A method to assess the wildfire induced breakdown of high-voltage transmission lines

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Abstract. Wildfire is responsible for many breakdown faults of high voltage transmission lines. How to evaluate the risk of wildfire induced breakdown is of concern to the line managers. This paper presents a risk assessment method of wildfire induced breakdown of high voltage transmission lines, by combination of the wildfire model and the breakdown mechanism. The method is consisted of three modules. The wildfire module predicts the fire characteristic parameters, the breakdown module provides the electric field strength of breakdown, and the risk assessment module evaluates the breakdown risk according to two typical breakdown scenarios. A case study gives a preliminary evidence of the method’s validity. Since the method is module based, it can be updated easily and assess the breakdown risk induced by different fire types.

1. Introduction

High voltage (HV) overhead power transmission lines are generally the lowest-cost and most effective method of long distance transmission for large quantities of electric energy. Their safe and uninterrupted delivery of electric energy is important for utilities and users. However, there are many kinds of faults that break down the HV transmission lines or even the grid network. It is reported that the occurrence of fires under transmission lines is responsible for a great number of line breakdowns in many countries. In South Africa, 1699 fire related faults were recorded and constituted about 21% of the total outranges during 1993-2003 [1, 2]. The Brazilian HV transmission lines suffered many faults caused by sugar cane fires in the period of 1979-1985 [3]. In China, the long-distance HV transmission lines from west to east China also have encountered many wildfire induced breakdowns. Research on the mechanism of fire induced breakdown and the measures to avoid this kind of breakdown is important for the delivery safety of electric energy.

Many researches focus on the mechanism of air gap breakdown during fire. Because of its dielectric properties, air acts as an isolation medium between the live conductors and the ground below it in HV transmission line system. During a fire, the properties of the air change and an electrical discharge or breakdown will occur. There are three models to describe the breakdown mechanism of the short or long air gaps in the literature [1, 4-12]. The first and most important model indicates that breakdown is induced due to the conductive properties of the flame present in the air gap (the flame conductivity model). The second model suggests that breakdown is due to the reduced air density that results from fire heating (the reduced air density model). And the third model suggests that the small
smoke particles present in fire cause electric field distortions that induce flashover (the particle initiated flashover model). Particles floating in air gap reduce the breakdown voltage by shorting out part of the gap, but this effect is not prominent for large air gaps (~10 m) in HV transmission lines [4, 5]. The first and second models are thought to be responsible greatly for fire induced breakdown of HV transmission lines.

The mechanism study promotes our understanding on the mechanism of fire induced breakdown. However, the HV transmission line managers prefer some practical measures to avoid this kind of faults. A method to assess the fire induced breakdown risk of the lines quickly is a precondition for further actions. Eskom company of South Africa adopts satellite-base fire monitoring system to detect fire events near to line infrastructure [13]. Lines could be shut down before nearby fires caused breakdown. A detailed agricultural fire model was also proposed to understand the combustion and spreading mechanism of fire beneath or nearby HV transmission lines in another research [14]. These two researches mainly focus on fire detection and modeling. On the other hand, Fonseca et al proposed a vegetation clearance distance based on the measured fire induced breakdown voltage. Fire behavior is simply assumed that there is a maximum flame length of 12 m above the ground and a temperature of 120 °C to the flames [3]. To the authors’ knowledge, there is no research to combine fire behavior and breakdown mechanism to evaluate the fire induced breakdown risk of the lines.

This paper will propose a quick risk assessment method of wildfire induced breakdown of HV transmission lines for line management, based on a wildfire model and the breakdown mechanism of the lines. Section 2 will present the investigation of wildfire induced breakdown faults in China. Section 3 will propose the framework and the modules of the risk assessment method. Section 4 will present a case study of the method.

2. Wildfire induced breakdown of HV lines in Southern China during 2006-2010

According to fault reports, there were 33 wildfire induced breakdowns of 220 kV and 500 kV transmission lines in southern China during 2006-2010. The faults occurred mostly during afternoon in Spring, when the wildfire danger rate is highest of the year. Statistic analysis shows that 32 fires occurred in sunny slopes and 1 in shady slope. Wildland fuels in sunny slope receive more sun radiation and have much lower moisture content, which is favorable for fire ignition and spreading. The fuels for combustion were mainly shrubs, grasses and some trees. The typical trees were eucalypt and pine trees. There are many eucalypt forests for economic plantation in southern China. Fine fuels, such as shrubs, grasses, leaves or needles of trees, are easy to ignite and burn. They contribute to the intensity and spreading rate of fire. Statistic analysis also shows that most breakdowns (27 faults) occurred from the line conductor to earth (tree or ground) and some (6 faults) from phase to phase (conductor to conductor). The distances of breakdown point above ground were between 6.5-24.0 m.

