Flow cryogenic supply systems for HTS power systems

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Abstract. Operation principles of cryogenic supply systems for power HTS systems have been examined. Two flow cryogenic supply systems have been described. These cryogenic supply systems have been created in MAI and utilized to ensure the operation of HTS power devices (power cables, electric motors, and generators, transformers, etc.).

1. Introduction
Discovery of high-temperature superconductivity (HTS) and recently achieved values of critical parameters of superconductors in high-current devices have opened up conceptually new opportunities for its practical implementation (cables, electric machines, current limiters, etc.). Operation of superconducting high-current devices requires the use of cryogenic supply systems, that enable maintenance of the necessary level of temperature of high-temperature superconductors.

Since 2002, in MAI 4 cryogenic supply systems were created: two flow and two non-flow (autonomous) cryogenic supply systems. These cryogenic supply systems are employed to ensure the operation of HTS power devices (power cables, electric motors, and generators, transformers, etc.).

2. Materials and methods
Cryogenic supply system of HTS three-phase transformer - CSST-01 is an example of flow cryogenic supply system [1]. Its purpose is to maintain the constant level and temperature of liquid nitrogen in three cryostats of the windings of HTS transformer (1000kVA, 10/0.4 kW).

Cryogenic supply system of HTS windings of three-phase transformer has a refrigeration capacity of up to 3.5kW and maintains the temperature of superconductors (SCs) within the range of 77.4…78K. Liquid nitrogen is used as a coolant due to its operational safety and low cost. The temperature of cryostatting the transformer windings corresponds to the saturation temperature of liquid nitrogen at the atmospheric pressure. The diagram of CSST–01 is presented in figure 1.

The transformer windings of each phase are placed in three individual non-metallic cryostats, integrated with one another by thermally insulated pipelines located beneath lower bottoms. Upper covers of cryostats allow for a slight excess of pressure inside cryostats over the ambient pressure. CSST-01 is comprised of three cryostats with low (LV) and high voltage (HV) windings for each phase. Two supply tanks of liquid nitrogen of 370 l volume (14) and the system of delivering liquid nitrogen from supply tanks into the cryostats of windings ensure cooldown and maintenance of the required level of liquid in cryostats. Supply tanks are charged with liquid nitrogen from portable Dewar vessels (23) or transport LOT –7 of 1.5m3 capacity. To fulfil all CSST-01 functions, a computer-based control system is used.
Cryogenic supply system fully evaporates liquid nitrogen in the transformer cryostats due to heat influxes and emissions in its windings. Vapour is removed from cryostats through drain lines into the ambient.

Liquid nitrogen from the bottom of supply tanks (14) is supplied using valves (8) and electrohydraulic valve (10) along pipeline (20) into compartments of transformer cryostats (1) by two parallel channels. Pressure drop that makes the medium move, exceeds hydraulic losses in the flow path of supply lines and transformer ducts. The pressure in supply tanks of liquid nitrogen slightly exceeds atmospheric pressure (0.2…0.7 bar at the temperature of 78…80 K).

All the elements of pneumohydroscheme, located at a distance of less than 1.5m from the transformer windings, are nonconductive, including pipelines, connecting nitrogen compartments of three cryostats (1). They are made of fluoroplastic pipes with the diameter of 10mm.

The structure and sizes of a cryostat for one phase are shown in figure 2. External (3) and internal (5) cylinders create a cavity (6) filled with liquid nitrogen. Inside the cryostat a lower bottom of glass textolite 12mm thick is installed, on which the coils of low and high voltage HTS windings are mounted. Cryostats are made of urethane foam insulation "Isolan-123" and reinforced by glass-fibre fabric across all surfaces. Since the weight of windings may be as much as 100kg, power supports made of glass textolite with minimum axial heat conductivity are provided (1). Supports are glued in between power textolite bottoms 12mm thick, placed on the bottom cover of the cryostat.

The minimum thickness of the internal cylinder wall is 30mm, of the external cylinder – 40mm. An installation diagram of the cryostat of one phase on the transformer magnetic conductor is shown in figure 2. Figure 3 presents a general view of the transformer. Thermal insulation "Cryogel Z" is applied on low-temperature surfaces of the supply system elements.

