Gestion de la chaleur des lignes haute tension souterraines - une nouvelle approche prometteuse

Heat management of underground high-voltage power lines – a promising new approach

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Résumé

La production d'énergie décentralisée, la sécurité de l'approvisionnement en électricité et le besoin constant de renouveler/étendre les lignes à très haute tension existantes, combinés à l'acceptation sociale, conduisent à la construction de plus en plus de lignes haute tension dans l'espace souterrain. Par rapport aux lignes électriques aériennes, la capacité de transmission, l'élimination de la chaleur résiduelle et les coûts sont des défis majeurs, d'autant plus que ces sujets sont étroitement liés via la gestion de la chaleur.

La conception des lignes électriques souterraines à très haute tension (220 à 380 kV) se basait auparavant sur les codes de conception courants (IEC), en supposant un état d'équilibre thermique ainsi que le fait que la chaleur résiduelle est soit complètement transférée à la surface, soit éliminée par un flux d'air. Dans le cadre d'une étude de la société nationale responsable du réseau de transport de l'électricité (Swissgrid), explorant les possibilités de solutions durables pour les lignes électriques souterraines, une nouvelle approche de conception est développée, basée sur les expériences en matière d'échange de chaleur/climat dans différentes installations souterraines telles que les tunnels de base en Suisse.

Un code numérique spécifique a été développé afin de simuler les températures des conducteurs pour de nombreuses combinaisons de géométries de tunnels, de charges électriques ainsi que de thermodynamique ambiante et souterraine. La méthode développée offre une approche moderne de la conception par rapport à la méthode existante très conservatrice et prend en compte les résultats basés sur les expériences dans les tunnels exploités. Par rapport à la conception existante, cette nouvelle approche permet de réduire les coûts de construction et d'exploitation et donc d'augmenter la compétitivité des lignes souterraines par rapport aux lignes aériennes traditionnelles.

Abstract

Decentralized energy production, secure electricity supply and the constant need to renew/extend existing extra-high-voltage power lines in combination with social acceptance lead to the construction of more and more extra-high-voltage power lines in the underground space. Compared to overhead power lines, transmission capacity, waste heat removal and costs are major challenges, particularly as these topics are closely related via the heat management.

The design of underground extra-high-voltage power line (220 to 380 kV) facilities used to be based on common (IEC) design codes, assuming a thermal steady state as well as the fact that waste heat is either completely transferred to the surface or removed by air flow. Within a study of the Swiss National Grid company (Swissgrid), exploring the scope of sustainable solutions for underground power lines, a new design approach is developed, based on the experiences in heat exchange/climate in different underground facilities such as the base tunnels in Switzerland.

A particular numerical code has been developed in order to simulate conductor temperatures for manifold combinations of tunnel geometries, power loads as well as thermodynamics of the ambient and underground. The developed method offers a modern design approach to the existing but very conservative method and considers findings based on experiences in operated tunnels. Compared to traditional design this novel approach allows reducing construction as well as operation costs and thus increasing the competitiveness of underground lines compared to traditional overhead lines.

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1 Introduction

Worldwide the electric power consumption increases whereas its generation is progressively decentralized (e.g., with offshore wind parcs). Consequently, the power transmission grids are extended continuously. Predominantly high-voltage power lines are realized in the open air, with common impact on the landscape. Beside restricted space, particularly in urban areas, the declining social acceptance calls for solutions underground.

To encounter the increasing demand of underground power lines, the Swiss national grid company (Swissgrid) launched an extensive, interdisciplinary study for highest-level power lines (voltages greater than 220 kV). Besides civil and electrical design, the study covered the analysis of heat management, whereas in particular, transient loads have been investigated.

For many cases small but accessible tunnels have become convenient (cf. Figure 1). On the one hand the accessibility allows control, maintenance and repair of the cables, on the other hand, these utility tunnels may hold additional infrastructure like water supply, energy (e.g., gas tubes) and/or data carriers (e.g., fibre-optic cables) and offer additional benefits.

