condition. Furthermore, the transient thermal rating of the cable is analyzed in this paper, and temperature variation of the conductor under different overload conditions is discussed, which provides effective information for the operation and control of the system.

Keywords

Conductor Temperature, Influential Factors, Power Cable, Static Thermal Rating, Transient Temperature

1. Introduction

With the acceleration of urban construction, the use of power cable in distribution and transmission systems has grown significantly over the years with the rapid increase in demand for electric energy and increasing population density in different regions [1]. Therefore, comparing with overhead lines, the power cables have many advantages such as less damage from weather conditions (mainly lightning, and wind), greatly reduced electromagnetic fields emission. Moreover, power cables need a narrower surrounding strip compared with overhead lines, also, underground cables are safer because cables pose no shock hazard to low-flying aircraft or wildlife [2]. However, as the increasing difficulty in laying the new power cable, how to improve the existing cable carrying capacity under the safe operation conditions has the very realistic significance.

Traditionally, the power cables have been operated based on static thermal rating. The fixed rating is

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Corresponding Author: Yanling Wang (wangyanling@sdu.edu.cn)
* School of Mechanical, Electrical and Information Engineering, Shandong University, Weihai, China (tronq@sdu.edu.cn, 896090989@qq.com, {wangyanling, lianglikai}@sdu.edu.cn)
** State Grid Heilongjiang Electric Power Company Ltd, Harbin, China (32155678@qq.com)
*** Shandong Electric Power Dispatching Control Center, Jinan, China (zq8027@163.com)

usually determined using a set of conservative assumptions about the ambient operating conditions. It is established with the goal to ensure large safety margins for cable operation [3-5]. However, extreme weather conditions occur at a small risk, if viewing the carrying capacity under conservative boundary condition, the power cable real ampacity will be limited most of the time, resulting in a lower utilization of cable transmission capacity, preventing their efficient use and increasing costs of their operation [6]. Moreover, the frequent occurrence of line faults requires higher transmission capacity of the cable [7]. In order to solve these problems, some countries and regions are trying to study various steady thermal rating under many different operation circumstances, these studies have proved that the evaluation of ampacity using real-time actual weather and conductor conditions allows to transport more power that can be as much as double compared with static thermal rating in many circumstances [5]. Therefore, to an extent, it can upgrade the transmission ampacity of existing power cable in comparison to the traditional approach.

As the emergency overload situation often occurs, the safety of the cable under operation is facing a certain threat. The study of the transient transmission capacity of cable in short time when emergency happens can provides theoretical support for the cable predicting fault, thus guarantees the safe operation of the cable [8].

In this paper, we calculate the diverse steady state ampacity under different actual circumstances, and use control variate method to discuss the rank of influence of various factors related on the ampacity by specific quantitative data. The information can provide an effective basis for research of cable transmission ampacity. Moreover, we study transient thermal rating and analyze the change of conductor temperature when short-time overload happens in different over current situations, which can provide effective information for operators, improve the line transport ampacity in short time when emergency happens. Thus this will be able to win time for emergency scheduling and improve the security of the system operation [9].

This paper is organized as follows. Section 2 introduces the model of ampacity calculation, and then describes the thermal resistance, alternating current (AC) resistance, metal sheath loss, armor loss, and dielectric loss in detail. Section 3 gives the method of cable transient temperature calculation. Example results and performance analysis are presented in Section 4. Conclusions and remarks on possible further work are given finally in Section 5.

2. Calculation of Ampacity

When the working temperature of cable for a long time is given, equivalent thermal circuit can be shown in Fig. 1, which is based on the analysis on factors influencing ampacity and structure of cable.

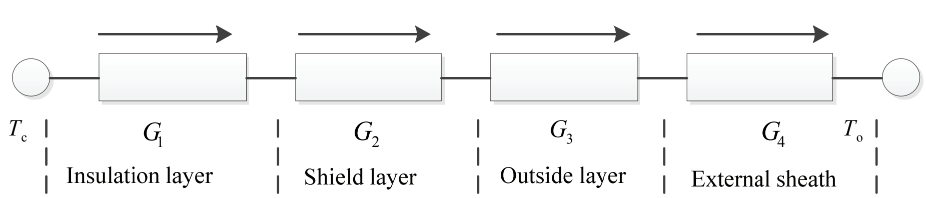

Fig. 1. Cable equivalent thermal circuit.