To measure the level of liquid nitrogen in the transformer cryostats (1), a designed optoelectronic float-type water level gauge (22) (LG) is used, that allows for keeping track of the position of liquid nitrogen surface within ± 5mm (figure 1). Information from the level gauge is transmitted using a pair of fibre-optic cables 10m long.

**Figure 1.** Diagram of CSST-01 cryogenic supply system: 1 – winding cryostat, 2 – drainage pipeline, 3 – phase indicator, 4 – pressure sensors, 5 – drainage valves, 6 – supercharging valves, 7 – drainage valves, 8 – valves of supplying liquid to cryostat, 9 – valves of supplying liquid to cryostat, 10 – electric valve of charging cryostat, 11 – supercharging compressor, 12 – pressure manometer in Dewar vessel, 13 – electronic balance (M-ER 333A-300.50), 14 – supply tanks of liquid nitrogen (V=2×185=370l), 15 – supercharging valve of charge vessel, 16 – shut-off valve of supercharging line, 17 – system of controlling charge of supply tanks, 18 – CSST-1 control unit, 19 – level gauge in Dewar vessel, 20 – non-metallic pipeline of charging winding cryostat, 21 – HTS windings of transformer (LV – low voltage, HV – high voltage), 22 – level gauge in the transformer cryostat, 23 – transport Dewar vessel.
Figure 2. Cryostat of the transformer winding: 1 – support; 2 – bottom; 3 – external cylinder of PU foam "Isolan-123"; 4 – cover of PU foam "Isolan-123"; 5 – internal cylinder of PU foam "Isolan-123"; 6 – compartment with liquid nitrogen.

Figure 3. Installation diagram of the cryostat of one phase of the transformer: 1 – transformer magnetic conductor, 2 – cryostat, 3 – cryostat cover, 4 – current lead, 5 – pipeline of supplying liquid nitrogen, 6 – drainage pipeline.

Figure 4. Cryostats after the transformer assembly.

The level sensor ensures constant filling of cryostats (1) with liquid through controlling the operation of the electromagnetic fill valve (EV) (10).

When the level of liquid nitrogen in the transformer cryostat decreases below normal, controller conveys a signal to open the electromagnetic valve. Software is used to ensure the hysteresis effect in regulating the level of liquid nitrogen.

Control system contains microcontroller, enabling the interface between sensors and actuation mechanisms, and control panel as well, implemented based on a tablet computer, connected with
microcontroller by radio channel (Bluetooth). The control panel is made based on the tablet computer, operating under Android 4.2 OS, for which a special software (S) is designed. The software allows for visually representing the state of cryostatting system (CS), retrieving information for visual control, and issuing warnings about emergency and critical situations in routine operations and during charging. The control system includes a controller of cryostatting system. It ensures the interface between sensors and actuation devices of the cryogenic supply system, and control panel, implemented based on a tablet computer (TC), connected with microcontroller by radio channel (BT). The controller is created based on eight-bit microcontroller ATmega 328. The weight of liquid in supply tanks (14) is measured using two strain-gauge balances (13). Controller ensures their connection by RS-232 interface. Readings of balance are used to conduct operations of charging supply tanks 14 with liquid nitrogen and to control the weight of liquid nitrogen while working, and to issue a command to series connection of supply tanks to the system circuit. The use of two supply tanks ensures continuous operation of the system due to their series time-wise connection using valves 8 and drainage valves 5. This information is displayed on the PC screen for visually controlling the nitrogen level and issuing warnings about emergency and critical situations during CSST-01 normal operation and charging. Pressure sensors PS1 and PS2 measure the pressure level in supply tanks for visually controlling on the personal computer (PC) display and issuing warnings about emergency and critical situations.

When charging supply tanks 14, pressure of up to 0.25MPa is created in transport LOT-7. Completion of charging transformer cryostats is controlled by a created sensor of the flow phase state of anemometric type (3) (phase indicator PI1). Phase indicator is installed at the outlet of drainage pipeline of the transformer cryostat, and it specifies the moment of liquid nitrogen overflow while charging cryostats and when emergency situations arise. Supply tanks 14 are equipped with relief valves and blowout diaphragms. The value of pressure in tanks (14) is specified by supercharging system using standard gasifiers of these tanks and supercharging gear box. When the pressure in tanks is exceeded, drainage valves 5 and control system are used.

