Investigation of Thickness Effect on Electric Breakdown Strength of Polymers Under Nanosecond Pulses

Liang Zhao, Guo-zhi Liu, Jian-cang Su, Ya-feng Pan, and Xi-bo Zhang

***Abstract*—The thickness effect on electric breakdown strength (E_{BD}) of four kinds of polymers under nanosecond pulses is investigated. The polymers are polyethylene, PTFE, PMMA, and nylon. The test samples are 0.5–3.5 mm in thickness (d) and are immersed in transformer oil. The nanosecond pulse is based on a Tesla-type generator, TPG200, which is with values of pulsewidth of 8.5 ns and rise time of 1.5 ns. The experimental results show that E_{BD} is 1–2 MV/cm and decreases as d increases. The dependence of E_{BD} on d is analyzed with the Weibull statistical distribution. It is concluded that $\log E_{\mathrm{BD}}$ versus $\log d$ is linear. By replotting the experimental data and by comparing with Martin's results, it is found that the slope for the linear dependence is about $-1/8$. With this conclusion, the breakdown probability is researched. It is shown that, to get a breakdown probability as low as 0.5%, the applied field should be decreased to about half of E_{BD}.**

***Index Terms*—Breakdown mechanism, electric breakdown strength, polymers, thickness effect, Weibull distribution.**

I. Introduction

POLYMERS are widely used in pulsed-power systems as insulators and supports [1]–[4]. It is of great importance to research the breakdown characteristics of polymers under nanosecond pulses. In 1960s, Martin presented some results and formulas on this subject, which were about the volume and the pulse number effects on the electric breakdown strength (E_{BD}) [5], [6]. Some other experimental results on this subject were also reported, which are about the pulsewidth effect on E_{BD} [7], pulse polarity effect on E_{BD} [7], and repetition-rate effect on E_{BD} [8], [9]. These literatures are useful for the design and application of polymers in nanosecond time scale.

Aside from these reports, the thickness effect on E_{BD} should also be researched, since this effect is directly related to the size and volume of an insulator or a support. However, there is scarce literature on this research; there are only literatures on the thickness effect in microsecond time scale [10]–[12] and in ac/dc time scales [13]–[18]. These literatures are valuable since they can be used as reference for carrying on the investigation on the thickness effect in nanosecond time scale.

This paper reports the experiments on the thickness effect conducted in the Northwest Institute of Nuclear Technology (NINT). The experiments are with two features: First, the test samples are common in pulsed-power systems with thickness ranging from 0.5 to 3.5 mm, and second, the nanosecond pulse is trapezoidal with a pulsewidth of 8.5 ns. The test samples and the experimental setup are introduced in Section II. The experimental results are presented in Section III. The theoretical analysis is dealt with in Section IV. The breakdown probability indicated by the thickness effect is discussed in Section V. The last section, Section VI, is devoted for the conclusions of this paper.

II. Experimental Setup and Procedures

This section mainly introduces the experimental setup, test samples, electrodes, and a set of procedures to provide a better understanding for the experimental results.

A. Experimental Setup

Fig. 1 shows the experimental setup, which comprises a TPG200 generator, a sample tank, a load tank, a diagnostic system, a dc charging power, and a trigger generator. The output values of the experimental setup are listed in Table I. For this setup, TPG200 is a Tesla-type pulsed-power generator; a Tesla transformer built in pulse forming line and a gas switch (also the main switch) are the main components of this kind of generator [4], [19]. The sample tank is cascaded with TPG200 to accommodate the electrode and the test sample. The load tank is bypassed with the sample tank and has a matched high-frequency membrane resistor in it to absorb the reflected energy from the test sample. Both the two tanks are filled with clear transformer oil to prevent surface flashover as well as to dissipate heat. The diagnostic system monitors four signals: voltage on the Tesla transformer, voltage on the membrane resistance, voltage on the test sample, and current through the test sample. The four signals are linked to an oscillograph—DPO4000. The dc charging power supplies energy for TPG200. The trigger generator triggers TPG200.

B. Test Samples

Fig. 2 shows the test samples, which are made of polyethylene (PE), PMMA (organic glass), PTFE (Teflon), and

Manuscript received January 27, 2011; revised March 7, 2011 and April 5, 2011; accepted April 10, 2011. Date of publication May 19, 2011; date of current version July 8, 2011.