A major challenge of operating such tunnels is the heat management to ensure undisrupted power transmission. The International Electrotechnical Commission (IEC) has published two standards which are used in general practice (IEC 2015, IEC 2017) for designing underground cables. However, the application of these standards is limited to steady-state power loads. Also, the heat conduction in the soil surrounding the tunnel is considered in a very basic manner as no thermal inertia is taken into account. These two assumptions tend to lead to very conservative designs or even to the conclusion that an underground cable is not feasible.

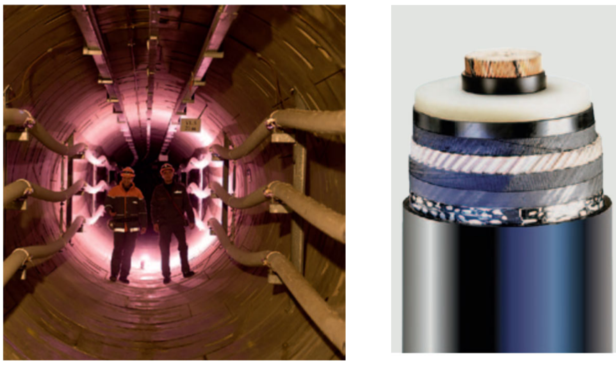

Figure 1. Cable tunnel with two systems of high voltage power lines (left) and typical high-voltage cable (right; both 380 kV, Berlin, see 50Hertz 2019)

2 Heat Management Concept

In general, several options of heat removal in cable and utility tunnels are available. Table 1 includes the most common cooling concepts. Except for concept 4, these cooling options require installation and operation of electromechanical equipment.

Following a sustainable approach, i.e. keeping the investment and life cycle costs as low as possible, the performance of concept 4 has been explored with optional involvement of concept 3 upon demand. These concepts are schematically illustrated in Figure 2.

Table 1. Common cable cooling concepts

No.	Concept	Description
1	Active cable cooling	Mechanical cooling of cable surface with heat carrier media flow (e.g. water in pipes) incl. circulation pumps and heat exchanger units
2	Active tunnel cooling	Mechanical cooling of tunnel air with heat carrier media flow (e.g. water in pipes) incl. circulation pumps and heat exchanger units
3	Active tunnel ventilation	Mechanical ventilation to ensure fresh air supply and heat removal incl. fan plants and/or jet fans
4	Natural tunnel ventilation	Natural flow (e.g. due to thermal draft or meteorological pressure difference) to ensure fresh air supply and heat removal

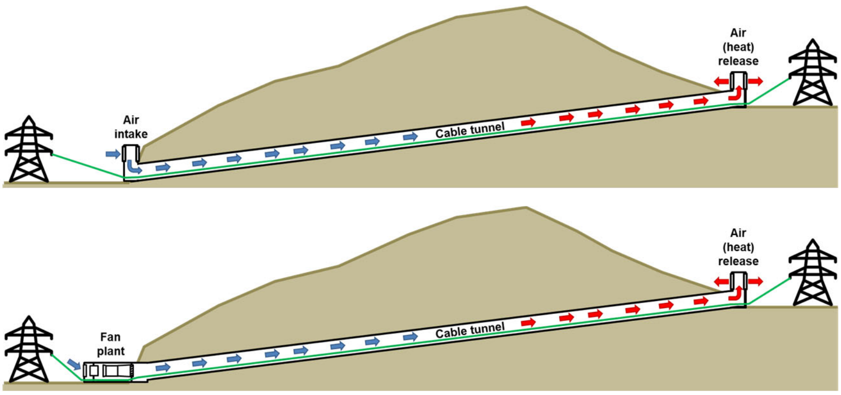

Figure 2. Schematics of natural (above) and active cable tunnel ventilation (below)

3 Fundamentals

3.1 Heat emission of power lines

Electric power transmission includes heat loss essentially due to ohmic resistance. Without heat management, the cable conductor temperature rises continuously. Exceeding maximum conductor temperatures (e.g. for XLPE-cables 90 °C for long term exposure and 105 °C for short term exposure) leads to increased deterioration and thus lifetime reduction as well as failure of the power transmission.

With open air power lines, the heat naturally dissipates in the massive air reservoir surrounding the cables. Typically, the conductors do not overheat. Design is therefore done for the maximum allowable continuous load considering a steady state.

