IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 16, 2020, accepted October 19, 2020, date of publication October 30, 2020, date of current version November 11, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3034901

Electrical-Mechanical Model of Electrical Breakdown of Epoxy-Impregnated-Paper Insulated Tubular Busbar With Bubble Defects

XIANG REN[1], LING RUAN[1], HAIYUN JIN[2], AND GUANJUN ZHANG[2], (Member, IEEE)
[1]Electric Power Research Institute, State Grid Hubei Electric Power Company Ltd., Wuhan 430077, China
[2]State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an 710049, China

Corresponding author: Xiang Ren (renxiang8888@163.com)

This work was supported by the Science and Technology Project of Chinese State Grid under Grant 52153216000S.

ABSTRACT Insulated tubular busbar is a new type of current-carrying equipment with excellent performance. However, the research on this equipment is insufficient because of the short application and the lack of technical digestion, which has resulted in many accidents. In this paper, the full-scale model of epoxy-impregnated-paper insulated tubular busbar with bubble defects was designed and produced, its electrical breakdown process was investigated by withstand voltage test. In the experiment, the failure mode of breakdown caused by gas expansion was found for the first time. The research showed that the electrical-mechanical breakdown process could be divided into two stages: gas increase stage and breakdown threshold stage. The research also obtained the characteristics and the change criterions of the two stages. The gas in the bubble defects generated from epoxy decomposition which caused by partial discharge. When the gas pressure exceeds the critical fracture toughness of the bubble defects wall, the unstable crack extension occurs, therefore, improving the ability about resistance to partial discharge of epoxy resin or improving the fracture toughness of epoxy resin by modifying would enhance the breakdown performance of insulated tubular busbar. The result also has reference significance for other epoxy-impregnated-paper insulated electrical equipment.

INDEX TERMS Electrical breakdown, epoxy-impregnated-paper insulated tubular busbar, fracture toughness, partial discharge.

I. INTRODUCTION

Insulated tubular busbar is a new type of busbar product coated with solid insulation, which use tubular copper as the conductor. It is mostly used to connect the low-voltage side of the transformer and the switchgear, which is the main collection equipment for power transfer in substations. Compared with traditional rectangular busbars, insulated tubular busbars have the unique advantages of large current-carrying capacity, high mechanical strength, strong electrical insulation performance, and saving floor space. At present, the insulation structure of the insulated tubular busbar is a composite system of epoxy resin impregnated paper. The production process originated from Europe and has become the technical benchmark of the domestic busbar industry. However, because of the short application of epoxy insulated tubular busbar in China and the lack of technical digestion and in-depth study, busbar failures have occurred frequently in recent years, which has caused serious hidden dangers to the stable operation of power systems.

The bubble defect is the most common defect in the insulation layer of epoxy-impregnated-paper insulated tubular busbars: The bubbles will be formed in the insulation layer of the busbar due to the insufficient epoxy impregnation in the impregnating process and careless construction during installation. Under the action of a certain external electric field, partial discharge will occur at the place of bubble defect. The effects of electricity, heat, and high-energy particles generated by partial discharge will cause the breakage and carbonization of the molecular chain of the material around the bubble wall, erode the surrounding insulating material, and further develop the bubble defect, which eventually forms a penetrating channel along the direction of the electric field so that the insulation of the busbar is breakdown.

The associate editor coordinating the review of this manuscript and approving it for publication was Nagarajan Raghavan.

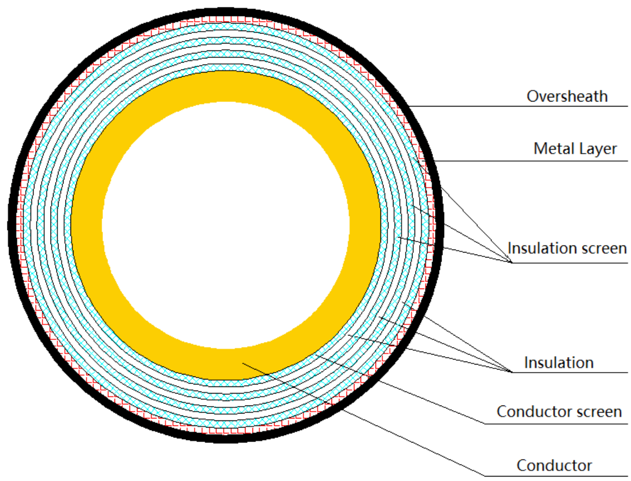


FIGURE 1. Radial section of the typical body structure.

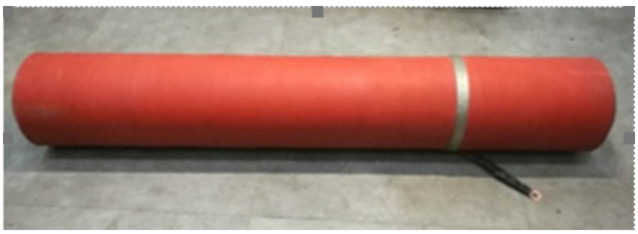


FIGURE 2. Experimental sample of insulated tubular busbar.

