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Abstract of a Doctoral Dissertation

Optimization of the cost of construction and operation of high voltage power cable lines

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ABSTRACT

During the cable system design process, engineers must perform several calculations to determine the required cable size and the laying conditions that will satisfy ampacity requirements whilst considering the cost constraints imposed by the investor. As pointed out in the IEC Standard 60287-3-2, (2012), 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 practice is to minimize the initial cost of the cable system using the smallest required conductor corss section. However, the sum of the initial cost plus the cost of losses over the life of the system should be optimized. To do so, 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.

The heat generated by an electric power transmitting conductor has to dissipate through the cable insulations and the surrounding soil. To facilitate heat dissipation, the cable is normally backfilled in a controlled manner. The purpose of this “corrective backfill” is to provide a stable thermal environment for the cables, against the effects of seasonal weather factors and variability of natural soil conditions. To reach optimal transmission efficiency, the thermal resistance of the backfill should be as low and as stable as possible. This thermal resistance is affected not only by the thermal resistivity of the backfill material, but also by the dimensions of the thermal envelop.

There are two competing factors affecting backfilling operation. One is the substantial cost involved, and the other is the need to increase cable ampacity. In this thesis, the author presents an optimization algorithm, which tries to balance these two factors. The first attempt to address this problem can be found in (El-Kaddy, 1982) and is further discussed in (Anders, 2005). A recent paper (Ocłoń et al., 2018) presents a numerical solution to the problem.

The thermal analysis of power cables in backfill has been well established and numerous studies confirmed that a relatively small amount of backfill material around the cable leads

to an appreciable increase in cable ampacity. Thermal backfill design involves the determination of several parameters including, for example, thickness, thermal resistivities, width, and so on. These parameters establish both the overall cost of a cable system and its thermal performance.

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. Since the goal of the optimization model is to obtain a cable cross section that minimizes the total cost of the installation while satisfying the ampacity requirements, the detailed cost model focuses on the conductor diameter and its cross section S as well as the backfill dimensions, relating all the other cable construction components to these values.

The total cost CT is given as:

$$CT = CI(S) + CL + C_D + C_{inst} \qquad (1)$$

where:

$CI(S)$ = 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, $
C_D = the cost of the backfill, $
C_{inst} = cable circuit installation cost, $.

The model assumes a load growth during the economic life of the cable, with a given value of the initial value of the current. This growth can be represented by an increase in the peak value as well as a change in the load factor.

The dissertation presents a detailed mathematical model of the cable cost followed by an introduction of a simple linear model proposed in the IEC Standard 60287-3-2 (2012) and proves that it is correct.

The thesis presents a description of the optimization model and numerical results aiming at minimizing the total cost given by (1). Calculation of the cost of backfill is discussed in subsequent chapters.

For the most economic selection of optimal conductor size, all the above costs are expressed as a function of the equivalent conductor diameter, and hence, as a function of its cross section *S* or its diameter.

A typical installation is shown in Fig. 1.

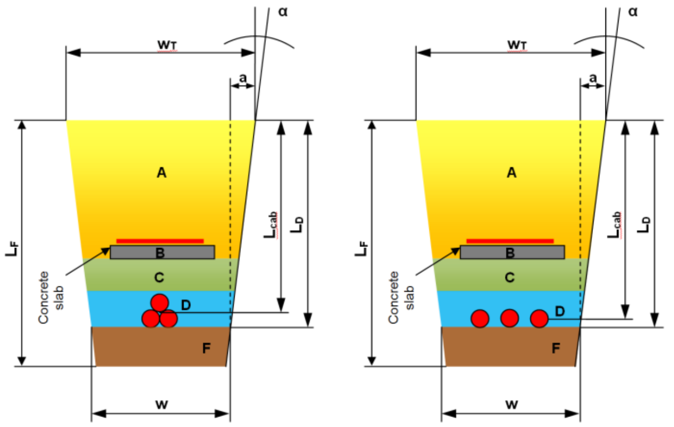

Fig. 1 Cables in backfill laid in trefoil and in flat configuration

Fig. 2 shows the dimensions of the backfill.