In underground facilities with restricted air volumes, sufficient heat removal may become a challenge. Particularly this applies to periods of increased transmission loads (e.g. 2000 A instead of 600 A). Maximum loads occur while cables compensate reduced grid capacity, e.g. caused by the lack of availability of another power line. Figure 3 shows typical maximum load cycles of a high-voltage power line (incident with temporarily increased power transmission). Additionally, maximum load cases can happen during periods of normal or increased power load.

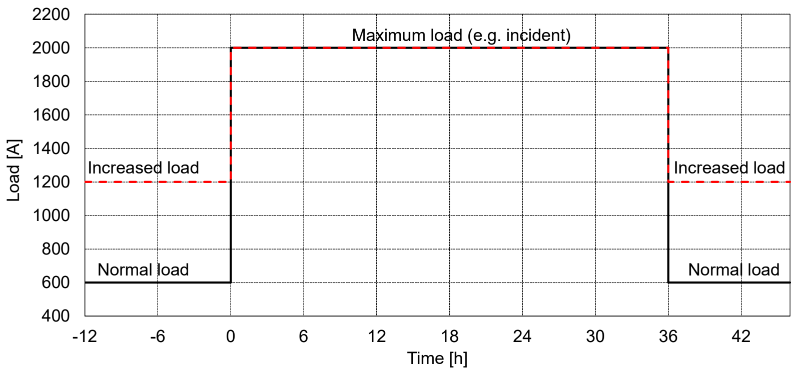

Figure 3. Typical maximum load cycles of high-voltage power lines

The approaches designing for steady state situations are not applicable to underground power lines, as on the one hand, they do not reflect real load cycles. On the other hand, such an approach leads to oversized cooling systems.

3.2 Heat transfer in tunnel

The specific amount of heat emitted from a high-voltage cable depends on its specification and load (cf. IEC 2017).

The removal of this heat via tunnel air is governed by many, partially interacting parameters. E.g., both the heat transfer between cable and tunnel air as well as between tunnel air and tunnel wall strongly relate to the air speed. Vice-versa, in cases of natural ventilation, air speed is depending on air temperatures.

Mainly the following two effects apply:

a) Radial heat removal to the underground: The cable heat dissipates to the tunnel air. Hence it is transferred radially to the tunnel walls and the surrounding underground, e.g. bed rock. This involves a couple of transport mechanisms like heat transfer (between cable and air as well as between air and walls), convection (by air circulation in tunnel), conduction (in cable and rock) and radiation. The resulting heating of the tunnel and its vicinity, i.e. the temperature distribution in a tunnel cross-section is shown exemplarily in Figure 4.
b) Axial heat removal to the ambient: The dissipated cable heat is removed by a longitudinal air flow along the tunnel and, through a portal, passed to the surroundings. Again, different thermal effects take part, but primarily, heat is transferred (between cable and air) and convected (by air flow along tunnel).

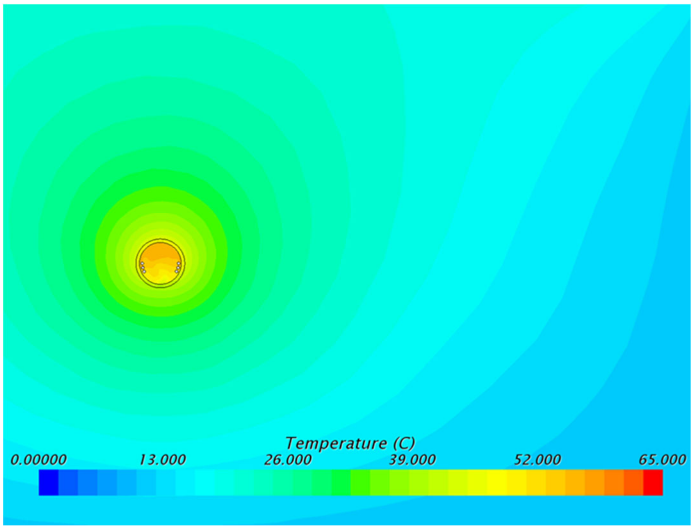

Figure 4. Temperatures in cable tunnel and surrounding rock without longitudinal air flow (exemplarily, simulation results)

The axial heat removal (cf. b) requires a longitudinal air flow in the tunnel. This can be established as a natural, thermally induced flow (thermal up or down draft) or with an active, mechanical ventilation (e.g. by axial fans). Increasing the air flow supports both the heat removal according to a) (i.e. elevated heat transfer cable to air and air to wall) and b) (i.e. elevated heat transfer cable to air and transport along tunnel).

