Review of surface transient charge measurement on solid insulating materials via the Pockels technique

Bo Zhang | Jianyi Xue | Xingyu Chen | Sile Chen | Haibao Mu | Yang Xu | Guanjun Zhang

State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi’an Jiaotong University, Xi’an, Shaanxi, People’s Republic of China.

Correspondence Guanjun Zhang, State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi’an Jiaotong University, Xi’an, Shaanxi 710049, China. Email: gjzhang@xjtu.edu.cn

Funding information National Natural Science Foundation of China, Grant/Award Number: 11775175; National Natural Science Foundation of China, Grant/Award Number: U1766218

Abstract Surface charges accumulated on solid insulating materials in electrical apparatuses and electronic devices could distort the initial electric field and severely damage the insulation performance. Accurate transient surface charge measurement is critical to determine the mechanisms of charge transport and flashover occurrence, and estimate surface insulation strength under high voltage. The measurement technique based on the Pockels electro-optic effect is considered as the only approach for 2-D dynamic charge distribution behaviour so far, and it has good capability to avoid original electric field distortion caused by conventional methods featured by metal probes. This paper reviews recent progress of the non-invasive dynamic surface charge measurement systems on the Pockels technique. We focus especially on typical systems with transmitting and reflecting configurations and the frequently used fast inversion algorithms. It can be inferred that higher spatial-temporal resolution, higher signal-to-noise ratio, and better compatibility for both transparent and opaque materials are the future development trends, which greatly depend on multiple technological breakthroughs at impact-resistant electro-optic crystals, advanced high-speed photography and high-performance inversion algorithms. In addition, the recent studies on transient behaviour of surface discharge, together with the present limitation and future prospects are discussed. It is expected that more ideas will be inspired in transient surface charge measurement by the Pockels technique and other relevant electro-optic methods.

1 | INTRODUCTION

Solid dielectrics are widely used as support elements in different electrical and electronic systems due to their advantages in insulating and mechanical performance [1,2]. Surface charge accumulation which is an interesting and complex phenomenon on solid insulating materials remains a research hotspot in the fields of electric insulation [3,4], electrostatic safety [5,6] and gas discharge [7,8]. For example, charges accumulated on spacer surface in gas-insulated metal-enclosed transmission lines (GIL) induce flashover and directly decrease the withstand voltage [9]. Breakdown across the insulation surface is usually more severe than the bulk one of the same size [10,11]. It is commonly believed that these failures are closely related to distortion of the original electric field and abundant seed charges induced by surface charge on gas–solid or vacuum–solid interfaces [12]. To acquire stable and predictable insulation performance under high electric field, much efforts have been devoted to the detection of surface charge distribution [13], mechanisms of accumulation and dissipation [14,15] and strategies of charge regulation [16–18]. Among these, accurate measurement of surface charge density distribution accurately plays a fundamental role in quantitative estimation and design of electrical insulation.

Both on-line and off-line diagnostic approaches are required for surface charge detection. The most essential difference between these two categories is whether the exciting sources that generate the surface charge are applied during the measurement process. Off-line cases mean that the diagnostic systems are operated to detect the decay process of residual charge after withdrawing the excitation sources. However, the situation when excitations are acting on insulating materials can only be detected in on-line cases. Actually, charges on the insulation surface continuously accumulate, expand, transfer...
and dissipate under the effect of high electric field [19], glow or streamer discharges exposure [20,21], electron-beam and gamma-ray irradiation [22,23]. The duration of dynamic process ranges from several nanoseconds to dozens of minutes and even extends to a much longer time after withdrawing these excitations, greatly relying on material properties [24]. Therefore, multiple kinds of diagnostic methods with different sampling resolutions are required. Meanwhile, minimising the interference from the detection system to surface charge is critical to an accurate result. So far, measurements are mostly undertaken in the off-line way, which has been summarised in previous reviews [25,26]. Despite considerable pioneering research work and academic achievements, mechanisms of charge transfer and the evolution from charge deposition to breakdown are still vague and debatable. This is mainly due to a lack of solid experimental results of transient surface charge distribution by on-line detection. The way that charges transfer on dielectrics under excitation is quite different from the off-line results due to the fast decaying behaviour. Therefore, on-line measurement is imperative regardless of how many challenges which have never been encountered in the off-line cases.

To the best of our knowledge, the Pockels effect, also known as linear electro-optic effect, is considered as the only feasible measurement technique for transient surface charge diagnosis so far [27]. Different from conductive metal needles suspended close to surface in off-line methods, which greatly disturb the distribution of original electric field and surface charge [28,29], dielectric electro-optic crystals with weak conductance are employed in the Pockels techniques, hiding under samples to avoid interference with electric field above. Usually, this non-invasive online measurement needs to cooperate with high-speed camera devices to acquire a higher temporal-spatial resolution [30]. Therefore, the Pockels effect method has a great advantage in dynamic measurement of surface charge and is experiencing rapid development in recent decades.

Herein, we discuss our perspective on the current status of transient surface charge measurement based on the Pockels effect, including two typical measurement systems, the fast surface charge inversion algorithms and the latest progress of transient charge behaviour. A series of interesting and fundamental results are summarised, followed by the limitation of the current research studies and the outlook for future development of surface charge measurement with this electro-optic technique.

2 | EVOLUTION OF POCKELS TECHNIQUE IN SURFACE CHARGE MEASUREMENT

Those conventional techniques employed to observe surface charge can be classified into three methods in principle which are based on dust figure, electrostatic probe (EP), and electrostatic field microscope (EFM). Dust figures, known as Lichtenberg figures, are formed when coloured powder with unipolar charge (red positive lead oxide or yellow-white negative sulphur) is absorbed on the charged region [31,32]. Although the charge polarities and distribution patterns can be identified, it is impossible to quantitatively obtain surface charge density [33]. EP method is a quantitative diagnostic method where an electrostatic probe suspended still or forced to move above dielectrics is used to record potential induced by local surface charge [34]. This method has also been improved by replacing the passive probe with an active one (Kelvin vibrating probe) for higher accuracy [35] and grouping up into a matrix for higher sampling rate [36]. EFM method based on atom force microscope (AFM) has a higher resolution up to the µm scale and mV order because the surface micromorphology is taken into consideration [28,37]. Although the EP and EFM methods have been developed perfectly, the inherent disadvantages of inevitable distortion to the original electric field limit their extended application in on-line measurement.

Applying the Pockels technique to detect surface charge started later than the off-line methods. The EP method which was first adopted by D. K. Davies in 1967 has been widely utilized in surface charge detection with the commercialized electrostatic measuring devices. The Pockels effect was observed by and named after F. Pockels in 1893, but it was until 1991 when Kawasaki et al. applied it to detect two-dimensional (2-D) distribution of surface charge [38]. Charge-coupled devices (CCDs) which came into commercial production in the 1970s [39] contributed significantly to this highly temporal-spatial resolved 2-D measurement because of their unique capability to linearly convert the light intensity of captured images containing charge density distribution to a series of computable matrices.

The key function of these on-line measurement systems depends on Pockels electro-optic crystals, which are used to sense surface charge distribution by converting the charge-induced electric field to the internal optical properties. A linear relationship is established between induced electric field by surface charge and the variation of refractive index of crystals, known as the optical birefringent phenomenon [33]. Meanwhile, electrical properties of Pockels crystals are also significant to the measurement systems. Relative dielectric constant and volume conductivity of the frequently used Pockels crystals (e.g. BSO and BGO) are 40–56 and 10⁻¹² S/m, respectively. The dielectric characteristic and lower conductivity of Pockels crystals give this optical diagnosis a great advantage over those conventional metal-probe-based off-line EP and EFM methods by involving less interference to the original charge-induced electric field. Furthermore, the extremely short response time of index variation to electric field within several sub-nanosecond durations, together with the high-speed photography, endues these 2D surface charge measurement systems with high spatial-temporal resolutions.

Table 1 lists several representative experimental studies that have adopted the Pockels technique for surface charge detection. A series of measurement systems have been technically realized with different temporal resolutions, charge resolutions, valid regions and measurement ranges since the first report in 1991. The tested materials have involved several common polymers like polyimide (PI), polyester (PET), polyethylene (PE), polyvinylidene fluoride (PVDF) and so on. These
measurement results showed that systems using this electro-optic technique can measure surface charge density with range of around $\pm 150 \text{ nC/cm}^2$ and accuracy of $0.5 \text{ nC/cm}^2$ on flat samples with size of less than 40 mm, which is almost the limiting size of the thin and crispy cutting Pockels crystals. It is also worth noting that the time resolution of these optical systems ranges from several nanoseconds to tens of milliseconds, mainly depending on the minimum shutter time of equipped high-speed signal acquisition devices or shortest pulse duration of light sources. The time scale of framing in high-speed photography has undergone through four periods, namely low frequency (LF, $10^{-1}–10^{-2} \text{ s}$), medium frequency (MF, $10^{-2}–10^{-3} \text{ s}$), high frequency (HF, $10^{-4}–10^{-6} \text{ s}$), and the currently developing ultrahigh frequency (UHF, $10^{-6}–10^{-13} \text{ s}$) [51]. It was in the HF period when the fast imaging technology was introduced to transient surface charge detection with relatively lower time resolutions of 1.5–53 ms at the early stages. Fortunately, this parameter has been continuously improved to microsecond and nanosecond scales as the UHF high-speed photography became increasingly more advanced and mature. Meanwhile, the shortest duration of light sources available for high-speed photography has been reduced from $10^{-3}–10^{-6} \text{ s}$ (e.g. flash bulbs, argon bomb, electrical spark) to $10^{-7}–10^{-9} \text{ s}$ (e.g. LED, pulsed laser, X-ray flash) [52]. So far, the reported highest time resolution of surface charge behaviour has been improved to 0.2 ns realized by Kumada et al. with a streak camera and charge-coupled device cameras [41], making it possible to observe the transient potential distribution of a propagating negative surface discharge in atmospheric air.