L. Zhao and G. Liu are with the Key Laboratory of Physical Electronics and Devices of Ministry of Education, Xi'an Jiaotong University, Xi'an 710049, China and also with the Northwest Institute of Nuclear Technology, Xi'an 710024, China.

J. Su, Y. Pan, and X. Zhang are with the Northwest Institute of Nuclear Technology, Xi'an 710024, China.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2011.2143435

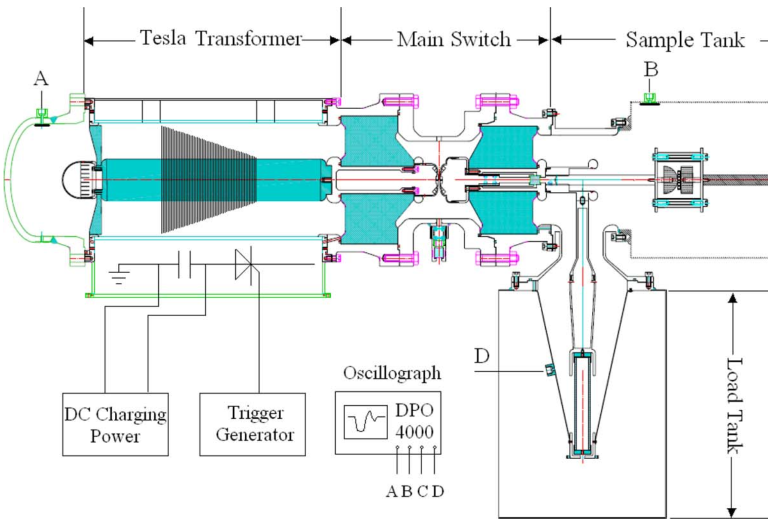


Fig. 1. Schematic view of experimental setup TPG200. (A) Secondary voltage. (B) Sample voltage. (C) Sample current. (D) Load voltage.

TABLE I
OUTPUT VALUES OF THE EXPERIMENTAL SETUP

Parameter	Value
Maximum voltage on sample	300 kV
Pulse width	8.5 ns
Rise time	1.5 ns (60atm)
Output mode	+/- pulse
Repetition rate	Single shot/ 50Hz

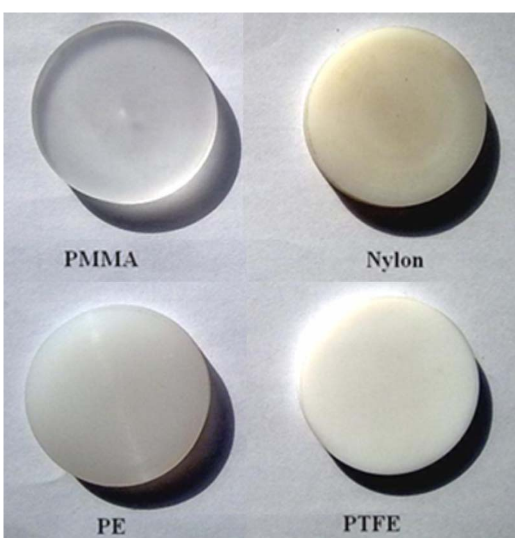


Fig. 2. Photograph of four kinds of polymers.

nylon (polyamide), respectively. The thickness for these samples ranges from 0.5 to 3.5 mm; the diameter is fixed as 40 mm. All four kinds of samples are cleaned and dried before being tested.

C. Electrodes

Fig. 3 shows the electrodes, which consist of a hemisphere and a cylinder. Both the hemisphere and the cylinder are made of copper and are 60 mm in diameter. The distance between the electrodes can be adjusted in a wide range. The field enhancement factor (FEF) for the electrodes is calculated according to the following formula [10]:

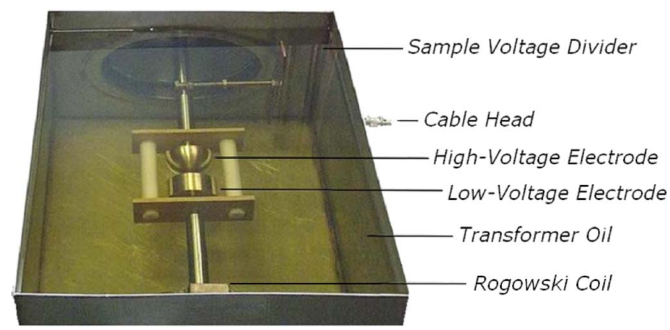


Fig. 3. Photograph of the electrodes.

$$f_{s-p} = \frac{2d^{1/2}(d+r)^{1/2}}{r \ln \left[\left(2d + r + 2d^{1/2}(d+r)^{1/2}\right) / r \right]} \tag{1}$$

where f_{s-p} is the FEF, d is the sample thickness, and r is the radius of the hemisphere. With this formula, the maximum FEF is calculated as 1.05. Therefore, the electric field can be considered quasi-uniform, and E_{BD} can be calculated as

$$E_{\mathrm{BD}} = \frac{V_{\mathrm{BD}}}{d}. \tag{2}$$

D. Experimental Procedures

The experimental procedures are as follows.

