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Cryogenic cooling aspects of HTS power cables - A review

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HTS (High Temperature Superconducting) cable has the ability of transmitting electrical power over long distances in an economical way, with improved stability and reliability. HTS Cable also provides a compact and low-loss transmission power line, in comparison with the conventional cable made out of copper or aluminium. The use of HTS tapes facilitates the cable operations with liquid nitrogen cooling system. A wide variety of HTS Cables with various cooling arrangements have been designed and developed. Their performance has been tested to obtain various thermo-hydaraulic and electrical data by installing the cables of different lengths in transmission and distribution networks. This paper reviews the cryogenic cooling aspects of previous and ongoing projects on superconducting cables for electrical power transmission around the world.

Keywords: *Cryogenic cooling system, HTS cable, liquid nitrogen, termination*

1.0 INTRODUCTION

High temperature superconducting (HTS) cable technology is rapidly approaching towards the real grid applications replacing Copper (Cu) counterparts. Numerous HTS cable demonstration projects are in progress to validate this technology worldwide. Recently India has started research programmes in this technologically-important area at Power Grid Corporation of India, Central Power research Institute, Bangalore, India and IIT Kharagpur. HTS cable has a limited range (65-75 K) of operating temperature to maintain its superconductivity [1]. For efficient operation of HTS cable, an uniform cooling is required. For this, various cryogenic cooling systems based on different refrigeration systems/arrangements, flow paths for subcooled liquid nitrogen (LN_2)coolant in the cable and the type of flow of LN_2 have been developed since last few decades by various researchers worldwide. The cooling process of HTS cable has to deal with the shrinkage of cable materials, thermal shock, thermal stress, hydrostatic vibration, pressure drop, rise in temperature of outgoing coolant and consumption of coolant to obtain reliable operation. The operating temperature has to be determined taking into account the stability of HTS cable and economy of the cooling system. Section-2 of this paper briefly describes the salient features of cable-structure, terminations and cooling issues. This is followed by a detailed description of different cryogenic cooling systems (section-3), employed in various ongonig HTS-cable projects (Table 1) around the world.

2.0 HTS CABLE SYSTEM

2.1 Cable structure

A typical HTS cable (Figure 1) consists of a Cu former, HTS conductor layer, dielectric insulation layer (Polypropylene laminated paper, PPLP), HTS and Cu Shield layers arranged co-axially around the former and housed in

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one thermally insulated double walled cryostat. During the fault current condition, crossing the critical current of HTS the copper former acts as an electrical by-pass to protect the HTS cable layer from burn-out [2], as the electrical resistivity of copper is much smaller than the normal state resistivity of HTS tapes.

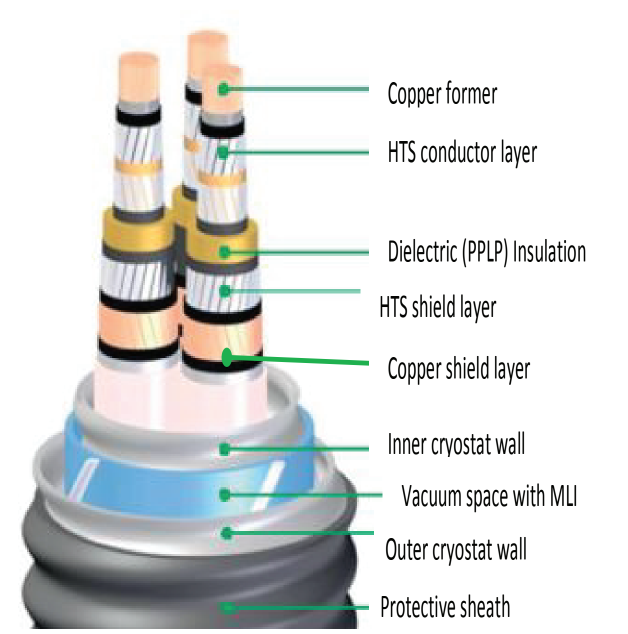

FIG. 1 CUT-VIEW OF A TYPICAL HTS POWER CABLE

The HTS cable has to be cooled down from ambient temperature (300 K) to LN_2 temperature (65-77 K). This results in a 0.3% contraction in cable length and huge mechanical stress. In case of three single phase cables enveloped in single cryostat to realize three phase operation, the cable cores have to strand loosely to absorb 0.3% contraction due to the temperature difference between ambient temperature to LN_2 temperature [3]. The Multi Layer Insulation (MLI) introduced in the surrounding vaccum space minimizes the heat in leak from the surrounding.

The cryostat made up of co-axial corrugated stainless steel pipes/aluminum pipes with annular space housing the multilayer thermal insulation on the inner cryostat wall has to be evacuated and sealed. Tension members made out of stainless steel tapes [3] should be wound around the cryostat for reinforcement against the stress being developed during the pulling action into the long underground duct [4].

2.2 Termination

The termination serves two purposes

i) Electrically connecting the HTS cable at cryogenic temperature to the overhead power line at ambient temperature.

ii) Thermally connecting the HTS cable with the cryogenic refrigeration system for LN_2 circulation.

