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Development of Supervisory Control and Data Acquisition System for India's First High Temperature Superconducting Cable Testing

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Abstract

High Temperature Superconductor (HTS) based power cable is a technological marvel which can transmit bulk power over large distances without any joule heating as compared to a conventional copper cable, owing to its zero DC resistance in superconducting state. However, to maintain this superconducting state, the cable must be at a temperature below its critical temperature under self-field. Commonly used HTS material includes BSCCO (T_c = 110 K) and YBCO (T_c = 93 K) and thus, requires cryogenic liquid nitrogen (77 K) for attaining superconductivity. Further, the voltage drops across the various joints such as joint box and current leads in the termination unit must be monitored to ensure optimal operation of the cable. This demands for sophisticated instrumentation operating under extreme low cryogenic temperatures for safe operation, performance monitoring, cryogenic measurements, and control of the HTS power cable cryogenic process. This paper presents the instrumentation scheme followed for testing India's first 6-meter HTS power cable. The instrumentation scheme involves housing of the various temperature sensors and location of voltage tapping, current measurement, cryogen flow measurements, operation of control valves, operation and measurement of high vacuum system, stray field measurement, insulation resistance measurement and dielectric measurements for cable are the important parameters for the successful operation of HTS power cable. To perform data logging NI-DAQ and LabVIEW software was used to develop in-house Supervisory Control and Data Acquisition (SCADA) system. This paper discusses intrinsic aspects of complete instrumentation and developed SCADA system for HTS power cable.

Keywords: Cryogenic Instrumentation, HTS Cable, LabVIEW, SCADA, Sensors

1. Introduction

The typical alienation of the load centers from the power generation facilities has nourished the power transmission companies since the evolution of electric power generation. Conventionally, synchronous power is transmitted through the metallic conductor-based cables as well as overhead lines at high voltages. The resistance of these conductors is significant leading to huge transmission losses (more than 20 % in India)[1–3]. High Temperature Superconducting (HTS) cables operating at Liquid Nitrogen (LN_2) temperature (77 K) offers zero DC resistance and can be used in transmitting bulk power with reduced transmission losses[1–3]. However, during the operation of HTS cables, to retain the superconductivity, it is must to maintain the HTS cable below its three critical parameters that is, critical temperature (T_c), critical current (I_c) and critical magnetic field intensity (H_c)[4–7]. In HTS cables, the parameter H_c is usually not significant until and unless it is subjected to the external high magnetic field intensity. The main challenge of HTS power cable lies in cool-down and maintaining uniform temperature (77 K or below) along the entire length for the operation. Hence, temperature monitoring sensors are required at various points along the length of the cable. In general, Resistance Temperature Detector (RTD PT-100) sensors are used in four probe configurations for temperature measurement. Also, the voltage differences at various joints must be monitored using voltage taps to

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sense the quench condition to avoid the heat generation which may lead to catastrophic conditions[8,9].

The faster cool-down and stable thermal operation of HTS power cable, the flow of the cryogen should be measured. The flow measurements help in deciding the control strategies for operating cryogenic control valves, avoiding pressure build-ups due to heat load at the time of cool-down and minimize the consumption of LN_2, ensuring optimal cooling of HTS cable during operation[4,10,11].

To minimize the boil-off of LN_2 in the cable cryostat during operation, sub-cooled liquid nitrogen (65 K) is preferred as a cryogen. In the current setup, sub-cooled liquid nitrogen is produced with the help of vacuum assisted sub-cooling unit. The temperature and cryogen level in the sub-cooling unit is measured using equally spaced RTDs along its height. These RTDs serve as both temperature sensor as well as a discreet level sensor[12].

The HTS cable must be insulated from the body of the metallic cryostat during high voltage operation. To ensure this, the cable is wrapped with multi- layered cold dielectric Poly Propylene Laminated Paper (PPLP). However, the PPLP undergoes thermal cycling as it is immersed in LN_2 throughout the operation of the cable[13,14]. This leads to deterioration in the dielectric properties of PPLP, leading to faulty operation of the cable. Thus, the PPLP layers must be tested for the retainment of their dielectric strength prior to installation and operation, to ensure the safe operation of the cable.