According to the law of energy conservation, the temperature which the cable conductor is higher than the surrounding medium should be equal to the sum of the temperature rise caused by cable current loss and the cable dielectric loss [1,5]. According to IEC standard cable thermal balance equation, the ampacity expression of single core cable under the condition of stable operation is shown as follows [2]:

$$I = \sqrt{\frac{(T_o - T_c) - W_d(\frac{1}{2}G_1 + G_2 + G_3 + G_4)}{R[G_1 + (1+\lambda_1)G_2 + (1+\lambda_1+\lambda_2)(G_3 + G_4)]}} \tag{1}$$

where I is the current of conductor, G_1, G_2, G_3, and G_4 mean insulation layer thermal resistance, shield layer thermal resistance, armor layer thermal resistance and external thermal resistance, respectively; T_o is the allowable cable conductor temperature; T_c is the temperature of the surrounding medium; W_d is the cable dielectric loss per unit length; R is the resistance per unit length at T_o; λ_1 is the ratio of the sheath loss and wire core loss; and λ_2 is the ratio of the total loss of armor and the wire core loss.

2.1 Thermal Resistance G_1, G_2, G_3, G_4

As for single core cable, insulation thermal resistance G_1 between conductor and metal sheath can be shown as follows:

$$G_1 = \frac{\rho_{T1}}{2\pi}\ln(1 + \frac{2d_1}{d_c}) \tag{2}$$

where ρ_{T1} is the thermal resistance coefficient of insulation material, d_c is the conductor diameter, d_1 is insulation layer thickness. The necessary thickness of the high-voltage XLPE cable insulation will allow the cable insulation layer withstand every possibility under the action of over voltage, which can be the basis of reliable operation [10]. If the insulation thickness is too conservative, it will increase the cost of cable, increase the cable diameter, and reduce the cable ampacity. We can deduce from the formula that the cable insulation thermal resistance G_1 will increase with the insulation layer thickness increasing. Thus, it will result in the rising of conductor temperature, and influencing cable ampacity.

Generally, shield layer is a special metal armor or shield protection layer. The shield layer thermal resistance is also the thermal resistance between sheath and armor [1,2]. With a concentric circular structure of the cable, it is assumed that the metal sheath is an isothermal surface and its thermal resistance is calculated as follows:

$$G_2 = \frac{\rho_{T2}}{2\pi}\ln(1 + \frac{2d_s}{D_s}) \tag{3}$$

where ρ_{T2} is the thermal resistance coefficient of shield material, d_s is the shield thickness, D_s is the metal sheath diameter. Shield layer is an important part for the protection of cable, the choice of composition of shield material and shield layer thickness will also directly affect the cable ampacity. It is also shown that when shield layer thickness increases, the thermal resistance of cable shield layer will also increase, which will affect the ampacity of the cable.

The main part of the external serving of the cable is the armor layer. Generally speaking, armor layer is made of the lapping of steel strip and steel wire, which is to reduce the mechanical damage of cable from the outside world and chemical etching [1]. The external serving of the cable generally has a concentric circular structure, the thermal resistance is calculated as follows:

$$G_3 = \frac{\rho_{T3}}{2\pi}\ln(1+\frac{2d}{D'_a}) \tag{4}$$

where ρ_{T3} is the thermal resistance coefficient of armor layer, d is the thickness of armor layer thickness, D'_a is the outside diameter of armor layer. As is shown that when the armor layer thickness increases, the thermal resistance of cable armor layer will also increase, which will reduce cable ampacity.

The value of external thermal resistance depends on the environment where the cable lays. External thermal insulation of single cable which is buried isolate is given as follows:

$$G_4 = \frac{\rho_{T4}}{2\pi}\ln(u+\sqrt{u^2-1}),\ u = \frac{2L}{D_e} \tag{5}$$

where ρ_{T4} is the soil thermal resistance coefficient, L is for the distance between cable axis and the surface, D_e is the cable diameter. Soil thermal resistance coefficient directly affects the buried cable heat dissipation. The soil thermal resistance will change along with the change of soil water content. When cable is running, the heat can make the soil moisture migrate, which can affect soil thermal resistance. So soil thermal resistance coefficient is not a static value [10]. In the analysis of cable carrying ampacity, the thermal conductivity of soil in a certain area is regarded as the fixed value and different regional soil coefficient of thermal conductivity also differs. Generally, wet natural soil thermal resistance coefficient is 0.6–0.9 k·m/W, general soil is 0.9–1.2 k·m/W, and dry soil is 1.2–1.5 k·m/W.