Thus the cable termination is designed to provide the following functions:

- A low impedance electrical transition from HTS tapes to standard electrical conductors.
- Electric insulation of the electrical phases from each other and from ground potential.
- A thermal gradient between ambient and the cryogenic operating temperatures of the HTS cable.
- A mechanical transition between atmospheric pressure and the vacuum in the cryostat.

The current lead made out of copper is a big source of heat penetrating into the system due to its high thermal conductivity and because of direct exposure to the surrounding atmospheric temperature. Terminations are constructed within a thermally insulated cryogenic vessel (as in Figure 2). The LN_2 is circulated within the termination to cool the HTS conductors and remove heat energy due to conduction heat transfer through the conventional conductor materials and heat invasion through the vessel walls. To decrease thermal stress during the cool down period, the termination should use a bellow as a connection part to the inner cryostat [5].

During HTS cable installation, the termination assemblies may be fixed or placed on rollers to permit cable contraction/expansion due to thermal cycling.

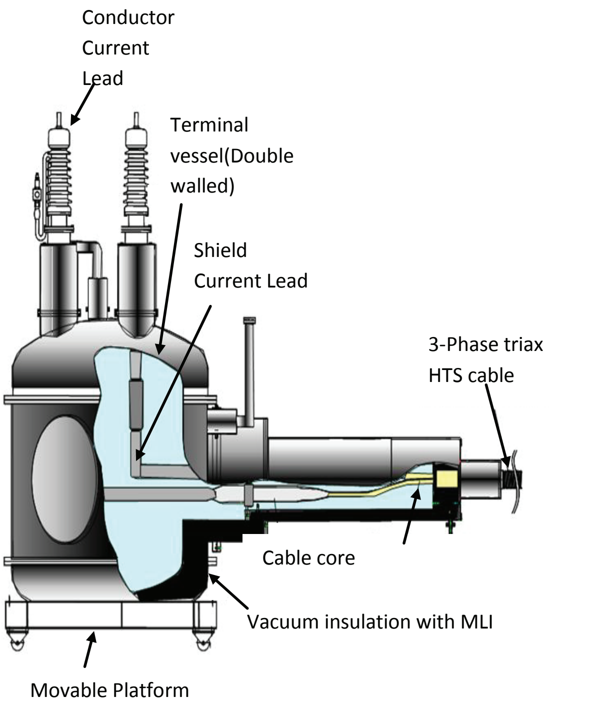

FIG. 2 SCHEMATIC DIAGRAM OF TERMINATION VESSEL

2.3 Cooling issues

2.3.1 Initial Cooling

During the initial cool-down, there is a chance of damage to the HTS cable as a result of thermal shock due to the large temperature difference between 300 to 77 K. To avoid this, the cable system is initially cooled slowly by cold nitrogen gas followed by LN_2, when the temperature difference along the cable is sufficiently small. Tension developed in the cable during cool down operation is an indicator of the degree of cooling and can be measured by the load cells at both the terminations [5].

TABLE 1

HTS CABLE PROJECTS

Project Title	Length (m)	Power (MVA)	Heat in leak w/m	Operating tempe-rature range (K)
KEPCO [19]	100	50	2.2	66-77
Yokohama [2]	30	200		
Albany [20]	350 (320+30)	48	2.9	67-77
LIPA [21]	600	574	1.3 x 3	65.5-71.9

2.3.2 Thermo-hydraulic issues involved in Cooling system

HTS cables have to be operated at very low temperatures. The temperature of LN_2 at the cable outlet should be less then its critical temperature. The sources of heat that continuously increase the temperature of HTS cable are the heat-in-leak from the surroundings due to the difference temperature between surrounding (Q_s) and LN_2, the generation of heat due to AC loss (Q_{AC}) and heat transfer due to frictional loss during LN_2 circulation (Q_f) within the cable. This much amount of heat should be removed continuously from the cable by the cooling system.

The energy balance equation for the flow is

$$\left(Q_s + Q_{AC} + Q_f\right) L = \dot{m} c_p \Delta T \quad ....(1)$$

$$\frac{\Delta T}{L} = \frac{\left(Q_s + Q_{AC} + Q_f\right)}{\dot{m} c_p} = \frac{\left(Q_s + Q_{AC} + Q_f\right)}{\rho A V c_P} \quad ....(2)$$

Where m: mass flow rate (kg/s), C_p; specific heat of LN_2 (J/kgK), A: cross-sectional area(m^2), ρ: density of LN_2 (kg/m^3), V: flow velocity (m/s), ΔT: Change in temperature between the inlet and exit of the cable (K): length of cable (m).

