

A Unified Formula for Five Basic Forms of Discharge in an Electric Field Under Short Pulses

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Abstract—This study proposes a unified formula for five basic forms of discharge—gas, liquid, solid, and vacuum breakdown, and vacuum surface flashover—under short pulses in an electric field. This formula considers the effects of the number of dimensions and pulsewidth on the electric field. It is verified by using the results of experiments reported at the Aldermaston Weapon Research Establishment (AWRE) and the Northwest Institute of Nuclear Technology. The ranges of application of this formula to different discharge forms are also summarized. The proposed formula can be used to transform experimental data at a small scale under a known pulsewidth into those at a large scale under the application pulsewidth and is thus important for designing insulation.

Index Terms—Gas, insulation design, liquid, pulsed power, solid, vacuum, vacuum surface.

I. INTRODUCTION

SEVERAL high-voltage (HV) accelerators that can generate short pulses at a high current have been constructed, such as the Z/ZR, Saturn, Magpie, Angara-5-1, PST, Yang, Flash-II, and Qiangguang-I. High-power microwave generators have also been manufactured to generate HV short pulses and include the Sinus- and Radan-series generators in Russia as well as the TPG-, CKP-, and CHP-series generators in China. The construction of these pulsed power generators has led to rapid developments in HV insulation technology under short pulses.

Starting in 1960, Martin [1], [4] at the Aldermaston Weapon Research Establishment (AWRE) in U.K. made significant contributions to the field of pulsed power. He proposed several formulas for the breakdown of gases, liquids, and solids as well as fast-pulsed vacuum surface flashover in an electric field. The breakdown of a gas in a quasi-unified field can be given by

$$E_g = 24.6p + 6.7(p/g)^{0.5} \quad (1)$$

where E_g is the electric field during gas breakdown (kV/cm), p is the gas pressure (atm), and g is the electrode gap (cm).

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Gas breakdown in a nonunified field [6] is given by

$$E_g t_e^{1/6} g^{1/6} = k_g p^n \quad (2)$$

where t_e is the effective duration of the electric field (μ s) and denotes the time for which the field exceeds $0.63 E_g$. k_g is a constant, and p ranges from 1 to 5 atm. The formula for liquid breakdown is

$$E_l t_e^{1/3} A_l^{1/10} = k_l \quad (3)$$

where E_l is the electric field during the breakdown of liquid, t_e is in units of μ s, A_l is the effective area of the electrode in the liquid that corresponds to the area in which the field exceeds $0.9 E_l$, and k_l is a constant. Vacuum surface flashover is given by

$$E_{vf} t_e^{1/6} A_{vf}^{1/10} = k_{vf} \quad (4)$$

where E_{vf} is the electric field during surface flashover, A_{vf} is the surface area of the insulator, and k_{vf} is a constant. Solid breakdown is given as follows:

$$E_s V_s^{1/10} = k_s \quad (5)$$

where E_s is the electric field during solid breakdown, V_s is the volume of the solid dielectric that sustains a field exceeding $0.9 E_s$, and k_s is a constant. The above formulas are widely accepted and used in insulation design for pulsed power.

Since 1966, a large number of experiments under nanosecond pulses have been conducted at the Tomsk Polytechnic University (TPU) in Russia to provide useful experimental data for practical design. A formula for the value of E_s of solid dielectrics was proposed [10]

$$\lg E_s = K_1 - K_2 \lg d - (K_3 - K_4 \lg d) \lg \tau \quad (6)$$

where d is the thickness of the dielectric in mm, τ is the pulsewidth in ns, and K_1 – K_4 are constants.

In 1996, a pulsed power formulary was published by the North Star Research Corporation (NSRC) in USA that summarized a large number of expressions for practical insulation [11]. In particular, the dependence of the breakdown field (E_v) of vacuum in the presence of a gap under a voltage of 500 kV was given as

$$E_v = k_v g_v^{-0.3} \quad (7)$$

where k_v is a constant and g_v is the vacuum gap.

In 1999, a formula for vacuum surface flashover for an insulator stack was reported by Sandia National Laboratories (SNL) in USA [12]

$$E_{of}(t_e C_b)^{1/10} \exp(-0.27/d) = 224 \quad (8)$$

where C_b is the bottom circumference of conical insulators (cm) and d is the thickness of the insulator. This formula was developed based on Martin's formula in (4). A set of formulas to calculate the threshold of vacuum flashover of a radial low-inductance insulator was also reported by Vitkovitsky [14] based on Martin's formula

$$\begin{cases} E_S \leq 5 \times 10^5 t_e^{-1/6} A^{-1/8.5} \\ E_T \leq 1.6 \times 10^6 t_e^{-1/6} A^{-1/8} \\ E_P \leq 5 \times 10^6 \end{cases} \quad (9)$$

where E_S is the field along the surface, E_T is the total field, and E_P is the field at the triple junction of the cathode or anode. In this formula, all the parameters are in the MKS systems of units.

Since 2000, the mechanisms of insulation as well as the characteristics of vacuum, gas, transformer oil, and the oil–solid surface under nanosecond pulses have been systematically explored at the Institute of Electrical Engineering (IEE) in China. Details have been provided in [16]. Some novel phenomena and regularities have been reported, such as the “wormhole effect” and E_g for gas breakdown

$$\rho t_d = A_1 \left(\frac{E_g}{\rho} \right)^{-B_1} \quad (10)$$

where ρ is the density of gas in g/cm^3 , t_d is the delay in breakdown (s), and A_1 and B_1 are constants. According to Shao *et al.* [18] at the IEE, $A_1 = 0.78$ and $B_1 = 2.14$. However, according to Martin [6], $A_1 = 97800$ and $B_1 = 3.44$; according to Mankowski [19], [20], $A_1 = 0.9$ and $B_1 = 2.25$.

Since 2010, the breakdown characteristics of solid dielectrics under nanosecond pulses, the characteristics of vacuum flashover under radio frequency pulses, and the characteristics of breakdown of a long-gap vacuum under microsecond pulses have been examined at the Northwest Institute of Nuclear Technology (NINT) in China, and some concise formulas and conclusions have been obtained. A formula for E_s in the context of the breakdown of a solid dielectric has been proposed as follows:

$$E_s = k_s \zeta^{-1/b} \quad (11)$$

where ζ represents one of d , V_s , or the area of the solid dielectric, A_s , and b is a constant ranging from 7 to 10 [21] and is averaged at 8. The NINT also reported a formula for the effect of pulsewidth on E_s [7]

$$E_s = k_\tau \tau^{-1/r}, \quad (\tau \leq t_{f_max}) \quad (12)$$

where r is a constant ranging from 2.5 to 6, with an average of 5, and t_{f_max} is the maximum formative time lag. For vacuum flashover under radio frequency, the grooving method [22] and magnetic method [23], [24] have been examined for improving E_{of} , and this has been summarized in [25]. For vacuum breakdown under microsecond pulses,

a formula for the breakdown field E_v in parallel electrode systems was given as follows [15], [26]:

$$E_v = 140 g_v^{-0.35}. \quad (13)$$

This formula can be applied over a range of 4 mm–4 m. In addition, the effect of the area on E_v can be summarized as follows:

$$E_v = k_v A_v^{-1/6} \quad (14)$$

where A_v is the area of the vacuum electrode sustaining a field exceeding $0.9 E_v$, in cm^2 . This formula can be applied to an area as large as 10^5 cm^2 .

All the above characteristics, regularities, methods, and formulas provide precious guidelines for practical insulation design in pulsed power fields. However, some problems arise during their application.

