



Detailed model for calculation of life-cycle cost of cable ownership and comparison with the IEC formula



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ABSTRACT

The purpose of this paper is to validate the model for the selection of the optimal power cable conductor cross section presented in the IEC Standard 60287-3-2. To this end, a detailed model for the calculation of the life-cycle cost of cable ownership is presented. The formula takes into account both the material and labor costs in the production of a power cable as well as the cost of losses during its operation. Since the formula is fairly complex, a genetic algorithm is proposed to solve the optimization problem. A real-life numerical example is presented.

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1. Introduction

As pointed out in IEC Standard 60287-3-2 [1], the financial and environmental costs of energy, together with the energy losses which result from conductors operating at higher than optimal temperatures, requires that cable size selection be considered in broader terms. The normal utility practice is to minimize the initial cost of the cable system using the smallest required conductor. However, the sum of the initial cost plus the cost of losses over the life of the system should be optimized. To optimize cable system cost, a larger conductor size could be chosen versus one based on the lowest initial cost. This would lead to lower losses, and a lower overall system cost than a cable system with a less than optimal conductor size. When thermal conditions require the use of the largest conductor size, the installation of a second parallel cable circuit can also result in reduced cost of ownership over the life of the cable system.

The problem has been addressed in References [1] and [2] with the explanation of the origins of the equations given in Reference [3]. The equations and examples given in these references are arranged to facilitate the calculation of the most economic conductor size after factors such as system voltage, cable route, cable configuration and sheath bonding arrangements have been decided. Although these factors are not considered in detail in this

paper, they have an impact on both the installation and operating costs of a cable system. The effect on the cost of the installation over its operational life that changing any of the above factors has, can be determined using the principles set out in this paper.

Optimization of power cable system design has been a topic of several recent publications. The subject of an optimal backfill design that provides the maximum ampacity with the acceptable initial investment cost is a focus of Reference [4].

The sensitivities of the cable temperatures on fluctuations in the cable circuit parameters are examined in Reference [5].

Moutassem and Anders [6] studied a problem of configuring the locations of any number of underground cables in a duct bank to achieve the highest total ampacity. They used a genetic algorithm in conjunction with some deterministic approaches.

Reference [7] proposed a method of finding the optimal configuration of the cables in a duct bank taking into account the current harmonics and their effects on the sheath losses. The optimal cable placement that maximizes the total ampacity was found using the Shuffled Frog Leaping Algorithm.

Application of a genetic algorithm for finding the dimensions and location of the most cost-effective shield that limits the magnetic field in a certain area, without restricting the ampacity of the mitigated cable, were discussed in Reference [8]. Their studies include the effects of different materials, phase configurations, shield geometry, and losses.

The fundamental question in all the optimization models pertains to the selection of the best cable construction for a particular

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application. The starting point of such analysis is the cost of the cable system. This topic is discussed next.

2. The cost of the cable system

The total cost of installing and operating a cable during its economic life, expressed in present values, is calculated as a sum of the initial investment and the cost of operating the cable during its forecasted economic life. Thus, the total cost is given as:

$$CT = CI + CL \quad (1)$$

where:

CI = the cost of the installed length of the cable, \$

CL = the equivalent cost, at the date the installation was purchased, of the losses during economic life of N years, \$.

References [1–3] discussed the calculations of these costs. Both components depend on the selected cable construction with emphasis placed on the calculation of the losses over the life of the cable. With the formulae for the cost of losses established fairly precisely, a simple linear model is proposed in Reference [1] that relates the investment cost to the conductor cross section. In proposing this model, little attention was given to the cost of the cable itself. The purpose of this paper is to remedy this shortcoming. In the next section, a detailed mathematical model of the cable cost will be presented followed by a description of the optimization model and numerical results aiming at minimizing the total cost given by Eq. (1).

Since the goal of the optimization model is to obtain a cable cross section that minimizes total cost while satisfying the ampacity requirements, the detailed cost model will focus on the conductor diameter and its cross section relating all the other cable construction components to these values. This will allow verification of the lifetime operating cost model in Reference [1].

3. Cable model

To determine the final cable price all costs must be divided into three main components:

- costs of materials,
- costs of production,
- manufacturer's margin (with the distributors' margin).

To determine materials costs, cable construction should be divided into individual and separate structural layers. The volume (in m^3) of each layer can be described geometrically. Knowing the material of each layer as well as all physical properties of the material and its costs, the price of each cable layer can be determined and thus the total cost of the cable is determined.

The geometric description of a cable can be reduced to three basic layers, structurally different from each other:

- conductor,
- extruded layers
- tapes and wires that are folded or wrapped,

Fig. 1 shows a general construction of two single conductor cables with two different conductor types RMC (Round Multi-wire Compressed) and RMS (Round Multiwire Segmental). Fig. 2 identifies different cable layers with a detailed description given in Table 1.

Differentiating the conductor from the wrapped layers is the result of its multiple layer structure, which is further compressed.

The above description concerns the most prevalent type of HV cables installed under standard conditions in Europe. Conductors

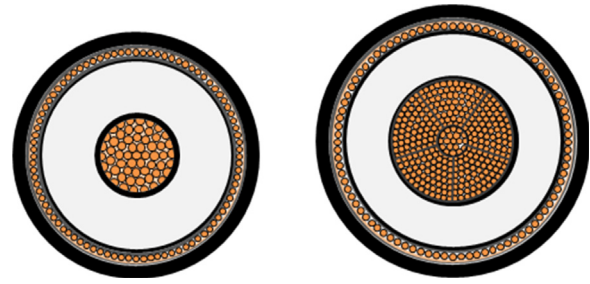


Fig. 1. Construction of a cable 2XS(FL)2Y (according to IEC) stranded RMC (left) and RMS (right).

with cross sections greater than 1000 mm^2 are made of several sectors (Milliken type) as shown on the right of Fig. 1. These conductors have the designation RMS.

In the developments below, the cost of any cable component will be computed from a general equation:

$$C_i = p_i \cdot m_i$$

$$p_i = \frac{C_{LME}}{1000} \cdot K_{cu} \quad (2)$$

$$m_i = \rho_i \cdot V_i$$

where:

C_i = price of the i^{th} component (net), \$/m.

p_i = price of the material of the i^{th} component, \$/kg.

C_{LME} = material price according to LME (London Metal Exchange) in \$/1000 kg.

K_{cu} = exchange rate of the currency unit against the U.S. dollar by official data (e.g., by the national bank of the country), if the price is to be expressed in different units than the USD.

m_i = weight of the material of the i^{th} component, kg.

V_i = volume of the i^{th} component, m^3 .

ρ_i = density of the material of the i^{th} component, kg/m^3 .

3.1. Conductor

For the calculation of the cost of material, the following assumptions are made:

- A stranded multi-wire bundle is represented as a single solid wire. When implementing this simplification, conductor single wire diameter is smaller than the diameter of the multi-wire stranded bundle (with the same cross section). To better represent actual geometry of the cable, the solid conductor diameter should be multiplied by a factor such that the weight and copper content in both conductors will be the same.
- A unit length of 1000 m (counting along the axis of the cable) will be considered.

Appendix A provides a justification for the first assumption with a detailed calculation of the material volume for a multilayer stranded circular or a segmental conductor.

With these assumptions, the price of the conductor can be computed from Eq. (2) with the diameter over the conductor, D_c , (m) given by:

$$D_c = d_c \cdot \delta \quad (3)$$

where:

d_c = diameter of an equivalent solid conductor, m

δ = conductor geometric factor taking into account the difference in diameter between single solid and stranded multi-wire compressed conductor. The values of this parameter for two conductor

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