The pressure drop along the cable is

$$\Delta P = \frac{f L \rho V^2}{2D} \quad ....(3)$$

(ΔP: pressure drop, f: friction factor, D: Hydraulic diameter)

The magnitude of heat transfer associated with frictional heat loss is very less as compared to other heat loss and can be neglected. Hence by neglecting Q_f, equation (2) becomes

$$\frac{\Delta T}{L} = \frac{\left(Q_s + Q_{AC}\right)}{\dot{m} c_p} = \frac{\left(Q_s + Q_{AC}\right)}{\rho A V c_P} \quad ....(4)$$

$$L = \frac{\Delta T \rho A V C_p}{(Q_s + Q_{AC})} \quad ....(5)$$

From the above equations ΔP becomes

$$\Delta P = \frac{f \rho^2 V^3 A \Delta T c_p}{2(Q_S + Q_{AC}) D} \quad ....(6)$$

Pumping power is, W (in watts) is given by

$$W = -\dot{m} \int \frac{dp}{\rho} = \frac{\Delta P \dot{m}}{\rho} \quad ....(7)$$

Pumping power is inversely proportional to the density of cryo-fluid. Hence LN_2 requires less work as compared to Hydrogen. The heat capacity of LN_2 is quite high and with multilayer insulation and vacuum, the temperature difference between the inlet and exit of the cable is within 1-2 K (Table 1). The operating temperature range of LN_2 is from 63.2 to 77.4 K at 1 atm. This gives a safety margin of 14.2 K when LN_2 is circulated at 1atm. This margin can be increased to 20 K if the operating pressure is increased to 2 atm.

The mass flow rate of HTS cable has the effect on following parameters.

- ΔT can be reduced by increasing the mass flow rate.
- The increase in mass flow rate will increase the ΔP correspondingly increasing the maximum discharge pressure of circulation pump and thereby increasing the inner-wall thickness of the cable-cryostat for safety.
- Increase in mass flow rate increases the pumping power of the pump.

3. CRYOGENIC COOLING SYSTEMS FOR HTS CABLES

3.1 KEPCO Project

M Watanabe *et al.* [6] reported the development and installation of 100 m HTS cable of 22.9 kV and 1250 A current capacity, a cooling system with LN_2 circulation and its testing. The entire HTS cable system is shown in Figure 3.

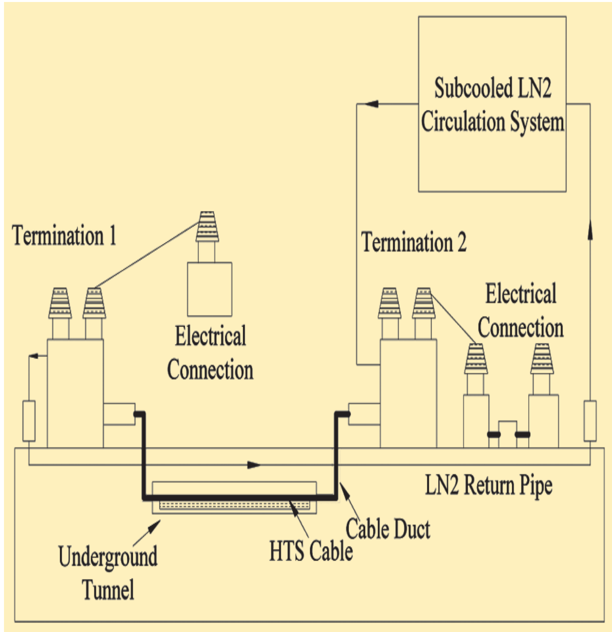

FIG. 3 HTS POWER CABLE SYSTEM CONFIGURATION

Installation of the HTS cable is done in a tunnel like structure (Figure 4). It uses one common cryostat to house all the three phases. The LN_2 circulation for cooling the cable is provided at one of the terminations. After manufacturing the actual cable, various pre-shipment tests including critical currect (I_c) and AC loss measurement, voltage withstand test, dielectric constant etc were conducted at SEI (Sumitomo Electric Industries Ltd.) Osaka Works and test site. Various on-site tests including initial cooling test, I_c measurement, voltage test, thermal loss measurement test, acceptance test have also been conducted. The whole system was first cooled by cold nitrogen gas followed by LN_2. To bring the whole system to LN_2 temperature it took 2 days. The flow rate of LN_2 was 40 L/min at 67 K for cable cooling operation. An estimated heat load of 2.5 W/m is obtained during no load (0 A) condition. During the actual operation at the rated current (AC 1250 A) an additional heat generation comes from AC losses (6.9 W/m) and accordingly the total heat load increased to 9.3 W/m.