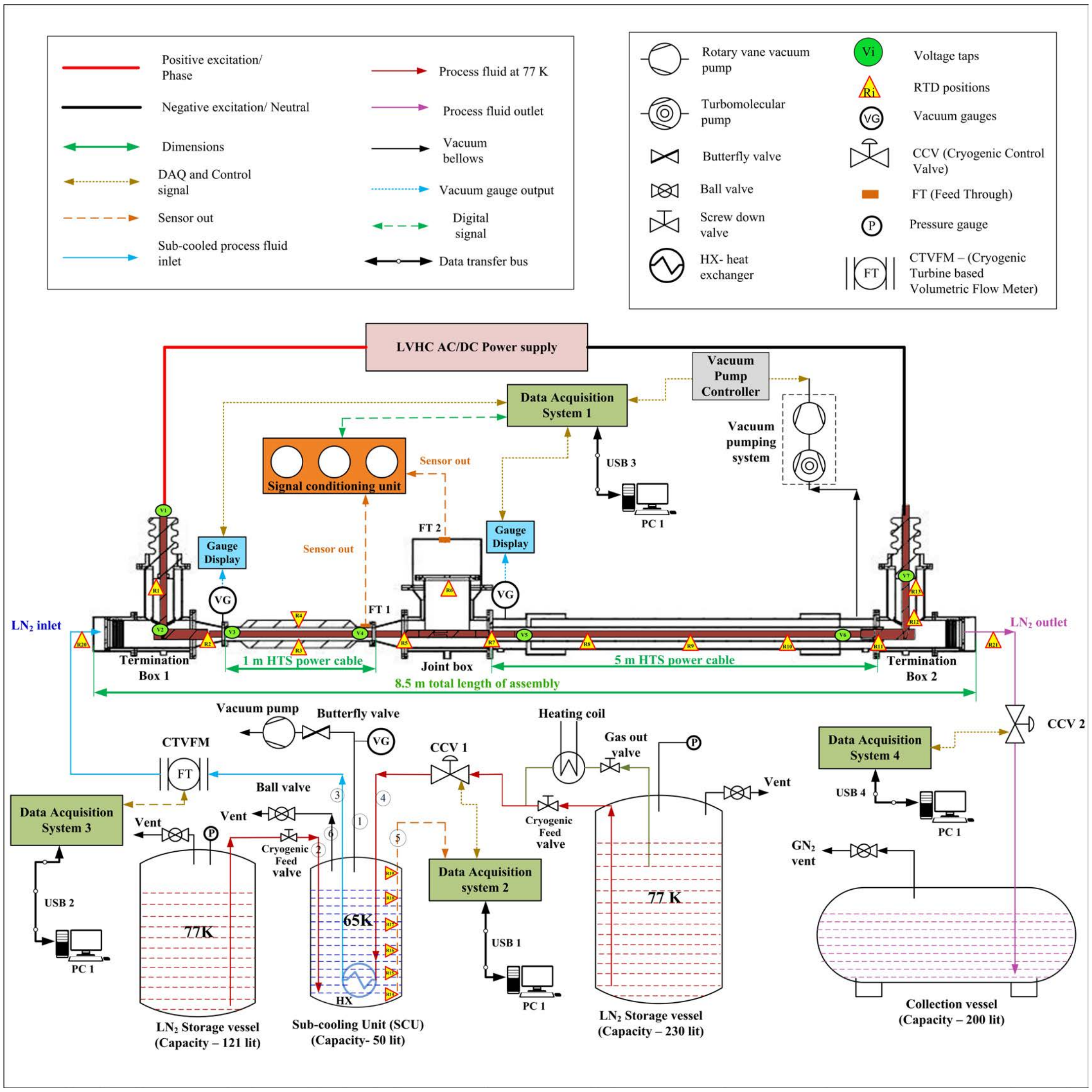


Figure 1. Schematic of the complete SCADA system for HTS cable assembly.

In this paper, the Supervisory Control and Data Acquisition (SCADA) system for testing India's first 6-meter HTS power cable is discussed. The overall SCADA system including the placement of temperature sensors, voltage taps, cryogenic flow measurement and control scheme, vacuum system, DAQ interface and feedthrough connections are explained in Section 2. Section 3 describes the methodology followed to characterize the cable dielectric. Section 4 discusses the challenges faced during mounting of temperature sensors, voltage taps, cryogenic calibration of the flowmeter, control valve operation and characterization of the cable dielectric along with the solutions adopted. Section 5 is the conclusion followed by the section 6 as the references.

