Investigation of Breakdown Characteristics of Transmission Lines Under Different Vegetation Fire Conditions

Nan Xiao*
College of Electrical Engineering and Automation
Fuzhou University
Fuzhou, China
xiaonannn2023@163.com
*Corresponding author

Shengwen Shu
College of Electrical Engineering and Automation
Fuzhou University
Fuzhou, China
shushengwen@fzu.edu.cn

Jun Xu
Electric Power Research Institute
State Grid Fujian Electric Power Co., Ltd.
Fuzhou, China
xujun8127@163.com

Chaoying Fang
Electric Power Research Institute
State Grid Fujian Electric Power Co., Ltd.
Fuzhou, China
fc5658779@163.com

Abstract—**With the increasing frequency of global climate change and extreme weather events, wildfires have become one of the major natural disasters posing a significant threat to power systems. This presents severe challenges to the safe and stable operation of power grids. Therefore, conducting an in-depth study of the breakdown characteristics of transmission line gaps under different vegetation fires, and developing a wildfire fault probability prediction model for power lines, is of great significance for enhancing the power grid's resilience to wildfire hazards and ensuring its safe and stable operation. Firstly, based on research into the insulation performance of transmission lines in wildfire environments, the specific impacts of different vegetation fires on line breakdown voltage were summarized. Then, on this basis, further discussion was provided on the breakdown voltage calculation formulas in the flame, ion, and smoke regions. Finally, a mathematical expression for the probability of transmission line tripping was introduced, and by substituting the previously obtained breakdown voltage reduction rates under vegetation fire conditions, a quantitative assessment of the tripping probability of transmission lines under different vegetation fires was achieved.**

Keywords—wildfires, transmission lines, gap, discharge characteristics

I. Introduction

With global climate warming, extreme weather events are occurring more frequently, making forest fires one of the most critical natural disasters globally. Currently, as China's power infrastructure continues to expand, many transmission lines must traverse diverse mountainous regions, which are characterized by a wide range of vegetation types. Dense vegetation often leads to fire-prone areas, significantly increasing the probability of forest fires affecting the transmission network. Fires can severely weaken the insulation performance of transmission lines, resulting in power failures and supply interruptions, potentially causing widespread blackouts or even the collapse of the power system. Moreover, the uncertainty introduced by different types of vegetation complicates the analysis of transmission line fault probabilities, posing a serious threat to the stable operation of the power system. Therefore, it is crucial for the academic community to conduct in-depth studies on the fundamental characteristics and patterns of fire spread, enhance research on the breakdown characteristics of transmission line gaps, and develop a fire fault probability model for transmission lines that accounts for different vegetation types.

In recent years, many researchers worldwide have conducted extensive studies on wildfire spread models and transmission line fault probability models. Wildfire spread is a highly complex process. In 1946, W.T. Fons developed the first mathematical model for wildfire spread, and since then, many countries have created their own forest fire spread models. Among these, Rothermel's model [1], McArthur's model [2], the Canadian Forest Fire Spread model, and Wang Zhengfei's model [3] are particularly notable. Research on transmission line fault probability models primarily focuses on two aspects. On the one hand, by simulating wildfire conditions and conducting experimental analysis, researchers have studied the breakdown characteristics of transmission line gaps. For instance, F.A. Albin from the United States [4], Lanioe R from the Quebec Hydropower Research Center in Canada [5], and Fonseca from Brazil [6] examined the average breakdown voltage gradients between phases and between phase and ground during the combustion of wood stacks, eucalyptus, and sugarcane leaves. Furthermore, A. Robledo-Martinez [7] explored the power-frequency breakdown characteristics of conductor-to-plate gaps at various gap distances and fuel types. On the other hand, another approach involves calculating the air gap breakdown voltage using mathematical models based on flame combustion characteristics. In 1970, Canada introduced the Forest Fire Weather Index (FWI) system, which provided a foundation for the quantitative assessment of wildfire risks. Subsequently, many countries developed their own fire risk evaluation methods. Zhou Enze and colleagues divided the gap beneath transmission lines into three regions: the smoke zone, ionized zone, and flame zone, and proposed calculation methods for breakdown voltage in each region. However, these studies have overlooked certain environmental factors, such as vegetation cover and rainfall, and have not fully considered the impact of different vegetation types on transmission line fault probabilities.

