Software Package for Polymeric Power Cable System Design

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ABSTRACT
As High voltage cables mainly used in congested locations such as down towns, laying cables in many locations were affected by the existing underground services i.e. gas, water, etc. The executed cable routs may widely differ than that originally planned due to un-documented underground difficulties. In addition to that cable arrangement may get changed due to similar circumstances and/or due to narrower corridor. In 220 Kv cable network in Tripoli-Libya, contractor and designer of the system had to re-route the cables in few sections and change the cable arrangement from triangle to flat in few other sections. A proper software recalculates the effect of change laying condition on the cable performance would be highly appreciated. This paper presents a developed software package calculates the minimum cross section area required for a given power network and calculates exact ampacity, induced voltage and permissible value of short circuit current according to the laying conditions in the given region.

1 INTRODUCTION
Selecting the kind and size of the cable required to carry certain given power does not only depend on the cross-sectional area of the conductor but also on many other important factors. Cable ampacity is determined based on the maximum temperature allowed on operation, thermal properties of the cable itself, the surrounding environment, methods of earthing the metallic sheath of the cable, arrangement of the cables, and number of cables in laid in the same trench. This means that it depends on the rate of cooling the generated heat in the cable to the surrounding environment.

Metallic sheath in the cable is used to prevent the leakage of humidity to the insulator and to carry the short-circuit current, so it must have an appropriate thickness and should be from conducting material, therefore the short circuit level of the system, where the cable is intended to be used, shall be considered when deciding choosing or designing suitable cables.

Cable metallic sheaths are grounded by various methods. A solid bonding method presents the simplest solution. But the grounded sheaths produce large cable losses. A single-point bonding method is applied in case of short route and less than two joints, and a cross bonding method is applied in case of long route and many joints. Special bonding methods may be applied to reduce the cable losses. Bonding produces standing sheath-induced voltages, while the cable system shall be designed to operate without jeopardizing the equipments to any dangerous situation that may be caused by excess voltage that may be induced over its metallic sheath. Therefore induced voltage has to be limited not to exceed the limiting maximum sheath voltage defined by international standards.

2 POLYMERIC POWER CABLE SYSTEM SOFTWARE (PPCS)
Polymeric Power Cable System software (PPCS) designed to be friendly used and tailored to different engineer's needs, such as a quick estimation to the cable size for a given load and laying conditions. Exact cable ampacity when cable parameters, construction, laying methods and bonding techniques used all are known. Recalculate cable ampacity, and induced voltage when laying conditions change during cable laying (i.e. forced to change due ground obstacles such as other services, narrow corridor, soil changes ...etc.).

Three sections form PPCS and all equations used are the IEC standard system of equations. The power cable design software is designed to assist the user to find the most appropriate cable size considering climatic conditions, bonding and earthing methods and all aspects that may affect cable ampacity. PCSS main flow chart is shown in figure (1).

3 AMPACITY CALCULATIONS
As this step aimed at calculating the exact ampacity of a cable, all necessary information about cable construction has to be available. Flow chart is shown in figure (2). Ampacity in 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. There are three standardized Ampacity ratings:
Steady state, transient (or emergency) and short-circuit. The temperature rise in the cable is due to the heat generated in the conductor \( (I^2R) \), in the insulation \( (W_d) \) and in the sheath and armour \( (\lambda I^2R) \) with allowance being made by multiplying each of these by the thermal resistance of the layers through which the heat flows \( (T) \).

Ampacity computations of power cable require solution of heat transfer equations which define a functional relationship between the conductor current and temperature within the cable and in its surroundings. The heat is transferred through the cable and its surroundings in several ways.

The maximum permissible current rating is the loading in amperes which, applied continuously until steady conditions are reached, will produce the maximum allowable conductor temperature. Steady state is reached when the rate of heat generation in the cable is exactly equal to the rate of heat dissipation from the surface of the cable. This steady state is the only condition considered when calculating the maximum permissible continuous current rating.