Researches relevant on insulated tubular busbars have been carried out. However, most of the current researches focus on the electric field simulation and static parameter measurement of insulated tubular busbars, and lack of the study on the electrical breakdown process of insulated tubular busbars under the condition of defect. So far, there is no any relevant reports. By referring to the data related to the electrical breakdown process, this paper finds that the previous research objects are mostly epoxy resin and cross-linked polyethylene flaky samples, and the research ideas and results may deviate from the actual power equipment. Therefore, this paper cooperated with domestic tubular busbar manufacturers to design and prepare samples of epoxy-impregnated-paper insulated tubular busbar containing bubble defects, and carried out electrical degradation tests on the samples, and it studied the process of electrical breakdown for the insulated tubular busbars containing bubble defects.

II. EXPERIMENTAL SETUP

The insulation system, structure size and production process of the defect samples in the paper are as follows: the tubular conductor is made of T2 copper, and the main insulation structure is epoxy-impregnated-paper insulation system. The capacitive screen is a semi-conductive material containing graphite. the external thermal shrinkable sleeve is PVC material, the grounding wire is a braided aluminum tape with a copper ring. The typical body structure is shown in Fig. 1, and the experimental sample is shown in Fig. 2.

TABLE 1. Test data of the bubble defect sample.

Capacitance (nF)	Tan (10^{-3})	PD inception voltage / (kV)
1.81923	4.6	7.2

The production process is as followed. Firstly, the insulating paper is wrapped layer by layer around the copper conductor to the given thickness. During the wrapping process, the semi-conductor screen is also wrapped at the specific thickness in the same way. Secondly, the "paper skeleton", including the semi-conductor screen, is tightly sealed with a specific mold and hanged in the curing oven. Then, a vacuum pump is connected to the bottom of the "paper skeleton" while two filling tubes of epoxy resin are connected to the top part. The "paper skeleton" is difficult to get to the vacuum condition, but lower than 50 Pa actually. It is hard to get to the real vacuum condition and not essential to the vacuuming work. And 50 Pa is the optimal choice for the financial considerations. The outer metal layer is also wrapped around the semi-conductor screen and then coated by the insulating paper to certain thickness. After that, the vacuumizing and filling are performed at the same time, which can make the epoxy resin well impregnate into the "paper skeleton".

After the curing procedure, the metal layer is also inside the solid epoxy resin. A small hole is excavated to weld a metal ground wire. The outer sleeve is a kind of heat shrinkable sleeve, usually made of PVC, special sealing hot melt adhesive and some other material, forming a strong anticorrosion sheath. The shrinking temperature of the sleeve is about 125°C

The rated voltage / current of the sample is 6kV / 6300A, the length of the conductor is 1000mm, the outer diameter of the conductor is 140mm, the maximum outer diameter of the sample is 170mm (including the thickness of the oversheath), and the thickness of the insulating layer is about 10mm. There is an equidistant capacitive screen retreat structure inside the sample: 0^{th} screen closely adheres to the copper conductor, 30 mm from the end of the conductor; the exiting screen distance for 1^{st}, 2^{nd}, 3^{rd} is 40 mm, screen spacing is about 3 mm; semi-conductive layer thickness is about 0.5~1 mm. A ground ring is installed at the ground screen (the 3^{rd} screen) at a distance of 250 mm from the conductor.

The key technology of sample production is epoxy resin impregnating paper in vacuum pressure, about 50 Pa actually. In the paper, 10 - 15 mL of air is injected with an injector through one of the filling tubes when the filled resin is getting near to the bottom part. So, the bubbles are likely to locate at anywhere throughout the epoxy system, which forms a micro-porous air gap in the main insulation. And there is no idea to locate the position and size of the bubbles.

After the sample preparation was completed, the corresponding test in factory was carried out. The result is shown in Tab. 1.

In order to study the process of the electrical degradation of the insulated tubular busbar, a transformer is used to perform electrical degradation on the long-term withstand voltage of the busbar sample. The effective value of the voltage is 30kV; during the withstand voltage process, it is measured offline by a digital partial discharge measuring instrument (LSD-6) for the partial discharge characteristic parameters of the sample to infer the development status of its internal breakdown path. After the breakdown of the insulation, the sample is dissected and analyzed for the fault gas extraction. The specific partial discharge test is conducted and the inception voltage of partial discharge and the partial discharge parameters of the sample under 1.0 U_N and 1.2 U_N are measured, where U_N stands for the rated phase voltage. The electrical destruction test and insulation property test of the samples are carried out at room temperature and normal pressure. A gas chromatograph-mass spectrometer (Thermo Fisher) is used to analyze the gas composition and a scanning electron microscope (VE9800) for observing the dissected slice.

III. RESULT AND ANALYSIS

It is 126.5h for the total electrical degradation time of the bubble defect sample from the beginning of electrical destruction to insulation failure, and the gas bulging phenomenon appeared on the surface of the failed sample. Under the condition of electrical damage, the insulation failure of the tubular busbar and the appearance of gas bulging on the surface are the first findings of this type of research (the previous forms of damage are mostly ablation or cracks), indicating that its breakdown is not a simple electro-thermal process. Decomposition and mechanical destruction play an important role. In order to explore the relationship between this gas bulge phenomenon and the electrical breakdown of the insulated tubular busbar, it is necessary to analyze the composition of the gas in the bulge, dissect the insulating layer of the sample, and then conduct an in-depth study on the breakdown process.

A. ANALYSIS ON THE BULGES OF INSULATION

After electrical damage of 126.5h, the insulation failure of the sample was broken down, and a bulge was generated under the outer jacket layers at both ends, as shown in Fig.3.