2.2. Alternating Current Resistance

Conductor heating is one of the important reasons for the rising of conductor temperature [1,7]. As the temperature rises, the resistance also increases, along with increasing in conductor heat, which will cause the cable temperature rise. As for single core cable, the direct-current (DC) resistance R_t of unit length of cable conductor and AC resistance R can be obtained as follows:

$$R_t = R_{20}[1+\alpha(T_o - 20)] \tag{6}$$

$$R = R_t(1+Y_s+Y_p) \tag{7}$$

where R_{20} is the maximum DC resistance of unit length of conductors when the temperature is 20°C α is the conductor temperature coefficient of resistance, Y_s is skin effect factor, and Y_p is proximity effect factor.

2.3 Metal Sheath Loss and Armor Loss

When the AC current goes through a conductor, induced electromotive force will cause harm to the safe operation of the cable. So in most cases, both ends of the cable metal sheath are needed to be grounded, which can constitute a current loop and produce metal sheath loss. Metal sheathed power loss (λ_1) includes circulation loss (λ_1') and proximity effect loss (λ_1''):

$$\lambda_1 = \lambda_1' + \lambda_1'' \tag{8}$$

If the cable is in armored structure, the armor will change sheath current in different degree, and the loss will change. Armor types include non-magnetic armor and magnetic armor. Magnetic armor includes steel wire armor and steel tape armor. As type of armored loss is different, calculation is also different. Because the armored loss formula derivation process of calculation is cumbersome, only a simple recommended formula of IEC is introduced. For steel tape armored cable, the calculation formula is:

$$\lambda_2 = \lambda_2' + \lambda_2'' \tag{9}$$

where λ_2 is the ratio of armored total loss and core loss, λ_2' is the ratio of hysteresis loss and core loss in armor, and λ_2'' is the ratio of eddy current loss and wire core loss.

2.4 Dielectric Loss

Dielectric loss W_d is the energy loss produced in the cable insulation. As the fever features of cable shows, if cable dielectric loss increases, the heat generated by the cable itself will increase. This will increase operating temperature of the wire core and lower the ampacity of the cable [2]. On the other hand, when the dielectric loss decreases, wire core temperature is reduced, and cable thermal load ampacity will be increased too.

Cable dielectric loss mainly depends on cable capacitance, rated voltage, dielectric loss factor, and power frequency [11]. Cable capacitance is determined by the relative dielectric constant and size of the cable structure.

The unit length of the cable insulation layer capacitance can be calculated as follows:

$$C = \frac{2\pi\varepsilon\varepsilon_0}{\ln\frac{D_\mathrm{i}}{D_\mathrm{c}}} \tag{10}$$

where D_c is the external diameter of cable shielding, D_i is the outside diameter of insulation, ε is the relative dielectric constant of medium, ε_0=8.86×10^{-12} F/m.

The unit length of dielectric loss can be calculated by Eq. (11):

$$W_\mathrm{d} = U_\mathrm{o}^2\omega C tg\delta \tag{11}$$

where U_o is the rated voltage for the cable, ω is for the power frequency, $tg\delta$ is the dielectric loss factor in the power system and work temperature.

3. The Calculation Method of Transient Cable Temperature

Cable conductor temperature under operation is the decisive factor which affects the service life of insulating materials [4]. Because of the limitation of technology, the conductor temperature cannot be accurately measured. Commonly in engineering, the calculated conductor temperature is often used. When the cable is in stable operation, once the ampacity of the cable increases, the original stable state will be broken. The temperature of the cable will change, resulting in a transient temperature rise and it finally will reach a stable state [12].

When single core cables run continuously under the rated ampacity, conductor, insulation and metal sheath will all produce loss and heat, and then form a stable temperature field. In this case, IEC 60287 standard can be used to solve the conductor temperature. In the actual operation, when the load current changes suddenly, because of the cable internal heat capacity, the temperature will not mutate at once. On the other hand, it shows a gradual change over time and finally reaches steady state. This process is called the transient temperature rise of the cable [12,13]. For the cable whose insulating layer is thinner, the temperature rise can be seen as the index changes. The cable can be seen as a first-order network where an equivalent heat capacity is in parallel with the equivalent thermal resistance. But for the cable whose insulating layer is thicker, the curve of the conductor temperature rise is the sum of multiple index functions [14]. In fact, cable thermal process is an infinite chain-shaped network. The differential equation is called the partial differential equation. For convenient calculation, the second order or third order differential equation is commonly used instead of partial differential equations in engineering. Using π network rather than the infinite chain network, as the calculation results error is small, it can meet the engineering need for accuracy.

