Investment Cost Analysis with Structural Design of Concrete Duct Bank Power Cables

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Abstract. Capital investment in underground duct bank cables is very expensive. Therefore, the design and planning for underground power cables is important. It is often done with analysis of the power demands minimizing costs over the lifetime of the cables. This work presents an evaluation of underground power cable ampacity and the total costs during the anticipated operational life of the equipment. It was evaluated with variation of concrete duct bank dimensions. Analysis of ampacity depends on temperature. The thermal model of the current study uses a finite element method. The total costs evaluated by the economic model in terms of net present value analysis consist of the initial investment costs and the value of losses over the life of the cable. These were based on installation costs, load factors, annual load growth, the price of energy, the price of demand charges and the forecast discount rate. The results show that cable spacing parameters are a significant factor that influences ampacity. Ampacity can be improved while reducing the losses in power cables. This is because appropriate cable spacing can reduce the effect of Joule heating from neighboring cables. However, this leads to increased construction costs. The total costs of power cables over their lifetime can be reduced by decreasing the horizontal distance between the center of a casing pipe and the side edge of the concrete layer. This is because the contribution of reduced construction costs is more than that of the effect of increased losses. Therefore, the dimensions of the concrete duct bank significantly influence ampacity, the construction costs and the losses of power cables in an analysis of total costs over the lifetime of power cables.

1. Introduction

Underground power systems are widely used in urban areas because they improve the appearance of a city. Additionally, an underground power system is more secure, safe and reliable compared to overhead power systems [1-7]. However, their installation and the material costs are higher [1, 7, 8]. Maintenance and repair times are longer and it can be difficult to find the location of a cable fault [1]. Therefore, an underground cable design should consider energy demand, safety and reliability [7, 9-11].

Underground cable planning is done with the goal of installing new lines or expansions to meet the power demand over the lifetime of the cable at minimum capital costs with a sufficient level of safety and reliability. The total costs of a project consist of anticipated investment and operating costs over the system’s operational life [9, 10, 12-14]. Moreover, economic evaluation is essential to project decision making.
Power cable efficiency for servicing an energy demand is specified by ampacity. This represents the maximum electrical current carrying capacity. It is limited by the critical insulation temperature \[1, 8, 15, 16\]. The construction conditions and material properties determine the cable ampacity. Numerical methods based on heat transfer theory are used to evaluate power cable ampacity \[17-19\]. The international electrotechnical commission standard, (IEC) 62095, is based on finite element analysis. It can be applied for solving more complicated problems than the conventional method \[15, 16, 20-22\]. Several researchers have investigated the effect of geometric configuration on power cable ampacity in a concrete duct bank and with a thermal backfill material \[4, 5, 7, 15, 23-26\]. In various designs, the dimension of the duct bank is a significant factor impacting power cable ampacity.

Generally, the capital investment for cable installation increases with the structural size of a concrete duct bank. Cable ampacity is improved while their temperature is reduced under an operating current \[7, 26\]. Conversely, cable Joule losses decrease at lower conductor temperatures \[10, 17\]. The cost of such losses over the lifetime of the cable may be quite substantial. Several publications present models of economic evaluation for selection of cable sizes by minimising total costs of the project over the lifetime of the cable in terms of net present values \[10-12, 20, 27\]. The mathematical model proposed in the current study includes several parameters describing economic assumptions about cable operating conditions and the rate of load growth \[10, 27\]. Therefore, the design of the structural size of a concrete duct bank should be considered as well as the cable ampacity and the total costs over the system lifetime.

The goal of this work is to present a design with variable concrete duct bank dimension and the effect on power cable ampacity and total costs of the project over the system’s lifetime. To solve this steady state heat transfer problem, a finite element method was applied. An economic model was used for evaluating the capital investment in terms of net present values. The results of this parametric analysis can be used to optimize the design of concrete duct bank power cable systems.

2. Models and calculations

2.1. Thermal model

For analysis of underground power cable ampacity, the system voltage, \(U\), was 115 kV while the frequency of a three-phase system, \(f\), was 50 Hz for high voltage. The cross-sectional area of the underground power cable was 800 mm\(^2\), in a pipe casing. The cable was arranged in a rectangular manner and covered by reinforced concrete in a concrete duct bank.

