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Dynamic Simulation of Power Systems Considering Transmission Lines Icing and Insulators Flashover in Extreme Weather

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ABSTRACT Global climate deterioration caused by excessive carbon emissions poses a severe threat to the stable operation of power systems. In extreme snow and ice weather, complex faults, such as ice-covered line breakage and insulator flashover, may be triggered. Hybrid simulations to reveal the influence mechanism and dynamic interaction process between extreme weather and power systems have become a research focus. Relationship models between meteorological conditions and grid failure were constructed in ice accretion and insulator flashover scenarios. Based on the above two models, a multi-variable and multi-time scale hybrid simulation of the meteorological process and power system, considering line icing and insulator flashover, was realized. An example was provided to verify the feasibility of the proposed simulation scheme.

INDEX TERMS Extreme snow and ice weather, line icing, insulator flashover, hybrid simulation.

I. INTRODUCTION

In recent years, extreme weather events have had a significant impact on the exposed components and equipment of the power grid, such as transmission lines and insulators. According to the CIGRE WG.SCB 2.54 report, tower structures and electrical failures due to severe weather events are the main factors affecting the safe operation of overhead transmission lines. The massive blackout in Texas (March 2021) has given new thought to the grid's high proportion of renewable energy sources [1]. The construction of long-distance power transmission networks in China and the proposed concept of 'dual carbon' energy Internet are highly dependent on safe and reliable power transmission corridors [2]. The report, 'Unite in Science 2020', published by the World Meteorological Organization (WMO), highlights the increasing and irreversible impacts of climate change [3]. The worsening trend of extreme weather has become an essential factor threatening the regular operation of power grids and has gradually intensified.

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According to the statistical data of historical failures, snow, ice, and strong winds have caused far more outages in the power system than other extreme weather events. The impacts of snow and ice weather on the power grid include two main categories. First, the weight of ice on the transmission line exceeds its carrying capacity limit and results in line breaking or tower collapse, thus resulting in line tripping and power transfer. Second, when the insulator is covered with ice, the insulation tolerance and performance are reduced or even lost, leading to a single-phase grounding fault. Therefore, the power system's main threat of extreme snow and ice weather is reflected in the above mechanical weight and electrical insulation mechanisms.

Many studies have been conducted on the icing mechanism and modelling of transmission lines. Typical icing models constructed based on the formation mechanism include the Imai (1954) [4], Lenhard (1955) [5], and Makkonen (2000) models [6]. Makkonen considered more factors in the proposed model, which has been widely recognized in the field. In recent years, researchers have deployed new models that consider more factors. In [7], a model was proposed to simulate the critical ice-melting current on an iced conductor.

Based on this model, the value of the critical ice melting current was calculated using various parameters. A transmission line ice coating prediction model based on ensemble empirical mode decomposition feature extraction was proposed in [8]. A field-data-driven online prediction model for icing loads on transmission lines was proposed in [9]. Some studies have been conducted based on the relevant models. The collapse caused by ice shedding and its influencing parameters have been systematically studied in [10]. A new online de-icing and deicing method based on external excitation resonance was proposed in [11]. It is worth mentioning that, although an increasing number of factors are considered in the model, the effect mechanism and process between the transmission line current and ice accretion have always been ignored.

The problem of ice flashover on insulators has also attracted significant research attention. The ice flashover processes of the AC and DC were significantly different. In [12], the effects of icing degree and string length on various types of arcs were analyzed, and the leakage distance utilization ratio was defined to analyze the influence of the DC flashover path on the flashover voltage. In [13] and [14], the arc development process of glaze ice-covered insulators and the effect of ice shedding on the discharge characteristics were analyzed in an AC flashover scenario. The flashover characteristics for different insulators are also different, which were discussed in [15] and [16]. Further research on ice flashover was conducted based on the above mechanistic analysis. In [17], a three-dimensional electric field simulation was performed, and the flashover path of ice-covered suspension insulators was analyzed. In [18], an AC flashover test under a natural ice environment was carried out at the Xuefeng Mountain ice coating test station, and the AC flashover voltages of long strings of insulators with different degrees of pollution and ice coatings were obtained. In fact, the flashover process has a high probability, which should be widely described with the U50% index, as mentioned in [19]. Therefore, based on the above achievements, a further relationship model is essential between the environmental data and power grid faults caused by insulator flashover.