4 Method

The common approach in cable tunnel design (see IEC 2015, IEC 2017) considers cable heat loads and heat transfer in a steady state manner. But in reality, both effects are of a transient nature. Hence the existing method overestimates the heat load in cable tunnels and therefore leads to oversized or unnecessary cooling installations. As a novelty and particularly to illustrate the potential of heat removal by natural ventilation, a transient approach is followed hereafter.

The performance of the natural and mechanical ventilation regarding cable heat removal has been explored by numerical simulation. To consider axial and radial heat transport a quasi-three-dimensional simulation code has been developed.

For this purpose, BAUKLIMA, a versatile simulation suite of thermodynamics in underground facilities (HBI Haerter, see Béguin et. al. 2021), has been extended with the thermal specifications of power cables (based on MATLAB). The code consists of the following main characteristics:

- numerical simulation of heat transport along tunnels and within the surrounding underground (cylindrical model with shells)
- numerical simulation of natural air flow (thermal up and down draft) or forced air flow
- calculation of cable heat emission (heat loss) according to standards (see IEC 2017)
- calculation of conductor temperatures according to standards (see IEC 2017)

The main process of the code is illustrated in the flow chart of Figure 5.

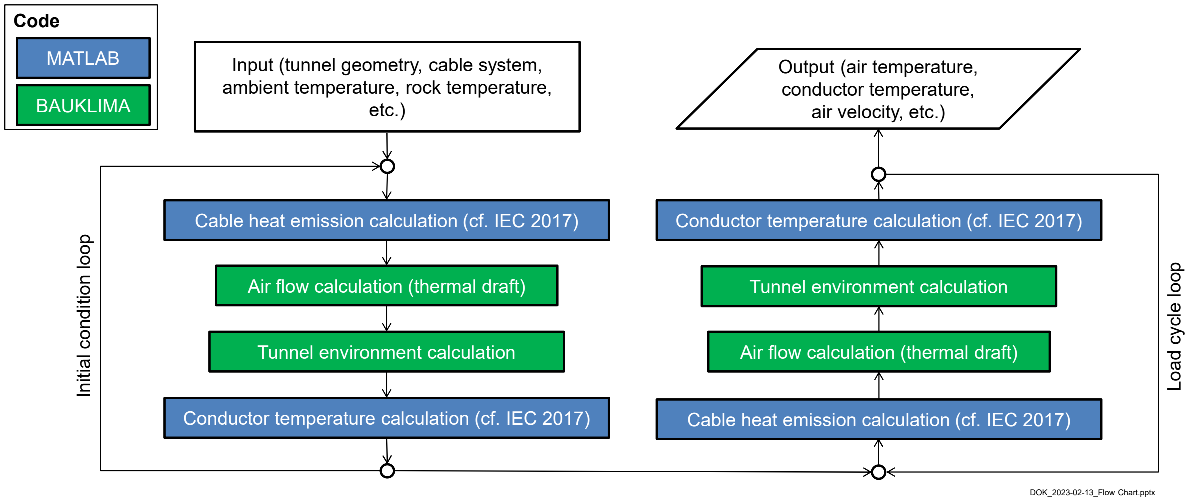

Figure 5. Flow chart of MATLAB-BAUKLIMA-code

5 Comparison of current and new design approach

To assess the advantages of the new design approach, conductor temperatures determined by the current design method (IEC 2017) and the new design approach are directly compared. Figure 6 shows the conductor temperature determined by the current design approach (IEC 2017) and the conductor temperature determined by the novel design approach both considering a ventilated tunnel (2 m/s) and a maximum load of 2000 A. The typical long term exposure limit of 90 °C is not respected when applying the current design approach. When using the novel, and more realistic approach, lower and acceptable conductor temperatures are resulting as the heat capacity of the surrounding ground acts as buffer storage and only gets saturated over a very long period of time.

