Gas/Solid Interface Charging Phenomena

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Surface charge accumulation in the spacer modifies local electric fields, which restricts the industrialization of high voltage direct current (HVDC) gas-insulated transmission lines (GILs). In this paper, the state of art in gas/solid interface charging physics and models, covering areas of charge measurement techniques, charge transport mechanisms, charge related DC surface flashover models, and charge control methods, is reviewed and discussed. Key issues that should be considered in future studies are summarized and proposed. The purpose of this work is to provide a brief update on the most important and latest progress in this research area, and to educate readers as to the current state of the gas-solid interface charging phenomenon, which has seen great progress in the past few years.

HVDC GIL surface flashover surface charge charge measurement

material modification

1. Introduction

High voltage alternating current (HVAC) gas-insulated transmission lines (GILs) can realize large-capacity power transmission in complex environments, and have been in use since 1960s[1]. However, under high voltage direct current (HVDC), the influence of the surface charge accumulation in spacers must be considered before development of HVDC GIL. At DC voltage, charges transport along electric field lines both in the gas phase and in the spacer bulk, and accumulate on the surface of spacers inside GILs[2]. The local electric field over spacer surface gets more disordered, and is prone to generating a higher local electric field strength as a consequence of the influence of the charge migration[3][4]. Under these conditions, a surface flashover is more easily triggered[5][6].

In recent years, the urgent need for HVDC GIL, driven by offshore projects, requires more urgent breakthroughs in this field, and the problem of charge accumulation has become tremendously pronounced[7][8][9]. As a result, an increasing number of researchers over the past few years have focused on this area, and have made significant efforts to tackle difficult problems that are still a specific challenge to us[10][11]. The rapid progress of related research can be reflected both in a surging amount of research, and in special topical issues of the past 5 years[12][13][14][15][16].

Despite the extensive studies and output during the past few years, charge behaviors such as charge generation, transport, and relaxation in dielectrics should be studied, as these fields of research have still not been fully understood[17].

2. Surface Charge Measurement

The Lichtenberg dust figure method can be used to reflect surface charge distribution based on the property that a charged surface can adsorb dust particles with hetero-polarities, as shown in Figure 1a [21]. Based on the principle that dielectrics can be polarized inside electric fields, the electric field density due to charge accumulation on the surface can be depicted by polarized dielectric particles, as shown in Figure 1b. More details regarding polarized surface charge cluster formation and dust pattern phase transition can be found in the literature[22][23]. In recent years, Kelvin probe methods have been more widely used. As an oscillating feedback capacitive probe, the Kelvin probe is a typical representative of an active electrostatic probe, by which the potential can be obtained from the measured point[7]. The distribution of surface charge density can be obtained by a simulation algorithm based on the surface potential measurement result. The comparison of these two methods is shown in Table 1.

