1-22-2019

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Recommended Citation

S. Dian et al., "Integrating Wildfires Propagation Prediction Into Early Warning of Electrical Transmission Line Outages," in IEEE Access, vol. 7, pp. 27586-27603, 2019, doi: 10.1109/ACCESS.2019.2894141.

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IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 20, 2018, accepted January 11, 2019, date of publication January 22, 2019, date of current version March 13, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2894141

Integrating Wildfires Propagation Prediction Into Early Warning of Electrical Transmission Line Outages

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This work was supported in part by the Natural Science Foundation of China (NSFC) under Grant 51475391, in part by the China Postdoctoral Science Foundation under Grant 2017M612958, and in part by the Research Project of State Key Laboratory of Southwest Jiaotong University under Grant TPL1502.

ABSTRACT Wildfires could pose a significant danger to electrical transmission lines and cause considerable losses to the power grids and residents nearby. Previous studies of preventing wildfire damages to electrical transmission lines mostly analyze wildfire and power system security independently due to their differences in disciplines and cannot satisfy the requirement of the power grid for active and timely responses. In this paper, we have designed an integrated wildfire early warning system framework for power grids, taking prediction of wildfires and early warning of line outage probability together. First, the proposed model simulates the spatiotemporal process of wildfires via a geography cellular automata model and predicts when and where wildfires initially get into the security buffer of an electrical transmission line. It is developed in the context of electrical transmission line operating with various situations of topography, vegetation, wind and, especially, multiple ignition points. Second, we have proposed a line outage model (LOM), based on wildfire prediction and breakdown mechanisms of the air gap, to predict the breakdown probability varying with time and the most vulnerable poles at the holistic line scale. Finally, to illustrate the validation and rationality of our proposed system, a case study for a 500-kV transmission line near Miyi county, China, is presented, and the results under various wildfire situations are studied and compared. By integrating wildfire prediction into the LOM and alarming the holistic line breakdown probability along time, this paper makes a significant contribution in the early warning system to prevent transmission lines to be damaged by wildfires, illustrating the related breakdown mechanisms at the line operation level rather than laboratory experiments only. Meanwhile, the implementation of cellular automata model under comprehensive environmental conditions and simulation of the breakdown probability for the 500-kV transmission line could serve as references for other studies in the community.

INDEX TERMS Cellular automata, electrical transmission lines, earning warning, wildfire.

I. INTRODUCTION

Wildfire is a major natural cause of transmission line evacuation as flames threatened power lines that feed line outages and seriously threaten the safety and stable functioning of power grids [1]. Compared with other natural disasters, particulate matter from wildfires can continuously result in breakdowns of air gap and lead to extended blackouts [2]. According to incomplete statistics, there were 63 outages of electrical transmission line caused by wildfires in China Southern Power Grid from 2001 to 2009 [3], [4]. In the spring of 2014, wildfires have caused 47 outages for the national Power Grid Corporation of China [5]. In 2017, a massive wildfire in California, USA triggered a new round

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

of evacuation as flames threatened power lines that feed Yosemite National Park [6]. Specifically, it is reported that the high voltage and extra high voltage systems are most vulnerable to wildfire disasters, and the median outage probability is at 27.2% [7].

Currently, most power grid administrative systems utilize a passive response scheme, in which staffs cannot master the tendency and potential impacts of wildfires [8]. Consequently, the staffs usually could not take any action until the wildfires have already reached the security scope of electrical transmission lines. In emergency like that, they have to shut down the whole transmission line, which is obviously not cost-effective [9]. To optimize arrangement of firefighting resources and reduce economic losses, it is important to monitor and predict the spatial and temporal dynamics of fire propagation and its potential impacts on the grid in advance. Therefore, there is a critical necessity to build an early alarming system, which could provide administrative staffs early warning information of predicted spatiotemporal process of the wildfire and its possible damages to the transmission line. Such systems will provide staffs sufficient time to actively deploy emergency measures and make arrangements in advance [2]. However, building a reliable system like that is a non-trivial work.

To fulfill this and integrate wildfires propagation prediction into early warning of electrical transmission line outages, there are two key points to be figured out. The first one is to predict fire propagation scientifically with appropriate environmental factors and methods in the context of power grid security. The second one is to estimate the probability of line outages once wildfires reached the security scope of power transmission line. For the first question, [10] and [11] argue that the modeling of forest fire propagation should take the influence of vegetation, slope, wind speed and other factors into consideration; and to justify the argument, the authors have compared fire propagation velocities under different fuel types. A similar and more general argument could be found from researches of a collaborative group from the United States and Quebec Hydropower Research, Canada, which contend that the terrain of transmission line corridors, wind speed, and wind direction, etc., should be considered comprehensively in the study of fire prevention for the power grid [5], [12].

For the second question, it is generally accepted that the outages mechanism of air gap breakdown under different fire conditions and line voltage levels mainly involves two factors: flame temperature and ash particle. Their combined impacts significantly reduce the gap's insulation strength, easily resulting in outages of the electrical transmission line [13]. Specifically, Huang et al. argue that insulation intensity of air gap is inversely proportional to flame temperature [5]. In addition, vegetation would produce considerable ashes and particles during burning, which could adhere to the transmission line and result in continuous air gap breakdown [5]. Based on the above principles, [14] found gap insulation declined by 42% compared with the pure air after blowing suspending cold ashes into transmission line gap. In general, ashes have a multiplier effect for triggering air gap discharge under fire conditions, which can lead to a dramatic decline of the breakdown voltage, droping to 1/10 of the original value maximally [15]. In our model, this value of ash density multiplier has been adopted to build the prototype of early warning system. Reference [5] established an experimental platforms for studying the phase-to-phase breakdown characteristics of air gaps under various flame conditions. However, those studies of transmission line outage mechanisms are all in experimental lab level, and we still need a discussion on mechanisms of line outage during real operation.

In this paper, following the above principles, we have adopted Cellular Automata (CA) model to simulate fire propagation and developed a Line Outages Probability model to decode the mechanism of the transmission line outage caused by wildfire during line operation. CA is a model discrete in time and space, and the overall behavior of the model relies entirely on interactions among simple individuals. It has strong capabilities for simulation and analysis of fire propagation [16], [17]. In this paper, the temporal and spatial dynamics of wildfire spread is simulated via CA considering vegetation, terrain slope, wind direction, wind speed, ignition points, and a random variable. The random variable is used to denote the influence of miscellaneous and unknown factors, and this variable could be assigned as a 'fixed bias' for improving robustness of model. In addition, comparing with existed wildfire models which predominately consider only a single wildfire, the joint influence of multiple fires from different ignition points, which often occurs in the context of electrical transmission line outages, are taken into consideration in our model. Regarding the breakdown measurement of the transmission line, Song et al. have developed a convenient and favorable probabilistic estimation expression of transmission line breakdown for an 110kV transmission line [18]. However, there is still a lack of line outage probability model for higher line voltage level. Furthermore, previous studies on line outage mechanism are mostly analyzed based on lab experiment [5], [15]. Although it paves the way for exploring ways to prepare and harden the grid, the community still needs more discussions on variations of flame temperature, ash density and the resulted breakdown probabilities with time at the operating line level. In this paper, we have developed a Line Outage Model (LOM) for 500kV based on [18] and analyzed the line outage probability surface with respect to temperature and ash density. In addition, it is also feasible to compute the specific transmission line outage probabilities and the three most venerable line poles with respect to time under different conditions of wildfires, making the system capable for a real-time alarming. The above outcomes are combined in our paper and a novel integrated early alarming system is proposed. Finally, we take Miyi county, China as a case study to test the proposed system in various environmental conditions.

The rest of the paper is arranged as follows: section II introduces the models and computational methods used in our system. In section III, we demonstrate the simulation results of our method given the background of Miyi county, China. Section IV evaluates the performance of the model and discusses the major contribution of our system. Section V is the conclusion.

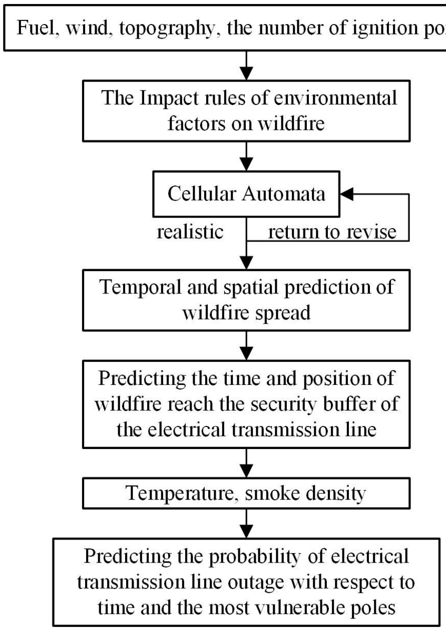

FIGURE 1. **Flow chart of early warning of wildfires for the electrical transmission lines.**

II. MATERIALS AND METHODS

A. OVERVIEW OF THE APPROACH FOR EARLY WARNING SYSTEM

Figure 1 shows the approach for early warning system. Once a fire occurred, wildfire starting points could be monitored by MODIS on Terra and Aqua satellites (MCD14ML product). After acquisition of the starting points of fire (ignition points), we could simulate the actual propagation process of fire, and its distance to the electrical transmission line. Specifically, wind direction and speed, topography, burning resources distribution, and other random factors are considered to predict the initial time and location of wildfire impacts. Combing flame temperature and ash density with the specific voltage level, we assess the possibilities of fire threating the power grid. We assume a 5-hour warning before the fire reached power system in the case study. The 5-hour warning is just for demonstration, and can be modified according to customized acquirement. If the system predicts that after 5 hours, the fire would not spread to the electrical transmission line, the early warning signal would not be triggered. On the contrary, if the system predicts the transmission line will be reach within 5 hours, the alarm will be triggered and the system will start to calculate the real-time probabilities for the power line to be damaged by the wildfire and figure out the most endangered poles.

