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Breakdown Strength Improvement of Polyethylene Insulation used in Power System Cables

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Abstract: Studies conducted via the measurement of the breakdown strength to monitor improvement of the properties of the power system cables used in the transmission lines which is usually made of Polyethylene (PE). The PE sample is fabricated in the form of a disc shape containing a variety of semiconducting materials to obtain a layer forming an interface having a semiconducting ground electrode. Each semiconductor material is perturbed with the additive content to observe the improved behavior of the PE specimens. The average breakdown strength of these specimens is determined and analyzed using Weibull statistical methods.

Key words: Cable, polyethylene, semiconductor, statistical analysis

INTRODUCTION

The reduction of insulation thickness of the power system cables is necessary for the development of the power transmission. This allows improvement of the properties of the material, cost saving and aiding in the cost reduction of the commercially prepared end product in addition to lowering installation costs of the underground power transmission lines. The average breakdown strength of the power cables is about 70 kV mm^{-1} under the ac stress. This indicates a possible reduction of insulation thickness since the intrinsic breakdown strength[1] of the Polyethylene (PE) exceeds 500 kV mm^{-1}. In general, it is conducive to increase the breakdown strength of the PE in order to reduce the insulation thickness from application, handling and cost standpoint.

There are several reasons for the insulation breakdown at very high electric fields[2-4]. These include manufacturing defects and materials' faults attributing to the weak region for the finite leakage current. Due to the specific structure of the power cables, the interface comprising of the semiconducting layer and the insulation layer may be originating such defects[1]. Thus, serious attention have been put on the study on the influence of the interface to the electrical tree and breakdown properties. It was found that initial electrical trees can be originated at the interface regions and then the interface region may also initiate breakdown of the insulation[4].

In this study, the interface between the PE and the semiconducting materials in the form of the cylindrical discs were used to simulate the actual interface of the cross-linked polyethylene (XLPE) power cables. Several additives, mainly glycerides, were added to the semiconducting materials to modify the physical properties of PE near the interface regions. The semiconducting material consisted mainly Ethylene Ethyl Acetate (EEA) copolymer and contained some acetylene black.

MATERIALS AND METHODS

The disc specimen depicting three regions noted as PE disc plate, semiconducting layer and semiconducting film serving as ground electrode are displayed in Fig. 1. Each region is prepared separately then pressed to obtain a single piece disc shape at 170°C and 15 MPa. The experiment was then conducted at the State Key Laboratory of Electrical Insulation for Power Equipment at Xi'an Jiatong University.

Several glycerides additives were used in the semiconducting layer of the disc specimen. The semiconducting material comprised of mainly EEA copolymer and Acetylene black. These glycerides additives are denoted as A (coupling agent), B (surfactant) and C (voltage stabilizing compounds) including commercially denoted P, M and F compounds. AB stands for the combination of A and B following a notation AB, the following number indicates the content in semiconducting layer of the disc specimen. Thus, higher the number indicates higher the content of the AB additive in the disc specimen. In the same way notation

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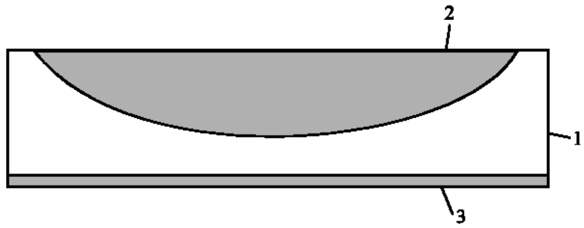

Fig. 1: Three regions (parts) of the disc specimen consisting: 1-PE disc plate of 5 mm thick and 80 mm diameter; 2-semi-sphere semiconducting layer having 32 mm diameter; 3 -semiconducting film as ground electrode having 60 mm diameter and 0.2 mm thickness

for the combination such as BP, AM, AF, etc. is used in the semiconductor layer.

The disc specimen was then immersed in the silicone oil at room temperature and ac voltage was applied from 0 to 20 kV by stepping 2 kV. The region 2 in Fig. 1 was used as high voltage electrode and region 3 in Fig. 1 was used as ground electrode. At each applied voltage the pausing time was about 30 sec. After attaining 20 kV the applied voltage was increased at a rate of 400 V sec^{-1}. This operation continued until the breakdown occurred. The breakdown strength of each specimen was obtained as the breakdown voltage of each specimen divided by its minimum insulation thickness, namely region 1 in Fig. 1. The insulation thickness across the HV electrode located at the semiconducting layer and the ground electrode was strictly controlled in the range between 0.45 and 0.55 mm. The breakdown strength of each type of specimen was the average of 7 measurements. The average breakdown strength E_{av} is designated to the samples containing the additives while E_{0av} corresponds to the sample without the additive. The X-ray Diffraction (XRD) of the degraded material was conducted with the X-ray (Japanese Dmax-III A type Rigaku Gesgerflex) device having Cu target. The XRD technique is used in investigating the relationship between the breakdown strength improvement and the interfacial properties. Three kinds of additives, conventional semiconducting material 0 (reference material), additive A and AB2 are chosen to represent different specimens. They are pressed with the PE films (100 μm) using foregoing temperature (170°C) and pressure (15 MPa). Then the semiconducting layers were taken away when cooled to room temperature. The PE films are used in the XRD measurement.