- 1) The ranges of application of these formulas are not clear.
- 2) The formulas are different and are not systematic. For example, the formulas for gas breakdown in (2) and (10) are not the same. Moreover, the formula for solid breakdown in (6) reflects the effect of pulsewidth on E_s , whereas (5) by Martin [1] does not include this effect.
- 3) Key parameters in the formulas for the same form of insulation are not consistent. For example, the parameters (A_1 , B_1) for gas breakdown in (10) are different. As another example, the power exponents for the effect of the volume of solid dielectrics on E_s in (5) and (11) are not the same, i.e., 1/10 and 1/8, respectively.

The above formulas for the insulation serve as a bridge to apply raw experimental data at a small scale under a known pulsewidth to large insulation structures under the application pulsewidth. However, the abovementioned problems hinder their application. This study proposes a unified formula for the breakdown electric field or surface flashover field (E_b or E_f) under short pulses for five basic discharge forms—gas, liquid, solid, and vacuum breakdown, and vacuum surface flashover—by reviewing the relevant literature. Section II is devoted to the physical nature of five basic discharge forms. Section III is devoted to theoretical deductions and Section IV provides support for the deduced formula. Section V summarizes the range of application for the proposed formula and Section VI compares it with competing formulas in the literature. Section VII is devoted to describing the applications of this unified formula, and Section VIII offers the conclusion of this study.

II. PHYSICAL PICTURE OF FIVE FORMS OF DISCHARGE

A. Review on the Discharge Mechanisms

The mechanisms responsible for five forms of discharge are reviewed first.

The basic process of gas, liquid, and solid breakdown is similar and can be concluded as follows: the primary electrons are injected from the cathode to the insulation media via thermal emission (T-emission), thermal–field emission (T-F emission), or field emission (F-emission), which depends on the applied field level, as shown in Fig. 1(a); the electrons (holes are as versus, and here, only electrons are used as examples)

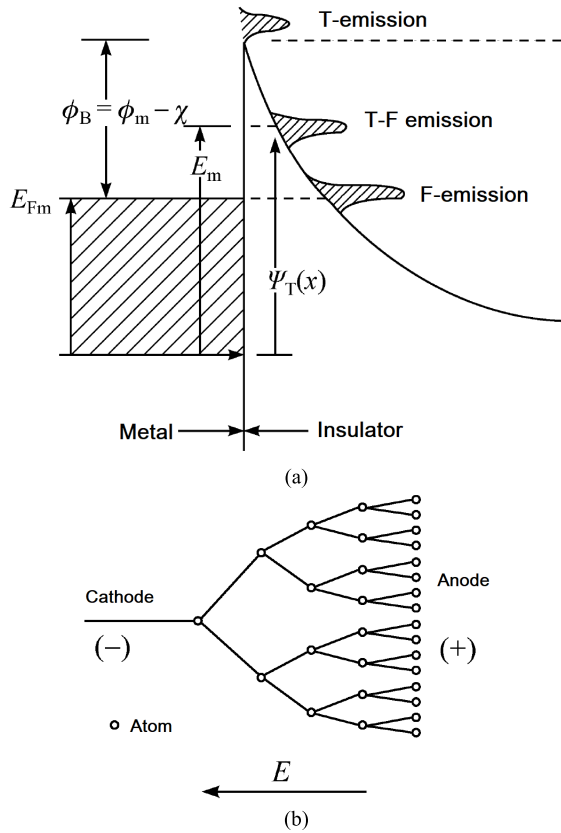


Fig. 1. Schematics of solid, gas, and liquid breakdown. (a) Three injection way and (b) schematics of electron multiplication.

are then accelerated in the electric field, gain enough energy, and impact the atoms of molecules of the insulation media, leading to the ionization of the atoms, as shown in Fig. 1(b). Simultaneously, the electrons are multiplied and the number is increased; the increased electrons are continuously accelerated, impacting, and multiplied, which forms an electron avalanche. Once the electron avalanche increases to a certain extent or reaches the anode, a breakdown takes place.

As to the vacuum breakdown process, the primary electrons are emitted from the cathode, directly bombard the anode, knock out positive ions, and produce metallic vapor from the anode surface. When the positive ions reach the cathode, they will cause secondary emission of electrons and produce metallic vapor from the cathode surface. The secondary electrons impact the metallic vapor, leading to ionization of the vapor. Once the plasma of the ionized vapor bridges the two electrons, a breakdown takes place, as shown in Fig. 2.

As to the vacuum surface flashover, the primary electrons are emitted from the CTJ (junctions of cathode, vacuum, and insulator), impact the insulator surface, and realize multiplication when the secondary electron yielding factor (δ) of the insulator material is greater than 1, i.e., secondary electrons are emitted from insulator surface; these secondary electrons are accelerated in the field and impact the insulator surface again, forming an electron avalanche. Simultaneously, the gas molecules absorbed on the insulator surface are desorbed, forming a thin gas layer near the insulator surface. The secondary electrons impact the gas, leading to ionization of the

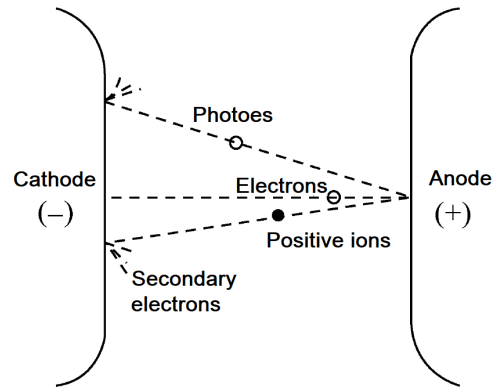


Fig. 2. Schematics of vacuum breakdown.

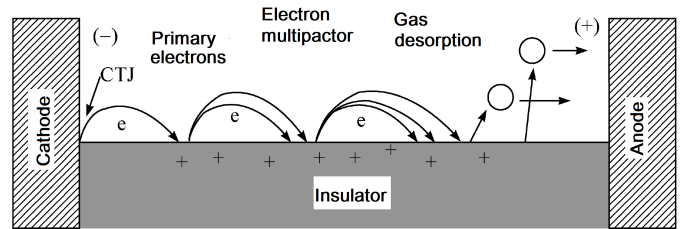


Fig. 3. Schematics of vacuum flashover.

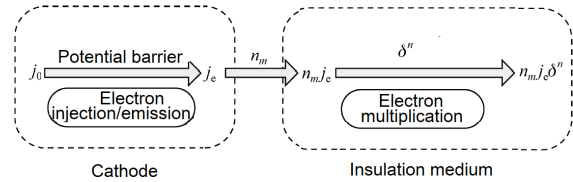


Fig. 4. Simplified model for five forms of discharge.

gas. Once the electron avalanche and the ionized gas region expand to the anode, a vacuum flashover takes place. This is the so-called SEEA theory (secondary electron emission avalanche), as shown in Fig. 3 [27].

B. Similarities in Mechanism for Five Forms of Discharge

Simply, the five forms of discharge involve the satisfaction of two major criteria: initial primary electrons (or holes) and subsequent impact ionization. In addition, a feedback process is required to ensure that the carrier multiplication can continuously increase to the final avalanche. These are the similarities in discharge mechanisms among gases, liquids, solids, vacuum, and vacuum surface.

Here, the first criterion for the five forms of discharge is summarized. As to gas, liquid, and solid breakdown, the cathode material or the material of the carrier-injecting contacts plays the role of suitable source of primary electrons to start the breakdown processes. As to vacuum breakdown, the cathode itself plays the role of electron source. As to vacuum surface flashover, the CTJ plays the role.

