Adoption of getter pump for HTS superconducting cable system

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Abstract. For the superconducting cable operation in the real grid for over decades, one of the important technical challenges is maintaining vacuum rate of the thermal insulation cryostat vessels for avoiding system heat loss increase. When the vacuum rate is getting worse, turbo-molecular pumps etc. are usually adopted for that system. However, these pumps need to have some installation space and some electricity for the operation and moreover, periodic troublesome maintenance is needed. For the countermeasure of such issues, getter pump is selected and tested because of its smaller size, less electricity consumption and easy maintenance features. After confirming its effectivity as the vacuum pump by several investigations, this pump was employed for the termination vacuum vessel of the superconducting cable system in Yokohama. From the results of 3 weeks operation, evacuating performance exceeds turbo molecular pump and keeps vacuum state less than 1e-3 Pa stably, are confirmed respectively. This paper describes test results of the getter pump and its operation results for the real in grid system.

1. Introduction

Recently, large capacity power cables has been required around the growing city area because of their rapid growth and the huge electricity demand is increasing in a very short-time period. However especially in developing areas, it has been getting more difficult for constructing an extra power cable lines because of underground congestion already used for other lifelines or subways in these years. At this point, employing ordinal oil filled cables, pipe-type OF cables or cross-linked polyethylene cables may have some difficulties because of its transmission capacity with limited installation space [1][2][3].

From this background, requirement of high temperature superconducting (HTS) cable is considered one of the solutions because of its larger amounts of electric power capacity with compact cable size due to the high current density of the HTS conductor.

TEPCO and Sumitomo Electric have been conducting research and development of HTS cable systems since 1990. Based on these studies, a new HTS cable demonstration project started in 2007 with MAYEKAWA establishing the cooling system for the cable.

2. Analysis result of system heat load

At the superconducting cable system operating, the refrigerator or other cooling method is necessary to remove sensible heat of the circulating liquid nitrogen to suppress temperature rising liquid nitrogen and...
also to prevent its evaporation. So maintaining the vacuum state of their vacuum insulating cryostat vessel for avoiding an increasing of the thermal invasion from ambient to liquid nitrogen vessel to reduce cooling load of the refrigeration system and improve operation efficiency of the superconducting cable is one of the important engineering.

For investigating this performance, at the operation with real power grid by HTS superconducting cable system in Yokohama, vacuum rate and heat in leak from ambient into liquid nitrogen vessel of the system were observed for every separated cryostat such as cables, terminations and joint. Heat load of the high temperature superconducting cable system with liquid nitrogen circulating cooling is calculated by the calorimetric method described in the expression (1) in condition of negligible friction heat loss with smaller pressure drop.

\[ W = C \times \dot{m} \times dT \quad \text{[W]} \]

Where \( C \) is Liquid nitrogen heat capacity at constant pressure \([\text{J/kg/K}]\), \( \dot{m} \) is mass flow rate of circulating liquid nitrogen \([\text{kg/sec}]\), \( dT \) is liquid nitrogen temperature difference of the HTS cable system \([\text{K}]\). Using the measured data, total heat load of the system after initial cooling of the system was found with an average of approximately 2.4 kW at no load in the night without the influence of the sunlight and outside temperature of 23 degrees Celsius, average liquid-nitrogen temperature of around 69.6 K, and vacuum of less than 1e-4 Torr conditions, respectively \([4]\).

For more than one year, power transmission to real customer of TEPCO through superconducting cable at Asahi substation both in 2012 and 2017 were carried out, totally around 2 years \([5],[6]\). Through this long term in-grid operation, it was recognized that one of the technical issues is vacuum management of the thermal insulation layer. It is necessary to maintain a vacuum degree in less than 1e-4 Torr to maintain properly heat in leak into nitrogen from atmosphere via vacuum vessel with containing multi-layer insulation inside it \([7]\).

However, as a result of observing one-year transition of sealing vacuum state in 2017, the vacuum degree had been getting worse from the initial value of less than e-5Torr level to the 1e-3Torr level by the influence of a room temperature rise and sunlight in the summer. This transition is considered outgas increasing from the component of vacuum vessel caused by temperature rise and heating themselves \([8]\). The amount of the increasing outgas is estimated to be around 3 Torr L with volume of the vacuum vessel of the termination is 3000 Litter.

