

Review of accumulative failure of winding insulation subjected to repetitive impulse voltages

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Abstract: The premature failure phenomenon that occurs in solid insulation under the application of repetitive impulse voltages is known as the accumulative effect of impulse voltages on a solid dielectric. The accumulative failure of winding insulation is considered to be a core problem resulting from this phenomenon. The main problems include the accumulative failure of motor winding insulation under pulse-width modulation impulses and the accumulative failure of transformer winding insulation under the application of overvoltages, and these problems represent new challenges in the safe and stable operation of power grids. With regards to the above problems, this study reviews the results of recent research on the accumulative failure characteristics and mechanisms of winding insulation when subjected to repetitive impulse voltages. The challenges faced are discussed at the end of this study.

1 Introduction

The accumulative effect, which first appeared in psychological research, is an important term in this paper. Psychologists define this term as the continuous action of a specific external factor on an object that leads to change in the object's properties and state. In 1956, the concept of the accumulative effect was first proposed for use in electrical engineering research by Strandring. He studied the breakdown characteristics of synthetic resin-bonded paper sheets and found that the solid dielectric broke down under application of repetitive impulse voltages, despite the amplitude of the applied impulse voltage is much lower than that of the breakdown voltage of the dielectric [1]. In the following decades, the accumulative effect of repetitive impulse voltages on insulation did not draw much attention until the 1990s, when researchers found that premature failure may occur when the winding insulation of inverter-fed motors was subjected to repetitive impulse voltages caused by pulse-width modulation (PWM)-type inverters. This interesting phenomenon is a typical accumulative insulation failure and raised widespread concern [2–5]. Thereafter, in 1996, it was pointed out that oil–paper insulation used in power transformers broke down prematurely when subjected to repetitive impulse voltages [6]. Later, in the 2010s, and following an appeal by Okabe, an increasing number of researchers began to study the accumulative failure phenomenon in oil–paper insulation subjected to repetitive impulse voltages and many useful results were obtained [7–9]. The present paper reviews important achievements made in recent decades with regards to the accumulative failure of winding insulation subjected to repetitive impulse voltages and discusses future challenges in this research area.

2 Accumulative failure of inverter-fed-motor winding insulation

The square output waves of PWM-type inverters have fast front/tail voltage waves and high frequencies and amplitudes. These repetitive impulse voltages can lead to premature failure of the winding insulation in inverter-fed motors [10–20].

2.1 Impulse voltage waveform on winding insulation in inverter-fed motors

In the PWM drive system of an inverter-fed-motor, the PWM-type inverter outputs square-wave voltages with various pulse widths. The circuit structure of the PWM drive system is illustrated in Fig. 1.

Reflection and refraction of the wave may occur when an impulse wave travels through the cable that connects the motor to the PWM drive system. An impedance mismatch can double or triple the front voltage of the impulse [21, 22]. A typical impulse voltage of an inverter-fed-motor is plotted in Fig. 2 [23].

The rise time of the insulated-gate bipolar transistor used in the circuit generally varies from 50 ns to several microseconds, which can lead to an extremely high rise rate for the output square wave [24]. When an impulse voltage with such a high rise rate is applied to the winding insulation of the motor, the voltage distribution across the windings becomes extremely uneven. It is believed that the inter-turn insulation on the head of the windings suffers the highest electric field intensity [25–29]. The relationship between the rising rate of the impulse voltage and the voltage distribution is illustrated in Fig. 3 [30–32].

2.2 Accumulative failure of winding insulation in inverter-fed motors and its mechanism

Motor winding insulation can be classified into type I and type II insulations. Motors with operating voltage levels lower than 700 V may have either type I or type II insulation. However, above this voltage level, type II winding insulation is generally used. The insulation material that is used between electromagnetic wires is generally organic material such as polyimide, polyester, or epoxy [33–36]. The presence of defects and sharp points in the windings and air gaps in the insulating dielectric, as shown in Fig. 4, are unavoidable in the manufacture of inverter-fed motors. When repetitive impulse voltages are applied to these windings, the electric fields of these defects, sharp points, and air gaps become strong, which means that the windings will age more easily or even fail prematurely.

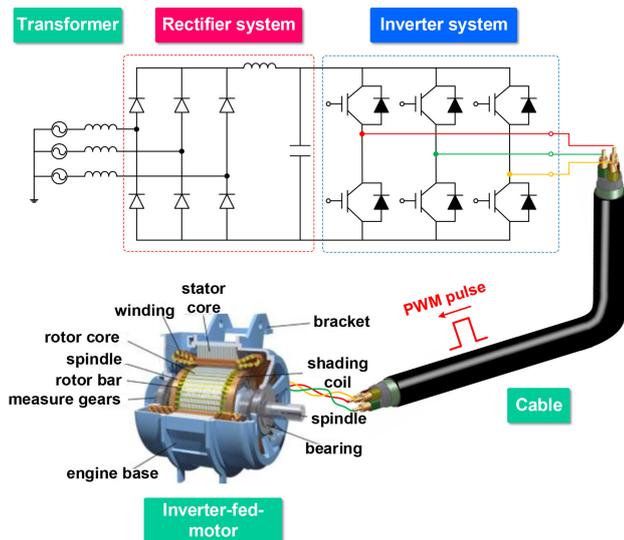


Fig. 1 Circuit structure of the PWM drive system

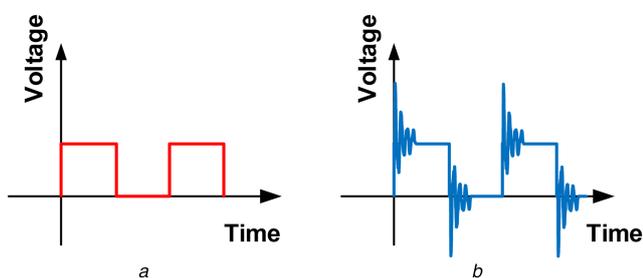


Fig. 2 Typical impulse voltage of an inverter-fed motor
Note that the impulse voltage presented in Fig. 2 is a typical waveform, the shape, frequency, and duty cycle can vary under operational conditions

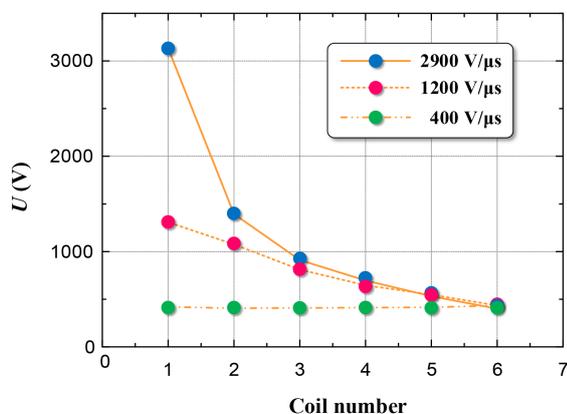


Fig. 3 Effect of voltage rising rate on the voltage distribution

2.2.1 Factors affecting the failure characteristics of turn-to-turn insulation and lifetime model: International Electrotechnical Commission (IEC) 60851-5 [37] defined the test regulation for the accumulative failure characteristics of electromagnetic wires subjected to repetitive impulse voltages, which requires an electromagnetic wire swathed within a polyimide film to be bent into a U shape. Note that twisted pairs are also widely used for this test. Refer to IEC 60172 for specific details [38]. The test sample must be placed in a metal container that is filled with steel balls having a diameter < 2 mm. The metal container and steel balls are used as the grounding electrode and repetitive impulse voltages are applied to the electromagnetic wire until it breaks down. The experimental setup is shown in Fig. 5.

In general, the amplitude, frequency, polarity, and rise time of the impulse voltage are the main factors that affect the accumulative failure characteristics of the dielectric. The lifetime of the winding insulation decreases dramatically as the amplitude/frequency of the applied impulse voltage increases [39–41].

Studies have indicated that the failure characteristics of the winding insulation under the application of bipolar impulses, positive impulses, and negative impulses are different. The lifetime of the winding insulation under the application of bipolar impulses is the shortest, whereas the lifetime under application of positive impulses is the longest. When the rise time of the impulses is longer than $0.07 \mu\text{s}$, the lifetime of the winding insulation is observed to increase with increasing rise time. However, when the rise time of the impulses is shorter than $0.07 \mu\text{s}$, the effects of the rise time are limited [42, 43].

Researchers have reported many results with regards to life models of motor winding insulation subjected to repetitive impulse voltages.

It was presented in [44] that the failure characteristics of bisphenol epoxy subjected to repetitive voltage surges and established a life model

$$L = 2.3 \times 10^{10} V^{-5} R^{0.3} \quad (1)$$

$$L = 3.3 \times 10^{13} V^{-8.2} R^{0.48} \quad (2)$$

where L is the number of surges required to initiate a tree; V is the surge voltage in kV; and R is the number of surges applied to the insulation per second. Equations (1) and (2), respectively, relate to positive and negative surges.

Guastavino *et al.* [40] pointed out that the lifetime of the dielectric is directly related to the frequency and amplitude of the impulse voltage and temperature. The study proposed a phenomenological life model based on a large number of test data

$$D(V, f, \theta) = \frac{\alpha E + \beta \theta^a \times V^{b\theta^c}}{f} \quad (3)$$

where D is the lifetime of enamelled copper wires; V and f are, respectively, the amplitude and frequency of the applied voltage; and θ is the environmental temperature. Here, α , β , a , b , and c are coefficients with values that are summarised in Table 1.

In addition, it is believed that the voltage waveform has a significant effect on the dielectric's lifetime. The different lifetimes of twisted pairs, when subjected to repetitive impulse voltages with different waveforms, are plotted in Fig. 6 [45, 46]. The partial discharge (PD) characteristics of a dielectric under the application of impulse voltages with different waveforms are also different, resulting in differences in the failure characteristics. It was found, for example, that a long rise time of the applied voltage could lead to a low PD magnitude, and the PD frequency spectrum was also changed when the rise time varies [47]. The waveshape of the applied voltage was found to affect the PD extinction voltage (This effect depends on the type of dielectric and insulation structure [48]).