The current Pockels techniques for surface charge detection can be classified into transmission-type and reflection-type measurement systems based on their specific configurations as shown in Figure 1. Both the two typical systems in Table 1 have undergone great development in the past 3 decades for their own advantages and disadvantages, which will be elaborated and compared in Chapter 3. These electro-optic diagnostic systems with various temporal resolution and charge measurement accuracy were improved for various specific applications, such as detecting transferred charge from gas discharges [27,30,59,60] and measuring surface charge deposited on various solid insulations [55,61].

As the only practical on-line diagnosis to observe surface charge, the Pockels effect method is still under continuous

| Type        | Crystal | Insulation | Time Resolution | Charge Resolution | Area          | Range        | Comments                                                                 | Ref. |
|-------------|---------|------------|----------------|-------------------|---------------|--------------|--------------------------------------------------------------------------|------|
| Transmitting| BSO     |            | 33 ms          | 5 nC/cm²          | 10 mm square   | ±70 nC/cm²   | Surface charge deposited by a needle-plate electrode                       | 1991 [38] |
| Reflecting  | BSO     | 36 μm PET | 1.5 ms         | 1 nC/cm²          | 15 mm square   | ±90 nC/cm²   | Surface charge on dielectric materials excited by 50 Hz AC voltage       | 1994 [40] |
| Reflecting  | BGO     | Dielectric mirror coat | 2.0 ns | 0.17 kV       | 50 mm line     | ±6 kV        | Potential distribution measurement with sub-nanosecond resolution       | 2002 [41] |
| Transmitting| KDP     |            | 10 μs          | 0.1 nC/cm²        | 10 mm square   | ±5 nC/cm²   | Average wall voltage and total charge on dielectrics in Ar barrier discharge | 2003 [42] |
| Reflecting  | BSO     |            | 10 μs          | 0.5 nC/cm²        | Φ 40 mm circular | ±10 nC/cm²  | Spatial charge distribution in dielectric barrier discharge               | 2007 [43] |
| Transmitting| BGO     |            | 0.5 μs         | 0.2 nC/cm²        | 100 x 40 mm²   | ±10 nC/cm²   | Transferred charge in the coplanar dielectric barrier discharge           | 2008 [44] |
| Reflecting  | BGO     | Dielectric mirror coat | 3.2 ns |            | 25.4 mm square | ±70 nC/cm²   | Potential, electric field and charge of transient positive air surface streamer | 2009 [45] |
| Transmitting| BSO     | 7.5 μm PI  | 1 ms           | 1 nC/cm²          | 20 mm square   | ±150 nC/cm²  | Transient surface charge distribution on different polymers               | 2011 [46] |
|             |         | 25 μm FET  |                |                   |               |              |                                                                         |      |
|             |         | 4.5 μm PVDF|                |                   |               |              |                                                                         |      |
| Reflecting  | BSO     |            | 10 μs          | 0.1 nC/cm²        | Φ 15 mm circular | ±10 nC/cm²  | Surface charge deposition of dielectric barrier under two modes           | 2012 [47] |
| Transmitting| BSO     |            | 1 μs           | 0.1 kV            | 4 mm square    | ±5 kV/cm     | Induced electric field by charge transferred from a kHz plasma jet        | 2016 [48] |
| Reflecting  | BSO     | 6 μm PE   | 0.1 ms         | 0.1 nC/cm²        | Φ 10 mm circular | ±30 nC/cm²  | Surface charge distribution influenced by gas flow rate in air and N₂     | 2019 [49] |
| Transmitting| BSO     |            | 25 ns          | 1 nC/cm²          | 4 mm square    | ±50 nC/cm²   | Transient charging of a dielectric surface by a pulsed plasma jet         | 2019 [50] |
development. To obtain better performances as listed in Table 2, including a higher time resolution and charge resolution, larger effective area and range, and lower noise level, several disadvantages and challenges need to be overcome, such as limitation in transparent and thin-film materials due to their inherent optical properties [26], and low signal-to-noise ratio caused by fluttering of laser sources and by inherent noise of CCD cameras [62]. The major influence factors and their corresponding methods have been involved in Table 2. Development of technologies that are related with on-line surface charge density measurement is meaningful for estimating gas–solid interface insulation. Research on the application and improvement of the Pockels technique in charge detection have been undertaken for several years.

3 | TYPICAL POCKELS MEASUREMENT SYSTEMS

The construction of Pockels measurement systems is to realize the conversion from the invisible charge density distribution to light signal intensities that can be quantitatively captured by digital cameras. This chapter will give a brief overview of two typical Pockels measurement systems featured with transmitting and reflecting configurations. The following descriptions are mainly about the process of converting the electric field induced the deposited surface charge to an optical signal, and the methods to optimise for higher accuracy.

3.1 | Transmission-type system

Measurement systems with the optical transmitting configuration are relatively easier to understand and operate. The schematic structure is shown in Figure 1a. A beam of parallel rays emitted from LED lights or expanded He-Ne laser passes through several optical elements, carries information of surface charge and projects it on images capture. Distribution of surface charge density is transformed into measurable intensities of optical signals. Realization of transmission-type measurement systems can be divided into two steps, including detection of deposited charge and transformation to optical signal.

Electro-optic crystals that possess properties of a cubic symmetry and optical activity, including Lithium Niobate (LiNbO₃), Bismuth Germanium Oxide (Bi₁₂Ge₂O₂₀) and Bismuth Silicate (Bi₁₂SiO₂₀), are utilised to detect the deposited surface charge [44]. These crystals which are grown by the Czochralski method are usually fabricated in z-cut slices with two flat surfaces parallel to the two ex-ordinary optical axes. If no electric field is applied, these crystals are uniaxial and free of natural birefringence. Once the electric stress is applied perpendicular to surface, optical birefringence appears with two fast and slow axes in the plane. Fast and slow axes are two important directions in biaxial crystals, whose spatial angle to the polarized light directly determines the accuracy in this system. Fast and slow axes physically refer to two principle directions along which the biaxial crystals are capable of maintaining the state of linear polarization of incident light. The fast axis corresponds to the vibration direction with a lower refractive index n₁, that is inversely proportional to the phase velocity of light. The difference in refractive indexes between two optical axes results in a phase retardation δ for the light beam of a certain wavelength, which can be described by Equation (1) [63].

\[
\delta = \frac{2\pi n_0 n_1}{\lambda} U_z \quad (1)
\]

where λ is the wavelength of light beam, and n₀ is the original refractive index for light travelling through the Pockels crystal along the normal direction, γ₄₁ is the electro-optic coefficient of crystal. Uₓ is the induced potential difference on both sides of the crystal. Once the birefringence in Pockels crystals occurs, relationship between surface charge and optical signal is established that the phase retardation δ is directly proportional to the induced voltage Uₓ.

The constructed light path is meant to transform phase retardation δ to the measurable light intensity. As shown in Figure 1(a), the Pockels cell is placed between a polariser (θ = 0°) and a crossed analyser (θ = 90°). A quarter-wave plate between the polariser and the Pockels cell is used to radiate circular polarized light consisting of two perpendicular electromagnetic wave planes of equal amplitude and 90° difference in phase. The angles between spatial x-axis and the fast axis in both the quarter-wave plate and Pockels crystal are fixed at 45°. Then the light intensity I₀ in captured images can be expressed as Equation (2) [46].

\[
\frac{I_0 - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} = \sin^2 \left( \frac{\delta + \pi/2}{2} \right) \quad (2)
\]

here I₀ and I_{max} and I_{min} are the minimum and maximum values of output light intensity, respectively. The minimum intensity I_{min} needs to be carefully considered and captured in the calculation due to the errors caused by natural retardation of Pockels crystals, the angle aberration in other optical components, background noise in high-speed imaging devices and optical absorption by ambient gas. I_{max} refers to the largest optical intensity projected on image capture and is usually twice as much as that of no-charge deposition. According to Equations (1) and (2), the potential difference induced by surface charge can be detected through light intensity in captured images. It is worth noting that inserting a quarter-wave plate in the light path is critical due to its key role in distinguishing the polarities of surface charge. Without the one-fourth λ plate, both positive and negative charge with the same surface density would correspond to one light intensity value I₀. This situation can be improved by transforming incident linear polarized light into a circularly polarized one as the eventual relative light intensity rises from 0 to one when the negative surface charge flips to positive within half-wave voltage.
Multiple techniques have been adopted to improve the transmitting configuration. For instance, to eliminate the inherent optical noise from light sources and electrical noise caused by image capture devices, technologies of square-pulsed modulation and image lock-in processing were developed by Zhu et al. in process of the two-dimensional measurement and mathematical analysis [64]. The reliability of measurement results was also ensured by an on-line defect diagnosis technique.