Among them, the bulge A is far from the grounding wire, the center of the bulge is about 100mm~120mm from the copper conductor, the shape is like oval, the diameter is 60mm and 110mm, the expansion degree of the bulge is different, away from the center point, the expansion degree is reduced; the bulge B is near to the ground wire, the center of the bulge is about 120mm~140mm from the copper conductor, the shape is close to a sphere, and the diameter is about 56mm. The gas in the drum was collected and analyzed by gas chromatography, and the result is shown in Fig.4.

As shown in Figure 4, the outer sleeve is not damaged while the main insulation layer is seriously carbonized in the breakdown. The gas in the bulges can only come from the main insulation since it has formed as a strong tightly

(a) bulge A (b) bulge B

FIGURE 3. External bulge after sample insulation failure.

solid. According to the analysis report, the first peak of the gas released from the sample is O_2; the second peak group is short-chain hydrocarbons containing carbon-carbon double bonds; the third peak group corresponds to xylene (C_8H_{10}); the fourth peak group corresponds to nonanes; the fifth peak group is aromatic hydrocarbon molecules.

The insulation structure of the sample is an epoxy resin insulation paper composite insulation system, in which the epoxy resin is a bisphenol-A epoxy resin with a benzene ring structure, as shown in Fig. 5. And all the decomposition products should be originated from the bisphenol-A epoxy resin and the insulating paper with a long-chain hydrocarbon.

The gas chromatography results can determine that the evolved gas is the decomposition product of the epoxy resin composite material in the sample insulation.

Under the action of electric, heat, and high-energy particles in the partial discharge of the air gap defect inside the sample, the molecular chain of the insulating material of the bubble wall, the interface of the bubble and the insulating material, is destroyed and cracked, thereby generating short-chain hydrocarbon gas and aromatic gas, and the formation of high air pressure in the bubble defect, on the one hand, it affects the partial discharge in the bubble, on the other hand, it also causes pressure on the bubble wall, which becomes one of the reasons for the destruction of the bubble wall and the formation of breakdown paths.

After collecting and analyzing the escaping gas, the outer sheath of the sample was dissected for better observation of the main insulation. It can be seen from Fig. 6 that there are two breakdown points on the sample insulation layer, which correspond to the bulge positions. According to our dissection of the experimental sample after breakdown, no penetrating breakdown has formed in the location of both the bubble A and B. The outer part of the insulation of bubble A, about 2.2mm of penetration depth from the breakdown point, has been carbonized seriously. It is quite different with that of bubble B. The inner part of bubble B has been carbonized seriously and the penetration depth is about 4.1mm.

The insulation material is carbonized, the closer to the center point at the breakdown point, the more obvious the carbonization trace, and the color is much darker, the material at the center point has been burnt black.The insulating material structure around the breakdown point becomes loose and brittle, all of which proves that the epoxy resin material has been destroyed and decomposed.

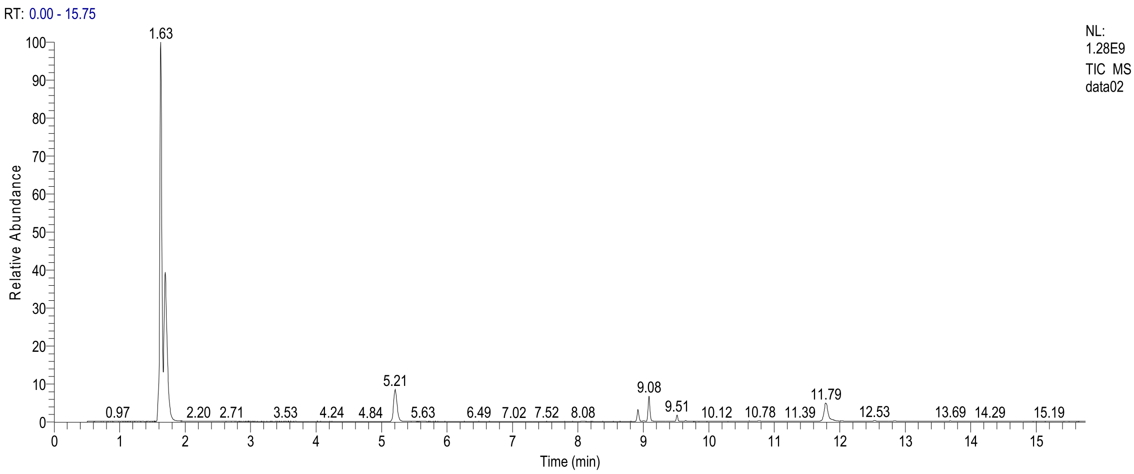


FIGURE 4. The gas chromatogram of escape gas.

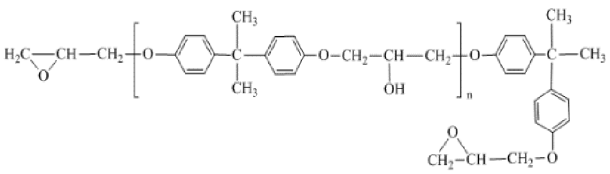


FIGURE 5. Molecular formula of bisphenol-A epoxy resin.