To address the issues mentioned above, this study investigates the discharge voltage characteristics of air gaps under various vegetation fire conditions. By analyzing the decrease in insulation strength in air gaps across different vegetation types, we have developed a transmission line fault probability model that incorporates multiple factors, including vegetation type.

II. STUDY ON BREAKDOWN VOLTAGE CHARACTERISTICS OF TRANSMISSION LINES UNDER WILDFIRE CONDITIONS

A. Discharge Mechanisms and Breakdown Characteristics of Transmission Line Gaps

Many experts have conducted extensive research and testing on models for transmission line tripping following wildfires. For example, F.A. Albin, a researcher from the United States, used the experimental setup shown in Fig.1 to simulate the effects of wood stack combustion on dielectric breakdown phenomena. In the experiment, the fixed distance between the conductor and the ground, as well as the uniform spacing between conductors, was established. Additionally, the varying heights caused by the wood stacks were considered, resulting in breakdown voltage strengths of 26.7 kV/m and 49.3 kV/m for the respective ground gaps.

Lanioe R and colleagues from the Quebec Hydropower Research Center in Canada used the experimental platform shown in Fig.2 to study the insulation performance of ±450 kV DC transmission lines under eucalyptus fire conditions.

In Brazil, Fonseca and colleagues used the apparatus shown in Fig.3 to investigate the breakdown voltage during the combustion of sugarcane leaves. The average breakdown voltage gradient was 35 kV/m when the flame fully bridged the gap, and when the height of the fuel stack was considered, the average breakdown voltage gradient was reduced to 11.7 kV/m. It was also noted that the reduction in withstand voltage was caused by the large number of floating particles within the gap.

A.Robledo-Martinez and colleagues established the experimental platform shown in Fig.4 to conduct an in-depth study of the power-frequency breakdown characteristics in a 70 kV transmission line model under different fuels and gap distances. They found that, compared to no-fire conditions, the breakdown levels decreased significantly: gas, sugarcane leaves, sugarcane residue, and wood stacks reduced to 49%, 37%, 29%, and 27% of the values under pure air conditions, respectively. As the conductor gap increased, the breakdown voltage showed a clear upward trend, but the rate of increase under flame conditions was slower than in no-fire conditions.

In Mexico, Moreno's research explored the effects of temperature and fuel flames on the breakdown voltage gradient between conductors and plates at power frequencies, emphasizing that temperature had a significant impact on the insulation strength of the gap.

Yu Fei and his team used simulated experiments to study the voltage breakdown behavior of various conductor splits and ground gaps under the influence of wood stack flames. Zhang Yun and his team conducted an in-depth investigation into the discharge behavior of medium-scale high-voltage transmission lines during fire events, concluding that the intensity of the fire was directly related to the average breakdown field strength. Wu Tian and others used simulated wildfire technology to study how multiple variables influence the breakdown characteristics of gaps and observed that the combined effects of flame temperature, electrons, ions, and solid particles led to a significant decrease in insulation strength across transmission line gaps. Pu Ziheng and colleagues analyzed the discharge characteristics of conductor-to-plate gaps under DC voltage using simulated wildfire experiments and revealed a polarity effect in the significant reduction of gap insulation strength under flame conditions.