Based on the mechanism and model, further research has been conducted, including the assessment and improvement measurement of power grids exposed to extreme weather. The key features, theoretical framework, and strategies for improving the resilience of power grids against natural disasters in [20]–[23]. Relevant research achievements have also been applied in Iceland and Brazil, based on a framework combining weather-dependent component failure probabilities in [24] and [25]. However, the dynamic interaction effect between meteorological and power systems is always simplified with the probability model of meteorological weather, neglecting the reaction of the power system. Some studies have been conducted to improve the performance of power grids. As mentioned in [26]–[28], a dynamic thermal rating (DTR) system was used to enhance overhead line ratings. The DTR system deploys sensors to record real-time weather data and uses them to determine and predict actual line ratings, which can enhance the power grid's ability to withstand extreme weather. The consideration of dynamic processes is essential and effective in the research on power systems in extreme weather. In [29] and [30], this idea was applied to the simulation of a power system considering the effects of icing and line galloping. However, the insulator flashover was ignored. The processes of insulator flashover may significantly lead to electrical faults [31].

Most importantly, the dynamic processes between meteorological and power systems are always simplified and replaced with a probability model of extreme weather, which cannot satisfy the model and simulation requirements. Therefore, the following contributions were made to provide a research platform and method for power grid exposure to extreme weather. First, a model revealing the relationship between the ice weight accumulated on the transmission lines and electrical disturbances was established. Second, based on the factors affecting insulator insulation, an electrical fault model of the relationship between the ice thickness on the insulator and the electrical disturbance was proposed. Finally, a multi-process alternating self-fitting variable-step-size hybrid simulation framework is proposed based on the meteorological fault-electrical disturbance coupling model. The framework provides the research method and platform for two systems with different time characteristics considering impact mechanisms of extreme snow and ice weather.

The remainder of this paper is organized as follows to describe our work. The second part was realized by modelling the corresponding relationships between meteorological conditions, meteorological faults, and electrical faults. The third part describes the multi-time scale hybrid process simulation framework and critical problems. The corresponding implementation processes and case verification are presented in the remaining parts.

II. NUMERICAL MODELING OF ICING AND FLASHOVER PROCESS

A. ICING MODELING

The modeling of mechanical faults on transmission lines under the influence of snow and ice weather involves modeling the weight of the icing process and the carrying capacity of transmission lines, as shown in FIGURE 1.

1) ICING WEIGHT MODEL

A single-degree-freedom model was deployed to model the ice accretion process on power transmission lines. The following model was adopted to perform the mechanical force analysis on the weakest location of the lines. The thermal temperature coefficient of the current is introduced to a typical ice weight model. The selection of the coefficient was determined based on the historical fault data of different regions [29].

$$M_{\mathrm{i}}=\int_0^{\tau}[\frac{4}{\pi}r(t)(1+\frac{C_{\mathrm{a}}V_{\mathrm{a}}}{S_{\mathrm{w}}r})^{-1}S_{\mathrm{w}}C_{\mathrm{w}}C_{\mathrm{c}}\sin\theta_1\sin\theta_2+C_{\mathrm{i}}I]\mathrm{d}t \tag{1}$$

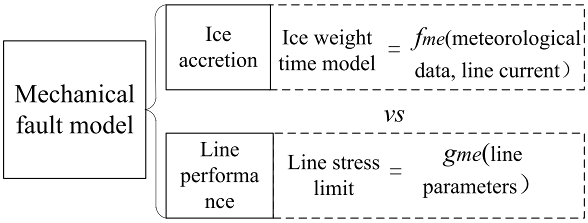


FIGURE 1. Principle model of a mechanical circuit failure in snow and ice weather.

where

- M_i weight of ice, kg;
- r radius of ice-covered transmission line, m;
- S_w wind speed, m/s;
- C_w density of liquid water in the air, kg/m^3;
- I current of transmission lines, A;
- C_c collection coefficient;
- C_a icing coefficient;
- V_a air movement index;
- C_i current thermal effect coefficient;
- θ_1 angles between precipitation and transmission lines;
- θ_2 angles between wind and transmission lines;
- $r(t)$ the sum of transmission line radius and icing thickness, m.

