21, rue d'Artois, F-75008 PARIS
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Thermoelectric Vapor Chamber Smart Cooling System for EHV Power Cables in Underground Tunnels

A. GUREVICH, I. STEINER
Double Check Ltd
Israel

E. HUANG
Leading Edge Associates Co., Ltd
Japan

SUMMARY

A new method of cooling EHV power cables in underground tunnels has been developed and proved.
Efficient cooling is one the most important issues in design of electrical power transmission in underground tunnels. The most popular existing solution: water cooling has some disadvantages including need in on-ground chiller stations, high noise level unacceptable in urban region, impossibility to provide selective cooling power supply on the length of tunnel, long response time on daily change in power transmission.
A new concept is based on direct transfer of heat energy from active thermoelectric cooling system through concrete walls of tunnel to surrounding soil. A novel cooling solution is based on combination of two high performance thermal technologies: Thermoelectric and Vapor Chamber (TVC technology). Main features of the concept:
- The cooling system consists of multiple TVC units distributed over the length of tunnel
- The units are attached to the concrete wall of the tunnel
- Heat power generated on the hot side of thermoelectric modules is transferred to soil through concrete wall
- Cooling power is dissipated by finned heat sink with fan
- Temperature control is provided individually for each cooling unit depending on cable or air temperature near the unit location.

Concept of TVC cooling system has been proved by computer thermal simulations. It was shown that TVC unit is capable to transferred heat power from thermoelectric unit through the tunnel concrete wall. Efficient method of attachment TVC unit to concrete wall has been developed and proved. It allows to ensure good thermal contact between TVC and wall at any wall surface flatness.
Prototype of TVC unit has been designed, manufactured and tested in laboratory conditions. It has been shown that TVC units is capable to maintain temperature of less than 35°C inside chamber modelling tunnel environment.

E-mail: alex@dc-ts.com

The TVC cooling concept opens new possibilities of improvement cooling efficiency, reliability of cables transmission system, reduction of installation and maintenance cost based on:

- Selective distribution of TVC units in accordance with environmental and soil condition in each section of underground tunnel allows to reduce installation cost on more than 50% in comparison with water cooling system.
- Individual temperature control of each TVC unit in conjunction with Distributed Temperature Sensing system allows to prevent hotspots formation especially near the cables joints and improves reliability of cables.
- Fast feedback on daily power transmission changes allow to use TVC system more efficiently and reduce power consumption on about 40%
- Utilization of machine learning technology for control of TVC system will allow reduction of power consumption on about 40%.

KEYWORDS

EHV cables, underground tunnel, thermoelectric, vapor chamber, selective temperature control

Introduction.
Although the most of existing Extra High Voltage (EHV) networks are overhead lines, the construction of new areal lines has met with strong opposition by local authorities and environmental organisations. Therefore, undergrounding of those sections of aerial lines that face environmental problems needs to be considered as realistic solution in spite of the higher construction costs involved [1]. Use of underground tunnels has some significant advantages in comparison with overhead lines:

- Do not require place on land for installation
- Do not emit electric and magnetic fields
- Have better power loss characteristics.
- Require less maintenance than overhead cables.

In the past, underground transmission lines were installed in pipes or directly buried in the ground. However, these methods have become difficult as the number of cable circuits and other underground facilities increases [2]. Due to increased electricity demand more and more power suppliers make large investments to house these cables in deep tunnels which offers several advantages:

- Allow large power to be transmitted
- Easy maintenance
- Optimum security from severe weather conditions [3].

As a result, underground cables tunnels have some important advantages for power transmission across the following areas:

- Urban areas
- Areas where the surface on the land is unavailable
- Rivers and other natural obstacles
- Land with special natural or environmental features
- Areas of significant or prestigious infrastructure development

A tunnel system which accommodates many transmission and distribution cables with applied cooling is the solution [4]. There are some optional cooling solutions for cables in underground tunnels:

- Forced air convection by electric fans: appropriate for relatively small power transmission levels due to low heat capacity of air.
- Water cooling through the pipes passing over the length of tunnel. This method is more efficient but requires much more expensive installation including chiller stations located on land and costly maintenance.