RESULTS AND DISCUSSION

The variation in the breakdown strength depicted as normalized parameter, E_{av}/E_{0av}, in Fig. 2. It is observed that

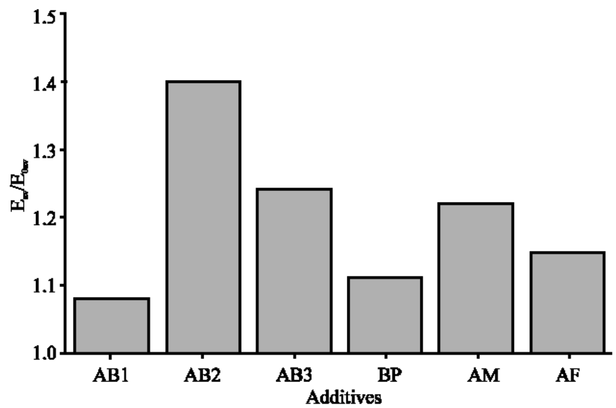

Fig. 2: Comparison of the average breakdown field improved by incorporating various additives in the semiconducting material

the average breakdown strength of the specimen containing AB2, AB3, AM, BP and AF additive in a sequential manner is enhanced. The enhancement in the average breakdown strength is observed for each specimen designated as AB3, AM, BP and AF with respect to the specimen AB1.

In order to comprehend the effect of the additives, the cumulative breakdown probability of the specimens is plotted against the breakdown strength using Weibull analysis[5] which is a commonly used statistical method in the research of electrical breakdown problems. E_{50}, E_{10} and E_1 represent the breakdown strength corresponding to 50, 10 and 1% cumulative probability, respectively. E_1 is the lowest breakdown strength and is very important in comparing the improvement of the additives. Specimen designated as 0 refers to the sample containing semiconducting material without the additive. The highest value of E_1 among these specimens such as for AB2 is more than twice of the original specimen containing usual semiconducting material (Table 1). This type of result indicates that there is a significant possibility to improve the breakdown strength of the actual XLPE power cables. However, the interface between the semiconducting layer and the insulation in a real power cable is much rougher than in the specimen of this study. Therefore, the effect of additives may be reduced by the interface roughness of a real cable.

Figure 3 shows the XRD results via usual intensity versus 2θ (θ is the angle of diffraction) plot of the PE films pressed with various additives. Two peaks are prominent, one peak corresponds to [110] plane direction at about slightly above 21°. The other peak corresponds to the [020] plane direction at about slightly less than 24°. Figure 3a shows the peak corresponds to [110] plane is much higher than the [020] plane for the original specimen

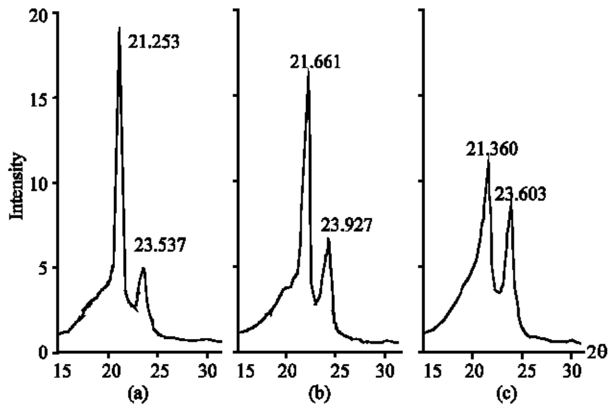

Fig. 3: The XRD results of specimens containing various additives
(a) PE film hot-pressed with semiconducting material.
(b) PE film hot-pressed with semiconducting material containing additive A.
(c) PE film hot-pressed with semiconducting material containing additive AB2.

Table 1: Breakdown strength of the samples containing various additives*

	Simple average				Weibull probability			
Additives	σ_E	V_{av}	D	E_{av}	B	E_{50}	E_{10}	E_1
None or 0	7	41	0.49	84	3.6	82	67	54
AB1	2	47	0.52	89	11.6	89	83	81
AB2	7	56	0.48	117	3.5	118	105	102
AB3	5	53	0.51	104	3.6	113	103	89
BP	6	46	0.50	94	3.8	93	79	76
AM	4	50	0.49	101	4.0	102	92	89
AF	3	46	0.48	96	8.9	96	90	88

*V_{av} : Average breakdown voltage (kV),
D : Minimum thickness (mm),
E_{av} : Average breakdown field (kV mm^{-1}),
σ_E : Standard deviation of the breakdown strength (kV mm^{-1}),
E_{50} : 50% Weibull breakdown strength (kV mm^{-1}),
E_{10} : 10% Weibull breakdown strength (kV mm^{-1}),
E_1 : 1% Weibull breakdown strength (kV mm^{-1}),
B : Weibull scale parameter

having only semiconducting material in the disc. When A and AB2 additives are introduced sequentially in the semiconducting material of the disc, the intensity of the peak changes to the lower value for the [110] plane and to the higher value for the [020] plane as depicted in Fig. 3b and 3c, respectively. Figure 3c matches Table 1 quite well as the role of the structural transition in the AB2 specimen is reasonably noted for the improvement in the breakdown strength. It is further proposed that such a transition may lead to the improved distribution of the lamellar angle, which is the angle between the lamellar line and the line perpendicular to the electrode, at the interface region of the PE and semiconducting material[1] that may result in the improved breakdown strength.

CONCLUSIONS

The specimen of the PE cable samples containing additive in the semiconductor layer usually exhibited an overall improvement in the breakdown strength. The average breakdown strength of each sample evaluated using XRD conforms to the pattern observed via intensity and 2θ value for total diffraction in a specific direction. There is a clear indication of improvement in the PE cable specimens with respect to the additive content in the semiconducting layer material.

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