B. SIMULATION OF SPATIAL-TEMPORAL DYNAMICS OF FIRE PROPAGATION

Intuitively, by calculating the time for the wildfire takes to spread to certain points, we will be able to obtain whether and when the transmission line will be affected. Based on this information, we could take corresponding measures on different parts of the transmission line and obtain the optimal policy which can protect the transmission line with minimum costs.

Based on the above assumptions, an important part in this task is to determine when and where the transmission line will be threatened by wildfire. The commonly-used standard is to see whether wildfire has reached the so-called 'buffer zone,' which could be regarded as certain distance neighborhood of the transmission line. In our experiments, since the geographical resolution is 1 km, it is safe to regard the area of transmission line as a combination of the line and a buffer zone of distance m=0.5 km. Thus, when computing the results under our settings, the transmission line will be threatened only if fire(s) reach it, which could be regarded as the overlaps of pixels in the image.

As it is stated above, a Cellular Automata (CA) model is used to simulate the spatial and temporal dynamics of wildfire. In this section, we will discuss the following aspects of the model.

1) TRANSITION RULES

A cellular automaton is composed of four elements: cellular, state, neighborhoods, and the transition rules. The transition rule is the relationship between cellular state and the neighborhoods, and determines the cellular automata dynamic evolution process. It can be defined as:

$$CA = (C, S, NE, R) \tag{1}$$

Cellular automata are discrete systems of cells in an n-dimensional grid. The cells interact with each other through rules depending only on local characteristics, but lead to global behavior. Cellular evolve in time steps according to the transition rules. In the above equation, C represents a regularly divided lattice, and each lattice is a cellular unit. S is a finite set, and it is used to indicate the cellular status. NE represents the neighborhood, and R represents the transition rules. The model determines the states of the cellular value at the time $t + 1$ based on states of the cellular and all its neighbors of time t.

The state propagation through neighboring cells is based on energy transfer and heat accumulation. The life cycle (R) of a burning cell can be quantified from 0% to 100%, and it increases with heat accumulation. 0% represents not burnt, the first and fourth quantiles (0%~25, 75~100%) represent smoldering fires, 20%~75% represents flaming fire, and 100% represents burnt up. Thus, the cell status is divided into four states: not burnt, smoldering, flaming, and burnt up. In addition, we take deduction of theory of energy accumulation that 17% of the heat required for the burning cellular is released by the diagonal cells, and the remaining 83% is

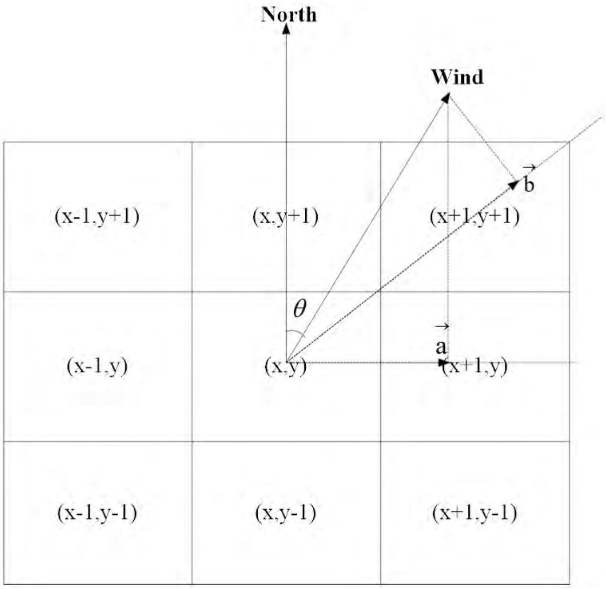

FIGURE 2. **The illustration of neighborhoods of cellular automata for wild fire propagation and wind impact.**

made up of the adjacent cellular [19]. V is the spreading speed of heat from the center cell (x, y) to its eight neiborhood cells. Adjacent cells are cell (x, y+1), (x+1, y), (x, y−1), (x−1, y), and the diagonal cells are cell (x+1, y+1), (x+1, y−1), (x−1, y−1), (x−1, y+1), as shown in the Figure 2. The corrected heat transfer velocity V multiplying the time span and dividing by its corresponding distance (*cell length* for adjacent cells, and $\sqrt{2} \times$ *cell length* for diagonal cells) is heat transferred in the corresponding time span. Accumulating the transferred heat should be the evolution of life cycle of the cell as in the formula (2):

$$\begin{cases} V = V_0 \times Ks \times Kw \times K\psi \times RA \\ R^{t+1}_{x,y} = R^{t}_{x,y} \\ + \dfrac{\left(V^t_{x-1,y} + V^t_{x,y-1} + V^t_{x+1,y} + V^t_{x,y+1}\right)\Delta t}{a} * 0.83 \\ + \dfrac{\left(V^t_{x-1,y-1} + V^t_{x+1,y-1} + V^t_{x+1,y-1} + V^t_{x+1,y+1}\right)\Delta t}{\sqrt{2}a} \\ *0.17 \end{cases} \tag{2}$$

where V_0 indicates the initial spread speed of wind, and we take 0.2 m/s in the case study; K_s represents pattern of flammable fuels; K_w indicates the impacts of wind, including wind direction and speed; K_ψ stands for the influences of topography. *RA* is to include results of random impacts. The effects of these factors on wildfire spread are described below.

2) IMPACT OF FLAMMABLE FUELS

K_s is used to indicate the degree of fuel flammability. Among all the fuels, the obstacles for fire spread like water and built-up regions are taken as 0, signifying no possibility for fire propagation there. Other fuel flammability are depended primarily on the corresponding vegetation type. For example, shrub is very likely to facilitate fire propagation due to its highly flammable property and vegetation structure, thus it could be assigned to a high value of fuel parameter (1.8); in contrast, low-density grassland, which is less intense in promoting flaming, will be assigned a lower value of fuel parameter (1.2). The full information regarding vegetation and fuel flammability used in our system could be found in Table 1. The categorization of land cover and the determination of fuel parameters are based on Land Use and Cover Change system and previous experiences [20], and should be modified according to the specific environment.

TABLE 1. **Fuel flammability for different vegetation in Miyi county.**

Land cover type	K_s
Shrub	1.8
Forest	1.5
Sparse forest	1.2
Orchard	1.1
High density grassland	1.3
Medium density grassland	1.2
Low density grassland	1.1
Cropland	1
Non-vegetation	0

3) IMPACT OF WIND

One of the most critical factors determining fire spread is wind, including wind speed and direction. K_w not only reflects the amount of air circulation for burning, but also includes boosting effects of wildfires due to moisture reduction of flammable material, which can increase fire line intensity and flame height. For the difference between the fire spread angle and the wind direction, the wind effects should be decomposed to the corresponding fire spread angle θ. K_w of the adjacent cellular can be calculated as follows:

$$K_w = \frac{\mathrm{e}^{0.1783 \times \mathrm{V} \times \cos(\theta)} \times \tau}{a} \tag{3}$$

where a represents the length of cellular, and V is the wind speed, τ is the time span between every simulation step, and the coefficient 0.1783 is fitted from field experiments [11], [19].

4) IMPACT OF TOPOGRAPHY

K_ψ represents the topographical impacts on the heat spread during wildfires. It is a function of slope:

$$\mathrm{K}\varphi = e^{3.533 \times (-1)^G \times |\mathrm{slope}|^{1.2}} \tag{4}$$

This relationship and the parameter 3.3533 is from experiments and calculation of previous work [11], [19]. Slope can be calculated by elevation difference divided by distance between cellular. Take the adjacent cells (x−1, y) and (x, y) for instance, its slope can be calculated by dem(x − 1, y) − dem(x, y)/a, while for the diagonal cells, e.g., cells (x−1, y−1) and (x, y), its slope is (dem (x − 1, y − 1) −dem (x, y))/a/$\sqrt{2}$. Where dem(x,y) is the elevation of cell(x,y), and a represents the length of cellular. In addition, uphill topography has a positive effect on wildfire propagation, while downhill topography has a negative impact on wildfire spreading. Therefore, the value of G is set to 0 for uphill (slope>0); in contrast, the value of G is set to 1 for downhill (slope<0).

5) IMPACT OF RANDOM FACTOR

Random effect is taken into account because of the complex impacts of environmental factors and their interactions, which sometimes lead to the real fire propagation diverging from the model prediction. By analyzing the reason of the randomness, it could be found that the reason for the randomness is because the model only considers major factors (wind, vegetation, etc.) but leaves out some minor elements. Thus, introducing the random parameter could improve the model performance by representing impacts of neglected minor factors. The random variable is quantified via the formula:

$$RA = 1 + (-ln\gamma) \tag{5}$$

where γ is a single uniformly distributed random number in the interval (0.1, 1).