2. Overall Cable Instrumentations

The schematic of the complete SCADA system for the HTS cable assembly is shown in Figure 1. The HTS cable assembly developed consists of two parts- (a) 1-meter (YBCO based)[4] and (b) 5-meter (GdBCO based) respectively, joined at a joint box through copper male-female connector. The power is fed through the current leads in the termination boxes 1 and 2 respectively using AC/DC power supplies. Entire assembly is cooled using sub-cooled LN_2 fed through the termination unit 1 and collected at the end of termination unit 2. The flow control for the process stream is carried out using a cryogenic control valve and the volume flowrate is recorded using a cryogenic turbine based volumetric flowmeter.

2.1 RTD Locations

The temperature at specific locations along the length of the HTS power cable is monitored using 15 Pt-100 RTDs (yellow triangular markers with red borders in Figure 1), using 4 probe method. The inlet and outlet temperatures of the process stream are monitored using RTDs R_{20} and R_{21} respectively. The RTDs R_1 and R_{13} are placed at the transition of the vertical current leads from ambient temperature (300 K) to sub-cooled LN_2 temperature (70 K) in termination box 1 and 2 respectively. Similarly, R_2 and R_{11} are placed at the joints of the HTS cable and the horizontal current leads in termination box 1 and 2 respectively. R_5 and R_7 measure the temperatures across the male-female joint in the joint box. R_3 and R_4 are on the top and bottom walls at the center of 1 meter cable cryostat to monitor the quality of the process stream. R_6 measures the temperature rise due to boil-off in the joint box and R_{12} measures the joint temperature of vertical and horizontal current leads in termination box 2. RTDs R_8 to R_{10} are placed equally spaced at an interval of 1-meter along the length of the 5-meter HTS cable, to observe the temperature gradient throughout its length. Additionally, six more RTDs from R_{14} to R_{19} are housed inside the sub-cooling unit to record its internal temperature. These RTDs also function as a discrete level sensor to monitor the level of sub-cooled LN_2 inside.

2.2 Location of Voltage Taps

The entire cable length maybe divided into several superconducting and non-superconducting segments. Each of these segments will have different voltage drops across its length which is required to be monitored with the help of voltage taps. This is necessary to monitor the health of the cable and avoid quenching during operation of the HTS power cable.

In the present scheme, 7 voltage taps (marked as green circles with black borders in Figure 1), are tapped from the entire length of the cable. V_1 is tapped from the outermost point on the vertical current lead and V_2 is placed just after the joint between the vertical and horizontal current leads in termination box 1. Voltage taps V_3 and V_4 are placed at the terminals of the 1-meter cable just before and after the HTS to copper transitions. Similarly, V_5 and V_6 are on the HTS to copper transitions on the 5-meter cable. The last voltage tap V_7 is positioned just below the Teflon bushing on the vertical current lead inside joint box 2. All the voltages are measured in differential mode with respect to the ground.

2.3 Cryogen Flow Measurement and Control

For maintaining the cable in superconducting state, it must cool down below its critical temperature (T_c) for the given operating current and self-field. This is achieved by using sub-cooled liquid nitrogen (70 K, 1 bara at the entry of cable cryostat) obtained from the sub-cooling unit.

Liquid nitrogen at 77 K is fed to the sub-cooling unit from a 230-liter Dewar, through a Cryogenic Control Valve (CCV) to control the volume flow rate of the cryogen stream. This control valve is pneumatically controlled, excited using a current of 4-20 milliamperes corresponding to minimum and maximum volume flowrates. The liquid nitrogen is then passed through a helical heat exchanger inside the sub-cooled cryostat of the sub-cooling unit maintained at 65 K. The level inside the sub-cooling unit is maintained by using another liquid nitrogen Dewar of 121-liter capacity. The detailed construction and operation of the sub-cooling unit is discussed elsewhere[12].

The output sub-cooled stream is then passed through a Cryogenic Turbine based Volumetric Flowmeter (CTVFM) which is pre-calibrated at the stream temperature. CTVFM used here is a Rockwin TFM 1010-1/2 (for 1/2-inch pipes) with E018 P Indicator/Totalizer with HART communication with a minimum and maximum sensible analog output current of 4-20 mA for a corresponding flowrate of fluid at 3.6 – 36 lpm[15].