Then, the second criterion for breakdown, i.e., impact ionization, is discussed. As summarized by Kao [28], electrons must have a mean free path large enough for them to gain

TABLE I
TWO CRITERIA FOR FIVE FORMS OF DISCHARGE

Discharge form	Primary electron sources	Impact ionization Region	Feedback mechanisms
Gas breakdown	Cathode electrical contacts	Gas itself	Continuous carrier injection from the cathode
Liquid breakdown		Bubbles in front of cathode	
Solid breakdown		LDDs	
Vacuum breakdown	Cathode	Metallic vapor	Continuous bombardment to insulator surfaces
Vacuum surface flashover	CTJ	Desorbed gas	Continuous bombardment to electrodes

sufficient energy from the applied field, which are achieved via low-density regions. In these regions, the density of constituent molecules is much smaller than in solids, implying that the regions must be in the gas phase. In solids, the low-density regions are created by carriers injected from electrical contacts and, subsequently, dissociative trapping and recombination, which is the so-called low-density domains (LDD) [29]. In liquids, the bubbles formed near the cathode before the occurrence of breakdown can be considered as the low-density regions. In gases, the gas itself is just the low-density regions. In vacuum, the metallic vapor and the desorbed gas play the role of low-density regions for vacuum breakdown and vacuum flashover, respectively.

Table I lists the two criteria for the five forms of discharge, together with the feedback mechanisms to boost carrier multiplication until breakdown occurs.

C. Simplified Model

Based on the two criteria mentioned above, a simplified model is proposed to describe the five forms of discharge as shown in Fig. 4. Assume that j_e electrons are ejected/emitted from the cathode from each ejection/emission point and there are n_m points. Then, the total primary electron number is $n_m j_e$. Also, assume that these electrons are impacting and multiplied in a field of E in the insulation medium by n times with a secondary electron yielding factor of δ . Thus, the final secondary electron number j_n is

$$j_n = n_m j_e \delta^n. \quad (15)$$

If j_n can exceed a critical values, j_c , it is said that breakdown or surface flashover takes place, i.e.,

$$E = E_c |_{j_n \geq j_c}. \quad (16)$$

A short analysis is given for each parameter in (15).

- 1) j_e is related to the applied field, E . Namely, the larger is E , the greater is j_e .
- 2) n_m is related to the electrode area for gas, liquid, solid, and vacuum breakdown; n_m is related to the CTJ circle for vacuum surface flashover. The larger is n_m , the lower the field threshold.

- 3) δ depends on the insulation media's condition or the electrode condition. Taking solid dielectrics as an example, a dielectric with shallow traps may have a large δ since the shallowly trapped electrons can be easily stimulated to be free electrons. In turn, a large δ corresponds to a low field threshold.
- 4) n depends on the insulation media's size. For gas, liquid, and solid, n can be written as

$$n = \alpha_e l \quad (17)$$

where α_e is the electron ionization coefficient, which means that α_e times of impacts to the atoms can take place when an electron moves a distance of 1 cm along the inverse field direction. With (17), it is seen that a larger l corresponds to a larger n . If n is larger, j_e can be smaller, which means that the field threshold can be lower. In other words, a large insulation media size corresponds to a low field threshold.

As a summary, the electrode size, the electrode material, the insulation media configuration, and the condition can all have influences on the field threshold. In addition, the applied field duration also affects the field threshold. All these factors cause to field for breakdown or flashover to become distribution, rather than a fixed value.

In the next section, the influences of the field duration, the insulation media configuration, and the electrode size on the electric field for discharge are analyzed.

III. DEDUCTION OF UNIFIED FORMULA

A. Effects of Number of Dimensions and Time

The failure of insulation is affected by many factors, such as the parameters of the dielectric (number of dimensions, type, and purity), electrode (metal type, configuration, and roughness), and pulse (waveform, pulsewidth, and rise time). These factors determine whether E_b or E_f takes on statistical characteristics. Statistical methods are thus widely used to analyze breakdown/flashover phenomena, among which the Weibull statistical distribution is the most widely accepted one [30]. The two-parameter Weibull distribution is given as follows:

$$F(E) = 1 - \exp\left(-\frac{E^b}{\eta}\right) \quad (18)$$

where b is the shape parameter of the Weibull distribution that determines the specific distribution of the probability of breakdown $F(E)$ and η is the dimensional parameter related to dimension transformation. When $F(E)$ is equal to 63%, $E = \eta^{1/b}$, which is defined as the characteristics field, is $E_{63.2\%}$. From the perspective of the failure of insulation, the field is just defined as E_b or E_f . The Weibull distribution involving time is given as follows:

$$F(E, t) = 1 - \exp(-ct^a E^b) (a, b, c > 0) \quad (19)$$

where a , b , and c are all positive constants and t represents the effect of time on $F(E)$. The two-parameter Weibull distribution in (18) is typically used to analyze the insulation phenomena related to dimensional transformation, such as

the effects of its volume, area, thickness, and length. The time-involved Weibull distribution in (19) is typically used to analyze time-relevant effects, such as those of the lifetime and the pulsewidth. All the parameters in (19) have physical meanings. For example, a in (19) is defined as the shape parameter over time, and b is simply the shape parameter as defined in (18). c is related to the characteristic field. If t is fixed as a constant, t_c , (19) degrades to

$$F(E)|_{t=t_c} = 1 - \exp(-ct_c^a E^b) = 1 - \exp\left(-\frac{E^b}{1/ct_c^a}\right). \quad (20)$$

By comparing (20) with (18), we see that $1/\eta = ct_c^a$.

The effect of the number of dimensions on E_b or E_f is first considered (in the following, E is used to represent E_b or E_f for conciseness). When the time factor t is fixed at t_1 , we consider the breakdown of a solid as an example. Assume that the dimensions of a solid dielectric in an electrode system increase from Ω_1 to Ω_2 by N times, where Ω can represent one of the thicknesses of the dielectric (d), its area (A_s), or volume (V_s). Assume also that the failure probability $F(E)|_{\Omega_1}$ of Ω_1 can be expressed as (20)

$$F(E)|_{\Omega_1} = 1 - \exp(-ct_1^a E^b). \quad (21)$$

Two strong assumptions are made here: Ω_2 is composed of N subsystems, Ω_1 , and each Ω_1 conforms to the same failure probability as in (21). In [8], it was proven that for solid dielectrics, the failure probability $F(E)|_{\Omega_2}$ of Ω_2 satisfies the following relation, regardless of whether these N subsystems are in series, parallel, or in both

$$1 - F(E)|_{\Omega_2} = [1 - F(E)|_{\Omega_1}]^N. \quad (22)$$

The characteristic field E_{Ω_2} of Ω_2 is given as follows:

$$E_{\Omega_2} = E_{\Omega_1} N^{-\frac{1}{b}} \quad (23)$$

where $E_{\Omega_1} = (ct_1^a)^{-1/b}$. The expression in (23) has been verified by a number of experiments [31], [32]. For gas, liquid, vacuum, breakdown, and vacuum surface flashovers, it is assumed that the characteristic field also conforms to the field described in (23) when the vacuum gap (g_v) or gas gap (g), vacuum electrode area (A_v), the area of the liquid (A_l), or surface area of the vacuum insulator (A_{vf}) is increased N times from Ω_1 to Ω_2 . Once g_v , g , A_l , A_v , or A_{vf} in an insulated system changes, the reliability $R (=1 - F)$ of the system changes accordingly. The larger is the dimensional size of the insulation system, the lower is R , and the lower is the characteristic field. In light of this, (23) reflects this physical fact. Further discussion of this issue is provided in Section VIII. Thus, (23) can be accepted as describing the effect of the number of dimensions of an insulation system.