Step 1) Choose six samples with the same thickness of one kind of polymer. Test each of them, and average the data to obtain one E_{BD}-versus-d point.

Step 2) Repeat step 1) five times. For each time, the sample thickness is increased. Thus, five E_{BD}-versus-d points of one kind of polymer are obtained.

Step 3) Change the polymer type. Repeat steps 1) and 2) for the other three kinds of polymers. Therefore, the E_{BD}-versus-d data for four kinds of polymers are obtained.

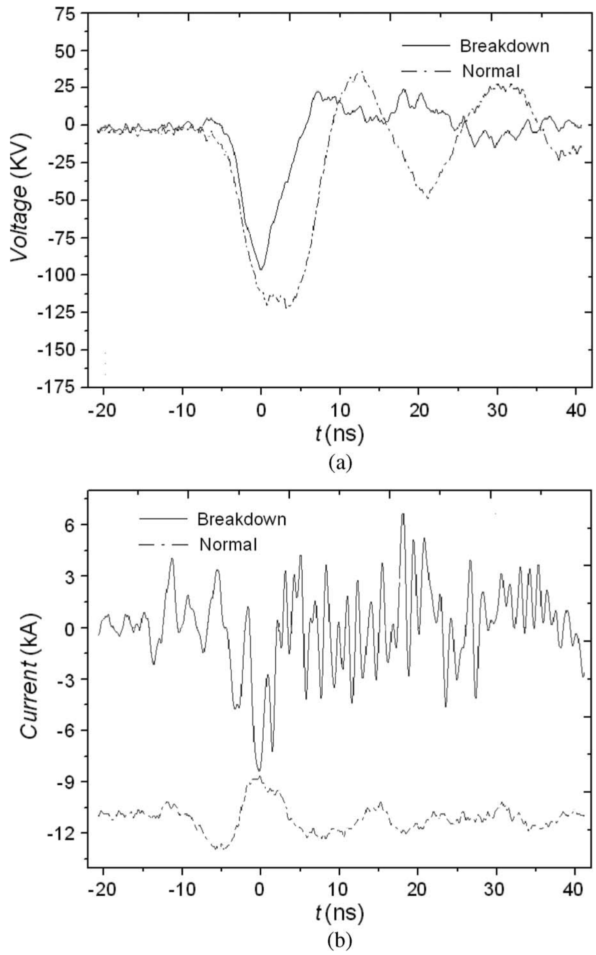


Fig. 4. Breakdown and normal waveforms on the test sample. (a) Voltage waveforms. (b) Current waveforms.

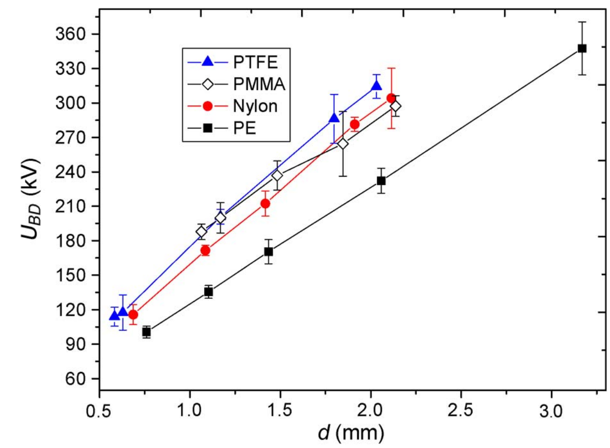


Fig. 5. U_{BD} versus d for four kinds of polymers.