The weight of ice is applied to construct the relationship model between ice weather and the power grid, as expressed in Eq.(1). The coefficient C_i is introduced in this paper to describe the effect of the current, which has always been ignored in previous research. The ice thickness model is formulated as follows:

$$s = \sqrt{\frac{M}{\pi \rho_i} + r^2} - r \tag{2}$$

$$\rho_i = \rho_{ref}(R/(R+1.5))^2 \tag{3}$$

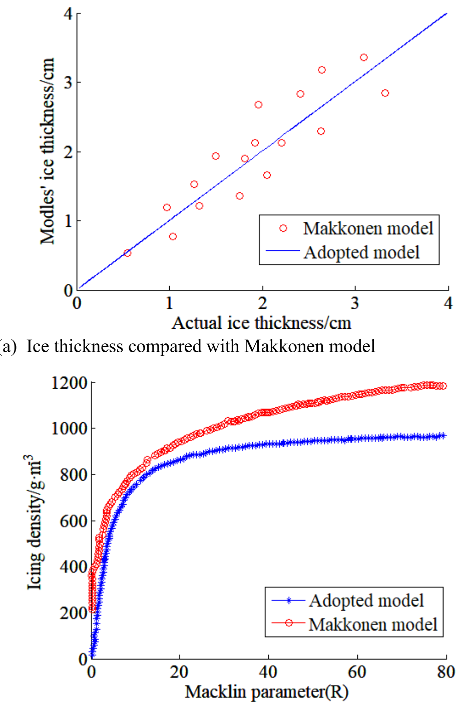
$$R = V_e d_m/(2T_s) \tag{4}$$

where

- s ice thickness, cm;
- M ice weight, kg;
- r radius of ice-covered transmission line, m;
- ρ_{ref} reference density of 4°c water, kg/m3;
- R Macklin parameter;
- V_e hit speed of raindrops, m/s;
- d_m raindrop median volume diameter, cm;
- T_s surface temperature, °c.

The ice thickness and density models are compared with the typical Makkonen model in FIGURE 2.

From figure (a), we can see that the model adopted is highly consistent with the Makkonen model. As shown in figure (b), the ice density model proposed by Makkonen is too large. In particular, when R>30, the ice density exceeded 1000 kg/m^3, which is unreasonable. This problem was corrected in the model adopted in this study.



(a) Ice thickness compared with Makkonen model

(b) Icing density compared with Makkonen model

FIGURE 2. Adopted model compared with Makkonen model.

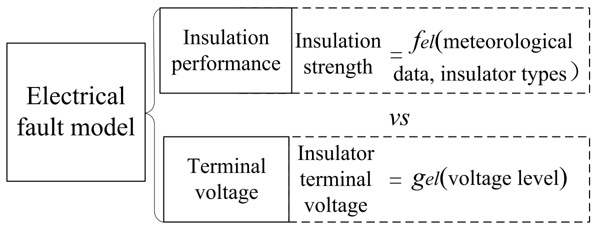


FIGURE 3. Principle model of electrical failure in snow and ice weather.

2) ICING WEIGHT - POWER GRID FAILURE MODEL

When the weight of ice on the transmission lines exceeds the line stress limit, a line-breaking fault is triggered. The following relationship model was established between the icing weight and line breaking failure rate, as shown in Eq. (5).

$$P_b = \begin{cases} 0, & M_i < M_o \\ 1, & M_i \geq M_o \end{cases} \tag{5}$$

where

- M_i weight of ice, kg;
- Mo line stress limit, kg;
- P_b failure rate of line breaking.

B. INSULATOR FLASHOVER MODELING

Electrical fault modeling on insulators under the influence of snow and ice weather is used to build a relationship model between the insulator tolerance voltage and the operating voltage on both sides of the insulator, as shown in FIGURE 3.

1) INSULATOR FLASHOVER MODEL

When the breakdown voltage exceeds the minimum flashover voltage, flashover is triggered. In this case, two main fault scenarios may occur. When icing is severe, a bridge of icicles is formed between the insulators, which leads to susceptibility to of ice flashover. However, when melting, water forms on the surface of the icicle, which can increase the leakage current of the insulator.

The flashover mechanism of ice-covered insulators evolved from the Obenaus model of pollution discharge, as shown in FIGURE 4 [32].

