FITTING OF HIGH VOLTAGE CABLES IN EXISTING DUCT BANKS UNDER NEW REGULATIONS: THEORETICAL MODELLING AND PILOT PROJECT

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ABSTRACT

ewz, the DSO of the city of Zurich, operates a 150 kV cable network. The cables with a total length of 90 km are installed in concrete duct banks. New and stricter regulations regarding magnetic field emissions complicate the approval process for lines and hence the use of existing duct banks for renewal or new connections. The current revision of the directive poses a substantial risk that new cables in existing duct banks will violate the future regulation. A depreciation of significant asset values is a possible result. In this paper, solution options based on three-core HV cables are analysed considering thermal and mechanical constraints. The challenge of these solutions is to fit and operate three-core HV cables in duct banks designed for single-core cables. A pilot project will show whether this solution is feasible.

INTRODUCTION

The 150 kV grid feeding the 15 HV/MV substations of the Zurich has a total length of 160 km. 90 km are underground cables located in the city centre and installed in concrete duct banks. They protect the cables from damage, offer a good thermal conductivity and permit cable renewal without road work. All developers in the Zurich coordinate their projects to minimize road work. Therefore, ewz has been constructing duct banks for future grid requirements together with road work of other utilities. Most of the existing cable routes, including 40 km of reserve duct banks, have been built before the "Ordinance on the protection against non-ionising radiation (NISV)" [1] came into effect in 2000. The NISV comprises magnetic field limits and approval processes. The resulting constraints complicate the renewal of existing cables and the use of reserve duct banks for new connections. These duct banks constitute a high value asset for ewz. Therefore, it is crucial for ewz to find a solution which allows the use of existing duct banks under the new regulations.

PLANNING CHALLENGE

Long-term planning for the supply of Zurich from the transmission grid comprises the reduction from four to three 220/150 kV stations and increased capacity of transformer units. The two connections stations Obfelden and Samstagern located in the south outside of Zurich will be replaced by the new 220/150 kV station Waldegg (WAL) in the city. Therefore, new cable connections have to be installed in previously built reserve duct banks. Fig. 1 shows the new concept and the corresponding reserve duct banks.

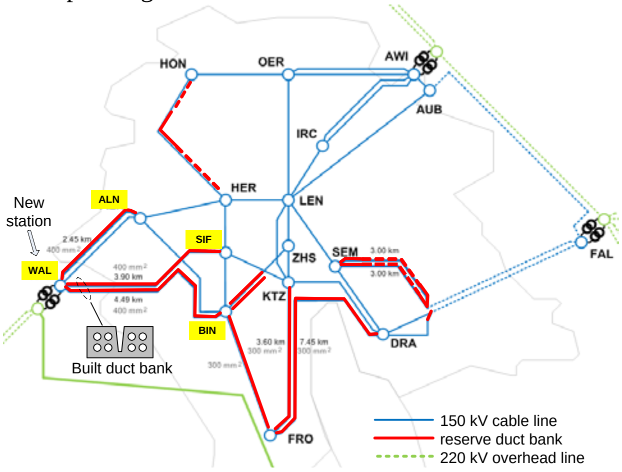


Figure 1 New supply concept and reserve duct banks

Since 2000, the NISV sets limits for magnetic fields. The limit is 1 μT in locations with sensitive utilization and 100 μT for all other accessible locations. Renewal of lines in existing routes is permitted if the magnetic fields of new installations do not exceed those of the previous installations. The approval process for pulling in a new cable includes a right of objection for all neighbours within the double width of the 1 μT corridor or within a minimal distance of 20 m on both sides of the planned route. In a densely populated city like Zurich, this leads to approval procedures of unforeseeable duration. In future, the regulations are expected to become stricter. The NISV is currently renewed and a draft NISV has already been published. It requires compliance with the 1 μT limit also for routes that have been built before 2000.

SOLUTION OPTIONS

Various solutions have been evaluated to enable the use existing duct banks and implement the new supply concept. The optimal arrangement of cables and the installation of magnetic shielding present two solutions. However, they cannot always fulfil the magnetic field limits in locations with sensitive utilization. Furthermore, the latter has substantial cost and the disadvantage of road work.

A third solution is the installation of twisted three-core cable instead of three single-core cables. A comparison of the costs showed that this can be an efficient solution for a new route [2]. Therefore, this paper addresses the solution with twisted three-core cables for existing duct banks. Their design leads to low magnetic field emissions and hence a simplified approval process. Then, the project will be reduced to a predictable implementation period of two to three years. This advantage is together with costs a decisive factor in the overall assessment.