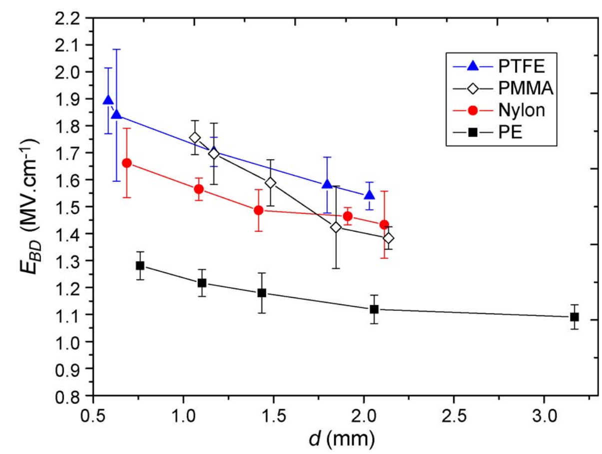


Fig. 6. E_{BD} versus d for four kinds of polymers.

Fig. 4(a) and (b) shows the typical breakdown voltage and current waveforms, respectively. From Fig. 4(a), it is seen that, although the two voltage waveforms are with the same electric field rise time rate, the flatness of the breakdown waveform vanishes which results in a triangular waveform. Moreover, the oscillations in the wave tail become smaller. From Fig. 4(b), it is seen that the breakdown current waveform is oscillating, and its amplitude gets larger. Both the details on the voltage and current waveforms denote that breakdown has occurred on the test sample and the sample does not hold the pulse any more.

III. Experimental Results

Fig. 5 shows the breakdown voltage versus polymer thickness. From this figure, it is seen that the breakdown voltage (U_{BD}) increases as d increases for all the four kinds of polymers. Based on the data in Fig. 5 and with (2), E_{BD} versus d is obtained and shown in Fig. 6. This figure indicates that E_{BD} decreases as d increases. Moreover, the tendency is nonlinear.

IV. Theoretical Analysis

The dependence of E_{BD} on polymer thickness is analyzed with the Weibull statistical distribution. Moreover, Martin's formula is reanalyzed to derive the E_{BD}-versus-d regularity.

A. Thickness Dependence Indicated by Weibull Distribution

The Weibull distribution is a widely used method to evaluate the high-voltage breakdown phenomenon [20]–[23]. The two-parameter Weibull distribution is shown as follows:

$$F(E) = 1 - \exp\left(-\frac{E^m}{\eta}\right) \tag{3}$$

where $F(E)$ is the breakdown probability, E is the applied field, and m and η are the shape parameter and the dimension parameter, respectively. If E is equal to $\eta^{1/m}$, $F(E) = 0.6321$. Moreover, this field is defined as E_{BD}.

To derive the dependence of E_{BD} on d, suppose two conditions. First, a group of thin samples with thickness of d_0 is tested. Second, a group of thick samples with thickness of d $(d = Nd_0)$ is tested. The two groups are with the same cross section. Define that the breakdown probability for the thin group can be depicted by (3) and its breakdown strength is E_{BD0}. For the thick group, assume that each sample is equivalent to N thin samples stuck together. Hence, the probability for this group without breakdown is

$$R_N(E) = \exp\left(-\frac{E^m}{\eta}\right)^N = \exp\left(-\frac{E^m}{\frac{\eta}{N}}\right). \tag{4}$$

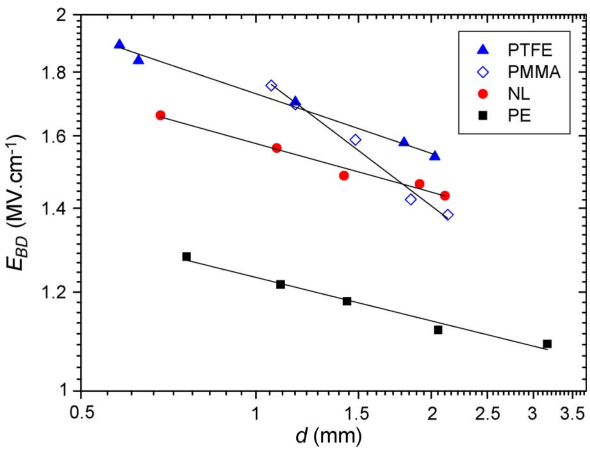


Fig. 7. E_{BD} versus d in a log–log coordinate system.