The effect of time on E on an insulation structure with a fixed dimensional size of Ω_1 is now considered. We assume that the failure probability, $F(E)|_{t_1}$, of an insulation system Ω_1 at t_1 can be expressed as (21). When the time for which Ω_1 is sustained increases from t_1 to t_2 , the failure probability $F(E)|_{t_2}$ at t_2 should be equal to $F(E)|_{t_1}$ once a breakdown or flashover occurs, i.e.,

$$F(E)|_{t_2} = F(E)|_{t_1}. \quad (24)$$

Solving (24) gives

$$E_{t_2} = E_{t_1} \left(\frac{t_2}{t_1}\right)^{-\frac{a}{b}}. \quad (25)$$

Because a/b is positive, E_{t_2} decreases as the duration for which the field is sustained increases. In other words, the longer is this duration, the lower is the field. This agrees with common sense. In addition, a number of experimental results have proven the physical fact in (25) [7], [10]. In light of this, (25) can be used to describe the effect of time on E .

B. Transition From State (Ω_1, t_1) to (Ω_2, t_1)

With (23) and (25), the transformation from state (Ω_1, t_1) to state (Ω_2, t_2) can be considered. To this end, a transitional state (Ω_2, t_1) is inserted between (Ω_1, t_1) and (Ω_2, t_2) in two steps: 1) transform state (Ω_1, t_1) into state (Ω_2, t_1) and 2) transform state (Ω_2, t_1) into state (Ω_2, t_2) .

Based on the above analysis, Step 1 is simply a dimensional transformation, and the characteristic field E_{Ω_2, t_1} in the transitional stage of (Ω_2, t_1) is given as follows according to (23):

$$E_{\Omega_2, t_1} = E_{\Omega_1, t_1} N^{-\frac{1}{b}} \quad (26)$$

where E_{Ω_1, t_1} is given as follows:

$$E_{\Omega_1, t_1} = (ct_1^a)^{-\frac{1}{b}}. \quad (27)$$

In addition, Step 2 is simply the effect of time with increasing duration for which the field is sustained. According to (25), the characteristic field, E_{Ω_2, t_2} , in the final stage (Ω_2, t_2) is given as follows:

$$E_{\Omega_2, t_2} = E_{\Omega_2, t_1} \left(\frac{t_2}{t_1}\right)^{-\frac{a}{b}}. \quad (28)$$

Now, inserting (27) and (26) into (28) gives

$$E_{\Omega_2, t_2} = (ct_1^a)^{-\frac{1}{b}} N^{-\frac{1}{b}} \left(\frac{t_2}{t_1}\right)^{-\frac{a}{b}}. \quad (29)$$

Considering that $N = \Omega_2/\Omega_1$, (29) can be changed to

$$E_{\Omega_2, t_2} = \left(\frac{\Omega_1}{c}\right)^{\frac{1}{b}} \Omega_2^{-\frac{1}{b}} t_2^{-\frac{a}{b}}. \quad (30)$$

Deleting the subscript "2" and defining $k = (\Omega_1/c)^{1/b}$, $\beta = b$, and $\alpha = a/b$ yield

$$Et^{\frac{1}{\alpha}} \Omega^{\frac{1}{\beta}} = k \quad (31)$$

where α and β are positive constants. The formulation in (31) is the final expression of the unified formula for the electric field in the cases of the breakdown of gas, liquid, solid or vacuum, and vacuum surface flashover. β represents the variance (σ) of E , i.e., $\sigma(E) \approx 1/\beta$. The larger is β , the more concentrated of the E -field distribution. α represents the ratio of the formative time's jitter to the E -field's variance since $\alpha = (1/a)/(1/b)$.

IV. SUPPORT FOR UNIFIED FORMULA

A number of experimental results and empirical formulas from both the AWRE and the NINT support (31). The empirical formulas due to the AWRE are first reviewed, followed by the theoretical formulas in the NINT.

A. Support From AWRE

With regard to the field E_g for gas breakdown in (2), if ρ is fixed as a constant, (2) can be changed into the following by defining $k_{g,p} = k_g \rho^n$:

$$E_g t_e^{1/6} g^{1/6} = k_{g,p}. \quad (32)$$

The above formula is identical to that in (31), where $\alpha = 6$ and $\beta = 6$. The field E_l for liquid breakdown in (3) is identical to that in (31), where $\alpha = 3$ and $\beta = 10$. The field E_{vf} in (4) for vacuum surface flashover is identical to that in (31), where $\alpha = 6$ and $\beta = 10$.

B. Support From NINT

For the breakdown field, E_s , for the solid dielectric in (11) and (12), the effects of size and pulswidth can be combined because these two arguments are independent of each other, i.e.,

$$E_s \tau^{1/r} \zeta^{1/\beta} = k_s. \quad (33)$$

As mentioned in Section I, the average value of r is 5 and that of β is 8. In addition, the nature of the effect of pulswidth is the formative time lag or the effective time of sustenance t_e [7]. If all these aspects are considered, (33) can be rewritten as

$$E_s t_e^{1/5} \zeta^{1/8} = k_s. \quad (34)$$

Thus, (34) for the field E_s of a solid dielectric is identical to that in (31), with $\alpha = 5$ and $\beta = 8$.

With regard to vacuum breakdown with a large gap under short pulses, according to [33], the effect of pulswidth on E_b conforms to a negative power relation of $\tau^{-1/6}$, i.e., $E_b \propto \tau^{-1/6}$. If this effect of the pulswidth is combined with the effect of the vacuum gap in (13), it is transformed as follows:

$$E_v = k_{vg} g_v^{-0.35} \tau^{-1/6}. \quad (35)$$

Similarly, by considering that τ can be substituted with t_e and 0.35 is close to 1/3, (35) can be rewritten as

$$E_v t_e^{1/6} g_v^{1/3} = k_{vg}. \quad (36)$$

The above formula represents the breakdown field E_v of a vacuum, which is identical to that in (31) with $\alpha = 6$ and $\beta = 3$. Similarly, if the effect of pulswidth is considered for the effect of electrode area on E_v in (14) and τ is replaced with t_e , we get

$$E_v t_e^{1/6} A_{vb}^{1/6} = k_{vA}. \quad (37)$$

This formula represents the breakdown field E_v for a vacuum, which is identical to that in (31) with $\alpha = 6$ and $\beta = 6$.

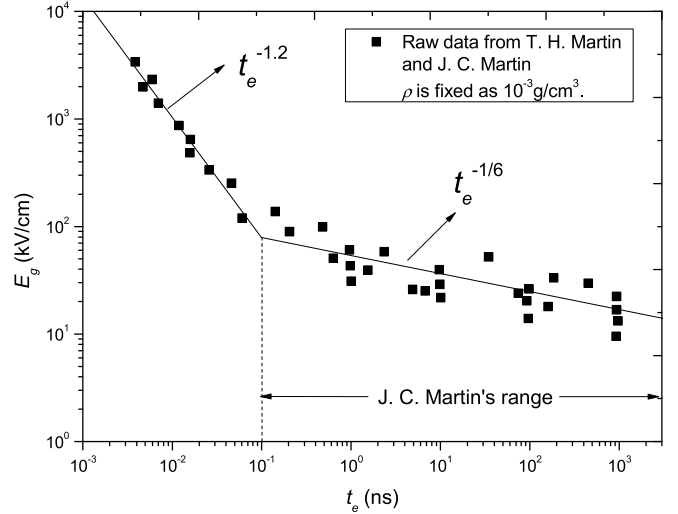


Fig. 5. Range of application of the effect of time on the field for the breakdown of gas. The raw data are from [34] and were summarized by Martin.

