International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

Review Article

Cryogenic system for High Temperature Superconducting Power Cable-A Review

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Accepted 12 March 2017, Available online 16 March 2017, **Special Issue-7 (March 2017)**

Abstract

Materials which shows superconductivity above liquid nitrogen temperature are known as high temperature superconductors. J.G. Bednorz and K.A. Mueller were awarded noble prize for discovering high temperature superconductors in 1987. Since last 3 decades there has been significant augmentation in the field of superconductivity. The primary advantage of HTS power cable over conventional cable is the ability to carry more power per circuit with lower energy cost per megawatt delivered. Power transmission is loosely defined as the transfer of electrical energy from source to a load over conductors that carry relatively large currents, while being maintained at large voltage. In order to achieve liquid nitrogen temperature, efficient cryogenic system is required. Hence, it is integrated with HTS power cables. Several HTS cables have been designed, developed and operated in various parts around the world. Most of them are used for experimentation purpose. Very few of them are used in electrical grids. Use of high temperature superconductivity in electrical grids will have a major positive impact on power system operation and control. HTS power cable is placed into heat-insulated pipe which is filled with cryogen. Circulation of cryogen removes heat seeping through the insulation. HTS power cables with different design considerations can be used for transmission of AC and DC.

Keywords: *Superconductor, cryogen, HTS Power Cable, Cryogenics, Liquid Nitrogen*

1. Introduction

The property of zero electrical resistance in some substances at very low absolute temperatures is called superconductivity. These substances include metallic elements, intermetallic compounds, and alloys. The state of the superconductivity is governed by three parameters. They are temperature (K), current density (A/mm2) and magnetic field (Tesla). Superconducting materials are distinguished depending upon the critical temperature they exhibit. Earlier, the materials having transition temperature above 30 K were called as High Tc or HTS materials. Nowadays, the materials which uses LN2 for their superconductivity are termed as HTS materials. HTS applications are approaching practical use in areas such as power cables, current limiters, transformers and motors.

A cooling system is mandatory to achieve superconductivity for HTS application. A cooling system should have high coefficient of performance, long maintenance interval and compactness. A cooling system uses cryogen to overcome low temperature heat loading. The temperature of cryogen should be maintained below its boiling point and above its freezing point. Liquid nitrogen is the most commonly used cryogen for HTS applications.

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Energy optimization can be achieved using HTS power cable in energy distribution. Short distance (few hundred meters) HTS power cables are being used in industry at present. Soon long distance HTS power cables will be implemented in electrical grids.

2. Placing the figures

2.1 Modes of heat penetration

Table 1 Modes of heat penetration

Component	Type
Storage Dewar	Radiation Conduction
Transfer Line	Radiation Conduction
Core Cryostat	Radiation Conduction
Cold Box	Radiation Conduction
HTS Cable	Radiation Conduction

Type of heat seepage in cryogenic system is shown in table 1. It contains heat leak of storage dewar, core cryostat, cold box, transfer line and HTS cable.

2.2 Cryogens

In HTS power cables sub-cooled liquid nitrogen is used as cryogen. Liquid nitrogen are used to absorb the heat penetrated from the surroundings and internal heat generated in the conductor. It maintains the temperature of conductor below its critical temperature. After liquid nitrogen has absorbed this heat, it is cooled with help of a cryogenic refrigerator.