Main disadvantages the existing methods:

- Cooling conditions are changed from inlet to outlet points due to the heating of coolant flow
- Impossibility to provide sufficiently fast feedback to power dissipation variations caused by daily changes in power transmission
- Impossibility to fit cooling power to changes in environmental and soil conditions over the length of tunnel

Solution description

We present new concept of cooling solution for underground EHV cables tunnel cooling based on combination of Thermoelectric and Vapor Chamber technologies (TVC technology). Main features of the concept:

- The cooling system consists of multiple TVC units distributed over the length of tunnel
- The units are attached to the concrete wall of the tunnel
- Heat power generated on the hot side of thermoelectric modules is transferred to soil through concrete wall
- Cooling power is dissipated by finned heat sink with fan
- Temperature control is provided individually for each cooling unit depending on cable or air temperature near the unit location.

General scheme of the concept is shown on the Fig. 1:

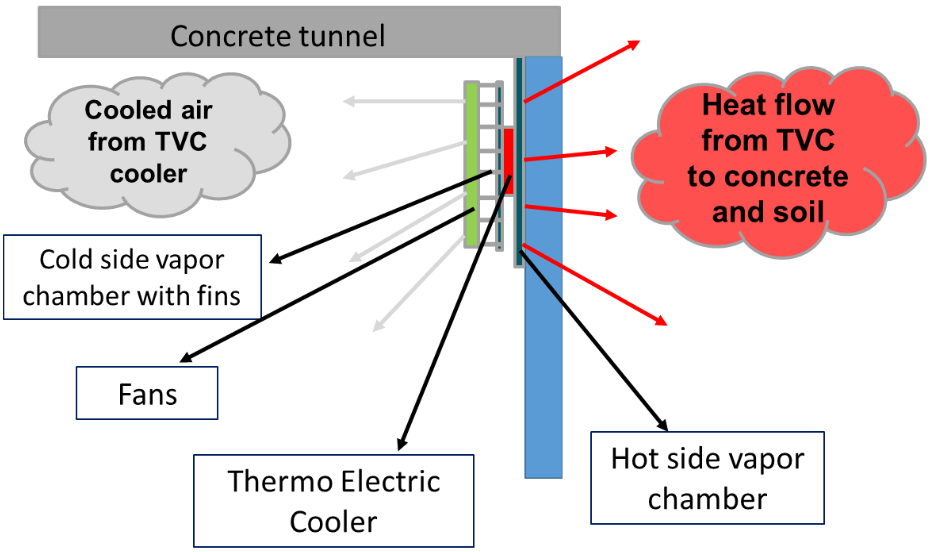


Fig. 1 Concept scheme

As we can see from Fig. 1 the cooling unit consists of the following main components:

- Thermoelectric modules
- Vapor chamber located on the hot side of thermoelectric module for spreading of heat power from the modules on the contact surface of tunnel wall
- Finned heat sink with fan for cooled air dissipation
- Vapor chamber used as base plate of fins to improve heat sink performance.

Concept background

The most important feature of the concept is transfer of heat power from thermoelectric unit to soil through the concrete wall. A series of computer simulations has been performed to show that it is feasible.

The simulated temperature distribution over concrete wall is shown on the Fig. 2

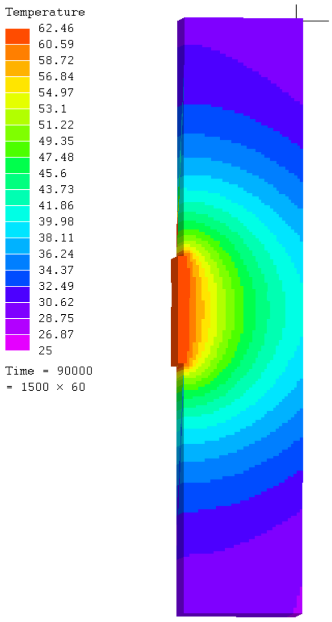


Fig. 2 Temperature distribution over concrete wall.

The simulation has been performed at the following conditions: wall thickness 200 mm, concrete thermal conductivity 1.6 W/(m*K).

As we can see from the Fig. 2 heat power is transferred over the limited area around the thermoelectric unit and don't cause heating of large area on the concrete wall. Due to this feature surface of the wall remains cooled and don't dissipate heat back to the cable's environment.

Another important issue of the concept is necessity to provide efficient heat transfer from the TVC unit to concrete wall. Real surface of tunnel concrete wall is not flat with distortions reaching few millimetres. At such conditions thermal interface materials are not capable to provide sufficient thermal conductance. We have designed solution allowing to provide thermal contact not depending on the concrete wall surface flatness: the base plate of TVC unit contains rods made from metal with high thermal conductivity (copper or aluminium) that are inserted into the wall (as it is shown on the Fig. 3) and transfer heat power to the wall.