The power cable in the pipe casing consists of cable conductor, cross-linked polyethylene (XLPE) insulation, a metallic sheath and a non-metallic sheath or an outer jacket. There was a gap between the outer cable, inner pipe and high-density polyethylene (HDPE) pipe casing, as shown in Fig. 1. Table 1 presents the dimensions and thermal properties of a power cable. The parameters in Table 1 used for estimating the cable ampacity were adapted from \[5, 28, 29\]. The metallic sheath is bounded and earthed at a single point. Additionally, the gap in pipe casing is filled with a sand and bentonite mixture (SBM). The SBM can improve the cable ampacity by reducing its thermal resistivity in the vicinity of the cable \[4, 5\]. When the cable core temperature is higher than 90 °C, the XLPE cable insulation melts leading directly to a transmission line malfunction.

The arrangement of concrete duct bank in native soil, with the depth of the cable duct bank at \(D = 2.5\) m, is shown in Fig. 2. The parameter of \(W\) represents the horizontal distance between the center of the pipe casing and the side edge of the concrete layer. The distance between the center of the pipe casing to the top and bottom of the concrete layer is defined by \(H\). The parameter of \(S\) is the spacing between the cable conductors.

The ambient temperature at ground level, \(T_g\), was 30 °C and the native soil thermal resistivity, \(\rho_s\), was 1 K-m/W \[28\]. The IEEE Standard 835 determined the concrete thermal resistivity, \(\rho_c\), of 0.6 K-m/W \[19\]. The SBM thermal resistivity, \(\rho_{sbm}\), was 1.0562 K-m/W \[5\].
Figure 1. Cross-sectional layout and arrangement of a power cable in a pipe casing.

Figure 2. The geometry of a concrete duct bank.

2.2. Analysis for power cable ampacity

Power cable ampacity, $I_{90}$, calculations are required. This yields a solution of the heat transfer equations that define a functional relationship between the conductor current and the temperature of the cable and its surroundings. This was accomplished by assigning a conductor current while calculating the corresponding conductor temperature. For this analysis, the conductor current, $I$, was varied continuously with increasing temperature to the critical temperature, $T_{cc}$, of insulation, 90 °C for an XLPE insulator. The cable ampacity evaluation by FEM was slightly different from the conventional method. Moreover, the FEM can be used to solve complex problems with irregular geometries [7, 13].

Table 1. Dimensions and thermal properties for power distribution system at 115 kV with an 800 mm² power cable in a pipe casing adapted from [5, 28, 29].

| Description            | Radius (mm) | Thermal resistivity $\rho$ (K·m/W) |
|------------------------|-------------|-----------------------------------|
| Copper conductor       | 190         | 2.5×10⁻³                         |
| XLPE Insulation        | 370         | 3.5                               |
| Copper sheath          | 385         | 2.5×10⁻³                         |
| PE jacket              | 430         | 3.5                               |
| HDPE casing pipe       | 800         | 3.5                               |

The FEM was used to solve the heat conduction equation by considering steady state heat transfer in two dimensions at any point in the $xy$ plane around the power cable, calculated by solving:

$$\frac{1}{\rho} \frac{\partial^2 T}{\partial x^2} + \frac{1}{\rho} \frac{\partial^2 T}{\partial y^2} + Q = 0$$  \hspace{1cm} (1)

where $T$ is temperature (°C) and $\rho$ is the thermal resistivity of the material (K·m/W). $Q$ is the heat generation rate in the cable dependent which depends upon the heat losses per unit of cable volume (W/(m³)), defined by:

$$Q = \frac{W}{A_{hs}}$$  \hspace{1cm} (2)

where $A_{hs}$ is the cross-sectional area of the heat source. $W$ denotes the cable heat losses per unit length (W/m). It is also called Joule losses. The heat losses of conductor $W_c$, dielectric $W_d$ and sheath $W_s$ losses (except those caused by circulating currents) can be calculated using the following equation and
the material electrical properties of the IEC 60287-1-1. The cable core temperature, $T_{cc}$, was 90 °C and the cable sheath temperature, $T_{sc}$, was 70 °C [26].

The heat losses of conductor per unit length of the power cable is given by:

$$W_c = I^2 R_{c,ac}(T_{cc})$$  \hspace{1cm} (3)

where $I$ is the conductor current (A). It was varied to power cable ampacity, $I_{90}$. The $R_{c,ac}(T_{cc})$ is the alternating current electrical resistance of the conductor at temperature $T_{cc}$.

The dielectric heat losses per unit length of the power cable are given by:

$$W_d = \omega C \left( \frac{U}{\sqrt{3}} \right)^2 \tan \delta$$  \hspace{1cm} (4)

where $\omega$ is the angular frequency of a three-phase system (rad/s) for an $f$ value of 50 Hz, $C$ is operating capacitance per phase and unit length, 0.227 µF/km, and $\tan \delta$ is dielectric loss factor of 0.001.

