Return to Session

CURRENT RATING OF CABLES INSTALLED IN PLASTIC DUCTS

Christophe MOREAU, EDF R&D, (France), christophe.moreau@edf.fr
Ludovic COURSET, RTE / CNER, (France), ludovic.courset@rte-france.com

ABSTRACT

In relation with current rating calculation described in IEC 60287-2-1 Standard ([1]), this paper shows the results of investigations carried out in order to determine U, V and Y coefficients adapted to the installation of the underground cables in plastic ducts.

The influence of various parameters as the ratio between the internal diameter of the duct and the external diameter of the cable and the nature of the duct are discussed.
Both ducts filled with air and with water are considered.

KEYWORDS

Cable, plastic duct, current rating

INTRODUCTION

With respect to underground cables installed in ducts, the bases of current rating calculation in steady state condition were established in the 1950s by Neher, Buller and McGrath and supplemented in experiments by the data of Greebler and Barnett ([2], [3], [4]). They result from an approach combined between the theory of heat transfer (with some simplifying assumptions) and many experimental data. At that time, the ducts were made with metal, concrete, fibre or earthenware.

Nowadays, the installation of HV underground cables in ducts is commonly used. It makes it possible to proceed to the complete link construction in opening only small sections of trenches at the same time. Consequently, it largely facilitates the establishment of underground links in urban area. Moreover, it has advantages in case of possible replacement or later in dismantling.

IEC 60287-2-1 standard uses the results of the studies undertaken in the 1950s and proposes an empirical formula for the evaluation of thermal resistance between the cable and the duct. This resistance is conventionally symbolized T'4. The formula contains 3 coefficients U, V, and Y which are fixed for a given installation condition.

Up to now, there is no standard value for U, V, Y for the installations using plastic ducts (PVC or HDPE) whereas this type of installation is very largely used.

THERMAL EXCHANGES IN DUCTS

IEC formulae

The thermal resistance between a cable and a duct (T'_4) in steady state condition is given by the formulae (1) issued from IEC 60287-2-1.

$$T'_4 = \frac{U}{1 + 0{,}1\,(V + Y\,\theta_m)\,D_e} \qquad (1)$$

where:

- U, V, Y are constants, depending on the installation conditions
- D_e is the external diameter of the cable (mm)
- θ_m is the mean temperature of the medium filling the space between cable and duct (°C)

This formulae is nowadays widely accepted by the community of cable experts and used in many companies to design underground links. Even if the use of more elaborated software tools (i.e. finite element simulation) could provide a more accurate result there is still a need for simple and agreed formulas as far as they can provide a quick and rather good result.

Basic assumptions

In general heat transfer between a cable and a duct through a filling medium is due to conduction, convection and radiation. Usually, the cable is laid on the bottom of the duct and the theoretical solution of heat transfer is not simple.

In order to combine the thermal theory of exchange with experimental data some simplifying assumptions have been applied:

- ○ Cable and duct are assumed to be concentric cylinders
- ○ External surface of the cable is assumed to be isothermal (outer covering temperature is constant)
- ○ Internal surface of the duct is assumed to be isothermal
- ○ The cable and duct are long enough (no end effects)
- ○ Convection is natural

Expression of thermal resistances

The total heat flow through the filling medium is given by:

$$W_{total} = W_{conduction} + W_{convection} + W_{radiation} \qquad (2)$$

Dividing each part of (2) by the difference of temperature in the filling medium it may also be expressed in steady state condition by (3):

$$1/T'_4 = 1/T_{conduction} + 1/T_{convection} + 1/T_{radiation} \qquad (3)$$

When the filling medium is air, each term of (3) can be calculated according to (4), (5), (6) that can be find in the literature.

$$\frac{1}{T_{conduction}} = \frac{2\pi}{\rho_{air}.\ln\left(\frac{D_i}{D_e}\right)} \qquad (4)$$

$$\frac{1}{T_{convection}} = 4{,}744 \cdot \frac{(D_e)^{3/4}}{1{,}39 + \frac{D_e}{D_i}} \cdot P^{1/2} \cdot (\theta_e - \theta_i)^{1/4} \qquad (5)$$

$$\frac{1}{T_{radiation}} = \frac{\varepsilon.\sigma.\pi.D_e.\left(\theta_e^4 - \theta_i^4\right)}{(\theta_e - \theta_i)} \qquad (6)$$

where:

- ρ_{air}: thermal resistivity of the air (K.m/W)
- D_e: external diameter of the cable (m)
- D_i: internal diameter of the duct (m)
- θ_e: temperature of the cable outer covering (K)
- θ_i: internal temperature of the duct (K)
- P: air pressure (atmospheres)
- ε: emissivity of cable and duct surfaces (assumed to be equal)
- σ: Stephan-Boltzmann const. $5{,}67.10^{-8}$ W/($m^2.K^4$)

Equations (4) and (6) are basic formulas applicable for concentric cylinders.