Another improvement was made to avoid interference or shade in light path. One disadvantage of the conventional configuration is that enough light transmission has to be ensured and only transparent plate (e.g. ITO coating) or tiny needle electrodes can be utilised [30,44,55]. Recently, an

---

**TABLE 2** Influence factors and improvement methods of main performances in measurement systems on the Pockels technique

| Performances        | Influence Factors                                                   | Methods                                                                 |
|---------------------|---------------------------------------------------------------------|------------------------------------------------------------------------|
| Time resolution     | Minimum shutter duration of cameras                                  | √ Equip ultra-fast imaging technologies [41]                           |
|                     | Narrowest pulse width of light sources                               | √ Adopt ultra-short pulse LED or laser sources [53]                    |
| Charge resolution   | Thickness of tested samples                                         | √ Prepare thinner film or plate samples [54]                           |
|                     | Half-wave voltage of Pockels cells                                   | √ Utilise frequency-domain 2D Fourier transform inversion algorithm [46]|
|                     | Anti-noise surface charge inversion algorithms                       |                                                                        |
| Effective area      | Maximum area of Pockels crystals                                     | √ Replace with needle or transparent electrodes [55]                  |
|                     | Blockage in light path by electrodes                                 | √ Control induced electric field at 45° to light path [50]             |
|                     |                                                                      | √ Operate in reflection-type measurement systems [56]                 |
| Change range        | Wavelength of light sources                                         | √ Use lasers or LED sources with larger wavelengths [27]              |
|                     | Electro-optic coefficient of Pockels crystals                        |                                                                        |
|                     | Thickness of tested samples                                         |                                                                        |
| Signal-to-noise ratio | Fluttering of laser sources                                        | √ Apply image lock-in processing technology [57]                       |
|                     | Background noise of CCD cameras                                     | √ Introduce Wiener filter technique [58]                               |
improved measurement setup was reported by Slikboer et al. that the Pockels cell was examined at an inclined angle of 45°. A plasma jet that acted as an ions source impacted the crystal at normal incidence 10 mm away from BSO surface, as shown in Figure 2a. Therefore, the interference with light path by electrodes can be eliminated. Furthermore, electric field components in three directions $E_x$, $E_y$ and $E_z$ can be isolated as shown in Figure 2b by controlling a Mueller polarimeter and an intensified charge-coupled device (ICCD) simultaneously [50].

It is a great advantage of Pockels crystals over the traditional electrostatic probes on detecting 2D surface charge distribution with higher temporal-spatial resolution and fewer measurement errors. However, these transmission-type measurement systems are still restricted to observe dynamic surface charge distribution on the bared electro-optic crystals or transparent thin films with high luminousness, although much devotion has been made to alleviate influence of electrodes on light path. In other words, it is impossible to apply the transmission-type system to detect most opaque electrical insulating materials, such as polytetrafluoroethylene (PTFE), ceramic and silicon rubber.

### 3.2 | Reflection-type system

In 1994, 3 years after the optical transmitting configuration was covered, a modified surface charge measurement system with optical reflecting configuration was reported by Kawasaki et al. in the same research team [40,65]. Since then, lots of relevant research studies have proved that these improved systems seemed to be a more effective and compatible approach. Figure 1b shows the schematic configuration of the reflection-type system. A polarization beam split (PBS) is utilised to polarize the incident parallel ray and analyse reflected light from the metal or dielectric film. A $1\lambda$ wave plate with fast axis set at an angle of 45° is placed between PBS and the Pockels cell and radiates circularly polarized light. Samples that would absorb or disperse light are placed on the reflective surface, with the indium tin oxide (ITO) transparent coating on the opposite surface. Once the charge is deposited on sample surfaces, the birefringence which is similar to that in transmission-type systems can also be caused by the induced electric field in the Pockels crystal. Since the polarized light is reflected without passing through the samples, the influence of poor transmittance of certain insulating materials on measurement accuracy can be completely eliminated. Therefore, the relationship between the captured light intensity $I_0$ and phase retardation in this system can be described as

$$\frac{I_0 - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} = \sin^2\left(\frac{2\delta + \pi/2}{2}\right)$$

where the phase retardation $\delta$ is doubled because the light passes through the Pockels cell twice.

Temporal resolution is one of the key parameters in this measurement system. Usually, expanding the discharge cycle [55] or sampling in various intervals of multi-period [56] were both adopted to acquire enough resolution. At the very beginning when the highest speed of camera was limited to less than 1000 frames/s, researchers can only study the cases under power frequency or even a lower frequency of 20 Hz [46,65]. Afterward, improvement has been made for higher temporal resolution. Akiko Kumada et al. developed an advanced optical reflecting measurement system with nanosecond time-resolution. As shown in Figure 3, two independent light paths were formed for two lasers with different wavelengths. A streak camera with 2–3 ns time domain and an argon ion laser were used to observe potential distribution on a 50 mm linear path. Simultaneously, another 25 mm square area was measured with a CCD camera and a Nd: YAG laser with 0.2 ns pulse duration [41]. In these cases, the reflecting configurations equipped with multiple high-speed image technologies can achieve high temporal resolution of transient charge behaviour.

Since 2010, the reflection-type system has been used to detect transient surface charge distribution in dielectric barrier discharge (DBD), which can efficiently generate large-area non-thermal plasma at atmospheric pressure for material surface treatment, environmental protection, energy utilization, and
biomedicine [47]. The discharge characteristics are greatly influenced by surface charge deposited on barriers, which, however, was difficult to be accurately detected. The Pockels technique with the optical reflecting configuration offers a practical solution where the electro-optic crystal was employed as a dielectric barrier to hold and sense the charge. The transient charge behaviour in diffuse and filamentary DBDs was explored under different applied voltage, pressure and ambient atmosphere [66, 67], which will be further discussed in Section 5.1. To some extent, these studies also contribute to a better understanding of charge accumulation on insulating materials.

The optical reflecting configuration could also be employed in a surface potential probe as an alternative to electrostatic probes [68]. As shown in Figure 4, the optical probe which was developed by Kumada et al. mainly consisted of a BGO crystal, a polarized beam splitter, a 1/8λ wave plate and a luminescent diode. A metal mirror attached to one end face of BGO was used as a sensing electrode and insulated from the reference electrode which is a transparent conductive ITO layer on the other side. It was estimated that the spatial resolution and measurement sensitivity of this optical probe could reach 2 mm and 10V, respectively. Obviously, this optical probe can be an alternative off-line diagnosis to the EP method. Its advantage lies in the improved measurement accuracy under a close vertical gap of 0.5 mm which benefited from the dielectric property of BGO.

3.3 Discussion on two systems

The transition- and reflection-type surface charge measurement systems are both developed based on the same fundamental technical principle. Pockels crystals are the core component that serves as sensors attached to the bottom of sample to detect electric field induced by surface charge deposition. The optical birefringence phenomenon in electro-optic crystals acts as a bridge between the induced potential difference and measurable light intensities, as described in Equations (1)–(3). Furthermore, the two configurations are both transversely modulated, which means that the light and electric field travel in the same or opposite directions which are perpendicular to the surface defined by fast- and slow-axis. Although the direction of the electric field was intentionally designed to not coincident with the optical path to avoid blocking light [50], these deviations were offset when another induced electric field with the same magnitude but in the opposite direction was additionally considered by precisely depositing charge on the other surface of the crystal.

The two systems were originally intended for dielectric materials with different transmittance. Since all information of surface charge distribution is conveyed by a laser beam or a monochromatic LED light propagating through wave plates, electro-optic crystals and analysers (or PBS crystals), any disturbance or shade by samples in optical path would bring a large error in calculations of potential distribution and charge density. In transmission-type systems, the polarized light should be allowed to evenly penetrate transparent dielectrics, such as mono-crystalline metal or non-metal oxides (Al₂O₃, MgO, SiO₂, etc.), polymer films (PE, PI, PET, etc.), or only bare Pockels crystals. It is equally necessary to eliminate the obstruction by electrodes to light by adopting tiny needles or highly transparent ITO layers. However, it is unnecessary to worry about this issue in reflection-type systems because the light signal is reflected by a dielectric mirror coating without passing through the interior of insulating materials. Most opaque electric insulating materials, including ceramic, silicon rubber, pressboard and their enhanced versions with the nanoscale-doped process or surface modification, can be handled with the reflecting configuration. Therefore, reflection-type systems seem to have a distinct advantage of extensive compatibility over the transmitting structure with both transparent and opaque insulating materials.