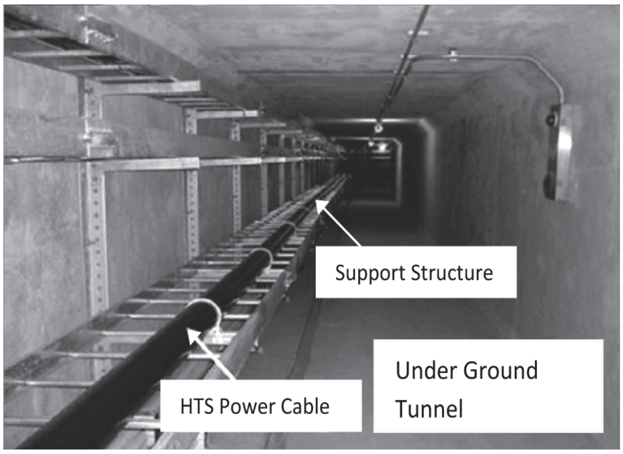

FIG. 4 CABLE INSTALLATION IN A TUNNEL

J H Lim *et al.* [7] has reported several thermal cycle tests were conducted on vacuum pump driven open-loop refrigeration system of 3 kW capacity between LN_2 temperature and ambient temperature. The open loop cooling system was not effective from economic point of view, as the consumption of LN_2 was larger than expected. To solve the problem of LN_2 consumption and to secure against unexpected emergencies, a hybrid cryogenic cooling system was designed. The hybrid cooling system consists of an open-loop refrigeration system and a stirling cryocooler of 4 kW cooling capacity at 77 K. The cryocooler operates at normal heat load condition and at the advent of unexpected failure in the main cryocooler, the entire thermal load is shifted to open refrigeration system. The cooling capacity of cooling system using open-loop refrigeration system and stirling cryocooler were 3 kW and 2.8 kW at 66.4 K respectively. Hence a cooling capacity of 5.8 kW hybrid cooling system can be achieved [7]

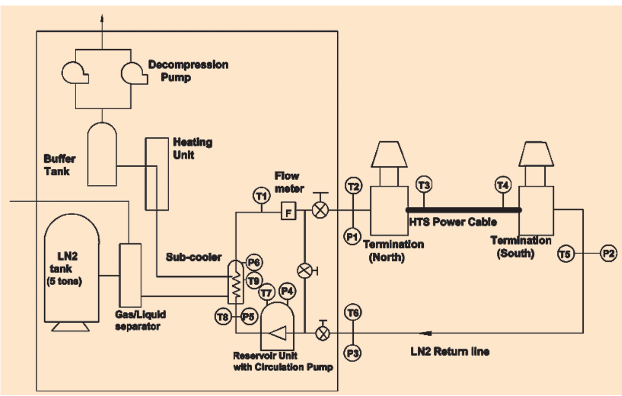

FIG. 5 SCHEMATIC DIAGRAM OF OPEN LOOP REFRIGERATION SYSTEM

Yang *et al* [8] summarized the performance test results of existing (open loop) cooling system (as in Figure 5) in HTS power cable system and introduced the outline and installation of the hybrid cooling system of 4 kW at 77 K cooling capacity. The inlet condition of LN_2 circulation was 66.4 K and 40 L/min. A Periodic filling of LN_2 was required due to boil-off. Hence it was done at an average of 3 times/hour (volume 49.91 liters) making volume consumption of LN_2 as 1198 litters/day. The heat loads were calculated using the following equation

$$Q = \dot{m}c_p\Delta T \qquad ....(8)$$

Q : heat load (kW), m: mass flow rate of LN_2 (kg/s), c_p : Specific heat of LN_2, ΔT: Cable entrance to-exit temperature difference (K). The heat load was 1.16 kW at 0 A and 2.3 kW at 1250 A. Since the flow rate of LN_2 and the pressure difference over the pump were at constant values of 40 L/min and 150 kPa respectively, the heat load to circulation pump was about 0.4 kW which remained constant with the variation of load from 0A to 1250 A. The KEPCO HTS power cable system has been tested and demonstrated over 9000 hrs and no fault was observed [8].

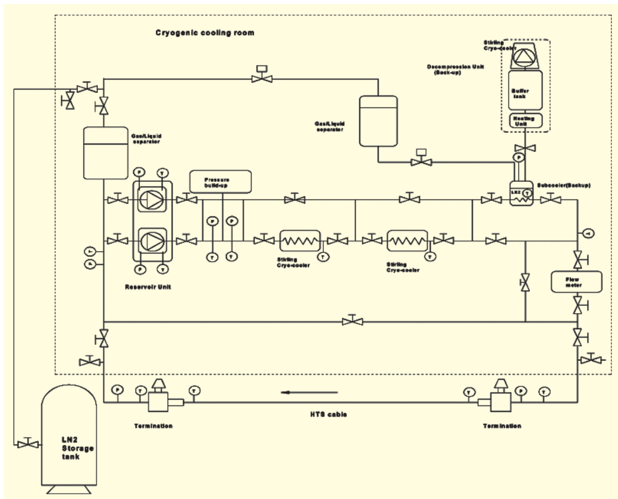

FIG. 6 SCHEMATIC DIAGRAM OF HYBRID REFRIGERATION SYSTEM

Choi *et al.* [9] reported the progress on the performance test of HTS cable and discussed the change in the temperature and pressure of the system with respect to the supply current. The installation of the hybrid cooling system (as in

Figure 6) in real grid application was described. The temperature increased from 0.69 K at 0 A to 1.72 K at 1250 A. With increase in loading current from 0 A to 1250 A, the heat load has increased because of the AC loss. The pressure drop along the HTS power cable was below 20 kPa under various LN_2 flow rates (20, 30, 40 L/min) during the performance test. The hybrid refrigeration system of 8 kW capacity at 77 K and 5.8 kW at 66 K was constructed (Figure 7) for performance test. During the long run operation, no major fault was found. Meanwhile they have completed the design of 500 m HTS power cable system.