Considering the mean value $\theta_m = (\theta_e + \theta_i)/2$, equation (6) can be linearised around a mean value of θ_m and expressed by:

$$\frac{1}{T_{radiation}} = 13{,}2.\varepsilon.D_e.(1 + 0{,}0167.\theta_m) \qquad (7)$$

where θ_m is the mean temperature of the air (°C)

Convection is more complex to model. (5) is an empirical formulae issued from studies on thermal transfers carried out by McAdams. Moreover some assumptions are made on the ratio D_i/D_e range and the thermal properties of air are considered constant.

With some limitations eccentric cylinders can be considered from a theoretical point of view. Nevertheless, the particular but common case where the cable touches the internal surface of the duct is not covered.

Combination of model and experience

Generally the approach to combine model and experience is made by linearisation of equations (4), (5) and (7) and adjustment of coefficients to fit to experimental data (see [3]). It is also made use of some refinements taking advantage of the particularities of the application. In particular the effect of the variation of the ratio D_i/D_e that may deeply influence the thermal resistance evaluation is noticed to be shown on a small part of the exchanges (conduction) and has opposite effects on conduction and convection terms.

Finally, with some restrictions on diameter and temperature ranges, the approach results in the simple IEC formulae (1).

The same approach shows that this combination is also applicable for thermal exchanges in pipes filled with oil and the IEC formulae is still relevant in that configuration.

PRINCIPLE OF THE TESTS

HV cables are laid into plastic ducts which are installed into an enclosure. The enclosure is then filled with sand. A constant RMS value of 50Hz current is applied to the cable conductors in order to increase the temperature of the cables and the surroundings.

Temperature measurements are collected at different locations of the test installation and especially at the border or inside the medium comprised between the cables and the ducts.

When the steady-state condition of heat flow is reached, temperature measurements are used to calculate an equivalent resistivity of the medium.

INVESTIGATED PARAMETERS

The data issued from the experiments carried out during the 1950s and the different installation conditions standardized in IEC 60287-2-1 show that influence of various parameters has been investigated in the past.
For the series of tests carried out with plastic ducts filled with air the influence of the following parameters has been considered:

- ○ Nature of the duct material (PVC or HDPE)
- ○ Ratio between the internal diameter of the duct and the external diameter of the cable (from 1,35 to 2,7)
- ○ installation configuration (single phase or trefoil)

Complementary investigations have been carried out with a cable installed in a PVC duct filled with stagnant water.

EXPERIMENTAL TEST SET UP

General

Experimental test set up is represented on figure 1.

The ducts are encased in sand with granular parts sized between 0 to 5 mm. It's comparable to the granularity of a common backfill.

The conductor temperature is kept homogenous all along the cable length. In order to eliminate end effects:

- ○ The ends of the ducts are sealed
- ○ The cable end connections to the current source are thermally insulated.

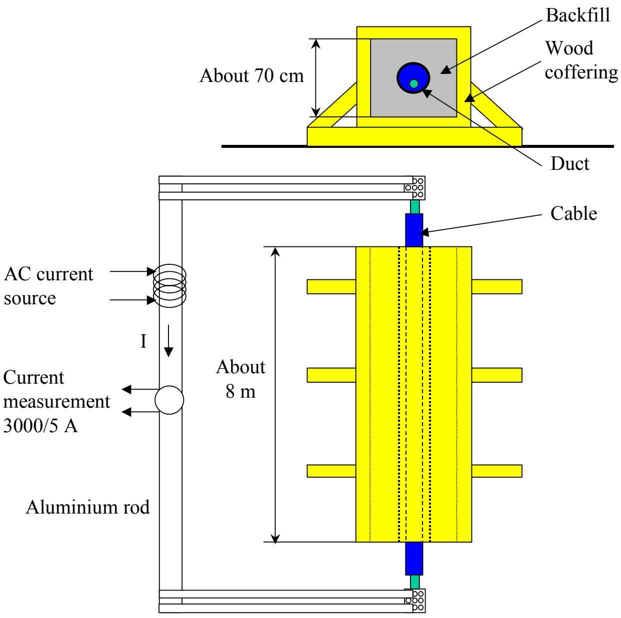

Figure 1: Experimental test set up

The cable is heated by a 50 Hz current circulating in its conductor. In the series of tests, the value of the current is adjusted in order to reach steady state temperatures of the conductor comprised between 50 to 90°C. The steady state temperature is assumed to be reached when the temperature variations of the measurements are less than 1°C per 24 hours.