3. The risk assessment method

According to faults investigation and the breakdown mechanism of air gap, fire induced faults of HV transmission lines can be categorized to two typical scenarios:

(1) Fire flame is high enough to engulf the conductors of HV transmission lines. Flame ionization and high temperature will distort the electric field and reduce the dielectric strength of air gaps. The flashover of the lines may occur through the shortest path between the line and earth (tree or ground), or between the conductors with different voltage phases.

(2) Fire flame is located beneath the lines. The flame and plume may bridge the air gap between the conductor and earth and induce a flashover. The high temperature of plume also may engulf the conductors with different voltage phases and cause a phase to phase flashover.

Based on the typical scenario identification, a framework of the risk assessment method is designed as figure 1. This method is consisted of three modules, wildfire simulation module, breakdown module and risk assessment module. The modules can be replaced easily for specific applications. For example, the wildfire simulation module can be replaced easily by sugar cane fire module for risk
assessment of line breakdown in presence of sugar cane fire. This kind of module design can make the method be easily updated.

Figure 1 illustrates the flowchart of the risk assessment method. Firstly the parameters of fuel, weather and topography are measured in field and the wildfire behavior (flame height and plume temperature) is predicted. By comparing the flame height of wildfire with the height of HV transmission lines, the spatial relation between fire and the lines, that is, whether fire flame engulfs the conductors or not, can be determined. According to the spatial relation, the risk assessment module will categorize the breakdown faults into two typical scenarios, and predict the breakdown risk aided by the breakdown parameters provided by the breakdown module. After the risk is assessed, some measures to avoid fire induced breakdown, such as vegetation clearance, can be suggested.

Figure 1. Framework of risk assessment algorithm of wildfire induced breakdown of HV transmission lines.

The following will present the details of the three modules.

3.1. Risk assessment module
Risk assessment module evaluates the breakdown risk of HV transmission lines according to the relative spatial positions of fire and the lines. It is based on the safety distance calculation for the lines. If the spatial distance of lines is higher than the corresponding safety distance, the lines are safe from fire induced breakdown. Figure 2 presents the sketch map of safety distance calculation for the lines. In this figure, the tower height is \( H \) and the conductor sag in middle span is \( H_{sag} \). Fire (flame height \( H_{\text{flame}} \) ) is assumed to occur in the middle of the lines, where the distance of the conductors to ground is shortest due to sag. This configuration represents the worst breakdown scenario. Because of fire heating, the conductor will expand and the sag will increase a little \([15, 16]\), which is denoted as \( H_{sag,T} \). The sag increase of 220 m span conductor due to fire heating is reported to be 0.55 m \([3]\) and this value is used in the present method.
Figure 2. Sketch map of safety distance calculation for the lines. (a) flame engulfs the lines; and (b) flame is underneath the lines.

Figure 2(a) represents the first typical scenario (flame engulfs the lines). In this scenario, the air gaps between the conductor to tree (\(H_{air}\) long) and between conductors with different voltage phases (\(D\) long) are full of flame. The breakdown may occur in these two gaps. If the average electric field strength of breakdown in flame is denoted as \(E_f\) (kV/m) and the voltage differences of the gaps are denoted as \(U_{c-t}\) and \(U_{c-c}\) (kV), respectively, the breakdown from conductor to tree can not happen only if

\[
H_{air} > U_{c-t} / E_f
\]  
(1)

And the breakdown from conductor to conductor can not happen only if

\[
D > U_{c-c} / E_f
\]  
(2)
Figure 2(b) represents the second typical scenario of which flame is below the lines. In this scenario, the air gap between the conductor to tree are partially occupied by flame and partially by high temperature fire plume, while the air gap between conductors with different phases are occupied by high temperature fire plume. If the average electric field strength of breakdown in hot fire plume is denoted as \( E_s \) (kV/m), the breakdown from conductor to tree can not happen only if

\[
H_{air} > H_{flame} + \left( U_{c-t} - E_f H_{flame} \right) / E_s
\]

And the breakdown from conductor to conductor can not happen only if

\[
D > U_{c-c} / E_s
\]

In the above analysis, \( H_{flame} \) is calculated by wildland fire simulation module and \( E_f \) and \( E_s \) are determined by breakdown experiment module. The other parameters are the characteristic parameters of HV transmission lines. If these parameters are provided, the breakdown risk can be assessed according to Eqs (1-4).