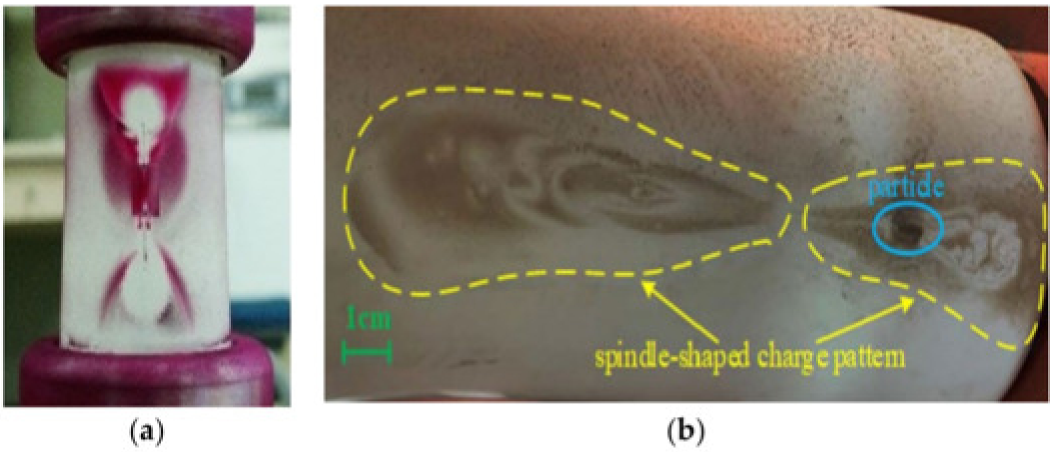

Figure 1. Measurement results obtained by Lichtenberg dust figure method. (**a**) Via toner dust [21], and (**b**) via silicate dust[22].

Table 1. Comparison of the Lichtenberg dust figure method and the Kelvin probe method.

Methods	Advantages	Disadvantages
Lichtenberg dust figure	Measurement result is not restricted by surface potential value and is not influenced by charge decay process during measurement.	Cannot quantitatively characterize charge density (or electric field strength); dust adsorbed may have a certain impact on local electric field.
Kelvin probe	Surface potential value can be quantitatively characterized with a high sensitivity.	Low spatial resolution and relative low voltage range; measurement takes longer.

However, at present, it is still very difficult to obtain a "net" surface charge distribution unaffected from the bulk polarization using the above-mentioned methods. Additionally, to calculate the charge density by the surface potential distribution from one side potential measurement introduces large errors, since charges on the opposite side of the spacer affect the potential measurement indirectly, which has already been verified in previous studies[24].

Bilateral surface potential measurements of spacers are an option to avoid such influence[24][25]. The influence of probe geometry and errors from spatial resolution should be further calibrated [26]. Additionally, the effect of the internal quick depolarization process on the surface potential measurement is also rarely considered.

3. Charge Transport and Models

As early in 1982, Cooke proposed that the discharge in SF_6 near the insulator can become a source of hetero-polarity charges [27]. Later, it was discovered that homo-polarity charges injected to the volume might also dominant surface potential polarity [28]. It is generally believed that surface charges can come from the gas phase and bulk of the solid spacer. Various charge accumulation models were proposed based on each individual experimental setup and its results, where the charge sources were believed to be mainly due to uneven material distribution, bulk injection charges, partial discharges (PDs), corona discharges, volume polarization, etc.[29][30].

Pioneering studies by Li proposed a field-dependent theory to explain surface charge patterns and charge origin in spacers[31]. This model confirms that the surface potential measurement result reflects the combined contribution of both the normal component of the bulk leakage current and the gas leakage current that ends in the spacer surface. The charging property of spacers is dominant from the volume below an electric field of 2.5 kV/mm. When the electric field stress is higher than 2.5 kV/mm, the charging property of spacers is dominated by the enhanced gas ionization, due to local sharp protrusions on the grounded conductor surface. The field-dependent model of dominant charge behavior is shown in Figure 2.