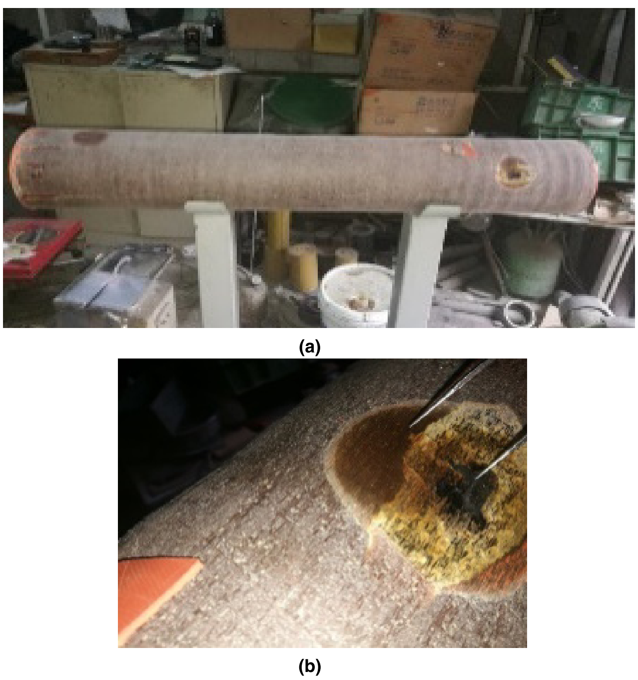


FIGURE 6. Appearance inspection of main insulation.

For further research, the differential scanning calorimetry (DSC) is applied to 3 points, which stands for place far from the breakdown point (#1), near the breakdown point (#2) and the breakdown point (#3) separately. Then three DSC curves, expression of the relationship between the heat flowing and temperature of the insulating material, are obtained and shown in Fig. 7.

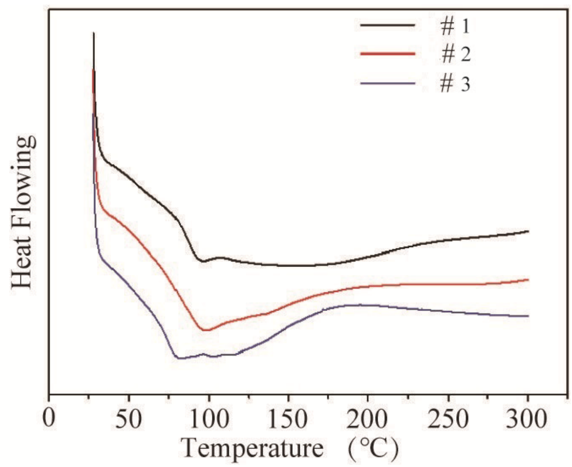
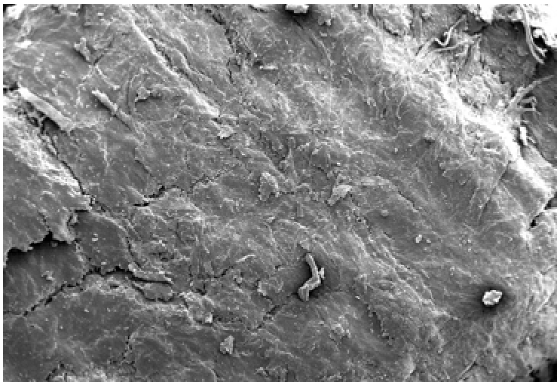


FIGURE 7. DSC curves of three points (#1, #2, #3).

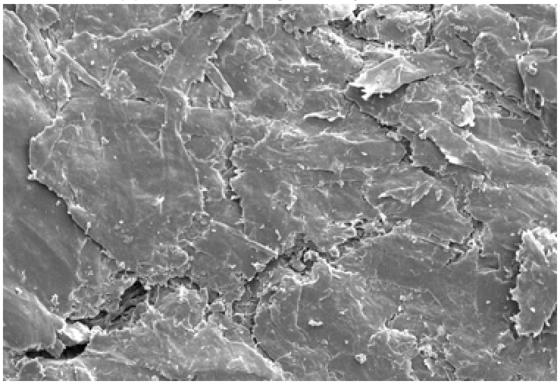
According to Fig.7, the glass transition temperature (T_g) can be calculated, 87.99°C for #1, 95.94°C for #2 and 77.72 for #3. T_g of #2 is a little higher than that of #1 because of the high temperature during the breakdown. The transient high temperature, but not high enough, could make the epoxy resin undergo further curing. But the T_g of #3 decrease a lot since the material there has been carbonized seriously.

Subsequently, a sample of epoxy insulating material that has not been fully carbonized, insulation of #2, is extracted and observed using a scanning electron microscope (SEM) to verify the explanation above. The result is shown in Fig.8, while that of #3 is shown in Fig. 9.

It can be found from Fig. 7 to Fig. 9 that the epoxy resin in the insulating material near the breakdown point has been carbonized seriously and became loose and brittle, many cracks have appeared, and the crack morphology exhibits obvious mechanical damage. The epoxy material in this paper is a brittle material, which has certain similarity with ceramic