2.2.2 Accumulative failure mechanism: It is believed that PDs are mainly responsible for the accumulative failure of winding insulation [2, 48–57]. It is generally believed that premature failure of winding insulation begins with the occurrence of PDs [12, 28, 52, 53]. PDs in small voids within the dielectric damage the insulation dielectric in several ways; e.g. through chemical reactions, the bombardment of high-energy ions/electrons, and ultraviolet radiation [58, 59]. Under the effects of bombardments and ultraviolet radiation in the PD process, covalent bonds at the void surface are broken and radicals form. These radicals react with gas and polymer and form by-product liquid droplets, which deposit on the surface of voids (where the chemical composition depends on many factors; i.e. insulating material, gas, voltage, time, and discharge type) [59, 60]. This increases the conductivity and roughness of the void surface. Meanwhile, the local temperature increases and this can melt the dielectric and intensify damage [33]. Furthermore, PDs can result in the formation of crystal by-products with an acidic nature. The electric field on the tip of crystals is strengthened, which further intensifies PD activity. Finally, an electrical tree grows and there is breakdown [61, 62]. Physical models considering thermodynamic and electrokinetic

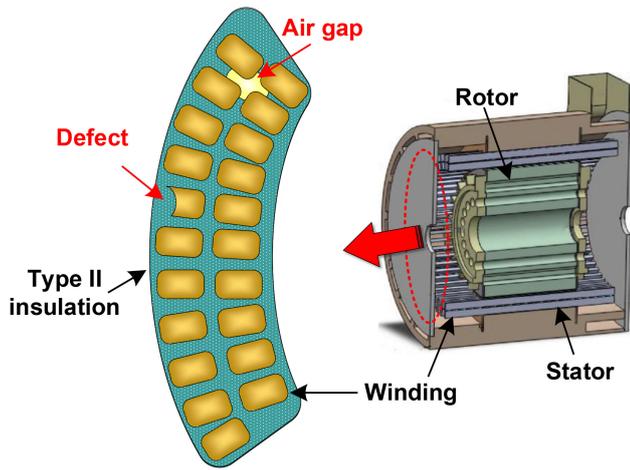


Fig. 4 Structure of motor windings

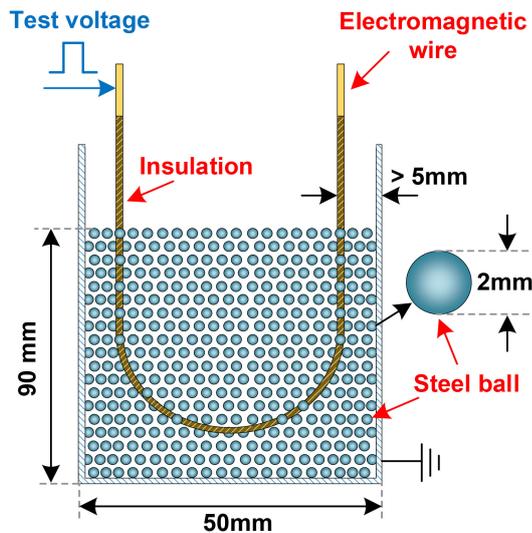


Fig. 5 Experimental setup for testing the accumulative failure characteristics of electromagnetic wires as defined by IEC 60851-5

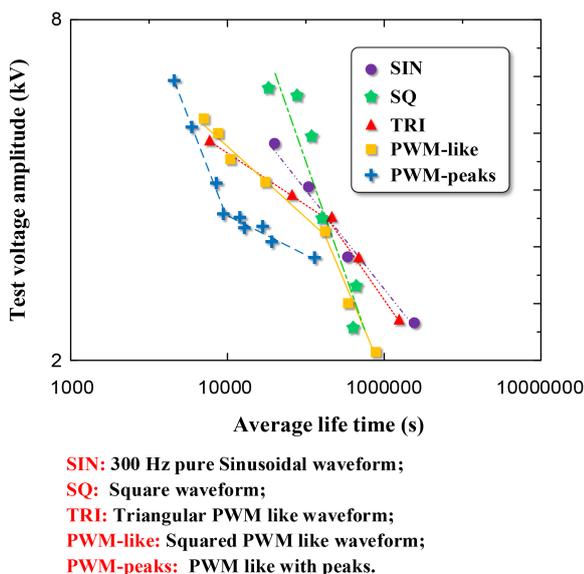


Fig. 6 Results of life tests on twisted pairs in the presence of PDs: effects of the voltage waveform

Table 1 Values of coefficients in the phenomenological life model of (3)

Coefficients	A	β	a	b	c
values	3.816	19	-2.95	-4.322	-0.1358

processes have been established to describe the bond-breaking mechanism of an insulating dielectric subjected to repetitive impulses [63, 64].

Many scholars studied PD behaviour in solid dielectrics containing voids or gaps. Studies have introduced ‘Townsend-like’ discharge and ‘streamer-like’ discharge based on the Townsend and streamer breakdown mechanisms [65, 66]. The authors of the references believe the PD mechanism in voids has different features as the conditions change. One study [58] further pointed out that the discharge process of voids in dielectric can be classified into three stages (streamer-like, Townsend-like, and ‘pitting’ discharges). These stages are successive in time. The mechanisms and features of the above-mentioned discharges are different, and the damage caused by the discharges is, therefore, also different. Different by-products and morphologies were observed under the above three types of PDs. Generally, the transition between streamer-like discharges and Townsend-like discharges occurs when certain conditions are reached (see the literatures for more details [58, 65, 66]).

Note that the PD characteristics of dielectrics are closely related to the amplitude, frequency [11, 54], waveform [45, 46], polarity [16], and rise time [55, 56] of the impulse voltage. This behaviour is consistent with the statements given in Section 2.2.1. The factors listed above determine the accumulative failure characteristics and the lifetime of the dielectric by affecting the PD characteristics. However, one study found that even though PDs can reduce the lifetime of winding insulation, lifetime decreases when there are repetitive impulses in the absence of PDs [67]. Many researchers maintain that the surface/space charge plays an important role in the accumulative failure process of winding insulation. According to field-limited space charge current theory, there is a threshold field, denoted by E_c , below which the injected charges have low but finite mobility. Above E_c , the strongly non-linear dependence of this mobility on the electric field causes the space charge clouds to penetrate rapidly into the bulk insulation. Under the application of an AC voltage, large numbers of charges are injected and extracted, and this may then cause localised degradation [57, 68–72]. Note that the trapped charges may recombine, releasing residue energy and shifting the energy to other electrons through radiation. Radicals then form when high-energy electrons attract macromolecules [73]. It has been found that surface/space charges accumulating in a dielectric are causes of ageing because of the relevant local field enhancement and associated electromechanical energy storage [74]. The authors of the cited study established the Dissado–Mazzanti–Montanari (DMM) model (including the DC DMM model and AC DMM model) to explain space charge-induced long-term degradation of insulation (see the literatures for more details [57, 72, 75, 76]).

The effects of the surface charge on the failure of the dielectric are also closely related to the PD in the dielectric. The following analysis of this behaviour has been proposed [3, 77–79].

PDs first occur in air gaps in the insulation or between windings. Assuming that $E(t)$, with a maximum magnitude of E_0 , is applied to the air gap. E_p is the internal electric field that is generated by the surface charges in the air gap. The total electric field E_t of the air gap can then be obtained as the difference between E_0 and E_p .

In Fig. 7a, discharge can occur when the total electric field E_t of the air gap reaches the minimum breakdown electric field E_{min} . E_i then reduces to the residual value E_{res} . More residual charges are generated during this discharge process, which enhance E_p . Therefore, E_i , which is equal to $(E_0 - E_p)$, will be lower than the minimum breakdown electric field E_{min} , and the PD is thus extinguished, as shown in Fig. 7b.

When the polarity of the external electric field $E(t)$ is reversed, the polarities of the residual surface charges barely change because

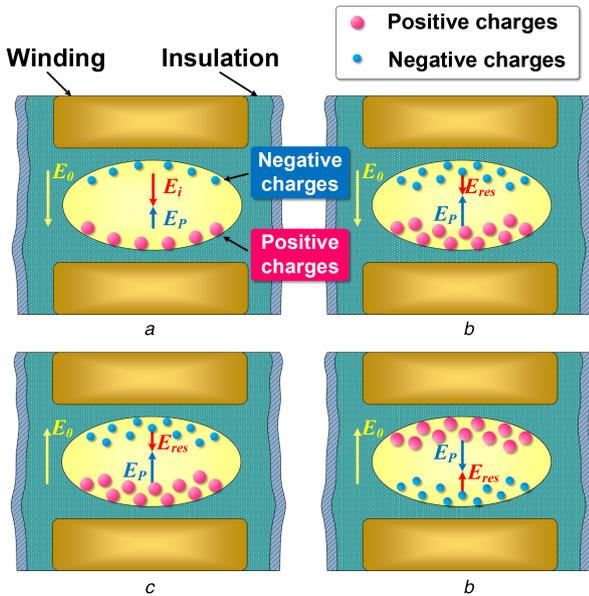


Fig. 7 Effect of surface charges on the PD of the dielectric
 Note: For the first PD to occur, only injected space charges can exist in the air gaps. In this case, the space charge distribution may differ from that shown in Fig. 7a

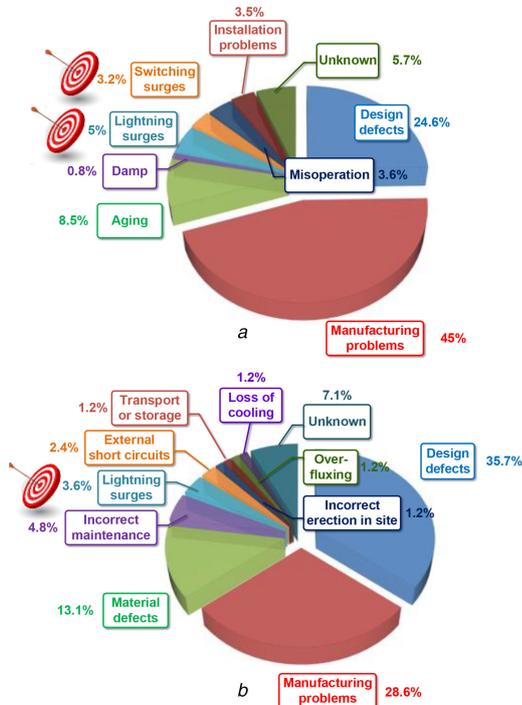


Fig. 8 Failure causes of power transformers

of the very limited time. The total electric field E_i of the air gap is then equal to $(E_0 + E_p)$, as shown in Fig. 7c.

Since the electric field E_p , which is governed by the surface charges in the air gap, is nearly equal to $(E_0 - E_{res})$, the total electric field in the air gap is given by $(2E_0 - E_{res})$. Another discharge then starts in the air gap. The total electric field in the void drops again to E_{res} and the surface charges in the air gap move to the opposite position under the effect of the electric field, as shown in Fig. 7d.

Yin [42, 43] and Yin *et al.* [80] believe that the premature failure of the winding insulation is due to PDs, surface charge, and dielectric heating. Among these three factors, dielectric heating plays an important role and is considered unavoidable under operational conditions. It has been noted that dielectric heating is one potential ageing mechanism that is active below the PD inception voltage (PDIV) in dielectric materials [81]. The operating temperature of a motor winding is typically higher than 80°C [82].