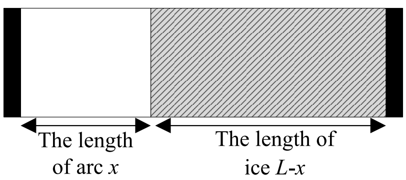


FIGURE 4. Schematic diagram of ice-covered insulator.

The simplified numerical model is as shown in FIGURE 5.

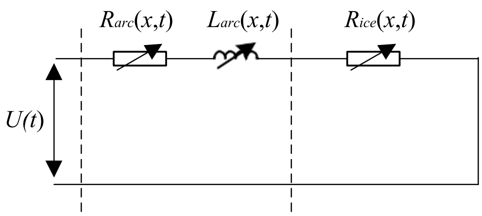


FIGURE 5. Simplified numerical model of ice-covered insulator.

Each element in the figure satisfies the following relational expression [32].

$$U(t) = I_{arc}(R_{arc} + R_{ice}) + L_{arc}\frac{dI_{arc}}{dt} \tag{6}$$

The above model reveals the fault mechanism of the ice flashover. In simulation research, the U50% flashover voltage model is more widely applied and is obtained based on statistical data in the laboratory or field.

The following two assumptions were considered. First, a flashover is triggered when the insulator terminal voltage is lower than the flashover voltage. Second, the voltage is uniformly distributed on the insulators.

The numerical model of flashover voltage is adopted as shown below [18].

$$U_f = A \times S^{-b} \times \left(1 - \frac{H}{45.1}\right)^{3.22} \times \left(1 - \frac{W}{45.1}\right)^{4.36} \tag{7}$$

where

- U_f flashover voltage, kV;
- A A constant, obtained from test results;
- b pollution influence characteristic index;
- S pollution degree of insulator surface, mg/cm^2;
- H height, km;
- W weight of ice on the insulator, kg/piece.

The flashover model in reference [18] was proposed by the Chongqing University team. The icing environment of the operational transmission line is significantly different from that of the laboratory. To study the flashover characteristics under natural icing conditions, an experimental platform was built at the Xuefeng Mountain Energy Equipment Safety State Field Science Observation and Research Station. A flashover model was constructed based on numerous observational data in the field. Therefore, the model proposed in [18] was adopted.

For AC, the local arc may appear to be extinguished when the voltage crosses the zero point in the pre-period. However, when the terminal voltage is sufficiently large, an arc reignites and develops. With the accumulation of ice on the transmission lines, the arc is assumed to reignite after the crossing of the zero point, and will not lead to flashover interruption.

It is worth mentioning that our proposed hybrid simulation scheme is a customizable framework, which can be enriched and expanded with more accurate models or parameters in further research. The simulation scheme is constructed based on the effect mechanism between extreme weather events and the power grid.

2) FLASHOVER VOLTAGE-GRID FAULT MODEL

The 50% flashover voltage model was adopted in this study, as shown in formula (8) [19]. The 50% flashover voltage is higher than the operating terminal voltage of the insulator in the normal state. The flashover voltage decreases with the change in external conditions until it becomes lower than the operating voltage.

$$P_f = \begin{cases} 50\%, & U_f < U_i \\ 0, & U_f \geq U_i \end{cases} \tag{8}$$

where

- U_f 50% flashover voltage, kV;
- U_i insulator terminal voltage, kV;
- P_f flashover failure rate.

III. SIMULATION FRAMEWORK AND KEY ISSUES

A. SIMULATION FRAMEWORK

Based on the above model, the following framework is proposed to realize the hybrid simulation of meteorological and power systems considering the influence of line icing and insulator flashover.

In this framework, meteorological information and grid parameters were used as input information. The time flow and information flow are deployed based on periodic and fault logic criteria. The meteorological and electrical results of the entire process simulation are shown in FIGURE 6.

B. KEY ISSUES

In the simulation framework, the following vital problems are to be solved.