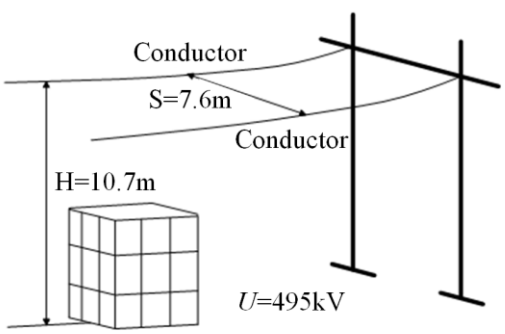

Fig. 1. Experimental Platform of the U.S. Electric Power Research Institute

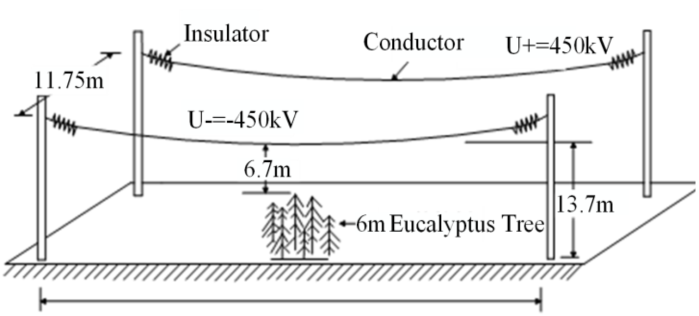

Fig. 2. Experimental Platform of the Quebec Hydropower Research Center

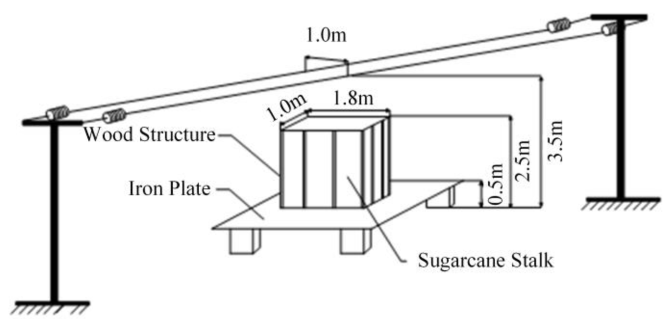

Fig. 3. Brazilian Experimental Platform

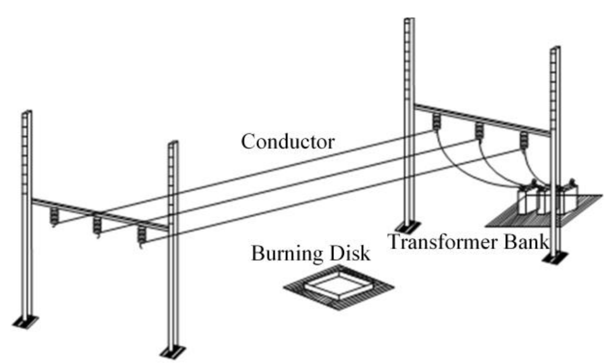

Fig. 4. Mexican Experimental Platform

B. The Impact of Different Vegetation Fires on Transmission Line Breakdown Voltage

In response to the hazards posed by wildfires to power grid operations, researchers both domestically and internationally have conducted extensive and in-depth studies on the discharge and breakdown characteristics of transmission line gaps under flame conditions, particularly focusing on vegetation fires. Numerous simulation experiments have been performed, demonstrating that the breakdown voltage of transmission facilities varies significantly across different vegetation fire environments. Fujian Province, located along the southeastern coast of China, is renowned for its abundant forestry resources but frequently experiences wildfires. The forestry administration has published data on vegetation types, as shown in Fig.5, clearly illustrating the distribution of vegetation across Fujian. Fig.6 provides a detailed breakdown of the proportions of different vegetation types in the province.

Table 1 summarizes the findings from simulation experiments on gap discharges under various vegetation fire conditions. Fig. 7 illustrates the reduction ratio of breakdown voltage gradients during the burning of different vegetation types compared to non-fire conditions.