C. WILDFIRES INDUCED OUTAGE PROBABILITY OF TRANSMISSION LINE

Wildfires result in air gap breakdown mainly via two factors: change of air density due to flame temperature and reduction of air insulation strength due to particle from smoke. In addition, the voltage level of the electrical transmission line also plays a crucial part. It is generally accepted that the breakdown probability of air gap can be represented by a normal distribution, which is associated with 50% breakdown voltage (U_{50}) [21], [22]. With voltage level of the transmission line U_l and the length of air gap, we can get U_{50} in normal condition via looking up the empirical table of long air gap breakdown voltage under power frequency voltage. Applying the impact factors of temperature and smoke, the modified 50% breakdown voltage is obtained. Based on the references [18], [21], [22], to compute the factors of flame temperature and smoke density, the measurement of relative density of air δ should firstly be obtained by:

$$\delta = \frac{273 + T_0}{273 + T} \tag{6}$$

where T_0 and T are the air temperature in the standard condition and wildfire condition, respectively. In our case study, we have assumed air temperature in the standard condition in Miyi is $T_0 = 20°\mathrm{C}$. To denote the fire and smoke effects to the U_{50} voltage, we need to compute the correction factors of temperature (C_T) and smoke (C_S). The temperature correction factor could be computed with the equation below:

$$C_T = \delta^m \tag{7}$$

where m is its index, and there will be $C_T \in [\delta, 1]$ because $m \in [0,1]$. Smoke density of wildfires can be represented by S, which is 100% when the air gap is filled with particles, and 0% for no smoke at all. It is reported that the breakdown voltage is only 1/10 of the original when smoke density is 100% [15]. Therefore, we have assumed smoke correction factor C_S possessing a relationship with S as below.

$$C_S = \frac{1}{9S + 1} \tag{8}$$

With C_T and C_S we will be able to compute the modified $\hat{U}_{50}$, based on the references [18], [21], [22]:

$$\hat{U}_{50} = U_{50} \times C_T \times C_S \tag{9}$$

Finally, by plugging in the $\hat{U_{50}}$ voltage and a variation coefficient z (varies from 2% to 8% in different air gap and types of breakdown voltage), the final probability of breakdown could be denoted as follows:

$$p(b) = \frac{1}{\sqrt{2\pi}\sigma} e^{\int_{-inf}^{U} \frac{(x-\hat{U}_{50})^2}{2\sigma^2} dx}$$
$$\sigma = z\hat{U}_{50} \tag{10}$$

where $p(b)$ is the air gap breakdown probability, and U is the real peak voltage. z is around 2% in normal conditions, but will likely increase to 4% during wildfires because smoke particles can make air gaps not even [21]. Here in our experiment, the value of z is set to 4%.

The peak of voltage is $\sqrt{2/3}U_l$ for phase-to-ground scenario, and $\sqrt{2}U_l$ for phase-to-phase situation. This peak voltage represents U and we can get the air gap breakdown probability via the formula (10).

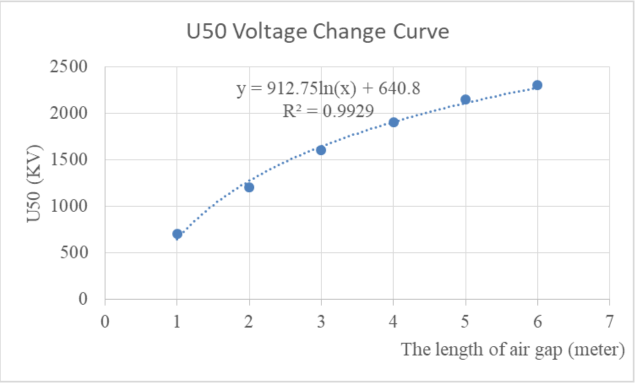

FIGURE 3. **U_{50} change curve.**

Since there are insufficient reports and experiments regarding the baseline 50% breakdown voltage (U_{50}) for 500 kV lines [18]), which is essential for Line Outage Model (LOM), in our paper several functions were tried to extrapolate the U_{50} of 500 kV based on existed experimental results [22], and finally a logarithm function is adopted due to its best performance (Figure 3). By referring to setting of local grid, the length of air gap under 500 kV here is 14.8m. And the

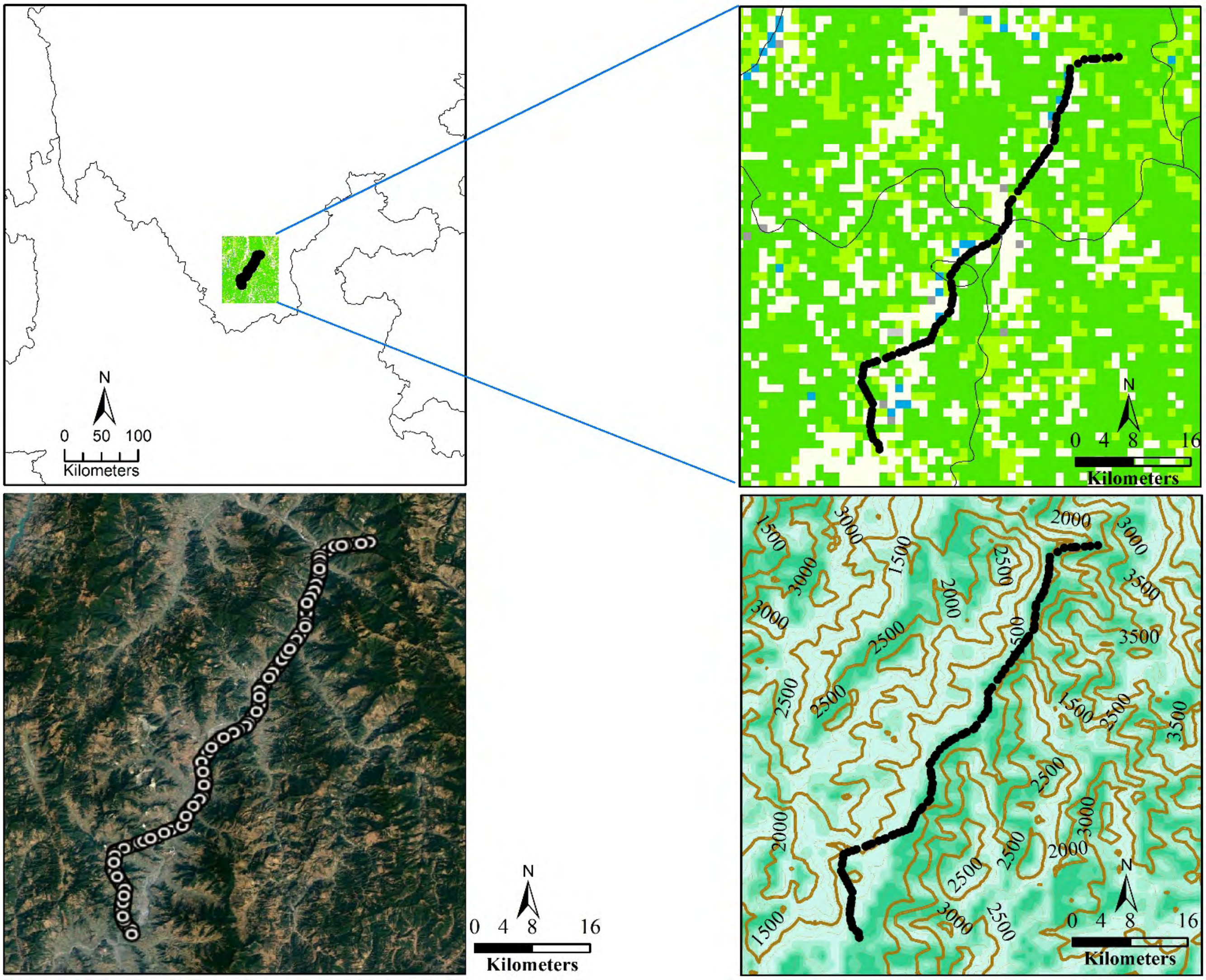

FIGURE 4. The location (the top panels) and satellite image (the lower left panel), topographical map (the lower right panel) of the case study region.

U_{50} value with respect to this length could be modeled as the follows:

$$U_{50}(x) = 912.75log(x) + 640.8 \tag{11}$$

where x denotes the length of air gap for the electrical transmission line.

And based on the above result, we could compute that the U_{50} voltage under the situation of 500kv should be $912.75 * log(14.8) + 640.8 = 3100.321$. In practice, we choose $U_{50} = 3100$ KV as an approximation for the convenience of computation.

To illustrate the results of breakdown probability, there are two graph representations for us to consider. Firstly, we can build up the 3D model for the air gap breakdown probability with respect to temperature and smoke. This will provide an intuitive understanding of the change of probability under various flame conditions. Secondly, we evaluate the breakdown probability among time and alarm the most vulnerable poles. This will lead to a better understanding of the breakdown mechanism of transmission line, and it will be of great practicality for an integrated warning system.

D. CASE STUDY: MIYI COUNTY

We chose a region (109 km × 92 km) covering a 500 KV transmission line in Miyi county, Sichuan Province, China as a case study. The location map (the top panels) and satellite image (downloaded from GoogleEarth Pro, accessed 10/15/2018), topographical map (generated from DEM) of the case study region are shown in Figure 4, and the poles of the electrical transmission line to study are labeled with black points. Miyi County, located in Panxi plateau, is featured with dry climate and high temperature, and makes up a major part of fire-power grid accidents in Sichuan province. There were cases of severe transmission line tripping caused by fires in records here, which made the regional grid an isolated island.