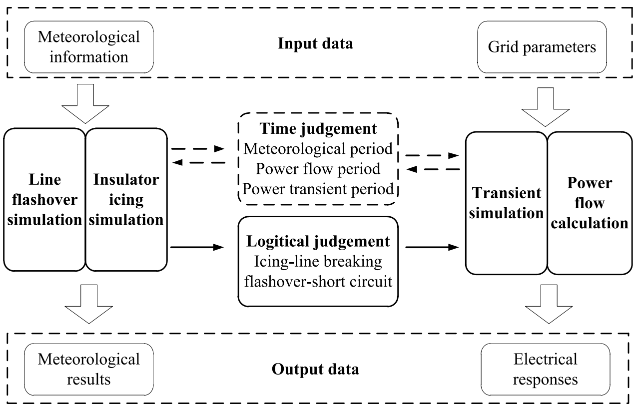


FIGURE 6. Hybrid simulation framework of meteorological - power system.

1) DECOUPLING OF MULTI-SYSTEM VARIABLES

The construction of the meteorological and power system model aims to research the effect mechanism between extreme weather events and the power grid and reveal it through corresponding numerical relation expressions. In essence, this is the revelation of the coupling mechanism and the description of the coupling relationship. The numerical model can be expressed as follows.

$$\begin{cases} \dot{x} = F_e(x, y, z, h) \\ 0 = G_e(x, y, z, h) \\ \dot{z} = F_m(x, y, z, h) \\ 0 = G_m(x, y, z, h) \\ F_l(if\,(h \in C_1)) \end{cases} \tag{9}$$

where

- x state quantity of power system;
- y algebraic quantity of power system;
- z state quantity of meteorological system;
- h algebraic quantity of meteorological system;
- F_e differential relation expressions of the power system;
- G_e algebraic relation expressions of the power system;
- F_m differential relation expressions of the meteorological system;
- G_m algebraic relation expressions of the meteorological system;
- F_l logical judgment statement when $h \in C_1$.

2) DECOUPLING OF MULTI-PROCESS AND MULTI-TIME SCALE PROCESSES

The alternation between the various processes follows two criteria. The first is whether the electrical fault is triggered by a meteorological fault, which is executed at each step of the meteorological simulation. Once satisfied, a new transient simulation was deployed immediately. The second criterion is the simulation time criterion. The simulation period of the processes can be divided from small to large as the power system transient, power system medium and long term, power flow, and meteorological. When the simulation time of the former process reached the simulation step of the latter, the simulation of the latter process was triggered. An adaptive strategy is adopted to realize the alternate execution of each process using the two criteria above. The adaptive step-size alternation simulation scheme is shown in FIGURE 7.

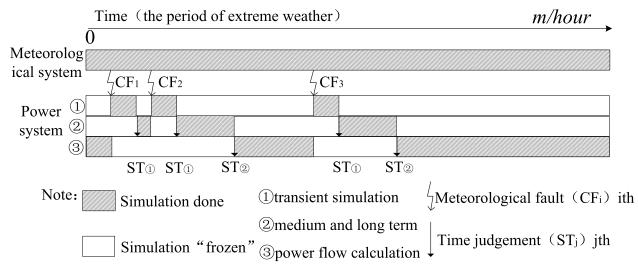


FIGURE 7. Schematic diagram of alternating hybrid simulation.

In summary, the electromechanical transient simulation was triggered and lasted for a short period (20 s) when failure occurred. In the simulation process, the power flow is calculated and updated at every step, resulting in high precision and low efficiency. Therefore, when no fault occurs, this high-precision simulation process is converted to a normal step-size power flow calculation.

IV. SIMULATION IMPLEMENTATION

The detailed implementation of simulation is deployed as FIGURE 8.

① Preset each simulation process's simulation step and period and input relevant meteorological and power grid information to initialize the simulation.

② Perform meteorological simulation, power flow calculation (the fluctuation characteristics of daily load variation considered), and judgment of the simulation period. The simulation was terminated if the preset period was reached. Otherwise, we proceed to the next step.

③ Determine whether the electrical faults are triggered by extreme events based on the proposed failure rate model. Otherwise, the power flow calculation is continued. Otherwise, we performed a transient simulation.

④ Perform a transient simulation to determine whether the preset meteorological simulation period is reached. Otherwise, execute the corresponding stability criterion and continue the transient simulation to the next step. Otherwise, perform a meteorological simulation and return to the transient simulation. The above processes was repeated until the end of the preset period of the transient simulation. Then, we turn to a mid-term simulation.

⑤ Perform a mid-term simulation and repeat processes similar with ④ until the end of the mid-term preset period. Subsequently, the power flow calculation was performed.