The more realistic time dependent conductor temperature allows to reduce drastically the installed ventilation/cooling capacity and the overall cost related to the heat management (installation, operation, and maintenance cost) by considering a mainly naturally ventilated tunnel. Accordingly, higher transmission capacities can be envisaged when considering the transient heat transfer and the proper behaviour of the heat storage in the surrounding ground. Therefore, when using the novel design approach, underground lines become more applicable and more competitive compared to conventional overhead power lines.

Moreover, the efforts of the new approach are comparable to the current design codes as no complex analysis must be performed. As the effort per simulation is low, the method allows for sensitivity studies in order to assess different parameters like soil characteristics, geometrical variations or variation of the transferred power.

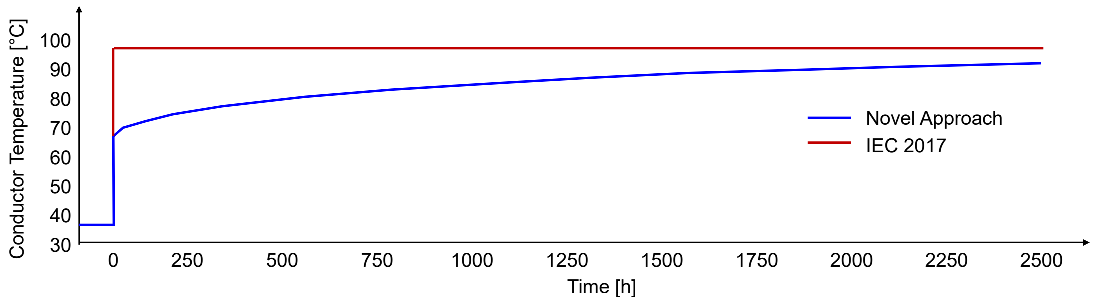

Figure 6. Comparison of transient conductor temperatures: current versus new design method

6 Assessment of different heat management concepts

In order to highlight the performance limits of naturally ventilated cable tunnels respectively the need for a forced ventilation, a generic sensitivity study is performed.

6.1 Thermal characteristics of naturally ventilated cable tunnels

The following results relate to micro-tunnels with high voltage systems (3 cables each) installed at both tunnel sides (see Figure 1). The maximum load incident (see red curve in Figure 3) only affects one system whereas the other remains with the initial load. Furthermore, the sensitivity study is based on a reference geometry (gradient 1 %, length 1.5 km and diameter 2.2 m).

Figure 7 illustrates the evolution of the air and conductor temperatures as well as of the air velocity during a maximum load cycle (increased to maximum load, see Figure 3) of cable system 1. Mainly the following is observed:

- The air and conductor temperatures respond immediately to the load increase and decrease. The main reason is the low heat capacity of the tunnel air.
- There is little delay to the reaction of the air velocity due to inertia.
- The air temperature and velocity grow with increasing conductor temperatures.
- The major impact of the load cycle is observed with conductor temperature of the affected system 1 (approx. 150 % of initial value; other temperatures and air velocity approx. 110 %).
- Following the immediate increase, the conductor temperature keeps on rising slowly but continuously. This is mainly caused by the steadily reducing heat transport to the underground.
- After the maximum load incident, the conductor temperatures remain increased. Particularly the heat restauration of the surrounding underground is delayed and the absolute thermal recovery to the initial values may take days.