When calculating the thicker insulation high-voltage electric power cable thermal transient process, the π network can be used to approximate the value, as shown in Fig. 2.

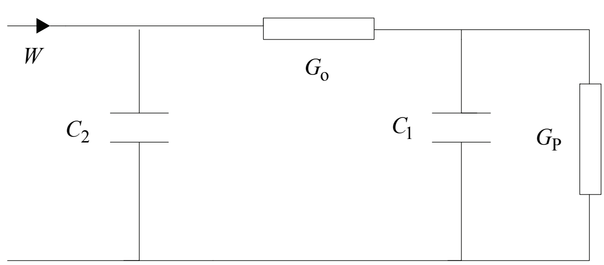

Fig. 2. Equivalent network of high voltage power cable.

In Fig. 2, W is the line loss (W/m); C_1 is the heat capacity of conducting wire core and other parts of the insulation (J/°C); C_2 is the heat capacity of sheath and part of the insulation layer (J/°C); G_o is the internal thermal resistance of the cable, ℃ /W; G_p is the external thermal resistance of the cable (°C/W).

Among them, expression of the heat capacity and thermal resistance are as follows:

$$\begin{aligned} C_1 &= C_c + pC_i \\ C_2 &= (1-p)C_i + (C_m + p'C_j)/q_s \\ G_o &= G_a \\ G_p &= q_s G_b + G_c \end{aligned} \tag{12}$$

where C_c is heat capacity of single core conductor; C_i is insulation heat capacity; C_m is the metal sheath heat capacity; C_j is the external armor layer heat capacity; G_b is the armor layer thermal resistance; G_c is the outside medium thermal resistance; q_s is the ratio of the loss of the core and metal sheath and wire core loss, and it is used to gauge additional loss of metal sheath; p is the proportional factor for allocating the total heat capacity G_a of insulation, which represents the distribution of heat capacity on the core insulation and external armor layer. The expression of p is:

$$p = \frac{1}{2\ln(\frac{D_i}{d_c})} - \frac{1}{(\frac{D_i}{d_c})^2 - 1} \tag{13}$$

p' is the distribution proportion factor of allocating heat capacity of the external armor layer, the expression of p' is:

$$p' = \frac{1}{2\ln(\frac{D_e}{D_s})} - \frac{1}{(\frac{D_e}{D_s})^2 - 1} \tag{14}$$

When a constant current goes through the conductor, the differential equation of the transient temperature rise of the wire core is as follows:

$$C_1 C_2 G_o G_p \frac{d^2 T}{dt^2} + [(G_o + G_p)C_1 + C_2 G_2]\frac{dT}{dt} + T = W(G_o + G_p),\ W = I^2 R \tag{15}$$

Eq. (16) reflects the temperature dynamics of the cable conductor when the current flowing through the cable changes, which can also be referred as dynamic thermal equilibrium equation of cable [12]. T is the transient temperature rise of conductor (°C); t is time (s); W is line loss (W/m).

If the cable has reached steady state before the disturbance, for the moment when a disturbance happens (noted for $t = 0$), there is:

$$T\big|_{t=0} = T_s,\ \frac{dT}{dt}\bigg|_{t=0} = \frac{W}{C_1} \tag{16}$$

T_s is the temperature of cable in steady state before disturbance, where the heat lost and the calorific value of the cable reach a balance. When given an initial value, firstly, the second-order differential equation of line core transient temperature rise can be transformed into the first-order differential equation with the help of variable substitution method, and then use the Runge-Kutta method to solve the problem.

4. Analysis of Examples

4.1 Analysis of the Ampacity in Static Thermal Balance

Parameters of power cable which will affect the cable ampacity include the thickness of insulating layer, shield thickness, and armor layer thickness. Parameters of environment which will affect the cable ampacity mainly include maximum permissible temperature the cable allowed, the buried depth, the ambient temperature, and the soil thermal resistance coefficient. It is important to analyze the effect of various parameters on ampacity, which can determine the effective cable ampacity. The version of cable we choose in this paper is: YJV-26/35-1×630. It is a kind of single core copper crosslink polyethylene insulated PVC armor layered cable. The initial parameters according to the simulation of the actual circumstances are set as follows: buried depth (700 mm), insulation thickness (10.9 mm), shield thickness (1.2 mm), armor layer thickness (2.9 mm), ambient temperature (30°C), the thermal resistance coefficient of soil (1.0 k·m/W), maximum permissible temperature (90°C). The simulation of ampacity under the condition of changing the relevant variables with keeping other variables constantly is given in Fig. 3.