The second difference between the two configurations lies in systematic error inherent in their light paths. It is
assumed that the ideal relationships between light intensity $I_0$ and phase retardation $\delta$ neglect the interferences from natural optical rotation or surface reflection of electro-optic crystals to measured optical signals. The optical rotation with 20° per mm which depends on the crystal thickness is actually the main factor affecting the precision of the transmission-type system. To eliminate the influence of optical rotation effect, the thin and brittle Pockels crystals are usually processed with a thickness of less than 0.5 mm, and the analyser is slightly rotated. However, the source of measurement error is not the optical rotation in the reflecting configuration because the angle equals zero when light passes through the crystal twice in opposite directions. Instead, the reflected light that is formed on Pockels crystal when the incident light first enters the crystal requires serious consideration. It is necessary to separate the interfering reflection from the main light path by shaping the crystal into a wedge or subtracting the light intensity with graphics processing afterwards. Therefore, realizing a reflection-type system for precise surface charge measurement is more complicated and challenging in comparison with the transmitting configuration.

4 | SURFACE CHARGE INVERSION ALGORITHMS

Accurate measurement of transient surface charge with the Pockels technique also depends on the inversion algorithms. It is necessary to backstep from the potential difference $U$ across Pockels crystals to the surface charge density $\sigma$ on solid insulations. Usually, the insulation surface is divided into massive meshes or areas corresponding to pixels in the acquired images. This problem eventually transfers to the solution of the complex 2-D matrices of $\sigma$ and $U$ by programing calculation, which greatly relies on efficient and accurate inversion algorithms.

Algorithms with the similar function have already been studied and employed in EP and EFM methods to inverse induced potential on insulation surface to charge density [29]. These algorithms have been reviewed [69] including linear method [70,71], analytical method [72], $\lambda$ function method [73], $\Theta$ function method [74], and improved $\lambda$ function method with reduced noise [75]. However, it is still to develop new algorithms for the Pockels measurement systems mainly due to two reasons. Firstly, the measured induced potential here drops across the crystals, not on or above the insulation as the cases of EP or EFM methods. Properties of insulation materials and distribution of electric field inside need to be considered. Secondly, highly spatial resolution of the electro-optic method (around $10^5$–$10^6$ points, depends on sizes of CCD pixels) would greatly increase the computation complexity. Therefore, calibration and improvement need to be made in algorithms for Pockels effect methods. Until now, two methods including linear inversion algorithm and two-dimensional Fourier transform algorithm have been developed.

4.1 | Linear inversion algorithm (LIA) on uniform-field approximation principle

LIA is a simplified algorithm based on uniform-field approximation principle that a linear relationship is assumed to exist between the deposited charge and induced voltage drop [76]. As shown in Figure 5, an extremely thin sample with a relative permittivity of $\varepsilon_1$ is attached on the Pockels crystal. The electric strength $E_i$ induced by a unit surface charge is assumed to be approximately uniform. In this area, electric flux through the crystal is equal to the total charge deposited on sample. So, the relationship between the charge density $\sigma$ and induced voltage drop $U_i$ can be described in Equation (4)

$$\sigma = \varepsilon_0 \varepsilon r U_i / d_i$$  \hspace{1cm} (4)

here $\varepsilon_0$ is the permittivity of vacuum, $d_i$, and $\varepsilon_r$ are the thickness and relative permittivity of Pockels crystals, respectively. Based on Equation (1), the linear relationship between $\sigma$ and phase retardation $\delta$ is described in Equation (5).

$$\sigma = \frac{\lambda}{2\pi} \frac{\varepsilon_0 \varepsilon_r}{d_i} \frac{m_0^3}{\delta_1}$$  \hspace{1cm} (5)

Accuracy of charge density $\sigma$ calculated by LIA greatly depends on the constant coefficients in Equation (5). However, the electro-optic coefficient could slightly differ from literature value due to uncertainties in crystallization process or temperature shift. Therefore, it is necessary to take a coefficient calibration before surface charge measurement. Stollenwerk calibrated the sensitivity of a BSO crystal in a DBD reactor in advance and introduced a calibration factor throughout the calculation [77]. As shown in Figure 6, the expected and measured sensistivities are compared. The expected proportionality coefficient using material constant from manufacturer was 13.7 pC/V and depicted in dashed line. The measured one, described in a linear-fit straight line of date points, was calculated to be 12.8 pC/V. As a result, the calibration factor of 13.7/12.8 was obtained by this method and introduced in LIA.

Although LIA is a simple and efficient method to calculate charge density, low accuracy is still one disadvantage because the uniform-field approximation principle is not always satisfied. The thickness of tested dielectrics is required to be thin enough, usually, less than 0.5 mm, so that the electric field induced by charge can be shaped uniformly. Otherwise, the inhomogeneity of the electric field and influence of adjacent charge cannot be neglected, which would result in considerable errors in application of LIA for various materials with different thicknesses.

4.2 | Two-dimensional Fourier transform algorithm (2D-FTA) on shift-invariant system

Another fast inversion algorithm, 2D-FTA, has been employed in the Pockels measurement systems to calculate the surface
charge density distribution, especially in a shift-invariant system. Conventionally, the 2-D surface is divided into \( n \) parts, and a \( n \times n \) coefficient matrix \( H \) is defined to represent the relationship between charge density in all parts and their corresponding induced potential. This relationship is depicted in formula (6),

\[
\begin{bmatrix}
    b_{1,1} & b_{1,2} & \cdots & b_{1,n-1} & b_{1,n} \\
    b_{2,1} & b_{2,2} & \cdots & b_{2,n-1} & b_{2,n} \\
    \vdots & \vdots & \ddots & \vdots & \vdots \\
    b_{n-1,1} & b_{n-1,2} & \cdots & b_{n-1,n-1} & b_{n-1,n} \\
    b_{n,1} & b_{n,2} & \cdots & b_{n,n-1} & b_{n,n}
\end{bmatrix}
\begin{bmatrix}
    \sigma_1 \\
    \sigma_2 \\
    \vdots \\
    \sigma_{n-1} \\
    \sigma_n
\end{bmatrix}
= 
\begin{bmatrix}
    u_1 \\
    u_2 \\
    \vdots \\
    u_{n-1} \\
    u_n
\end{bmatrix}
\]

(6)

here, each line of \( H \) contains all contributions to the potential in one part by surface charge density on all parts. It is quite complex and time-consuming to acquire all the contributions in \( H \) because of the \( n^2 \) electric field calculations. Furthermore, higher spatial resolution in this electro-optic measurement makes the situation more tedious. For the purpose of reducing the computational complexity and obtaining precise surface charge distribution, Kumada et al. developed a different algorithm to calculate matrix calculation in spatial frequency domain which combined 2D-FTA and Wiener filter [45,75]. This algorithm can be briefly described as: for an infinite shift-invariant system in frequency domain, the relationship between distributed charge and practical measured surface potential is consistent with the case of an ideal unit charge and its corresponding potential distribution. Usually, an infinite plane plate of constant thickness or an infinite long rod of constant diameter can be regarded as the infinite shift-invariant systems. Furthermore, the digital Wiener filter was introduced to suppress the high-frequency noise in the captured images. For those off-line measurement systems based on Pockels probes or metal probes, the level of noise greatly depends on the gap distance, the outer radius of guard electrode and the positioning error [78]. For this electro-optical system, random noise is mainly determined by fluttering of laser sources and background noise of CCD cameras [58]. In this way, the complex convolution operation in the time-domain is converted to a simpler multiply in the frequency-domain. The highest spatial resolution of visualised charge distribution can reach 25–40 \( \mu \)m, depending on effective area of Pockels crystals allowing light penetration and pixels of CCD cameras [45,46].

Figure 7 illustrates the schematic of a plate plane as a typical example of the shift-invariant system for 2D-FTA. After charge is accumulated on samples, the voltage across a crystal at position \((x, y)\), \(u(x, y)\), can be calculated according to formula (7):

\[
u(x,y) = b(x,y) * \sigma(x,y) \\
= \iint b(x-x',y-y') \cdot \sigma(x',y') dxdy
\]

(7)

where \( \sigma(x, y) \) describes the distribution of surface charge on samples at \((x, y)\), and \( b(x,y) \) represents the induced voltage \( u_{\text{BISO}} \) across crystal induced by the unit charge.