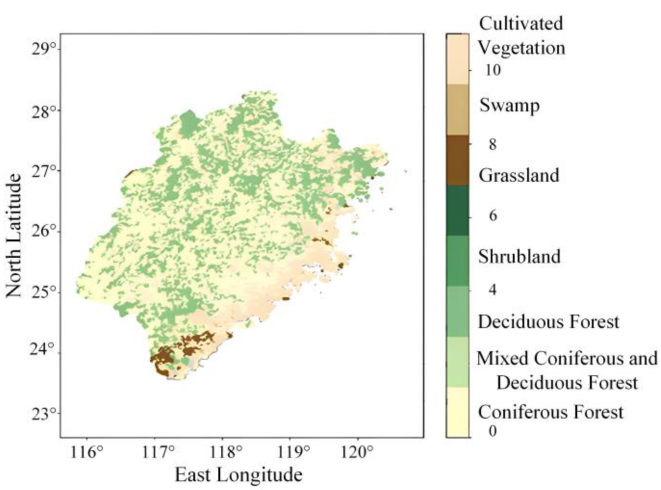

Fig.5 Vegetation Distribution in Fujian Province

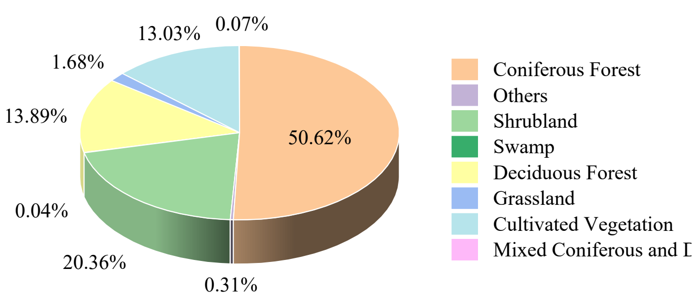

Fig.6 Vegetation Proportions in Fujian Province

TABLE I. BREAKDOWN VOLTAGE GRADIENTS UNDER DIFFERENT VEGETATION FIRE CONDITIONS

Author	Vegetation Type	Breakdown Voltage (kV/m)	Decline Ratio	Notes
F A Albini	Wood Pile	26.7	/	Phase-to-ground gap, without considering pile height
		49.3	/	Phase-to-ground gap, considering pile height
		65.0	/	Phase-to-phase gap
Lanoie R	Eucalyptus	32.8	/	Without considering eucalyptus height
		58.4	/	Considering eucalyptus height
Robledo-Martinez A	Sugarcane Residue	/	71.0%	/
	Sugarcane Leaves	/	63.0%	/
	Wood Pile	/	73.0%	/
	Butane Gas	/	51.0%	/
	Cold Ash	/	58.0%	/
Fonseca J R	Wood Pile Structure and Sugarcane Stalk	35	/	Without considering combustion pile height
		11.7	/	Considering combustion pile height
Moreno M.	Gasoline	100	60.0%	/
	Alcohol	80	68.0%	/
	Sugarcane Stalk and Leaves	50	80.0%	/
Wu Tian	Wood Pile	87.5	77.0%	/
		170	74.1%	Sphere-plate electrode
		/	77.0%	Rod-plate electrode
Deno D.W.	Wood Structure	46.3	/	/
You Fei	Wood Pile	93.5	72.7%	Single strand
		94.8	66.5%	Double split
		115.9	66.7%	Four split
Zhang Yun	Wood Pile	113.8	64.9%	Average
Pu Ziheng	Wood Pile	90	80.0%	Average
Lu Wei	Cedar	70	79.0%	/
	Pine Tree	76	77.0%	
	Eucalyptus	83	75.0%	
	Shrub	52	84.5%	
	Cogon Grass	49	85.4%	
	Straw	42	87.5%	

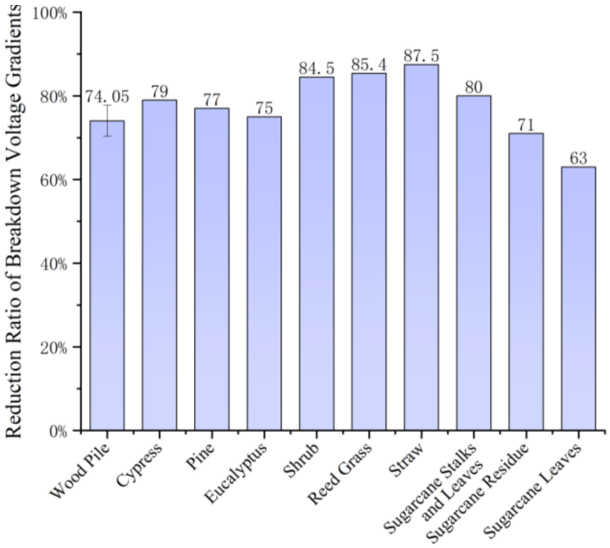

Fig. 7. Reduction Ratios of Breakdown Voltage Under Different Vegetat ion Fire Conditions