⑥ Repeat step ② until the end of the final preset weather simulation period.

The above hybrid simulation module can be verified using accurate weather and power grid parameters. However, the

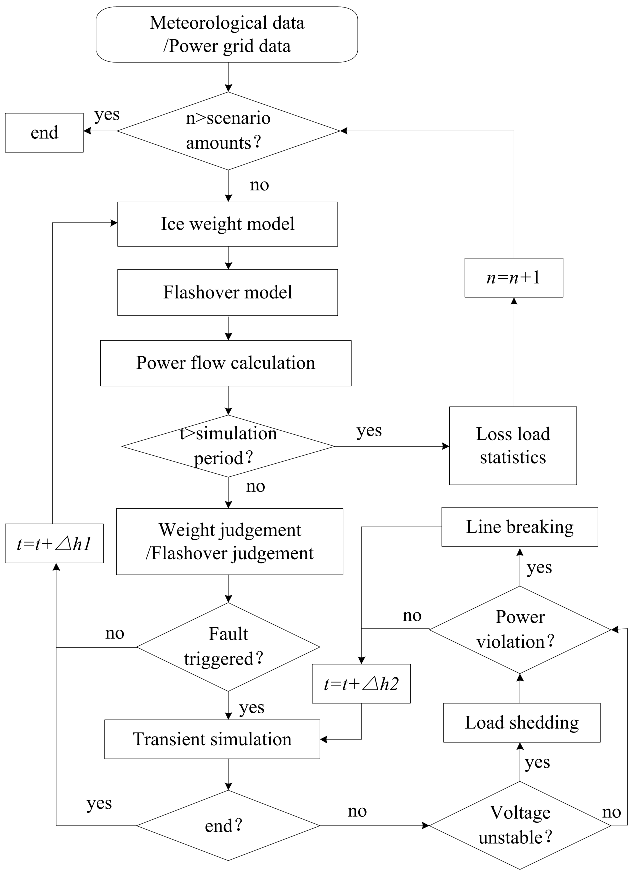


FIGURE 8. Hybrid simulation flow of meteorological and power system.

following causes pose great challenges to validation. First, the occurrence of extreme weather events has low probability, which makes it impossible to provide sufficient statistical data. Second, deploy meteorological measurement devices are insufficient when extreme weather events occur. The simulation method proposed in this study provides an innovative solution scheme, which will be further enriched with the improvement of the layout of meteorological measuring devices in the power grid of high-risk areas.

V. CASE STUDY

A. SIMULATION PARAMETER SETTING

1) METEOROLOGICAL PARAMETERS

In snow and ice weather, factors influencing icing and flashover include temperature, precipitation, wind speed, and wind direction. Simulated meteorological data were used to demonstrate the realization of the hybrid simulation.

The freezing coefficient is affected by temperature, which is set as the sinusoidal variation of 72 h with a maximum of −5°C and a minimum of −10°C. Air is affected by precipitation, which is set at 20% and fluctuates randomly every five minutes based on 1 mm/h. The wind speed and direction were converted into wind speeds perpendicular to the direction of the transmission line. The wind speed was set at 20% based on 5 m/s and 8 m/s in different areas.

The above weather is shown as FIGURE 9.

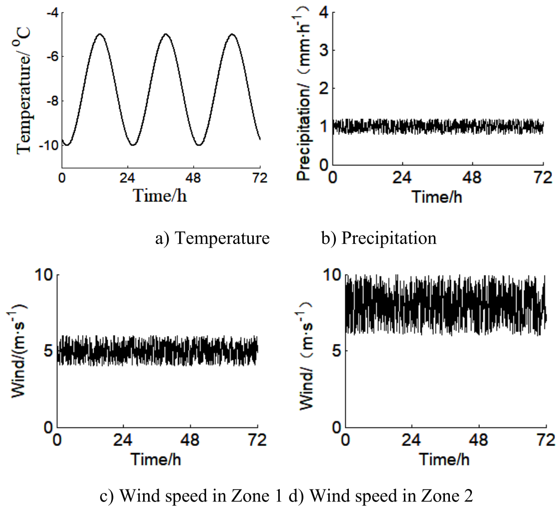


FIGURE 9. Preset snow and ice weather.