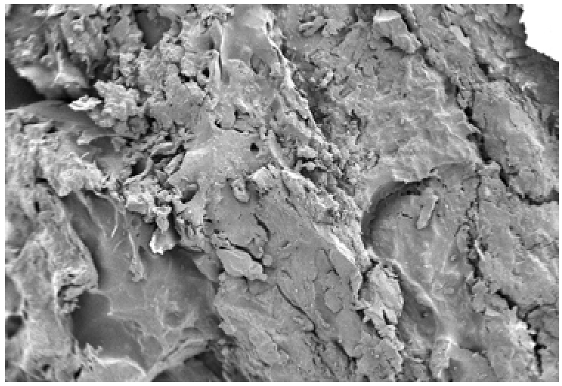


(a) SEM result magnified by 50 times

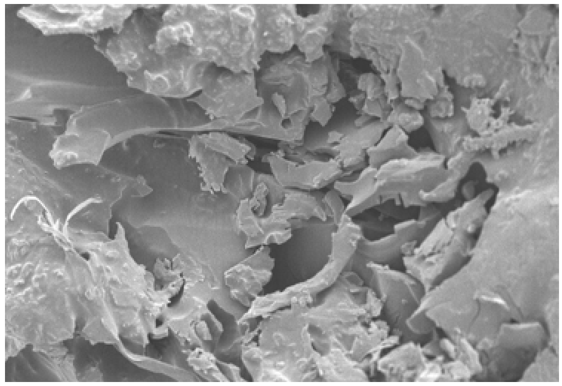


(b) SEM result magnified by 200 times

FIGURE 8. SEM results of epoxy insulation of #2.



(a) SEM result magnified by 50 times



(b) SEM result magnified by 200 times

FIGURE 9. SEM results of epoxy insulation of #3.

materials. Researcher [16] has pointed out that in brittle materials, once a crack has occurred, the stress state will cause the crack to start to propagate, and there is no Large energy absorption process compared to plastic deformation. Therefore, there is no process to limit the applied stress, so the crack continues to propagate in a uniform stress field until it is destroyed completely. This means that the occurrence of cracks is a critical stage of the destruction process.

The crack propagation mode in Fig. 6 is a typical material instability failure. The reason is that the gas pressure in the pores exceeds the critical value of the fracture toughness of the bubble wall material under the action of partial discharge. The Fracture Toughness Critical Value (K_{IC}) is a material mechanical strength concept that characterizes the impedance value displayed when an unstable fracture occurs in a sample or component with cracks or crack-like defects.

The above experimental phenomenon shows that the destruction of the epoxy insulating material is not only a pure electrical effect, but also mechanical destruction. Under long-term partial discharge activities, the pressure inside the bubble keeps rising, and the pressure on the bubble wall is also increased. At the same time, partial discharges have an erosive effect on the inner wall of the bubble. The critical value of the material's inherent fracture toughness drops. Under the combined effect of two aspects, the gas inside the bubble breaks through the bubble wall, forming instability and expanding cracks, and these microscopically expanding cracks constitute a macroscopic penetration path for sample insulation.

B. PERFORMANCE OF THE PD DURING THE BREAKDOWN PROCESS

The PD inception voltage U_{i} varies with the degradation time when the electrical degradation test is applied to the samples, as shown in Fig. 10.

The inception value of the partial discharge starting voltage Ui of the sample is 7.6kV (the factory test value is 7kV). After a short period of electrical degradation (about 10h), the partial discharge starting voltage U_{i} of the sample quickly decreases to 2.6kV. During the subsequent electrical degradation, the partial discharge inception voltage U_{i} of the sample has been maintained at this level, fluctuating in the range of 2.5kV$\sim$3kV.

According to the collision ionization theory of gas discharge in [18], within size range of a certain air gap, the characteristic value of the gas discharge-the effective number of collisions Z is determined by the free stroke of electrons λ, the number of electron collisions N and the kinetic energy E accumulated in the free stroke of electrons, where λ and N are related to the concentration of the gas (that is, the gas pressure p), the greater the concentration of the gas, the greater λ and N will be. E accumulated in λ is related to the applied electric field strength (that is, a function of the applied voltage U). The larger the field strength, the greater the kinetic energy E

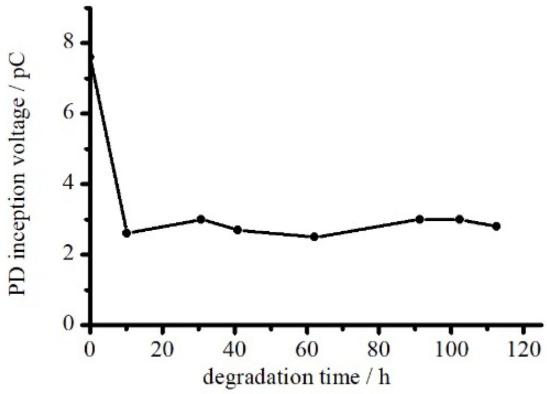


FIGURE 10. Sample partial discharge inception voltage Ui as a function of degradation time.

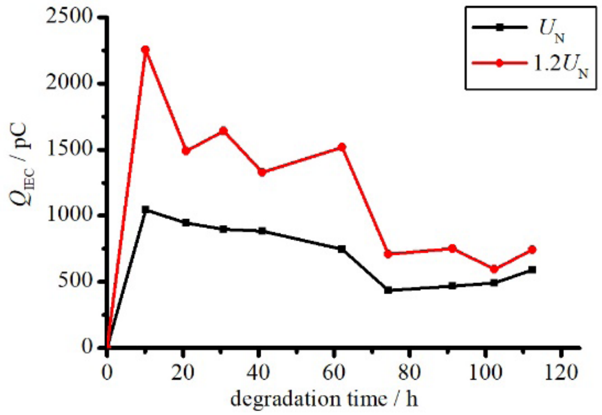


FIGURE 11. U_N, 1.2 U_N measured voltage partial discharge amount Q_{IEC} as a function of degradation time.