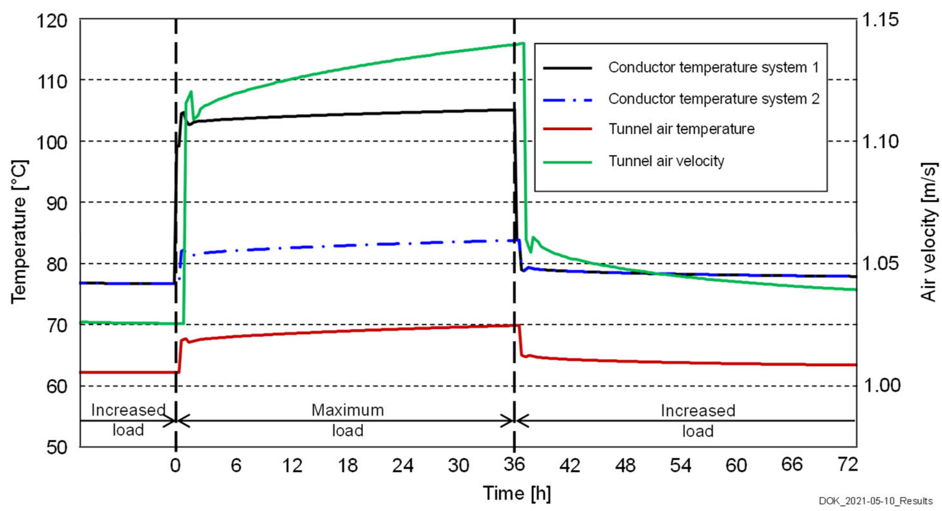

Figure 7. Temperatures and air velocity during maximum load cycle of one cable system in a reference micro-tunnel (maximum load only for system 1, see Figure 2), natural ventilation (thermal draft)

6.2 Sensitivity analysis of heat management using natural ventilation

The following main parameters determining the natural air flow and heat removal of cables in tunnels have been investigated:

a) Tunnel gradient: The thermal draft in a tunnel depends on the difference in altitude of its openings to the atmosphere (average gradient). The greater the gradient the more the air flow and thus heat removal is increased.
b) Tunnel length: With a longitudinal air flow the temperatures increase steadily along the tunnel and reach their maximum at the downstream portal. The longer the tunnel the higher the temperatures evolve.
c) Tunnel diameter: The amount of heat transferred to the underground is governed by the size of the interface between tunnel air and wall, i.e., the wall surface. This surface directly relates to the tunnel diameter. Increasing the diameter supports the heat removal from the tunnel.

Figure 8 and Figure 9 illustrate the sensitivity of the conductor temperature regarding changes of the above-mentioned parameters a), b) and c).

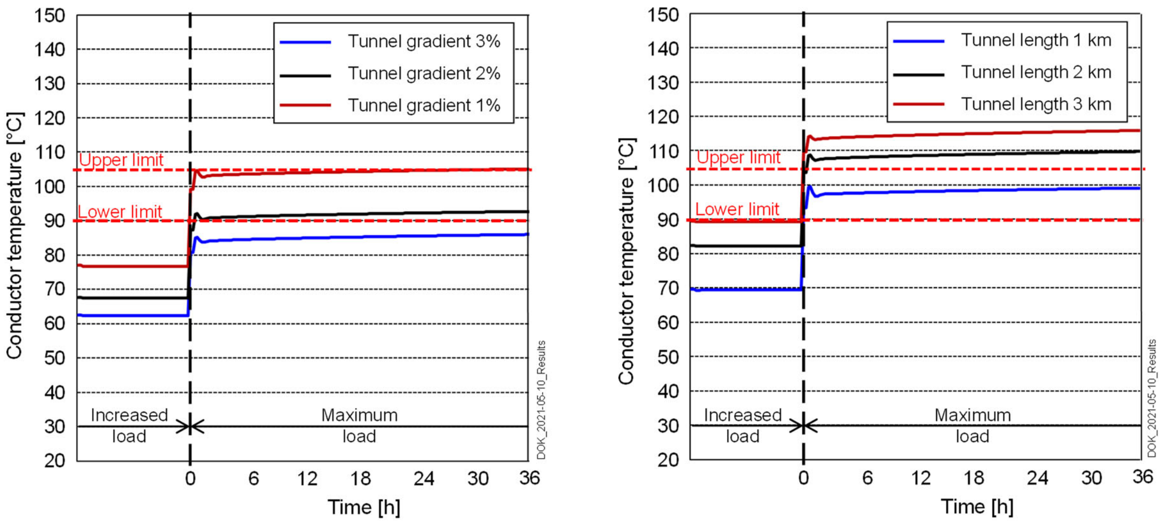

Figure 8. Conductor temperatures during maximum load cycle with natural ventilation, sensitivity of tunnel gradient (left) and tunnel length (right)

Already with a decent change of the tunnel gradient (see Figure 8, left) from 1 % to 2 % the heat removal is optimized essentially, i.e. the maximum conductor temperature is lowered by more than 10 °C. With further steepening of the tunnel, the effect reduces but remains important (7 °C from 2 % to 3 %). Generally, increased tunnel gradients allow fulfilling and falling below the limit values.