Fig. 3 shows the influence of cable intrinsic parameters on ampacity. Fig. 3(a) shows the effect of the variation of insulation thickness to the ampacity. According to the chart, with the increase of the insulation thickness, the maximum permissible ampacity will be decreased obviously. Fig. 3(b) shows a simulation of the effect of the shield thickness on the ampacity. The shield thickness changed within a range of 1–5 mm, with the increase of shield thickness, the cable ampacity tend to decrease. Fig. 3(c) shows the effect of the external armor layer thickness on the ampacity. The external armor layer thickness changes in a range of 2–6 mm, with the increase of the external armor layer thickness, the maximum permissible ampacity tend to decrease.

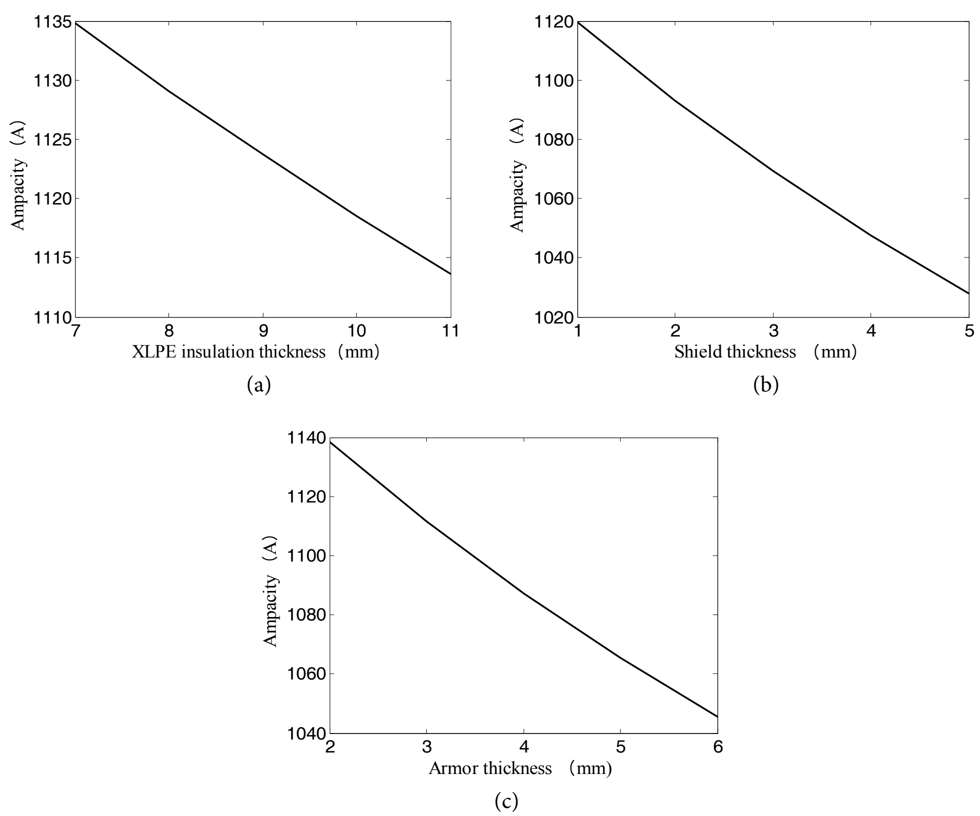

Fig. 3. The influence of cable intrinsic parameters on ampacity: (a) the variation of ampacity with XLPE insulation thickness changing, (b) the variation of ampacity with shield thickness changing, (c) the variation of ampacity with armor thickness changing.