III. PROBABILITY MODEL OF TRANSMISSION LINE FAULTS UNDER WILDFIRE CONDITIONS

A. Wildfire Spread Model

Based on extensive combustion experiments conducted in the Xiaoxing'an Mountains region of Northeast China, Professor Wang Zhengfei successfully developed a wildfire spread model. This model integrates crucial climatic factors such as maximum temperature, average wind speed, and minimum relative humidity, along with key geographical elements including topography, wind direction, and vegetation distribution. Its goal is to accurately predict the rate and pattern of forest fire spread. The fundamental equation is as follows:

$$R = R_0 K_s K_w K_\varphi \tag{1}$$

Where: R_0 represents the initial spread rate, K_S is the adjustment coefficient for fuel configuration, K_w is the wind correction factor, and K_φ is the terrain slope correction factor.

B. Comprehensive Model of Tripping Probability

The position of the flames, the amount of rainfall, and the type of vegetation significantly influence the probability of a power line trip during wildfires. Based on real-time fire data obtained through satellite monitoring technology, a comprehensive model for evaluating the probability of a power line trip caused by a wildfire is as follows:

$$P = D_R D_B D_F P_V \tag{2}$$

Where: P represents the overall probability of a power line trip caused by wildfires, D_R is the precipitation factor for tripping caused by wildfires, which takes a value of 1 only if the total precipitation in the region over the past three hours is less than 2 mm and the forecasted precipitation for the next hour is below 1 mm; otherwise, it is set to 0, D_B is the surface vegetation factor, which takes a value of 1 if the terrain between the fire point and the power line is covered by vegetation, such as grassland or forest; if the terrain is desert, rivers, roads, etc., the value is 0, as these conditions are unlikely to cause a power line trip, D_F represents the wildfire spread factor, and P_V is the flashover trip factor for power lines under wildfire conditions.

C. Breakdown Voltage Calculation for Different Gap Regions

If a power line is affected by a wildfire, the high temperatures generated by the fire can reduce air density, thereby impairing insulation performance. This situation divides the gap beneath the power line into three distinct zones: the flame zone, the ionized zone, and the smoke zone. Each of these corresponds to the breakdown voltage of the comprehensive flame zone, the breakdown voltage of the ionized zone, and the breakdown voltage of the smoke zone, respectively. The calculation for the phase-to-ground breakdown voltage of the power line under wildfire conditions is as follows:

$$U_{\text{jc}} = U_{\text{f}} + U_{\text{z}} + U_{\text{s}} \tag{3}$$

a) Breakdown Voltage of the Flame Zone

The height of the flame H_{f} is closely related to the distance between different zones, a factor that directly influences the insulation breakdown risk of power lines. Wang Zhengfei derived the following calculation formula by integrating Byram's computational method with specific combustion test data:

$$H_{\text{f}} = \sqrt{I / 250} \tag{4}$$

$$I = qWR \tag{5}$$

Where: W represents the effective combustible material load (kg/m^2), q denotes the heat of combustion per unit mass of the combustible material (kJ/kg), and R indicates the flame spread rate (m/s).