Cryogenic supply system is assembled as a dismountable compact module, what makes it convenient to transport and assemble at the substation. Figure 5 presents the general view of the CSST-01 system.

![General view of CSST-01 cryogenic supply system](image)

**Figure 5.** General view of CSST-01 cryogenic supply system (a – front view, b – rear view).
3. Results and Discussion
CSST-01 control system of HTS transformer makes it possible to control the parameters that define reliability of cooling transformer windings while working and fulfilling principal functions:

- Cooldown of transformer cryostat at a specified rate.
- Filling of transformer cryostat to the nominal level.
- Maintaining the level of liquid in the transformer cryostat from two supply tanks alternately.
- Charging and recharging of supply tanks from transport tank.

Active tanks are filled with liquid nitrogen from transport LOT-7. 100 litres of liquid nitrogen or 81kg are expended on cooldown of the structure of one cryostat and its filling to the operating level at the guaranteed gas blanket height of 100mm. Current weight of cryostat and all the process parameters are registered over time in the course of the experiment.

The results of measuring heat influxes to the cryostat by losses in liquid nitrogen weight from the cryostat have shown that the total heat influx to the cryostat does not exceed 450W or 1350W for three windings.

Temperature of the surfaces of cryostats was determined using thermovisor ThermaCAM P60 "FLIR systems". Figure 6 shows the results of measuring thermal state of the HTS transformer cryostats. It is apparent that the temperature of the external surface of the cryostat amounted to 5.3°C excluding zones. A decreased temperature (of up to -17°C) was seen on the external surface of pipelines, integrating cryostats on lower bottoms.

To carry out research studies on an extensive hydrogen hybrid line 30m long, a flow cryostatting system [2] was created. Thermal insulation of hydrogen hybrid line is made of three sections. Each section had its own structure of thermal insulation. Passive screen vacuum thermal insulation was employed for the first section. Evaporation cryostatting system (ECS) was installed in the second section. In addition to passive screen vacuum thermal insulation, a circular nitrogen shield was installed in the third section. One of the experiment tasks was to examine whether these options of thermal insulation structure are applicable for long power cables. It had been demonstrated that the use of traditional methods for protection against heat influxes using only passive thermal insulation fails to ensure the required temperature conditions of superconductors for long superconducting ducts. The use of nitrogen shield decreased heat influx into the hydrogen duct more than two-fold. Evaporation cryostatting system solves this problem well, to implement which special circular heat-exchange ducts (HD) are created. Cryogenic liquid enters these ducts through inlet dosing devices (jet nozzles) in conditions of supercritical pressure drop between the path of the main transport duct and the HD path.
The pressure below the saturation pressure in the path of the main duct is maintained in the heat exchanger ducts. The flow from HD paths is removed through an outlet dosing device (jet nozzle) towards the zone of decreased pressure.

The value of pressure in the ECS HD paths is maintained below the pressure in a transport path, though above the triple point pressure, what prevents potential formation of the solid phase. The temperature in the heat exchanger duct is lower than the temperature of the medium in the main path, hence a heat flow to the ECS HE duct from cooled medium emerges beyond the inlet dosing device. Liquid is evaporated and vapour is heated in the HD paths. The value of created temperature drop can exceed 6...4 К. On the internal surface of the HD path, a film flow of liquid (liquid film) emerges, and in the flow core a movement of vapour is seen with possible presence of few drops.

Refrigeration capacity of ECS is mostly defined by the value of mass flow rate of evaporating flow in the HE duct and vaporization heat. At section 2 with evaporation cryostatting system (ECS), the total heat influx to the hydrogen duct was fully compensated for by the ECS heat absorption. For some modes, the ECS operation had even led to reducing hydrogen temperature in the main path.

4. Conclusion

Hence, using ECS for cryostatting long hydrogen paths has the following advantages:

- Hydrogen flow in the main path can cool down or maintain constant temperature at any length.
- Hydraulic losses per length unit do not exceed 0.001...0.18 bar/m.

When employing ECS, the temperature of cable section, protected against heat influxes, will remain almost unchanged throughout its length. ECS functions as a power cable of heat exchanger, distributed lengthwise, and it fully compensates for exterior heat influxes. It creates conditions for retaining practical superconductivity of power cable and conditions for thermal stabilisation of superconductor. ECS can also be implemented in the closed circuit of cryostatting.

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