Practical and Theoretical Investigation of Current Carrying Capacity (Ampacity) of Underground Cables

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Abstract – In urban areas, underground cables are commonly used for bulk power transmission. The utilization of electricity in factories, domestic premises and other locations is typically performed by cables as they present the most practical means of conveying electrical power to equipment, tools and other different applications. Estimation of cable current carrying capacity (ampacity) gains higher potential in recent times due to the continuous increase of energy utilization in modern electric power systems. This paper presents a theoretical study based on relevant IEC standards to calculate the ampacity of underground cables under steady state conditions. The ampacity formula stated in IEC standards are coded using Matlab software. Further, an untraditional experimental ampacity test of a 38/66 kV - XLPE/CU - 1 X 630 mm² cable sample is performed in the extra high voltage research center. This paper proposes a new approach that uses the complementary laboratory measurements in cable ampacity data preparation. The modified approach gives more accurate estimation of cable parameters. The level of improvement is assessed through comparisons with the traditional ampacity calculation techniques. Main factors that affect cable ampacity, such as the insulation condition, soil thermal resistivity, bonding type, and depth of laying are examined. Based on paper results, cable ampacity is greatly affected by the installation conditions and material properties.

Keywords – Underground cable; Cable ampacity; Soil thermal resistivity; Bonding type; Depth of laying

1. Introduction

Compared with transient temperature rises caused by sudden application of bulk loads, the calculation of the temperature rise of cable systems under steady state conditions, which includes the effect of operation under a repetitive load cycle, is relatively simple. Steady state cable ampacity involves only the application of the thermal equivalents of Ohm’s and Kirchoff’s laws to a relatively simple thermal circuit. This analogy circuit usually has a number of parallel paths with heat flows entering at several points. However, heat flows and thermal resistances involved should be carefully addressed. Differing methods are sometimes used by various engineers. In general, all thermal resistances are developed according the conductor heat flowing through them. The ampacity or current carrying capacity of a cable is defined as the maximum current which the cable can carry continuously without the temperature at any point in the insulation exceeding the limits specified for the respectively material. The ampacity depends upon the rate of heat generation within the cable as well as the rate of heat dissipation from the cable to the surroundings. In the case of underground cable systems, it is convenient to utilize an effective thermal resistance for the earth portion of the thermal circuit which includes the effect of the loading cycle and the mutual heating effect of the other cable of the system. Ampacity of an underground cable system is determined by the capacity of the installation to extract heat from the cable and dissipate it in the surrounding soil and atmosphere. The maximum operating temperature of a cable is a function of the insulation damage experienced as a consequence of high operating temperatures. Based on the duration of the current circulating in the conductors, the cable insulation can withstand different temperature values [1]. There are three standardized ampacity ratings: steady state, transient (or emergency) and short-circuit. This paper focuses only on cable steady state ampacity ratings. Theoretical and experimental investigation of cable ampacity is conducted.

2. Cable ampacity calculation
The maximum temperature that the cable insulation can be endured for long term determines its ampacity. The long term and short term allowable maximum temperatures ensure that the cable can operate safely, reliably and economically. If the operating temperature exceeds certain limit, the insulation aging becomes faster and thus shortens the cable’s life span. In addition, the electrical and mechanical properties, and thermal behavior must be considered in choosing cable to ensure that the heat is not exceeding the limited value while the transmission capability is satisfied. The thermal behaviour of the cables in underground lines during regimes of normal load or under emergency not only depends on the previous knowledge of the constructive characteristics of the cable and the load curve that submitted, but also of the way conditions where it is installed. Thus other factors will have to be known as: amount of loaded conductors, geometric configuration between the cable, type of grounding of the metallic shields of the cable, thermal characteristics of the materials around of the cable (soil, ducts, concrete, "backfill", etc), effect of the typical variation of the environment (humidity and temperature in the land) and other interferences caused for external sources of heat. The maximum temperature that XLPE insulation enduring is 90 °C, so when the cable core come to this temperature, the current in the cable core is considered cable ampacity. IEC 60287 support a method for calculation the cable ampacity of 100% load current, which is a common method used in all over the world. To find the ampacity, we first note that the potential of every node in the circuit analogizes the temperature of the regions between the layers. Thus, the potential difference between the terminals of the circuits and the innermost current source represents the temperature rise of the core of the cable with respect to the ambient temperature. Therefore the temperature of the cable's core is the ambient temperature plus $\Delta t$. Figure 1 shows thermal electrical equivalent.