By applying the thermal equivalence of Kirchhoff’s and Ohm’s law to the circuit shown in figure (3), equation (1) is obtained \([1]\).

\[
\therefore I = \left[ \frac{\Delta \theta - W_d [0.5T_1 + n(T_2 + T_3 + T_4)]}{RT_1 + nR(1 + \lambda_1)T_2 + nR(1 + \lambda_1 + \lambda 2)(T_3 + T_4)} \right]^{0.5}
\]

However, this equation has to be adjusted for catering to the effect of intensity of solar radiation, for cases of cables laid in free air and directly exposed to the solar radiation.

The last equation contents many factors, these factors are as shown in the flow chart in figure (2); are calculated as following \([1]\).

\(a.\) Calculate temperature difference \((\Delta \theta)\).
This is the maximum permissible difference of operating temperature (between the cable and the ambient temperature). The maximum operating temperature varies according to the type of insulation used. The ambient temperature is usually taken as 30°C for above ground installations and 20°C for underground installations.

\(b.\) Calculate dielectric loss \((w_d)\).

The dielectric loss per unit length in each phase is given by equation.

\[W_d = \omega \times C \times V^2 \times \tan \delta \quad (W/m)\]

where \(C\) is the electrical capacitance and \(V_0\) is the phase-to-to-ground voltage.

\(c.\) Calculate A.C. resistance \((R)\).

The a.c. resistance per unit length of the conductor at its maximum operating temperature is given by IEC equation.

\[R = R' \left(1 + Y_s + Y_p\right)\]
Where $Y_S$, $Y_P$ are called skin effect and proximity effect factors, respectively

$$R' = R_0 \left[ 1 + \alpha_{20} (\theta - 20) \right]$$

$R_0$ is the DC resistance of the conductor at $20^\circ$C

$$R_o = \frac{\rho_{20}}{A} \quad (\Omega/m)$$

where;

$\rho_{20}$ is the electrical resistivity of the conductor material at $20^\circ$C

$\alpha_{20}$ is the temperature coefficient of resistance at $20^\circ$C.

d. Calculate sheath loss factor ($\lambda_1$).

It is convenient to express sheath/screen losses as a fraction of the conductor losses, as both are dependent on the square of current.

The power loss in the sheath or screen consists of losses caused by circulating current ($\lambda_1'$) and eddy current ($\lambda_2''$)

$$\lambda_1 = \lambda_1' + \lambda_2''$$

e. Calculate armor loss factor ($\lambda_2$).

The armor loss represents the power loss occurring in the armor as a factor of total power losses in all conductors.

The calculation of loss factor depends on the type of the armor. (i.e. Non-magnetic or Magnetic armor)

f. Non-Magnetic Armour

The general procedure is to combine the calculation of loss in the armor with that of the sheath. In place of sheath resistance, a parallel combination of sheath and armor can be used. (The root mean square value of sheath and armor diameter replaces the mean sheath diameter).

g. Magnetic armor

For the magnetic armor $\lambda_2$ is calculated according to the armor type (i.e. steel wire or steel tape) and the number of cores in the cable.

h. Calculate of Thermal resistances

Neglecting the thermal resistances of metallic portion, the heat path from the cable conductor(s) to the “sink” of heat, traverses the following items in turn.

Insulation (T1) $\rightarrow$ Bedding (T2) $\rightarrow$ Outer Serving (T3) $\rightarrow$ Ground or air (T4).

The total thermal resistance consists of resistances partly in series and partly in parallel, so that it is necessary to figure out the values of these so called partial thermal resistances. Each partial resistance can be split up into two factors, one being essentially the thermal resistivity of the material and the other a function of the material through which the heat passes (The latter factor being called the geometric factor).

The dimensions of the cable affect the thermal resistance, and calculations can be made in the case of single core cables, as the heat flow is radial to the core.

However, multi core cables offer a very complex problem owing to the distortion of the lines of heat flow. This problem has been resolved by the use of geometric factors \{2\}. The calculation of these factors $T_1$, $T_2$, $T_3$ is dependent on the cable materials and cable type.