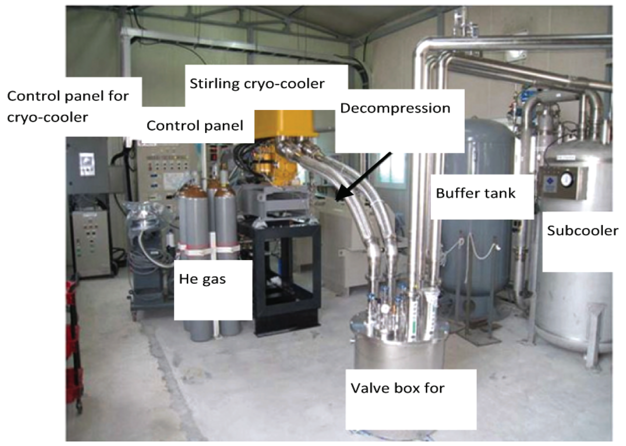

FIG. 7 HYBRID REFRIGERATION SYSTEM FOR HTS CABLE PERFORMANCE TEST

S H Sohn *et a1.* [10] have reported the design issues of a three phase 500 m long 22.9 kV, 50 MVA HTS cable, cable route (Figure 8) and a cryogenic refrigeration system. The system design was completed and verified through preliminary tests prior to on-site installation. The design of termination and joint box was completed.

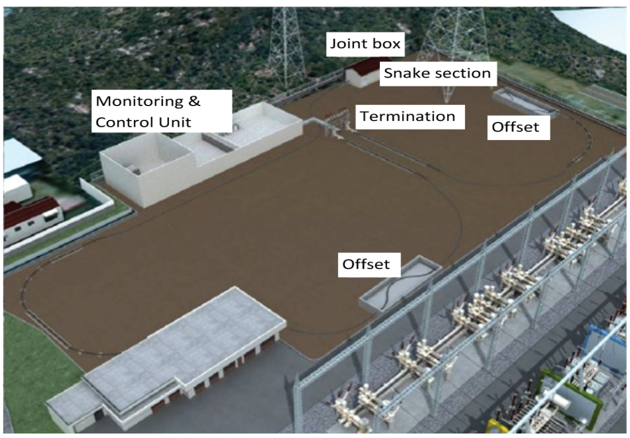

FIG. 8 LAYOUT OF CABLE ROUTE AND MONITORING / CONTROL BULIDING FOR CRYOGENIC COOLING SYSTEM

To simulate the on-site installation, the duct, vent, tunnel installation (underground), joint box and termination including the 90^o bend, U-bend of the cable route were designed. For absorbing thermal contraction due to the large temperature gradient between the ambient temperature and LN_2 temperature, the cable route was designed with offset and a snake section.

Y H Kim *et al.* [11] has summarized the design of the open-loop cryogenic system and the test results of grid operation. The cryogenic system consists of a pressure control system (PCS), gas / liquid separator, LN_2 circulation pump, decompression unit, filter etc as shown in Figure 9.

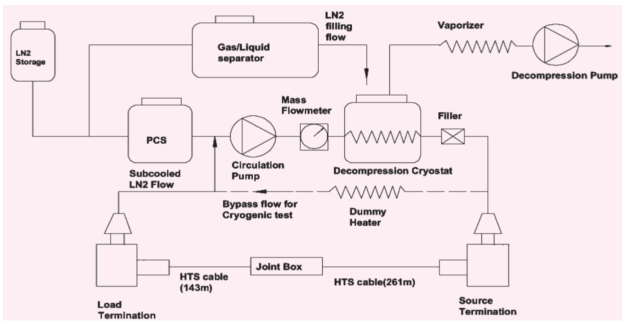

FIG. 9 DIAGRAM OF THE CRYOGENIC SYSTEM FOR HTS POWER CABLE

The PCS helps in regulating the pressure of the HTS cable system, the gas / liquid separator provides LN_2 to decompression unit and the circulation pump circulates LN_2 with required pressure head and mass flow rate through the HTS cable system. The decompression unit consists of a decompression cryostat, heat exchanger and vacuum pump for lowering the pressure of the decompression cryostat. The effectiveness-NTU method was used to design the heat exchanger. The decompression unit helps to keep the LN_2 in subcooled condition.

Y S Choi *et al.* [12] have reported the cooling performance test of a 500 m long HTS power cable with operating current and voltage of 1250 A and 22.9 kV in real power grid and discussed the temperature and pressure drop within the system with respect to the loading current level. The design, development and installation of open-loop refrigeration system was also described. The main components of open-loop refrigeration system are subcooler (with decompression pump driven by open-loop cooling unit), separator pump unit, valve box and reservoir. The total thermal load of the of the whole HTS cable system was estimated to be 5.06 kW; which was helpful in determining the cooling capacity of the refrigeration system and to decide the flow rate of LN_2. The subcooler consists of two decompression pumps (help in maintaining the sub cooled state of LN_2 in the subcooer), a buffer tank and a heating unit (to maintain the system temperature within the range of 64-77 K) with cooling capacity up to 10 kW. To ensure the reliability during real operation, the refrigeration system has a secondary subcooler unit for backup operation. Figure 10 shows the schematic of open-loop refrigeration system of 500 m HTS cable system.