Because this region is a national hydropower sending channel end, including an 1100 kV voltage lines, four 500 kV lines and 10 million kilowatts load, a fire transmission line tripping accident could lead to blockage of hydropower sending channel, further affecting the security and stability of the national power grid, posing a risk of blackouts nationwide. Based on the real geographical information around one 500 kv transmission line in the region, we predict the fire impacts on the transmission line based on various wind, ignition point, topology, and vegetation conditions.

III. RESULT

A. SIMULATION AND ANALYSIS OF THE SIMULATION MODEL OF MOUNTAIN FIRE SPREAD

Figs. 5–8 illustrate results under wind situations, ignition points, topology conditions and types of vegetation. For each plot in the figures, the part colored in crimson represents the spread of wildfire. The ignition points are marked with the darkest color and the surrounding colors are gradually lighter, representing the time the wildfire takes to spread to the site. By calculating the time for the wildfire to spread to certain points, we will be able to obtain whether and when the transmission line will be affected. Based on this information, we could take corresponding measures on different parts of the transmission line and obtain the optimal policy which could protect the transmission line with the minimum costs. To make the illustration more intuitive, the animations of wildfire propagation with respect to time are provided in the separated supplementary material. To determine under which condition will the transmission line be threatened by fire, the commonly-used standard is to see whether fire has reached the so-called 'buffer zone,' which could be regarded as a m-distance neighborhood of the transmission line. In our experiments, since the geographical resolution is 1 km, it is rational to regard the area of transmission line on the background image as a combination of the line and a buffer zone of distance m=0.5 km. Thus, when computing the results under our settings, the buffer area will be treated as the transmission line itself on the image, and the intersection between the wildfire and the line could be regarded as the overlaps of pixels.

The spread of fire is affected by multiple factors, including wind speed and direction, number and positions of ignition points, and topography and types of vegetation in the area. In our experiments, the spread of fire under various wind and ignition point conditions are simulated and the results are compared. In addition to the simulation with real topology and vegetation, the fire propagation models are also simulated under artificial topology and vegetation settings to better illustrate the influence of the two factors. The following four consecutive sections will be discussing the results with variable changing in wind, ignition point, topography and vegetation respectively.

B. IMPACTS OF WIND SPEED AND DIRECTION

Wind plays a prominent role in fire propagation. With the enhancement of wind, wildfire spread faster and result in greater elliptical flat rate of wildfire. The effects of wind in spreading fire are primarily affected by two attributes: speed and direction. In our simulations, three types of wind scenarios are taken into consideration: wind with speed 0 (equivalent to no wind), wind with speed 5 and direction of counterclockwise 90 from north (westwards), and wind with speed 5 and direction of clockwise 90 from north (eastwards). And with different wind condition, the varieties in results will be requiring different actions to protect the transmission line.

When there is no wind, the situation will be leading to a slow propagation for the fire to reach the buffer zone of the transmission line (scenario 1). Under this situation, although there are still necessaries for the firefighting facilities to be prepared, the danger for the transmission line to be damaged by fire is not significant, as the transmission line will not be affected after 5 hours. When the wind goes westward (scenario 2), the fire(s) will quickly spread to the direction of the transmission line. As we could observe from Figure 5, the sections of the transmission line marked between around 42 to around 60 will be affected by the fire within 4.5 to 5 hours. Thus, we need to take corresponding measures in a relatively more emergent level. In contrast, when the wind blends eastward (scenario 3), the fire(s) will spread to the direction away from transmission line, which makes it relatively safe at this time. In the experiments, the wind speed is with a constant of 5 m/s. It is straightforward to draw a corollary that when the wind speed is acuter, the wildfire spreads faster and the above effects will be further aggrandized.

The impacts of winds are more notable under the situation of multiple ignition points. From Figure 6, we could find out that under the setting of three ignition points, the westwards wind will affect a large area of the transmission line; and the eastwards wind, which previously drives fire away from the transmission line under the setting of single ignition point, will also bring high level of risk by accelerating fire from the west side spreading to the transmission line. This means, for the situations that ignition points start on both sides of the transmission line, wind in either direction will lead to a higher level of risk in general.

C. IMPACTS OF THE NUMBER OF FIRE IGNITION POINTS

As it is stated above, to study the influence of ignition points, fire propagation with different ignition point conditions are simulated. In theory, compared with the situation of single ignition point, the spread of wildfire with multiple ignition points could produce synergy, making the expanse faster and wider. Thus, instead of simply summing up the effects of fire from each ignition point, it is necessary to build a separate model to examine the joint effects of multiple ignition points. In our simulation, three ignition points are taken into consideration: the ignition point 1 and 2 are on the east of the transmission line, and ignition point 3 is on the west of the line. And with selected combinations of ignition points, three different situations are constructed under the wind condition of 5m/s westwards: the single-ignition point scenario with ignition point 1 solely (equivalent to scenario 2),

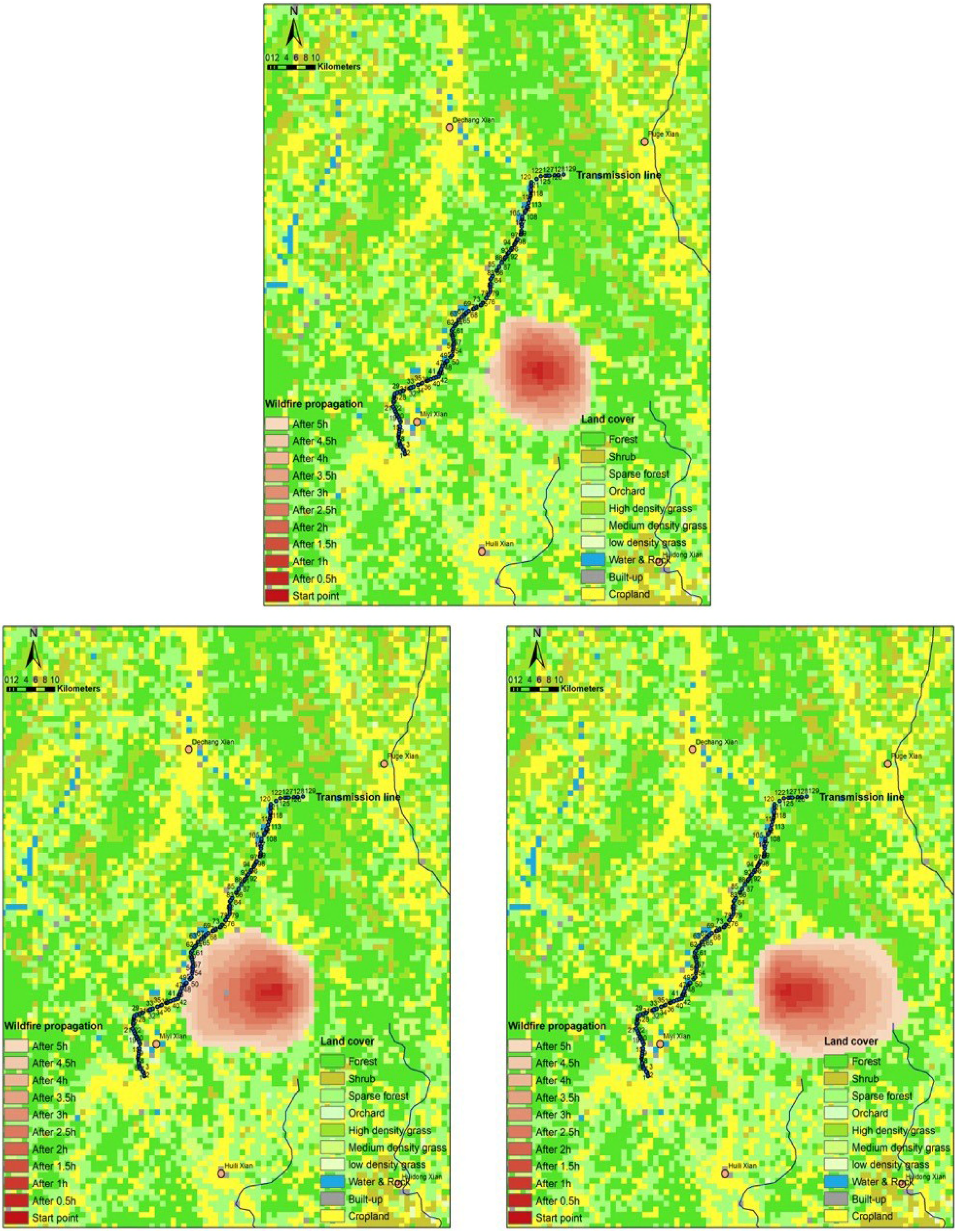

FIGURE 5. Wildfire propagation prediction for various wind conditions. The black line is the transmission line, and the pole numbers are labeled on the line. The upper panel is the wildfire prediction with no wind (scenario 1); the lower panels are the wildfire predictions with wind. The left one is of counterclockwise 90° wind direction with the north direction, and wind speed is 5 m/s(scenario 2). The right one is of clockwise 90° wind direction with the north direction, and wind speed is 5 m/s(scenario 3).

the double-ignition points scenario with ignition points 1 and 2 (scenario 4), and the triple-ignition points scenario with all ignition points 1, 2, and 3 (scenario 5). To illustrate the collective effects of wind and ignition points, the triple ignition points scenario is also simulated with wind condition of 5 m/s eastwards (scenario 6).

