CURRENT RATINGS OF UNDERGROUND CABLES FOR DISTRIBUTION MANAGEMENT SYSTEMS

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Real-time current ratings of distribution cables are discussed in this paper. The total current-carrying capacity of the cable (ampacity) is not constant but depends e.g. on the time duration of the current and ambient temperature. A method to calculate the real-time current ratings of the cable and a system to manage the load capability of the whole underground cable network is introduced. An example of calculation considering the real-time current ratings is presented. The data needed in calculations and open questions related to this management system are discussed as well.

INTRODUCTION

The full utilisation of the existing transfer capacity of distribution networks is an essential issue in developing assets management of a network company. Traditionally when planning and operating underground cable networks the steady state long term load forecast as far as up to 20 years and related current rating tables have been a major criterion. This principle is simple and safe but often leads to over capacity and thus to extra capital costs. However, it does not contribute to the management of short duration exceptional overloads, which appear e.g. in backup routes when clearing fault conditions.

A real-time approach is required for efficient system operation. The warming behaviour and temperature duration of insulation and the present and past loads of the critical points of the cable system are needed for real-time management of an electricity distribution system. New applications of information technology such as AM/FM-GIS and DMS give us a good support.

The structure and procedures of a proposed current-carrying capacity management system of a cable network will be introduced in this paper.

The main goal of this research work was to collect information about calculating the current ratings of the cables for short durations and to develop a current-carrying capacity management system for the medium voltage cables. The system should be able to be integrated to an AM/FM-GIS or DMS [1]. Methods for transient heat calculations have been selected from those introduced in various standards and literature. Availability of required data for the calculation and the management system is discussed as well as how to keep the data needed to a minimum.

METHODS TO CALCULATE THE CURRENT-CARRYING CAPACITY

The temperature rise of the cable insulation is mainly caused by the heat losses inside the conductor. The temperature is not allowed to rise so much that the mechanical or electrical characteristics of the cable would be changed and the cable would damage. Thus, the calculation of current ratings of the cable is related to the temperature response to the conductor due to the conductor losses. There are mainly three different ways to calculate the temperature response of the cable depending on the load behaviour:

1. Temperature response of the steady state load
2. Temperature response of the transient load change
3. Temperature response of the cyclical load

The most commonly used and tabulated nominal currents of the cables are calculated using the method of temperature response of the steady state load. The conductor temperature approaches its maximum allowed value during infinite time in this kind of calculations. The well-known and widely used calculation method is given in the standard IEC 60287 [2,3]

The conductor temperature does not reach its steady state value at that very moment when the heat losses of the cable rapidly change form its initial value to another. This kind of phenomenon is a consequence of the thermal resistance and the thermal capacitance of the cable and its surroundings. The generally used method to calculate the temperature response of the transient load change is to construct the thermal circuit of the cable as shown in figure 2 [4-10]. First, the conductor temperature is solved from the circuit and then the temperature rise of the cable surrounding is added to it. This method is applicable when the current is arbitrarily chanced as well, because the loss load curve can be regarded as a sum of many little transient portions as shown in figure 3 [8].

One other way to calculate the temperature response of the conductor of a cyclically or arbitrarily loaded cable is based on Fourier series or Fourier transform representation of the load current. This kind of method is used in [11-14].

THE CURRENT-CARRYING CAPACITY MANAGEMENT SYSTEM

The load-carrying capacity of a cable depends on constant factors and some variables as well. The constants are, for example, construction parameters of the cable and the parameters of its surroundings. Load losses of the cable and time are considered as variables. It is obvious that the maximum allowed current of a cooler cable is much higher than a hotter one. Because load current and load losses are varying all the time, the maximum allowed current is changing too. This leads to a need of a sophisticated load capability management algorithm so that the whole power transfer capacity of the cable can be utilised all the time.

The current-carrying capacity management system for cables introduced here is based on the knowledge of the conductor temperature response of transient change of the load current. The steps to manage the load-carrying capacity of the cable system are:

1. The hottest portion of the cable route is described by the constant parameters. This means that the parameters of the cable and its surroundings have to be collected and stored.
2. The temperature function of the considered cable p is formulated in terms of changeable variables. These variables are the time t and the loss powers of the considered cable per cable length P_p and other heat sources P_k near the cable p. The temperature function is then $T_p(P_p,P_k,t)$.
3. The histories of loss powers P_p and P_k are known to the present time t_0.
4. The loss powers P_{k0} are estimated for the time interval $t_0 \ldots t'$. Then the maximum losses P_{p0} and the maximum allowed current of the cable p, $I_{max,t'}$ can be calculated.
5. The calculation can be repeated at the time t'' and $I_{max,t''}$ can be produced in the same way as in step 4.