The 2-D Fourier transformation can converse the convolution in formula (7) to multiply in formula (8):

\[
U(\mu, \nu) = H(\mu, \nu) \times \sigma(\mu, \nu)
\]

(8)

where \( U(\mu, \nu) \), \( H(\mu, \nu) \) and \( \sigma(\mu, \nu) \) are the Fourier transformations of \( u(x, y) \), \( b(x, y) \) and \( \sigma(x, y) \), respectively. Two parameters \( \mu \) and \( \nu \) represent coordinates in the frequency domain, corresponding to the frequencies of Fourier expansion in the time domain. Because of the discretely sampled data, 2-D discrete Fourier transform is utilised here. Taking \( U(\mu, \nu) \) for example, if the captured images have \( M \times N \) pixels, then it can be obtained using Equation (9):

\[
U(\mu, \nu) = \sum_{x=0}^{M} \sum_{y=0}^{N} u(x,y) \exp \left\{ -j2\pi \left( \frac{\mu x}{M} + \frac{\nu y}{N} \right) \right\}
\]

(9)

Actually, \( U(\mu, \nu) \) is the measurement result obtained by Pockels measurement systems discussed in Chapter 2, and \( H(\mu, \nu) \) is transformed from the simulated result of a pre-set unit charge. Therefore, the charge density in the frequency domain and the time domain can be depicted in Equation (10) and (11).

\[
\sigma(\mu, \nu) = U(\mu, \nu)/H(\mu, \nu)
\]

(10)
\[ \sigma(x, y) = \frac{1}{MN} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} \sigma(\mu, \nu) \exp \left\{ j2\pi \left( \frac{\mu x}{M} + \frac{\nu y}{N} \right) \right\} \] (11)

It is significant to improve signal-to-noise ratio for obtaining the precise surface charge density calculation by 2D-FTA. One disadvantage of 2D-FTA that high-frequency noise is inevitably amplified and covers low-frequency signals, as shown in Figure 8(a). The digital Wiener filter that was used to increase signal-to-noise ratio by suppressing noise and ensuring stable calculation can be depicted as follows [58].

\[ W(\mu, \nu) = \frac{H^*(\mu, \nu)}{|H(\mu, \nu)|^2 + C} \] (12)

where \( H^*(\mu, \nu) \) is the conjugate matrix of \( H(\mu, \nu) \), \( C \) is the power ratio of noise-to-signal. As shown in Figure 8(b), adding a Wiener filter contributes to the suppression of high-frequency noise and the accurate calculation of the surface charge distribution.

### 4.3 Discussion on two inversion algorithms

The LIA and 2D-FTA in this chapter are two main inversion algorithms for fast charge density calculation in the Pockels technique. They are both based on the same Gauss theorem of the electrostatic field which describes the proportional relationship between the total normal electric displacement flux over a closed surface and the total charge enclosed by that surface. The critical function of these two algorithms is to establish a transformation between surface charge density on dielectrics and induced electric field in Pockels crystals. It should be noted that the directly calculated surface charge density is not equal to the actual one in most cases unless the phase retardation induced by the applied voltage between two electrodes is subtracted [45,54]. A common practice is to deduct a virtual surface charge distribution numerically calculated by surface electric field distribution under the boundary condition of measured applied voltage on electrodes. So far, almost all studies on the electro-optic surface charge measurement have been employing these two algorithms due to their unique advantages in reducing the computational cost when solving the large matrices from highly spatial-resolved optical images.

The most prominent difference of LIA and 2D-FTA to invert for surface charge density relates to how to consider the influence on the electric field by an adjacent point charge. In LIA, it is assumed that the uniformly distributed electric field induced by a unit charge is independent of the neighbouring surface charge. Although a linear relationship between the voltage drop and surface charge is formed on this assumption, such simplification usually leads to a smaller charge density calculation. The error would become larger with the increase of dielectric thickness or decrease of permittivity. However, when it comes to 2D-FTA, the theoretical electric field has a coincidence with the physical distribution by taking the effect of
unit charge on the electric field nearby into consideration. Furthermore, transformation into frequency-domain greatly reduces the original computational complexity in time-domain caused by the coupling of adjacent points. Therefore, it is indicated that the 2D-FTA has nearly the same operation speed but a higher calculation accuracy of surface charge density and distribution in comparison with LIA.

5 | TRANSIENT BEHAVIOR OF SURFACE CHARGE ON SOLID INSULATION

The Pockels effect method offers a non-invasive and fast diagnosis for observing transient behaviour of surface charge. During the past 2 decades, this continuously developing electro-optic technique has always been a quantification method for observing the charge deposition phenomenon, bringing new insights into the fast process of interaction with dielectric materials by different types of gas discharge. Limited by the weak high-temperature resistance of Pockels crystals, researchers are looking beyond the measurement system itself and partly turning to the combination with low-temperature discharge and non-thermal plasma process, including plasma jet (mentioned in Figure 2) [48], DBD [56], surface streamer [55], cavity partial discharge [66], and others. It is found that Pockels cells in most studies on surface streamer have the same electrode configuration as that in needle-to-dielectric discharges with several millimetres gap. Also, the configuration of Pockels cells and surface charge distribution characteristic in partial discharge (PD) are similar to those in DBD under the filamentary mode [66]. Therefore, this chapter mainly focuses on two fields including the mode transition of DBD and dynamic charge under surface streamer.

5.1 | Charge deposition in DBD under different modes

It is known that two discharge modes occur in DBD, namely the filamentary and diffuse mode, which theoretically rely on the ratio of secondary γ coefficients at electrodes to the ionization in the discharge volume [79,80]. Meanwhile, the surface charges deposited on dielectric barrier play an important role in releasing electrons from surface and development of next discharge streamers. But it was challenging to diagnose surface charge distribution on dielectrics in DBD due to its high spatial-temporal resolution and sensitivity to environment parameters [60]. Recently, this problem is solved by the Pockels technique combined with high-speed photography.

Pockels crystals, acting as the dielectric barriers, were inserted into DBD reactors to hold and detect the transferred charge. Usually, the optical reflecting measurement system is constructed as shown in Figure 9, with a metal mirror as the ground electrode and a transparent ITO layer as the high-voltage electrode [54,56,60,61,67,81]. Various dielectrics, such as borosilicate glass, mono-crystalline alumina, magnesia and PE film were attached on Pockels crystals to investigate influence of material properties on transient behaviour of surface charge in different modes [27,59]. The dielectrics used here should be transparent and thin as much as possible.

Meaningful experimental results have been achieved about transient behaviour of surface charge in two filamentary and diffuse mode of DBD. Gas composition was adjusted to control modes, ranging from pure He or N₂ for diffuse mode to their mixtures or air for filamentary mode. This transition can also be realized by changing voltage amplitude in He with N₂ admixture of percent. It was found that the pattern of surface charge distribution qualitatively agrees with the patterns of luminescent images [43]. The total deposited charge accumulated by surface charge was approximately equal to the integration of discharge current [47,49,66]. The profiles of the Gaussian-distributed charge spots in the filamentary DBD remained constant after the accumulation process, indicating that the charge is trapped in deep levels [56]. The distinctive charge distribution in two modes was responsible for providing experimental evidence for the explanation of discharge modes.

Surface charge memory effect plays an important role in the stabilisation of filamentary discharge [81]. It was observed by Wild et al. that the charge reversal starts in the centre of a residual charge spot where the electric field is highest, and extends outwards gradually [63], as shown in Figure 10. This effect could be suppressed under smaller admixture impurities, leading to the transformation to a homogenous pattern [49]. In the diffuse mode, all the deposited charge reverses simultaneously, contributing to an approximately constant electric field during the whole breakdown process. Similar results were reported by Kai Wu et al. that the surface charge distribution of PD in the void larger than 0.1 mm under 50 Hz AC excitation appeared as multiple charge spots instead of uniform pattern. Discharges tended to re-ignite at the sites covered with opposite charges, proving the dominating role of memory effect in discharge patterns [66]. Furthermore, these multiple streamers could turn into the homogeneous discharge at a higher airflow velocity, because the memory effect was weakened as the residual charges and metastable particles were blown away, and as the electrons in shallow traps on dielectrics were desorbed into the gas phase [49].

5.2 | Transient charge distribution by surface streamer

Different surface discharge patterns were observed by the Pockels electro-optic effect of surface streamers in the needle-
plate electrode configuration. Researchers have found that the electrode gap spacing, polymeric insulating materials and gas pressure could greatly influence the surface charge patterns. It was reported by Zhu et al. that, as the electrode gap spacing increases from 0 to 3 mm, the pattern could be transitioned from a spoke-like, filamentary pattern to a pattern consisting of spark and corona discharges [65].

Mu et al. in our research group investigated the process of discharge streamers interacting with different insulating samples. An interesting phenomenon was reported that the positive charge densities on PET and PI are lower than those on PVDF. The material properties including the permittivity and thickness may influence the electric field strength, causing the difference in discharge intensity and charge density. What is more, it was observed that the transient charge distribution behave distinctively on these materials as special interesting patterns, ranging from a snake-like pattern on PI and PET to a spoke-like pattern on PVDF [46], as shown in Figure 11. It seems that the distinct patterns are closely related to the energy band gaps. Meanwhile, gas pressure is another factor influencing the patterns. Figure 12 gives surface discharge patterns under various gas pressure. It is found that as gas pressure decreases from 101 to 21 kPa, the width and number of branches rise, but charge density drops [55]. Therefore, both characteristics of gas discharge and properties of material surface determine the dynamic accumulation of surface charge.