Moreover, the breakdown probability is

$$F_N(E) = 1 - R_N(E) = 1 - \exp\left(-\frac{E^m}{\frac{\eta}{N}}\right). \tag{5}$$

Hence, the breakdown strength for the thick group is

$$E_{\mathrm{BD}_N} = \left(\frac{\eta}{N}\right)^{\frac{1}{m}} = \left(\frac{1}{N}\right)^{\frac{1}{m}} \cdot \eta^{\frac{1}{m}}. \tag{6}$$

Take into account the preconditions that $d = Nd_0$ and $\eta^{1/m} = E_{\mathrm{BD0}}$, (6) is simplified as

$$E_{\mathrm{BD}_N} = \frac{d_0^{\frac{1}{m}} E_{\mathrm{BD0}}}{d^{\frac{1}{m}}}. \tag{7}$$

If the thin samples are standard with unit thickness (for example, $d_0 = 1$ mm), then $d_0^{1/m} E_{\mathrm{BD0}} = E_{\mathrm{BD0}}$. Getting rid of the subscript N in (7) gives

$$E_{\mathrm{BD}} = \frac{E_{\mathrm{BD0}}}{d^{\frac{1}{m}}}. \tag{8}$$

Since $1/m > 0$, E_{BD} will decrease as d increases. This agrees with the E_{BD}-versus-d tendency shown in Fig. 6.

Making a logarithmic transformation for (8) and letting $C = \log E_{\mathrm{BD0}}$ give

$$\log E_{\mathrm{BD}} = C - \frac{1}{m} \log d. \tag{9}$$

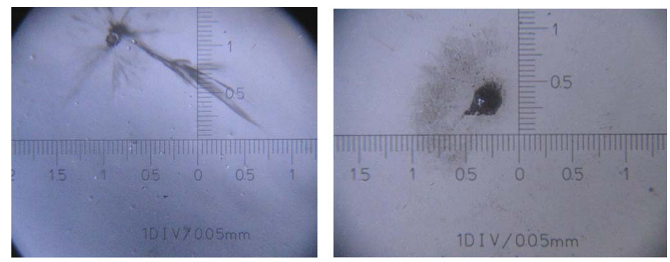
Equation (9) shows that $\log E_{\mathrm{BD}}$ is linear to $\log d$. Based on this conclusion, the E_{BD}-versus-d data in Fig. 6 are replotted in a log–log coordinate system, as shown in Fig. 7. From this figure, one can find a good linearity for each kind of polymer. Therefore, (9) is proved. Moreover, the E_{BD}-versus-d regularity shown in (8) is also proved.

Table II lists the fitting parameters of $1/m$ and E_{BD0} for each kind of polymer. From this table, it is found that the slope of $1/m$ for each polymer is around 1/8, except that of PMMA.

For this exception, it is believed that this results from the material's poor property. Fig. 8 shows the microscopic photographs of a breakdown PMMA sample and a PE sample. From the two photographs, one can find that there are pores and void in the PMMA sample, whereas there are few pores

TABLE II
FITTING PARAMETERS FOR FIG. 7

Polymer	$1/m$	E_{BD0}
PE	1/8.66	1.233
Nylon	1/7.74	1.578
PTFE	1/6.42	1.729
PMMA	1/2.83	1.798



(a) (b)

Fig. 8. Enlarged photographs of the breakdown (a) PMMA and (b) PE samples.

and void in the PE sample. It is considered that the relatively larger amount of the pores and void is the reason that the E_{BD} of PMMA decreases faster as the thickness increases.

B. Further Analysis on Thickness Effect on E_{BD}

To further research the E_{BD}-versus-d regularity of polymers, the famous formula suggested by Martin in the Atomic Weapons Research Establishment (AWRE) [5], [6] is reanalyzed, which is

$$E_{\mathrm{BD}} V^{\frac{1}{10}} = k \tag{10}$$

where V is the volume in cubic centimeters and k is a constant. By supposing that the test samples are with the same cross section S, V can be expressed as

$$V = S \cdot d. \tag{11}$$

Additionally, (10) can be rewritten as

$$E_{\mathrm{BD}} = \frac{k}{(S \cdot d)^{\frac{1}{10}}} = \frac{k \cdot S^{-\frac{1}{10}}}{d^{\frac{1}{10}}}. \tag{12}$$

Since k and S are both defined as constants, $kS^{-1/10}$ is therefore a constant. By comparing (12) with (8), it is found that the two equations are with the same form, except the power exponent.

To make sure of the exact value of the power exponent, the experimental results in AWRE are replotted and compared with the data obtained in this paper, as shown in Fig. 9. From this figure, it is seen that the two sets of data are basically parallel to each other. Table III lists the slopes for each kind of polymer in AWRE as well as in NINT. From this table, it is found that the slope is in the vicinity of $-1/8$. This value is consistent with that in NINT. Thus, it can be concluded that the exponent for the power relation of E_{BD} versus d in (8) is averaged 1/8.