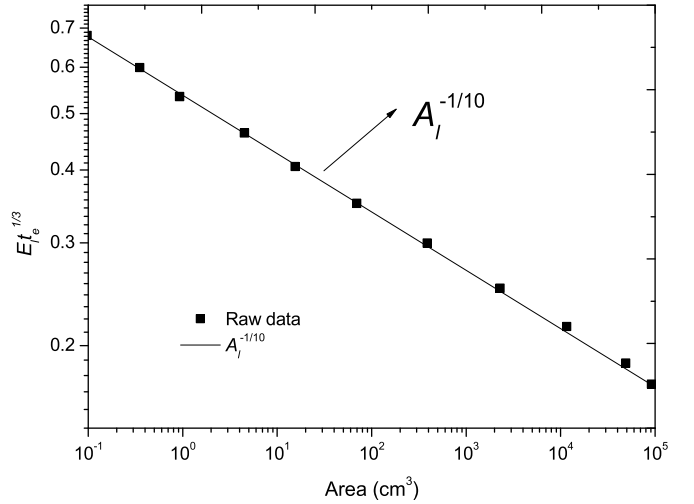


Fig. 6. Range of application of the effect of area on the breakdown field of transformer oil. The raw data are from [5].

V. RANGE OF APPLICATION

The conditions for the application of (32)–(37) are not clear. We focus on this issue in this section.

The expression, in (2) or (32), for gas breakdown developed by Martin [1] should be used in nonunified fields, where g can have a range as large as 10 cm. With regard to the range of time, Martin [1] suggested that the expression is applicable to nanosecond pulses. However, the specific range of t_e was not provided. By reviewing and replottting the experimental data reported by Martin [34], we find that t_e ranges from 0.1 ns to 10 μ s, as shown in Fig. 5.

For the formula for the breakdown of a liquid in (3), Martin [1] also did not give a specific range of application. Similarly, the relevant literature provides some clues. t_e is in the range from 0.1 to 10 μ s for a unified field, as shown in [3, p. 39]. A_l ranges from 0.1 to 10⁵ cm² for transformer oil, as reported in [5, p. 311]. The raw data are replotted for the sake of clarity in Fig. 6.

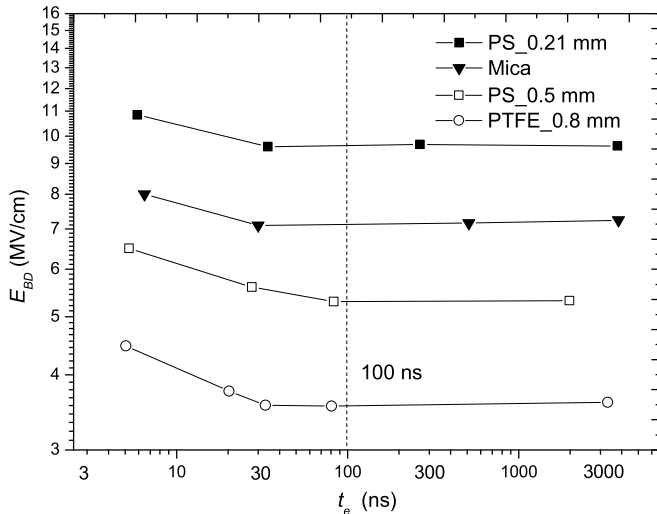


Fig. 7. Range of application of the effects of time on the breakdown of solid [7]. PS: polystyrene. PTEF: polytetrafluoroethylene.

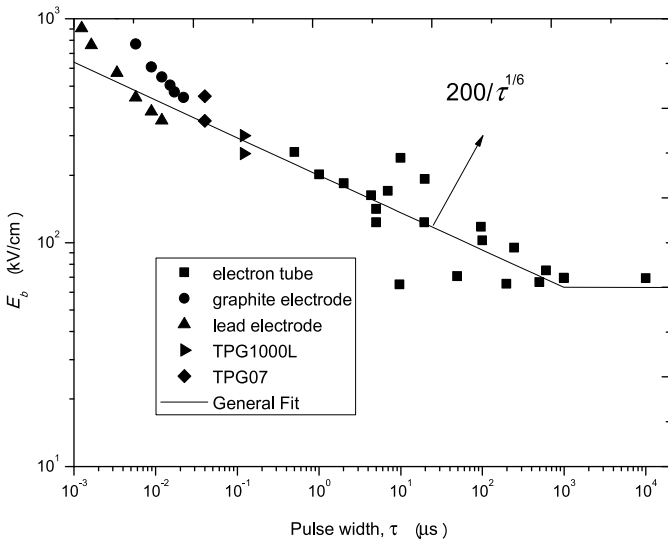


Fig. 8. Range of application of the effect of time on the field of vacuum breakdown. The raw data are from [13] and [33].

Martin [1] also did not give the specific range of application for the expression for vacuum surface flashover in (4). The literature shows that for a single insulator, the effect of time holds from 10 ns to 10 μ s [9], and A_{vf} is as large as 40 cm² according to Martin *et al.* [4]. For a graded insulator stack, t_e ranges from 30 ns to 1 μ s, as reported in [5, p. 321], and A_{vf} is as large as 4×10^4 cm² according to Stygar *et al.* in [12].

For the expression of the breakdown of a solid dielectric in (34), the upper limit of the effect of time was theoretically calculated to be 100 ns by Zhao *et al.* [7] and [35] and can be experimentally verified by results from the TPU [10], as shown in Fig. 7. The effect of volume on E_s holds within 10^{-6} – 10^4 cm³, as shown in [8]. Martin *et al.* [4, p. 231] gave the same limit for the volume upper. The effect of area on E_s holds within an upper limit of 10^4 cm², as reported in [8]. The effect of thickness on E_s holds from hundreds of nanometers to the order of centimeters, as shown in [31].

For the formula for vacuum breakdown in (36) and (37), the effect of time holds from 1 ns to 10 μ s, as reported in [13, p. 420], and is replotted in Fig. 8. The range for the effect of the vacuum gap on E_v ranges from 0.4 to 400 cm [13] and that for the effect of area on E_v ranges from 2×10^3 to 7×10^5 cm² [17].

As a subconclusion, Table II lists the specific expressions, definitions of the key parameters, and range of application of each type of insulation.

VI. COMPARISON WITH OTHER FORMULAS

A question persists: why have different formulas for the insulation been proposed in the literature or what are the differences between the unified formula and those mentioned in Section I? We focus on this question here.

A. Analysis of Gas Formulas

The formulas for gas breakdown are first analyzed. The formula in (1) is applicable to a unified field and thus is clearly different from (2) and (32). A transformation of the formula in (10) for E_g gives

$$E_g t_d^{\frac{1}{B_1}} = A_1^{\frac{1}{B_1}} \rho^{1-\frac{1}{B_1}}. \quad (38)$$

As mentioned above, t_d has the same physical meaning as t_e . In addition, the relation between the density of gas ρ and the pressure p is

$$\rho = \frac{Mp}{R_c T} = k_R p \quad (39)$$

where M is the molecular mass, R_c is the Clapeyron constant, T is the temperature, and $k_R = M/R_c T$. By substituting t_d with t_e and inserting (39) into (38), one can obtain

$$E_g t_e^{\frac{1}{B_1}} = A_1^{\frac{1}{B_1}} k_R^{1-\frac{1}{B_1}} p^{1-\frac{1}{B_1}}. \quad (40)$$

Because A_1 , B_1 , and k_R are constant, (40) can be compared with (2). When g is fixed in (2), the two formulas are similar to each other. In addition, B_1 should be equal to β , and $(1-1/B_1)$ should be equal to n . According to the results of fitting reported by Shao *et al.* [18] ($B_1 = 2.14$), Martin [6] ($B_1 = 2.25$), and Mankowski [19], [20] ($B_1 = 3.44$), the average B_1 is 2.61. However, β is 6 according to Martin [1]. This difference occurs due to the limitations of the experimental conditions. Martin's [1] results, t_e ranges from 0.1 to 1000 ns, and fitting the relevant data gives a slope of $-1/6$, as shown in Fig. 1. However, the other three researchers fit the experimental data over a wider range of t_e from 0.001 to 1000 ns, which led to a slope of $-1/2.61$, as shown by the red dashed line in Fig. 9. In addition, when $\beta = 2.61$, the power exponent of p is equal to 0.616, which is close to the value of 0.6 for air suggested by Martin [1]. Thus, the formula for the breakdown field of gas in (2) has the same nature as that in (10).