The challenge of this solution is that the duct banks have been constructed for single-core cables. Fig. 2 shows the scheme of a standard duct bank in Zurich. It contains eight PE pipes with an inner diameter of 148 mm. A pilot project investigates if it is technically feasible to pull in and to operate three-core cables of sufficient capacity. The paper focuses on the operation specifically the capacity and thermal expansion.

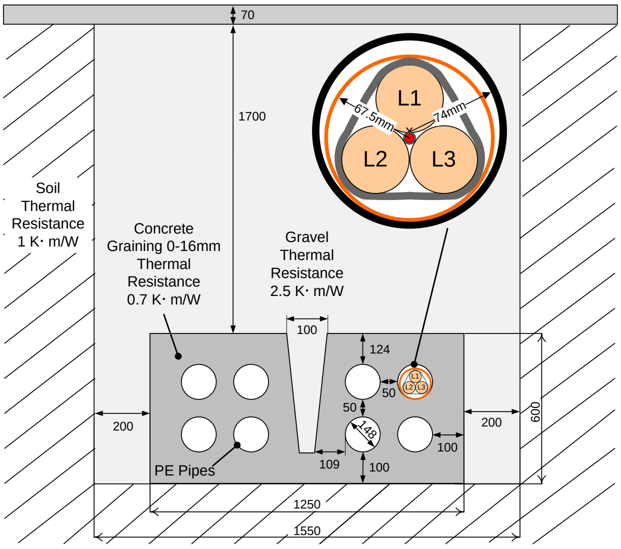


Figure 2 Standard duct bank with three-core cable

PILOT PROJECT

Pulling in the cables and operating a three-core cable in a duct bank designed for single-core cable poses several challenges. The pipe is calibrated with a tolerance of 10%. Therefore, there is no guarantee that the cable fits. During operation, high voltage cables are exposed to thermal stresses. The thermal expansion leads to a longer cable which still must fit in the duct banks. Therefore, ewz has initiated a pilot project both to control the thermoelectric simulation and to verify the thermal expansion model. Through these findings, the previous, conservative standards for the planning guidelines may be revised.

The chosen cable connection is a HV cable between the planned 220/150 kV substation WAL and the existing substation Binz (BIN) (Fig. 1). These two substations are about 4.5 km apart and connected by a standard duct bank (Fig. 2). The installation was originally planned for 2x3 single-core cables with a cross section of 400 mm^2. It has to be ensured that a maximum power of 560 MVA can be transmitted from WAL to the three substations BIN, SIF and ALN (Fig. 1). The routes WAL-BIN and WAL-SIF share the same duct bank on a length of about 2 km. In the duct bank WAL-ALN, a 1x3 single-core cable connection already exists and an additional connection is possible. The most critical part of the route WAL-BIN for a three-core cable regarding the thermal expansion will be a straight section of 770 m.

For the pilot project a temperature monitoring system will be installed to avoid thermal overloading of the cable. The DTS (Distributed Temperature Sensing) method enables the temperature measurement along a cable line. During periods of high load, the permissible duration of the congestion is calculated through the monitoring system software. Therefore, the power limit of the cable system can be optimally used with acceptable strain to the cable. The process is illustrated in more detail in [4].

THEORETICAL MODELLING

In this section, the thermoelectric effect and the thermal expansion of the cable duct are modelled. The models serve as a feasibility study of 150 kV three-core cables in the existing, narrow duct banks and a preparation of the pilot project.

Thermoelectric Modelling

The thermal behaviour of three-core cables differs significantly from single-core cables. Therefore, the conductor diameter for a given load has to be analysed for the specific installation. The installation is modelled and simulated using a commercial program (CYMCAP [3]). It allows simulating the cable, duct bank and several soil layers using a finite element approach. The steady state simulation has been conducted to assess the maximum transmissible power at 90°C. According to the manufacturer's instructions 90°C is the maximum conductor temperature for normal operation.

Fig. 3 shows the investigated versions and the results of the simulations. For the original version 1, the route WAL-BIN includes 2x3 single-core cables with a conductor cross section of 400 mm^2. Version 2 uses four three-core cables with a conductor cross section of 400 mm^2. For the alternative route WAL-ALN a single-core cable connection has already been installed and in versions 3 and 4 the effect of one or two additional three-phase cable connections have been analysed. In the two latter cases, the impedance of the three-core cables is lower compared to the parallel single-core cables. Therefore, the three-core cables will be more loaded and reach first the thermal limit. The dimensions and parameters displayed in Fig. 2 have been applied in the simulations.

