NUMERICAL SIMULATION OF DE-ICING PROCESS OF ICED MULTI-SPAN TRANSMISSION LINES UNDER SHOCK LOAD

Chen Kequan, Yan Bo*, Cheng Haoyue, Liu Xiaohui
Department of Engineering Mechanics, Chongqing University, Chongqing, China
*Email: boyan@cqu.edu.cn

Abstract: The numerical models of typical sections of iced multi-span transmission lines are set up by means of ABAQUS finite element software, and the processes of de-icing under impulsive excitations are numerically simulated. The user material subroutine VUMAT is developed to describe the porous elastic constitutive model of the ice and delete the broken elements identified by tensile failure criterion. A large number of de-icing scenarios are numerically simulated to investigate the effects of various factors, including span length, ice thickness, number of spans and amplitude of shock load, on the rate of de-icing.

1. INTRODUCTION

Icing on transmission lines, which may lead to failure and even collapse of towers, breakage of conductors, flashover, galloping and so on, is one of the most serious factors jeopardizing the safe operation of power supply system. The investigation on efficient de-icing methods is an urgent task. In the previous works, the authors only concentrated on the investigation of the de-icing process of isolated span. Therefore, this paper concentrates on the investigation of de-icing process of iced transmission lines with multi-span under shock load by means of numerical method.

2. RESULTS AND DISCUSSION

The results of the numerical simulations under different number of spans are listed in Table 1. It is shown that the rate of de-icing is influenced obviously by the adjacent spans, and the rate of de-icing of the loading span is the highest.

Table 1: The rate of de-icing in the cases of different number of spans

Shock load amplitude （KN）	Rate of de-icing（%）								
	isolated span	Three spans			Five spans				
		Span 1	Span 2	Span 3	Span 1	Span 2	Span 3	Span 4	Span 5
5	42.1	16	21.7	0	10.8	0	12.7	0	0
6	60	29.8	50.9	8.8	13.3	0	44	0	15.5
7	87.3	36.4	66.3	13.1	24.8	0	69.9	5.3	36.3
8	100	29.2	84.7	33.7	18.3	24.9	73.6	2.4	34.2
9	100	37.5	100	54.2	32.3	37	96.1	28.9	53.1
10	100	49.5	100	68.7	41	56.4	99.5	48.1	44.7

The variation of the rate of de-icing with the amplitude of shock load is shown in Fig1. It is observed that the rate of de-icing increases with the amplitude of shock load.

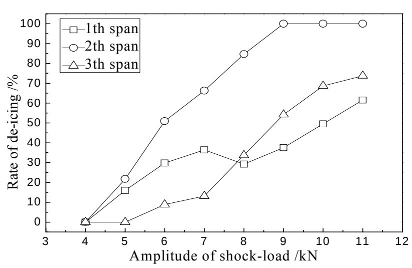

Fig 1: Rate of de-icing varies with amplitude of shock load

The rates of de-icing with different span lengths are listed in Table 3. It is obvious that the rate of de-icing decreases with the span length.

Table 3: The rate of de-icing in different span length

Span length(m)	Rate of de-icing（%）		
	Span 1	Span 2	Span 3
200	29.2	84.7	33.7
300	15.7	62.2	23
400	8.3	24.5	15.2
500	0	3	10.2

The rates of de-icing with different ice thickness are listed in Table 4. It is discovered that the smaller the ice thickness is, the higher the rate of de-icing.

Table 4: The rate of de-icing in different ice thickness

Ice thickness (mm）	Rate of de-icing（%）		
	1th span	2th span	3th span
5	57.5	100	68.5
10	29.2	84.7	33.7
15	33.4	66.7	21.8
20	33.8	41.8	2.2

3. CONCLUSIONS

The numerical simulation method of de-icing process of iced multi-span transmission lines under shock load is presented. The results indicate that the process of de-icing of transmission line is influenced obviously by the adjacent spans. The smaller the number of spans, ice thickness and span length are, the higher the rate of de-icing; and the larger the amplitude of shock load is, the larger the rate of de-icing.

4. REFERENCES

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Numerical Simulation of De-icing Process of Iced Multi-Span Transmission Lines under Shock Load

Chen Kequan Yan Bo Cheng Haoyue Liu Xiaohui
Department of Engineering Mechanics, Chongqing University, Chongqing, China

***Abstract*—The numerical models of typical sections of iced multi-span transmission lines are set up by means of ABAQUS finite element software, and the processes of de-icing under impulsive excitations are numerically simulated. The user material subroutine VUMAT of the ABAQUS software is developed to describe the porous elastic constitutive model of the ice and delete the broken elements whose axial stress exceeds the tensile strength of the ice. A large number of de-icing scenarios are numerically simulated to investigate the effects of various factors, including span length, ice thickness, number of spans and amplitude of shock load, on the rate of de-icing. The obtained numerical results provide a reference for the mechanical de-icing technique in practice.**

Keywords—Iced transmission lines; De-icing; Shock load; Numerical simulation

I. INTRODUCTION

Icing on transmission lines, which may lead to failure and even collapse of towers, breakage of conductors, flashover, galloping and so on, is one of the most serious factors jeopardizing the safe operation of power supply system. China is one of the countries seriously affected by heavy ice. In 2008, the ice storm happen in the South area of China brought about a direct economic loss more than 110 billion RMB. Therefore, the investigation on efficient de-icing methods is an urgent task.