Polarity effect is another interesting phenomenon in the accumulation and decay of surface charge. During the accumulation process, negative charge tends to distribute uniformly or diffusely, while the positive charge distribution usually appears in a uniform core region and then develops into a stream pattern [46]. It is also reported that the positive surface charge decays much faster than the negative one because of difference in the charge neutralisation [59]. To some extent, the monopolar voltage would be more popular in surface charge measurement due to the avoidance of the polarity effect.

6 | DISCUSSION AND OUTLOOK

Surface charge measurement systems with the Pockels electro-optic technique and corresponding inversion algorithms are powerful tools for non-invasive detection of spatial-temporal resolved distribution of transient surface charge and theoretical analysis of flashover across insulation surface. In terms of technical principle, these systems exhibit independence from gas pressure, theoretically ranging from the vacuum ($10^{-9}$ – $10^{-6}$ MPa) to relatively high pressure (0.1–0.5 MPa). This is mainly because the electro-optic crystals attached closed to tested samples could avoid contacting with the gas environment and interrupting surface discharge and charge transferring. Another reason is that only a transparent observation window is required on the sealed high-pressure chamber to allow the light signal to pass through, having an advantage over the cable connections to Kelvin vibrating probes and displacement platforms in EP method. Although the reported gas pressure only ranges from 0.02 to 0.1 MPa [55,61], it is still implementable to realize this system under high pressure environment, which shall be a good supplement to the current research studies.

Accuracy and range of the complicated and sensitive measurement systems greatly depend on the cooperation of multiple advanced and frontier technologies, including stable control of laser sources, manufacture of oriented electro-optic crystals, operation of high-speed photography with sub-nanosecond resolution, and fast image processing algorithms for surface charge inversion with high spatial resolution. Therefore, every bit of progress is time-consuming and precious.
In our opinion, there is still a long distance to polish up this Pockels electro-optic method before it can solve the long-standing problem existing in on-site electrical apparatus in real-time detection of surface charge on insulating components. One fundamental reason is that it is hard for these flat manufactured crystals and their optical axes to adapt to complex insulation design. However, there is enormous application prospect in laboratory-scale testing to estimate insulation performance, explore the mechanism of charge transfer, support material design, even provide calibration for potential online methods. It should be emphasised that transient charge plays a fundamental role in explaining the basic phenomena of volume or surface discharge. For instance, the spatially fixed re-ignition during consecutive discharge breakdowns is called ‘memory effect’, as discussed in Chapter 5, which is currently considered as a result of long-lifetime metastable species (bulk effect) and deposited surface charge (surface effect) [81]. Another case when the first stochastic discharge develops into a stable and repeatable mode after hundreds of continuous pulses is called ‘accumulation effect’, which is affected by the concentration of specific long-living species [82]. The Pockels measurement of surface charge distribution is vital to understand these phenomena by offering a quantitative detection of transient charge and the direct evidence to mechanisms. Therefore, several deficiencies of the electro-optic surface charge measurement system shall be revealed and demonstrate the directions for future development, so that breakthroughs and further progress can be reached in these fields. In the following part of this chapter, we discuss several shortcomings of the current research studies, as well as their corresponding outlooks.

6.1 Ultrafast photography for higher temporal resolution

One basic cognition of the transient surface charge measurement in recent research is that behaviour of accumulation, expansion and dissipation on dielectrics usually occur at a fast rate within several nanoseconds. To observe this process in a clear time sequence, there is a high demand for supporting high-speed imaging technology, especially ultrafast photography. Those imaging approaches at an ultra-high frequency can usually be classified into stroboscopic and single-shot categories. In the current stage, almost all of the 2D surface
charge distribution with nanosecond resolution are captured with the former approach. The stroboscopic way is applicable for transient cases that are highly repeatable in each cycle under periodic excitations, such as the propagation of guided ionization wave [83] and atmospheric pressure glow discharge [84]. Images extracted from multiple cycles after various delay time are accumulated and connected to approximately exhibit the evolution in one cycle. However, this method cannot deal with the other unstable and unpredictable circumstances that can only be detected by the single-shot method. Most cases of charge distribution on dielectrics are usually unrepeatable in different cycles with spoke-like branches.

To obtain a higher time resolution, several advanced single-shot ultrafast imaging techniques can be introduced to this electro-optic measurement system. One is the direct imaging method which totally relies on the multiple light paths and CCD components together with data acquisition speed, such as ultrafast framing/sampling cameras [85]. The other technique is to reconstruct images that are taken in one image by compressed sensing-based photography and streak camera techniques, and then extracted with specific computational algorithms, such as compressed ultrafast photography (CUP) [86]. It is reported that the time resolution of CUP can reach 10 trillion frames per second, further increasing the framing rate of CCD or CMOS cameras.

6.2 Precise measurement for thicker insulation

One disadvantage of current Pockels surface charge diagnosis lies in the small thickness of measured samples. The Pockels crystal is attached to the sample back to detect electric field induced by charge on the front side. Therefore, samples are shaped as thin as possible to ensure enough voltage drop across Pockels crystal with high relative permittivity of 40–60. As listed in Table 1, the thickness of measured films or glass is usually less than 0.1 mm. However, the small thickness makes it difficult to distinguish the charge dissipating on the surface or flowing into insulation bulk. Also, charges deposited on conventional electrical insulating materials with relatively larger thickness could not be precisely diagnosed.

The application of Pockels effect in surface charge measurement on thicker insulating materials has been attempted by Kumada et al. via a reflection-type Pockels probe as mentioned in Figure 4 and Section 3.2 [68]. The thickness of tested polymethyl methacrylate (PMMA) sample could reach 2 mm mainly because the probe was hanged above instead of beneath attachment. So, this technology is essentially not an on-line detector, but provides a better alternative to the conventional EP method because voltage had to be withdrawn in measurement.

For the purpose of improving the capability of measuring transient surface charge on thicker materials, two methods are worth trying. On one hand, the properties of material thickness and crystal sensitivity should be balanced by optimising the electric field in Pockels cells. On the other hand, accuracy and stabilisation of charge density inversion algorithms need to be continuously polished up.

6.3 Transient surface charge under weaker vertical component of electric stress

Traditionally, a strong vertical electric field caused by the deposited charge is perpendicular to the surface of crystal and leads to the linear birefringence. Nevertheless, the relatively weaker vertical electric field is usually stressed on the solid insulations, on which surface flashover and discharge characteristics along the gas/solid interfaces are not the same as the strong vertical cases. The transient surface charge under the weaker vertical electric field is fundamental to a better understanding of flashover in real high-voltage devices, and the instructive estimation of new materials and technologies with higher insulation performance. However, few studies have been reported, mainly because it is difficult to deal with the parallel electric field component. Under a weaker vertical field, the linear relationship between the phase retardation and potential difference described in Equation (1) cannot be well established for the existence of parallel field component.

One compromise method can be utilised that one side of the Pockels crystal is attached to the back of sample, and the other side is deposited with the ground ITO layer. The originally parallel electric field line is turned to the vertical direction, and eventually causes birefringence in crystal. Dynamic distribution observed with this method can be used to understand that in flashover discharge, but they are not completely equivalent.

More inversion algorithms are also required for more accurate charge calculation during surface flashover under the relatively weaker vertical component of electric stress. Different from the former reported cases, the electric field discussed here is neither uniform nor shift-variant, indicating that the calculation accuracy will seriously decrease if the LIA or 2D-FTA is adopted. The balance between accuracy and calculation complexity also requires careful consideration because of the high spatial-temporal resolution.

6.4 Dynamic distribution in coupling multi-physics

The coupling effect of multi-physics is responsible for the complex transient behaviour of surface charge. It is well known that the properties of insulating materials and characteristics of gas discharge are dominated by electric, magnetic, thermal, flow and radiation fields. Impurity on the insulating surfaces, like dust, moisture and metal particle, can also influence charge distribution. However, current studies on electro-optic charge diagnosis almost focus on the electric field. So far, the influence of coupling multi-physics on transient behaviour has not been discussed.

The weak mechanical and dielectric strength of Pockels crystal and the poor heat stability limit the detection under extreme environments and coupling multi-physics. The crystal
should be carefully protected under relatively temperate circumstances for accurate measurement. Besides, the cooperation with the electrostatic probe method also deserves consideration when the sample is slowly charged by non-electrical sources.

7 | SUMMARY

Charges that continuously accumulate, transfer and decay on solid insulating materials are the main factor directly damaging surface insulation performance. Measurement of the Pockels electro-optic effect, acting as a supplement to the conventional EP method, provides a non-invasive and quantitative tool for detecting the transient surface charge online, estimating the insulation design, and understanding mechanisms of transient charge behaviour and resultant flashover.

The recent progress of applying the Pockels technique to surface charge detection is reviewed, including two typical transmission-type and reflection-type measurement systems, the fast inversion algorithms and the latest reported results of transient surface charge on dielectrics in DBD and surface streamer. It is concluded that systems with reflecting configuration have greater advantages in charge detection due to their compatibility with both transparent and opaque electrical materials. Although the two algorithms both perform well in saving computational cost, the accuracy of 2D-FTA is better than that of LIA because the former takes the induced electric field of adjacent point charge into consideration.