2) SIMULATION PARAMETERS

The total time for the hybrid simulation was set to 72 h to simulate extreme snow and ice meteorological events. The simulation period was 72 h for the meteorological system and the simulation step was 2 s. In the power system, the period of the transient simulation is 20 s, and the simulation step is 0.01 seconds. The power flow calculation period was the interval between the two failures, and the step length was the load fluctuation period (1 h).

When the power exceeds the rated values of transmission lines or transformers, a related protection action is triggered. The following settings were set according to the line voltage levels in TABLE 1.

TABLE 1. Transmission lines power over limit action settings.

Voltage grade /kV	Rated power /MVA	Tripping time /s	Reclosing time (single-phase)/s
220	400	0.12	1
500	800	0.1	1

The two-round control scheme is adopted in the low voltage load shedding module with the following ternary table, [0.85p.u., 0.5s, 20%] and [0.75p.u., 0.5s, 40%], corresponding to voltage, duration, and load shedding amount.

3) POWER GRID PARAMETERS

Six machines and 23 nodes case of PSS/E were adopted. Six generators and 23 transmission lines were located in three areas of the network. The generator and load parameters are presented in TABLE 2 and 3 below.

Some transmission line parameters are shown in TABLE 4.

The weight-bearing capacity limit of the transmission line and parameters related to the insulator inter-chip voltage are listed in TABLE 5.

TABLE 2. Parameters of some generators in the power grid.

The generator	Bus	Generating power /MW
# 1	101	750
# 2	102	750
# 3	206	800
# 4	211	600
# 5	3011	260
# 6	3018	100

TABLE 3. Partial load parameters of the power grid.

Load	Bus	Active power/MW
# 1	153	200
# 2	154	600
# 3	154	400
# 4	203	300
# 5	205	1200
# 6	3005	100
# 7	3007	200
# 8	3008	200

TABLE 4. Transmission line parameters.

Line no.	The line name	Voltage grade /kV	Span/km	Line weight /(kg/km)
# 6	203-205/1	220	1.1	960
# 7	203-205/2		0.9	
# 8	3001-3003		0.8	
# 9	3003-3005/1		1.2	
# 16	151-152/1	500	1.2	1600
# 17	151-152/2		1.1	
# 18	151-201		0.9	
# 19	152-202		0.8	

TABLE 5. Line bearing limit and insulator parameters.

Voltage grade /kV	Line carrying capacity /N	Number of insulator pieces/piece	Inter-chip voltage /kV
220	3000	14	$\frac{220}{\sqrt{3}\times 14}$
500	5000	28	$\frac{500}{\sqrt{3}\times 28}$

B. ANALYSIS OF SIMULATION RESULTS

1) FAILURE RESULTS

The simulation is performed in the proposed platform based on the above 72-hour meteorological data and power grid parameters.

TABLE 6. Simulation faults list.

Time/h	Line	The fault types		
		Flashover tripping	Ice overweight	Power overload
17.97	# 1	√		
	# 2			√
	# 4			√
	# 13			√
	# 15			√
	# 3			√
	# 11			√
	# 12			√
	# 5	√		
17.98	# 9	√		
18.86	# 13	√		
19.55	# 2	√		
19.56	# 6	√		
	# 7			√
19.57	# 10	√		
21.39	# 14	√		
23.92	# 3	√		
	# 7	√		
25.67	# 15	√		
26.57	# 4	√		
	# 8	√		
28.45	# 11	√		
31.00	# 12	√		
64.98	# 1		√	
64.99	# 5		√	
	# 9		√	
68.36	# 13		√	

The simulation results are presented in TABLE 6, and three types of fault were triggered. The flashover of insulators results in line tripping, and an overweight or overload of transmission lines leads to line breaking.

The topology of the power grid after the simulation is shown in FIGURE 10, where the dashed lines represent out-of-service lines. Colors and arrows indicate the voltage level and power direction, respectively. The figure shows that the generator runs in the islanding mode in the lower-left corner, where the other parts are networked.

2) FAULT RESULT ANALYSIS

Take four 220kV transmission lines, as shown in FIGURE 11. The ordinate represents the insulator tolerance voltage, and the dashed line represents the operating voltage between the phases. For line #2, the insulation tolerance voltage was lower than the phase voltage at 19.55h, resulting in a flashover.