The machine's cooling ability is significantly reduced at low operating speeds because it decreases with a decreasing shaft fan speed. Additionally, voltage harmonics and a high dv/dt cause increased dielectric losses in both the stator windings and the core insulation. This results in accelerated thermal deterioration, which shortens the remaining lifetime of the insulation [21].

In summary, studies on the accumulative failure of winding insulation used in inverter-fed motor flourished in the 1990s. Researchers around the world have made considerable advances in this area. To date, a consensus has already been reached on the failure characteristics and failure mechanism of winding insulation when subjected to repetitive impulse voltages, which has laid a firm foundation for studies of the accumulative failure of solid dielectrics.

3 Accumulative failure of oil–paper insulation

3.1 Background

Oil–paper insulation, acting as both the main insulation and inter-turn insulation, is widely used in power transformers. Operating data indicate that most recorded transformer faults are due to insulation failure [83–86]. According to operating data provided by the State Grid Corporation of China, 226 of their transformers (in voltage classes of 110 kV and over) were out of order over the period from 2000 to 2005, and most faults involved were related to insulation failure. The failure causes are summarised in Fig. 8a, whereas Fig. 8b plots corresponding data from the International Council on Large Electric Systems (CIGRE) [87, 88].

The statistical data indicate that the impulse voltage is not the main cause of transformer faults, with insulation failures directly due to impulse voltages accounting for only 8.2% of faults. However, impulse voltages, which include lightning impulse voltages and switching impulse voltages, occur frequently in power systems. Long-term monitoring results indicate that a typical power transformer may be subjected to tens of thousands of impulse voltages during its life cycle [89–91]. The oil–paper insulation that is used in power transformers may temporarily maintain its electrical performance after the accumulation of repetitive impulse voltages. However, during the accumulation process, the cellulose fibres in the paper could be destroyed and new substances that adhere to the oil-impregnated paper (OIP) may also be generated, enhancing the unevenness of the insulating surface structure and increasing the risk of overheating failure [92]. More importantly, long-term accumulation of these repetitive impulse voltages may cause unrecoverable damage to the OIP and affect its electrical performance, which then threatens the safe operation of the power transformer. It is noted that because the frequency of the repetitive impulse voltages in inverter-fed motors is much higher than that in power transformers, the accumulation of repetitive impulse voltages is only considered to be an indirect factor that may lead to transformer faults.

In practise, the impulse voltages that are applied to the OIP in power transformers have the following features:

- i. **High amplitude:** While the arresters that are installed in substations can, to a certain extent, restrict the amplitude and steepness of the impulse voltages, they cannot guarantee complete isolation of the transformer from the impulse voltages. When an impulse voltage is applied to the transformer windings, a complex electromagnetic transient process occurs in the windings, resulting in an uneven voltage distribution on the windings. In this case, g on the head of the windings becomes extremely high (and much higher than the AC electric field acting on the winding insulation) [93–95].
- ii. **Complex waveform characteristics:** Owing to factors including the input line attenuation, the wave processes in the windings, and arrester operation, the impulse voltage in the transformer winding is no longer the standard double-exponential wave recommended by the IEC standard (1.2/50 and 250/2500 μ s [96]) but is in fact a non-standard wave. The typical waveform of a transformer-invading impulse voltage is shown in Fig. 9 [89–91]. For example, Okabe *et al.* presented four typical non-standard impulse waveforms that were recorded at a power

substation. They maintained that most impulse voltages recorded at this substation differed from the standard forms [96–114]. Even impulse voltages measured on transmission lines may also differ from the standard impulse voltage [113–117]. Studies have monitored the voltages and currents produced by lightning impulses on towers and transmission lines and found that the measurement results were directly related to the measurement position and method or even to the measurement device [118, 119]. In those studies, some of the recorded data were not the same as the standard data. These non-standard impulse voltages may cause more severe damage to the OIP and complicate the study of the accumulative failure of OIP insulation.

- iii. *Repeated application:* An overvoltage monitoring system has been installed in a 110 kV substation located in China [89–91]. The voltage sensor was installed on the bushing tap of the main transformer. The monitoring work was performed for 11 years, and statistical data indicated that more than 50 lightning impulse voltages were recorded per year [89–91]. If we assume that the lifetime of a typical power transformer is 30 years, then the transformer will suffer more than 1500 lightning impulses during its lifetime. The frequency of the occurrence of switching impulse voltages is even higher. The reactive-load compensation equipment used in this substation is generally operated four to five times per day. The power transformer will thus suffer more than 40,000 switching impulses during its 30 year lifetime [120].

3.2 Accumulative failure of OIP and its mechanism

3.2.1 Finding the accumulative failure of OIP: In 1996, Okabe *et al.* found that an OIP sample broke down under the application of repetitive impulse voltages with amplitudes that were much lower than the OIP breakdown voltage. After the accumulation of more than 1000 impulses, both the breakdown voltage and the PDIV declined by <10%. They maintained that the reduction in the breakdown voltage could be considered as being the result of probabilistic breakdown; i.e. where the effect of the number of applications of the breakdown voltage is related to the breakdown probability, which is determined by the inherent weak points composed of the oil gaps or the pressboard barriers inside the parallel electrode system, rather than by the deterioration of the insulation due to repeated impulse voltage application [6].

Okabe *et al.* then obtained the accumulative failure characteristics of oil–paper insulation materials with various structures. The test voltage used was the standard lightning/switching impulse voltage. They determined the relationship between the amplitude of the impulse voltage (V) and the number of applications of the impulse before breakdown (N); i.e. the V – N characteristics. This relationship can be expressed using an exponential model [121]

$$V = AN^{-1/n} \quad (4)$$

where V is the minimum breakdown voltage, N is the number of impulses before breakdown at magnitude V , A is the breakdown voltage of the dielectric, and n is a shape parameter.

Test results indicated that the n -values (i.e. the inclinations) of the V – N characteristics were, in most cases, distributed at around 70 for both the standard lightning/switching impulse voltage and at ~40 in turn-to-turn insulation models only [121].

In 2008, the CIGRE working group C4.302 simplified the Weibull distribution model and recommended the use of this simplified model to describe the V – N characteristics. The expressed form of the simplified Weibull distribution model is the same as that of the exponential model proposed in the literatures [7, 122]. In 2011, Balaji *et al.* [7] used this model to fit their test data and found that the values of A and n increased with a rising wavefront time. The effect of the wave-tail time on the value of A was limited, while the value of n decreased with decreasing wave-tail time [7]. Additionally, the authors noted that impulse withstand tests are widely used during the lifetimes of power transformers.

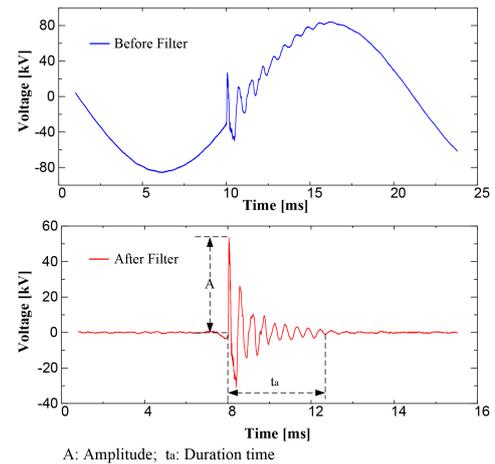


Fig. 9 Measured overvoltage waveform

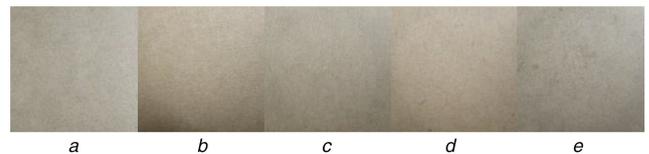


Fig. 10 Morphology of cellulose paper specimens extracted using acetone (a) Virgin OIP, (b)–(e) OIP under applications of 100, 200, 300, and 400 lightning impulses, respectively

Frequent application of impulse voltages on the transformer may also affect the electrical performance of the OIP, and this point is worthy of further attention. This view was supported by Okabe, who maintained that the accumulative effect mainly appeared during impulse tests. When deciding the insulation levels that are required for high-voltage equipment, detailed and precise data on the V – N characteristics of the insulating elements are essential to provide protection from lightning impulse voltages and switching impulse voltages [123].

In 2011, the development processes of streamers at the interface between oil and OIP were observed [124, 125]. The authors of the cited studies found that, under the application of repetitive lightning impulses, the length of the streamer grows with an increasing number of impulse applications. Flashover ultimately occurs. However, this phenomenon was not detected when the OIP was removed. This indicates that the accumulative effect appears not only during dielectric breakdown but also on flashover at the oil–paper interface [124, 125].

3.2.2 Effect of repetitive impulse voltages on the OIP: A translucent gelatinous substance was detected on the surface of an OIP that had been subjected to repetitive double-exponential impulses. This translucent gelatinous substance was easily dissolved in acetone. In addition, the colour of the OIP surface that had been covered by the electrode had changed and differed from that of the surface areas away from the electrode, as shown in Fig. 10. This indicates that the accumulation of repetitive impulse voltages can damage the surface of OIP [92].

Using an atomic force microscope, the surface micro-morphology of fresh OIP and that of OIP subjected to 200, 400, 600, and 800 standard lightning impulses have been observed [92]. That study found that the accumulation of repetitive lightning impulses can dramatically increase surface roughness, which is believed to be caused by PDs in the oil film between the electrode and the OIP sample, as shown in Fig. 11.