The method may need many mathematical calculation operations and saturate the computer especially if the cable network is wide. However, it is not necessary to repeat the calculation all the time. The calculations can be started after the certain current limit I_n is reached. I_n can be, for example, the tabulated steady state maximum current.

The loss power data P_p and P_k are needed all the time. This means that the history of the heating power must be known and stored although the current limit I_n is not reached yet. Storing this data needs a lot of memory so it is reasonable to use some kind of measured or calculated hourly average values and a long time average value as stored data. In a practical case, collecting the power data is very difficult to carry out. By help of SCADA systems, the direct measurement is one possibility to get this information but the most promising way to get the data is to use some distribution network state estimation tool. The procedures of the current-carrying capacity management system are shown in figure 1.

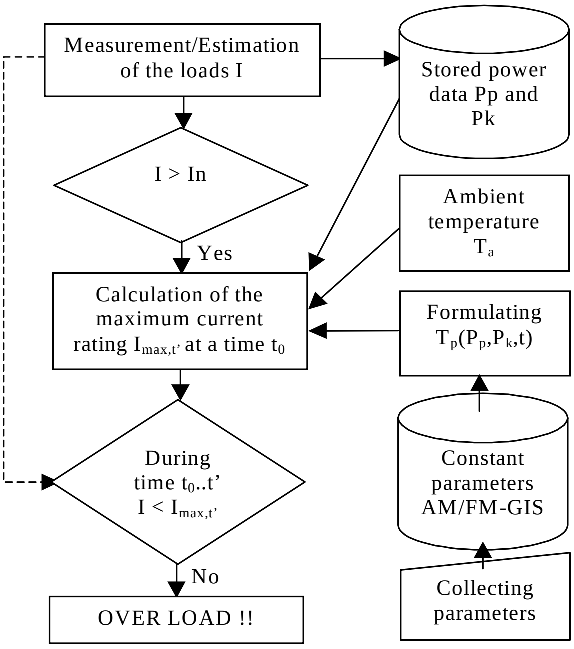

Figure 1. The flow chart of the current-carrying capacity management system

FORMULATING THE TEMPERATURE FUNCTION $T_P(P_P,P_K,T)$

To be able to formulate the temperature function of the cable p, the hottest portion of the cable line must be known. District heating pipes or other power cables or any kind of heat sources must be taken into account in the calculations. The temperature of the conductor is calculated as follows:

1. The conductor temperature $\theta_p(P_p,t)$, °C of the cable p is calculated considering only the heating power P_p, W/m in terms of time t. The other heat sources are considered to be zero.
2. The temperature rise $\theta_{pk}(P_k,t)$, °C at the location of the cable p caused by another heat source k is calculated one by one while the other heat sources are considered to be zero.
3. The temperatures calculated above are added up together.

The formulations of the functions are described briefly in the next subsections. The calculation in details can be found in references [4-6].

The temperature rise θ_p due to the considered cable itself

The transient temperature response of the cable depends on thermal capacitance C_{th}, J/°Cm and thermal resistance R_{th}, °Cm/W of the whole system of the cable and the surrounding soil. The common way to calculate the temperature response is to divide the system into two parts. The temperatures rise inside the cable $\theta_C(\Delta P_p,t)$ at time t from the beginning of the transient change of the loss load ΔP_p is calculated first. The temperatures rise above ambient soil temperature $\theta_E(\Delta P_p,t)$ is calculated afterwards. The final temperature rise is then the sum of these two.

$$\theta_p(\Delta P_p,t) = \theta_C(\Delta P_P,t) + \theta_E(\Delta P_p,t) \tag{1}$$

The temperature response in the cable θ_C. The temperature rise in the cable p is calculated by solving the thermal circuit of the cable shown in figure 2. The structure of the thermal circuit is described in details in [4-6]. The transient change of the loss load ΔP_p is considered as input at a conductor and the temperatures at any nodes are considered as outputs. Then the temperature rise above ambient is

$$\theta_c(\Delta P_p,t) = \Delta P_p \cdot \sum_{j=1}^{n} A_j (1 - e^{\tau_j \cdot t}) \tag{2}$$

Where A_j, °Cm/W is coefficient, τ_j, 1/s is time constant and n is number of the nodes in figure 2.

