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# SUPERCONDUCTING CABLES – ANALYSIS OF THEIR OPERATION AND APPLICATIONS IN ELECTRIC GRIDS

**ABSTRACT** *In this paper the use of high temperature superconducting cables for transporting electrical energy is analysed. The construction of a short model of a superconducting cable is explained, global progress in this field is examined and related electromagnetic phenomena are discussed, particularly those concerning pinning potential barrier formation. The paper analyses the results of investigations into the current-voltage characteristics of superconducting cable model working in the temperature of liquid nitrogen, allowing to reach the value of critical current equal to 45 A.*

**Keywords:** *superconducting cables, high temperature superconductivity, electric energy transport, pinning phenomena*
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## 1. SUPERCONDUCTING CABLES

Improvements to make methods of delivering energy more economical are necessary to help resolve the current energy crisis. A very promising solution lies in the use of high temperature superconducting cables, which enable direct current to be transported with almost no power loss. However, losses can occur while transporting alternating current through superconducting cables, due to electromagnetic phenomena specific for superconducting materials. Therefore superconducting cables are designed to reduce AC losses, for instance in the form of the so called Roebel cables [1], in which transposition is used to reduce losses, by cutting and linking tape. This transposition technique, while effective for reducing power loss in copper wires, is difficult to use with HTc superconducting cables due to the fragile structure of the tapes used to form them.

Almost nine-fold reduction in the size of superconducting cables, compared to analogous copper busbars, is a second important advantage. This issue has particular importance in big conglomerations such as New York, Tokyo and even the old districts

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of Polish cities like Warsaw and Krakow. The issue of superconducting cables and generally application of HTc superconductors is especially relevant after the recent discovery of the ultra-high critical superconductivity temperature of 203 K in the sulfur hydride system $H_2S$, solidified under the pressure of 2 GPa [2]. This material is also especially interesting because it is isostructural with water $H_2O$. This discovery has technical as well as scientific ramifications because the critical temperature value is a basic criterion affecting the use of superconducting devices such as cables. Primary constructions based on low temperature superconducting wires made from NbTi with a critical temperature in the region of 10 K, built in the second half of the last century, were not acceptable due to the high costs of cooling the superconductors in liquid helium, as this negated their economic advantages. The issue of high temperature superconducting cables is currently being investigated especially in developed countries such as Germany, South Korea, Japan, the USA and also Russia. In Europe a 30 m long three-phase high temperature superconducting cable has been constructed in Denmark, at the Institute of Technology in Lyngby and it was tested early this century in the Copenhagen electric grid. In 2011 in the USA, a 600 m long single-phase 138 kV superconducting cable was constructed, which transported a current of 2.4 kA, using second generation YBaCuO superconducting tapes. Second generation tapes are currently the most promising superconducting wires, because they enable a current of over 200 A to be sent through a superconducting layer of a width of several millimeters at liquid nitrogen temperature.

