Conductors in Cryogenic Environment Used in Power Engineering

Lucian DIODIU, Aronel MATEI, Daniel Alexandru DRAGOMIR, Octavian ISAICU

University of Petrosani, Str. Universității nr. 20, 332006, Petroșani, jud. Hunedoara, Romania; email: red_rose_ro2000@yahoo.com

http://doi.org/10.29227/IM-2019-01-12

Submission date: *11-07-2018* | Review date: *02-04-2019*

Abstract

The tendency to increase the carrying capacity of the electric load in the supply networks can be done in two directions, namely:

- *the construction of several transmission and distribution lines linking the energy source to the consumer (current trend), having the effect of damaging the environment, or*
- *limiting the construction of transport lines and, implicitly, the destruction of the environment by using technologies and materials capable of carrying a very large amount of electricity.*

Keywords: cryogenic environment, nitrogen, electric charge, cryogen cables, superconductivity

Overconductibility is a phenomenon that has, at least until now, been manifested only at cryogenic temperatures and which has been seen for the first time due the discovery of helium liquid. Overconductivity is given by the very rapid drop to zero of the electrical resistance below a specific temperature called superconducting transition temperature or critical temperature, Tc.

The electrical resistance of the conductors is directly proportional to the temperature through the relationship:

$$R = R_0\,(1+\alpha\Delta t) \tag{1}$$

where:

R_0 is the conductor resistance at 20°C,

α is the coefficient of thermal expansion.

As the temperature rises, the electrical resistance is higher and so the electrical load carrying capacity of a conductor is reduced.

In order to increase the intensity of the electric current running through a conductor, two trends can be drawn, namely:

- increasing the section of conductors or constructing in parallel several electric lines,
- reducing the working temperature around the conductors.

Low temperatures around the conductors can be achieved with cryogenic fluids.

Liquid nitrogen is a cryogenic fluid that is in the form of isotopes and can be obtained by the fractionation of air.

The thermal conductivity of the nitrogen relative to the temperature is linear, that ranges from a conductivity of 0,94 W·m-1 x102 for the temperature T =100K, to 2,61 $W \cdot m^{-1}\ x10^2$ for the temperature T = 300K.

In the environment with very low temperatures, in the cryogenic field, the properties of the materials have an evolution that cannot be extrapolated to the environment with normal working temperatures.

The behavior of materials in a cryogenic environment is different; the study of main parameters may support the choice of materials to be used.

If the environment it takes a few hours to allow thermal equilibrium in cryogenic environment enough minutes.

Specific heat becomes an important dimension in the use of conductors in cryogenic environments.

Applying the quantum theory of thermal vibrations in solids and assuming that all the particles present in a crystal vibrate with the same frequency f0, the oscillator energy is:

$$E = n \cdot h \cdot f_0 \tag{2}$$

where:

n is an integer

h is Planch's constant ($h = 6{,}63 \cdot 10^{-34}$ Js)

Using Boltzman's law considering that all states are equally degenerate, the average energy of an oscillator can be written:

$$E_m = \frac{3\sum_{n=0}^{\infty} E_n \exp\left(-E_{n/kT}\right)}{\sum_{n=0}^{\infty} \exp\left(-E_{n/kT}\right)} \tag{3}$$

or

$$E_m = \frac{3hf_0}{e^{-\frac{hf}{kT}} - 1} \tag{4}$$

The specific heat value will be:

$$C_v = \left(\frac{\partial U}{\partial T}\right) = 3\,R\left\{\frac{\left(\frac{hf_0}{kT}\right)^2 \exp\left(\frac{hf_o}{kT}\right)}{\left[\left[\exp\left(\frac{hf_o}{kT}\right)-1\right]\right]^2}\right\} = 3\,RE\,(\theta_E/T) \quad (5) \tag{5}$$

where θE = hf0/kT and is called Einstein's temperature for very low temperature values we will have:

$$C_v = 3\,RE\,(\theta_E/T)^2 \exp\left(-\theta_E/T\right)) \tag{6}$$

At low temperatures the quantification of the network reduces the specific heat in relation to the classical heat.

This is because the exponential variation of the specific heat, in this temperature range, is much faster than the T^3 variation observed at low temperatures.

Electrical conductivity

According to Ohm's law, when a current of electric intensity I pass through a conductor with the resistance R, there is a voltage U of value:

$$U = R\ I \tag{7}$$

Depending on the nature and properties of the material, the electrical resistance is given by:

$$R= \rho \cdot l/S \tag{8}$$

where:
ρ is the electrical resistivity of the material
l is the length
S is the section

With the passing of the electric current I, through a conductor, the Joule effect, its heating, generates electricity losses that can be determined with the relation:

$$P = R \cdot I^2 \tag{9}$$

The behavior of a metal's resistivity according to temperature in a cryogenic environment varies with the temperature cube.