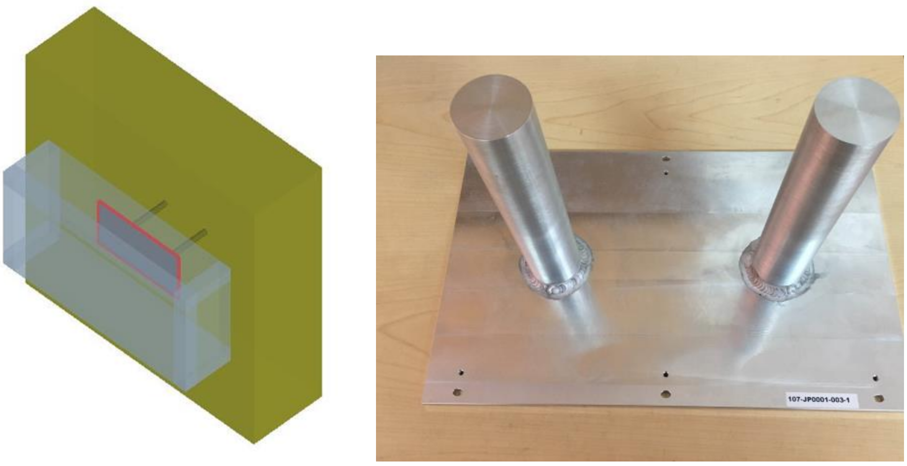
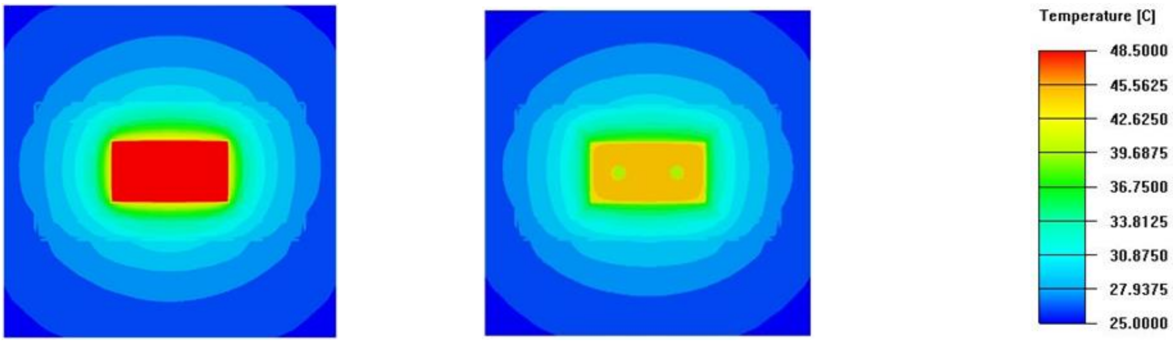


Fig. 3 Unit attachment by conducting rods

Results of thermal simulations for the rods design and comparison with flat contact design are shown on the Fig. 4:



(a) (b)

Fig. 4 Effect of conducting rods on heat transfer: (a) – flat design without rods, (b) – design with rods having diameter 40 mm

As we can see from Fig. 4 use of rods allows to reduce hot side temperature of TVC unit on more than 5 °C.

Prototype fabrication and test

Series of prototypes of TVC units for EHV cables underground tunnel has been designed and fabricated. The prototypes have been designed to provide cooling solution for the real underground tunnel with EHV cables shown on the Fig. 5:

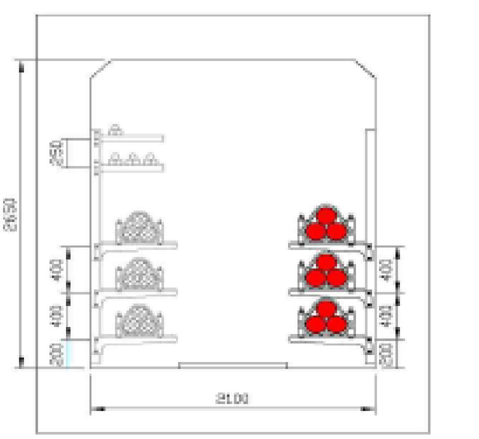


Fig. 5 Real underground tunnel with EHV cables

The cable system consists of three 345 kV circuits and two 154 kV circuits. Power dissipation of this EHV cables system for real operation conditions is 200 W per meter of the tunnel length.