For a given air gap, the breakdown voltage is primarily influenced by temperature and air humidity. However, under flame conditions, the effect of humidity can be considered negligible. Consequently, the breakdown field strength of the flame zone can be expressed as follows:

$$E_{\text{f}} = \frac{T_{\text{a}}}{T_{\text{f}}} E_0 \tag{6}$$

Where: T_{a} represents the ambient temperature (K), T_{f} denotes the average temperature of the flame zone (K), and E_0 is the breakdown field strength under standard atmospheric conditions (kV/m). The relationship between these variables is as follows:

$$T_{\text{f}} = T_{\text{a}} + 3.9 \frac{I^{2/3}}{z_{\text{d}}} e^{-\alpha (z - z_{\text{d}})^2} \tag{7}$$

$$\alpha = \frac{1}{H_1 (H_1 + z_{\text{d}})} \tag{8}$$

$$H_1 = H_{\text{f}} \tag{9}$$

Where: z_{d} represents the height of the vegetation (m), and H_1 denotes the height of the gap in the flame zone (m).

In summary, the breakdown voltage of the flame zone can be expressed as follows:

$$U_{\mathrm{f}} = \int_{z_{\mathrm{d}}}^{H_1+z_{\mathrm{d}}} E_0 \frac{T_{\mathrm{a}}}{T_{\mathrm{f}}} dz \tag{10}$$

b) Breakdown Voltage of the Ionized Zone

When a wildfire begins to burn, the ionosphere above the flame zone tends to accumulate a significant amount of electrical charge. The breakdown voltage of the ionized region is represented as follows:

$$U_{\mathrm{z}} = \frac{1}{1+C} E_0 H_2 \tag{11}$$

$$H_2 = 0.1 H_{\mathrm{f}} \tag{12}$$

Where: H_2 represents the length of the ionized zone gap (m), and C is the vegetation correction factor for the breakdown field strength in the ionized zone.

c) Breakdown Voltage of the Smoke Zone

The particle-triggered flashover model proposed by Sadurski et al. [8] examines the influence of smoke concentration on the electric field distribution. Therefore, the correction factor for smoke concentration can be expressed as follows:

$$\eta = \frac{1}{14s+1} \tag{13}$$

Where: s represents the smoke concentration, which can range from 0 to 100%. Additionally, s can be expressed using the diffusion coefficient as follows:

$$s = e^{-(H-H_1)^2/(2\sigma_H)} \tag{14}$$

Where: H represents the height of the power line (m), and σ_H denotes the diffusion parameter of smoke in the H direction, which can be obtained from the diffusion parameter table.

The breakdown field strength in the smoke zone can be expressed as follows:

$$H_3 = H - H_1 - H_2 - z_{\mathrm{d}} \tag{15}$$

$$U_{\mathrm{s}} = \eta E_0 H_3 \tag{16}$$

D. Calculation of Transmission Line Tripping Probability

The probability of line flashover tripping during wildfire disasters can be approximated by a normal distribution. The calculation formula for the probability $P_{\mathrm{g,p}}$ of power line tripping due to wildfires at the occurrence site is as follows:

$$P_{\mathrm{g,p}} = \begin{cases} 0, U < U_{99} \\ \dfrac{U - U_{99}}{U_{\mathrm{jc}} - U_{99}}, U_{99} < U < U_{\mathrm{jc}} \\ 1, U > U_{\mathrm{jc}} \end{cases} \tag{17}$$

$$U_{99} = 0.756 U_{jc} \tag{18}$$

Where: U represents the phase voltage of the power line, and U_{99} denotes the 99% withstand breakdown voltage of the power line.

The gradients of breakdown voltage under different vegetation fire conditions are illustrated in Figure 8. Assuming a phase-to-ground distance of 3.3 m for a 220 kV line, the breakdown voltages and tripping probabilities for various vegetation types are presented in Figures 9 and 10. For a 500 kV line with a phase-to-ground distance of 7.4 m, the corresponding breakdown voltages and tripping probabilities are shown in Figures 11 and 12.

The mathematical formulas presented below offer a high level of accuracy in predicting tripping scenarios for power transmission lines under wildfire conditions.

$$p_{\mathrm{v}} = \begin{cases} p_{\mathrm{g}}, U_1 < 220 \text{ kV} \\ 1 - (1 - p_{\mathrm{g}})(1 - p_{\mathrm{p}}), U_1 \geq 220 \text{ kV} \end{cases} \tag{19}$$

Where: p_{g} and p_{p} represent the tripping probabilities for phase-to-ground and phase-to-phase power transmission lines, p_{v} denotes the overall tripping probability, and U_1 represents the voltage level of the line (kV).