4 INDUCED VOLTAGE CALCULATION

The induced voltage $V_s$ within a cable system depends on the mutual inductance between core and sheath, the conductor current and finally on the cable length. To decrease the induced voltage and current, possible methods of earthing are used such as:-

i. 1- Both-end Bonding.

Both ends of the cable sheath are connected to the system earth. With this method no standing voltages occur at the cable ends, as shown in figure (3), this fig explains the maximum induced voltage by mid distance between bonding, which makes it the most secure regarding safety aspects. On the other hand, circulating currents may flow in the sheath as the loop between the two earthing points is closed through the ground.

![Figure (3) induced voltage distribution at both-end bonding](image)


One end of the cable sheath is connected to the system earth, so that at the other end ("open end") the standing voltage appears, which is induced linearly along the cable length as shown in figure (4).

![Figure (4) single-ended bonding](image)
Figure (4) Induced voltage distribution at single-end bonding

k. Cross-Bonding.

This earthing method shall be applied for longer route lengths where joints are required due to the limited cable delivery length. A cross-bonding system consists of three equal sections with cyclic sheath crossing after each section.

Figure (5) Induced voltage distribution at cross-bonding

l. Calculation of the Induced Voltage in Single Circuit.

Any conductor (p), laid parallel with a set of three conductors carrying balanced three-phase currents will have a voltage gradient \( V_p \) induced along its length, given by Equation {4}:

\[
V_p = j \alpha I_p \times 2 \times 10^{-7} \left[ \frac{1}{2} \log \left( \frac{S_{ap}}{S_{bp}} \right) + j \frac{\sqrt{3}}{2} \log \left( \frac{S_{cp}}{S_{bp}} \right) \right] V/m
\]

Where:
- \( I_p \) = r.m.s value of current in conductor p Amps.
- \( \omega \) = angular frequency of the system (2\( \pi \)f).
- \( S_{ap} \) = axial spacing of the parallel conductor and phase “a” conductor.
- \( S_{bp} \) = axial spacing of the parallel conductor and phase “b” conductor.
- \( S_{cp} \) = axial spacing of the parallel conductor and phase “c” conductor.

And these spacing may be in any convenient common unit. It is assumed that the phase rotation is such that:
- \( I_p = a \cdot I_p \) and \( I_c = a^2 \cdot I_p \)

Where:
- \( a = - \frac{1}{2} + j \frac{\sqrt{3}}{2} \)
- \( I_p = I_0 (1+j0) \)
- \( I_0 \) = magnitude of load current

I Trefoil Formation Single Circuit

For cables in trefoil where \( S_{ab} = S_{bc} = S_{ac} \) these equations are reduce to the following equations:

\[
V_a = j \alpha I_p \left( 2 \times 10^{-7} \right) \left[ - \frac{1}{2} + j \frac{\sqrt{3}}{2} \right] \log \left( \frac{2S}{d} \right) V/m
\]

\[
V_b = j \alpha I_p \left( 2 \times 10^{-7} \right) \log \left( \frac{2S}{d} \right) V/m
\]

\[
V_c = j \alpha I_p \left( 2 \times 10^{-7} \right) \left[ - \frac{1}{2} - j \frac{\sqrt{3}}{2} \right] \log \left( \frac{2S}{d} \right) V/m
\]

2 Flat Formation Single Circuit

For the other common formation of cables laid flat in which the axial spacing adjacent cables = S, the sheath voltage gradients are given by the following equations:

\[
V_a = j \alpha I_p \left( 2 \times 10^{-7} \right) \left[ - \frac{1}{2} \log \left( \frac{S}{d} \right) + j \frac{\sqrt{3}}{2} \log \left( \frac{4S}{d} \right) \right] V/m
\]

\[
V_b = j \alpha I_p \left( 2 \times 10^{-7} \right) \log \left( \frac{2S}{d} \right) V/m
\]

\[
V_c = j \alpha I_p \left( 2 \times 10^{-7} \right) \left[ - \frac{1}{2} - j \frac{\sqrt{3}}{2} \right] \log \left( \frac{2S}{d} \right) V/m
\]

3- Calculation of Permissible Short-circuit Current

Short-circuit ratings can be calculated using either the adiabatic method, which assumes that all of the heat generated remains trapped within the current carrying component, or non-adiabatic method, which allow for heat absorption by adjacent materials.