2.4 Vacuum System Operation

To avoid heat-in-leak to cryogen inside, the entire cable cryostat, joint box, and termination units must be evacuated for thermal insulation. For this, all the individual units are connected through bellow connectors and evacuated using a turbo-pumping unit. The annular space once evacuated, must be sealed using a vacuum plunger and bullet in the vacuum port and vacuum pumping unit can be switched off. However, due to inherent leaks within the length of the system, it is better to keep the turbo-pumping unit on during the operation of the cable. The vacuum levels at various points should be monitored using reliable vacuum gauges integrated with SCADA.

The sub-cooled LN_2 is obtained by evacuating the ullage space inside the sub-cool cryostat, using a rotary vacuum pump which is under continuous operation to ensure the sub-cooling unit is maintained at the specified temperature (65K).

2.5 DAQ Interface

The output from all the sensors and transducers are sensed and recorded using NI-DAQ modules. The RTDs are connected in a 4-probe configuration which requires a constant current excitation of 1 mA through two connecting wires. This is provided by using NI 9265 current output modules with 0-20 mA excitation range available at 8 output ports[16]. The remaining two wires connected to the RTDs are used to measure the voltage drops across them using NI 9207 modules. For the present testing scheme, 3 modules each of NI 9265 and NI 9207 have been utilized[16,17].

The voltage taps from the cable are sensed using a NI 9221 analog input module[18] which can sense 8 different voltages simultaneously.

The CTVFM is available with an integrated display module which directly displays the flowrate. However, for data acquisition the analog current output from the CTVFM can be acquired using analog current input mode of NI 9265 module. These current values are then be provided as an argument to a pre-determined curve fit equation through the calibration of the CTVFM [calibration CTVFM] which directly provides the flowrate as output. The pneumatic circuit of the CCV is pressurized to 0.2 MPa using the regular compressed air line available in the laboratory. The current excitation is provided using a separate NI module with 4-20 mA output [ ].

All the DAQs are connected to a centralized computing unit running a LabVIEW GUI for data acquisition, control, and real time display operations.

2.6 Dielectric Characterization Setup

The PPLP layers wrapped onto the cable undergoes thermal cycling during the operation of the cable. This may result in deterioration in the dielectric properties of the PPLP which will prevent the safe operation of the HTS power cable. To optimize the number of layers needed to prevent any malfunctioning during operation, dielectric characterization is necessary.

Dielectric characterization is done by measurement of tan**δ** losses and the dielectric breakdown strength of PPLP. For tanδ measurement, an in-house setup was developed (see Figure 2). The measurement of dielectric constant, dissipation factor, capacitance and resistance are done by using an LCR meter in parallel mode at different

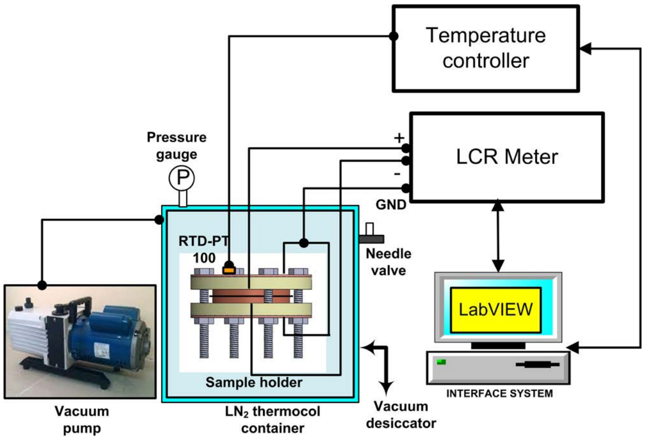


Figure 2. Schematic of tanδ loss measurement setup.

values of temperatures and for different number of layers, to finally calculate the tanδ losses.

To measure the dielectric breakdown strength of PPLP, another setup was developed in-house (see Figure 3). In this, the PPLP samples were exposed to a high voltage (maximum 60 kV) at different values of temperature and for different number of layers. The voltage and current reading were recorded till the puncture voltage to derive the V-I characteristics of PPLP for various layers at different temperatures along with the dielectric strength. All the voltages and currents from the various sensors related to dielectric characterization are coupled to SCADA for continuous monitoring and analysis.