Instrumentation

Cable, duct and medium surrounding cable and duct are instrumented with type T thermocouples. Each dot on figure 2 shows a thermocouple location.

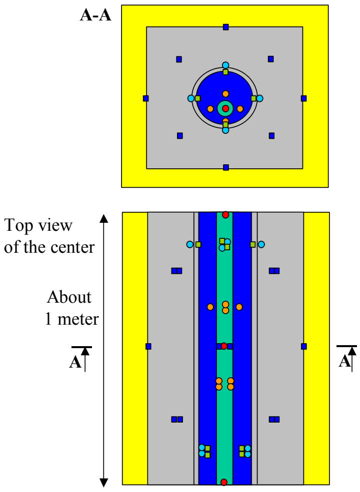

Figure 2: Thermocouple locations

RESULTS WITH AIR AS THE FILLING MEDIUM

General

Investigations has been carried out with conductor temperature comprised between 65°C and 90°C, both in PVC and HDPE ducts. The ratio D_i/D_e is mainly adjusted by the use of two different HV cables with conductor cross sections of 400mm² and 1600mm².

A complementary investigation has been made with 3 HDPE ducts in trefoil configuration.

Distribution of thermal exchanges

Table 1: Ratios of heat transfer modes issued from tests

Heat transfer mode	Ratio
Conduction	10% - 20%
Convection	20% - 30%
Radiation	60%

Basic assumptions used for the theoretical formulation (concentric cylinders) make that conduction is under estimated by the model.

Conduction decreases when the volume of air increases. This effect is compensated by convection.

Radiation exchanges are dominating. They are only increasing by 2% within the full range of filling medium temperature that has been explored.

Return to Session

Influence of ratio D_i/D_e

Investigations completed in the 1950s have considered a small air gap between the cable and the duct. The ratio D_i/D_e was about 1,15.
The present practices on the French network are to use a higher ratio, generally close to 1,5. Tests have been carried out with a ratio comprised from 1,35 to 2,7.

A high ratio means a big air volume. It produces a high resistivity of the filling medium and a big difference of temperature between the outer covering of the cable and the inner surface of the duct.

In order to increase the current rating of the link, the lower the ratio is the better it is. Nevertheless for lower ratios, dry out of backfill in contact with the duct may occur and can affect the current rating.

Influence of the nature of the duct

Two duct materials have been investigated during the series of tests: PVC and HDPE.

No particular difference of behaviour has been noticed when using one nature of duct or the other. It is assumed that U, V and Y coefficients can be applicable for both duct materials.

Evaluation of U, V and Y constants

Figure 3 shows experimental and estimated values of T'_4 represented as a function of the mean value of the filling medium temperature.

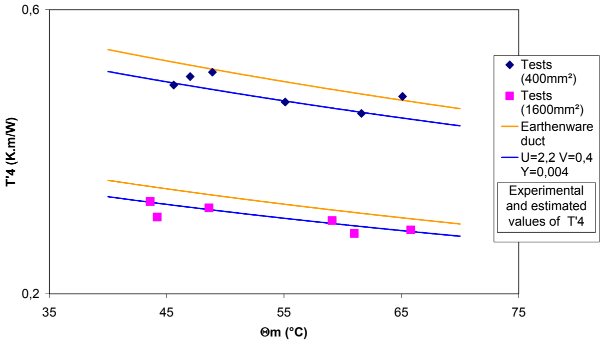

Figure 3: Experimental and calculated values of T'_4 as a function of θ_m (air)

Equivalent thermal resistivity can be define as the thermal resistivity of a solid filling medium ensuring the same global thermal exchange than air as the filling medium. Depending on the configuration, equivalent thermal resistivity is comprised between 3 and 7 K.m/W. As expected it decreases when the temperature of the filling medium increases.

Figure 3 stands out a linear behaviour of $T'_4(\theta_m)$. It's observed that different sets of values (U; V; Y) can provide a good evaluation of T'_4 with an acceptable accuracy. (U=1,87; V=0,28; Y=0,0036) corresponding to installation in earthenware ducts and sometimes used for the dimensioning in plastic ducts give a relatively good estimation of T'_4. Earthenware ducts constants leads to an estimation of T'_4 with less than 15% inaccuracy.