Progress of dynamic measurement on the Pockels effect greatly depends on multiple technological breakthroughs, including the robust electro-optic crystals resistant to discharge impact, advanced high-speed photography for rapid development of nanosecond discharge process, high-performance inversion algorithms, etc. In addition, it is meaningful to expand applications of these systems to more aspects, such as dynamic distribution on thicker insulation, or during surface flashover, or under coupling multi-physics. Overall, this review provides a thorough understanding of transient surface charge measurement via the Pockels technique. In consideration of the fundamental roles of charge dynamic characteristic in mechanisms of surface discharge at gas/vacuum–solid interface, it is necessary to undertake further studies to develop this technique.

ACKNOWLEDGEMENT

This work was supported in part by National Natural Science Foundation of China (11775175 and U1766218).

ORCID

Bo Zhang https://orcid.org/0000-0001-8994-3002

REFERENCES

1. Li, C., et al.: Understanding surface charge accumulation and surface flashover on spacers in compressed gas insulation. IEEE Trans. Dielectr. Electr. Insul. 25(4), 1152–1166 (2018)
2. Takabayashi, K., et al.: High voltage DC partial discharge and flashover characteristics with surface charging on solid insulators in air. IEEE Electr. Insul. Mag. 34(5), 18–26 (2018)
3. Qi, B., et al.: Influence of moisture on the interface charge of oil-pressboard composite insulation under DC voltage. High Volt. 3(1), 73–77 (2018)
4. Tanaka, H., et al.: Finite-difference time-domain simulation of partial discharges in a gas insulated switchgear. High Volt. 1(1), 52–56 (2016)
5. Hogue, M.D., et al.: Dynamic gas flow effects on the ESD of aerospace vehicle surfaces. J. Electrostat. 91, 21–27 (2018)
6. Kim, E.-Y., Kim, S.-C.: Electrostatic interaction of charged surfaces with semipermeable membranes. J. Korean Phys. Soc. 68(5), 658–667 (2016)
7. Cheng, H., et al.: Numerical study on propagation mechanism and biomedicine applications of plasma jet. High Volt. 1(2), 62–73 (2016)
8. Shao, T., et al.: Atmospheric - pressure pulsed discharges and plasmas: mechanism, characteristics and applications. High Volt. 3(1), 14–20 (2018)
9. Li, C., Hu, J., Lin, C., et al.: The potentially neglected culprit of DC surface flashover: electron migration under temperature gradients. Sci. Rep. 7(1) (2017)
10. Xie, Q., et al.: Distribution of polymer surface charge under DC voltage and its influence on surface flashover characteristics. IEEE Trans. Dielectr. Electr. Insul. 25(6), 2157–2168 (2018)
11. Li, D., et al.: Charge accumulation characteristic on polymer insulator surface under AC voltage in air and C4FN/CO2 mixtures. High Volt. 5(2), 160–165 (2020)
12. Zhang, G.-J., et al.: Pulsed flashover across a solid dielectric in vacuum. IEEE Trans. Dielectr. Electr. Insul. 25(6), 2321–2339 (2018)
13. Liu, Y., et al.: Surface charge accumulation behaviour and its influence on surface flashover performance of Al2O3-filled epoxy resin insulators under DC voltages. Plasma Sci. Technol. 21(5), 055501 (2019)
14. Gao, C., et al.: The surface charge of Al2O3 ceramic insulator under nanosecond pulse voltage in high vacuum: characteristics and its impact on surface electric field. J. Phys. D Appl. Phys. 53(5), 055501 (2020)
15. Amer, M., et al.: New experimental study on the DC flashover voltage of polymer insulators: combined effect of surface charges and air humidity. High Volt. 4(4), 316–323 (2019)
16. Li, X.-R., et al.: 3D printing fabrication of conductivity non-uniform insulator for surface flashover mitigation. IEEE Trans. Dielectr. Electr. Insul. 26(4), 1172–1180 (2019)
17. Shao, T., et al.: Correlation between surface charge and DC surface flashover of plasma treated epoxy resin. IEEE Trans. Dielectr. Electr. Insul. 25(4), 1267–1274 (2018)
18. Wang, C., et al.: Enhancing electrical strength of acrylic polymer by using fluorinated monomer as surface modifier. Mater. Lett. 249, 17–20 (2019)
19. Xue, J., et al.: Effects of surface roughness on surface charge accumulation characteristics and surface flashover performance of alumina-filled epoxy resin spacers. J. Appl. Phys. 124(8), 083502 (2018)
20. Meyer, H.K., et al.: Streamer and surface charge dynamics in non-uniform air gaps with a dielectric barrier. IEEE Trans.Dielectr. Electr. Insul. 26(4), 1163–1171 (2019)
21. Du, B.X., Li, J.: Surface charge coupling behaviour of fluorinated polyimide film under DC and pulse voltage. IEEE Trans. Dielectr. Electr. Insul. 24(1), 567–573 (2017)
22. Li, G., et al.: Dynamic charge transport characteristics in polyimide surface and surface layer under low-energy electron radiation. IEEE Trans. Dielectr. Electr. Insul. 23(4), 2393–2403 (2016)
23. Xing, Y., et al.: Effects of electron beam irradiation on insulation characteristics of epoxy/AIN nanocomposites. IEEE Trans. Appl. Supercond. 29(2), 7700804 (2019)
24. Pan, C., et al.: Decay characters of charges on an insulator surface after different types of discharge. Plasma Sci. Technol. 19(7), 075503 (2017)
25. Zhang, L., et al.: Gas–solid interface charge characterisation techniques for HVDC GIS/GIL insulators. High Volt. 5(2), 95–109 (2020)
26. Othman, N.A., Piah, M.A.M., Adzis, Z.: Charge distribution measurement of solid insulator materials: a review and new approach. Renew. Sust. Energ. Rev. 70, 413–426 (2017)
27. Tschiersch, R., et al.: Surface charge measurements on different dielectrics in diffuse and filamentary barrier discharges. J. Phys. D Appl. Phys. 50(10), 105207 (2017)
28. Deschler, J., Seller, J., Kindersberger, J.: Detection of charges at the interphase of polymeric nanocomposites. IEEE Trans. Dielectr. Electr. Insul. 24(2), 1027–1037 (2017)
29. Kong, F., et al.: Effects of nanosecond pulse voltage parameters on characteristics of surface charge for epoxy resin. IEEE Trans. Dielectr. Electr. Insul. 25(6), 2058–2066 (2018)
30. Skikboeß, E., et al.: Charge transfer to a dielectric target by guided ionization waves using electric field measurements. Plasma Sources Sci. Technol. 26(3), 035002 (2017)
31. Murooka, Y., Koyama, S.: Nanosecond surface discharge study by using Dust figure techniques. J. Appl. Phys. 44(4), 1576–1580 (1973)
32. Kawahata, H., Yamaguchi, T., Yamaguchi, T.: Visualization of residual charges by atmospheric pressure plasma jet irradiation using dust figures. EURASIP J. Surf. Sci. Nanotechnol. 15(0), 55–64 (2017)
33. Murooka, Y., Takada, T., Hidaka, K.: Nanosecond surface discharge and charge density evaluation part I: review and experiments. IEEE Electr. Insul. Mag. 17(2), 6–16 (2001)
34. Liu, X., Kitamura, K., Terabe, K.: Surface potential imaging of nanoscale LiNbO₃ domains investigated by electrostatic force microscopy. Appl. Phys. Lett. 89(3), 132905 (2006)
35. Du, B., et al.: Temperature-dependent surface charge and discharge behaviour of converter transformer oil-paper insulation under DC voltage. IET Sci. Meas. Technol. 13(1), 29–34 (2019)
36. Bondarenko, P., Belko, V., Emelyanov, O., Shemet, M.: Matrix method of surface charge distribution measurement for PD series prediction and recognition. In 2016 IEEE International Conference on Dielectrics (ICD). 468–471. IEEE, (2016). https://doi.org/10.1109/ICD.2016.7547644
37. Han, B., et al.: Study on micro interfacial charge motion of polyethylene nanocomposite based on electrostatic force microscopy. Polymers. 11(12), 2035 (2019)
38. Kawasaki, T., Arai, Y., Takada, T.: Two-dimensional measurement of electrical surface charge distribution on insulating material by electro-optic Pockels effect. Jpn. J. Appl. Phys. 30(6), 1262–1265 (1991)
39. Hatate, Y., Ohta, H.: Recent trends of contact type linear image sensor. J. Inst. Telev. Eng. Jpn. 38(6), 512–519 (1984)
40. Kawasaki, T., et al.: AC surface discharge on dielectric materials observed by advanced Pockels effect technique. J. Appl. Phys. 76(6), 3724–3729 (1994)
41. Kumada, A., et al.: Two-dimensional potential distribution measurement of surface discharge with subnanosecond resolution. Rev. Sci. Instrum. 73(4), 1939–1944 (2002)
42. Sugimoto, K., et al.: Measurement of wall voltage in barrier discharges using an electro-optic nonlinear crystal. J. Phys. D Appl. Phys. 36(23), 2887–2890 (2003)
