A Novel Electrical Insulating Material for 275 kV High-Voltage HTS Cable with Low Dielectric Loss

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Abstract. In the case of high temperature superconducting (HTS) power transmission cables at high voltage operation, the electrical insulation technique in consideration of the dielectric loss reduction becomes crucial. In this paper, we focused on a Tyvek/polyethylene (PE) sheet, instead of the conventional polypropylene laminated paper (PPLP). We obtained the dielectric characteristics ($\varepsilon_r$, tan$\delta$) and partial discharge inception strength (PDIE) of PPLP, Tyvek and Tyvek/PE. We pointed out that the dielectric loss of 275 kV HTS cable with Tyvek/PE insulation will be reduced to 21% of that with PPLP, and the total electrical loss including the AC loss will be reduced to 41%.

1. Introduction

High temperature superconductivity (HTS) cables have been investigating in the world for realization of high density, large capacity, and low loss transmission of electric power [1]-[3]. Electrical insulation structure of the HTS cables generally has used liquid nitrogen (LN₂) / laminated tapes composite insulation system. Due to the occurrence local partial discharge (PD) in this system, dielectric strength will deteriorate and breakdown (BD) will occur. Therefore, electrical insulation at cryogenic temperatures is a key and common technique for the practical development of HTS cables [4]-[10]. Especially, in the case of HTS cables at high voltage operation, the electrical insulation technique in consideration of the dielectric loss reduction becomes crucial. For example, the dielectric loss of electrical insulation layer for 275 kV HTS cable (Figure 1) in Japanese M-PACC (Materials and Power Applications of Coated Conductors) project is estimated to be three times larger than the AC loss of HTS conductors [1]. Since the dielectric loss depends on the relative permittivity ($\varepsilon_r$) and dielectric dissipation factor (tan$\delta$) of the electrical insulating material, a novel electrical insulating material with high electrical insulation strength and low dielectric loss is required for the high-voltage HTS cables.

From the above background, we have been investigating the feasibility of a novel insulating material for high-voltage HTS cables. In this paper, we focused on a Tyvek/polyethylene (PE) sheet, instead of the conventional polypropylene laminated paper (PPLP), and evaluated the PD inception and dielectric characteristics for the insulation design of 275 kV HTS cables with Tyvek/PE sheet.
2. Applicability of novel electrical insulating material (Tyvek/PE)

Tyvek/PE is a synthetic paper which is bonding PE-sheet on Tyvek by heat. Tyvek/PE has a low \( \varepsilon_r \) and \( \tan\delta \) and is also expected to improve the poor electrical insulation performance of Tyvek due to its porous structure. Figure 2 shows the experimental setup and configuration of cable sample for PD measurement. Six cable samples (inner diameter: 20.4 mm, insulation thickness: 1 mm, effective length: 100 mm) were immersed in LN\(_2\) in the inner vessel of the cryostat. Sample numbers were 4 for PPLP (C-Type), 10 for Tyvek and 4 for Tyvek/PE, respectively. AC high voltage of 60 Hz was applied to the cable sample and generated PD. PD inception voltage (PDIV) was measured 10 times for different LN\(_2\) pressures \( P \) (0.1-0.3 MPa) at 77 K. PD inception strength with 0.1 % probability (0.1 % PDIE) at high voltage (HV) electrode surface was calculated by the Weibull analysis. In addition, the dielectric characteristics (\( \varepsilon_r \), tan\(\delta\)) of each sample were measured using schering bridge (300 V/mm).

Figure 3 shows 0.1 % PDIE and relative standard deviation of each insulating material. In Figure 3 (a), 0.1 % PDIE of Tyvek/PE at \( P = 0.3 \) MPa is 25.5 kV\(_{\text{rms}}\)/mm, which is the same level as that of PPLP and about 15 % higher than that of Tyvek. In Figure 3 (b), relative standard deviation of Tyvek/PE is smaller than that of Tyvek.

Figure 4 shows relative permittivity (\( \varepsilon_r \)) and dielectric dissipation factor (tan\(\delta\)) of each insulating material (relative ratio against the value of PPLP). Experimental results revealed that the dielectric loss (\( \varepsilon_r \ast \tan\delta \)) of Tyvek and Tyvek/PE was about 20 % of that of PPLP, which means that the dielectric loss of HTS cables insulated by Tyvek or Tyvek/PE will be reduced to 20 %, compared with that with PPLP insulation. These results suggest the technical feasibility of Tyvek/PE as the insulating material of high-voltage HTS cables.

Figure 1. Design of 275 kV-3 kA HTS cable (M-PACC)

Figure 2. Experimental setup and configuration of cable sample
3. Electrical insulation and power loss characteristics of 275 kV HTS cable

Using the obtained dielectric and insulation characteristics of Tyvek/PE shown in Table 1, we designed the 275 kV HTS cable in the M-PACC project. Including the evaluation of a composite insulation system with PPLP-C and Tyvek/PE (from the viewpoint of potential distribution, PPLP-C with the higher $\varepsilon_r$ is arranged inside), we evaluated PDIV and electrical loss as a function of the radius $c$ of PPLP-C layer ($c = a$: All Tyvek, $c = b$: All PPLP-C) as shown in Figure 5.

Figure 6 shows the results of PDIV and electrical loss of 275 kV HTS cable. In Figure 6, the dielectric loss of 275 kV HTS cable with Tyvek/PE insulation will be reduced to 21% (from 0.60 W/m to 0.125 W/m) of that with PPLP, and the total electrical loss including the AC loss (0.20 W/m) will be reduced to 41% (from 0.80 W/m to 0.325 W/m), where PDIV based on the 0.1% PDIE exceeds the testing voltage (310 kV) for 275 kV HTS cables.

### Table 1. Insulation material data for 275 kV HTS cable

| Condition: LN$_2$(T = 77 K) | PPLP-C | Tyvek/PE |
|-----------------------------|--------|----------|
| 0.1% PDIE at $P = 0.3$ MPa  | 25.7   | 25.5     |
| [kV$_{rms}$/mm]             |        |          |
| $\varepsilon_r$             | 1.90   | 1.73     |
| tan$\delta$                | 0.00058 | 0.00013  |
Consequently, we could obtain the consistency between the high electrical insulation performance and the low dielectric loss performance of 275 kV high-voltage HTS cables by using Tyvek/PE as the electrical insulating material.

4. Conclusions
We investigated the electrical insulation and power loss characteristics of a novel electrical insulating material (Tyvek/PE) for high-voltage HTS cables. The main results in this paper can be summarized as follows:

1. 0.1 % PDIE of Tyvek/PE is the same level as that of PPLP.
2. Dielectric loss factor $\varepsilon_r * \tan\delta$ of Tyvek/PE is 20 % of that of PPLP.
3. Total electrical loss of 275 kV HTS cable in Japanese M-PACC project will be reduced to 41 % by using Tyvek/PE insulation, compared with the conventional design with PPLP insulation.

The above results suggested the technical feasibility of Tyvek/PE as the insulating material of high-voltage HTS cables with the coordination between high insulation performance and low dielectric loss.

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