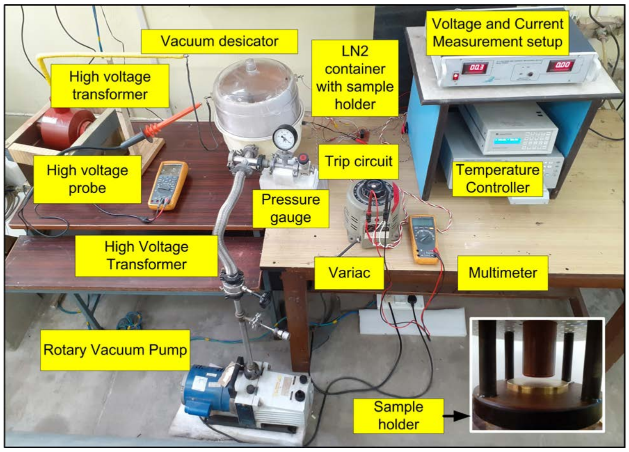
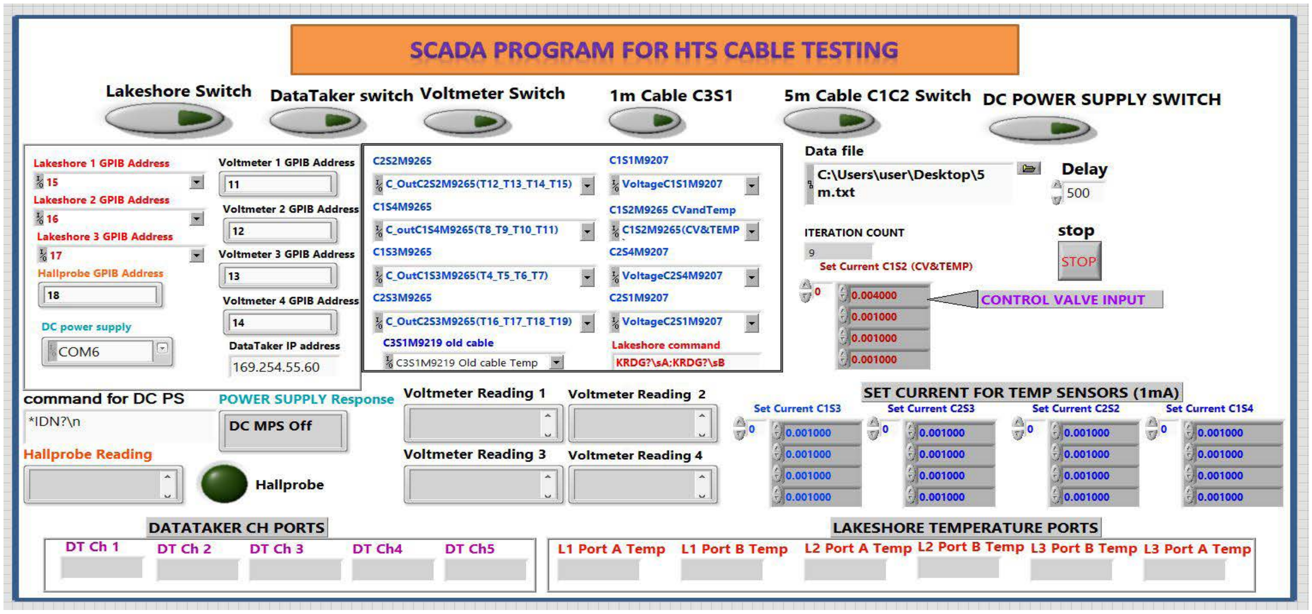


Figure 3. Photograph of High voltage setup without Faraday cage.

3. Technical Challenges and Mitigation

The instrumentations for the HTS power cable have their own technical challenges. All the temperature sensors must be pre-calibrated to obtain temperature vs resistance curve fitting equations. These equations are to be fed to the SCADA control to directly display the temperature values at the specific locations. For this, a separate calibration setup was utilized and the RTDs were calibrated from 65 K to 300K. Excitation of all the RTDs simultaneously is also a major challenge as an equal and known value of current must be passed through all of them simultaneously to calculate the resistance using the ratio of measured voltage and the known excitation current. For, this the RTDs must be separately excited using a dedicated current source for each sensor as explained in the previous section. The RTDs are mounted on the cable body itself before the insulation using a Kapton tape. The sensor wires are then routed out by twisting it around the cable for mechanical strength and preventing kinks on the PPLP to be wrapped above it.

For the voltage taps, thin insulated copper wire is wrapped and soldered to the HTS tapes. Soldering must be done very carefully with minimum heating of the HTS tapes to prevent minimal deterioration to their superconductivity.