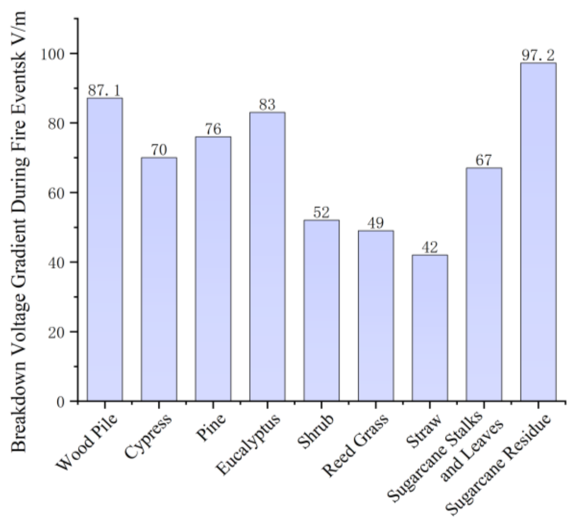

Fig. 8. Breakdown Voltage Gradients Under Different Vegetation Fire Conditions

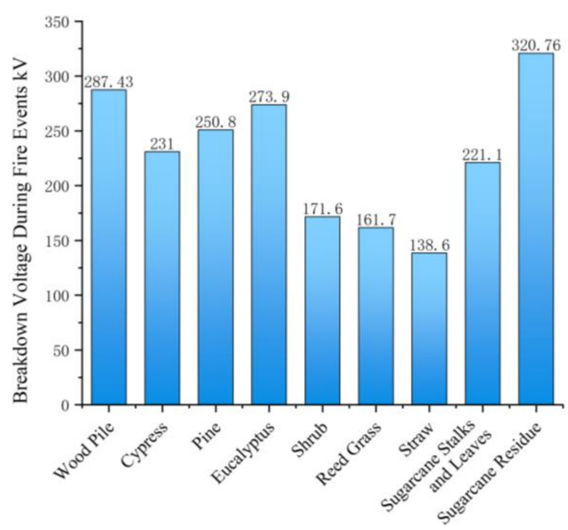

Fig. 9. Breakdown Voltage of 220 kV Lines Under Different Vegetation Fire Conditions

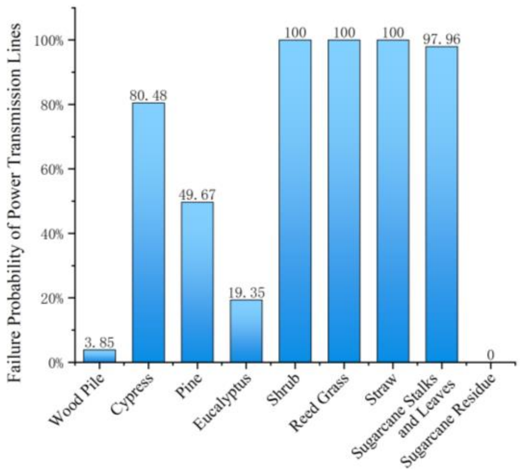

Fig. 10. Tripping Probability of 220 kV Lines Under Different Vegetation Fire Conditions

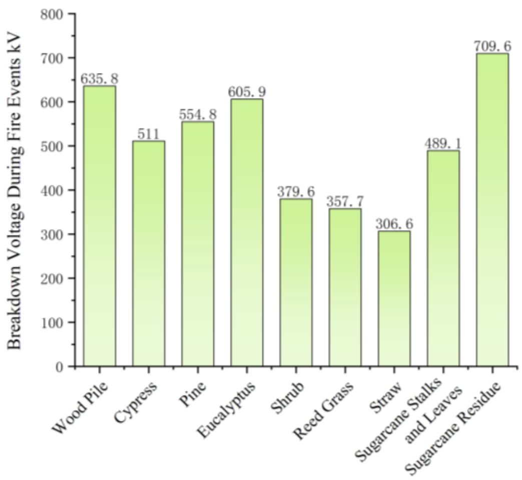

Fig. 11. Breakdown Voltage of 500 kV Lines Under Different Vegetation Fire Conditions