TABLE II
 SUMMARY OF ELECTRIC FIELD FORMULAS FOR DIFFERENT FORMS OF INSULATION FAILURE UNDER SHORT PULSES

Insulation failure forms	Insulation formulae	Definitions and units	α	β	Application condition	Researchers
Gas breakdown	$E_g t_e^{1/6} g^{1/6} = k_{g,p}$	E_g - gas breakdown field in kV/cm; t_e -the time for which a field exceeding $0.63 E_g$ is sustained, in μ s; g - in cm; $k_{g,p}$ - constant related to pressure.	6	6	In non-unified field, $0.1 \text{ ns} < t_e < 1 \mu\text{s}$; g is as large as 10 cm [1, 2].	J. C. Martin
Liquid breakdown	$E_l t_e^{1/3} A_l^{1/10} = k_l$	E_l - liquid breakdown field in MV/cm; t_e - in μ s; A_l - the electrode area sustaining a field exceeding $0.9 E_l$ in cm^2 ; k_l - constant.	3	10	In unified field, $0.1 \mu\text{s} < t_e < 1 \mu\text{s}$ [3]; for transformer oil, $0.1 \text{ cm}^3 < A_l < 10^3 \text{ cm}^3$ [5].	J. C. Martin
Solid breakdown	$E_s t_e^{1/5} \zeta^{1/8} = k_s$	E_s - solid dielectric breakdown field in MV/cm; t_e - in ns; ζ - thickness of solid dielectric, in cm, area, in cm^2 , or volume in cm^3 ; k_s - constant.	5	8	In unified field, $t_e < 100 \text{ ns}$ [7]; for effect of volume, $V < 10^4 \text{ cm}^3$; for effect of area, $A < 10^3 \text{ cm}^2$; for effect of thickness, d ranges from nm class to cm class [8].	L. Zhao
Vacuum surface flashover	$E_{vf} t_e^{1/6} A_{vf}^{1/10} = k_{vf}$	E_{vf} - vacuum surface flashover field in kV/cm; t_e - in μ s; A_{vf} - the insulator surface sustaining a field exceeding $0.9 E_{vf}$ in cm^2 ; k_{vf} - constant.	6	10	For surface flashover switch, $10 \text{ ns} < t_e < 10 \mu\text{s}$ [9]; A_{vf} as large as 40 cm^2 was reported in [4]; for insulator stack, $30 \text{ ns} < t_e < 1 \mu\text{s}$ [5]. A_{vf} is as large as $4 \times 10^4 \text{ cm}^2$ [12].	J. C. Martin
Vacuum breakdown	$E_v t_e^{1/6} g_v^{1/3} = k_{vg}$	E_v - vacuum breakdown field in kV/cm; t_e - in μ s; g_v - vacuum separation in cm; A_v - electrode area sustaining a field exceeding $0.9 E_v$ in cm^2 ; k_{vg} - constant related to the electrode area; k_{vA} - constant related to electrode separation.	6	3	10 ns $< t_e < 10 \mu\text{s}$ [13]; for parallel electrode, $0.4 \text{ cm} < g < 400 \text{ cm}$ [15]; for coaxial electrode, g is as large as 10 cm , $2 \times 10^3 \text{ cm}^2 < A_v < 7 \times 10^5 \text{ cm}^2$ [17].	L. Zhao
	$E_v t_e^{1/6} A_v^{1/6} = k_{vA}$		6	6		L. Zhao

B. Analysis of Formulas for Solid

First, we compare the formula for the breakdown of a solid dielectric in (5), developed by Martin [1], with the unified formula for it in (34). The effect of time is not considered in (5) due to the limitations of the experimental conditions. In Martin's experiments, the pulswidth was fixed at 10 ns, because of which he could not determine the effect of pulswidth on E_s . However, in the experiments in the NINT, the pulswidth was changed such that its effect was observed. In addition, the power exponent in Martin's formula (5) is 1/10, whereas the corresponding exponent in the unified formula is 1/8. By refitting Martin's raw data, we find that they also give a power exponent of 1/8 rather than 1/10, as shown in Fig. 10. The value of 1/10 was used by Martin *et al.* [4, p. 231] probably because he wanted to apply his formula to a much wider range of volumes, as evidenced from his remarks.

Second, we compare the formula for the breakdown of a solid dielectric from the TPU in (6) with the unified formula in (34). For convenience, a logarithmic transformation is applied to (34), which gives

$$\lg E_s = k_{lg} - 1/8 \lg d - 1/5 \lg t_e \quad (41)$$

where $k_{lg} = \lg k_s$ and ζ is substituted by d . By comparing (6) and (41), we find that the two equations are similar. In addition, $(K_3 - K_4 \lg d)$ should be equal to 1/5. To clarify this issue, the data from TPU were reanalyzed. Fig. 11 shows the results of calculation of $(K_3 - K_4 \lg d)$ for PE based on the raw data in [10]. This figure reveals two pieces of

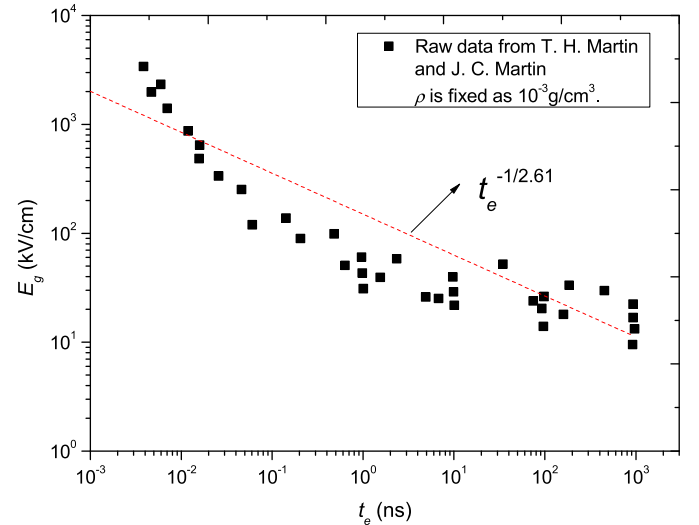


Fig. 9. Refitting for the effect of time on the field of gas breakdown over a range from 0.001 to 1000 ns. The raw data are from [13].

information: 1) the average value of $(K_3 - K_4 \lg d)$ was about 0.2 in different test conditions and 2) when d increased from 1 mm to 1 cm, $(K_3 - K_4 \lg d)$ remained the same, which means that the contribution of $-K_4 \lg d$ was a smaller part than that of K_3 . $-K_4 \lg d$ can thus be neglected for the sake of simplicity. Once $-K_4 \lg d$ has been neglected in (6), it is identical to (41). Thus, the formula from the TPU in (41) and the unified formula in (34) can be considered to be the same.