obtained by electrons within the same free travel λ; A fixed value can be used as an indicator of the beginning of partial discharge, and then the approximate function relationship between λ and N, and it can obtained the kinetic energy E accumulated by electrons in free stroke, as in (1).

$$g(\lambda NE) = Z \tag{1}$$

In the early stage of electrical breakdown, the bubble defect in the sample is in low pressure state and the gas inside is thin. Though the free stroke of the electron (λ) is large, the number of collisions (N) is small. Therefore, only when the external electric field of the gas is strong and kinetic energy of the electron accumulated during the free stroke is large enough, sufficient effective number of collisions can be generated, showing a higher partial discharge initial voltage of the sample (in the initial stage, the partial discharge initial voltage of the sample is higher, 7kV).

With the electric breakdown going, the gas molecules produced by partial discharge enter the bubble defect, increasing the concentration of gas molecules, and increasing the number of electron collisions when the electron free stroke does not change so much, so when the external electric field is not that high, sufficient effective collisions can also be generated in the bubble defect, showing a drop in the partial discharge initial voltage of the sample; during the following electrical breakdown, the gas pressure in the bubble defect further increases, the descent effect of electron free stroke and the increase effect of the number of electron collisions strike a balance, so that the partial discharge starting voltage of the sample continues to maintain a lower voltage level (the partial discharge starting voltage of the sample is maintained at the level of 2kV∼3kV), which can also imply that the range of bubble defects does not change greatly, namely the penetration channel and did not develop rapidly.

The voltage partial discharge amount Q_{IEC} under U_N and 1.2 U_N are measured, and the variation curve with the degradation time is shown in Fig.11.

It can be concluded from Fig. 11 that before the electrical breakdown, there is no partial discharge (<2pC) in the sample at the U_N and 1.2 U_N voltage; and after a short period of electrical degradation (about 10h), the partial discharge of the sample Q_{IEC} increase rapidly, The value of Q_{IEC} is 1045pC at the U_N voltage, and the value is 2253pC at the 1.2 U_N voltage; henceforth, as the degradation time increases, the partial discharge amount Q_{IEC} of the sample gradually decreases, and eventually maintains at a relatively stable level. Before the electrical breakdown of the sample, namely the destruction time is 112h, the Q_{IEC} value of the sample is about 600pC at the U_N voltage, and the Q_{IEC} value of the sample is about 700pC at the 1.2 U_N voltage. The partial discharge amount of samples under different voltages during electrical breakdown shows the system difference. At the 1.2U_N voltage, the Q_{IEC} value of the sample is higher than that at the U_N voltage. The gap reaches the top (about 1200pC,) at the initial stage of degradation. With the destruction develops, the gap gradually reduced to the range of 200pC∼300pC.

In addition to the gas pressure in the bubble defect, the change of the partial discharge of the sample is also related to the surface appearance of the inner wall of bubble. Referring to some relevant electrical tree data, when the inner wall of the bubble is not damaged and is rough, the partial discharge is large. Activities in the bubble wall are often suppressed and the amount of partial discharge is reduced accordingly. This process shows a gradual decrease in the partial discharge of the sample at the U_N and 1.2 U_N voltages during the electrical breakdown.

C. THE ELECTRICAL-MECHANICAL MODEL OF ELECTRICAL BREAKDOWN

Based on the test phenomena and data mentioned above, this study establishes an electrical-mechanical model of electrical breakdown of epoxy-impregnated-paper insulated tubular busbar with bubble defects: the partial discharge effect in the bubble defects destroys the structure of the macromolecules of the insulated material and thus deteriorates the performance of material. The short-chain molecular gas enters the air gap of the bubble, forming a high pressure in the air gap, which in turn affecting the partial discharge activity in the air gap. Eventually, the gas in the bubble defects generated from epoxy decomposition which caused by partial discharge. When the gas pressure exceeds the critical fracture toughness (K_{IC}) of the bubble defects wall, the unstable crack occurs, and leads to the breakdown of the bubble-defective insulated tubular busbar.

The breakdown process of the bubble-defective insulated tubular busbar could be divided into two stages: gas increase stage and breakdown threshold stage. In the gas increase stage, when PD occurs at the bubbles, the insulation nearby is limited to a certain range at the beginning, no penetrating breakdown channels are formed, and the gas pressure in the bubble has been continuously increasing, showing that the initial voltage of the partial discharge decreases and remains stable, and the partial discharge amount continues to decrease, just as shown in Fig. 10 and Fig. 11.

In the gas increase stage, the partial discharges are not only to enhance the gas pressure in the bubble defect, but also to erode the inner wall of the bubble. While improving the smoothness of the inner wall of the bubble, the molecular chain of the insulating material on the bubble wall is continuously destroyed, leading the electrical and mechanical properties of the insulated material on the bubble wall decreasing.