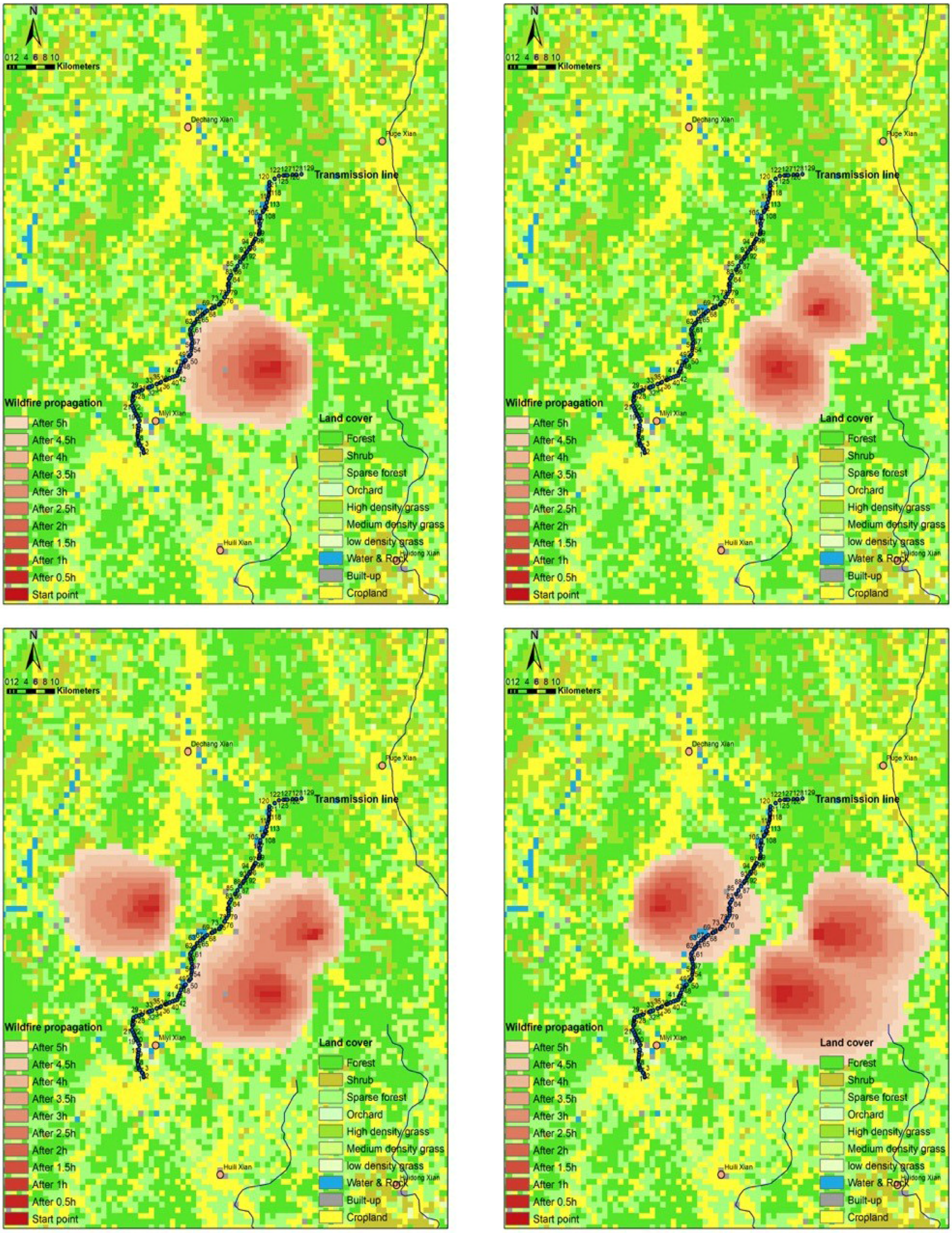

FIGURE 6. Wildfire propagation prediction for the different number of ignition points (animation in gif format available in the online supplementary material). For the upper panel, the left plot is under only one ignition point (scenario 2) and the right plot is under two ignition points (scenario 4). The wind direction is of counterclockwise 90° wind direction with the north direction, and wind speed is 5 m/s. For the lower panel, the situations are both with three ignition points and wind speed 5 m/s(scenario 5). The wind direction of the left part is counterclockwise 90° from the north and the right one is in the opposite direction (scenario 6).

From the results in Figure 6, we can find out that with multiple ignition points, the fire propagates quicker and causes a larger portion of the transmission line under threat. In the area around the pole 68 of the transmission line, it could be observed that fire spread wider under the situation of double ignition points. As for the triple-ignition point situation,

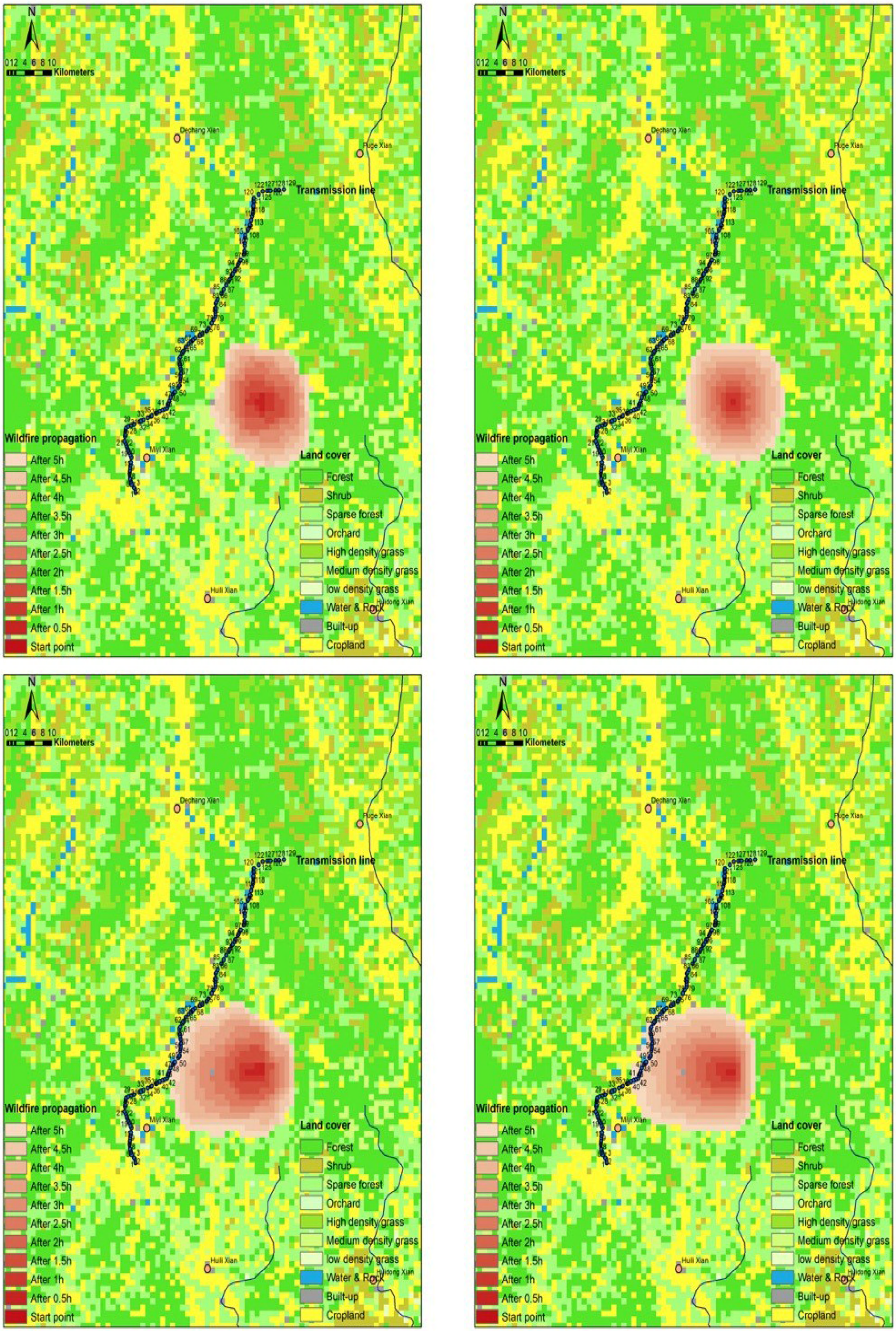

FIGURE 7. Wildfire propagation prediction comparison between different topographies. For both the upper and lower parts, the left panel is with ordinary topography (scenario 1 and scenario 2) while the topography in the right panel are all set to one, which means no topographical effects. The winds of the upper panel are in speed 0 (scenario 7, the upper right panel), and in contrast, the winds of the lower part are in a speed of 5 m/s with direction counterclockwise 90° with north (scenario 8, the lower right panel).

scenario 5, since the westward wind will drive the fire originated from the west away from the line, the fire effects to the transmission line is roughly equivalent to that in scenario 4. If the wind condition changes to eastwards, the fire began