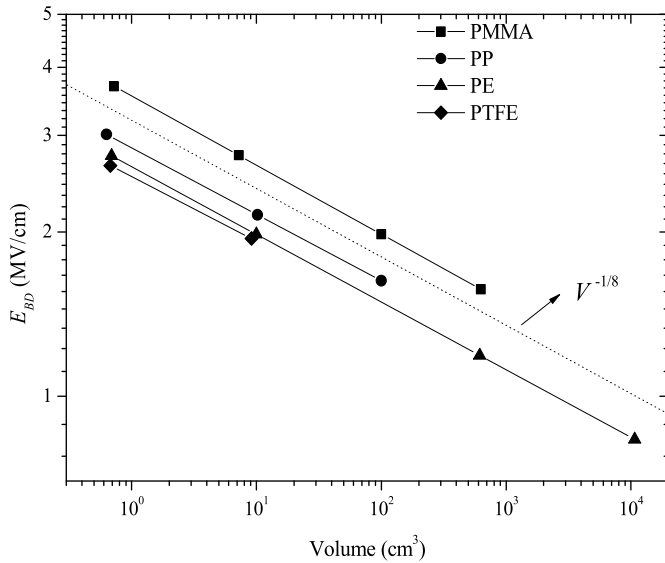


Fig. 10. Refitting Martin's data on the temporal effect of volume on the breakdown field of a solid dielectric on the field for the breakdown of a gas. The raw data are from [4].

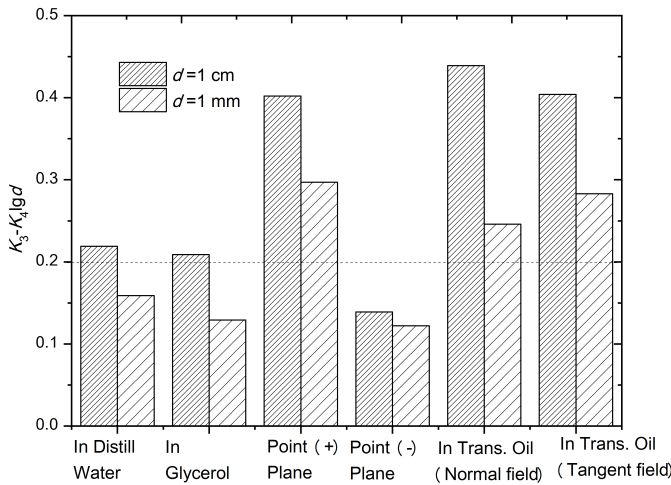


Fig. 11. Results of calculation of $K_3 - K_4 \lg d$ for PE with data from the TPU in [10].

C. Analysis of Surface Flashover Formulas

First, we compare the formula for vacuum surface flashover from the SNL in (8) with the unified formula for surface flashover (4). We note that (8) was deduced using a statistical method similar to the time-involved Weibull distribution and was based on a group of experimental data for conical insulators truncated at an angle of 45° . The expression for the surface area of the insulator A_{vf} is dependent on its thickness d and the bottom circumstance C_b , and this can be written as follows:

$$A_{vf} = d(\sqrt{2} C_b - \pi d). \quad (42)$$

Note that in Stygar's experiments, d was no smaller than $0.12 C_b$. Thus, (42) can be approximated as follows:

$$A_{vf} \approx \sqrt{2} C_b d. \quad (43)$$

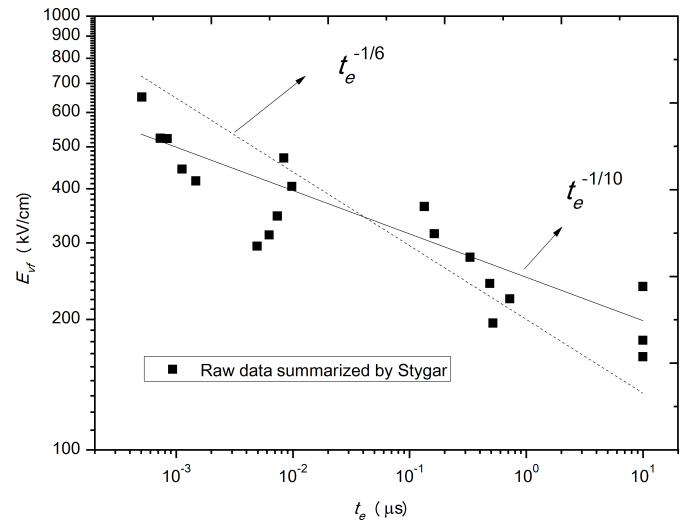


Fig. 12. Replotting and fitting data on E_{vf} versus t_e for a truncated insulator in [12].

The insertion of (43) into the formula for the unified vacuum flashover field in (4) gives

$$E_{vf} t_e^{1/6} C_b^{1/10} = k_{vf} (\sqrt{2} d)^{-1/10}. \quad (44)$$

The formula for the field for vacuum surface flashover in (8) can then be rewritten as follows:

$$E_f t_e^{1/10} C_b^{1/10} = 224 \exp(0.27/d). \quad (45)$$

A comparison of (44) and (45) shows that if d is a constant, the two formulas are identical, with only a difference in the power exponent of t_e , i.e., its value in one is $1/6$ and in the other is $1/10$. To clarify this difference, the data for E_{vf} regarding t_e in [12] are replotted and fit, as shown in Fig. 12. It shows that both kinds of fitting passed the main range of the data. Given this, both formulas can be used in practice.

Second, the formula for the field of vacuum flashover in (9) was compared with the unified formula in (4). It shows that (9) has the same form as (4), except for a restriction on the CTP field of E_P , i.e., E_P should be smaller than 50 kV/cm . As (9) is used for a series of insulator stacks with a large area, it should be stricter than (4) in theory.

As a subconclusion of this section, all formulas for the insulation mentioned in Section I have the same nature as that of the proposed unified formula for it.

VII. APPLICATIONS OF THE PROPOSED FORMULA

A. Transformation for Practical Case

The unified formula for the insulation in the case of E_b or E_f can first be used to transform the experimental data at a small scale under a known pulsewidth into one at a large scale under an empirical pulsewidth. A large number of experimental data have been obtained at the AWRE, NSRC, SNL, TPU, NINT, and IEE by using a few test samples under a given pulsewidth. However, we need to know how to use these data for practical insulation design. This question can

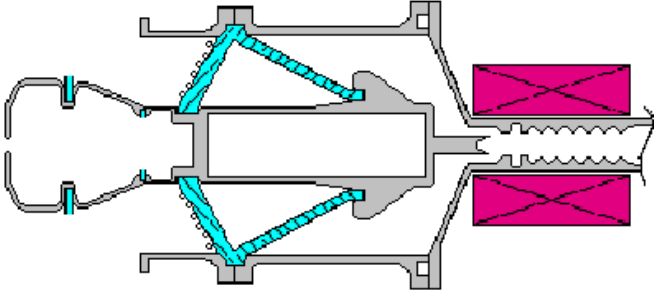


Fig. 13. Schematics of a multifunctional HV vacuum insulator with BWO.

be solved in theory by using the proposed unified formula

$$E_{\Omega_2, t_2} = E_{\Omega_1, t_1} \left(\frac{t_1}{t_2} \right)^{\frac{1}{\alpha}} \left(\frac{\Omega_1}{\Omega_2} \right)^{\frac{1}{\beta}} \quad (46)$$

where E_{Ω_2, t_2} is expected in the state (Ω_2, t_2) , Ω_2 represents the enlarged dimensions, and t_2 is the applied pulsewidth. E_{Ω_1, t_1} represents the breakdown or flashover field obtained by using samples with a characteristic dimensional size of Ω_1 under a pulsewidth of t_1 . E_{Ω_2, t_2} represents a failure probability of 50% because E_{Ω_1, t_1} is an average experimental value corresponding to a breakdown or a surface flashover probability of 50%.