The freezing point and boiling point of liquid nitrogen and critical temperature of conductor govern the working range of liquid nitrogen .When temperature of liquid nitrogen goes beyond the critical temperature of conductor, it will lose its superconductivity. When circulating liquid nitrogen boils off, it decreases the pump efficiency and increases power consumption. If the liquid nitrogen freezes in the cryostat, it will partially block or completely block the flow in the cryostat which will adversely affect the cryogenic system. At 1 atm liquid nitrogen has a boiling temperature of 77.4 K and freezing point of 63.2K. Hence the working range of liquid nitrogen is 14.2K at 1 atm. Although it can be expanded by increasing the pressure in the system (comprising, for example, 20.6 K at 2 atm.), but the lower temperature limit (the freezing temperature) remains almost unchanged(Yury Ivanova, *et al*, 2012). In case of short distance HTS power cable the temperature drop across the cryostat is 1-2K. But in case of long distance HTS power cable the larger temperature drop is allowed to reduce the pressure drop. For convenience the temperature drop is assumed 10K in the case of long distance HTS cable.(Victor Sytnikov, *et al*, 2013) But expanding of the temperature range leads to the increasing of the temperature at the cryogenic tube outlet and, hence, to the undesirable lowering of the critical current. The operating pressure range lies within the 1.0 – 15.0 atm. Ideally pressure drop across the cryostat must be ideally zero. But during actual operations due to hydraulic frictional losses there is pressure drop across the cryostat. Pressure drop in not significant in case of short distance (few hundred meters) HTS power cable and power of pump is sufficient to overcome it. .In case of long distance HTS(more than one kilometer) cables there is significant pressure drop. Reduction of pressure drop to the lowest practical level is critical in case of long HTS cables. In this case the circulation rate is kept low to reduce the pressure loss. In case of long distance HTS power cable one single large pumping unit is not used but several intermediate pumping stations at suitable distance are used to achieve reduced equipment cost and maintenance costs.

2.3 Refrigeration System

In early days before the development of closed cycles for HTS power cable, a simple decompression system was used to cool and maintain the temperature of conductor. This was a type of open system which required large amounts of liquid nitrogen to be supplied over a period of time. It consisted of a liquid nitrogen container at sub-atmospheric pressure which acted as a liquid nitrogen subcooler. In this container the heat is removed from circulating liquid nitrogen flow. This system is not suitable for continuous operation of HTS power cable. For continuous operation of HTS power cycle, a closed cycle refrigerators are used. On the basis of heat exchangers used in refrigerators used, they are classified as regenerative cryogenic refrigerator and recuperative cryogenic refrigerators.

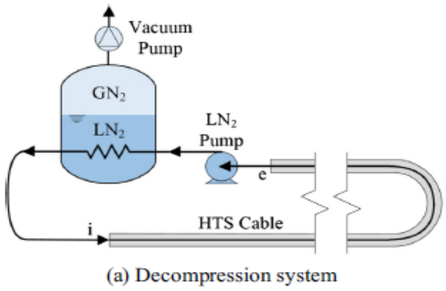

Fig 1 Open Cycle

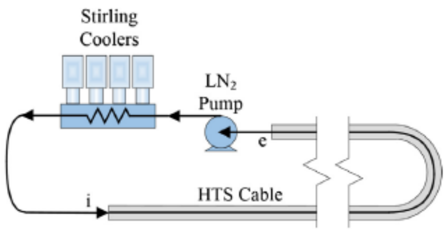

Fig 2 Regenerative Cycle

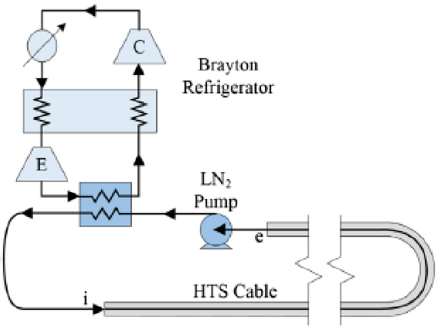

Fig 3 Recuperative Cycle

In a recuperative heat exchanger, the flow direction of two fluids is constant and is simultaneous. The two fluids are separated by a solid boundary across which the warm and cold fluids exchange heat. The direction of the fluid flow may either be counter flow, cross flow or parallel flow. Recuperative cryogenic refrigerator are based on Joule-Thomson cycle, Brayton refrigeration cycle and Claude cycle. For heavier thermal load, recuperative refrigerators (based on Joule-Thomson, Brayton, or Claude cycle) are more suitable, not only because the cooling capacity can be greater, but also much larger surface area can be provided for cooling liquid nitrogen with high-effectiveness heat exchangers. As the cost of Joule-Thomson refrigerator is least among all the recuperative refrigerators, more attention should be given on development of high efficiency Joule-Thomson refrigerators.