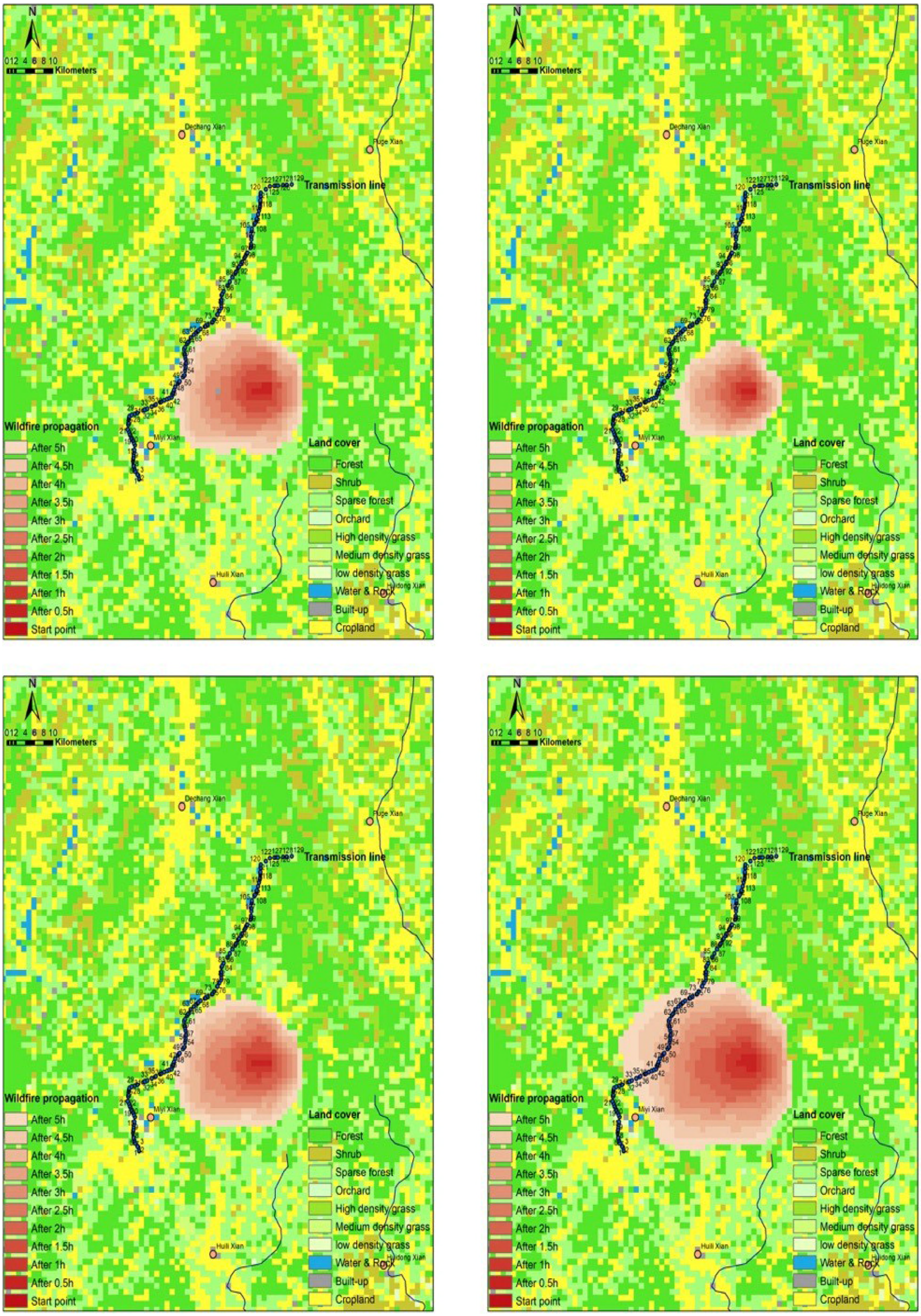

FIGURE 8. Wildfire propagation prediction comparison between different types of vegetation. The winds in all the four panels are characterized by 5m/s with a direction counterclockwise 90° with north. The four plots illustrate the situations under full vegetation (scenario 2, the upper left panel), all vegetation setting to cropland with value 1 (scenario 9, the upper right panel), all vegetation setting to grassland (scenario 10, the lower left panel), and all vegetation setting to shrub (scenario 11, the lower right panel), respectively.

from the ignition points on the east will have little effects on the line, but the fire from ignition points in the left part of the line will potentially damage around 30 poles after around 4-5 hours (Simulation Gif in Supplementary Material).

It is noticeable that with multiple ignition points, the interactions of wildfires could be further complex, leading to potentially promoting or canceling effects. This is further related with the breakdown probability with respect to smoke and temperature, and a more detailed discussion about this will be given in the corresponding subsection.

D. IMPACTS OF TOPOGRAPHY AND THE TYPES OF VEGETATION

In addition to wind and ignition points, topology and types of vegetation are two other significant factors that could affect the spread of fire. Unlike wind and ignition points, which will mainly determine the propagation direction and areas of the fire, topology and vegetation will instead affect the distribution of fire spreading, caving the shape of burnt area dedicatedly. In our simulations, the impacts of topographies are examined by setting the topography to 'uniform' (all areas with value 1) and comparing the result with the original. The fire spreading models with 'uniform topography' are obtained with the setting of calm wind (scenario 7) and westwards wind in 5 m/s (scenario 8). The impacts of vegetation are studied by setting all the areas in the map with vegetation type of uniform cropland (all area with value 1, scenario 9), grassland (all area with value 1.3, scenario 10), and shrub (all area with value 1.8, scenario 11), respectively.

Figure 7 shows the impacts of topography under different types of winds. It can be found that topography could change the extent of spread of fire in different directions, and will therefore bring different effects to the transmission line. In general, the 'uniform topology' will lead to a more 'uniformly' distributed fire propagation model: this phenomenon is more significant in the comparison between scenarios 1 and 7. If we compare scenario 2 with scenario 8, it will be found that although the fire propagating area does not change significantly, it does vary in the propagation process and this will lead to different poles on the transmission line to be affected. For instance, pole 40 is relatively safe under the full topology settings since the fire is still several kilometers away after 5 hours; however, under the setting of 'uniform topology,' the same pole will be covered by fire after 5 hours.

The propagation of wildfire under different types of vegetation are illustrated in Figure 8. It could be discerned that vegetation could be primarily regarded as a 'shrinkage factor' in affecting the spreading of wildfire, which means, it primarily affects the size that wildfire would pervade. A clear comparison could be drawn between scenario 9, 10 and 11, where each scenario has one distinct (constant) value for vegetation around the whole area. With uniform vegetation value (1.0), the wildfire will result in a smaller affected area comparing to the original vegetation settings. In contrast, in the most extreme case with all the ground covered by shrub, there will be 50 poles affected by the wildfire and the quickest damage will be happening in 3.5 hours, making the firefighting task in an urgent priority.

E. OUTAGE PROBABILITY OF THE ELECTRICAL TRANSMISSION LINE

While fires will definitely impose adverse impacts to transmission lines, the detailed mechanism for wildfires to damage the line is complex and difficult to be fully simulated by a single model. Nevertheless, with the breakdown probability formula introduced, it is still possible to build a relatively reliable model by computing the breakdown probability with respect to smoke-and-temperature. This will result in a 3-d surface with each point representing the breakdown probability of the transmission line under the settings of current temperature and smoke.

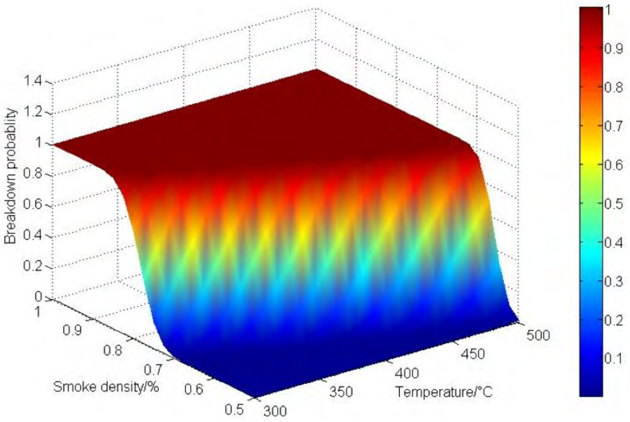

FIGURE 9. **The Surface of breakdown probability of electrical transmission Line with respect to Temperature and Smoke.**

Figure 9 shows the 3-D breakdown probability of phase-to-phase air gap in front of wildfires. It can be figured out that electrical transmission line breakdown probability rises up with smoke density. With the information of the temperature and smoke of the wildfire, which will be relatively convenient to measure, the breakdown probability of each pole on the transmission line will be able to obtain and we could, therefore, determine our transmission line protection policy based on the probabilities. Intuitively, a simple policy could be to take measurements when the probability of collapse exceeds a certain threshold. A slightly more complicated but much more effective policy is to take different actions with respect to different probability intervals. This paper aims to discuss the effects of wildfires on transmission lines and does not put emphasis on corresponding policymaking. Nevertheless, this topic could be a potential future point of research in the future.

IV. DISCUSSION

Wildfire could result in transmission line outages and cause massive damages to power grid and people around [1]. To optimize the grid arrangement of firefighting resources and reduce economic losses, it is important to predict the spatial and temporal dynamics of fire propagation and integrate wildfire prediction into power transmission line for an early warning system. For the purpose of developing the early warning system, there are studies on two categories:

1) the studies mainly focused on wildfires e.g., monitoring fires with satellite or sensor networks [2], [23]–[25], or the mathematical modeling of the fire propagation toward transmission lines only [26]; and 2) the studies on consequences of transmission line confronting wildfires, through statistical approaches [27], [28], mathematical modeling [29] and high voltage experiments for flashover mechanisms [13], [30]. However, emphasizing solely on one aspect could not satisfy the requirements of a timely early warning system for transmission line confront wildfires. In this study, we consider the paradigm to integrate wildfire and line outage mechanisms together, to provide a sufficient comprehensive framework for the early warning system buildup.