Then, the unified formula can be used to calculate the reliability R of an insulation structure under a given field, E_{op} , because R is equal to $1 - F$. As mentioned in Section III, the parameter β in the unified formula is just the scale parameter b in the two-parameter Weibull distribution in (18). Once b and the characteristics field $E_{63.2\%}$ are known for a specific Weibull distribution, R can be calculated for a given E_{op} with the following formula:

$$R(E) = \exp \left[- \left(\frac{E}{E_{63.2\%}} \right)^{\beta} \right] \quad (47)$$

where β for the five basic forms of insulation are listed in Table I. $E_{63.2\%}$ can be calculated as follows:

$$E_{63.2\%} = (\ln 2)^{-1/m} E_{50\%}. \quad (48)$$

In (48), $E_{50\%}$ is just $E(\Omega_2, t_2)$ in (46). The deduction of (48) has been provided in [36].

B. Example

Fig. 13 shows a multifunctional HV vacuum insulator assembled in a coaxial line [37]. It has a profile λ and is made of nylon, which was used to separate the 5-atm SF₆ gas on the left side to supply a vacuum for the backward-wave oscillator (BWO) on the right side. It is needed to sustain 660-kV nanosecond pulses with a width of 45 ns. The outer radius of the coaxial line was 200 mm, the inner radius was 90 mm, and the angle of the insulator was 45°. There were two metal-shielding rings at the two ends of the insulator that were used to shield the field and fix the insulator. The shortest distance between the surface of each of the shielding rings and the outer conductor of the coaxial line was 87 mm. The thickness

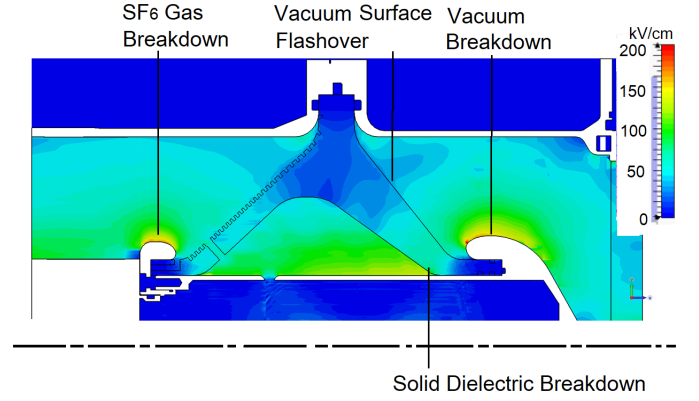


Fig. 14. Electric field distribution of a coaxial HV vacuum insulator working under 45-ns pulses.

TABLE III

CALCULATION OF ELECTRIC FIELD THRESHOLDS FOR HV INSULATOR

Potential failure patterns	Small-scale E_b or E_f under known pulse width	Large-scale conditions under 45 ns	Deduced E_b or E_f , kV/cm	$E_{63.2\%}$, kV/cm
Gas breakdown	For SF ₆ , when $g=5$ mm, $t_e=40$ ns, and $p=2.7$ atm, $E_g=240$ kV/cm [38]	$g'=87$ mm $t_e'=45$ ns $p'=5$ atm	$E_g'=187$	198
Vacuum breakdown	For stainless steel, when $g=17$ mm and $t_e=100$ ns, $E_v=300$ kV/cm [11]	$g'=87$ mm $t_e'=45$ ns	$E_v'=198$	224
Vacuum surface flashover	For nylon, when $A_v=942$ mm ² and $t_e=30$ ns, $E_v=150$ kV/cm [39]	$A_v'=1.4 \times 10^5$ mm ² $t_e'=45$ ns	$E_v'=85$	88.2
Solid breakdown	For nylon, when $d=1$ mm and $t_e=10$ ns, $E_s=1.7$ MV/cm [32]	$d'=13$ mm $t_e'=45$ ns	$E_s'=913$	956

of the insulator near the inner surface of the coaxial line was 13 mm.

There were four types of failure for this insulator: 1) SF₆ gas breakdown, which may happen between the shielding ring of the left cathode and the outer conductor; 2) vacuum surface flashover, which may happen along the right-outer surface of the insulator; 3) vacuum breakdown, which may occur between the right shielding ring and the outer conductor; and 4) solid dielectric breakdown, which may occur on the cuneate region on the surface of the inner conductor, as shown in Fig. 14.

To ensure a reliable design of the insulation, the unified formulas for insulation in the case of gas breakdown, vacuum surface flashover, vacuum breakdown, and solid breakdown were used. Some small-scale data on breakdown and surface flashover under given pulsewidths were used to calculate the field for large-scale breakdown or surface flashover under 45 ns. Table II lists the experimental data, test conditions, application conditions, and the deduced failure field. In addition, the characteristic field, $E_{63.2\%}$, was calculated based on (48) and is listed in Table II.

The deduced E_b or E_f in Table II presents the criteria for the design of this multifunctional HV vacuum insulator. In addition, by using the 2-D distribution of the electric field shown in Fig. 14, E_{op} for each form of insulation can be easily determined. By using $E_{63.2\%}$ from Table III and E_{op} from Fig. 14, the reliability R of each type of insulation can be easily calculated using (47). Of the values of R , the lowest one should be used to improve the local design.

VIII. REMARKS AND CONCLUSION

A. Remarks

There are two points which needs to be remarked.

1) In the deduction process of the unified formula from the state (Ω_1, t_1) to the state (Ω_2, t_2) , there is a strong assumption that the large-dimensional insulation system Ω_2 can be divided into N small-dimensional insulation system Ω_1 . As to solid insulation, it can be easily thought out that a thick insulator can be cut into N -thin insulators like bread and this division model as well as the deduction process is verified in practice. As to gas breakdown, vacuum breakdown, liquid breakdown, and vacuum surface flashover, whether this kind of division is feasible, there is no direct proof. In addition, the assumption that the reliability of each small-scale insulation system Ω_1 is the same lacks of strong support. In future, these two questions will be focused on.

2) Even though the application ranges for the five basic insulation forms are summarized, the upper limit and the lower limit of the ranges of each insulation formula should still need to be explored via experiments for practical insulation applications.

B. Conclusion

There are three conclusions in this paper.

- 1) A unified formula for five basic forms of discharge—gas, liquid, solid, and vacuum breakdown, and vacuum surface flashover—under short pulses in an electric field is proposed, which is $E t^{1/\alpha} \Omega^{1/\beta} = k$. As to different insulation forms, (α, β) have the different values. For gas breakdown, (α, β) is (6, 6) and Ω represents the gas gap g ; for liquid breakdown, (α, β) is (3, 10) and Ω represents the electrode area A_l ; for solid dielectric breakdown, (α, β) is (5, 8) and Ω represents one of the solid dielectric thickness d , the solid area A_s , and the volume V_s ; for vacuum surface flashover, (α, β) is (6, 10) and Ω represents the insulator surface area A_{vf} ; for the vacuum breakdown dependent on vacuum separation, (α, β) is (6, 3) and Ω represents the vacuum separation g_v ; and for the vacuum breakdown dependent on electrode area, (α, β) is (6, 6) and Ω represents the electrode area A_v .
- 2) The ranges of application of this formula to different discharge forms are summarized.
- 3) The suggested formula can be used to transform experimental data at a small scale under a known pulsewidth into those at a large scale under the application pulsewidth.

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