In a regenerative heat exchanger, a matrix is used as an intermediate heat exchange medium between the warm and cold fluids. The flow is periodic in nature alternating between the warm and cold fluids across the matrix. It is important to note that, it is an example of indirect heat transfer. Stirling refrigerator, Gifford-Mcmahon refrigerator and pulse tube refrigerator are types of regenerative cryogenic refrigerator. These are small refrigerators which are capable of providing cooling power form several watts to 1KW and range of temperature from 100K to 3K. For small HTS applications cooled by comparatively small cryogenic refrigerator mentioned above, either a direct cooling method where a G-M cryogenic refrigerators is used or a cooling method where a cryogen, such as liquid nitrogen, is placed inside and a cryogenic refrigerators is used to cool the cryogen are applied developing G-M, Stirling, and pulse tube cryogenic refrigerator of several kW is technologically difficult, due to such problems as thermal exchange inside the cryogenic refrigerator.(H. Hirai, *et al*, 2009).When the thermal load is relatively small, multiple units of regenerative cryogenic refrigerator can be conveniently used. In some cases, the decompression units have been installed in parallel as a back-up or in preparation for emergency operation.(Ho-Myung Chang, *et al*, 2016)

Both closed and open cycle require pump for circulation of liquid nitrogen. Investigation a new concept of cryogenic cooling system that integrates the liquid nitrogen circulation loop into the refrigerator cycle have been going on. The main idea is to eliminate the LN pump, but generate a large LN flow rate with the power of compressors at ambient temperature. In the integrated design, the working fluid (refrigerant) of refrigeration cycle is nitrogen itself, and the Liquid Nitrogen circulation loop along HTS cable is a part of the closed cycle.(Ho-Myung Chang, *et al*, 2016).

The first basic integrated system is the standard cycle cooled with Joule-Thomson stream, where the high-pressure Liquid Nitrogen is supplied to HTS cable and returned to Joule-Thomson valve. The high-pressure nitrogen divides into two streams called "expander stream" and "Joule-Thomson stream", and these two streams coalesce at the same level of low-pressure. The modification done in next cycle is that the pressure levels of expander stream and Joule-Thomson stream are set differently, where the Joule-Thomson stream has a higher supply pressure than the expander stream. This cycle is called the dual pressure cycle cooled with Joule-Thomson stream. For using expander stream for cooling the return pressure of expander stream is set higher than the pressure of Joule-Thomson stream. These two streams merge at ambient temperature. This cycle is called the dual-pressure cycle cooled with expander stream. A counter-flow heat exchanger(HX) is added between the expander and Joule-Thomson streams at the cold end. The role of heat exchanger(HX) is to further sub-cool the Liquid Nitrogen flow. This cycle is called the modified dual pressure cycle cooled with expander stream.

Cooling fluids which can be used in cryogenics are helium, Hydrogen, neon and Argon. Use of hydrogen for industrial purpose is avoided because of its inflammable and explosive nature. Although helium could be selected as working fluid for refrigerator, neon is better energy carrier since it has higher heat capacity and larger molecular weight than helium at a temperature around 70 K in order to make a refrigerator smaller in size. Study and experimentation of mixed refrigerants in Joule- Thomson cycle and Brayton cycle is under progress. Use of mixed refrigerants on commercial basis will reduce cost of operation and increase efficiency.