Fig. 4 shows the influence of surrounding parameters on cable ampacity. Fig. 4(a) shows the effect of the variation of the cable maximum permitted temperature on the ampacity. The range of temperature is 60°C–110°C, with the increase of the maximum permitted temperature. The ampacity increases linearly, and the variation range is about 389 A. Fig. 4(b) shows the effect of the buried depth on the ampacity, when the buried depth becomes larger, the heat dissipation of the cable will become worse, which leads to the decrease of the cable ampacity. Keeping other parameters unchanged, the range of cable burying depth is 0.6–0.9 m. The change trend of the cable ampacity is as shown: when the buried depth increases, the ampacity will change regularly. With each 0.1 m the buried depth growing, the ampacity will decrease about 10 A. Fig. 4(c) shows the effect of the variation of environmental temperature on the ampacity. With the ambient temperature growing high, the ampacity will be influenced by the bad situation of cable's heat dissipation. The soil temperature is selected as the range of 10°C–40°C. When the other parameters were kept constant, the soil temperature increases by 1°C and the ampacity decreases by 8.3 A. Fig. 4(d) shows the effect of the variation of the soil thermal resistance coefficient on the ampacity. This coefficient plays an important role in affecting the ampacity. The range of soil thermal resistance coefficient is 0.6–2.0 k·m/W, and the other parameters are constant. With the increase of the soil thermal resistance coefficient, the ampacity decreases nonlinearly which means that the influence from the soil thermal resistance coefficient on the ampacity getting weak.

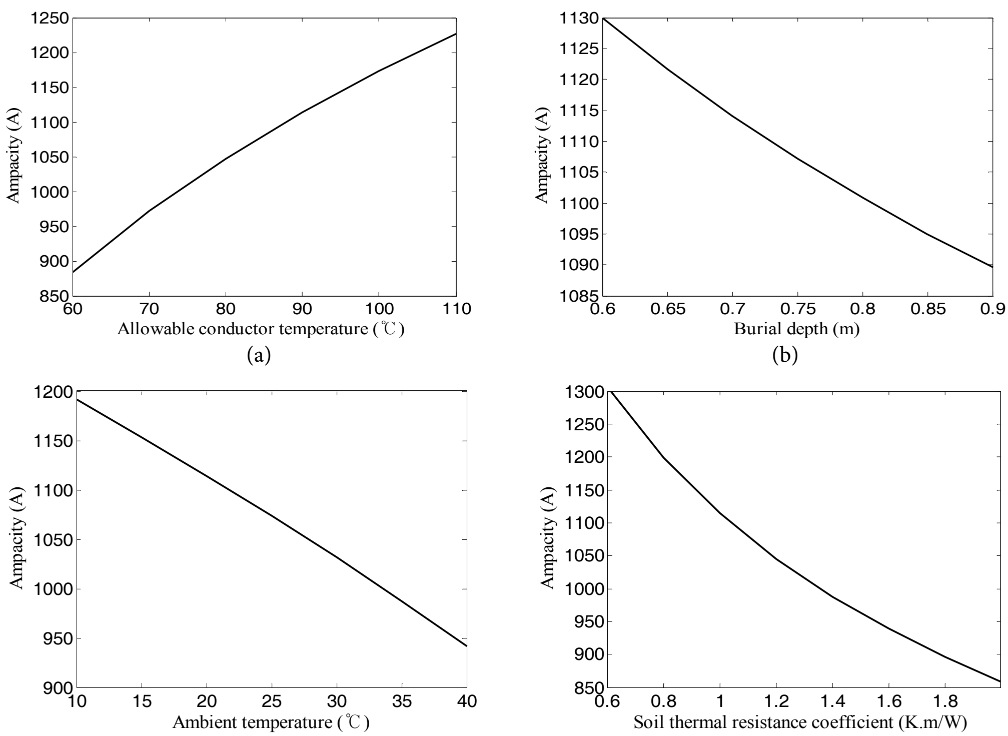

Fig. 4. The influence of surrounding parameters on cable ampacity: (a) the variation of ampacity with allowable conductor temperature changing, (b) the variation of ampacity with burial depth changing, (c) the variation of ampacity with ambient temperature changing, (d) the variation of ampacity with soil thermal resistance coefficient changing.

Cable ampacity calculating by the static thermal rating does not consider the influence from environmental condition. Conservative environmental parameters cause the ampacity to be a fixed conservative value. According to [1], the conditional static thermal rating of the cable is 940 A. It can be seen from the above diagrams, compared with the static thermal rating 940 A, the actual ampacity of cable combined with the ambient conditions in most situations is much higher. Under wet soil area condition, the ampacity can increased by 40% on the basis of the static thermal rating. The result indicates that the use of actual ambient conditions in ampacity calculation will has the potential to significantly improve over static thermal rating. When other parameters remain unchanged as the initial value, variation of related parameters of cable itself is 4 mm. The external parameters are selected according to the environment and the actual laying situation, and the difference of the corresponding cable ampacity is shown in Table 1. The influence of various parameters on the cable ampacity can be judged according to the difference. This paper lists three degrees for the influence: high (more than 200 A), medium (more than 50 A and less than 200 A), and low (less than 50 A). The influence rank is shown in Table 1. It can be easily seen that the influence of the thermal resistance coefficient of soil is most obvious on ampacity. The next is maximum allowable conductor temperature and environmental temperature. The insulation layer thickness has minimal effects on cable ampacity.