At the operation in 2012, for the countermeasure to recover vacuum state as an initial condition, outgases were evacuated by the turbo molecular pump over a period time, and the heat loss of the cable system was recovered as an initial value after evacuation as expected, shows in figure 1. But when considering inconveniences of molecular pump for its installation, maintenance, sudden pump shutdown by some failure or difficulties alongside HTS cable where there has no enough space, electricity and workers, and maintenance or backup system cost etc., it may be to the neck of the operation with use the superconducting cable as an electricity apparatus in commercial use.
3. Investigating adoption of getter pump

3.1. Study fundamental mechanism and performance of the getter pump

In order to solve such problems or issues, the study was conducted to investigate whether a getter pump can be operated for the system evacuation in place of molecular pump etc. by taking its characteristic advantages such as compactness, low power consuming, easier maintenance and so on. The getter pump that was investigated on this study consists of sintering porous alloys materials and it can capture H\textsubscript{2} gas by solid solution effect and capture active gases such as N\textsubscript{2}, O\textsubscript{2}, CO\textsubscript{2} etc. by chemisorption at the surface of the getter materials and diffusing it from the surface into inside of the materials. Fig. 2. shows vacuum pumping characteristics for some kind of the gas. Getter pump Capacitor\textsuperscript{®} HV200 with CF35 flange by SAES Getters S.p.A. [9], used for this study has some other features compare with the ordinal mechanical pumps as follows.

1) Compact (82 mm Dia., 245 mm length) and light weight (about 3 kg), no mechanical drive unit and thus trouble-proof.
2) There is no possibility to desorb the chemisorbed active gas species. During the re-activation process, only Hydrogen is partially released and quickly re-absorbed by the pump itself once the procedure is finished.
3) Only small electricity of 8 watts for keeping its good performance.
4) Inactive or inert gases such as He, Ar etc. cannot be captured.
5) The quantity of the captured gas depends on the amount of the getter material implemented in the pump i.e. on the overall pump capacity. The re-activation procedure restores the pumping performances by physically diffusing the captured species deep into the bulk of the getter material. More than 20 re-activations are possible before exhausting the pump capacity.

From these characteristics and features, it was thought that getter pump has a potential to be used for an evacuation method if it can be operated properly for ensure keeping good vacuum conditions of the cable system. So some tests with getter pump unit were conducted for checking its capability and reliability.
3.2. Outgas composition analysis of the HTS cable vacuum vessel

As described above, getter pump can only vacuum limited kinds of gases, so at first, types of outgas in the vacuum vessel of the HTS cable system is analyzed for confirming whether outgas from the system can be absorbed by getter pump or not. After finishing in grid operation and warmed up the system from LN2 to room temperature in 2013, out gas analysis was conducted with the quadrupole mass spectrometer (QMS) to find emitting gas causing thermal insulation degradation while the long-term operation.

In parallel, the out gas analysis of the composite materials such as stainless steel, super insulation and spacer in the vacuum vessel was conducted. An analysis result is shown in Fig.3. This analysis shows the out gas ingredient of the vacuum insulation layer are H2, CO, N2, and O2 that can exist a gas inside the vacuum vessel at around 77 K of the operation temperature and they transport heat energy from room temperature surface to low temperature surface. Detected gas of H2O and CO2 will be reducing their gas pressure at around 77K because of ‘Cold trap effect’ that means capturing gases on the surface of the cryogenic surface in the vacuum vessel.
Table 1 Detected residual gases from vacuum vessels of HTS cable system and composite

| Vacuum vessel | Detected gases (Pp > 1e-4 Torr) |
|---------------|---------------------------------|
| Termination   | H₂O, N₂, O₂, CO₂                |
| Cable         | H₂, H₂O, CO, N₂, CO₂            |
| Joint         | H₂, CO, N₂,                  |
| Composite     | H₂, CH₄, CO, N₂,              |

This heat transfer mechanism by gas convection is dominant when saturated steam pressure of the combined gas exceeds 1e-4 Torr. On the other hand, from the composite materials, H₂, CH₄, CO, N₂ gas emissions were found and these gases were also detected at vacuum chamber of the superconducting cable. This result suggests that mixture gas emitting or remaining in the superconducting cable system vacuum chamber is thought to be comprised of the out gas from materials and a remaining air.