The dielectric properties of OIP vary when repetitive impulse voltages are applied to the OIP sample. It was found that the real and imaginary parts of relative permittivity, the conductivity, and the dielectric loss tangent $\tan \delta$ of the OIP increase with the number of impulse applications. This phenomenon was more obvious at low frequency [126, 127]. One study analysed the relationship between dielectric properties and microcosmic damaging process and proposed that high-energy electrons

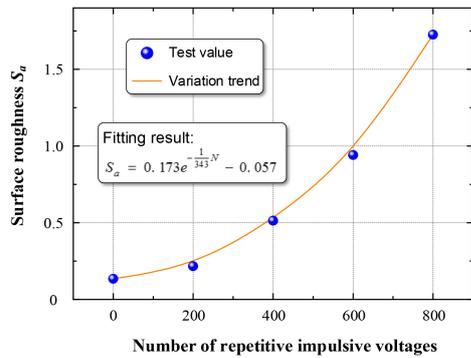


Fig. 11 Surface roughness of OIP when subjected to repetitive impulse voltages

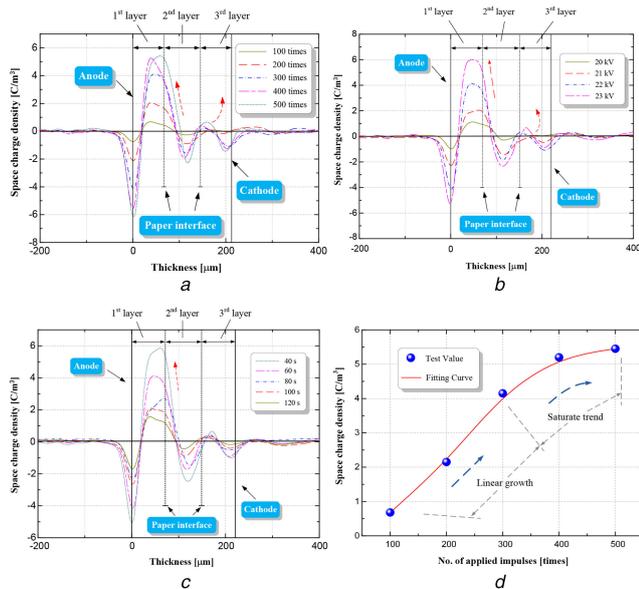


Fig. 12 Space charge distribution in OIP subjected to repetitive impulse voltages

(a) Effect of the number of applications, (b) Effect of the voltage amplitude, (c) Effect of the interval time, (d) Maximum space charge

bombard the oil/cellulose molecules and break hydrogen bonds between the cellulose chain and covalent bonds [92]. This process generates polar by-products that improve the dielectric's polarisation ability. It is noted that while some of the cellulose chains were broken, the effect of the repetitive impulse voltages on the degree of polymerisation was limited. This result indicates that most of the cellulose chains remain intact under the application of repetitive impulses [128].

Furthermore, it has been found that the accumulation of repetitive impulse voltages reduces the PDIV of the OIP (where PDs occur in the pores within this paper) [92], which is consistent with the test results of Okabe [6].

3.2.3 Accumulative failure mechanism of OIP: As noted in the previous section, repetitive application of impulse voltages can cause accumulative damage to the OIP and thus lead to a reduction in the electrical performance; i.e. when an impulse voltage is applied to an OIP sample, the electric field intensity in the oil pores becomes extremely high. PDs thus occur repeatedly in the oil pores. As a result of collisions between charged particles and electrons, some of the cellulose fibres break and form new substances. During this process, the cellulose paper suffers unrecoverable damage and this reduces the OIP breakdown voltage [92, 128].

It is believed, however, that accumulative damage is not the sole reason for the premature failure of OIP. Space charges also play an important role in this failure process. In general, there are two aspects to the effects of space charges on dielectric

performance. On the one hand, the existence, migration, and dissipation of space charges affect the electric field distribution in the dielectric directly. This can either weaken or strengthen the local electric field in the dielectric and thus affects the breakdown voltage of the dielectric [129–131]. On the other hand, the trapping, detrapping, and recombination of space charges may cause emission of photons or release local mechanical energy, which can break the chemical bonds in the dielectric and thus affect the insulation characteristics of the dielectric [74, 132].

Researchers have argued that the study of the space charge characteristics in OIP that has been subjected to repetitive impulsive voltages lacks an engineering application background because space charges may dissipate before application of the next impulse voltage. The authors of this review believe that in areas where thunderstorms commonly occur, there are frequent lightning impulse voltages in power systems. The effects of space charge accumulation are, therefore, worthy of study to some extent. During a thunderstorm process, several return strokes can appear within a single lightning strike. The interval time between these return strokes varies from tens to hundreds of milliseconds [133]. Even the interval time between two independent lightning strikes generally varies from tens of seconds to several minutes. In this case, the space charges that accumulate in the OIP do not have sufficient time to dissipate, which may then affect the accumulative failure characteristics of the OIP [134].

The pulsed electro-acoustic method was adopted to determine the space charge distributions in OIP samples subjected to repetitive lightning impulses with different numbers of applications, different amplitudes, and different interval times, with the results shown in Fig. 12. Most space charges detected in the OIP samples had the same polarity. As the number of applications and the amplitude of the impulse voltage increased, the space charge density in the OIP gradually increased, showing a saturation trend. Increases in the interval time between the applied impulses contribute to the dissipation of the space charge and thus reduce the space charge density [134].

The effects of space charge on the accumulative failure of OIP insulation are summarised as follows. Under the effect of repetitive impulse voltages, numerous positive charges are injected into the OIP and tend to accumulate in the dielectric near the anode. Meanwhile, electrons are injected from the cathode, and some pass through the dielectric and are then neutralised in the anode. As the accumulation of lightning impulses continues, some of the positive charges near the anode escape their traps and migrate toward the cathode under the effect of the applied impulses. Finally, the numerous positive charges become dominant in the bulk. These charges enhance the electric field intensity near the cathode and thereby contribute to the failure of the OIP [133, 134].

Dielectric accumulative damage and space charge accumulation are considered to be the two main reasons for premature failure of the OIP. The following experiment was designed to determine which of these factors plays the main role in accumulative failure.

Since the space charges dissipate during the interval between two consecutive impulses, a finite interval time is required for the space charge to play a role in the accumulative failure of the OIP. The amplitude of the applied impulse voltage and the interval time were, respectively, set at 20 kV and 60 s. It was found that the OIP sample broke down after an average of 124 impulse applications. Using an unchanged test setup, repetitive impulse voltages were then applied to the OIP sample. After each batch of 30 shots, the test was stopped for 2 h. During this time, an automatic grounding rod was connected to the high-voltage terminal to release the space charge in the OIP sample. It is interesting to note that, in this case, an average value of 1001 impulses had to be applied to breakdown the OIP sample, which is a higher number than in the test without the 2 h waiting period. The test indicates that the space charge plays the main role in the accumulative breakdown process. To some extent, however, this test also verifies the effects of the electrical degradation caused by repetitive lightning impulses, because the breakdown of the OIP sample still occurred without the effects of the space charge [135].

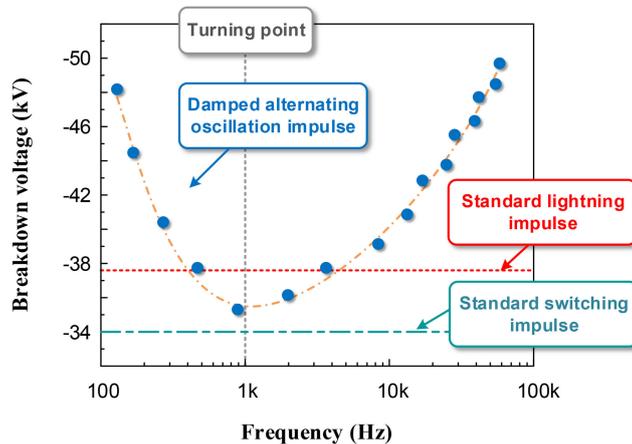


Fig. 13 Breakdown voltage of OIP under the application of damped alternating oscillation impulses with different frequencies



Fig. 14 Paste-like substance on the surface of an OIP sample subjected to 200 damped alternating oscillation impulses

3.2.4 Effects of waveform parameters on the $V-N$ characteristics:

A recorded non-standard impulse waveform was converted into a double-exponential impulse waveform using the equivalent energy. The statistical wavefront and wave-tail times of the converted non-standard impulse are 20/198 μs [89, 90]. Under standard lightning impulse (1.2/50 μs), standard switching impulse (250/2500 μs), and converted non-standard impulse (20/198 μs) conditions, the 50% breakdown voltages of OIP are, respectively, 58.7, 56.7, and 60.2 kV. In the case that the amplitudes of all test impulse voltages are the same, the numbers of impulse applications required before breakdown increased in the order of the standard lightning impulse <converted non-standard impulse<standard switching impulse [89, 135].

The effects of the waveform parameters of the double-exponential impulse voltage on the $V-N$ characteristics are understood clearly. As the wavefront time increases, the breakdown voltage of the OIP and its ability to resist repetitive impulse voltages both increase accordingly, while the effect of the wave-tail time on the breakdown voltage is very limited. The ability of the OIP to resist repetitive impulse voltages weakens with increasing wave-tail time [89, 135]. The mechanism by which the waveform parameters affect the breakdown voltage and the $V-N$ characteristics can be summarised as follows. On the one hand, the waveform parameters affect the movement of the positive charges within the micro oil pores contained in the OIP, which can affect the electric field distributions in these micro oil pores to a remarkable extent. On the other hand, the waveform parameters affect the trapping and detrapping balance between the charged particles in the OIP. All the above phenomena are closely related to both the breakdown voltage and the $V-N$ characteristics [136].

In contrast, the failure characteristics of the OIP under the application of damped alternating oscillation impulses are much more complex [137–139]. When the oscillation frequency is increased from 200 Hz to 50 kHz, the OIP breakdown voltage initially decreases and then increases. The turning point in the breakdown voltage corresponds to an oscillation frequency of 1 kHz (as shown in Fig. 13). When the half-peak time is varied from 35 to 160 μs , the OIP breakdown voltage decreases with increasing half-peak time [140]. One study [140] defined the peak times t_{max}

and t_{con} , which are the total sum of the time periods for which the voltage was at V_{th} (a threshold level) or higher. On the basis of further tests that study determined the relationship between the two variables above and estimated the breakdown voltage under the application of damped alternating oscillation impulses as

$$\hat{U}_{50} = -\left(U_0 + A_1 t_{\text{con}}^{R_0} + A_2 t_{\text{max}}\right) \quad (5)$$

where U_0 , A_1 , and A_2 are fitting parameters.

For damped alternating oscillation impulses with various waveform parameters, the $V-N$ characteristics curve for the OIP moves upwards as the oscillation frequency increases. When the half-peak time increases, the $V-N$ characteristics curve of OIP moves upwards and tends to flatten at an earlier stage [140].

3.2.5 Difference between failure characteristics under the application of double-exponential impulses and damped alternating oscillation impulses:

The OIP failure characteristics under application of double-exponential impulses differ from the characteristics under application of damped alternating oscillation impulses. Sun *et al.* [89] and Sima *et al.* [90] showed the equivalence of these two impulses, i.e. they found that the breakdown voltage of OIP under a specific damped alternating oscillation impulse is the same as that under the equivalent double-exponential impulse. However, a follow-up study indicated that even under the application of a damped alternating oscillation impulse and its equivalent double-exponential impulse, the $V-N$ characteristics obtained for those two equivalent impulses still differ. When the amplitudes of the applied impulses are the same, the ability of OIP to resist repetitive damped alternating oscillation impulses is stronger than the ability of OIP to resist repetitive equivalent double-exponential impulses. More importantly, a paste-like substance (as shown in Fig. 14) was detected on the surface of OIP that had been subjected to repetitive damped alternating oscillation impulses. This paste-like substance differs from the translucent gelatinous substance found during the double-exponential impulse accumulation test. This indicates that the accumulative damage mechanisms of the two impulses described above may be different. In addition, the space charge distribution in OIP subjected to damped alternating oscillation impulses is different from that in OIP subjected to double-exponential impulses. Therefore, the determination of the accumulative failure mechanisms of these two types of impulses is an interesting prospective research direction.