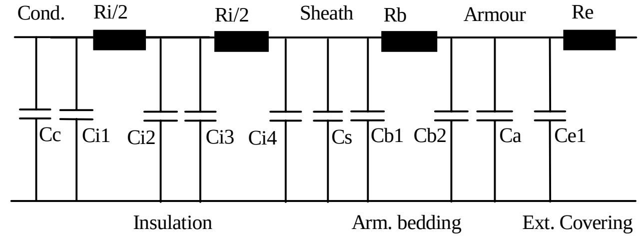

Figure 2. The thermal circuit of the cable [6].

The temperature response of the surrounding soil θ_E. The temperature rise of cable surface above the ambient soil temperature can be calculated as shown in [4-6]. The temperature function $\theta_E(\Delta P_p,t)$ can be formulated if installation data of the cable and the surrounding soil is known. For example, the thermal resistivity of the soil ρ_s, °Cm/W and the axial depth of burial of the cable L, m have to be known. The effect of ductbank and different encasement materials can be taken into account as well.

The temperature rise due to the other heat sources θ_{pk}

The temperature rise caused by the other heat sources near the considered cable p must be taken into account. If the transient change of the loss power of the heat source k is ΔP_k then the temperature rise at the location of the cable p is $\theta_{pk}(\Delta P_k,t)$ as described in [4-6]. The data that is needed in this case are for example axial distances of heat source k and its image source to the cable p (d_{pk} and d'_{pk}, m) defined in [3].

The final temperature function $T_p(P_p,P_k,t)$

When the history of the loss powers P_p and P_k are known they can be divided into parts as illustrated in the figure 3.

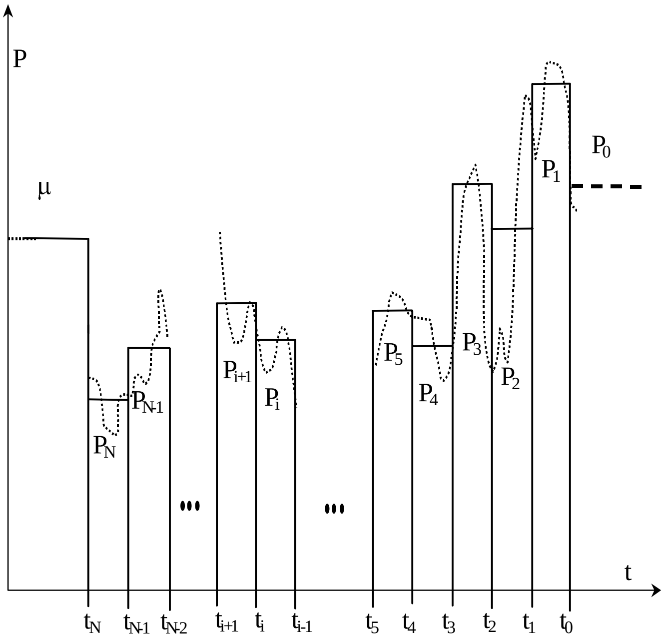

Figure 3. Loss power P divided into the parts P_i.

For example, the power P_p can be divided into parts so that the power applied during the time interval $t_i \ldots t_{i-1}$ is P_{pi}. The long time average of the loss power P_p is μ_p. The transient change of the loss power ΔP_{pi} is applied at time t_i and is defined as

$$\Delta P_{pi} = (P_{pi} - P_{pi+1}) \tag{3}$$

The final conductor temperature at a moment t can be calculated by adding up all the temperature rises caused by the individual transient changes of loss power. Thus, the temperature rise above the ambient soil temperature at the conductor can be formulated as

$$\begin{aligned} T_p(P_p,P_k,t) &= \theta_p(\mu_p,\infty) + \sum_{i=0}^{N} \theta_p(\Delta P_{pi}, t - t_i) \\ &\quad + \sum_k \left\{ \theta_{pk}(\mu_k,\infty) + \sum_{i=0}^{N} \theta_{pk}(\Delta P_{ki}, t - t_i) \right\} \end{aligned} \tag{4}$$

THE REAL TIME CURRENT RATINGS

Let us consider the time t_0 as present time. The temperature of the conductor at time t = t' can be calculated by equation (4) if next conditions are fulfilled

1. The history of loss powers P_k and P_p are known as described earlier
2. The loss powers P_k are estimated to be $P_{k0} = P_{k1}$. (The loss power P_{p0} is regarded as unknown)

The maximum loss power P_{p0} allowed can be solved then from the following equation

$$T_p(P_p, P_k, t') = T_{C,\max} - T_a \quad (5)$$

Where $T_{C,\max}$, °C is the maximum conductor temperature and T_a, °C is the ambient soil temperature.