\[
\begin{align*}
\Delta t &= \left( W_c + \frac{1}{2} W_d \right) T_1 (W_c + W_a + W_s) T_2 + \\
&\quad \left( W_c + W_d + W_a \right) T_3 + T_4
\end{align*}
\]

From expression (3) one can compute the ampacity of a cable by calculating the thermal resistances $T$, the loss factors $\lambda$ and the $ac$ resistance $R$ of the core of the cable. The loss factors $\lambda$ take into account eddy losses induced and circulating currents, while $R$ considers the temperature dependency of the resistance $[2,3,4,5]$. $T_1, T_2$ is related with insulation material and the cable’s physical dimension. Besides the cable’s construction, $T_4$ also has relationship with the soil thermal resistance coefficient, namely the earth’s property and moisture content. If the three cables contact with each other, the interrelationship of these cables also should be considered in. The loss factor $\lambda_1, \lambda_2, \lambda_3$ relate to the resistance of sheath and armour. The resistance is the function of temperature. In IEC standard, the temperature of sheath and armour are estimated by the maximum temperature insulation endured, but in effect, they also have some relationship with ambient temperature and the current in the cable core. So the cable ampacity calculated by IEC standard has some errors. An iterative method for calculation ampacity is provided in this paper based on precise calculation of circulating current in cable sheath. Firstly, the cable core is given an initial current, and the...
initial temperatures of the core and sheath are also given. Secondly, iterative calculate their temperatures under this current. Thirdly, change the core current continually based on the temperature difference between the core and its allowable maximum temperature, until this difference is smaller than the given error \[6\]. When the conductor is energized, heat is generated within the cable. This heat is generated due to the I^2R losses of the conductor, the dielectric losses in the insulation and losses in the metallic component of the cable. The ampacity of the cable is dependent on the way this heat is transmitted to the cable surface and ultimately dissipated to the surrounding. The thermal resistances control heat dissipation from the conductor. Thus the efficiency of heat dissipation is dependent upon the various thermal resistances of the cable material and the external backfill and soil plus the ambient temperature around the cable. If the cable is able to dissipate more heat, the cable can carry more current.

In the Neher-McGrath method \[1\], the thermal resistances are either computed from basic principles or from heuristics. One can appreciate, from Figure 3, that some of the internal layers of a cable can be considered as tubular geometries. The following expression is used for the computation of the thermal resistance of tubular geometries:

\[
T = \rho \frac{1}{A} = \rho \frac{L}{2\pi} \ln \left( \frac{r_2}{r_1} \right) \tag{4}
\]

Equation (4) is applicable for most internal to the cable layers \(T_1, T_2, T_3\). For complicated geometries and for the layers external to the cable, such as three-core cables, duct banks, etc., heuristics are used. The external to the cable thermal resistivity is commonly computed assuming that the surface of the earth in the neighborhood of the cable installation is an isothermal. Kennelly made this assumption in 1893 and it is still being used. This assumption allows for the application of the image method to compute the external to the cable thermal resistance \(T_4\). The following expression results from the image method:

\[
T = \rho \frac{1}{A} = \rho \frac{L}{2\pi} \ln \left( \frac{4L}{D_e} \right) \tag{5}
\]

The thermal resistance of the layers external to the cable \(T_4\) must also include the duct when present, and the air inside. The duct itself is of tubular geometry and it very easy to model, however, the treatment of the air inside of a duct is a complex matter. The heat transfer is dominated by convection and radiation and not by conduction. There exist simple formulas, which have been obtained experimentally and that work fine for the conditions tested \[5\]. A software code by Matlab is provided to calculate the ampacity at different cases and the flowchart that explained the program is shown in Figure 2.