3.2. Breakdown module

The breakdown module provides the electric field strength of line breakdown during fire flame or plume. Normally, the breakdown experiments in air are studied firstly and those experiments under various flames or plumes follow. The values of breakdown field strength under different conditions are compared and the influence of flame or plume on breakdown field strength is identified. There are some experimental studies on fire effect on the breakdown field strength of HV lines.

The breakdown experimental investigation on HV AC lines under crib fires shows the average breakdown field strengths of the lines are remarkably decreased due to flame presence [12]. The value of breakdown field strength in air is about 280-340 kV/m, while it is about 90-120 kV/m in crib flame. If some potassium chloride powder is added in the flame, the value will decrease more to 70 kV/m because the flame conductivity increases due to thermal ionization of potassium chloride in flame. Robledo-Martinez et al studied the dielectric properties of a 68 kV three-phase transmission line subjected to the effects of fire [4] and the results show that the presence of fire reduces the breakdown level of air and the reduction depends on the fuel employed. The comparison of the results obtained with different fuels shows that temperature and/or ionization are the most dangerous factors for air insulation. Experimental tests performed in a 3 m conductor-plane configuration clearly show the effect of temperatures and different fire sources on the dielectric strength of air gaps [3]. Without fire (15°C), the breakdown field strength is 250 kV/m. The breakdown field strength under alcohol fire is 80 kV/m while it is 50 kV/m under sugar cane leave fire. In a similar experiment, a value of 35 kV/m under sugar cane leave fire is obtained [3]. These studies indicate that the breakdown field strength is affected by flame characteristics. The value of breakdown field strength is higher under “clean” fire like alcohol flame while it is lower under biomass fire. The inorganic component in biomass can be ionized and increase the flame conductivity [9, 17, 18], which is favourable for breakdown. In the present risk assessment method, the breakdown field strength of 35 kV/m is adopted as \( E_f \) for conservative consideration.

As for high temperature effect on breakdown field strength, there is a relationship as [1, 12]

\[
E_t = E_a T_a / T_s
\]

Where \( E_a \) is the breakdown field strength under a reference condition of air gap. Experiments show that the breakdown field strength is 250kV/m when air is 15°C [3], which can be used as \( E_a \). If the temperature of fire plume at the conductor, \( T_s \), is known, the breakdown field strength \( E_t \) can be calculated. \( T_s \) will be calculated by wildfire simulation module.
3.3. Wildfire simulation module

The wildfire simulation module will provide the information about the fire, in particular the flame height and temperature profile of fire plume.

There are many kinds of wildfire simulation models, from empirical to physical [19-21]. The physical models need high computational (in terms of time, resources and data) requirements and detailed description of wildland fuel composition and distribution, which generally preclude their use as operational tools in wildland fire management [19]. On the contrary, the empirical or semi-empirical models provide the basis for all current operational fire spread prediction systems used around the world [20]. These models are generally easy to operate. By incorporating several independent variables of fuel, weather and topography, these models can predict fire spreading rate and other fire behaviour quantities. For risk assessment of wildfire induced breakdown of HV transmission lines, an empirical model is more suitable. With the empirical model, the line manager can collect the independent variables in field easily and calculate the fire parameters quickly to assess the risk of fire induced fault.

In the present wildfire simulation module, the McAuthur’s Forest danger rating systems (FDRS) for eucalypt forests [20, 22-23] is adopted. This is because that the eucalypt and pine trees, together with shrubs and grasses, are the fuels burning in wildfires that cause HV line breakdowns in southern China (Section 2). FDRS is a set of empirical correlations of observed fire behaviour and measured fuel and environmental variables from approximately 800 experimental fires [22]. By measuring fuel load, temperature, slope degree and wind speed in field, together with precipitation history record, the rate of spread of fire and flame height \( H_{\text{flame}} \) can be calculated.