It is worth mentioning that, for Martin's results, the slope of PMMA is 1/7.9. This presents another proof for the discrepancy of the PMMA data in NINT.

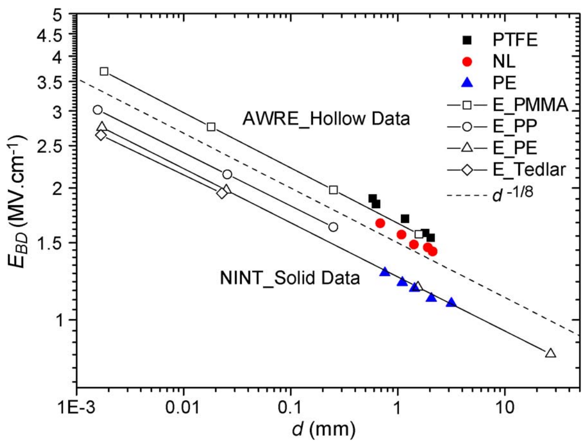


Fig. 9. Comparison of the E_{BD}-versus-d data in NINT and in AWRE. The conditions in NINT are pulsewidth of 8.5 ns, sphere–cylinder electrode, and quasi-uniform electric field. The conditions in AWRE are pulsewidth of 10 ns, $CuSO_4$-solution film electrode, and uniform electric field. The two sets of data are unified by choosing the E_{BD} of PE as a criterion and by employing thickness as argument.

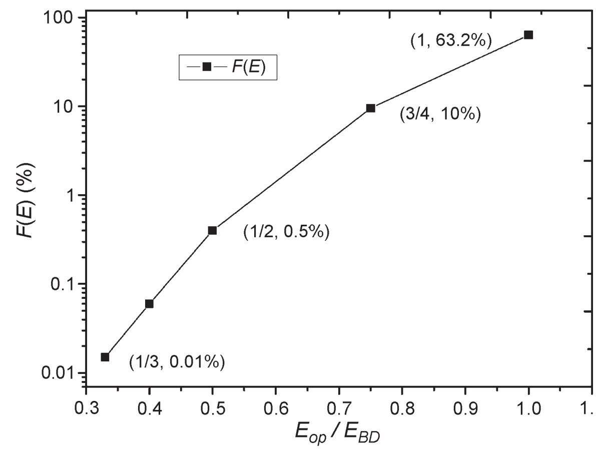


Fig. 10. Breakdown probability versus the normalized applied field.

TABLE III
FITTING PARAMETER OF $1/m$ FOR FIG. 9

Polymer	AWRE	NINT
PE	1/8.1	1/8.66
PTFE	—	1/6.42
PMMA	1/7.9	**1/2.83**
PP	1/8.2	—
Nylon	—	1/7.74
Tedlar	1/8.5	—

V. DISCUSSIONS

Based on the aforementioned experiments and analysis, discussions on the breakdown probability can be made.

With the conclusion in the aforementioned section and by substituting m of eight and η of E_{BD}^8 into (3), the specific expression of the Weibull distribution is obtained, which is

$$F(E) = 1 - \exp\left(-\left(\frac{E}{E_{\mathrm{BD}}}\right)^8\right). \tag{13}$$

According to this expression, the breakdown probability of polymers under nanosecond pulses can be predicted. For example, if the applied field is decreased to half of E_{BD}, then the breakdown probability will be as small as 0.4%; if the applied field is decreased to one-third of E_{BD}, the breakdown probability will be 0.01%, as shown in Fig. 10.

Since, in the engineering perspective, the breakdown probability of an insulator is expected to decrease to a certain low level to ensure the reliability, it is believed that (13) and Fig. 10 would be helpful for designers on insulator design.

VI. CONCLUSION

The thickness effect on electric breakdown strength of four kinds of polymers under nanosecond pulses is explored experimentally. It is derived that the relation of E_{BD} versus d submits to minus power law and the power exponent is 1/8. From the engineering perspective, if an insulator is expected with breakdown probability lower than 0.5%, the applied field should be smaller than half of E_{BD}.

Since the breakdown characteristics of polymers under nanosecond pulses are complicated and many factors would have effects on E_{BD}, future work is to research these relative factors. According to the arrangements in NINT, experiments on factors such as electrode material, electrode configuration, pulse polarity, and pulsewidth will be carried out successively. Moreover, a more specific breakdown mechanism will be focused on.