Requirements for the cooling system performance are as follows:

- Cooling power: 200 W/m
- Air temperature inside the tunnel: 35 °C maximum
- Operating voltage: 230 VAC

Possible locations of TVC cooling system elements are shown on the Fig. 6:

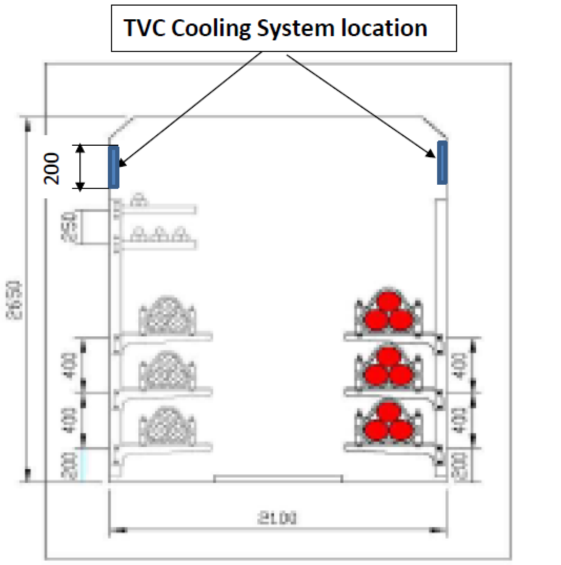


Fig. 6 Possible locations of TVC units

Picture of the prototypes is shown on the Fig. 7

Fig. 7 Prototypes of TVC cooling units

The prototypes have been tested in laboratory test chamber with dimensions: 6.0 x 3.0 x 3.0 meter (shown on the Fig. 8).

Fig. 8 TVC units assembled in the test chamber

The test has been performed according to the following procedure:

- Initial air temperature in the chamber was 25 °C
- Heat load has been supplied by electric heater with fan
- Heat load has been applied simultaneously with start of TVC Units operation
- Air temperature has been measured by three K-type thermocouples and average temperature has been calculated

Test results are shown on the Fig. 9

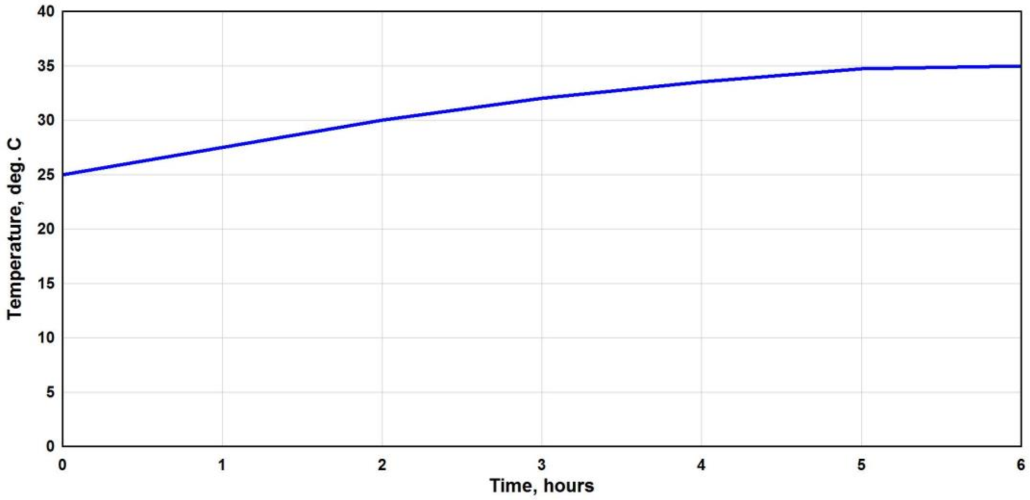


Fig. 9 Temperature inside the test chamber.

As we can see from Fig. 9 the maximum air temperature in the chamber was about 35 °C. So, the designed TVC cooling units allow to maintain required air temperature in the power cables tunnel environment.