4 Future challenges

To date, the premature failure characteristics and mechanisms of winding insulation materials subjected to repetitive impulse voltages have been studied widely. Numerous results have been reported within this area of research, particularly for the accumulative failure of motor winding insulation. However, the following problems have still to be addressed:

- i. *Further study of the microcosmic failure mechanism of winding insulation*: PDs and space/surface charges have a close relation and both affect the accumulative failure process of motor winding insulation. PDs are also considered a source of charge injection [3, 77–79]. It is important to experimentally investigate the charge behaviours and simultaneously observe PD activity in a microcosmic manner. This would be helpful in revealing the interaction mechanism of space/surface charge and PD [61]. Moreover, it is believed that the bombardment of high-energy electrons in the PD process breaks bonds and forms by-products [59, 60, 63, 64, 73, 141]. However, the microcosmic process of bonds breaking and degradation has not been fully revealed. Molecular dynamics simulation may further reveal the failure mechanism, considering the limitations of currently available measurement techniques.
- ii. *Differences in terms of failure characteristics and failure mechanisms of OIP when subjected to double-exponential impulses and damped alternating oscillation impulses*: Preliminary studies have indicated that the failure characteristics of OIP samples that have been subjected to standard/non-standard impulses are different. Determination of the failure mechanism of OIP, when subjected to damped alternating oscillation impulses and finding the difference with respect to the failure mechanism that occurs under the application of double-exponential impulses, will help clarify the accumulative failure phenomenon in depth. Moreover, the waveshape of the applied voltage is believed to affect PD activities in the dielectric [47]. Since PD is considered an important factor that results in the accumulative failure of OIP, it is important to study the relationship among the waveshape, PDs, and failure mechanism of OIP.
- iii. *A waveform equivalent method for both double-exponential impulses and damped alternating oscillation impulses*: Considering that, during operation, OIP insulation is subjected to damped alternating oscillation impulses rather than the double-exponential impulses recommended by the relevant IEC standard, the study of the failure characteristics of OIP insulation under damped alternating oscillation impulse conditions is important. However, the generation of damped alternating oscillation impulses in engineering practise is unrealistic. Therefore, the establishment of a waveform equivalent method between the double-exponential impulses and the damped alternating oscillation impulses will be important.
- iv. *Improvement in the ability of winding insulation to resist repetitive impulse voltages*: Non-thermal plasma treatments and nanomodification methods are widely used to improve the electrical performance of motor insulation [142–152]. For OIP, researchers have mainly adopted nanomodification methods that enhance the electrical performance. An attempt has been made to improve the ability of OIP to resist repetitive impulse voltages by suspending nanoparticles in the paper pulp and impregnating the paper using nanomodified oil. Both these methods have produced good results [84, 153–160]. However, more attention needs to be given to the comprehensive improvement of the insulating dielectric rather than the electrical performance; e.g. an increase in the space charge dissipation rate, enhancement of mechanical and thermal properties, and improvement of nanoparticle stability. Moreover, new methods may be important in improving the ability of the winding insulation to resist repetitive impulse voltages.

5 Conclusions

The above literature review reveals that motor winding insulation breaks down prematurely under the application of repetitive PWM-like impulses. The amplitude, frequency, polarity, and wavefront rise time of each of the applied impulses affect the lifetime of the winding insulation. PDs and the presence of space charges are considered to be the main reasons for the accumulative failure of motor winding insulation, with PDs playing the dominant role. With regards to the accumulative failure of OIP insulation in power

transformers, newly formed substances on the OIP surface were found during the accumulation process. It is believed that the waveform parameters affect the $V-N$ characteristics dramatically. The failure of OIP insulation is due to both accumulative damage and space charge accumulation. Specifically, the failure characteristics and failure mechanism of OIP subjected to double-exponential impulses differ from those of OIP subjected to damped alternating oscillation impulses. We believe that future challenges in this field of research are determination of the failure mechanism of OIP that has been subjected to damped alternating oscillation impulses, the proposal of a waveform equivalent method for double-exponential impulses and damped alternating oscillation impulses, and improvement of the ability of winding insulation to resist repetitive impulse voltages.

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7 References

- [1] Standring, W.G., Hughes, R.C.: 'Breakdown under impulse voltages of solid and liquid dielectrics in combination', *IEE Proc. Power Eng.*, 1956, **103**, pp. 583–597
- [2] Kaufhold, M., Borner, G., Eberhardt, M., *et al.*: 'Failure mechanism of the inter-turn insulation of low voltage electric machines fed by pulse-controlled inverters', *IEEE Electr. Insul. Mag.*, 1996, **12**, (5), pp. 9–16
- [3] Tong, L., Wu, G., Wen, F.: 'Mechanism and influencing factors of overvoltage on inverter-fed traction motor terminal', *J. Southwest Jiaotong Univ.*, 2005, **40**, (5), pp. 673–676, (in Chinese)
- [4] Wang, P., Cavallini, A., Montanari, G.C.: 'Characteristics of PD under square wave voltages and their influence on motor insulation endurance', *IEEE Trans. Dielectr. Electr. Insul.*, 2015, **22**, (6), pp. 3079–3086
- [5] Luo, Y., Wu, G., Liu, J., *et al.*: 'Characteristics and microscopic analysis of polyimide film used as turn insulation in inverter-fed motor', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (5), pp. 2237–2244
- [6] Okabe, S., Ohno, T., Zaima, E., *et al.*: 'AC $V-t$ and impulse $V-N$ characteristics of shell-form transformer insulation model', *Electr. Eng. Jpn.*, 1996, **116**, (44), pp. 49–63
- [7] Balaji, S.P., Merin Sheema, I.P., Krithika, G., *et al.*: 'Effect of repeated impulses on transformer insulation', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (6), pp. 2069–2073
- [8] Balaji, S.P., Lavanya, L., Usa, S.: 'Effect of repeated impulses on OIP'. IEEE Int. Conf. High Voltage Engineering and Application, Shanghai, China, 2012, pp. 558–561
- [9] Balaji, S.P., Usa, S.: 'Life estimation of transformer insulation under repeated impulses'. IEEE Int. Conf. Condition Assessment Techniques in Electrical Systems, Kolkata, India, 2014, pp. 331–334
- [10] Yang, J., Cho, J., Lee, S.B., *et al.*: 'An advanced stator winding insulation quality assessment technique for inverter-fed machines', *IEEE Trans. Ind. Appl.*, 2008, **44**, (2), pp. 555–564
- [11] Fabiani, D., Montanari, G.C., Cavallini, A., *et al.*: 'Relation between space charge accumulation and partial discharge activity in enameled wires under PWM-like voltage waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2004, **11**, (3), pp. 393–405
- [12] Kaufhold, M., Aninger, H., Berth, M., *et al.*: 'Electrical stress and failure mechanism of the winding insulation in PWM-inverter-fed low-voltage induction motors', *IEEE Trans. Ind. Electron.*, 2000, **47**, (2), pp. 396–402
- [13] Hudon, C., Amyot, N., Lebey, T., *et al.*: 'Testing of low-voltage motor turn insulation intended for pulse-width modulated applications', *IEEE Trans. Dielectr. Electr. Insul.*, 2002, **7**, (6), pp. 783–789
- [14] Bonnett, H.: 'Analysis of the impact of pulse-width modulated inverter voltage waveforms on AC induction motors', *IEEE Trans. Ind. Appl.*, 1996, **32**, (2), pp. 386–392
- [15] Hayakawa, N., Morikawa, M., Okubo, H.: 'Partial discharge inception and propagation characteristics of magnet wire for inverter-fed motor under surge voltage application', *IEEE Trans. Dielectr. Electr. Insul.*, 2007, **14**, (1), pp. 39–45
- [16] Hayakawa, N., Okubo, H.: 'Partial discharge characteristics of inverter-fed motor coil samples under AC and surge voltage conditions', *IEEE Electr. Insul. Mag.*, 2003, **21**, (1), pp. 5–10
- [17] Cavallini, A., Fabiani, D., Montanari, G.C.: 'A novel method to diagnose PWM-fed induction motors', *IEEE Trans. Dielectr. Electr. Insul.*, 2008, **15**, (5), pp. 1313–1321
- [18] Hayakawa, N., Inano, H., Nakamura, Y., *et al.*: 'Time variation of partial discharge activity leading to breakdown of magnet wire under repetitive surge voltage application', *IEEE Trans. Dielectr. Electr. Insul.*, 2008, **15**, (6), pp. 1701–1706