The gas increase stage is the first stage of electrical breakdown of the bubble-defective insulated tubular busbar, also the long-term stage of equipment breakdown. During the total electrical breakdown time (126.5h) of the samples, according to the partial discharge measurement results, it can be showed that the samples are in the gas increase phase for at least 115h. When the gas in the bubble defect increases to a certain degree, and even exceeds the critical fracture toughness of the bubble wall, the electrical breakdown is transferred to breakdown threshold stage. The main characteristic of breakdown threshold stage is that the bubble defect wall is destroyed, the surrounding insulated material becomes unstable and destroys. The cracks quickly extend, and finally penetrate the insulated layer, leading the sample breaking down and the gas escaping. Because the defect of this sample contains bubbles, the partial discharge activity is violent and the gas content is large, so it is showed that a significant gas bulge under the oversheath. The transition of electrical damage to the breakdown threshold stage is essentially the effect of accumulation of partial discharge activity in the bubble defect. The increase of the gas pressure in the bubble and the decrease in the critical value of the inherent fracture toughness of the bubble wall material eventually cause the gas in the bubble to break through the bubble wall and form rapid breakdown paths.

The breakdown threshold stage is the second stage of electrical breakdown of this kind insulated tubular busbar with bubble defects, which is also a short-term stage. Even before the sample breakdown, there was no phenomenon that the bubble wall was destroyed and the breakdown channel formed rapidly. The partial discharge measurement results of the sample remained the same as before.

From the experimental results and analysis mentioned above, it can be induced that the electrical-mechanical synergy effect is the main reason for the destruction of the sample. If the electrical breakdown performance of the epoxy-insulated tubular busbar is improved, we need to enhance the electrical breakdown property of the epoxy resin insulated material and its partial discharge and the inner fracture toughness value of the material. In addition, it is difficult to detect when the sample transfers to the breakdown threshold stage by the traditional non-destructive detection method. Whether it is in the partial discharge measurement result or the appearance test of the sample, it is hard to find this phenomenon, which namely explains the frequent failure of tubular current and also shows the importance of studying the electrical breakdown process of insulated tubular busbar from the internal process.

IV. CONCLUSION

The paper draws the following conclusions for epoxy-impregnated-paper insulated tubular busbar.

1) The electrical breakdown of the insulated tubular busbar with bubble defects should be the result of the combined electrical-mechanical effect, in which the formation of the penetrating breakdown channel is a sudden process.

2) The main reason for the breakdown of insulated tubular busbar containing bubble defects is that the air pressure of the air gap generated by partial discharge exceeds the critical value of the fracture toughness of the air gap wall, so we can improve the resistance to partial discharge and enhance the fracture toughness of the composite material in order to enhance the electrical breakdown performance of the bubble-defective epoxy-impregnated-paper insulated tubular busbar.

3) It is difficult to tell whether the epoxy-impregnated-paper insulated tubular busbar with bubble defects is transferred into the critical stage of breakdown by traditional detection methods, and a new detection technique can be developed to test the bubble pressure and bubble wall strength.

The research results can also be acted as a certain reference for other resin-impregnating insulated electrical equipment.

REFERENCES

[1] R. Ling and L. Chenglei, "Development status and research trend of insulated tubular busbar," *High Voltage App.*, vol. 54, no. 4, pp. 43–53, 2018.

[2] E. E. Woods and F. W. Heinrichs, "Cast epoxy insulation for high voltage switchgear and power transformers," in *Proc. EI Electr. Insul. Conf. Mater. Appl.*, Chicago, IL, USA, Sep. 1963, pp. 265–267.

[3] R. Rajvanshi and T. Hawkins, "Insulated bus bars in low-voltage systems: Reducing arc duration and energy emissions," *IEEE Ind. Appl. Mag.*, vol. 23, no. 3, pp. 48–53, May 2017.

[4] R. Worth, M. Islam, and C. Smith, "Insulated Bus Pipe (IBP) for power utility applications," in *Proc. IEEE 11th Int. Conf. Transmiss. Distrib. Construct., Operation Live-Line Maintenance*, Oct. 2006, pp. 1–5, doi: 10.1109/TDCLLM.2006.340727.

[5] Y. Fan, Z. Yaodong, and Z. Qiyi, "Comprehensive defect analysis and preventive measures for an insulated busbar fault," *Hubei Electr. Power*, vol. 39, no. 8, pp. 42–44, 2015.

[6] L. Bin, Y. Xin, and T. Zhihong, "Review and prospect of the organic insulated busbar in China," *High Voltage App.*, vol. 52, no. 6, pp. 9–17, 2016.

[7] Q. Changrong and C. Xiaolong, *Electrical Insulation Test Technology*. Beijing China: China Machine Press, 2001.