Because the resistance of the cable $R(T_{C,\max})$, Ω/m in that particular maximum temperature $T_{C,\max}$ is known the real time maximum current of the cable $I_{\max,t'}$ can be calculated.

The previous condition estimated $P_{k0}=P_{k1}$ is reasonable especially if the other heat sources k are located relatively far away from the cable p or the time interval t'…t_0 is short.

CALCULATED EXAMPLE

The real-time current ratings of the cable p for five hours is calculated from t = 0 and resulting values I_{norm} and I_{em} are shown in fig. 5. The hottest portion of the cable route is shown in fig. 4 and the load currents of both circuits are shown in fig. 5. The calculated temperature of the cable p is shown in figure 6. The needed data of the cable is shown in table 1.

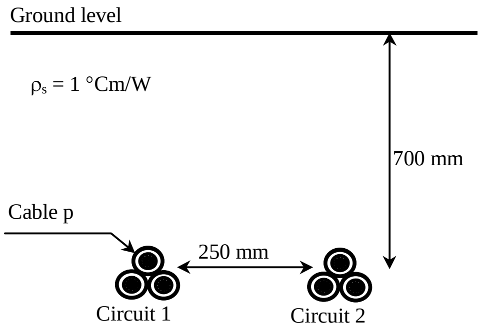

Figure 4. The hottest portion of the cable route. Both cable circuits 1 and 2 are similar to each other. Cable type is AHXCMK 1x800. Sheaths are grounded at both ends.

Table 1. Data of the cable AHXCMK 12/20 kV [15]

Conductor:	Al	Area 800 mm^2
Insulation:	XLPE	-
Sheath:	Cu wires	Area 50 mm^2
Over sheath:	PVC	Nominal diameter 59 mm

The following conclusions can be done:

1. The maximum allowed load current under normal operation I_{norm} is 1.52 times the tabulated steady state current I_N. In the example, normal operation means that the conductor temperature does not exceed +65 °C, which is given in [15].
2. The maximum allowed load current under emergency operation I_{em} is even 160% bigger than the tabulated steady state current. Emergency operation means that the conductor temperature does not exceed a certain emergency temperature but may exceed the normal operation temperature for a given time. Temperature +110 °C is regarded as an emergency temperature limit in this example.
3. There is possibility of over heating, if the load current is higher than I_{norm} or I_{em} during that five hours period.

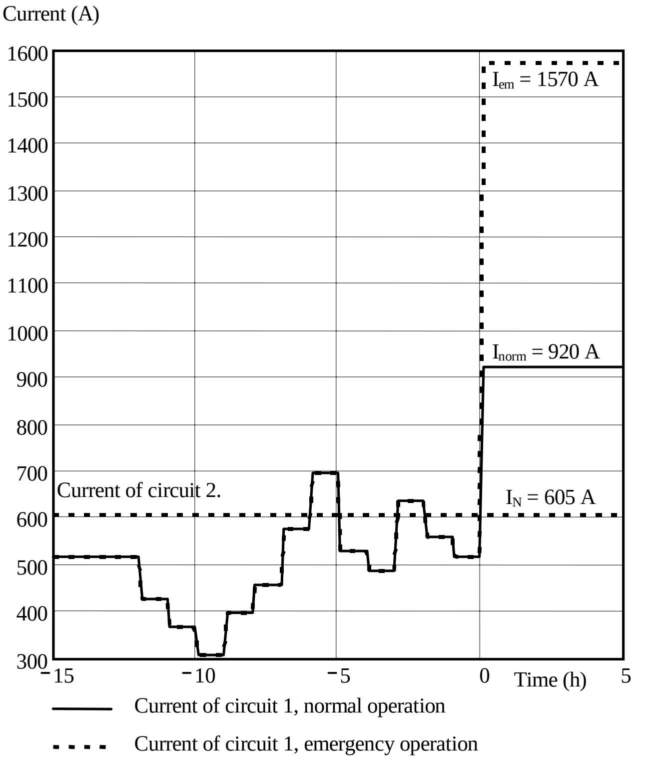

Figure 5. Load currents of cable circuits. The tabulated steady state current is I_N and the calculated maximum currents are I_{em} and I_{norm}.