- [19] Cavallini, A., Lindell, E., Montanari, G.C., *et al.*: 'Off-line PD testing of converter-fed wire-wound motors: when IEC TS 60034-18-41 may fail?', *IEEE Trans. Dielectr. Electr. Insul.*, 2010, **17**, (5), pp. 1385–1395
- [20] IEC Standard, 60034-18-41: 2006: 'Rotating electrical machines qualification and type tests for type I electrical insulation systems used in rotating electrical machines fed from voltage converters'. IEC Central Office, Switzerland, 2006
- [21] Yang, J., Cho, J., Sang, B.L.: 'An advanced stator winding insulation quality assessment technique for inverter-fed machines'. *IEEE Trans. Ind. Appl.*, 2008, **44**, (2), pp. 555–564
- [22] Tong, L., Wen, F., Wu, G., *et al.*: 'Calculation of transient voltage distribution in windings of inverter-fed traction motor'. *High Volt. Eng.*, 2006, **32**, (2), pp. 1–3, in Chinese
- [23] Kikuchi, H., Hanawa, H.: 'Inverter surge resistant enameled wire with nanocomposite insulating material'. *IEEE Trans. Dielectr. Electr. Insul.*, 2012, **19**, (1), pp. 99–106
- [24] Guastavino, F., Ratto, A., Torello, E., *et al.*: 'Electrical aging tests on different nanostructured enamels subjected to severe voltage waveforms'. IEEE Int. Symp. Diagnostics for Electric Machines, Power Electron Drives, Bologna, Italy, 2011, pp. 278–282
- [25] Mbaye, A., Bellomo, J.P., Lebey, T., *et al.*: 'Electrical stresses applied to stator insulation in low-voltage induction motors fed by PWM drives', *IEEE Proc. Electr. Power Appl.*, 1997, **144**, (3), pp. 191–198
- [26] Zhou, K., Li, X.: 'Aging characteristics of inter-turn insulation of form-wound stator windings of inverter-fed AC motors', *Electr. Mach. Power Syst.*, 2013, **41**, (13), pp. 1280–1293
- [27] Hyypio, D.B.: 'Simulation of cable and winding response to steep-fronted voltage waves'. Industry Applications Conf., Orlando, FL, USA, 1995, pp. 800–806
- [28] Mihailal, V., Duchesne, S., Roger, D.: 'A simulation method to predict the turn-to-turn voltage spikes in a PWM fed motor winding', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (5), pp. 1609–1615
- [29] Fenger, M., Campbell, S.R., Pedersen, J.: 'Motor winding problems caused by inverter drives', *IEEE Ind. Appl. Mag.*, 2003, **9**, (4), pp. 22–31
- [30] Bidan, P., Lebey, T., Montseny, G., *et al.*: 'Transient voltage distribution in inverter fed motor windings: experimental study and modeling', *IEEE Trans. Power Electron.*, 2001, **16**, (1), pp. 92–100
- [31] Toliyat, H.A., Kliman, G.B.: 'Handbook of electric motors' (CRC Press, Boca Raton, FL, USA, 2004), p. 12
- [32] Stone, G.C., Boulter, E.A., Culber, I.: 'Electrical insulation for rotating machines. Electrical insulation for rotating machines: design, evaluation, aging, testing, and repair' (Wiley-IEEE Press, Hoboken, NJ, USA, 2004), p. 65
- [33] Luo, Y., Wu, G., Liu, J., *et al.*: 'PD characteristics and microscopic analysis of polyimide film used as turn insulation in inverter-fed motor', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (5), pp. 2237–2244
- [34] Akram, S., Wu, G., Gao, G., *et al.*: 'Effect of surface discharge on nano filled polyimide film under square voltage'. IEEE Electrical Insulation Conf., Seattle, WA, USA, 2015, pp. 226–229
- [35] Du, B., Xing, Y.: 'Surface potential behavior of fluorinated polyimide film under low temperature', *IEEE Trans. Dielectr. Electr. Insul.*, 2016, **23**, (1), pp. 121–128
- [36] Phung, B., Shao, S., Rahman, M., *et al.*: 'Partial discharge measurements in PWM inverter-driven low-voltage motors'. Australasian Universities Power Engineering Conf., Adelaide, SA, Australia, 2009, pp. 1–6
- [37] IEC 60851-5-2011 Winding wires – test methods – part 5: electrical properties[S]. 2011
- [38] IEC 60172-2015 test procedure for the determination of the temperature index of enamelled and tape wrapped winding wires[S]. 2015
- [39] Gornicka, B., Prociow, K.: 'Insulating system of inverter-driven motors based on nanocomposites', *Adv. Manuf. Process.*, 2009, **24**, (10–11), pp. 1202–1206
- [40] Guastavino, F., Coletti, G., Torello, E.: 'Medium term aging characterization of enamelled for high frequency applications', *IEEE Trans. Dielectr. Electr. Insul.*, 2005, **12**, (3), pp. 524–529
- [41] Haq, S.U., Jayaram, S.H., Cherney, E.A.: 'Evaluation of medium voltage enameled wire exposed to fast repetitive voltage pulses', *IEEE Trans. Dielectr. Electr. Insul.*, 2007, **14**, (1), pp. 194–203
- [42] Yin, W.: 'Dielectric properties of an improved magnet wire for inverter-fed motors', *IEEE Electr. Insul. Mag.*, 1997, **13**, (4), pp. 17–23
- [43] Yin, W.: 'Failure mechanism of winding insulations in inverter-fed motors', *IEEE Electr. Insul. Mag.*, 1997, **13**, (6), pp. 18–23
- [44] Stone, G.C., Heeswijk, R.G., Bartnikas, R.: 'Electrical aging and electroluminescence in epoxy under repetitive voltage surges', *IEEE Trans. Electr. Insul.*, 2002, **27**, (2), pp. 233–244
- [45] Guastavino, F., Dardano, A.: 'Life tests on twisted pairs in presence of partial discharges: influence of the voltage waveform', *IEEE Trans. Dielectr. Electr. Insul.*, 2012, **19**, (1), pp. 45–52
- [46] Guastavino, F., Coletti, G., Torello, E.: 'Twisted pairs specimens subjected to several waveform voltages in presence of partial discharges'. IEEE Report Conf. Electrical Insulation and Dielectric Phenomena, Cancun, Quintana Roo, Mexico, 2002, pp. 450–453
- [47] Wang, P., Cavallini, A., Montanari, G.C., *et al.*: 'Effect of rise time on PD pulse features under repetitive square wave voltages'. *IEEE Trans. Dielectr. Electr. Insul.*, 2013, **20**, (1), pp. 245–254
- [48] Lindell, E., Bengtsson, T., Blennow, J., *et al.*: 'Influence of rise time on partial discharge extinction voltage at semi-square voltage waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2010, **17**, (1), pp. 141–148
- [49] Metzler, D.A., Hake, J.E.: 'The effect of mechanical deformation and wire size on the ozone erosion resistance of inverter-duty magnet wires'. Proc. Electrical Insulation Conf. Electrical Manufacturing and Coil Winding Conf., Roseman, USA, 1997, pp. 389–395
- [50] Beeckman, R.J., Harber, J.J., Wentz, S.J.: 'Studies on magnet wire degradation with inverter driven motors'. Proc. Electrical Insulation Conf. Electrical Manufacturing and Coil Winding Conf., Rosemont, IL, USA, 1997, pp. 383–387
- [51] Bonnett, H.: 'A comparison between insulation systems available for PWM-inverter-fed motors', *IEEE Trans. Ind. Appl.*, 1996, **33**, (5), pp. 1331–1341
- [52] Bellomo, J.P., Lebey, T., Oraison, J.M., *et al.*: 'Electrical aging of stator insulation of low voltage rotating machines supplied by inverters'. IEEE Int. Symp. Electrical Insulation, Montreal, Quebec, Canada, 1996, vol. **1**, pp. 210–213
- [53] Melfi, M., Sung, A.M.J., Bell, S., *et al.*: 'Effect of surge voltage rise time on the insulation of low-voltage machines fed by PWM converters', *IEEE Trans. Ind. Appl.*, 1998, **34**, (4), pp. 766–775
- [54] Haq, S.U.: 'A study on insulation problems in drive fed medium voltage induction motors' (University of Waterloo, Waterloo, 2007)
- [55] Florkowska, B., Roehrich, J., Zydroi, P., *et al.*: 'Measurement and analysis of surface partial discharges at semi-square voltage waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (4), pp. 990–996
- [56] Lindell, E., Bengtsson, T., Blennow, J., *et al.*: 'Measurement of partial discharges at rapidly changing voltages', *IEEE Trans. Dielectr. Electr. Insul.*, 2008, **15**, (3), pp. 823–831
- [57] Mazzanti, G., Montanari, G.C.: 'Electrical aging and life models: the role of space charge', *IEEE Trans. Dielectr. Electr. Insul.*, 2005, **12**, (5), pp. 876–890
- [58] Morshuis, P.H.F.: 'Partial discharge mechanisms' (Delft University of Technology, Delft, Netherlands, 1993)
- [59] Farahani, M., Borsi, H., Gockenbach, E., *et al.*: 'Partial discharge and dissipation factor behavior of model insulating systems for high voltage rotating machines under different stresses', *IEEE Electr. Insul. Mag.*, 2005, **21**, (5), pp. 5–19
- [60] Gamez-Garcia, M.: 'Synthesis reactions involving XLPE subjected to partial discharges', *IEEE Trans. Dielectr. Electr. Insul.*, 1987, **EI-22**, (2), pp. 199–205
- [61] Morshuis, P.H.F.: 'Degradation of solid dielectrics due to internal partial discharge: some thoughts on progress made and where to go now', *IEEE Trans. Dielectr. Electr. Insul.*, 2005, **12**, (5), pp. 905–913
- [62] Katrin, T.: 'Evaluation of surface changes in flat cavities due to ageing by means of phase-angle resolved partial discharge measurement', *J. Phys. D, Appl. Phys.*, 2000, **33**, (33), p. 603
- [63] Pietrini, G., Barater, D., Immovilli, F., *et al.*: 'Multi-stress lifetime model of the winding insulation of electrical machines'. 2017 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), Nottingham, UK, 2017, pp. 268–274
- [64] Parpal, J., Crine, J., Dang, C.: 'Electrical aging of extruded dielectric cables. A physical model', *IEEE Trans. Dielectr. Electr. Insul.*, 1997, **4**, (2), pp. 197–209
- [65] Devins, J.C.: 'Physics of partial discharges in solid dielectrics', *IEEE Trans. Dielectr. Electr. Insul.*, 1984, **19**, pp. 475–495
- [66] Morshuis, P.H.F., Smit, J.J.: 'Partial discharges at DC voltage: their mechanism, detection and analysis', *IEEE Trans. Dielectr. Electr. Insul.*, 2005, **12**, (2), pp. 328–340
- [67] Fabiani, D., Montanari, G.C., Contin, A.: 'Aging acceleration of insulating materials for electrical machine windings supplied by PWM in the presence and in the absence of partial discharges'. IEEE Seventh Int. Conf. Solid Dielectrics, Eindhoven, Netherlands, 2001, pp. 283–286
- [68] Mazzanti, G., Montanari, G.C., Dissado, L.A.A.: 'Space charge life model for AC electrical aging of polymers', *IEEE Trans. Dielectr. Electr. Insul.*, 1999, **6**, (6), pp. 864–875
- [69] Guastavino, F., Tiemblo, P.: 'Models for life prediction in surface PD on polymer films', *IEEE Trans. Dielectr. Electr. Insul.*, 1997, **4**, (2), pp. 189–196
- [70] Zheng, F., Zhang, Y., Xiao, C.: 'Relationship between breakdown in polymer dielectrics and space charge', *J. Mater. Sci. Eng.*, 2006, **24**, (2), pp. 315–316
- [71] Lau, K., Vaughan, A., Chen, G., *et al.*: 'On the space charge and DC breakdown behavior of polyethylene/silica nanocomposites', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (1), pp. 340–351
- [72] Mazzanti, G., Montanari, G.C., Dissado, L.A.A.: 'Elemental strain and trapped space charge in thermoelectrical aging of insulating materials: life modeling', *IEEE Trans. Dielectr. Electr. Insul.*, 2001, **8**, (6), pp. 966–971
- [73] Akram, S., Gao, G., Liu, Y., *et al.*: 'Degradation mechanism of Al₂O₃ nano filled polyimide film due to surface discharge under square impulse voltage', *IEEE Trans. Dielectr. Electr. Insul.*, 2015, **22**, (6), pp. 3341–3349
- [74] Montanari, G.C.: 'Bringing an insulation to failure: the role of space charge', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (2), pp. 339–364
- [75] Dissado, L.A., Mazzanti, G., Montanari, G.C.: 'The incorporation of space charge degradation in the life model for electrical insulating materials', *IEEE Trans. Dielectr. Electr. Insul.*, 1995, **2**, pp. 1147–1158
- [76] Mazzanti, G., Montanari, G.C., Dissado, L.A.: 'A space charge life model for AC electrical aging of polymers', *IEEE Trans. Dielectr. Electr. Insul.*, 1999, **6**, pp. 864–875
- [77] Wu, G., Cao, K., Luo, Y., *et al.*: 'Partial discharge characteristics of inter-turn insulation used for inverter-fed traction motor under bipolar impulses', *Sci. China E*, 2012, **55**, (8), pp. 2346–2354
- [78] Liu, J., Wu, G., Zhou, L., *et al.*: 'Measurement for space charge and analysis on insulation aging under PWM voltage'. Int. Conf. Properties and Applications of Dielectric Materials, Harbin, China, 2009, pp. 903–906
- [79] Wu, G., Wu, J., Zhou, L., *et al.*: 'Microscopic view of aging mechanism of polyimide film under pulse voltage in presence of partial discharge', *IEEE Trans. Dielectr. Electr. Insul.*, 2010, **17**, (1), pp. 125–132
- [80] Yin, W., Bultemeier, K., Barta, D.: 'Critical factors for early failure of magnet wires in inverter-fed motor'. IEEE Report Conf. Electrical Insulation and Dielectric Phenomena, Virginia Beach, VA, USA, 1995, pp. 258–261
- [81] Sonerud, B., Bengtsson, T., Blennow, J., *et al.*: 'Dielectric heating in insulating materials subjected to voltage waveforms with high harmonic content', *IEEE Trans. Dielectr. Electr. Insul.*, 2009, **16**, (4), pp. 926–933