[8] N. Hayakawa, H. Maeda, S. Chigusa, and H. Okubo, "Partial discharge inception characteristics of LN2/epoxy composite insulation system under thermal bubble condition," in *Proc. IEEE 13th Int. Conf. Dielectric Liquids (ICDL)*, Jul. 1999, pp. 392–395.
[9] L. Fenglian and X. Zhihang, "Operating characteristics and state evaluation methods for insulated tubular busbar," *High Voltage Eng.*, vol. 43, no. 12, pp. 4088–4095, 2017.
[10] P. Przybylek, Z. Nadolny, and H. Moscicka-Grzesiak, "Bubble effect as a consequence of dielectric losses in cellulose insulation," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 17, no. 3, pp. 913–919, Jun. 2010.
[11] L. Zhang, J. H. Li, J. Y. Tan, X. M. Hu, Y. M. Li, and Z. R. Tan, "Characteristics of surface partial discharge on joint of insulated copper busbar," *High Voltage App.*, vol. 49, no. 11, pp. 94–98, Nov. 2013.
[12] R. Rajvanshi and T. Hawkins, "Value of insulated bus bars in reducing arcing fault duration in low-voltage systems," *IEEE Trans. Ind. Appl.*, vol. 52, no. 2, pp. 1280–1284, Mar. 2016.
[13] D. D. Christantoni, G. E. Vardakis, and M. G. Danikas, "Propagation of electrical tree growth in a composite solid insulation consisted of epoxy resin and mica sheets: Simulation with the aid of cellular automata," in *Proc. 10th IEEE Int. Conf. Solid Dielectrics*, Jul. 2010, pp. 1–4.
[14] J. Champion, S. Dodd, and G. Stevens, "Analysis and modelling of electrical tree growth in synthetic resins over a wide range of stressing voltage," *J. Phys. D, Appl. Phys.*, vol. 33, no. 12, p. 1020, 2007.
[15] C. Xiang-rong, X. Yang, and X. Jie, "Propagation and partial discharge characteristics of electrical trees in 110 kV XLPE cable insulation at power frequency applied voltage," *High Voltage Eng.*, vol. 36, no. 10, pp. 2436–2443, 2010.
[16] W. David Kingery, H. K. Bowen, and R. D. Uhlmann, *Introduction to Ceramics*, 2nd ed. Hoboken, NJ, USA: Wiley, 1976, pp. 58–62.
[17] S. Huang, T. B. Boykin, R. S. Gorur, and B. Ray, "Electrical tree formation in polymer-filler composites," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 26, no. 6, pp. 1853–1858, Dec. 2019.
[18] J. I. N. Weifangm, *Dielectric Physics*. Beijing, China: China Machine Press, 1997, pp. 124–126.
[19] N. M. Chalashkanov, S. J. Dodd, L. A. Dissado, and J. C. Fothergill, "The role of bulk charge transport processes in electrical tree formation and breakdown mechanisms in epoxy resins," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 23, no. 6, pp. 3256–3266, Dec. 2016.
[20] A. Xie, X. Zheng, S. Li, and G. Chen, "Investigations of electrical trees in the inner layer of XLPE cable insulation using computer-aided image recording monitoring," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 17, no. 3, pp. 685–693, Jun. 2010.
[21] B. Du, M. Tian, J. Su, and T. Han, "Electrical tree growth characteristics in epoxy resin with harmonic superimposed DC voltage," *IEEE Access*, vol. 7, pp. 47273–47281, 2019.
[22] M. G. Danikas and T. Tanaka, "Nanocomposites–A review of electrical treeing and breakdown," *IEEE Elect. Insul. Mag.*, vol. 25, no. 4, pp. 19–25, Jul. 2009.
[23] H.-Z. Ding and B. R. Varlow, "Effect of nano-fillers on electrical treeing in epoxy resin subjected to AC voltage," in *Proc. 17th Annu. Meeting IEEE Lasers Electro-Optics Soc., . LEOS.*, 2004, pp. 332–335.
[24] L. Ying and C. Xiaolong, "Electrical tree initiation in XLPE cable insulation by application of DC and impulse voltage," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 20, no. 5, pp. 1691–1698, Oct. 2013.
[25] Y. Jiaming and L. Ruijin, "Analysis OT damage on oil-impregnated insulation paper using phase distribution of partial discharge," *High Voltage Eng.*, vol. 36, no. 10, pp. 2488–2493, 2010.
[26] P. Osmokrovic, A. Vasic, and T. Zivic, "The influence of the electric field shape on the gas breakdown under low pressure and small inter-electrode gap conditions," *IEEE Trans. Plasma Sci.*, vol. 33, no. 5, pp. 1677–1681, Oct. 2005.
[27] R. Shuangzan, W. Jingfeng, and Y. Chuankai, "Evolutional behavior and parameters characterization of partial discharge from a cavity defect in oil/paper insulation under aging conditions," *High Voltage App.*, vol. 54, no. 11, pp. 213–219, 2018.

XIANG REN received the Ph.D. degree in electrical engineering from Xi'an Jiaotong University, in 2016. After graduated, he joined the Electric Power Research Institute, State Grid Hubei Electric Power Company Ltd., and is currently working on the research of high-voltage technology, and the properties of insulating materials and the power cables.

LING RUAN was born was born in Wuhan, China, in 1961. He received the bachelor's degree in electrical engineering from the Huazhong University of Science and Technology, in 1986. He is a professor-level Senior Electrical Engineer with the Electric Power Research Institute, State Grid Hubei Electric Power Company Ltd. His research interest includes the field test of high-voltage technology.

HAIYUN JIN is a Professor and Doctoral Supervisor with the State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University. His research interests include the insulation structure of electric equipment, high-voltage testing technology, and the properties of insulating materials.

GUANJUN ZHANG (Member, IEEE) was born in Shandong, China, in October 1970. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Xi'an Jiaotong University (XJTU), Xi'an, China, in 1991, 1994, and 2001, respectively.

Since July 1994, he has been a Teacher Assistant with the XJTU. From October 1998 to September 1999, he was a Visiting Researcher with the Tokyo Institute of Technology, Tokyo, Japan, engaged in surface electroluminescence and the discharge phenomena of solid insulating materials. Since June 2004, he has been a Full Professor with the State Key Laboratory of Electrical Insulation and Power Equipment and the School of Electrical Engineering, XJTU. He has published more than 100 journal articles and conference papers. His current research interests include dielectric phenomena under high voltage, discharge physics and plasma technology, and the condition maintenance of power equipment.