ACKNOWLEDGMENT

The authors would like to thank Group 2 of HPM office in the Northwest Institute of Nuclear Technology, particularly L. M. Wang, X. Sun, and R. Li for their guidance on the establishment of the experimental setup and G. Qiu and Q. Lin for their help on the accomplishment of the experiments.

REFERENCES

[1] S. D. Korovin, V. V. Rostov, S. D. Polevin, I. V. Pegel, E. Schamiloglu, M. I. Fuks, and R. J. Barker, "Pulsed power-driven high-power microwave sources," *Proc. IEEE*, vol. 92, no. 7, pp. 1082–1095, Jul. 2004.

[2] I. S. Roth, P. S. Sincerny, L. Mandelcorn, M. Mendelsohn, D. Smith, T. G. Engel, L. Schlitt, and C. M. Cooke, "Vacuum insulator coating development," in *Proc. 11th IEEE Int. Pulsed Power Conf.*, G. Cooperstein and I. Vitkovitsky, Eds., Baltimore, MD, 1997, pp. 537–542.

[3] W. A. Stygar, J. A. Lott, T. C. Wagoner, V. Anaya, and H. C. Harjes, "Improved design of a high-voltage vacuum-insulator interface," *Phys. Rev. Spec. Top.-Accel. Beams*, vol. 8, no. 5, pp. 050 401-1–050 401-16, May 2005.

[4] L. Zhao, J. C. Peng, Y. F. Pan, X. B. Zhang, and J. C. Su, "Insulation analysis of a coaxial high-voltage vacuum insulator," *IEEE Trans. Plasma Sci.*, vol. 38, no. 6, pp. 1369–1374, Jun. 2010.

[5] J. C. Martin, "Nanosecond pulse techniques," *Proc. IEEE*, vol. 80, no. 6, pp. 934–945, Jun. 1992.

[6] T. H. Martin, A. H. Guenther, and M. Kristiansen, Eds., *J. C. Martin on Pulsed Power*. New York: Plenum, 1996.

[7] G. A. Mesyats, *Pulsed Power*. New York: Academic, 2005.

[8] T. Shao, C. Zhang, K.-H. Long, J. Wang, D.-D. Zhang, and P. Yan, "Measurement and control for a repetitive nanosecond-pulse breakdown experiment in polymer films," *Chin. Phys. B*, vol. 19, no. 4, p. 040 601 (5 pp.), Apr. 2010.

[9] M. Treanor, J. R. Laghari, and A. K. Hyder, "Repetitive phenomena in dielectrics," *IEEE Trans. Elect. Insul.*, vol. EI-22, no. 4, pp. 517–522, Aug. 1987.

[10] J. H. Mason, "Breakdown of solid dielectrics in divergent fields," *Proc. Inst. Elect. Eng.—Part C: Monographs*, vol. 102, no. 2, pp. 254–263, Sep. 1955.

[11] V. M. Morton and A. W. Stannett, "Volume dependence of electric strength of polymers," *Proc. Inst. Elect. Eng.*, vol. 115, no. 12, p. 1857, Dec. 1968.

[12] K. Yoshino, S. Harada, J. Kyokane, and Y. Inuishi, "Electrical properties of hexatriacontane single crystal," *J. Phys. D, Appl. Phys.*, vol. 12, no. 9, pp. 1535–1539, Sep. 1979.

[13] S. Cygan and J. R. Laghari, "Dependence of the electric strength on thickness area and volume of polypropylene," *IEEE Trans. Elect. Insul.*, vol. EI-22, no. 6, pp. 835–837, Dec. 1987.

[14] J. H. Mason, "Effects of thickness and area on the electric strength of polymers," *IEEE Trans. Elect. Insul.*, vol. 26, no. 2, pp. 318–322, Apr. 1991.

[15] P. Bjellheim and B. Helgee, "AC breakdown strength of aromatic polymers under partial discharge reducing conditions," *IEEE Trans. Dielectr. Elect. Insul.*, vol. 1, no. 1, pp. 89–96, Feb. 1994.

[16] B. Helgee and P. Bjellheim, "Electric breakdown strength of aromatic polymers: Dependence on film thickness and chemical structure," *IEEE Trans. Elect. Insul.*, vol. 26, no. 6, pp. 1147–1152, Dec. 1991.