TVC cooling system performance improvement

- The underground tunnel regularly passes through areas with different thermal characteristics of soil. For example, under lakes or rivers the soil is wet and its thermal conductivity is higher. So, in such Cold Zone the tunnel is cooled naturally better and less power from cooling system is required. The TVC cooling system is made from multiple units distributed over the length of tunnel, so number of TVC units in Cold Zone of the tunnel can be reduced (see scheme on the Fig. 10):

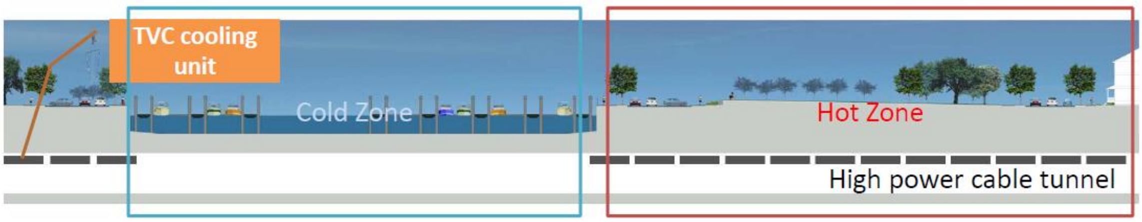


Fig.10 TVC system installation area.

Also, more TVC unit will be installed in the Hot Zone areas required more cooling power and less in the Cold Zone. Such selective installation is impossible for water cooling system. Due to this feature installation cost of TVC system is about 50% lower than cost of water cooling system for the same tunnel.

- One of the most common reasons of failures for underground power cables is overheating and temperature cycles in the area of cable joints [5]. TVC system made from multiple units in conjunction with Distributed Temperature Sensing System [6] is capable to control temperature near the joints area and prevent joints overheating. So, use of TVC system is prospective way to improve reliability and reduce maintenance cost of power transmission lines in underground tunnels.
- Another important feature of TVC system is possibility to fit immediately cooling power to daily changes of electrical power transmission. This is impossible for water cooling due to large water mass and thermal inertia of cooling equipment. According to the performance calculations, TVC system will save of more than 40% of energy consumption in the case when transmitting power is changed according to the graph shown on the Fig. 11.

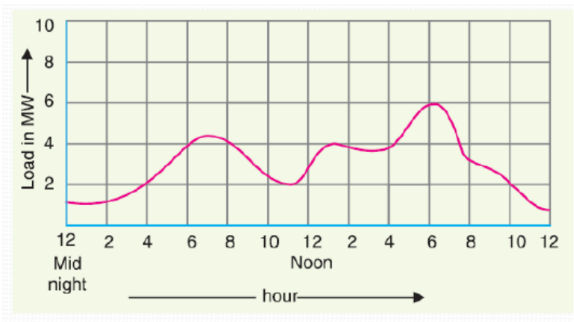


Fig. 11 Sample graph of power transmission daily changes

- One of the prospective ways to improve performance of cooling system consisting of many interfering units is utilization of AI technology. Utilization of machine learning technology for Google's data centre allowed improvement of the system's utility on about

40% [7,8]. TVC cooling system made from multiple units working at the same environment can be optimized by the similar approach.

Conclusion

1. New TVC cooling concept for EHV cables in underground tunnel has been designed and proved.
2. TVC cooling system consists of multiple units attached to concrete wall of tunnel and distributed over its length
3. Heat power from TVC units is transferred to soil through concrete walls of tunnel.
4. Feasibility of the heat power transfer concept has been proved by computer simulations.
5. Prototypes of TVC units has been designed and fabricated.
6. Performance test of the prototypes shows that TVC cooling system is capable to maintain air temperature of 35 °C under conditions modelling real power cable tunnel.
7. Prospective ways of performance improvement by utilization advantages of TVC concept are shown.

BIBLIOGRAPHY

[1] "Overview of the Potential for Undergrounding the Electricity Networks in Europe", Report for DG TREN/European Comission, ICF Consulting Ltd, 2003

[2] "Underground transmission line design", TEPCO, Corporate Information

[3] F. Boukrouche, C. Moreau, W. Frelin "Heat Transfer Modeling of Power Cables in Tunnels", COMSOL presentation

[4] M. Hayashi, K. Uchida, W Kumai, K. Sanjo, M. Mitani, N. Ichiyanagi, T. Goto "Development of Water Pipe Cooling System for Power Cables in Tunnels", IEEE Power Engineering Review, 1989.

[5] D. Fournier, N. Amyot "Diagnostic of Overheating Underground Distribution Cable Joints", 16th International Conference and Exhibition on Electricity Distribution, 2001

[6] "Long-Range Distributed Temperature Sensing System", LIOS Technology GmbH, Technical Information

[7] "Google Just Gave Control over Data Center Cooling to an AI", MIT Technology Review, 2018.

[8] J. Gao "Machine Learning Applications for Data Center Optimization", Google Technical Information