43. Stollenwerk, L., Laven, J.G., Purwins, H.G.: Spatially resolved surface-charge measurement in a planar dielectric-barrier discharge system. Phys. Rev. Lett. 98(25), 255001 (2007)
44. Gégot, F., et al.: Experimental protocol and critical assessment of the Pockels method for the measurement of surface charging in a dielectric barrier discharge. J. Phys. D Appl. Phys. 41(13), 135204 (2008)
45. Tanaka, D., et al.: Two-dimensional potential and charge distributions of positive surface streamer. J. Phys. D Appl. Phys. 42(7), 075204 (2009)
46. Mu, H.-B., et al.: Investigation of surface discharges on different polymeric materials under HVAC in atmospheric air. IEEE Trans. Dielectr. Electr. Insul. 18(2), 485–494 (2011)
47. Bogaczcyk, M., et al.: Surface charge accumulation and discharge development in diffuse and filamentary barrier discharges operating in He, N₂ and mixtures. J. Phys. D Appl. Phys. 45(46), 465202 (2012)
48. Skikboeß, E., Guaitella, O., Sobota, A.: Time-resolved electric field measurements during and after the initialisation of a kHz plasma jet—from streamers to guided streamers. Plasma Sources Sci. Technol. 25(3), 03LT04 (2016)
49. Du, Y., et al.: Influence of gas flow on partial discharge behaviours in air and nitrogen. IEEE Trans. Plasma Sci. 47(1), 136–144 (2019)
50. Skikboeß, E., et al.: Experimental and numerical investigation of the transient charging of a dielectric surface exposed to a plasma jet. Plasma Sources Sci. Technol. 28(9), 095016 (2019)
51. Liang, J., Wang, L.V.: Single-shot ultrafast optical imaging. Optica. 5(9), 1113–1127 (2018)
52. Xing, H. Z., et al.: High-speed photography and digital optical measurement techniques for geometrodynamics: fundamentals and applications. Rock Mech. Rock Eng. 50(6), 1611–1659 (2017)
53. Wild, R., et al.: Phase-resolved measurement of electric charge deposited by an atmospheric pressure plasma jet on a dielectric surface. J. Phys. D Appl. Phys. 47(4), 042001 (2014)
54. Bogaczcyk, M., et al.: Spatial-temporal characterisation of the multiple current pulse regime of diffuse barrier discharges in helium with nitrogen admixtures. J. Phys. D Appl. Phys. 50(41), 415202 (2017)
55. Mu, H.-B., et al.: Observation of surface discharge in nitrogen based on Pockels effect. IEEE Trans. Plasma Sci. 39(11), 2150–2151 (2011)
56. Tschiersch, M., Bogaczcyk, M., Wagner, H.E.: Systematic investigation of the barrier discharge operation in helium, nitrogen, and mixtures: discharge development, formation and decay of surface charges. J. Phys. D Appl. Phys. 47(36), 365204 (2014)
57. Kawasaki, T., et al.: Highly sensitive measurement of surface charge distribution using the Pockels effect and an image lock-in amplifier. J. Phys. D Appl. Phys. 27(8), 1646–1652 (1994)
58. Mu, H., Zhang, G.: Calibration algorithm of surface charge density on insulating materials measured by Pockels technique. Plasma Sci. Technol. 13(6), 645–650 (2011)
59. Pan, C., et al.: The effect of surface charge decay on the variation of partial discharge location. IEEE Trans. Dielectr. Electr. Insul. 23(4), 2241–2249 (2016)
60. Bogaczcyk, M., et al.: Development of barrier discharges: operation modes and structure formation. Contrib. Plasma Phys. 52(10), 847–855 (2012)
61. Wild, R., Benduhn, J., Stollenwerk, L.: Surface charge transport and decay in dielectric barrier discharges. J. Phys. D Appl. Phys. 47(43), 435204 (2014)
62. Zhu, Y., Takada, T., Tsutsumi, M., et al.: Optical measurement technique for studying residual surface charge distribution. J. Phys. D Appl. Phys. 28(1), 1468–1477 (1995)
63. Wild, R., Stollenwerk, L.: Phase-resolved measurement of the spatial surface charge distribution in a laterally patterned barrier discharge. New J. Phys. 16(11), 113040 (2014)
64. Zhu, Y., Takada, T., Murooka, Y.: Two-dimensional optical measurement techniques based on optical birefringence effects. Opt. Eng. 41(12), 3183–3192 (2002)
65. Zhu, Y., et al.: The dynamic measurement of surface charge distribution deposited from partial discharge in air by Pockels effect technique. J. Phys. D Appl. Phys. 29(1), 2892–2900 (1996)
66. Wu, K., et al.: Dynamic behaviour of surface charge distribution during partial discharge sequences. IEEE Trans. Dielectr. Electr. Insul. 20(2), 612–619 (2013)
67. Dosoudilová, L., et al.: Investigation of helium barrier discharges with small admixtures of oxygen. J. Phys. D Appl. Phys. 48(35), 355204 (2015)
68. Kumada, A., et al.: Pockels surface potential probe and surface charge density measurement. J. Electrost. 58(1), 45–58 (2003)
69. Lin, C., et al.: Surface charge inversion algorithm based on bilateral surface potential measurements of cone-type spacer. IEEE Trans. Dielectr. Electr. Insul. 24(3), 1905–1912 (2017)
70. Tatsumatsu, A., Hamada, S., Takuma, T.: A study on the accuracy of surface charge measurement. IEEE Trans. Dielectr. Electr. Insul. 9(3), 406–415 (2002)
71. Qi, B., et al.: Surface charge accumulation of solid insulator under nanosecond pulse in vacuum: 3D distribution features and mechanism. J. Phys. D Appl. Phys. 50(46), 465603 (2017)
72. Takuma, T., Yoshiha, M., Kawamoto, T.: Principle of surface charge measurement for thick insulating specimens. IEEE Trans. Dielectr. Electr. Insul. 5(4), 497–504 (1998)
73. Rupel, T.O., Crichton, G.C., Mcallister, I.W.: Using the λ function to evaluate probe measurements of charged dielectric surfaces. IEEE Trans. Dielectr. Electr. Insul. 3(6), 770–777 (1996)
74. Fairelo, D.C., Allen, N.L.: High resolution measurements of surface charge densities on insulator surfaces. IEEE Trans. Dielectr. Electr. Insul. 10(2), 285–290 (2003)
75. Kumada, A., Okabe, S., Hidaka, K.: Resolution and signal processing technique of surface charge density measurement with electrostatic probe. IEEE Trans. Dielectr. Electr. Insul. 11(1), 122–129 (2004)
76. Tran, T.N., et al.: Dynamic measurement of surface discharge under different gaseous environments and pressures. In: Conference Record of the IEEE International Symposium on Electrical Insulation, pp. 424–427 (2008)
77. Stollenwerk, L.: Interaction of current filaments in dielectric barrier discharges with relation to surface charge distributions. New J. Phys. 11(10), 103034 (2009)
78. Kumada, A., Okabe, S., Hidaka, K.: Influences of probe geometry and experimental errors on spatial resolution of surface charge measurement with electrostatic probe. IEEE Trans. Dielectr. Electr. Insul. 12(6), 1172–1181 (2005)
79. Yu, S., et al.: Study on the mode-transition of nanosecond-pulsed dielectric barrier discharge between uniform and filamentary by controlling pressures and pulse repetition frequencies. Phys. Plasmas. 23(2), 023510 (2016)
80. Meyer, C., et al.: Impact of homogeneous and filamentary discharge modes on the efficiency of dielectric barrier discharge ionization mass spectrometry. Anal. Bioanal. Chem. 405(14), 4729–35 (2013)
81. Tschiersch, R., et al.: Self-stabilised discharge filament in plane-parallel barrier discharge configuration: formation, breakdown mechanism, and memory effects. J. Phys. D Appl. Phys. 50(41), 415206 (2017)
82. Wu, S., Lu, X.: The role of residual charges in the repeatability of the dynamics of atmospheric pressure room temperature plasma plume. Phys. Plasmas. 21(1), 123509 (2014)
83. Lu, X., Ostrickov, K.: Guided ionization waves: the physics of repeatability. Appl. Phys. Rev. 5(1), 031102 (2018)
84. Yao, C., et al.: Transition from glow-like to streamer-like discharge in atmospheric pressure dielectric barrier discharge controlled by variable dielectric surface layer permittivity. Phys. Plasmas. 26(1), 060702 (2019)
85. Tiwari, V., Sutton, M.A., Mcneill, S.R.: Assessment of high speed imaging systems for 2D and 3D deformation measurements: methodology development and validation. Exp. Mech. 47(4), 561–579 (2007)
86. Gao, L., et al.: Single-shot compressed ultrafast photography at one hundred billion frames per second. Nature. 516(1), 74–77 (2014)

How to cite this article: Zhang B, Xue J, Chen X, et al. Review of surface transient charge measurement on solid insulating materials via the Pockels technique. High Voltage. 2021;1–17. https://doi.org/10.1049/hve2.12073