Compared to the discussed gradient effect, the impact of the tunnel length on the cable heat removal is less pronounced (see Figure 8, right). To gain a similar reduction in conductor temperature, the intervention to tunnel construction, i.e. its shortening, becomes considerable (e.g. length reduction from 2 km to 1 km for 10 °C).

Figure 9 includes the response of the conductor temperatures to changes in tunnel diameter. Increasing the diameter by around 20 % and 40 % triggers temperature reductions of about 10 °C and 15 °C. The general influence of tunnel diameter and gradient on heat removal resembles each other, even though their specific impact on tunnel construction might differ significantly.

Beside the above-mentioned, the sensitivity of the heat management to ambient temperature as well as to the temperature and thermal characteristics of the underground has been studied. To explore the range of thermal impact, the following three sets of parameters have been defined:

1) Normal conditions: According to experience, most likely definition of the parameter (i.e. typical ambient and ground condition in mountainous regions)
2) Unfavorable conditions: Definition of the parameter leading to the greatest possible reduction of cable heat removal (e.g. increased ground and ambient temperatures)
3) Favorable conditions: Definition of the parameter leading to the greatest possible increase of cable heat removal (e.g. reduced ground and ambient temperatures)

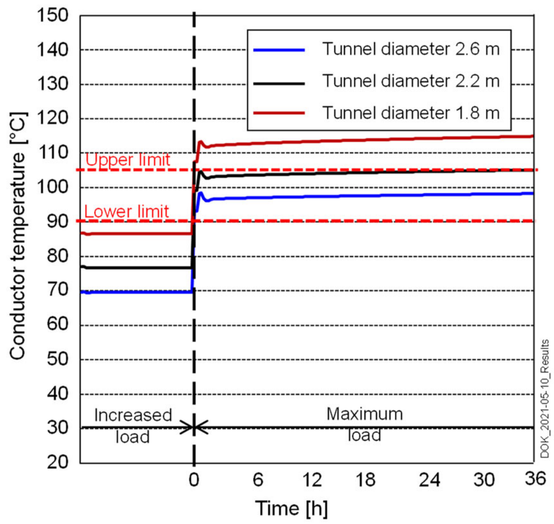

Figure 9. Conductor temperatures during maximum load cycle with natural ventilation, sensitivity of tunnel diameter

The according conductor temperatures during a maximum load cycle are shown in Figure 10. Obviously, these conditions heavily interfere with the heat removal from the tunnel. With favorable and normal conditions, the cables may be operated safely (at least upper temperature limit fulfilled). The unfavorable conditions provoke conductor temperatures far beyond the limit values.

6.3 Mechanical ventilation

With respect to the above mentioned imponderabilia regarding ground and ambient conditions, an active cable heat management might be required.

To accomplish this, the natural tunnel ventilation can be enforced with a mechanical ventilation (i.e. fan plant; see concepts 3 and 4 in Chapter 2 and Figure 2). However, best practice would be to only operate the fans on demand, i.e. during load incidents, only.

Figure 10 right illustrates the conductor temperatures for normal, unfavorable, and favorable conditions while operating the mechanical ventilation only during maximum load (constant air flow of 2 m/s). In contrast to Figure 10 left (i.e. exclusive natural ventilation) no substantial operation restrictions are expected (i.e. conductor temperature limits are fulfilled).