Table 1. The impact results of various factors on the cable

Parameter	Fixed value	Range	Ampacity difference (A)	Influence rank
Soil thermal resistance coefficient (k·m/W)	1.0	0.6–2.0	447.6	High
Allowable conductor temperature (°C)	90	60–110	342.7	High
Ambient temperature (°C)	20	10–40	249.8	High
Armor thickness (mm)	2.9	2.0–6.0	93.0	Medium
Shield thickness (mm)	1.2	1–5	91.7	Medium
Burial depth (m)	0.7	0.6–0.9	40.4	Low
Insulation thickness (mm)	10.9	7.0–11.0	21.2	Low

4.2 The Transient Temperature of Conductor

When the cable is under the steady state operation, the conductor temperature will also be in a stable state. If the current increases at a time, cable conductor temperature will significantly increase over a period of time. Take YJVW03-64/110-1×630 type power cable as an example, its working temperature allowed in the long-term is 90°C. The assumption that the environment in a period of time (the ambient temperature is 20°C, the soil resistance coefficient is 0.6 k·m/W, the buried depth is 1 m) does not change. When running cable ampacity is 800 A, the conductor temperature is 40°C, and the conductor is in a stable thermal equilibrium. When t = 4 h, electric current rises from 800 A to 1,500 A. keeping the current unchanged during a period of time, the change of conductor temperature can be shown as Fig. 5.

In Fig. 5, it illustrates that when cable ampacity is 800A, the cable works stably at 40°C. If apply an overload of 1,500 A on cable at t = 4 h, the cable heat balance is broken. The conductor temperature will rise. When t = 11 h, conductor operating temperature rises to the maximum allowable temperature 90°C. The changing time is about 7 hours. When t = 14 h, conductor temperature is about 97°C, which is higher than the maximum permissible cable temperature. Thus for dispatch staff, they can make full use of the thermal inertia of a conductor, and take measures for major changes of the cable load to guarantee the safe operation of the cable in a safe time.

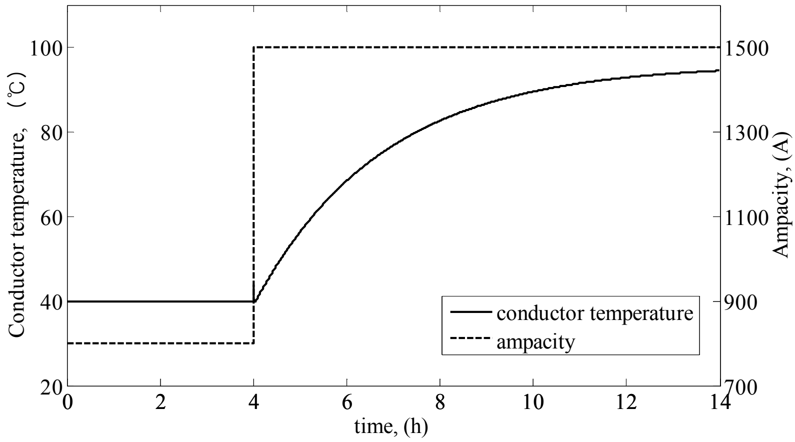

Fig. 5. The variation of the conductor temperature when the ampacity is 1,500 A.

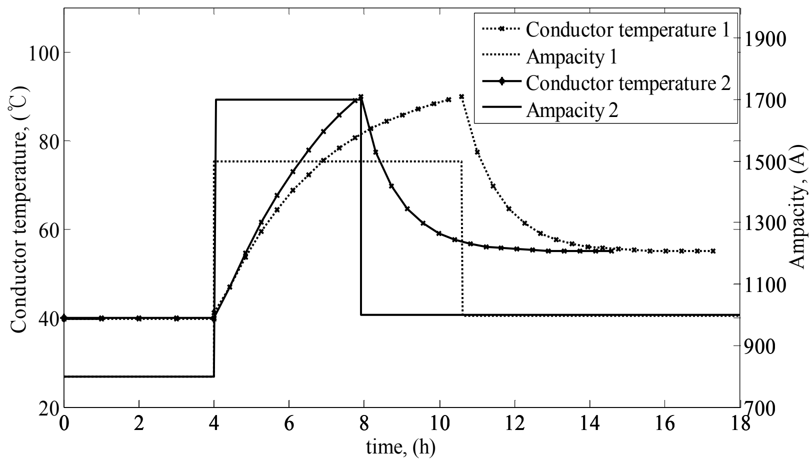

Fig. 6. The dynamic thermal process of conductor when the ampacity changes.