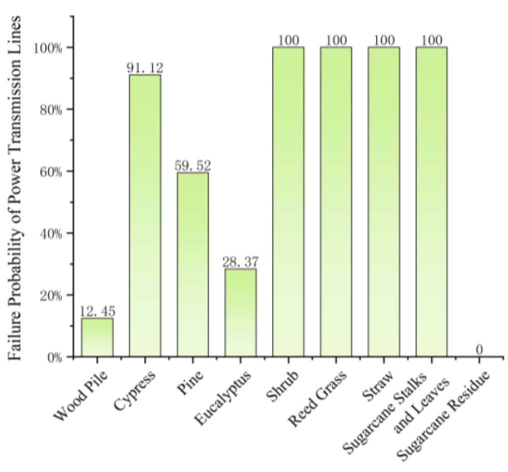

Fig. 12. Tripping Probability of 500 kV Lines Under Different Vegetation Fire Conditions

IV. CONCLUSION

To investigate the impact of different vegetation fire conditions on the breakdown characteristics of transmission line gaps, this study first summarizes the specific effects of various types of wildfires on line breakdown voltage, based on research into the insulation performance of transmission lines in wildfire environments. Subsequently, discussions are presented on the wildfire spread model, the comprehensive tripping probability model, and the calculation formulas for breakdown voltage in different regions. Finally, a mathematical expression for the tripping probability of transmission lines is introduced, allowing for the quantitative assessment of tripping probabilities under various vegetation fire conditions by substituting the previously obtained breakdown voltage reduction rates. This analysis will contribute to the subsequent research and evaluation of the resilience of power systems under different vegetation fire conditions.

The results indicate that under different types of vegetation fire conditions, the average breakdown voltage strength of the gaps exhibits a significant attenuation trend. Specifically, straw combustion leads to the highest reduction in transmission line breakdown voltage, reaching up to 87.5%. In comparison, the reduction in breakdown voltage gradient due to reed combustion is also notable, at 85.4%. The tripping probabilities of transmission lines at various voltage levels under different vegetation fire conditions were assessed. The lowest tripping probabilities occur during the combustion of sugarcane residue and wood piles, with probabilities of 0% and 3.85% for 220 kV lines, and 0% and 12.45% for 500 kV lines, respectively.

REFERENCES

[1] R. C. Rothermel. "A mathematical model for predicting fire spread in wildland fuels," Ogden, Utah: Intermountain Forest & Range Experiment Station, Forest Service, U.S. Dept. Of Agriculture, 1972.

[2] A. G. McArthur. "Fire behavior in eucalypt forests Canberra," ACT: Forestry and Timber B UREAU, 1967: 12.

[3] Z. Wang. "General forest fire danger rating system," Journal of Natural Disasters, 1992(3): 39-44.

[4] F. A. Albini. "Spot fire distance from burning trees: a predictive model," Ogden, USA: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Dept. of Agriculture, 1979.

[5] R. Lanoie, H. P. Mercure. "Influence of forest fires on power line insulation," 6th International Symposium on High Voltage Engineering (ISH). New Orleans, USA, 1989.

[6] J. R. Fonseca. "Effects of agricultural fires on the performance of overhead transmission lines," IEEE Transactions on Power Delivery, vol. 5, no. 2, pp. 687‑694, Apr. 1990.

[7] A. Robledo-Martinez, E. Guzman, and J. L. Hernandez, "Dielectric characteristics of a model transmission line in the presence of fire," IEEE Transactions on Electrical Insulation, vol. 26, no. 4, pp. 776‑782, Jan. 1991.

[8] K. J. Sadurski, J. P. Reynders. "High voltage AC breakdown in presence of fires," Sixth International Symposium on High Voltage Engineering. New Orleans, LA, USA: Sixth International Symposium on High Voltage Engineering, 1989: 1-4.