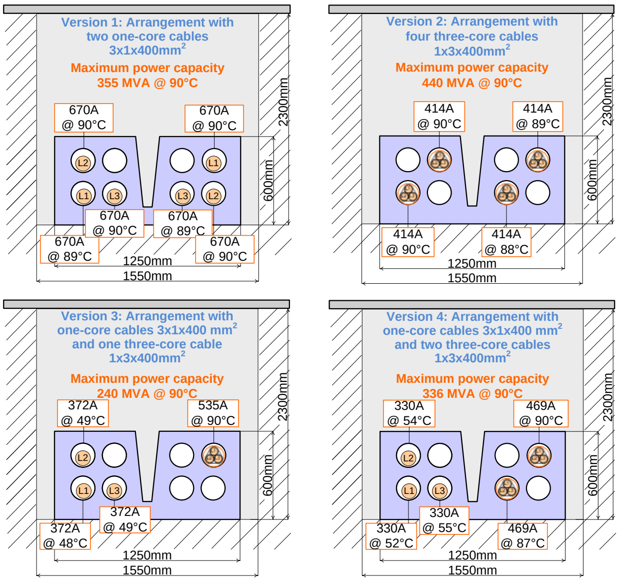


Figure 3 Investigated versions and simulation results

The results show that in version 2 in the existing standard cable ducts a maximum power capacity of 440 MVA can be transmitted. This is more than the maximum capacity of 355 MVA in version 1, though the cost of four three-core cables is higher than 2x3 single-core cables. The conductor cross section in version 2 is twice as big compared to version 1. A combined installation of single-core cable connection and one three-core cable allows a maximum power of 240 MVA. A combined installation of single-core cable connection and two three-core cables can transmit a maximum power of 336 MVA. This means that under the thermal constraint of 90°C the power could be distributed from WAL using three-core cables with a conductor diameter of 400 mm^2. The outer diameter of these cables is about 135 mm. It is only slightly below the inner diameter of the pipes and does not fulfil the 1.5:1 criterion. Therefore, the thermal expansion of the cable has to be analysed to assess the feasibility of the envisaged solution.

Thermal Expansion Modelling

When the cable is in operation and heated due to thermoelectric effects discussed in the previous section, the copper expands and the cable is assumed to deform. The linear thermal expansion of a straight copper cable with a length L is calculated by:

$$\Delta s = s \cdot \alpha_s^{cu} \Delta T$$

where α_s^{cu} is the thermal expansion coefficient for copper ($17 \cdot 10^{-6} K^{-1}$) and ΔT is the temperature difference.

The additional cable length needs to fit in the available space within the duct bank. It is assumed the expansion of the copper in the twisted cable leads to additional windings while the cable radius remains unchanged. In the following, capital and lower case letters indicate a parameter which is independent on the temperature and a parameter which is dependent on the temperature, respectively. Two different possible deformations of the twisted cable have been modelled. In the first model, it is assumed the cable stays on the bottom of the duct. Therefore, the windings of one cable are modelled as a helix with radius R_g which is hereinafter referred to as the inner helix with the guide line in the centre. By contrast, in the second model, it is assumed the cable can be lifted and moved in the available space of the duct which has the length D_s. This is considered by the introduction of a superimposed helix with radius R_s. The two helices result in a nested helix. The subscripts (g, s, n) indicate a parameter used in the calculation of the guide line, the superimposed curve and the nested curve, respectively. Fig. 4 depicts the winding of a cable which is lifted at one spot.

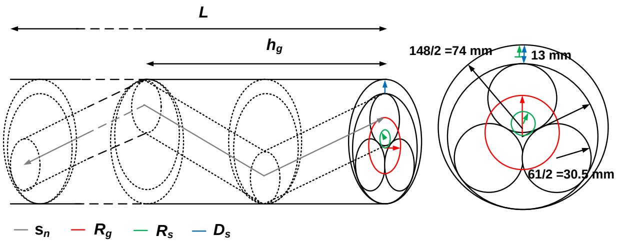


Figure 4 Twisted cable modelled as a nested helix consisting of an inner helix and a superimposed helix. The parameters used in the model are the length of the cable duct (L), lay length of the guide curve (h_g), the arc length (s_n), the radius of the guide curve (R_g), the radius of superimposed helix (R_s), and the distance between cable and cable tube (d = 2·r_s).

The length of the duct bank is denoted by L. The width of one complete turn is referred to as the lay length or the pitch of a helix denoted by h_g. For a 400 mm^2 cable it is 2.9 m at 20°C. The total length of the copper corresponds in geometry to the arc length and is denoted by s_n.