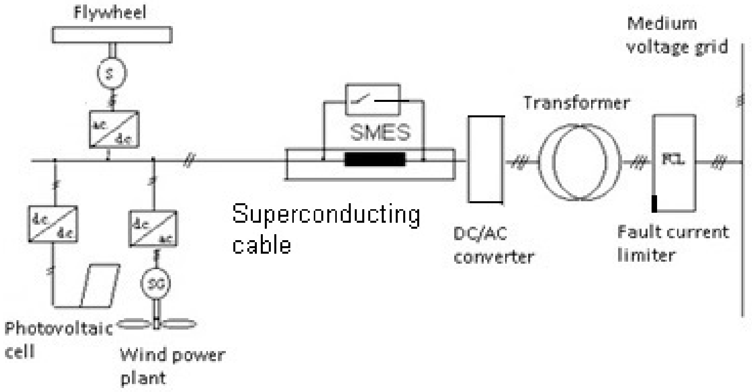

**Fig. 1. Schematic view of renewable energy plants connected to a medium voltage grid using HTc superconducting cable**

These tapes are also less prone to the uncontrolled transition to a normal state, termed quench behaviour, due to the high normal state resistivity of the thin YBaCuO film with which the tape is covered, which plays a self-limiting function. This type of superconducting cable is used in the Long Island Power Authority substation in New York. This start-up project was expanded in 2013 with a 240m long superconducting cable, transporting three-phase current of 4 kA at 13.8 kV. Currently the longest superconducting cable in use is in Essen in Germany. This is a 1 km cable constructed by Nexans, transporting three-phase current of 2.4 kA and 10 kV, made from BiSrCaCuO type wire, fabricated with traditional powder-in-tube technology, already familiar from the production of $Nb_3Sn$ wires. High temperature superconducting cables have also been constructed in South Korea, Russia and Japan, where a 200m three-phase cable, carrying 200 MVA at 66 kV, has been in use in Yokohama since 2012. In 2010 at the VNIIKP cable institute in the Russian town of Podolsk near Moscow a 200 m superconducting cable using Bi-2223 superconducting tapes was constructed, and now under construction is an $MgB_2$ based superconducting cable which is cooled by liquid hydrogen, which will also allow the cable cryostat to be used for transporting fuel for a new generation of hydrogen-powered cars. In Figure 1, there is schematically shown the superconducting cable being used to transport renewable energy from solar and off-shore wind farms to a medium voltage electric grid via a system of dc/ac converters, protected by fault current limiters. Excess energy is stored in a superconducting magnetic energy system (SMES) and in flywheels. The use of HTc superconducting cables enhances the efficiency of this renewable energy system because it requires much less energy and material than analogous conventional current transportation methods.

## 2. INVESTIGATION OF A SUPERCONDUCTING CABLE MODEL AND ITS ELECTROMAGNETIC PROPERTIES

Figure 2 shows a short model of a superconducting cable constructed by the author using first generation BiSrCaCuO tape with the high voltage current leads necessary for using such cables in power applications. Although dc current can flow through superconducting cable without loss even at low voltage, a high voltage regime is necessary if any high power energy device is to be supplied.

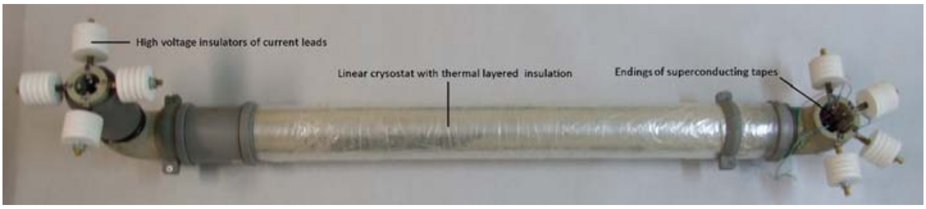

**Fig. 2. View of a model of a three-phase HTc superconducting cable**

The measured endurance of the current leads against high voltage impulse penetration was equal to 30 kV and it took the form of a surface discharge. The current lead maintained a voltage of 28 kV for measurement times longer than one minute. The current lead reliability to an alternating voltage of 50 Hz frequency was equal to 18 kV for one minute, while at 20 kV a surface discharge appeared.

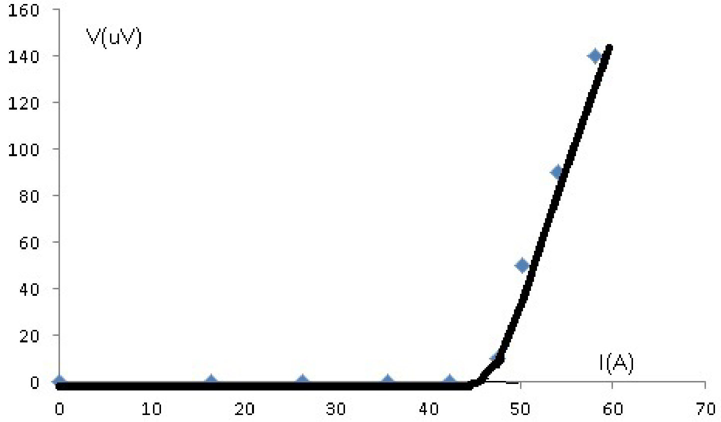

**Fig. 3. Measured current-voltage characteristics of the superconducting cable model, at temperature T = 77 K**

The current-voltage characteristics of the superconducting cable model were investigated at liquid nitrogen temperature and the resulting measurements are shown in Figure 3. The data show the critical current for this cable model is 45A. The thermal characteristics of the superconducting cable's cryostat, constructed from plastic tubes covered with insulating foil, without additional vacuum shields, were also tested. Figure 4 shows changes over time in the temperature ΔT in relation to room temperature on the surface of the cryostat, during the period when the cryostat chamber with the superconducting tapes that formed the cable were cooled by liquid nitrogen, and the subsequent reheating after the liquid nitrogen evaporated.