- [82] Toliyat, H.A., Kliman, G.B.: 'Handbook of electric motors' (Marcel Dekker, New York, 2004, 2nd edn.)
- [83] Liu, R., Jaksts, A.: 'Breakdown processes in transformer insulation under LI voltages'. IEEE Int. Conf. Dielectric Liquids, Coimbra, Portugal, Portugal, 2005, pp. 75–78
- [84] Sun, P., Sima, W., Yang, M., et al.: 'Influence of thermal aging on the breakdown characteristics of transformer oil impregnated paper', *IEEE Trans. Dielectr. Electr. Insul.*, 2016, **23**, (6), pp. 3373–3381
- [85] Wang, Z., Pang, L., Wang, T., et al.: 'Breakdown characteristics of oil–paper insulation under lightning impulse waveforms with oscillations', *IEEE Trans. Dielectr. Electr. Insul.*, 2015, **22**, (5), pp. 2620–2627
- [86] Du, B., Jiang, J., Zhang, J., et al.: 'Dynamic behavior of surface charge on double-layer oil–paper insulation under pulse voltage', *IEEE Trans. Dielectr. Electr. Insul.*, 2016, **23**, (5), pp. 2712–2719
- [87] Bossi, A., Dind, J.E., Frisson, J.M., et al.: 'An international survey on failures in large power transformers in service', *Electra*, 1983, **88**, pp. 21–48
- [88] Ralls, K.J.: 'The reliability of transmission and distribution equipment', *Power Eng. J.*, 1995, **9**, (3), pp. 109–112
- [89] Sun, P., Sima, W., Yang, M., et al.: 'Study on voltage-number characteristics of transformer insulation under transformer invading non-standard lightning impulses', *IEEE Trans. Dielectr. Electr. Insul.*, 2015, **22**, (6), pp. 3582–3591
- [90] Sima, W., Lan, X., Yang, Q., et al.: 'Statistical analysis on measured lightning overvoltage surges in a 110 kV air-insulated substation', *IET High Volt.*, 2016, **1**, (1), pp. 18–24
- [91] Sima, W., Sun, P., Yang, M., et al.: 'Impact of time parameters of lightning impulse on the breakdown characteristics of oil–paper insulation', *IET High Volt.*, 2016, **1**, (1), pp. 18–24
- [92] Sima, W., Sun, P., Yang, Q., et al.: 'Study on the accumulative effect of repeated lightning impulses on insulation characteristics of transformer oil impregnated paper', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (4), pp. 1933–1941
- [93] Florkowski, M., Furgal, J., Pajak, P.: 'Analysis of fast transient voltage distributions in transformer windings under different insulation conditions', *IEEE Trans. Dielectr. Electr. Insul.*, 2013, **19**, (6), pp. 1991–1998
- [94] Masdi, H., Mariun, N., Mohamed, A., et al.: 'Study of impulse voltage distribution in transformer windings'. IEEE Int. Conf. Power and Energy, Kuala Lumpur, Malaysia, 2011, pp. 379–383
- [95] Sabiha, N.A., Lehtonen, M.: 'Lightning-induced overvoltages transmitted over distribution transformer with MV spark-gap operation – part I: high-frequency transformer model', *IEEE Trans. Power Deliv.*, 2010, **25**, (4), pp. 2472–2480
- [96] IEC 60060-1, high voltage test techniques – part I: general definitions and test requirements[S]. 2010
- [97] Okabe, S., Koutou, M., Kawashima, T., et al.: 'Dielectric characteristics of oil-filled transformer insulation models under non-standard lightning impulse voltages'. High Voltage Engineering Symp., London, UK, 1999, pp. 345–348
- [98] Okabe, S., Yuasa, S., Kaneko, S.: 'Evaluation of breakdown characteristics of gas insulated switchgears for non-standard lightning impulse waveforms – analysis and generation circuit of non-standard lightning impulse waveforms in actual field', *IEEE Trans. Dielectr. Electr. Insul.*, 2007, **14**, (2), pp. 312–360
- [99] Okabe, S., Takami, J.: 'Evaluation of breakdown characteristics of oil-immersed transformers under non-standard lightning impulse waveforms – method for converting non-standard lightning impulse waveforms into standard lightning impulse waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2008, **15**, (5), pp. 1288–1296
- [100] Ueta, G., Kaneko, S., Okabe, S.: 'Evaluation of breakdown characteristics of gas insulated switchgears for non-standard lightning impulse waveforms – breakdown characteristics under non-uniform electric field', *IEEE Trans. Dielectr. Electr. Insul.*, 2008, **15**, (5), pp. 1430–1438
- [101] Ueta, G., Kaneko, S., Okabe, S.: 'Evaluation of breakdown characteristics of gas insulated switchgears for non-standard lightning impulse waveforms – breakdown characteristics for double-frequency oscillations under non-uniform electric field', *IEEE Trans. Dielectr. Electr. Insul.*, 2009, **16**, (3), pp. 815–825
- [102] Wada, J., Ueta, G., Okabe, S.: 'Evaluation of breakdown characteristics of N₂ gas for non-standard lightning impulse waveforms – breakdown characteristics under single-frequency oscillation waveforms and with bias voltages', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (5), pp. 1759–1766
- [103] Ueta, G., Wada, J., Okabe, S.: 'Evaluation of breakdown characteristics of CO₂ gas for non-standard lightning impulse waveforms – breakdown characteristics under single-frequency oscillation waveforms of 1.3 to 4.0 MHz', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (1), pp. 192–199
- [104] Ueta, G., Wada, J., Okabe, S.: 'Evaluation of breakdown characteristics of CO₂ gas for non-standard lightning impulse waveforms – breakdown characteristics under single-frequency oscillation waveforms of 5.3 to 20.0 MHz', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (1), pp. 238–245
- [105] Wada, J., Ueta, G., Okabe, S.: 'Evaluation of breakdown characteristics of CO₂ gas for non-standard lightning impulse waveforms under non-uniform electric field – breakdown characteristics for single-frequency oscillation waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (2), pp. 640–648
- [106] Yuasa, S., Suzuki, H., Okabe, S.: 'Insulation characteristics of GIS under nonstandard lightning-impulse oscillations: insulation characteristics under single-frequency oscillations with various frequencies and damping ratios', *Electr. Eng. Jpn.*, 2003, **145**, (3), pp. 43–49
- [107] Okabe, S., Koto, M., Kato, K., et al.: 'Insulation characteristics of GIS under oscillatory waveforms of non-standard lightning impulse'. High Voltage Engineering Symp., London, UK, 1999, pp. 269–272
- [108] Ueta, G., Wada, J., Okabe, S.: 'Evaluation of breakdown characteristics of CO₂ gas for non-standard lightning impulse waveforms - method for converting non-standard lightning impulse waveforms into standard lightning impulse waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (5), pp. 1724–1733
- [109] Okabe, S.: 'Evaluation of breakdown characteristics of oil-immersed transformers under non-standard lightning impulse-insulation characteristics for non-standard lightning impulse waveforms with oscillations', *IEEE Trans. Dielectr. Electr. Insul.*, 2007, **14**, (3), pp. 679–688
- [110] Wada, J., Ueta, G., Okabe, S.: 'Evaluation of breakdown characteristics of CO₂ gas for non-standard lightning impulse waveforms – breakdown characteristics in the presence of bias voltages under non-uniform electric field', *IEEE Trans. Dielectr. Electr. Insul.*, 2013, **20**, (1), pp. 112–121
- [111] Wada, J., Ueta, G., Okabe, S.: 'Evaluation of breakdown characteristics of N₂ gas for non-standard lightning impulse waveforms – method for converting non-standard lightning impulse waveforms into standard lightning impulse waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2013, **20**, (2), pp. 505–514
- [112] Wada, J., Ueta, G., Okabe, S.: 'Evaluation of breakdown characteristics of N₂ gas for non-standard lightning impulse waveforms under non-uniform electric field – breakdown characteristics for single-frequency oscillation waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2012, **19**, (1), pp. 263–273
- [113] Wada, J., Ueta, G., Okabe, S.: 'Evaluation of breakdown characteristics of CO₂ gas for non-standard lightning impulse waveforms – breakdown characteristics under double-frequency oscillation waveforms and single-frequency oscillation waveforms in the presence of bias voltage', *IEEE Trans. Dielectr. Electr. Insul.*, 2012, **19**, (5), pp. 1799–1809
- [114] Wada, J., Ueta, G., Okabe, S.: 'Evaluation of breakdown characteristics of N₂ gas for non-standard lightning impulse waveforms – breakdown characteristics under double-frequency oscillation waveforms and pressure-distance characteristics', *IEEE Trans. Dielectr. Electr. Insul.*, 2012, **19**, (5), pp. 1810–1818
- [115] Carrus, A., Cinieri, E., Fumi, A., et al.: 'Short tail lightning impulse behaviour of medium voltage line insulation', *IEEE Trans. Power Deliv.*, 1999, **14**, (1), pp. 218–226
- [116] Ancajima, A., Carrus, A., Cinieri, E., et al.: 'Breakdown characteristics of air spark-gaps stressed by standard and short-tail lightning impulses: experimental results and comparison with time to sparkover models', *J. Electrostat.*, 2007, **65**, pp. 282–288
- [117] Ancajima, A., Baran, I., Costea, M., et al.: 'Breakdown characteristics of MV distribution and electric traction lines insulators stressed by standard and short tail lightning impulses'. IEEE Conf. Power Technology, St. Petersburg, Russia, 2005, pp. 1–7
- [118] Rakov, V.A.: 'Lightning parameters for engineering applications'. Asia-Pacific Int. Symp. Electromagnetic Compatibility, Beijing, China, 2010, pp. 1120–1123
- [119] Husseina, M., Janischewskyj, W., Milewska, M., et al.: 'Current waveform parameters of CN tower lightning return strokes', *J. Electrostat.*, 2004, pp. 149–162
- [120] Lu, C.: 'Research on the damage and characteristic of oil–paper insulation under the accumulative effect of switching impulse voltage' (Chongqing University, Chongqing, 2014), in Chinese
- [121] Okabe, S.: 'Voltage-time and voltage-number characteristics of insulation elements with oil-filled transformers in EHV and UHV classes', *IEEE Trans. Dielectr. Electr. Insul.*, 2006, **13**, (1), pp. 436–444
- [122] CIGRE Report: insulation co-ordination related to internal insulation of gas insulated systems with SF₆ and nitrogen/SF₆ gas mixtures under AC condition. Working group C4. 302, No. 360, 2008
- [123] Okabe, S.: 'Insulation properties and degradation mechanism of insulating spacers in gas insulated switchgear (GIS) for repeated/long voltage application', *IEEE Trans. Dielectr. Electr. Insul.*, 2007, **14**, (1), pp. 101–110
- [124] Liu, Q., Wang, Z., Dyer, P.: 'Accumulative effect on streamer propagation of lightning impulses on oil/pressboard interface'. 2011 IEEE Int. Conf. Dielectric Liquids, Trondheim, Norway, 2011
- [125] Liu, Q., Wang, Z.: 'Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (1), pp. 285–294
- [126] Sima, W., Sun, P., Yang, Q., et al.: 'Accumulative effect of oil–paper insulation system under multiple lightning impulse voltage'. IEEE Conf. Electrical Insulation and Dielectric Phenomena, Shenzhen, 2013
- [127] Sima, W., Sun, P., Yang, Q., et al.: 'Dielectric characteristics analysis of oil–paper insulation under lightning impulse voltage'. 18th Int. Symp. High Voltage Engineering, Seoul, 2013
- [128] Sun, P., Sima, W., Yang, M., et al.: 'Accumulative effect of repeated lightning impulses on transformer insulation: mechanism analysis', *IEEE Trans. Dielectr. Electr. Insul.*, 2016, **23**, (4), pp. 2430–2437
- [129] Huang, M., Zhou, Y., Chen, W., et al.: 'Influence of voltage reversal on space charge behavior in oil–paper insulation', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (1), pp. 331–339
- [130] Li, W., Li, J., Wang, X., et al.: 'Physicochemical origin of space charge dynamics for aged XLPE cable insulation', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (2), pp. 809–820
- [131] Zhou, Y., Huang, M., Chen, W., et al.: 'Space charge behavior evolution with thermal aging of oil–paper insulation', *IEEE Trans. Dielectr. Electr. Insul.*, 2015, **22**, (3), pp. 1381–1388
- [132] Damamme, G., Gressus, C.L., De Reggi, A.S.: 'Space charge characterization for the 21st century', *IEEE Trans. Dielectr. Electr. Insul.*, 1997, **4**, (5), pp. 558–584
- [133] Rakov, V.A., Uman, M.A.: 'Lightning physics and effects' (Cambridge University Press, New York, 2003), p. 108
- [134] Sima, W., Sun, P., Yang, M., et al.: 'Effect of space charge on the accumulative characteristics of oil–paper insulation under repeated lightning impulses', *IEEE Trans. Dielectr. Electr. Insul.*, 2015, **22**, (5), pp. 2483–2490