In Cartesian coordinates, the following parameterisation formulates the position vector $\vec{r}_g(t)$ for the guide curve of the inner helix of a cable:

$$\vec{r}_g(t) = \begin{pmatrix} x_g(t) \\ y_g(t) \\ z_g(t) \end{pmatrix} = \begin{pmatrix} R_g \cos\left(\frac{2\pi t}{\mathrm{h}_g}\right) \\ \mathrm{R}_g \sin\left(\frac{2\pi t}{\mathrm{h}_g}\right) \\ t \end{pmatrix}, (0 \leq t \leq L)$$

Where $p_g \in \mathbb{R}$ denotes the total number of windings and t the position in vector $\vec{r}_g(t)$.

The arc length of the guide curve is calculated by:

$$s_g = \int_0^L \left|\vec{\dot{r}}_g(t)\right| dt = \frac{L}{h_g}\sqrt{\left(2\pi R_g\right)^2 + {h_g}^2}$$

The cable length when using only the inner helix is calculated by the number of windings p_g and the lay length h_g. In that case the cable length equals the duct length:

$$L = p_g \cdot h_g$$

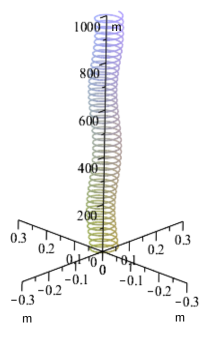
In the second model, the inner helix is superimposed with a second helix with radius R_s. The superimposition is formulated as Frenet-Serret frame set on the guide curve [5]. It describes a circle in the direction of the normal vector $\vec{v}_s(t)$. It is the cross product of the tangent vector $\vec{t}_s(t)$ and the normal vector which is defined as the binormal vector $\vec{b}_s(t) = \vec{t}_s(t) \text{ x } \vec{v}_s(t)$. The positon vector of the nested curve $\vec{r}_n(t)$ is:

$$\vec{r}_n(t) = \vec{r}_g(t) + R_s \cos\left(2\pi \frac{t}{h_s}\right) \cdot \vec{v}_s + R_s \sin\left(2\pi \frac{t}{h_s}\right) \cdot \vec{b}_s$$

The arc length of the superimposed curve is calculated by:

$$s_n = \int_0^L \left|\vec{\dot{r}}_n(t)\right| dt$$

The thermal expansion of the copper leads to an increase of the arc length by Δs_n. With the specification given in Fig. 4 and an assumed duct length of 1000 m, the increase Δs_n is shown in Table 1 for various values of h_s and a copper temperature of 110°C (reference case: 20°C, h_s=0).



Radius guide curve Rg = 37mm
Radius sup. curve Rs = 7 mm
Length cable duct: 1000m

conductor temperature	lay length guide helix	lay length sup. Helix	arc length nested curve	difference arc length
T (°C)	h_g (m)	h_s (m)	s_n (m)	Δs_n (m)
20	2.900	-	1003.21	0.00
110	2.396	-	1004.70	1.49
	2.407	500		
	2.455	100		
	2.517	50		
	2.911	14		
110	3.201	10	1004.70	1.49

Table 1. Simulation result for a cable duct of 1000 m length

Table 1 shows that according to the initial assumption the thermal expansion of a twisted cable is mainly compensated by a decrease of the lay length h_g when the superimposed curve is weakly twisted. Because the nested curve model is derived from geometrical considerations, mechanical forces are not calculated. The pilot project has to validate the assumption that an increase of the cable length leads to additional windings while maintaining the cable radius.

DISCUSSION AND CONCLUSIONS

The modelling of the thermoelectric behaviour and the thermal expansion of three-core cables in duct banks with eight ducts and a ratio of 1:1.1 outer diameter cable to inner diameter duct show that under the assumptions made the required power can be transmitted and the thermal expansion compensated by an increase of the twist strength of the cable. The results indicate that with more parallel connections and hence a larger total cross section of the conductors the required power can be transmitted in a duct designed for single-core cables. Regarding the thermal expansion the results of the superimposed helix model suggest that a major part of the length expansion can be compensated by an increased inner twisting of the three-core cable. In the pilot project temperature modelling and the installation of strain gauges for the measurement of tensile and compressive forces in the worst sleeve-sleeve section is planned. If problems arise, additional measures as expansion possibilities in prolonged sleeves are envisaged. If the theoretical findings can be confirmed, the existing duct banks can be used to make the necessary connections pulling in three-core cables and company standards regarding the ratio of cable and duct dimensions for existing duct banks will be revised. This will also show whether the available space is sufficient to pull the cables in the duct banks. For new duct banks the standards will be changed and designed for three conductors per duct with reduced space requirements [2].

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