The adiabatic method may be used when the ratio of short-circuit duration to conductor cross-sectional areas is less than 0.1 s/mm\(^2\) \( \{5\} \).

On smaller conductors such as, screen wires, as the short-circuit duration increases the loss of heat from the conductor becomes more significant. In such cases the non-adiabatic method can be used to provide a significant increase in permissible short-circuit current.

5 RESULTS AND DISCUSSION

A load of 47 MVA fed from 30 kV systems by a copper core, XLPE cable. The cable used in Tripoli and buried in flat or trefoil at 0.8 m where the temperature is 20°C. Feeding the PPCS by above data will result in a minimum size of the conductor that should be used under the given conditions as (514.75 mm\(^2\)). However the standard size should be 630 mm\(^2\). For comparison PPCS steps used to calculate ampacity, induced voltage and short circuit capacity during 1 sec for 630 mm\(^2\) single core cable, shown in fig (6), laid in Tripoli when directly buried in ground at depth of 0.8 m in trefoil and flat configuration at ambient ground conditions.
temperature of 20 °C. Bonding is considered as single point bonding. Table 1 summarizes the comparison.

Table 1: Comparative cable ampacity and induced voltage

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>Copper conductor</th>
<th>Copper conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trefoil</td>
<td>1262.86</td>
<td>1259.6</td>
</tr>
<tr>
<td>Flat</td>
<td>1259.6</td>
<td>1259.6</td>
</tr>
<tr>
<td>Maximum Induced Voltage at 500 m</td>
<td>$V_x = V_y = V_z = 80.5$</td>
<td>$V_x = V_y = V_z = 101.54$</td>
</tr>
<tr>
<td>Maximum Induced Voltage at 1000 m</td>
<td>$V_x = V_y = V_z = 160.97$</td>
<td>$V_x = V_y = V_z = 203.07$</td>
</tr>
</tbody>
</table>

The value of permissible short circuit current for the cable during non-adiabatic heating is (91.01 kA).

PPCS is also used to check the ampacity when changing the soil thermal resistivity from region to another. Table 2 summarizes the comparison.

Table 2: Summary of the comparison

<table>
<thead>
<tr>
<th>City</th>
<th>Tripoli</th>
<th>Tubruq</th>
<th>Sebha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil thermal resistivity (k.m/w)</td>
<td>1.2</td>
<td>2.7</td>
<td>2.0</td>
</tr>
<tr>
<td>30 kV single core, &quot;flat&quot; arrangement</td>
<td>Copper conductor</td>
<td>Copper conductor</td>
<td>Copper conductor</td>
</tr>
<tr>
<td>Amplitude (A)</td>
<td>1262.86</td>
<td>944.731</td>
<td>1060</td>
</tr>
<tr>
<td>Induced voltage at 500 m</td>
<td>80.49</td>
<td>60.21</td>
<td>67.56</td>
</tr>
</tbody>
</table>

Conclusions

This paper described a developed software package used to design a system of underground cables, PPCS. The output results of the PCSS when compared to few manufacturers’ tables were found to be excellent and efficient. The paper demonstrated the PCSS results when underground condition or cable laying arrangement changed. From various output results we can concluded the following:

1. Single core cable when laid flat carry slightly less current (0.5 – 2 %) than cables laid in trefoil formation.
2. In single point bonding the value of induced sheath voltage in trefoil formation is less than in flat formation.
3. The cable when laid in Tubruq city (coastal city in north east Libya) has less ampacity (26%) than cables laid in Tripoli, similarly cable laid in Sebha city (a city in south of Libya) has less ampacity than cables laid in Tripoli by (16%). However, induced voltage is high when cables are laid flat and single point bonded when compared to trefoil formation, but the difference becomes lower if cables are cross bonded. As induced voltage increases by distance, single point bonding is not recommended to be used in long lengths.

References

3. Electric Cables – Calculation of the current rating – Part 3: sections on operating conditions reference operating conditions and selection of cable type.