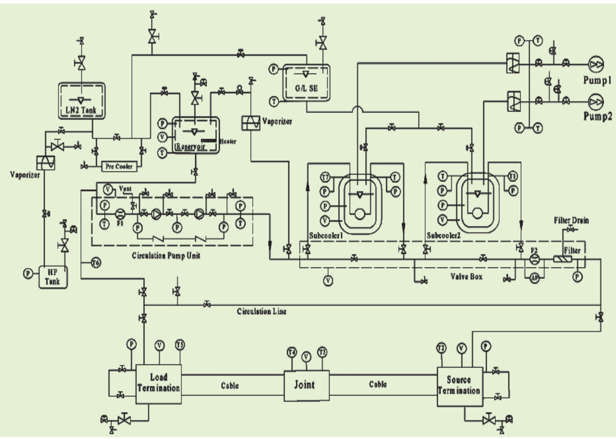

FIG. 10 SCHEMATIC OF OPEN-LOOP REFRIGERATION SYSTEM

A LN_2 storage tank of 5 tons capacity was installed for periodic refilling of LN_2 in every two or three days to compensate the boil-off due to thermal load in normal operation. After installation of the cooling system, the cable temperature first reduced to LN_2 temperature by pre-cooling in four steps: 200 K for 16 hrs, 150 K for 20 hrs, l00 K for 20 hrs and 80 K for 70 hrs by nitrogen gas as working fluid with a flow rate of 0.01-0.02 kg/s; the whole process took around 175 hrs. Different levels of current within the range of 0 A to 1250 A were supplied to the system to verify the refrigeration system. The increase of temperature difference varies with the rise in loading current, as it leads to increase AC loss. The rise in temperature was 2.5 K at OA and 4.3 K at 1250 A. The pressure drop along the HTS power cable was measured at different flow rates of LN_2 such as 0.4, 0.5, 0.6 kgs. During the cooling-performance test the pressure drop was approximately 70 kPa with the flow rate of 0.5 kg/s. The performance tests were performed without major loss and the HTS power cable was connected to the real grid [l2].

3.2 Yokohama Project

H. Yamura *et a1.* [13] has reported the manufacturing and installation of 66 kV, 200 MVA, 30 m HTS cable having 3-in-one structure. The cable has three cores (two HTS tape cores and one copper core) for the conductor. The schematic configuration is shown in Figure 11. The cable system consists of two HTS cables connected by a joint, two termination vessels and a cooling system of capacity 1.6 kW at 77 K. The cable layout has a 90^O and 5 m radius bending section within a 150 mm conduit.

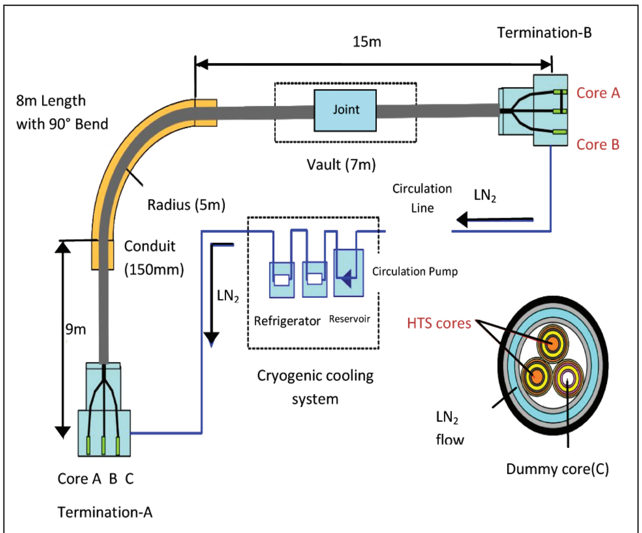

FIG. 11 30M HTS CABLE SYSTEM CONFIGURATION

After complete installation of the system, the performance test is done in three steps.

a) Initial cooling test

b) Heat cycle test

c) Tolerance confirmation test

During initial cooling test, the HTS cable system was first cooled by nitrogen gas and followed by LN_2 when the temperature was around -150° C. Initial cooling of the cable to LN_2 temperature was finished within two days. The tension appeared due to the temperature difference of HTS cable as both the terminations reached approximately 2500 kgf. At no load condition, the heat loss in the cable was estimated to be approximately 160 W including joint but the total heat loss (including termination and LN_2 piping) was about 1.0 kW. The values were in agreement with the designed values.

The heat cycle test was conducted to ensure the cable properties after several heat cycles by electrical, thermo-mechanical and thermal tests. The test results asserted that the system performance has not changed after experiencing the thermal cycles between LN_2 temperature and ambient temperature which is the largest thermo-mechanical stress in the system [13].

Masuda *et al.* [14] reported the design and test results of the pre-qualification test conducted on 30 m HTS power cable. During the trial of fault current, a maximum temperature rise of 1.8 K was noticed after 90 seconds of fault. This is due to some thermal resistance between the cable and LN_2 flow. The pressure increased about 140 kPa after 18 seconds due to the gasification at the hot spot in the conductor or shield layer. The cable capacitance got slightly reduced after the fault, as in the PPLP (polypropy1ene laminated paper) some LN_2 was replaced with the vaporized nitrogen gas and the inductive capacity of nitrogen gas (which is 1) is less then liquid nitrogen (which is 1.4). From the data of temperature, pressure and capacitance time transitions, it is calculated that the system took 90 minutes to get back to the steady state operation.