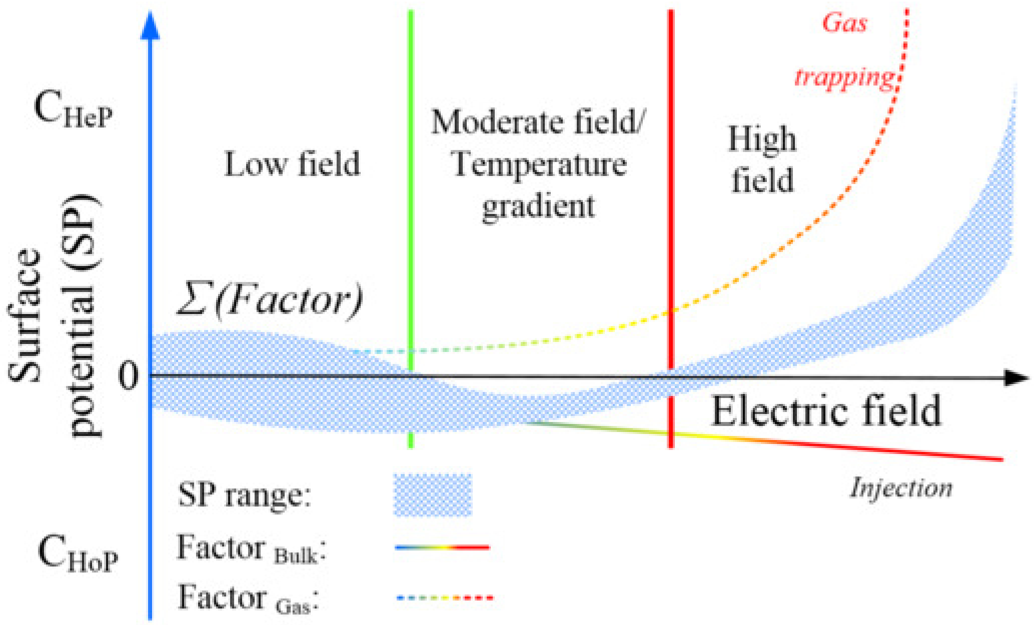

Figure 2. Field-dependent model of dominant charge behavior [31].

This model explains the existing research results and provides a link for the lateral comparison of previous research results from different researchers. However, the following issues still remain unsolved and need further verification:

- The experimental configuration is complicated, as different field strengths appear on various parts of the configuration. It would be better to adopt simpler configurations where the electric field is precisely defined, such as axisymmetric post-type spacers placed between parallel-plate electrodes.
- Due to the lack of calibration of local roughness, the effects of relative humidity and temperature gradient, the division in low-mid-high fields cannot be characterized quantitatively.
- The dimensions of this model need to be further filled and expanded, under the premise of considering the first two suggestions.

These unsolved issues are also key problems limiting the completion of gas/solid interface charging models, and should be further studied.

4. Charge Triggered DC Surface Flashover

Surface flashover is a gas breakdown phenomenon along a dielectric surface. At DC voltage, it can be triggered by different factors that affect surface electric field distribution. Surface charge accumulated at DC voltage causes local electric field distortion, which may induce the flashover along the surface. In 1994, it was reported that the low energy flashover on the spacer surface is likely to be related to surface charge accumulation [32]. The triggering of the flashover is not directly related to the number of surface charges, since it was found that a small amount of charge can also cause a high local electric field [33]. The presence of hetero-polarity charges is more likely to induce a surface flashover [34]. Recent studies have shown that the homo-polarity charges injected into the volume can result in a potential enhancement near the high voltage electrode, which is equivalent to the extension of the high voltage electrode to the direct of the ground electrode. Thereby, an “analogous ineffective region” is expanded, which reduces the flashover inception voltage [35]. This model explains the unpredictable flashover of the insulator with DC application. However, the model is obtained using sheet insulation structures, where the electric field distribution is very different to that of the spacers in GIL. Meanwhile, the charge is likely to accumulate at different insulation interfaces, which may have an influence on the definition of “analogous ineffective region” expansion.

Recent research showed that the unpredictable insulation surface flashover can be triggered by surface charge clusters under DC electric field [23]. The charge cluster is randomly formed when ions originating from local micro-protrusions accumulate on the insulation surface, the edge of which produces a strong electrical field to induce local streamers. These local streamers provide an inducing factor unpredictably triggering surface flashover [23].

In addition to the above, models to explain the unpredictable DC surface flashover of spacers triggered by charge accumulation inside SF_6 are still barely studied. It has been verified that both surfaces can be charged with charges of different polarities when DC was applied. Do these charges with different polarities affect the probability of flashover on both sides? What is the process and the mechanism of charge-induced unpredictable flashover? What is the inherent relationship between local charge accumulation (charge properties) and initial electron collapse? The invisibility of surface charge transport at various electric fields, as well as the instantaneous property of surface flashover, both introduce great difficulties into uncovering the mechanism of local charge induced surface flashover. Innovative research ideas or test methods are needed to verify the above issues.

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