### 3. Factors affecting cable ampacity

#### 3.1 Effect of soil resistivity

Dry soils have much higher thermal resistivity than moist soils. With sufficiently high ampacity thermal, run-away conditions can occur. If cable current is high enough, it will generate sufficient heat and if it is maintained for a long enough time, the soil will become unstable and the circuit will have to be de-rated or overheated. Cable ampacity varies with change of soil resistivity, for both with-conduit and the conduit-less cable. Cable ampacity is proportional to soil conductivity; rising soil conductivity dissipates more heat, and increase cable ampacity.

#### 3.2 Effect of cable depth

Depth affects the ampacity of cables that buried with conduit and conduit-less, in both homogeneous and heterogeneous soil. Soil conductivity is reduced by increasing the cable depth in the soil as well as less heat dissipation, less ampacity. The closer the cable to earth’s surface, the rate of cable ampacity changes will increase \[7\].

### 4. Test arrangement

#### 4.1 Theoretical study for ampacity

A computer program has been proposed using MATLAB to calculate the current carrying capacity (ampcity) for different underground cables. The flowchart is presented in Figure (1). The program takes into account the steady state conditions which based on the formulas in IEC standards. Equation (1) is used to calculate the cable ampacity and the parameters of the equation (1) should be separately calculated dependant on the various factors like cable construction types, installation types, installation environment. Steady state conditions is considered when the current flow through the cable is at a constant value and the temperature of the cable is also constant i.e. the heat generated is equal to the heat dissipated. The temperature depends on the type of cable and XLPE construction is chosen where the maximum temperature normally for steady-state is 90°C.
The MATLAB program is provided to calculate the cables ampacity for single bonded, double bonded and double bonded emergency with equal load. The ampacity is calculated at different grounding mode and comparing it with manufacturers based on IEC and it is shown in Table I and Figures from Figure 3 to Figure 6 for the following conditions; flat and trefoil formation, soil resistivity is 1.2 °C.m/w, the ground temperature at 25°C for cable sample 38/66 kV [8]. The thermal resistivity of soft depends on the type of soil encountered as well as the physical conditions of the soil. The conditions which most influence the resistivity of a specific soil are the moisture content and dry density. As the moisture content or dry density or both of a soil increases, the soil resistivity decreases. The structural composition of the soil also affects the soil resistivity. The shape of the soil particles determines the surface contact area between particles which affects the ability of the soil to conduct heat. Figure 3 and Figure 4 show the variation of ampacity for cable with soil resistivity and soil temperature, respectively. For underground cable system the main heat transfer mechanism is by conduction. Since, the longitudinal dimension of a cable is always much larger than the depth of the installation, the problem is considered a two-dimensional heat conduction problem. Figure 5 shows the effect of depth on cable ampacity and Figure 6 shows the variation of ampacity with cable temperature.

### Table 1. Comparison of cable ampacity between single circuit and double circuits with manufacturers

<table>
<thead>
<tr>
<th>Bonded number</th>
<th>Ampacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>240 mm²(Amp.)</td>
</tr>
<tr>
<td>Single Bonded</td>
<td>Flat</td>
</tr>
<tr>
<td></td>
<td>Trefoil</td>
</tr>
<tr>
<td>Double Bonded</td>
<td>Flat</td>
</tr>
<tr>
<td></td>
<td>Trefoil</td>
</tr>
<tr>
<td>Double Bonded Emergency</td>
<td>Flat</td>
</tr>
<tr>
<td></td>
<td>Trefoil</td>
</tr>
<tr>
<td>Manufacturers</td>
<td>Flat</td>
</tr>
<tr>
<td></td>
<td>Trefoil</td>
</tr>
</tbody>
</table>