Lakeshore 1 GPIB Address
15
Lakeshore 2 GPIB Address
16
Lakeshore 3 GPIB Address
17
Hallprobe GPIB Address
18
DC power supply
COM6

Voltmeter 1 GPIB Address
11
Voltmeter 2 GPIB Address
12
Voltmeter 3 GPIB Address
13
Voltmeter 4 GPIB Address
14
DataTaker IP address
169.254.55.60

C2S2M9265
C_OutC2S2M9265(T12_T13_T14_T15)
C1S4M9265
C_outC1S4M9265(T8_T9_T10_T11)
C1S3M9265
C_OutC1S3M9265(T4_T5_T6_T7)
C2S3M9265
C_OutC2S3M9265(T16_T17_T18_T19)
C3S1M9219 old cable
C3S1M9219 Old cable Temp

C1S1M9207
VoltageC1S1M9207
C1S2M9265 CVandTemp
C1S2M9265(CV&TEMP
C2S4M9207
VoltageC2S4M9207
C2S1M9207
VoltageC2S1M9207
Lakeshore command
KRDG?\sA;KRDG?\sB

Data file
C:\Users\user\Desktop\5 m.txt
Delay
500
ITERATION COUNT
9

Set Current C1S2 (CV&TEMP)
0
0.004000
0.001000
0.001000
0.001000

command for DC PS
*IDN?\n
POWER SUPPLY Response
DC MPS Off

Set Current C1S3
0
0.001000
0.001000
0.001000
0.001000

Set Current C2S3
0
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Set Current C2S2
0
0.001000
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Set Current C1S4
0
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Figure 4. Screenshot of the LabVIEW based SCADA interface.

All the RTD wires and voltage taps must be routed outside cable cryostat using feedthrough connectors. However, more wires require more feedthrough pins which require larger connectors adding to problems in thermal stability of the cryogen, evacuation of the cryostat and the feedthrough cost. To overcome this, multiplexer-based instrumentation scheme was adopted which significantly reduced the number of feedthrough wires and its associated issues. The multiplexer-based routing scheme has been discussed elsewhere [19]

The CTVFM was purchased, pre-calibrated with water at room temperature (300K) which is a single-phase liquid. However, for the present application, the CTVFM is operated at cryogenic temperatures (77 K or below). The saturated LN_2 (at 77 K, 0.1MPa) flows as a 2-phase fluid, resulting in erroneous reading in the CTVFM This created a need for re-calibrating the CTVFM with sub-cooled LN_2 (below 77 K at 0.1 MPa) to avoid the 2-phase problem and to account for the thermo-mechanical constraints appearing at cryogenic temperatures. The detailed calibration process has been discussed in [12].

The high sensitivity of the tanδ measurement setup with variation in the number of layers and torque on the bolts resulted in use of guard rings and torque wrench for controlled application of torque while tightening. Also, the feedthrough connections through the desiccator were designed to prevent any vacuum leaks.

The high voltage test setup was shielded inside a Faraday cage to prevent the high electric field to reach to the operator while experimenting. Also, instead of a single bellow, two bellows were coupled through a custom-made straight PVC connector having KF-25 flanges on both sides. This was to insulate the vacuum pump body from any residual high voltage in the evacuated gases.

4. Results and Discussions

The SCADA system for the HTS power cable is developed with LabVIEW interface as shown in Figure 3. The front panel of the interface has the provision to start and stop various DAQ systems responsible for recording temperature, pressure, flowrate data. Also, the control of the CCV can be achieved by varying the output current in the Control Valve input block. The current in the various temperature sensors can be varied. However, it is kept constant at 1 mA.

The cable designed is of 1000 A rating. Such high current output from the distribution transformer is cumbersome. Hence, for testing purpose, AC/DC power supplies were used with 10 V/1000 A rating to observe the effects of rated current at reduced voltage. The AC current source is manually controlled using an autotransformer whereas the DC current source can be controlled using the SCADA interface.

5. Conclusions

A complete SCADA system was developed for the testing of India's first 6-meter HTS power cable. Temperature sensors and flowmeter were calibrated, and respective curve fit equations were obtained. The sensor winding and feedthrough extraction methodology was decided, and necessary modifications were adopted. Also, the dielectric material properties were determined completely to ensure the effective insulation of the cable. A LabVIEW based command interface for the SCADA system was developed for signal conditioning and control of the various sensors and transducers. Further, a provision to extend the capabilities of the SCADA system for future expansion of cable length or inclusion of other devices has been made so that it can be successfully tested.

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