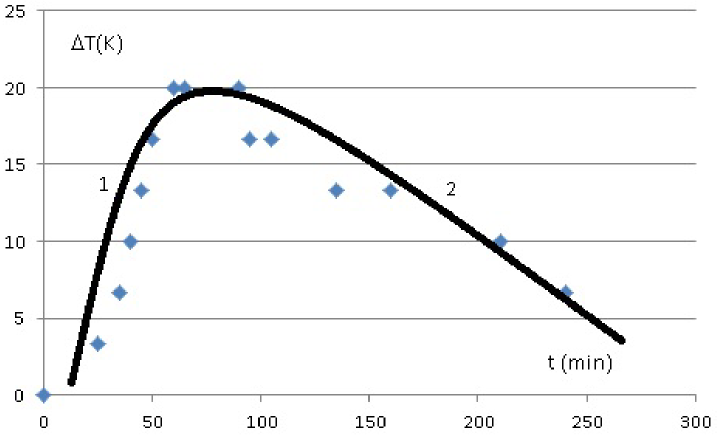

**Fig. 4. The change over time of the temperature ΔT on the surface of the linear cryostat of the superconducting cable model during the cryostat's cooling with liquid nitrogen (1) and then during its natural reheating with the liquid nitrogen evaporation (2)**

The efficiency of the superconducting cable is dependent on its current-voltage characteristics, as shown in Figure 3. A theoretical analysis of these characteristics was carried out based on a developed model which analyses the anchoring of flat magnetic pancake vortices on thin nanoscale defects, as shown in Figure 5.

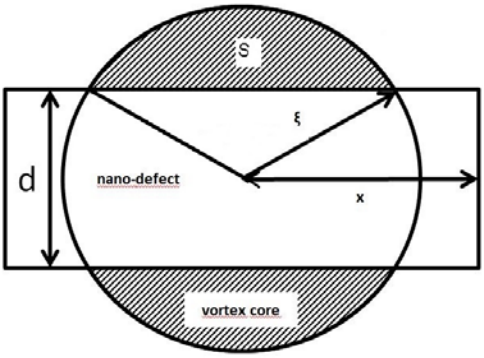

**Fig. 5. Scheme of a fully captured pancake vortex core inside a thin nanoscale defect**

In Figure 5 $x$ is the deflection of the vortex centre from the edge of the capturing defect, while the shadowed region S is the part of the vortex core outside the capturing centre. $\xi$ is the superconducting coherence length, $d$ the width of the pinning centre. The elaborated theoretical model [3] is based on the analysis of free energy $F$ of the captured multivortex system, described in the general form:

$$F\left(r_1, r_2, r_3, \ldots r_N\right) = \sum_{i=1}^{N} U\left(r_i\right) + \frac{1}{2}\sum_{i \neq j}^{N} F_{\text{inter}}\left(r_i - r_j\right) - J\phi_0 \sum_{i=1}^{N} l_i \delta r_i - \sum_{i=1}^{N} \frac{C \delta r_i^2}{2} V_i \qquad (1)$$

$U$ is the individual pinning potential, while $F_{inter}$ is the energy of the electromagnetic interaction between the vortices at positions $r_i$ and $r_j$. The summation concerns all N vortices, each of them transporting flux $\phi_0$. The third term is connected with the Lorentz force acting on the length $l_i$ shifting vortex initially being at position $r_i$ on the distance $\delta r_i$ in the flux creep process, and $J$ is the current density. The last term describes the energy connected with the elastic properties of the pancake vortex lattice. $V_i$ is the volume of the deformed lattice during the capture of the $i$-th vortex, while $C$ is the elastic spring constant of the vortex lattice. The equilibrium condition means the vanishing of the derivative of free energy $F$ for the specified form of the pinning potential $U$. The small size of the capturing centres allows the problem to be reduced to the individual interaction between the vortex and the nanoscale defect and allows the interaction between the pancake vortices themselves to be set aside. The shift of the vortex core from the initial equilibrium position as shown in Figure 5 leads to an variation of the pinning energy of the system and then the potential barrier $\Delta U$ arises determining the flux creep process of the captured vortices for forward and backward flux movement. The potential barrier in the current representation is the function of the reduced transport current density $i = j/j_c$ and the nanoscale defect size *d*. $j_c$ is the density of the critical current. For ultra-thin defects, as in the case of defects created in a fast neutrons irradiation process, d < 2ξ after applying the renormalization procedure leading to the vanishing of the energy barrier *ΔU* for the critical current density, it gives the form described by Eq. 2.

$$\Delta U(i) = \frac{\mu_0 H_c^2 l\,\xi^2}{2}\left[\begin{array}{l} -\arcsin(i) + 2\arcsin\dfrac{d}{2\xi} + \dfrac{d}{\xi}\sqrt{1-\left(\dfrac{d}{2\xi}\right)^2} \\ +i(\dfrac{\pi}{2} - \dfrac{d}{\xi}\sqrt{1-\left(\dfrac{d}{2\xi}\right)^2} - 2\arcsin\left(\dfrac{d}{2\xi}\right) - \sqrt{1-i^2}) \end{array}\right] \tag{2}$$

In Eq. 2, $H_c$ is the thermodynamic critical magnetic field and *l* is the thickness of the superconducting layer. Figure 6 shows the potential barrier as the function of current for various dimensions of pinning centres, which correspond to the various sizes and energies of heavy ions used for irradiation in superconducting accelerators.