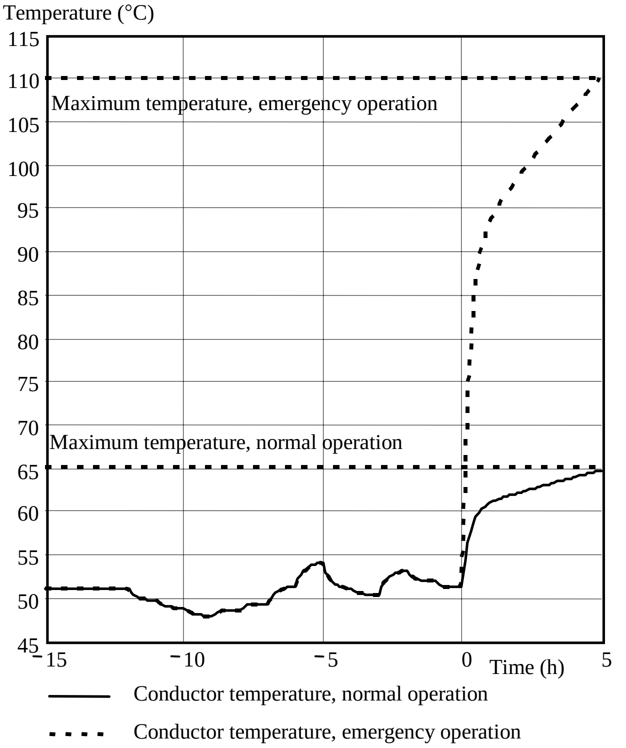

Figure 6. The temperature of cable p in circuit 1.

DATA REQUIREMENTS

It will be expensive or time consuming to get all the data, which is needed in the system, especially if the distribution cable network is huge. That is why the number of the parameters of the current-carrying capacity management system introduced above must be restricted. The data already existing in the AM/FM-GIS must be used if possible. The new data still needed must be easy to get. The essential types of data required are

- Cable constructions
- Thermal operation limits
- Installation and operation data
- Loss power data

Cable constructions

The data of the materials and dimensions of the cable structure are required for determining the components of the thermal equivalent circuit of the cable shown in the figure 2. Exact data may be obtained from the manufacturers. If not, the data may be obtained from specifications and standards. For example for extruded insulated cables using the standard IEC60502 [16], the following information is only needed

1. Rated voltage
2. General type of the cable (SL-type, screened, single core etc.)
3. Cross-sectional area of conductors
4. Materials of the different layers (Cu, Al, XLPE, PVC, PE, Pb etc.)
5. Overall diameter

Thermal operating limits

The maximum current carrying capacity of the cable depends on the maximum conductor temperature $T_{c,max}$ very closely. The value of ultimate temperature of the conductor, which is not allowed to exceed, can be found for example from [2,16-19]. Nevertheless, there are still many open questions as how reasonable these given temperature limits are. For example, cable withstands quite high temperature mechanically but high temperature may lead to drying out of the soil and thus changes soil thermal properties. If the soil parameters change too much, it might cause thermal runaway and then the cable will be over heated.

Installation and operation data

To find out the hottest portion of the real cable line section is a complicated problem of itself. The practical and safe way to find this kind of designing spot must be developed in the future.

When the hottest portion of the cable line is found out, the following data is needed

- The materials and dimensions of the ductbank etc.
- The type of the surrounding soil (sand, concrete etc.)
- The distances of the heat sources and depths of the burial
- Ambient soil temperature (it may be reasonable to use some average values, for example different values for winter and summer)
- The grounding of the cable sheaths etc.

Loss power data

The heating power of the cables and other heat sources must be known as described earlier. The loss power or load current must be measured or estimated at every moment and then the data must be stored in the database. The number of this stored data may be enormous depending on the cable network. That is why it is very important to think about what kind of data is really needed and how to get it.

The data of loss power of the cable can be obtained from load current and cable resistance. The problem is how to measure or estimate the previous load currents. New applications in the network management such as AM/FM-GIS, SCADA and DMS help us to solve this problem. The other problem is how much data must be stored. The hourly averages of loss power P_i and a long time average μ may be enough. For example, the hourly average of loss power for six previous hours and a long time average is used when calculating cyclic rating factor in reference [4]. Further study about this subject is still needed.

In case of other heat sources it may be impossible to get the exact hourly loss power data but the long time average μ_k could be easier to find out. This data can then be stored and used in the calculations.

CONCLUSIONS

A concept of current-carrying capacity management system for distribution cable network is introduced in this paper. The system is simple and it is applicable for large distribution networks as well as for power cable systems in different voltage levels. The whole load transfer capacity of cable networks can be utilised and extra savings can be done by the help of management system introduced in the paper.

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