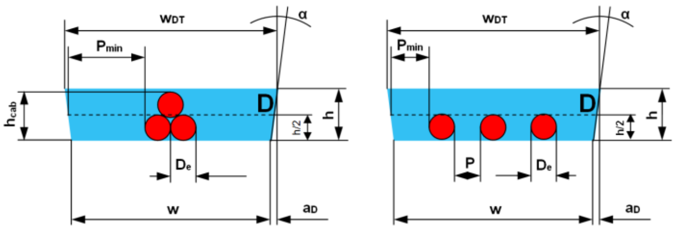

Fig. 2 Cables in backfills surrounded by native soil

The minimal values of w, S and h are functions of the cable diameter D_e.

The values assigned to the design variable are usually restricted by several inequality constraints. Some of these constraints represent physical lower and upper bounds on variables. For example, the constraint $\rho_c \geq \rho_c^l$ represents a lower bound on the backfill thermal resistivity associated with the available backfill material. Also, the constraint $w \leq w^u$ represents an upper bound on the width dictated by the available right-of-way. On the other hand, inequality constraints may represent inter-relationships between design variables. The lower and upper bounds are imposed on all design variables.

The primary purpose of the cost model introduced in this thesis is to find the optimal cable and backfill sizes that minimize the cost of cable purchase, installation and operation.

This requires the use of a suitable optimization method considering the numerical complexity of the problem and calculation time constraints.

There are several possibilities for selecting a suitable optimization algorithm. The author decided to use the genetic algorithm, which is a method belonging to the group of stochastic optimization models.

The proposed approach has been tested on several real cable constructions using real cable and installation costs. The model is described by several geometrical parameters (e.g., width of duct tape), the material parameters (copper or aluminum and polyethylene) and financial ones (e.g., the estimated inflation rate). In the calculations, it was assumed that when the cables are laid in trefoil, the sheaths are solidly bonded whereas, for a flat formation, single point bonding is assumed. These assumptions were selected to demonstrate the importance of the bonding scheme on the overall installation costs.

Table 1 shows the results of the optimization for the model described in the thesis. The optimal cable construction is 630 mm^2 copper conductor for the trefoil formation and 500 mm^2 for the flat arrangement.

Table 1 Optimal diameter of the cable cross section and the total cost of production, installation and operation of this circuit

Cost item	Trefoil	Flat
	Backfill dimensions	
	0.6m x 1.0m	1.1m x 0.5m
	Conductor size (mm^2)	
	630	500
	Cable spacing (mm)	
	77.5	275
Costs ($ x 1000)		
Conductor	43	33
Other layers	17	16.5
Operation	8.25	7
Other costs*	9.25	10
Total cable cost	77.5	66.5
Backfill material	34.25	50.75
Installation	148.75	178.5
Total installation cost	183	229.25
TOTAL COST	260.5	295.75

*Other costs include items such as profit (counted as 10% of the cost), wasted material and labor for making the cable.

In the optimal solution, the cost of the backfill is larger for the flat cable arrangement but because of the difference in the bonding scheme, a larger conductor size is required for the trefoil cable formation resulting in a larger cable cost.

In the example presented in the thesis, several parameters are uncertain. In particular, the cost of copper exhibited large price variations in recent months. Also, the cost of backfill material can vary widely. Dissertation illustrates the dependence of the total cost of the installation as a function of the cost of copper, price of the backfill as well as the effect of the ampacity constraint.

In the Conclusions chapter, it is stated that this thesis extended the models for economic conductor sizing discussed in the literature by presenting a detailed cost analysis of the cable itself. Additionally, a comprehensive optimization problem has been formulated allowing for the simultaneous selection of the conductor size and backfill dimensions such that the overall installation and operating cost is minimized. The final chapter of the thesis also suggests the directions of further research in this area.

REFERENCES

The thesis contains 109 references listed in alphabetical order of the first author's name. Below are the ones cited in this abstract.

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