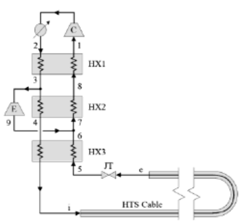

Fig 4 Standard cycle cooled with Joule- Thomson stream

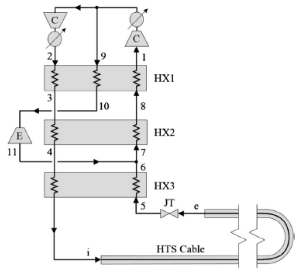

Fig 5 Dual pressure cycle cooled with Joule-Thomson stream

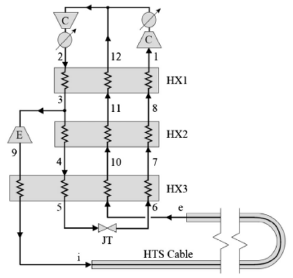

Fig 6 Dual pressure cycle cooled with expander stream

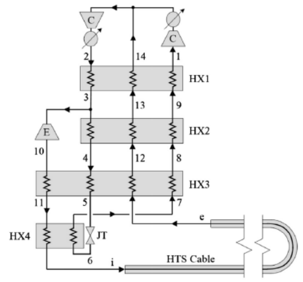

Fig 7 Modified dual pressure cycle cooled with expander stream

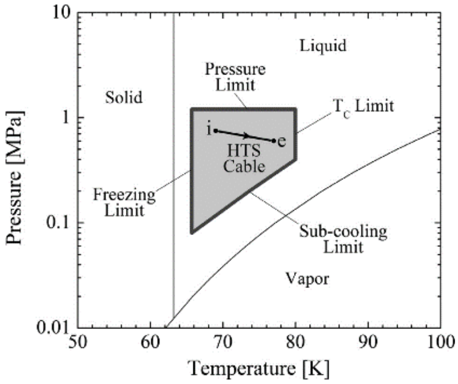

Fig 8 Cooling Requirement of Liquid Nitrogen

2.4 Cooling Requirements

The very basic requirement of any cryostat system is the upper limit of cooling temperature for HTS conductors. This is given by the right vertical line. Next requirement is the ''Sub-cooling Limit'', which is shown by the curve at bottom. The sub-cooled liquid state is very important consideration as any bubble formation within the system can affect the working adversely. Third requirement is the lower limit of temperature, as indicated by the left vertical line this is also known as ''Freezing Limit''. The possibility of LN freeze-out is a significant safety issue, when the coldest temperature of refrigerant is lower than the freezing temperature of Liquid Nitrogen. The last requirement is the ''Pressure Limit'', as indicated by the horizontal line at top. This is the maximum allowable pressure, which should be determined by the mechanical strength of cable cryostat, depending on the material and dimension of cryostat wall and the manufacturing process.

2.5 Components

- Storage Dewar: It is used for liquid nitrogen supply and storage. It consist of a pressure sensor, relief valve and auto fill system.
- Circulation Pump: Circulation pump is not mandatory in the proposed integrated design of cryogenic system. In the traditional cryogenic system circulation pump is used for transmission of liquid nitrogen.

2.6 Sub Cooling System

- Sub Cooling System is used for absorbing the heat leaking from subcooled liquid nitrogen.it consists of relief valve, heat exchanger, vacuum pump, massflow meter and control valves. The gas boiled off in the sub cooler can be directly vented to the atmosphere or discharged through the vacuum pump.

2.7 Control system

PID based or PLC based control systems are used for smooth and continuous operations of all the systems involved in HTS power cable transmission.

Conclusions

Practical analysis of hydraulic frictional loses and pumping efficiency is required to make long distance HTS power cable viable on commercial basis. Investigation of Joule-Thomson cycle running on mixed refrigerants for HTS application should be given priority. The integrated system can be developed in several ways with standard or modified Claude cycles such that the LN circulation loop along HTS cables is included as part of the cycle. It is concluded that the modified dual-pressure Claude cycle cooled by expander stream is primarily recommended. Turbo-Brayton cycle based refrigerators are compact and provide high cooling power.

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