In the previous sections, the novel system is proposed and the results are illustrated and discussed under various conditions. Simulation results have shown that our method has taken most major factors into considerations and it is reliable in predicting effects of wildfires on transmission line. In this section, considering existed model in the area, the paper will make several comparisons with respect to the methods and results, and discuss the advantages and shortcomings of them. The comparisons and discussion primarily lies in the following three categories: fire propagation models, electronic breakdown mechanisms, and the integrated early warning systems.

A. SIMULATION OF THE SPATIOTEMPORAL PROPAGATION OF WILDFIRES

There are plenty of choices in modeling fire propagation with various application contexts [31]–[34]. Despite the abundant number of available models, there has not been any model consistently outperforming other counterparts and each model does have its own merits. For example, Rothermel model is a fire propagation model based on the energy conservation law [35], and it is relatively universal and easy to be generalized. However, since it is a physical model based on the idealized conditions, there are massive difficulties in determining the factors and usefulness of the model in the context of power system alarming [36]. Another approach, namely McArthur model, could forecast fire weather and certain fire behavior parameters, which is helpful for firefighting deployment. Nevertheless, it is mainly developed for grassland and eucalyptus forests and its usefulness is constrained to the areas like northern Australia [37].

According to previous researches in the area [17], fire propagation models usually assume that the major factors influencing fire propagation are moisture, and spatial distribution of burning resources, wind speed, and slope. In addition to the baseline model, multiple further factors are also taken into consideration in our approach. Significant improvements comparing with the baseline model include different extent of influences between cellular, synergetic effects of fires from different ignition points, and randomness is introduced to the propagating procedure. Furthermore, comparing with existed models discussed in previous literature, the performances of our approach are analyzed with the context of electrical transmission line and modeled under comprehensive environmental conditions. The sufficiency of scenarios and potential field experiments with the power grid can make our propagation model more reliable and its behavior easier to be understood.

B. PREDICTION OF ELECTRICAL TRANSMISSION LINE BREAKDOWN

The wildfire propagation model provides information on two aspects for early warning of the electrical transmission line: 1) it estimates the path of wildfire propagation and the initial time and location that wildfire reach the security buffer of the electrical transmission line, indicating the cells needed to be considered for the breakdown probability calculation. 2) it clarifies the states of cells, which are used for calculating temperature and smoke density. Here, we predict the numbers of not burnt, flaming, smoldering, and burnt up cells (cells in different states), and calculate the predicted T and S for the holistic line and each pole via cell states. The breakdown probability can be calculated via the proposed LOM. Among this, we need to determine the relationship between T/S and cell states. However, it is difficult to set an invariable value. Here, we take setting of the flaming cells with condition of $T = 600°C$ and $S = 15$, while the smoldering cells will be possessed with $T = 200°C$ and $S = 75\%$ [38]–[42]. This setting should be suitable for most cases, and can be modified if used in other regions.

There have been plenty of theories trying to figure out breakdown voltages in lab experiment level [5], [29], [30]. Further in our paper, the process of the breakdown probability changes with time, determined by flame temperature and smoke density in the line buffer, also provides an illustration of the mechanism of impacts of wildfires to electrical transmission lines at the power system operating level. Figures 9–11 illustrate the predicted breakdown probabilities and the most three venerable poles to be broken with respect to time. The three figures are obtained with the condition of eastward wind, three ignition points, real topography and real vegetation (scenario 6), the condition of westward wind, single ignition point, uniform topography and real vegetation (scenario 8), and the condition of westward wind, single ignition point, real topography and uniform vegetation as shrub (scenario 11).

The breakdown probabilities will drop down after the majority of the cells turn into a 'flaming' situation, which will lead to a significantly lower outage probability. However, for wildfires that spread fast and wide enough through the transmission line (such as Figure 10), the breakdown probabilities will climb up again as new cells turn into 'smoldering' situation. Furthermore, the plots about the three most venerable poles could help us figuring out the points with changing risk priorities over time, and the range (length) of the demonstrated poles could roughly denote the area of the transmission line to be affected by the wildfire. The result is consistent with previous experimental studies [43], which

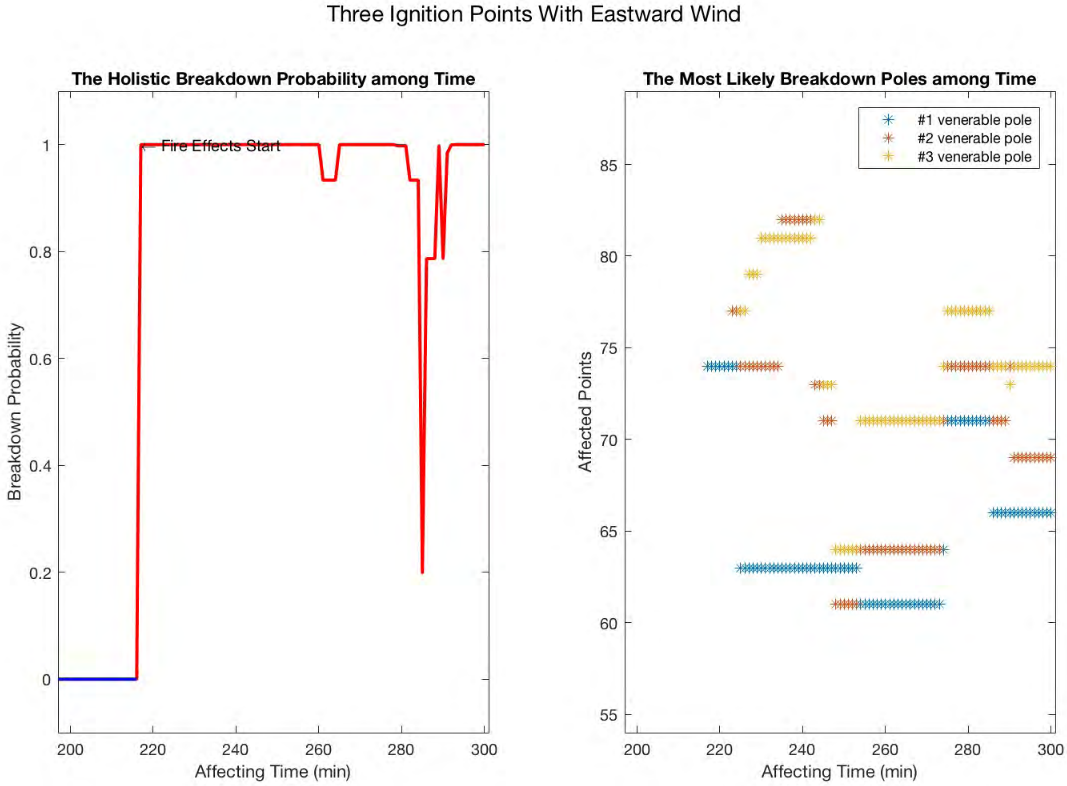

FIGURE 10. The breakdown probability and the most venerable poles with respect to time under triple ignition points and eastward wind (in the scenario 6).

argued that outage happens not during the whole gap is above the flame, but at the time of flame covers 60% of the gaps.

In our paper, the 3-D surface of breakdown probability with respect to smoke and temperature is constructed. As it is shown in Figure 8, the breakdown probability, in general, is positively related to smoke density and flame temperature. Moreover, smoke density has a much more significant effect than the temperature on the breakdown probability. Furthermore, given the condition that the transmission line is in a voltage of 500 kv, the U_{50} voltage fitting technique introduced in above sections could also serve as an innovative work. Following the fitting paradigm, it is possible to approximate the breakdown of any other transmission lines if there are lacking of records of the 50% breakdown voltage. In addition, the overall conditions of temperature and smoke in the holistic area is considered, which could be a valuable extension of previous work.

C. IMPLICATIONS AND LIMITATIONS OF THE EARLY WARNING SYSTEM

One novel contribution of our research is that rather than simply examining the propagation of wildfire, an integrated fire alarm system framework under electrical transmission line circumstance has been designed in the paper. In contrast, a majority of existed researches for the same topic primarily puts emphasis on fire propagation solely, without considering the breakdown mechanism of the transmission line and potential policies to deal with the situations. For instance, [29] presented a detailed mathematical model for agricultural fires propagation under electrical transmission lines based on a series of physical fire propagation functions; however, the research did not include the probability of transmission line outages. In terms of current early warning methods of wildfires, satellite remote sensing method can monitor occurrence of wildfires, but cannot achieve real-time monitoring wildfire propagation due to the limitation of satellite overpass time. In addition, major environment noises such as clouds could significantly restrict the effectiveness of satellite sensing [30]. Wireless sensor networks perform much better when facing environment noises, however, it is subject to the problem of battery and might be damaged in the wilderness by animals, which will seriously affect its data transmission [8].