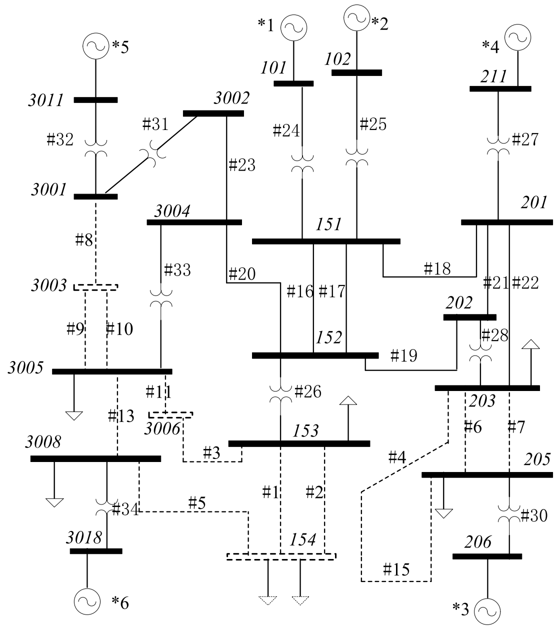


FIGURE 10. **Schematic diagram of simulation case.**

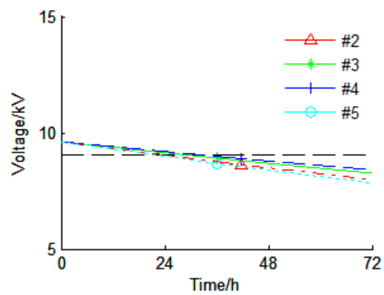


FIGURE 11. **Simulation results - voltage diagram.**

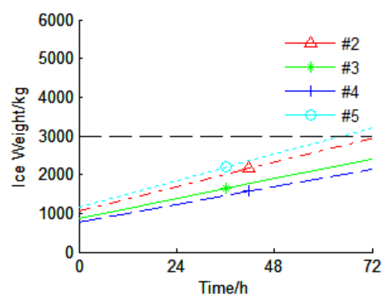


FIGURE 12. **Simulation results - ice weight diagram.**

Take four 220kV transmission lines, as shown in FIGURE 12. The ordinate represents the sum weight of the ice and lines, and the dotted line represents the line stress-bearing limit. For line #5, the weight of the icing exceeded the stress capacity of the line at 19.55h, leading to a line break.

The power fluctuation curves for the four lines are shown in FIGURE 13. The powers of lines #2, #3, #4, and #5 were

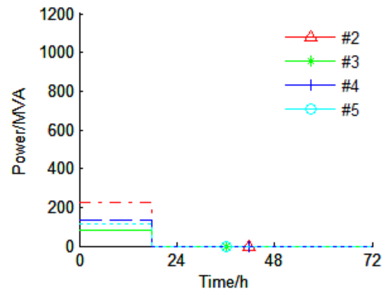


FIGURE 13. **Simulation results - Schematic diagram of transmission power.**

disconnected at 17.97h due to power overload and dropped to zero.

As can be seen from the simulation results above, cascading faults caused by power congestion in transmission lines play a critical role in power grid blackouts. Therefore, the application of network topology optimization techniques can optimize line switching to relieve network congestion and improve network flexibility. With a higher overhead line rating, the evolution process of the cascading faults may be interrupted. As mentioned in [33], a dynamic thermal rating system was used to enhance overhead line ratings. The DTR system deploys sensors to record real-time weather data and uses them to determine and predict the actual line ratings. The hybrid simulation platform constructed in this study provides a feasible method for the verification of the DTR system or other control measurements in further research.

VI. CONCLUSION

The influence mechanism between the power system and extreme ice weather is complex. Furthermore, multiple processes were involved in the simulation. The following solutions were proposed to solve the above problems.

① Based on historical fault data and events, the relationship between the meteorological conditions, line icing weight, and power grid failure rate was established to reveal the fault mechanism. Then, the relationships between snow and ice weather meteorological conditions, insulator flashover voltage, and power grid failure rate were established.

② A hybrid simulation scheme based on the above influence relationship models was proposed to realize efficient simulation of a hybrid system with multiple variables and multiple time scales. The simulation was carried out using a specific case to verify the effectiveness of the proposed scheme.

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