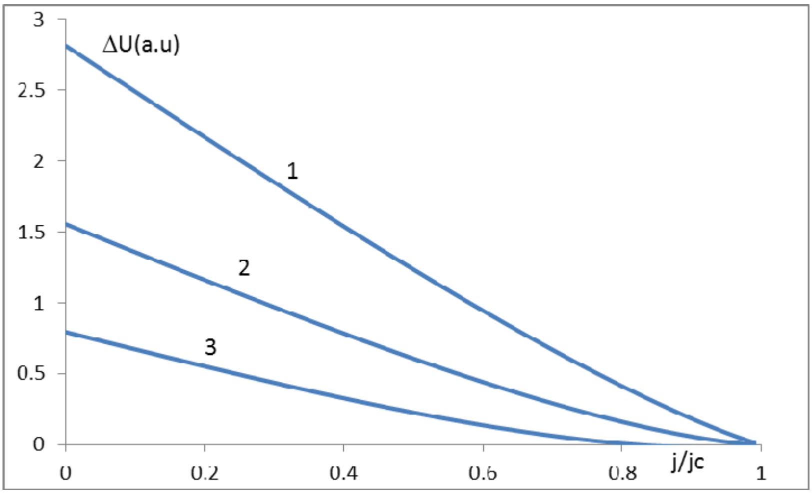

**Fig. 6. The influence of reduced current *j/j*$_C$ on potential barrier *ΔU* for initially totally pinned vortex as the function of the size of nanoscale defect: (1) *d/2ξ* = 0.8, (2) 0.4, (3) 0.2**

The above model allows the current-voltage characteristics of an HTc superconductor to be determined. The results of the calculations in Figure 7 show the current-voltage characteristics as the function of applied magnetic induction. They are in qualitative agreement with the experimental data shown in Figure 3, which confirm this model.

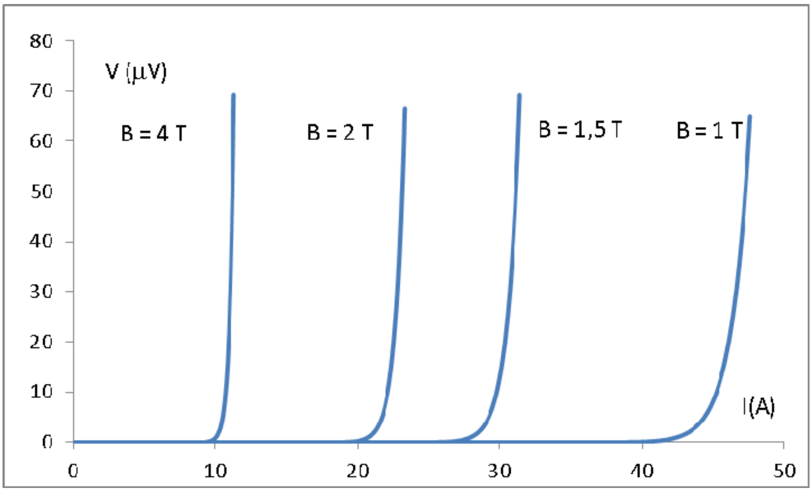

**Fig. 7. Calculated current-voltage characteristics as a function of magnetic induction**

## 3. CONCLUSIONS

A short model of an HTc superconducting cable built from Bi-2223 superconducting tapes has been discussed in this paper. The electromagnetic phenomena associated with the work of this device have been investigated. The pinning potential barrier formation and superconducting current-voltage characteristics have been analysed, and their shape is in qualitative agreement with the experimental data. Global progress in the application of these cables, one of most promising HTc superconducting devices, has been described.

## LITERATURE

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# KABLE NADPRZEWODNIKOWE – ANALIZA DZIAŁANIA I ZASTOSOWANIA W SIECIACH ENERGETYCZNYCH

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**STRESZCZENIE** *Przeprowadzono analizę wykorzystania wysokotemperaturowych kabli nadprzewodnikowych przy przesyle energii elektrycznej. Zaprezentowano konstrukcję i wyniki badań krótkiego modelu kabla o zmierzonym prądzie krytycznym 45 A. Omówiono światowe trendy w tym zagadnieniu i przedstawiono opracowany model teoretyczny opisujący związane problemy elektromagnetyczne, w tym powstawianie bariery potencjału zakotwiczenia, charakterystyki prądowo-napięciowe oraz prąd krytyczny.*

**Słowa kluczowe:** *kable nadprzewodnikowe, nadprzewodnictwo wysokotemperaturowe, przesył energii, siły zakotwiczenia*