The heat losses of the sheath per unit length of the power cable are given by:

$$W_s = W_c (\lambda'_s(T_{sc}) + \lambda''_s(T_{sc}))$$  \hspace{1cm} (5)

where $\lambda'_s(T_{sc})$ is loss factor due to circulating currents at a temperature, $T_{sc}$, and $\lambda''_s(T_{sc})$ is the loss factor due to eddy currents at temperature, $T_{sc}$.

The loss due to circulating currents in the sheath is negligible [17]. In the two dimensional thermal model, it can be assumed that the right and left boundary extends to 10 m from the center of the cable duct bank. The height of the boundary from top to bottom is 10 m. The right left and bottom boundaries are assumed to be the thermal insulation. The top edge (the ground level) temperature $T_g$ was set to 30 °C [4, 5].

2.3. Economic analysis of the total cost of underground power cable

Decision making in project management is done to yield the lowest total project cost. In an underground cable duct bank, the total cost for evaluation in the economic value of various dimensions of a concrete duct bank power cable is considered to include installation and operating costs during its projected operational life, expressed in terms of net present values.

The investment and operating costs have fixed and variable parts. The fixed part of the investment costs is the price of the power cable, while the variable part relates the construction work to the price of the cable. The operating costs also have fixed part and a variable part. The fixed cost is related to the costs of losses in the cable. These practically do not depend on the sizing of duct bank, while the variable part is related to the Joule losses of a power cable.

The economic value for the various dimension of concrete duct bank power cables considered the variable parts of the total project cost $CT$, calculated by:

$$CT = CI + CJ$$  \hspace{1cm} (6)

where $CI$ is the cost of an installed length of cable duct bank, $$/m$. $CJ$ is the equivalent cost at the date the installation was purchased, i.e., the net present value, of the joule losses during the anticipated operational life of $N$ years, $$/m.$

2.3.1. The cost for installing cable duct bank

The installation costs of cable duct bank consist of the civil works costs and the cable cost. In this case, the cable cost is constant therefore this not comparable.

Table 2 shows typical civil engineering works for cable and their corresponding costs [26].

The civil works costs of cable duct bank can be changed by varying the design variables. Based on the data given in Table 2, a total installation cost function $CI = C (H, W, S, D)$ may be formulated as:
where $H$, $W$, $S$ and $D$ have the units of meters. The total costs for installation of cables was based on the research conducted by Perović in 2018 in the suburbs of the northeastern USA. However, these costs do not differ significantly from the current total installation costs for other regions of the USA [26].

**Table 2. Costs of civil engineering that are typical for laying cables adapted from [26].**

| Civil engineering work                          | Cost | Cost term |
|-------------------------------------------------|------|-----------|
| Removal of existing asphalt pavement            | 13.5 $/\text{m}^2$ | $(2 \times W) + S + 0.6$ |
| Excavation and disposal of soil                 | 47.0 $/\text{m}^2$ | $(2 \times W + S) \times ((S / 2) + H + D)$ |
| Installation of the cable bedding (concrete cost)| 23.5 $/\text{m}^2$ | $(2 \times W + S) \times (2 \times H + S)$ |
| Repaving with asphalt                           | 17.8 $/\text{m}^2$ | $(2 \times W) + S + 0.6$ |

2.3.2 The joule losses during an anticipated operational life

To calculate the net present value of the costs and losses, it is necessary to choose appropriate values for the future development of the load, annual increases in the kW-h price and annual discount rates over the anticipated operational life of the cable. The calculation is as follows [27]:

$$CJ = \sum_{i=1}^{N} \frac{I_0^2 \times R_m \times N_p \times N_c \times ((T \times P) + D) \times [(1 + a)^2 + (1 + b)]^{N-1}}{(1+i)^N}$$ (8)

where $I_0$ is maximum load in the first year, $R_m$ is the mean conductor resistance per unit length, $L$ is cable length, $N_p$ is number of phase conductors per circuit, $N_c$ is the number of circuits carrying the same type and value of load, $T$ is operating time at maximum Joule loss ($T = \mu \times 8760$), $\mu$ is load loss factor ($\mu = p \times LF + (1-p) \times LF^2$), $LF$ is the load factor and the value of the constant, $p$, can be taken as equal to 0.3 for transmission circuits. $P$ is cost of one watt-hour at a relevant voltage level $$/\text{W-h}, D$ is demand charge each year $$/\text{W-year}, a$ is the increase in the load per year, and $b$ is the increase in the cost of energy per year.