Another problem in previously-existed fire alarming system is the insufficiency of detailed information about the threatening level of wildfire. Conventionally, fire alarming system will take the range and magnitude of wildfire into consideration, but will seldom consider whether and to what extent the wildfire will lead to a breakdown of the transmission line. Take a fire security system in Yunnan Province, China as an example, the power grid will deliver alarming messages when there are suspicious hotspots within a radius

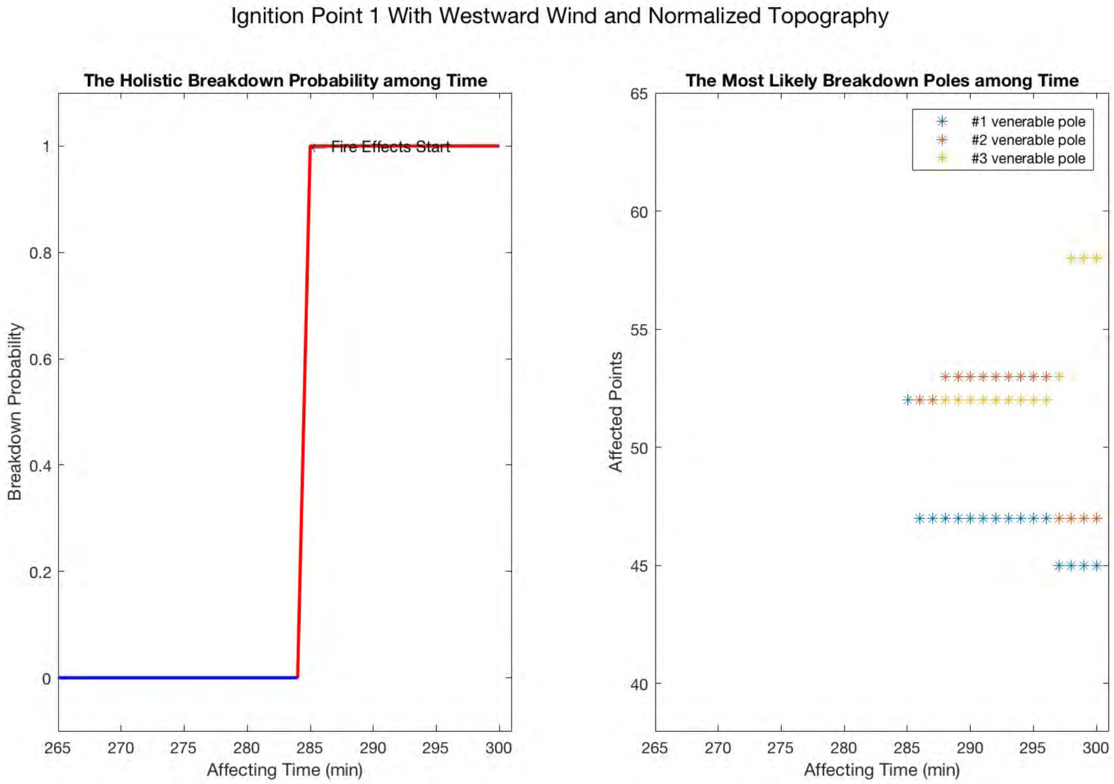

FIGURE 11. The breakdown probability and the most venerable poles with respect to time under single ignition point, westward wind and uniform topology (in the scenario 8).

of 1.5 km wide of electrical transmission lines. The message would be transmitted to the control center, facilitating the staffs to make a decision. However, a 1.5 km ahead alarming cannot sufficiently satisfy the requirements of active early warning and it demands human labors to determine how the fire will affect the transmission line.

The integrated fire alarming system designed in this paper has the following advantages. Firstly, the system can be utilized to electrical transmission line corridor, considering various topographies, vegetation, wind speed/directions, and especially for multiple ignition points. We have considered these environmental factors and included a case study via a Cellular Automata model, which could capture the wildfire spatiotemporal dynamics and make it possible to perform prediction of fire propagation with a relatively high precision. Secondly, the system designed in this paper developed a Line Outage Model (LOM) to determine the probability of line air gap breakdown, the most vulnerable poles and its variation with time, based on variation of smoke density and flame temperature, which could be helpful for automatically evaluating threats of wildfire imposed to the transmission line accuracies and reliabilities, and optimize the distribution of firefighting resources. It also serve for illustrating the mechanism of line outage confront wildfires at the power system operating level, rather than lab experiment level only. Thirdly, since the output of our breakdown evaluation model is probabilistic, it is convenient for us to precisely categorize the risks into different levels and make corresponding policies. For example, if the line breakdown probability is over 80%, it should be posed to a high priority; and in contrast, if the outage probability is lower than 20%, the priority level could be reduced to save resources for other areas. Finally, our system is able to capture the dynamic outage probabilities with respect to time and figure out poles in higher risk levels in advance. For an early warning system, this property will be of great importance in practice because it could provide an intuitive illustration for decision making and process monitoring. The rationality and validity of the results also imply that the breakdown probability computation formulas could be universal, and it is possible to build a reliable fire alarming system for electrical transmission lines under any conditions following our paradigms.

V. CONCLUSION

In this study, by applying a cellular automata model based on disaster geography principles to predict wildfire spatiotemporal process and employing the proposed electrical Line Outage Model (LOM) to illustrate the mechanism for wildfire to break transmission line, an innovative integrated early alarming system for fire damages to electrical transmission lines has been proposed. The system could forecast the spreading of fires and their potential risks to the transmission line in

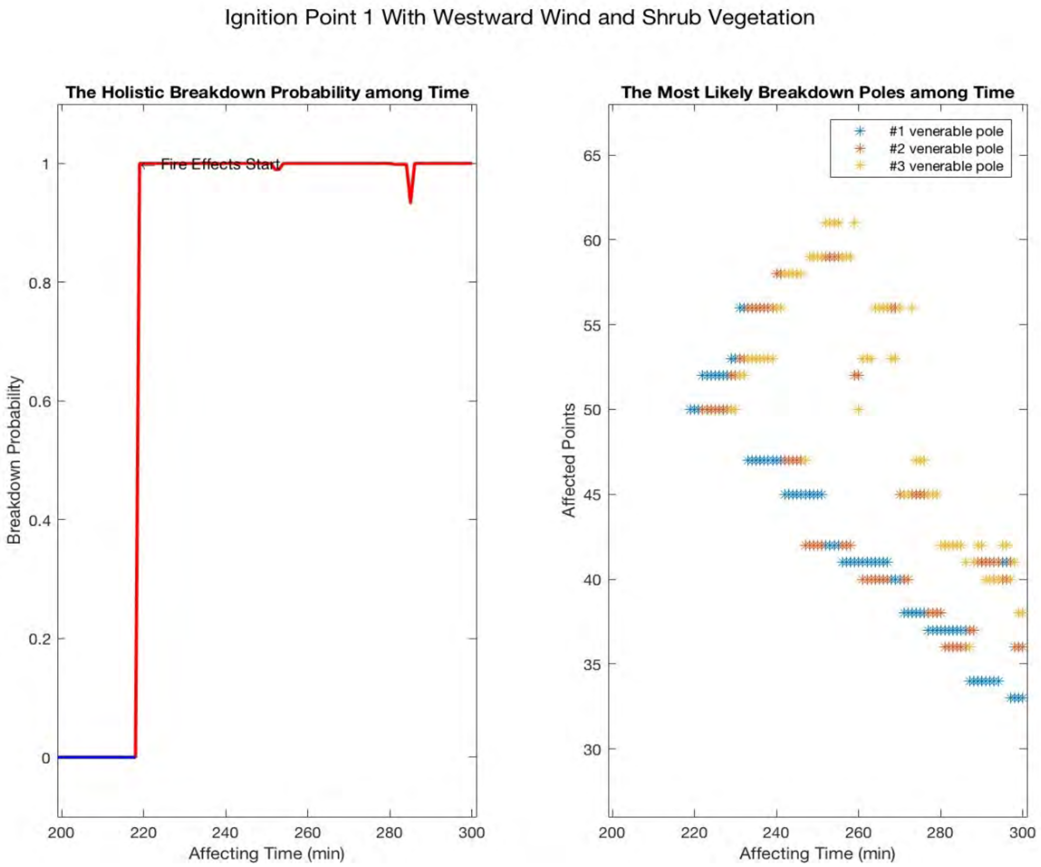

FIGURE 12. **The breakdown probability and the most venerable poles with respect to time under single ignition point, westward wind and shrub vegetation (in the scenario 11).**

advances for hours, and the integration property makes it possible for the system to process the alarming procedures automatically with a high efficiency. More importantly, it might illustrate more breakdown mechanism of line outage at the power system operation level, instead of lab experiment only. The rationality and effectiveness of the system is tested on a case study of a 500 KV transmission line near Miyi County, China, with various conditions of wind speed and direction, multiple ignition points, and different types of slopes and vegetation. The results are demonstrated and analyzed, and properties regarding the functions of our system have been discussed and compared with existed models.

To this end, the paper has made major contribution on revealing mechanisms of line outage at the power system operating level and developing integrated early alarming system for preventing power transmission lines to be damaged by wildfires. With the proposed system, it is possible to forecast the risk of wildfires, the most vulnerable poles and optimize the distribution of firefighting facilities. Meanwhile, the utilization of cellular automata model under multiple ignition points situations and the simulation of the power outage probability under the condition 500 kV transmission line could be regarded as innovative trials in the paper.

ACKNOWLEDGMENT

The authors would like to thank Garik Gutman at NASA and Louis Giglio in the University of Maryland for constructive discussion.

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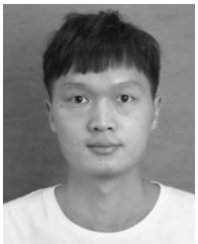

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