Make use of constants U=2,2 , V=0,4 and Y=0,004 leads to a good compromise limiting the estimation of T'_4 with less than 6% inaccuracy (obtained for trefoil configuration). In classical installation conditions with the use of these constants, the “theoretical” distribution of exchanges occurs as follows: conduction (20%), convection (25%) and radiation (55%).

RESULTS WITH WATER AS THE FILLING MEDIUM

Configuration

Complementary investigation has been carried out with a cable laid in a PVC duct which is filled with industrial water. Water tightness at the terminals is ensured by the use of a PVC reducer tube and a piece of rubber tied up to the reducer and to the cable (see figure 4).

Figure 4: Detailed view of a terminal

A sequence of tests has been completed with the cable conductor temperature comprised between 55°C and 90°C. The temperature of the water was also recorded.

As expected, the thermal exchanges obtained with this configuration are better than when air is the filling medium.

Consequently, the evaluation of T'_4 is less accurate because the temperature difference in the filling medium is lower. The uncertainty on temperature measurements counts for more.

Another point is that the outside temperature of the duct reaches higher values than before and drying out of the backfill occurs sooner.

Return to Session

Evaluation of U, V and Y constants

Figure 5 shows experimental and estimated values of T'_4 represented as a function of the mean value of the filling medium temperature.

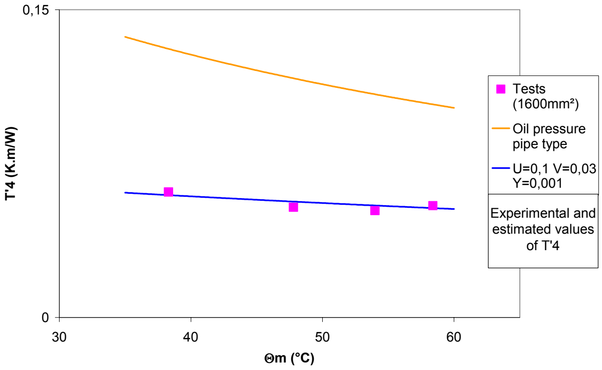

Figure 5: Experimental and calculated values of T'_4 as a function of θ_m (water)

Considering the theoretical formulation of a cable concentric and centred in a duct but using experimental data, (where in practice the cable is laid in the duct) conduction and convection exchanges are balanced.

The dispersion of the equivalent thermal resistivity as defined before is relatively limited in the range of filling medium temperature that has been investigated. A mean value of 0,8 K.m/W can be considered.

Figure 5 stands out a linear behaviour of $T'_4(\theta_m)$. As mentioned before different set of values (U; V; Y) can provide a good evaluation of T'_4 with an acceptable accuracy. (U=0,26; V=0,0; Y=0,0026) corresponding to oil pressure pipe-type cable installation gives a poor estimation of T'_4. It must not be used.

Make use of constants U=0,1 , V=0,03 and Y=0,001 provides an estimation of T'_4 with less than 5% inaccuracy.

CONCLUSIONS

Investigations and tests carried out on thermal exchanges of cables installed inside plastic ducts lead to the following conclusions:

- The format of the formulae given in IEC 60287-2-1 allowing to calculate T'_4 is adapted to the evaluation of thermal exchanges of cables installed inside plastic ducts

- For cable installed in a plastic duct (PVC or HDPE) filled with air:

  - Constants corresponding to installation in earthenware ducts give a relatively good evaluation of T'_4 with less than 15% inaccuracy. It can be acceptable because T'_4 doesn't “weigh” very much in comparison with other thermal resistances involved in the current rating calculation

  - Constants U=2,2 , V=0,4 and Y=0,004 leads to a good compromise limiting the estimation of T'_4 with less than 6% inaccuracy, both for PVC and HDPE ducts

- For a cable installed in a plastic duct (PVC) filled with stagnant water:

  - Constants corresponding to oil pressure pipe-type cable installation must not be used

  - Constants U=0,1 , V=0,03 and Y=0,001 provides a good estimation of T'_4.

REFERENCES

[1] *Electric cables – Calculation of the current rating – Part 2: Thermal resistance – Section 1: Calculation of thermal resistance*, 1994, IEC 60287-2-1

[2] P. Greebler, G.F. Barnett, 1950, "*Heat Transfer Study on Power Cable Ducts and Duct Assemblies*", AIEE vol. 69, pt. I, 357-367.

[3] F. H. Buller, J.H. Neher, 1950, "*The Thermal Resistance Between Cables and a Surrounding Pipe or Duct Wall*", AIEE vol. 69, pt. I, 342-349.

[4] J.H. Neher, M.H. McGrath, 1957, "The Calculation of the Temperature Rise and Load Capability of Cable Systems", AIEE.