The cryogenic medium which superconductivity occurs is given by the very rapid decrease to zero electrical resistance at a certain temperature of the superconducting transition.

An avalent resistivity determines an electrical system without "friction", electric circuits without Joule effect, ie without any dissipation of electrical energy.

For each superconductor there is a temperature range and a magnetic field below which the material is superconducting and over which it becomes normal.

The relationship between the critical field and the temperature is the parabolic one.

$$H_c = H_0\ [1-(T/T_c)^2] \tag{10}$$

where:
H_0 represents the critical field for T = 0 K
T_c is the maximum temperature at which the material is in the superconducting state when H = 0.

Electric power currently transported by conventional underground cables is of the order of 1000 MVA. For such great powers, it is necessary to evacuate the heat generated by Joule effect, ie forced cooling with oil or water. To meet the growing consumption of energy has made other cable systems such as superconducting cables.

Although they have a very low electrical resistivity compared to other conductors, copper and aluminum only permit a current density of the order of 1÷2 $A \cdot mm^{-2}$ at 20°C (293.15 K), if we want to we avoid sensitive heating by Joule effect.

By cooling these conductors at the liquid nitrogen temperature (77 K), the electrical resistivity of copper decreases with an order of magnitude almost. This cooling is provided for non-superconducting or cryo-resistive cryocabs.

If we start from 4.2 K, the boiling temperature of the helium at atmospheric pressure, the superconducting alloys whose transition temperature is higher, are materials that have a zero resistivity to a direct current and a very weak resistance (10^{-6} times that of copper) for an alternating current of 50 Hz.

In practice, because of the limitations given by the critical current, in these superconducting cables we can have a current density of 200 $A \cdot m^{-2}$. So, there is a ratio of 1: 200 in the favor of superconducting cables.

This report justifies economically the use of these cables, despite the energy they that is needed to be cooled below their transition temperature. Cryocabs will also compulsory need to be underground, the environment being protected.

Increasing the allowable current density for a conductor of a certain section can also have the effect of reducing the overall dimensions of the power equipment.

For an electric circuit by a current of I = 1000 A is passed, the copper wire section, which may also be part of a secondary winding of a power transformer in normal environment, should be at least 500 mm^2, admitting a current density of Jrated = 2 $A \cdot mm^{-2}$.

In a cryogenic environment, the superconducting current density may be Jcryogenic = 200$A \cdot mm^{-2}$, which would mean that the winding of a transformer from a cryogenic environment could be executed with a 5 mm^2 section conductor, which would mean the reduction of the gauge of the equipment.

The favorable environmental impact is achieved by both reduced gauges and the reduced number of high-capacity underground electricity lines.

Conclusions

Using wires in cryogenic environment is beneficial:

- on the electric load carrying capacity,
- diminishing the dimensions of the power equipment,
- reducing the impact on the environment through the construction of cryogenic underground lines.

Literatura – References

1. M.N. Wilson, Superconducting Magnets, Clarendon Press, Oxford (1983).
2. R.F. Barron, Criogenic Systems, Clarendon Press, Oxford (1985).
3. R.G. Scurlock, "History and Origins of Cryogenics". Ed. Clarendon Press, Oxford, 1992.
4. J. Senft, An Introduction to Low Temperature, Moriya Press (1996).
5. J.G. Weisend (editor), The Handbook of Cryogenic Engineering, Library Binding (1998).
6. Donabedian M., "Spacecraft Thermal Control Handbook", Cryogenics, 2003.
7. Burghardt, "Engineering thermodynamics applications", p.496-497, 2004.
8. Th. Flynn, Cryogenic Engineering, Second Edition, Revised and Expanded, Marcel Dekker, New York 2005.
9. Duţă O.D., „Sisteme criogenice cu heliu pentru aplicaţii militare şi spaţiale", Articol, Buletinul Ştiinţific 2/2009, Universitatea Tehnică de Construcţii, Bucureşti, 2009.
10. Cryogenic helium systems for military and space applications ", Article, Scientific Bulletin 2/2009, Technical University of Civil Engineering, Bucharest, 2009.

Przewodniki w środowisku kriogenicznym stosowane w energetyce

Tendencja do zwiększania obciążenia elektrycznego w sieciach zasilających może być realizowana w dwóch kierunkach, a mianowicie: budowa kilku linii przesyłowych i dystrybucyjnych łączących źródło energii z konsumentem (obecny trend), powodujących uszkodzenie środowiska, lub ograniczenie budowy linii transportowych i w efekcie ograniczenia zniszczenia środowiska poprzez zastosowanie technologii i urządzeń zdolnych do przenoszenia bardzo dużej ilości energii elektrycznej.

Słowa kluczowe: środowisko kriogeniczne, azot, ładunek elektryczny, kriogeniczne kable, nadprzewodnictwo