[17] G. Yilmaz and O. Kalenderli, "The effect of thickness and area on the electric strength of thin dielectric films," in *Proc. IEEE Int. Symp. Elect. Insul.*, 1996, vol. 2, pp. 478–481.

[18] Y. Yang, S. C. Zhang, F. Dogan, E. Schamiloglu, J. Gaudet, P. Castro, M. Roybal, M. Joler, and C. Christodoulou, "Influence of nanocrystalline grain size on the breakdown strength of ceramic dielectrics," in *Proc. 14th IEEE Int. Pulsed Power Conf.*, 2003, vol. 1, pp. 719–722.

[19] J. C. Su, X. B. Zhang, G. Z. Liu, X. X. Song, Y. F. Pan, L. M. Wang, J. C. Peng, and Z. J. Ding, "A long-pulse generator based on Tesla transformer and pulse-forming network," *IEEE Trans. Plasma Sci.*, vol. 37, no. 10, pp. 1954–1958, Oct. 2009.

[20] L. A. Dissado, J. C. Fothergill, S. V. Wolfe, and R. M. Hill, "Weibull statistics in dielectric breakdown; Theoretical basis, applications and implications," *IEEE Trans. Elect. Insul.*, vol. EI-19, no. 3, pp. 227–233, Jun. 1984.

[21] H. Bluhm, *Pulsed Power Systems*. Karlsruhe, Germany: Springer-Verlag, 2006.

[22] M. P. Wilson, M. J. Given, I. V. Timoshkin, S. J. MacGregor, M. A. Sinclair, K. J. Thomas, and J. M. Lehr, "Impulse-breakdown characteristics of polymers immersed in insulating oil," *IEEE Trans. Plasma Sci.*, vol. 38, no. 10, pp. 2611–2619, Oct. 2010.

[23] L. A. Dissado and J. C. Fothergill, *Electrical Degradation and Breakdown in Polymers*. London, U.K.: Inst. Eng. Technol., 1992.

Liang Zhao was born in Shaanxi, China, in May 1983. He received the B.E. degree in physical electronics from Xi'an Jiaotong University, Xi'an, China, in 2006, where he is currently working toward the Ph.D. degree.

He is also currently with the Northwest Institute of Nuclear Technology, Xi'an. His research interests include solid insulation and the pulsed-power technology.

Guo-zhi Liu was born in Liaoning, China, in 1960. He received the B.S., M.S., and Ph.D. degrees in physics from Tsinghua University, Beijing, China, in 1983, 1986, and 1992, respectively.

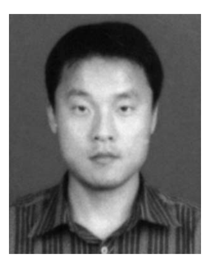
He joined the Pulsed Power Department, Northwest Institute of Nuclear Technology (NINT), Xi'an, China, in 1986. After receiving the Ph.D. degree, he established the Department of High Power Microwave, NINT, where he has been a Professor of physics and the Chairman of the department since 1992. Since 2002, he has been a Professor in physical electronics in Xi'an Jiaotong University. Since 2009, he has been an Academician with the Chinese Academy of Sciences. He has published over 200 journal articles and conference proceeding papers and has coauthored three books. His current research interests and specialties include the intense-electron-beam physics, high-power microwave generation, and insulation technology.

Jian-cang Su was born in Xi'an, China, in November 1965. He received the B.E. and Ph.D. degrees in physical electronics from Xi'an Jiaotong University, Xi'an, in 1987 and 2006, respectively.

Since 1987, he has been with the Northwest Institute of Nuclear Technology, Xi'an, where he is currently the Director of the Department of High Power Microwave. He has published over 20 journal articles and proceeding papers. His research interests include the high-power microwave and the pulsed-power technology.

Ya-feng Pan was born in Jiangsu, China, in July 1978. He received the M.S. degree in optic engineering from the National University of Defense Technology, Changsha, China, in 2002.

Since 2003, he has been with the Northwest Institute of Nuclear Technology, Xi'an, China. His research interests include the pulsed-power technology.



Xi-bo Zhang was born in Heilongjiang, China, in February 1979. He received the B.E. degree in nuclear technology from Tsinghua University, Beijing, China, in 2002 and the Ph.D. degree in physical electronics from the Northwest Institute of Nuclear Technology (NINT), Xi'an, China, in 2009.

Since 2002, he has been with NINT. His research interests include the pulsed generator technology.