The mean conductor resistance, as an average of the values during the first and last years, is as follows [27]:

$$R_m = \frac{R_{20}}{2} \times \left( \frac{\beta + T_a}{\beta + 20} \right) \times \left( \frac{1}{1 - \gamma} + \frac{1}{1 - g \gamma} \right) \times (1 + \lambda_1)$$ (9)

$$\gamma = \left[ \frac{I_0}{I_{90}} \right]^2 \times \left[ \frac{T_{cc} - T_{a}}{\beta + T_{cc}} \right]$$ (10)

where $R_{20}$ is AC resistance of the conductor at 20 °C, $\beta$ is the reciprocal of the temperature coefficient of resistivity of the conductor material at 0 °C. For copper, $\beta$ is 234.5. $T_a$ is the ambient temperature, 30 °C, and $\lambda_1$ is sheath loss factors, $g = (1 + a)^2 \times (N^{-1})$. 

$CI = 31.3 \times ((2 \times W) + S + 0.6) + 47 \times ((2 \times W) + S) \times (D + (2 \times H) + S)$ (7)
Figure 3. (a) The FEM mesh in duct bank power cable and (b) Thermal distribution of a traditional design using FEM.

3. Sample calculation
This section presents a procedure for economic analysis to arrive at the overall cost of a concrete duct bank containing underground cables over the projected operating lifetime of the line. The dimensions of the concrete duct bank system were varied to support effective decision making. The values of the design variable fell between the lower bounds, depending on the dimensions of pipe casing pipe and concrete cover and the upper bounds, identical to those of Ocloń et al. [4, 5]. The values of $H$ and $W$ were 0.09 – 0.4 m with an $S$ value of 0.16 – 0.6 m.

The traditional design of a concrete duct bank has dimension of $W$ equal to 0.180 m, $H$ of 0.180 m and $S$ of 0.250 m [29]. The results of the analysis of ampacity and the cross-sectional area determined optimal values of $A_c$, of concrete corresponding to the traditional design and also to the concrete resistivity, $\rho_c$, at 0.6 K·m/W, which has an $I_{90}$ value of 902 A, $CI$ of 127.04 $/m, $CJ$ of 1,484.22 $/m and $CT$ of 1,611.26 $/m. Fig. 3 shows the FEM mesh in a duct bank power cable and thermal distribution determined using FEM.

3.1. Ampacity with single design variation
The results of determining cable ampacity at different structural sizes of concrete duct banks with $H$ and $W$ ranging from 0.09 – 0.4 m and $S$ from 0.16 – 0.6 m with a concrete thermal resistivity of 0.6 K·m/W are shown in Fig. 4. The cable ampacity increased as the size of each concrete dimension following a polynomial function. The design of the concrete duct bank can improve the cable ampacity with varying $H$ and $W$ parameters from the lower to upper bound by -0.78% to 1.22% and varying the $S$ parameter from its lower and upper bounds by -8.43% to 11.64% when compared to the traditional design. Additionally, the lower value of $S$ parameter results in insufficient cable capacity during last year of its operational life (887.922 A). The smallest possible value of $S$ is 0.23 m.

3.2. Costs of civil works with single design variation
Although ampacity is important in the design of underground cable systems, construction costs of a concrete duct bank are the main point to consider in project evaluation. The construction costs of a concrete duct bank change with the dimensions of the design as is shown in Fig. 5. The construction costs of a concrete duct bank increased with the values of the $H$, $W$ and $S$ variables in a linear manner. The value of $H$ influences the construction costs of a concrete duct bank by -4.06% to 9.93%. The rate of change was 57.34 $/m. The construction cost also increased with the value of $H$ from -25.15% to 61.47%. Its rate of change was 354.94 $/m while $S$ increased by -3.69% to 61.33%. Its rate of change
was 218.6 $/m compared to the traditional design. The costs are most sensitive to changes in the $W$ distance than to $H$ and $S$.

3.3 Present value of the Joule losses with single design variation

The net present value of the Joule losses during the anticipated operational life is a significant factor in project evaluation. In this section present, the net present value of the Joule losses over 30 years with electrical and financial data are shown in Table 3. The various structural sizes of concrete duct banks are shown in Fig. 6. The Joule losses decreased with the size of each concrete dimension following a polynomial function. A concrete duct bank can reduce Joule losses by 0.23% to -0.41% by varying the $H$ and $W$ parameters from their lower to upper bounds. Varying $S$ from its lower to upper bounds reduced losses by 0.26% to -3.27% compared to the traditional design. Moreover, varying the $S$ parameter more efficiently reduced Joule losses of the cables than varying $H$ and $W$.