M Watanabe *et al.* [2] has introduced the fundamental characteristics of the HTS cable system and conceptual design of the cooling system for the cable demonstration project. The cooling system was located at both the ends of the cable and consists of LN_2 reservoir tank, circulation pump and cryo-refrigerator. The electrical losses and the heat invasion into the HTS cable system and refrigeration system were calculated to be in between 3-4 kW depending on the power load and seasonal variation. The domestic stirling type refrigerator either of capacity 1 kW at 77 K or 0.8 kW at 67 K was to be applied. The number of cryocoolers was determined to be 6 including one standby machine. All the six refrigerators were arranged in three parallel lines with two in series for each line. This arrangement helps in reducing pressure around half for the same flow rate. Two LN_2 pumps were set in parallel and driven alternatively for certain period. LlNCS (liquid nitrogen cooling system) was designed in such a way that every refrigerator or pump can be repaired independently without shutting down the whole system. The arrangement of the LlNCS is shown in Figure 12.

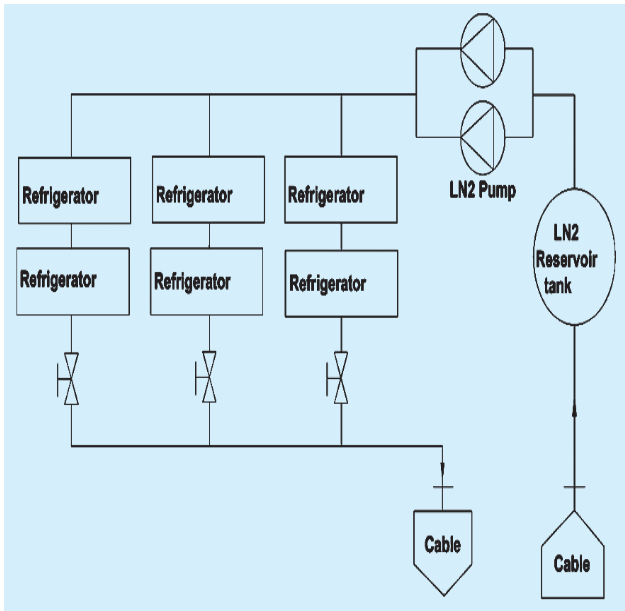

FIG. 12 FLOW DIAGRAM OF THE COOLING SYSTEM

M Ohya *et al.* [15] has reported the first in-grid demonstration of 240 m HTS cable with a cable -tocable joint and a cooling system connected to each cable termination (as in Figure 13), commenced at Asahi substation (Yokohama, Kanagawa). The maximum tension measured was 1.3 tons, but the designed tolerance was 2 tons. The cooling system has used six 1 kW Stirling type refrigerators. The test results satisfied all the required specifications.

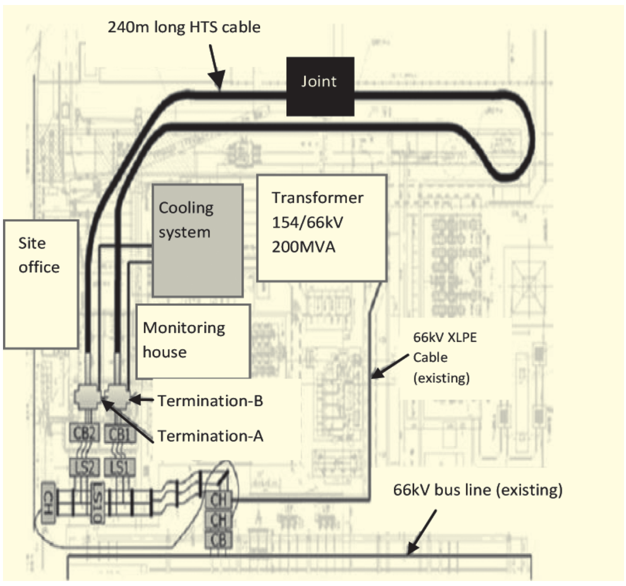

FIG. 13 LAYOUT OF THE DEMONSTRATION SYSTEM

3.3 Albany Project

A demonstration project on HTS cable was conducted in an actual grid of national grid company in Albany NY. The cable was installed in a 350 m underground conduit with an inner dia of 15 cm. It is the world's first cable-to-cable joint placed in a vault and both ends of the cable were connected to the overhead power transmission lines as shown in Figure 14 [18].