3.3. Gas capture property experiment of getter pump with mixture gas and vacuum state with higher pressure

The quantity of adsorption of each unit gas substance by the getter pump is shown in Fig. 2, but in real use, each gas is in a mixed condition at the vacuum insulation layer, so it is necessary to confirm the amount of the gas adsorption by the getter in this environment.

Also, this getter pump is basically designed for operating at high vacuum state less than e-5Torr order. However, vacuum rate of the superconducting cable has a case to exceed this value due to increasing outgases or some leakage, etc. At these vacuum conditions, molecular of the gas in the vacuum space are getting to increase and getter’s absorb performance has possibility to degrade because of the limitation of its chemical reaction or adsorption speed comes from getter’s characteristics. So it is necessary to confirm absorb characteristics under the mixed gas and vacuum rate with high pressure range conditions.

Based on this purpose, an adsorption examination was carried out with test circuit shown in Fig. 4. After attaching a getter pump to the vacuum test container with the capacity of V liters, this small vessel was evacuated at room temperature in advance, and after taking the activation, getter pump was connected to the vacuum container. The vacuum degree of the container is improved by the adsorption effect of the getter pump. After that, using the slow leak valve which is attached between atmosphere and the vacuum container, a small volume of the air, as an example of the mixture gas, was introduced slightly into the vacuum container, and pressure of the vessel climbed to be dP (Torr).

After that, the invaded gas was adsorbed by the getter pump while the pump is active and evacuated pressure is improved again. By repeating this operation for N times, the amount of captured gas by getter pump would be obtained to be N×dP×V (Torr·L). Repeating this operation and thus quantity of adsorption gas became approximately at least 20 (Torr·L) shown in Figure 5 with N = 18 times.

For example, volume of vacuum vessel of the superconducting termination is around 3000 L, so necessary adsorption amount of this vessel is calculated to be 3 (Torr·L) at assuming the vacuum rate of the vessel is increased to be 1e-3 (Torr). This amount is equivalent to about 1 km length of the HTS cable using at Yokohama substation. By this investigation, it was confirmed that this getter has enough amount to absorb outgases from one termination over 6 times by the estimation.
3.4. Getter gas adsorption practice with test vessel
Using the test apparatus shown in Fig. 4, the vacuum state of the chamber of the Yokohama system was simulated at every procedure, for example, bake out before cooling down, initial cooling, cooling operation with affection of sunlight. During every procedure, residual gases are analyzed by QMS for...
checking the distribution transition at every stage and investigating whether their gases can be absorbed by getter pump properly.

The test vessel has co-axial stainless tube structure and among an inner tube and the outside pipe forms vacuum thermal insulating space with placing same insulation materials as Yokohama system. The inside of the inner tube can contain liquid nitrogen, so it can simulate vacuum layer when HTS system is cooled down. Furthermore, an electrical heater is attached on the surface of the outer tube that is used both for bake-out of the vessel and for simulating the surface temperature rising by solar radiation especially at daytime in summer season. For this test vessel, turbo molecular pump (TMP), getter pump (GP), mass spectrometer (QMS), vacuum sensor, valves and piping are installed.

TMP is used for initial evacuation of the test vessel with baking procedure and for back pressure of the QMS. By use of this test unit, each procedure is experimentally simulated and the changes of the vacuum rate and residual gas component at every step are observed. Table 2 shows the result of transition of the vacuum rate at every step. After vacuuming and baking, test chamber is cooled down and vacuum pressure is reached lower than 1.2 e-5 Torr, but when cryostat surface is heated with 70 degree C. simulated sun radiation, vacuum state become worsening to be 1.4 e-3 Torr. At this time, getter pump and test vessel are connected and start evacuation by getter pump. As the result, vacuum rate is improved to be 1.7 e-6 Torr. This reached vacuum rate is better than TMP as of 5.7 e-6 Torr and confirmed this getter pump has good vacuuming performance compared to ordinal mechanical pump.