If the cable has the same initial state, when applying different load current, the time for cable conductor to reach the maximum allowable temperature is different. The dynamic thermal process of conductor can be shown from Fig. 6 when applying different load current. In Fig. 6, conductor temperature 1 and conductor temperature 2 show the variation of cable conductor temperature when the cable ampacity change with ampacity 1 and ampacity 2, respectively. When the cable ampacity is 800 A, the overflow of 1,500 A and 1,700 A are applied on the cable in the t = 4 h. When the conductor temperature reaches 90°C, reducing the ampacity to the rated current 1,000 A, the conductor temperature changes with time can be shown as Fig. 6. It can be seen that the time for cable conductor reaching 90°C is 7 hours and 4 hours, respectively. Thus it comes to the summary that the more serious the cable overload is, the shorter the time for the conductor temperature from ambient temperature rises to the maximum allowable temperature. So it is important to try to avoid excessive load current and long duration. Analysis of the dynamic thermal process is helpful to study problem of heating of the cable overload under the short-time or cable circuit failure conditions, which guarantees the safe operation of the cable.

5. Conclusion

In this paper, by analyzing the parameters from both the internal and external which will influence cable ampacity, here comes the conclusion that the thermal resistance coefficient of soil and the maximum allowable temperature of conductor have great influence on cable ampacity. The cable insulation layer thickness has the least effect. The analysis of the various cable ampacity under different conditions is of great significance for cable transmission capacity. Compared with the rated ampacity under the conservative condition, the research of this paper can effectively improve the cable utilization. Research in cable dynamic thermal rating helps solve problems when the cable is short-time overload or short circuit fault happens. It will also be able to get the allowable time needed for the conductor reaching the maximum temperature when the step current is applied to the cable. Moreover, it provides theoretical support for the cable predicting fault, thus guarantees the safe operation of the cable.

In the future work, we intend to analyze the cable thermal rating at different confidence levels and different time scales by using historical annual geographical and environmental data. By this work, the operational risk of power grids can be easily determined, which has important significance in guaranteeing the safe operation of power grid.

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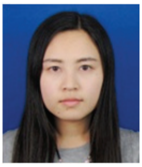
Qiang Tong https://orcid.org/0000-0003-3740-9830

He received his M.S. degree from Shandong University. He works at Shandong University for the school's hydropower management. His current research areas are power system operations and controls.



Jianping Qi https://orcid.org/0000-0001-5244-6635

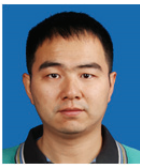
She is a postgraduate in School of Mechanical Electrical and Information Engineering at Shandong University. She is major in electronics and communication engineering. Her main research interests include current-carrying transmission and automation of electric power systems.

Yanling Wang https://orcid.org/0000-0003-0467-8356

She received her Ph.D. degree from Shandong University and now teaches in School of Mechanical Electrical and Information Engineering at Shandong University. Her current research areas are smart grid, power grid transmission capacity, power system operation and control.

Likai Liang https://orcid.org/0000-0003-1271-6906

She received her Ph.D. degree from School of Electrical Engineering from Shandong University in 2013. She teaches as an associate professor in School of Mechanical Electrical and Information Engineering at Shandong University. Her current research interests include power system operation and control.



Xiangxing Meng https://orcid.org/0000-0001-5490-0264

He received her Ph.D. degree from School of Electrical Engineering from Shandong University in 2007. He is currently a Senior Engineer with State Grid Heilongjiang Electric Power Company Ltd., Harbin, China. His current research interests include electric power dispatching theory and generation technology of electricity by new energy.

Qiang Zhang https://orcid.org/0000-0003-1457-5166

He received her Ph.D. degree from School of Electrical Engineering from Shandong University in 2007. He is currently a Senior Engineer with Shandong Electric Power Dispatching Control Center, Jinan, China. His current research interests include electric power system theory, operation and control.