![Figure 2. Flowchart of the Matlab program used for ampacity calculation](image-url)
4.2 Experimental study (Calibration of the temperature method)

The calibration should be carried out in a draught-free situation at a temperature of \(20 \pm 5 \, ^\circ C\). Temperature recorders should be used to measure the conductor, oversheath and ambient temperature simultaneously. The calibration should be performed on a minimum cable length \(10 \, m\), taken from the same cable under test. IEC adopts a cable system test approach and requires a minimum of \(10 \, m\) of the cable. The length should be such that the longitudinal heat transfer to the cable ends does not affect the temperature in the center \(2 \, m\) of the cable by more than \(1 \, ^\circ C\). During calibration and during the test of the main loop should be calculated according with either IEC 60287 or 60853\[9\], based on the measured external temperature of the oversheath (TC\(_S\)). The measurement should be done with a thermocouple at the hottest spot, attached to or under the external surface. The hottest current should be adjusted to obtain the required value of the calculated conductor temperature, based on the measured external temperature of the over-sheath \[9\]. The cable that used for calibration should be identical to that used for the test, and the way (path) of heat should be identical. After stabilization has been reached the following should be noted and drawing the curve as in Figure 7.

- Ambient temperature
- Conductor temperature
- Over-sheath temperature
- Heating current

The heating currents in both the reference loop and the test loop were kept equal at all time, thus the conductor temperature of the reference loop in representative for the conductor temperature of the test loop. The tests elevated temperature is carried out two hours after thermal
equilibrium has been established, it must develop a consistent heating cycle to maintain the conductor temperature adjustment generally cannot be made in sufficient time during testing due to the large thermal time constants of high voltage cables. In this test, the cable sample 38/66 kV – CU/XLPE/LEAD/HDPE – 1x 630 mm² with 15m length as shown in Table II and Figure 8.

**Table 2. Heating cycle for xlpe cables**

<table>
<thead>
<tr>
<th>No. of heating cycle</th>
<th>Required steady conductor temp. °C</th>
<th>Heating current at stable condition Amp.</th>
<th>Heating per cycle Total duration hr</th>
<th>Stable temp. hr</th>
<th>Cooling per cycle hr</th>
<th>Voltage Per cycle 2U₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>95-100</td>
<td>1600</td>
<td>8</td>
<td>2</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>72</td>
</tr>
</tbody>
</table>

**Figure 8.** Heating cycle for cable sample 38/66 kV – 1x 630 mm²

Ambient temperature (Lab. Temperature) affects the heating current as shown in Figure 9. Figure 10 shows the relation between heating current with conductor temperature during heating per cycle. The heating current varies with the ambient temperature during heating cycle. Steady state conditions are considered when the current flow through the cable is at a constant value and the temperature of the cable is also constant i.e. the heat generated is equal to the heat dissipated. The temperature depends on the type of cable but XLPE construction is searched where the maximum temperature normally for steady-state is 90°C. The IEC requirement is simply that the conductor be “at this temperature” for at least 2 hours of the current on period.

**Figure 9.** Variation of current with ambient temperature during test period

**Figure 10.** Variation of heating current conductor temperature
5. Conclusions

The theoretical and practical study for cable ampacity estimation under steady state conditions shows that the underground cable ampacity depends on the cable geometry installation, its depth as well as on the soil thermal resistivity. Cable ampacity is proportional to soil conductivity; when soil conductivity increases, cable ampacity will be increased. The results show that the cable ampacity decreases with the increase of cable depth installation under soil surface. By using MATLAB with the steady state conditions based on IEC standards and comparing with manufacturers, it gives good results. In facts that stand out the importance of interaction with the manufacturers, designer and installers of the line for attainment of coherent data with the reality. The maximum operating temperature of a cable is typically limited by its insulation material but can also be limited by the maximum temperature which the surrounding environment can be withstood without degradation.

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