Table 2 summary of vacuum state with CapaciTorr® HV200

| Condition | Vacuum state | Ambient temperature | Vacuum rate (Torr) |
|-----------|--------------|---------------------|-------------------|
| After bake-out, before LN2 cooling | Seal | Room temperature | 2.3e-4 |
| LN2 cooling | Seal | 70 deg. C Imitated sun radiation | 1.2e-5 |
| | Seal | Imitated sun radiation | 1.4e-3 |
| | Getter evacuate | | 1.7e-6 |
| | TMP evacuate | | 5.7e-6 |

Fig. 6 shows residual gas transient in vacuum layer of the test chamber before cooling down and after the liquid nitrogen cooling. Fig. 7 also shows the transient at influence of the sunlight affection at cooling and evacuation characteristics by getter pump. Fig. 6 shows volume of the residual gases in the vacuum vessel at room temperature which are decreasing after liquid nitrogen cooling by cold trap effect on the cryogenic surface of the inner pipe of the vacuum vessel. After that, by heating the surface of the cryostat at 70 deg. C., residual gas pressure is increased again as increasing emission of trapped gas from the piping surface to the vacuum room as shown in Fig.6. And Fig.7 also shows the gas distribution after using the getter pump, outgas of H2, N2, O2 and CO2 are absorbed by the getter pump, is confirmed.

From these studies in section 3, characteristics of the getter are found and cleared as follows.

- From the residential gas investigation for superconducting cable system, these detected gases are able to be absorbed by the getter pump.
- Amount of adsorption gas by the getter is tested and confirmed at least 20 Torr L at the condition of high pressure range and mixture gas, i.e. the air. And this value is enough for evacuating outgas from the termination for 1 year operation of 3 Torr L.
- By using test vessel, characteristics of the evacuation properties are checked both the getter pump and the turbo molecular pump, and found that the getter pump has better evacuation vacuum rate compared to the turbo molecular pump.

![Fig. 6. Residual gas distribution of the test vacuum vessel (1)](image1)

![Fig. 7. Residual gas distribution of the test vacuum vessel (2)](image2)

4. Getter pump evacuation test at Asahi substation

From the fundamental studies and examination results of the getter pump as described above, the getter pump’s effectiveness of evacuating performance is confirmed. As a next step, by use of this pump, evacuate outgases from the termination vacuum vessel which is used for real in grid power transmission test at Asahi substation in Yokohama was conducted.
4.1. Evacuation test for in grid HTS termination

After carried out the activation of the getter pump, this pump was connected to the vacuum vessel of the both termination in Asahi substation. The transient of the vacuum pressure of the both termination vessels are shown in Fig. 8. Before evacuation, both vacuum vessels were sealed over one year and its vacuum state was reached about to 1e-3 torr with 69 K operation. After that operation temperature was changed to about 76 K and vacuum rate became 4.4 e-3 Torr because cold effect trap was weaken. At this condition, the getter pump was connected to the vacuum vessel of the termination and started evacuation. After 8 hours from starting the test, vacuum rate of both vessels reached at around e-6 Torr order and maintained good vacuum pressure for more 3 weeks. At this test, the quantity of absorbed gas from the termination is estimated to be 13 Torr L.

5. Conclusion

In place of the ordinal mechanical pump, the getter pump is studied and tested for confirming its availability and reliability. From these results, it is evaluated that the getter pump has a good potential for applying to evacuation system for the HTS superconducting cable. Finally, this system has been tested with real in use HTS cable system in Asahi substation and demonstrated stable evacuation performance for 3 weeks. From these results, characteristics of the getter pump are summarized as follows.

1) Getter pump has good ability to absorb outgases of vacuum vessel of the superconducting cable system.

2) For example, vacuum rate of the superconducting termination is worsened to be 1e-3 Torr for one year operation with liquid nitrogen temperature of 69 K. For recovering vacuum state, an amount of adsorption is calculated to be about 3 Torr L. The getter pump has enough capacity of over 20 Torr L, so it is supposed that this getter pump can operate over 6 years without any maintenance.

3) Minimum vacuum pressure of the getter pump is smaller than ordinal turbo molecular pump and confirmed getter pump has good performance for evacuating to high vacuum rate.

4) Once evacuation performance is saturated, it can recover its ability by taking ‘re-activation’ procedure and can recover before exhausting the pump capacity.
For the next step, more long term operation will be needed to check its reliability and acceptability.

Acknowledgement
This work was supported in part by the Japanese Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO). And we would like to give thanks to Saes Getters S.p.A. for their support and comments to achieve all studies.

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