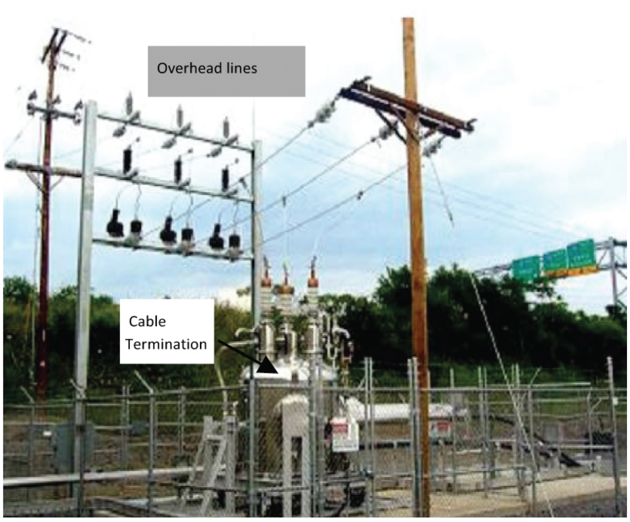

FIG. 14 HTS CABLE AND TERMINATION IN ALBANY

H Takigawa *et al.* [3] has reported the development and installation of a 34.5 kV, 800 A, 350 m long HTS cable at Albany. The cable has three cores in one cryostat and the cores are stranded loosely to accommodate 0.3 % contraction. To absorb mechanical stress, the stainless steel tape-tension members were placed on the cryostat. Both the edges of 320 m and 30 m cables were spliced and placed in a vault to get a long power line. The cable route was with a 90° bending portion as shown in Figure 15.

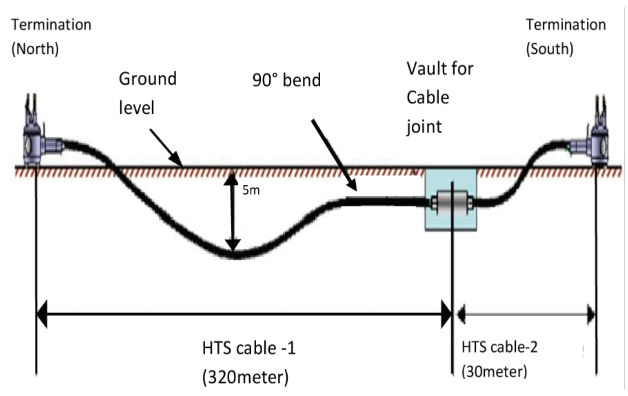

FIG. 15 CABLE ROUTE PROFILE FOR ALBANY PROJECT

Lee *et al.* [1] has described the design and initial test results of the CRS with cryocooler power of 5 kW at 77 K, 3.7 kW at 70 K. The major elements of CRS are shown in Figure 16. One of the Key features of the CRS was the thermosyphon vessel which provides a compact and thermally efficient interface between the refrigeration source (either open or closed) and the subcoled LN_2 loop. The normal operating temperature of subcooled liquid nitrogen loop was 70 K [l].

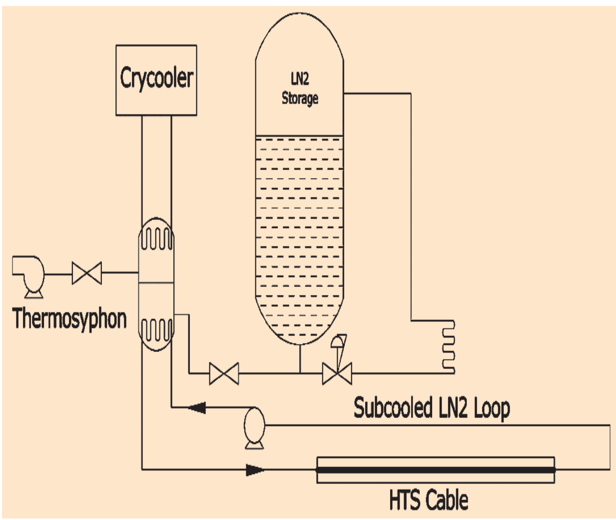

FIG. 16 SCHEMATIC OF CRYOGENIC REFRIGERATION SYSTEM

During the initial cooling, cold nitrogen gas was provided and when the temperature of the system was around -196° C, LN_2 was filled to the cable. The flow condition was. 40 L / min at 72 K [3]. Heat loss in the cable portion was 1.0 kW while the total heat loss excluding cryogenic refrigeration system was about 3.1 kW. During the installation, the tension developed was about 2.5 ton with the friction factor a 0.25. Termination vessel was fixed to the ground avoiding any movement during cooling and system operation[4].

3.4 LIPA Project

A 138 kV, 3 phase transmission cable was fabricated and integrated in the grid with a field repairable cryostat for LIPA-II project. In LIPA-I project the cable-cryostat has one vacuum space of 600 m length, whereas in LIPA-II project, the cable system includes number of suitably spaced vacuum barriers inside the cryostat. This is to ensure that at any vacuum-failure anywhere in the cable, the cryostat can be repaired independently [16, 17]. The cryostat reparability-test was successfully demonstrated and the thermal loss of the repaired section was found to be reasonable [17]. During the cooling down, the cable contracts by 0.3 % from room temperature to 77 K, hence for 600 m cable the length of contraction is about 1.8 m. To compensate this thermal contraction in the cable, an over-length cable can be introduced. A 22 kW at 72 K cryo-refrigerator based on reverse-turbo-Brayton cycle was under development for cooling such cables [16, 17]. All the tests for the cable and the joint have performed successfully.

4.0 CONCLUSIONS

A comprehensive review on various cooling strategies in HTS cable cooling system is presented. The thermo-hydraulics of cooling system is analysed. To enhance the cooling capacity, cryocoolers are implemented to the system in addition to liquid nitrogen, depending on the heat load of the total HTS power cable system.

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