- [135] Sun, P.: 'Study on accumulative effect of repeated lightning impulse on oil-paper insulation and its influence factors' (Chongqing University, Chongqing, 2016), in Chinese
- [136] Sun, P., Sima, W., Zhang, D., *et al.*: 'Impact of wavefront time of microsecond impulse on the breakdown voltage of oil impregnated paper: mechanism analysis', *IEEE Trans. Dielectr. Electr. Insul.*, 2018, **25**, (5), pp. 1706–1715
- [137] Okabe, S.: 'Voltage-time and voltage-number characteristics of insulation elements with large scale oil-immersed transformers under field-use conditions', *IEEE Trans. Dielectr. Electr. Insul.*, 2006, **13**, (6), pp. 1261–1271
- [138] Okabe, S., Yuasa, S., Kaneko, S., *et al.*: 'Evaluation of breakdown characteristics of gas insulated switchgears for non-standard lightning impulse waveforms – method for converting non-standard lightning impulse waveforms into standard lightning impulse waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2009, **16**, (1), pp. 42–51
- [139] Okabe, S., Yuasa, S., Kaneko, S.: 'Evaluation of breakdown characteristics of gas insulated switchgears for non-standard lightning impulse waveforms – breakdown characteristics for non-standard lightning impulse waveforms associated with lightning surges', *IEEE Trans. Dielectr. Electr. Insul.*, 2008, **15**, (2), pp. 407–415
- [140] Sima, W., Wu, J., Sun, P., *et al.*: 'Breakdown characteristics of oil-impregnated paper and influential factors for damped alternating oscillation waveforms', *IEEE Trans. Dielectr. Electr. Insul.*, 2016, **23**, (4), pp. 2079–2087
- [141] Cui, Y., Wu, G., Wu, C., *et al.*: 'Possible mechanism of electrical treeing and breakdown for polyimide nanocomposite film used in inverter-fed motor'. IEEE Electrical Insulation and Dielectric Phenomena, West Lafayette, IN, USA, 2011, pp. 1–4
- [142] Li, S., Min, D., Wang, W., *et al.*: 'Linking traps to dielectric breakdown through charge dynamics for polymer nanocomposites', *IEEE Trans. Dielectr. Electr. Insul.*, 2016, **23**, (5), pp. 2777–2785
- [143] Yin, Y., Dong, X., Chen, J., *et al.*: 'High field electrical conduction in the nanocomposite of low-density polyethylene and nano-SiO_x', *IEEJ Trans. Fundam. Mater.*, 2006, **126**, (11), pp. 1064–1071
- [144] Tu, Y., Zheng, Z., Li, X., *et al.*: 'Grain – boundary and thermally stimulated current characteristics of Y₂O₃ – doped ZnO varistor', *J. Am. Ceram. Soc.*, 2013, **96**, (11), pp. 3518–3522
- [145] Tu, Y., Chen, J., Wang, S., *et al.*: 'Moisture migration in oil-impregnated film insulation under thermal ageing', *IEEE Trans. Dielectr. Electr. Insul.*, 2016, **23**, (2), pp. 1135–1141
- [146] Tu, Y., Sun, W., Yue, C., *et al.*: 'Research of insulation properties of polymer materials using in oil-filled transformers under high temperature'. IEEE Conf. Electrical Insulation and Dielectric Phenomena, Cancun, Mexico, 2011, pp. 583–586
- [147] Zha, J., Song, H., Dang, Z., *et al.*: 'Mechanism analysis of improved corona-resistant characteristic in polyimide/TiO₂ nanohybrid films', *Appl. Phys. Lett.*, 2008, **93**, (19), p. 2190
- [148] Yan, W., Phung, B., Han, Z., *et al.*: 'Plasma polymer-coated on nanoparticles to improve dielectric and electrical insulation properties of nanocomposites', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (2), pp. 548–555
- [149] Yan, W., Han, Z., Phung, B., *et al.*: 'Silica nanoparticles treated by cold atmospheric-pressure plasmas improve the dielectric performance of organic-inorganic nanocomposites', *ACS Appl. Mater. Interfaces*, 2012, **4**, (5), pp. 2637–2642
- [150] Li, H., Liu, G., Liu, B., *et al.*: 'Dielectric properties of polyimide/Al₂O₃ hybrids synthesized by in-situ polymerization', *Mater. Lett.*, 2007, **61**, (7), pp. 1507–1511
- [151] Li, J., Du, B., Wang, F., *et al.*: 'The effect of nanoparticle surfactant polarization on trapping depth of vegetable insulating oil-based nanofluids', *Phys. Lett. A*, 2016, **380**, (4), pp. 604–608
- [152] Du, B., Li, J., Wang, F., *et al.*: 'Influence of monodisperse Fe₃O₄ nanoparticle size on electrical properties of vegetable oil-based nanofluids'. *J. Nanomater.*, 2015, **2015**, (1), p. 1
- [153] Liao, R., Lv, C., Yang, L., *et al.*: 'The insulation properties of oil-impregnated insulation paper reinforced with nano-TiO₂', *J. Nanomater.*, 2013, **2013**, (1), p. 1
- [154] Liao, R., Lv, C., Yang, L., *et al.*: 'Space charge behavior in oil-impregnated insulation paper reinforced with nano-TiO₂', *Bioresources*, 2013, **8**, (4), pp. 5655–5665
- [155] Sun, P., Sima, W., Zhang, D., *et al.*: 'Effects of impulse waveform parameters on the breakdown characteristics of nano-TiO₂ modified transformer oil', *IEEE Trans. Dielectr. Electr. Insul.*, 2018, **25**, (5), pp. 1651–1659
- [156] He, L., Liao, R., Lv, Y., *et al.*: 'Effect of nano-Al₂O₃ on the thermal aging physicochemical properties of insulating paper'. IEEE Int. Conf. Condition Monitoring and Diagnosis, Xi'an, China, 2016, pp. 254–257
- [157] Sun, P., Sima, W., Jiang, X., *et al.*: 'Failure characteristics and mechanism of nano-modified oil-impregnated paper subjected to repeated impulse voltage', *Nanomaterials*, 2018, **8**, (7), p. 5042018
- [158] Sun, P., Sima, W., Jiang, X., *et al.*: 'Failure of nano-modified oil impregnated paper under repeated impulse voltage: effects of nano-TiO₂ on space charge characteristics', *IEEE Trans. Dielectr. Electr. Insul.*, 2018, **25**, (6), pp. 2103–2111
- [159] Sun, P., Sima, W., Chen, J., *et al.*: 'An application area of C₆₀: overall improvement of insulating oil's electrical performance', *Appl. Phys. Lett.*, 2018, **112**, (14), p. 142902
- [160] Sun, P., Sima, W., Jiang, X., *et al.*: 'Failure characteristics and mechanism of nano-modified oil impregnated paper subjected to repeated impulse voltage', *Nanomaterials*, 2018, **8**, (7), p. 504