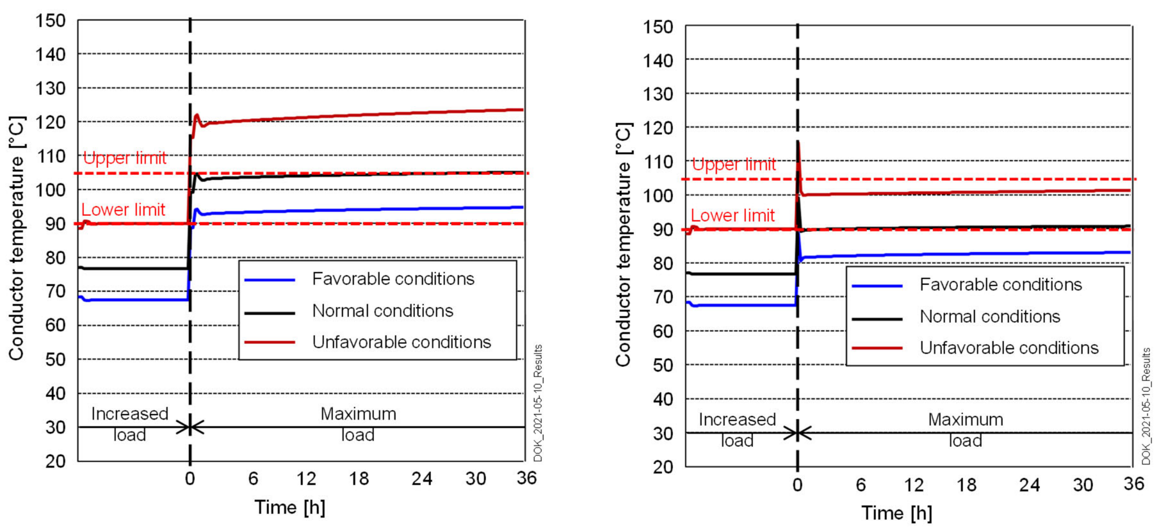

Figure 10. Conductor temperatures during maximum load cycle with natural ventilation (left) and mechanical ventilation (right), sensitivity to ground and ambient conditions

7 Conclusions

Compared to the current design method, the new approach of cable tunnel heat management design is a more realistic way to determine conductor temperatures for a given transmission power. This applies as transient effects are considered as well as a more realistic way of heat transfer in the surrounding soil. Compared to steady state analysis for a sudden increase of transmission load, important differences are found when using the novel approach. Therefore, no additional ventilation/cooling equipment may be needed in order to deal with such cases. Also, the need for ventilation under normal circumstances is reduced as surrounding ground can still receive heat and is not considered as thermally saturated. This more realistic method allows to drastically reduce the need of mechanical ventilation and simplifies an important challenge of underground cables: the heat management.

Based on the sensitivity analysis, natural ventilation (mainly by thermal draft) offers a highly sustainable (incl. resource- and energy-saving) cable tunnel heat management for a vast range of application at the lowest possible capital and operation costs. This becomes even more important with respect to the generally lower costs of open-air power lines compared to tunnel solutions.

The presented assessment of heat management concepts emphasizes the potential of natural ventilation for heat removal in high-voltage power cable tunnels. Formerly (based on steady state design) excluded solutions with natural ventilation may become valuable options for new cable tunnel projects. With this new approach, oversizing of heat management measures can be excluded to the greatest possible extent. Additionally, the reliability of planning and operation of cable tunnels is enhanced.

Based on these findings cable tunnel designer should consider the involvement of natural ventilation at an early project stage. This allows optimizing the tunnel alignment and geometry for the best possible natural heat removal (e.g. with increased tunnel gradient and diameter). Beside detailed information about the ground conditions (initial temperature and thermal characteristics), and ambient temperatures, the planned operation of the power lines incl. specific maximum load cycles must be considered.

In case of main uncertainties regarding the specific project conditions (e.g. ground and ambient temperatures), the concept of natural ventilation can be amended. With mechanical ventilation on demand, both the reliable cable tunnel operation and the lowest possible energy consumption can be ensured.

The Swiss national grid company Swissgrid is systematically applying the findings gathered by the new calculation method when assessing underground solutions as the current way of analysing the heat management of underground high voltage lines can be very conservative.

8 Acknowledgement

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