The temperature profile of plume of a spreading wildfire is correlated to the fireline intensity as [24]

\[
\Delta T = BI_L^{2/3}/z
\]  
(6)

Where \( \Delta T \) is the temperature increase of plume above ambient temperature \( T_0 \) and \( z \) is the height above the ground. The plume temperature is \( \Delta T + T_0 \). \( B \) is the correlation coefficient with the value of \( 4.47(K \cdot m^{2/3} \cdot kW^{-2/3}) \). \( I_L \) (kW/m) is the fireline intensity, which can be expressed empirically as [24]

\[
I_L = 273L_{\text{flame}}^{2.17}
\]  
(7)

Where \( L_{\text{flame}} \) is the flame length and is correlated to the flame height \( H_{\text{flame}} \). Considering that wildfire tilts forward during spreading, the flame height is a little lower than the flame length. Without the effect of wind and slope on spreading, they can be correlated as [24]

\[
H_{\text{flame}} = 0.9743L_{\text{flame}}
\]  
(8)

In windy cases, the fire tilts more and the flame height will be lower than the value predicted by Eq. (8). However, the flame height will be close to the flame length when fire spreads along a slope. In the present wildfire simulation module, Eq. (8) is adopted. After predicting the flame height by the FDRS firstly, the flame length can be calculated by Eq (8) and fireline intensity by Eq. (7). Finally the plume temperature can be calculated by Eq. (6).

4. A case study

The algorithm of risk assessment method in Section 3 is programmed by VC++ language and is testified by a breakdown faults with detailed information.

A wildfire induced breakdown of 500 kV transmission lines occurred in March 1, 2010 and a detailed investigation was carried out in March 14, 2010, by an expert team in the field of electrics and fire science. This accident occurred at E110°28'11'' and N23°15'75''. The flashover left a white point in the transmission line, which was 8.9 m above the pine tree. The line is 15.4 m above ground and the distance of conductors with different phases was 8 m.
The wildfire was reported to propagate uphill along a slope (angle 35°). The field investigation indicated that the fuels for burning were dry fine fuels, such as pine needles, shrub leaves and grasses. Sixteen fuel sampling plots (1 m² square) were planned in nearby wildland where fire didn’t pass. The fine fuels in the plots were collected and weighted. The average fuel load was 1829 g/m² or 18.29 ton/ha. The weather condition was referred to the weather records. The peak ambient temperature of the fire day was 30°C and the wind speed was 5 m/s.

By cooperating the above parameters, the risk assessment method predicts that flame height is 10.6 m and the conductors are engulfed by flame. The minimum safe height of the conductors above the ground is 17.4 m and the minimum safe distance of conductors with different phases is 14.3 m, both of which are higher than the corresponding actual values of the transmission lines. Thus the lines have a high risk to breakdown between conductor and tree or between conductors with different phases. In fact, the breakdown was reported to occur between conductor and tree, which supports the result of the risk assessment method. This case study provides a preliminary verification of risk assessment method. Because the detailed information for other faults are not available, there are no other validation. The authors will collect the required information after a wildfire-induced faults appears to prove this risk assessment method.

This risk assessment method can be being adopted in the line management. The fire induced breakdown risk can be assessed for a specific line at a specific location. If the breakdown risk is high, the vegetation below the lines can be removed or cleared to reduce the fuel load and the vegetation height.

5. Conclusions
This paper presents a risk assessment method of wildfire induced breakdown of high voltage transmission line, by combination of wildfire model and breakdown mechanism. This method is easily used in line management to reduce fire threat. The main conclusions of the present study are as follows.

(1) Based on the investigation of wildfire induced faults of HV lines, the method categorizes the faults into two typical scenarios, that is, fire engulfs the line conductors and fire is beneath the conductors.
(2) The method is based on three modules. The wildfire simulation module calculates flame height and plume temperature profile. The breakdown module provides the electric field strength of breakdown through laboratory experiments. The risk assessment module evaluates the breakdown risk of the lines for two typical scenarios by proposed criterions.
(3) The case study of a wildfire induced breakdown of 500 kV lines gives a preliminary evidence of the method’s validity. The method can be used for line management and guide the vegetation clearance.
(4) The risk assessment method is module based and can be updated easily with more specific modules for specific purpose.

Acknowledgements
This work was sponsored by National Key R&D Program of China (No. 2016YFC0800100) and National Natural Science Foundation of China (No. 51576184). HX Chen was supported by Science and Technological Fund of Anhui Province for Outstanding Youth (No 1808085J21) and Fundamental Research Funds for the Central University (WK2320000036).

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