![Figure 4. Cable ampacity, $\Delta I_{90}$ while varying the dimensions of the concrete duct bank.](image1)

![Figure 5. Construction costs, $CI$ versus as a function of the dimension of the concrete duct bank.](image2)

Table 3. Electrical and financial data for the current case study.

| Data                              | Symbol | Cost term       |
|-----------------------------------|--------|-----------------|
| Anticipated operational life      | $N$    | 30 year         |
| Maximum load in the first year    | $I_0$  | 500 A           |
| Load factor                       | $LF$   | 0.85            |
| Cost of energy                    | $P$    | $90 \times 10^{-6} \cdot $(W·h)$^{-1}$ |
| Demand charge per year            | $D$    | 0.5 $(W\cdot year)^{-1}$ |
| Annual increase of load           | $a$    | 2 %             |
| Annual increase of cost of energy | $b$    | 7 %             |
| Annual discounting rate           | $i$    | 7 %             |

3.4 Total specific costs for economic evaluation with single design variation

Transmission planning is aimed at installing new lines or expanding existing utilities to meet the power demand at minimal total costs with a sufficient level of quality and reliability. The total specific variable costs for economic evaluation in the current study involved a summation of the construction costs and the Joule losses during the anticipated operational life of the project, as is shown in Fig. 7. The value of the total specific costs when the parameter, $W$, increased followed a linear function from 1,582.70 $/m to 1,683.32 $/m. Changing the value of $W$ produced a monotonic increase in the total specific costs due to the effects of increasing costs of the concrete duct bank. However, the results of varying the $H$ and $S$ values increased following a polynomial function. The lowest and highest of the total specific costs of $H$ were 1,609.29 $/m at 0.11 m and 1,617.84 $/m at 0.40 m. Additionally, the lowest and highest of the total specific costs of $S$ were 1,606.41 $/m at 0.32 m and 1,640.71 $/m at 0.60 m. Changing the $H$ and $S$ parameters had a non-monotonic response on the total specific costs.
Increasing the $H$ and $S$ parameters increased the construction costs but reduced Joule losses. Therefore, the variation function of the total costs based on changes in various parameters is a disparate function.

![Figure 6. The present value of Joule losses, $C_J$ versus each of the dimensions of the concrete duct bank.](image)

![Figure 7. The total costs of the concrete duct bank power cable, $C_T$ versus each of the dimensions of the concrete duct bank.](image)

For the purpose of determining the concrete duct bank dimensions for minimal total specific costs over the lifetime of a unit length of cable, the current study examined two cases with different dimensions. Case 1 defined $H = 0.18$ m, $S = 0.32$ m (the minimum total specific cost point) and varied $W$ from $0.09 - 0.4$ m. In Case 2, $H = 0.18$ m, $W = 0.09$ m (the minimum total specific cost point) and $S$ was varied from $0.16 - 0.6$ m. The minimum total specific costs over the lifetime of cable per unit length in both cases was the same at $H = 0.18$ m, $W = 90$ m and $S = 0.32$ m. This decreased the total costs by 2.09% (1,577.57 $/m) and improved cable ampacity by 2.99% (929 A) compared to the traditional design, as shown in Fig. 8. The concrete duct bank design for minimal total specific costs over the lifetime of cable per unit length occurred where $H = 0.11$ m, $W = 0.09$ m and $S = 0.32$ m (minimum point with single parameter variation). This decreased the total specific costs by 2.19% (1,576.00 $/m) and improved cable ampacity by 2.55% (925 A) compared to the traditional design.

Finally, this study presents an example of a primary concrete duct bank design to minimize the total costs over its lifetime on the basis of cable length. Additional analysis is needed to determine if there will be any variation in the results due to location, environment, demand load and financial parameters.

![Figure 8. The total costs over the lifetime of cable per unit length analysis, (a) case 1 (b) case 2.](image)

4. Conclusions
A parametric study of the effects of structural design of concrete duct bank power cables on cable ampacity and total specific costs over the lifetime of a power cable system is presented. The analysis
includes an evaluation of cable ampacity by the FEM and measured economic values as net present values.

The sizing of a concrete duct bank substantially affects power cable ampacity and the total costs over an operational lifetime. Ampacity depends on temperature. It can be modeled using a thermal model with finite element analysis. Increased spacing between power cables, $S$, is important to improve power cable ampacity and reduce heating effects. In this case, increased spacing between power cables has a non-monotonic effect on the total costs.

Decreasing the horizontal distance between the center of the casing pipe and the side edge of the concrete layer, $W$, is important to reduce the total costs of over the operational lifetime of such systems, through reduced construction costs. However, the three dimensional parameters have different impacts on minimizing total costs. Varying three parameters during concrete duct bank design is more effective in reducing total costs and improving cable ampacity.

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