Although more than forty de-icing techniques have been reported for iced transmission lines, few effective measures are suitable for different situations. The mechanical de-icing approach behaves the advantage of low energy consumption and low cost, so the investigation on mechanical de-icing technology is attracting more and more attentions of researchers in recent years [1]. One type of the mechanical de-icing techniques is the ‘ad hoc’ method, in which manual operation, helicopters and even shotguns are used to de-ice. These techniques are neither safe nor efficient. Another method is the so-called rolling, in which a mobile pulley system is pulled by an operator on the ground. The efficiency and safety of this method is needed to be improved. A mechanical method employing mechanical shocks was developed to de-ice the ground wire taking advantage of the brittle behavior of ice at high strain rates [2]. The dynamic effects of shock-load-induced ice-shedding on overhead ground wires were simulated using the “element death upon rupture” option in ADINA by Kálmán et al. [3]. The de-icing process and the spread of the blasting shock wave along the iced ground lines were numerically investigated by CHEN [4]. Recently, the authors of this paper [5] numerically investigated the de-icing processes of a single span transmission line under shock load, in which the ice is simply simulated with isotropic elastic material model.

In the previous works, to the best of our knowledge, the authors concentrated on the investigation of the de-icing process of isolated span, no work on the effects of the adjacent spans and the insulators on the rate of de-icing have been reported up to now. Therefore, this paper concentrates on the investigation of de-icing process of iced transmission lines with multi-span under shock load by means of numerical method. The user material subroutine VUMAT of ABAQUS software is developed to describe the porous elastic constitutive model of the ice, and delete the broken ice elements(de-iced) identified by tensile failure criterion. A large number of de-icing scenarios are studied with the variables including the number of spans per line section, span length, ice thickness and the amplitude of shock load. The obtained results can provide a reference for the mechanical de-icing practice.

II. MECHANICAL PROPERTIES OF ICE

The mechanical properties of atmospheric ice on transmission lines depend on its crystal structure, temperature, presence of impurities and the rate of loading. In the case of short-term loading, ice behaves elastically and fails in brittle manner, but creep and plastic failure predominate when the loading rate is lower than $10^{-5}s^{-1}$ [6]. In this study, the properties of hard rime associated with short-term loading are assumed to prevail.

The elastic modulus and Poisson ratios of the hard rime, which is simplified as a transverse isotropic material, can be depicted as [7]:

$$
\begin{aligned}
&E_p=9.470\times10^9[1-1.471\times10^{-3}(T-T_0)]\\
&E_t=11.578\times10^9[1-1.471\times10^{-3}(T-T_0)]\\
&G_p=3.346\times10^9[1-1.471\times10^{-3}(T-T_0)] \qquad (1)\\
&G_t=2.946\times10^9[1-1.471\times10^{-3}(T-T_0)]\\
&\nu_p=0.415 \quad \nu_{tp}=0.274 \quad \nu_{pt}=0.224
\end{aligned}
$$

in which t and p stand for "transverse" or in column direction and isotropic plane respectively; T is the current temperature and T_0 the absolute zero temperature.

The compressive and tensile strengths of atmospheric ice depend on the ambient temperature and wind speed. Druez et al [8, 9] obtained the compressive and tensile strengths of ice at the same temperature under which the ice was accreted. The compressive strength, bending strength and the effective modulus of atmospheric ice accumulated in a closed loop wind tunnel were reported by Kermani et al [10, 11]. It indicated that the tensile strength of atmospheric ice is insensitive with strain rate and temperature [12]. In this study, the tensile strength of the ice accreted on transmission lines is set to be 1.5MPa, and the density to 852 kg·m^{-3} [9] .

III. NUMERICAL APPROACH

A. The finite element model

A simplified typical three-span line section model is shown as Fig.1. The type of conductor is A3/S3A-732/92, and its parameters are listed in Table 1. The tensile stress at the lowest point of each span under self-weight is 34.33X10^{6}Pa. The initial state of the line section under self-weight can be determined by the numerical method proposed by Yan et al [13]. The damping of iced transmission line cables can be depicted by means of the Rayleigh damping model as the follows

$$\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K} \tag{2}$$

The damping parameters α and β of the iced conductor are listed in table 1[14].

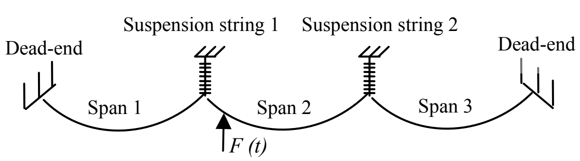

Fig 1: The model of a three-span line section

Table 1: Parameters of conductor A3/S3A-732/92

Young's Modulus (MPa)	Section Area (mm^2)	Mass per unit length (kg/m)	Expansion coefficient (/℃)	Tensile strength (MPa)	Damping coefficient	
					α	β
6.7×10^4	824.7	2.75	1.930×10^{-5}	107.39	0.1	0

Each conductor is discreted with 1000 cable elements, which are simulated by 3D two-node truss elements by setting material property to NO COMPRESSION in the input data file of ABAQUS software. The ice accreted on the conductor is modeled with pipe-beam element parallel to the cable element using common nodes [5], and the initial stresses of the accreted ice are neglected. The suspension insulator strings are modeled by 3D beam elements.

The flexibility of the towers and their foundations are ignored in the numerical model. The two ends of the line section are assumed rigidly fixed, and the translation degrees-of-freedom of the suspending point of each suspension insulators are constrained.

An impulsive load F(t) is applied on the iced line to simulate the external de-iced load. In the numerical simulation, a static analysis of the iced transmission line under the self-weight of the conductor and the accreted ice is carried out to determine its initial static state. Then the shock load, whose loading and unloading times are respectively set to be 0.1s and 0.001s, is applied on the line to simulate the de-ice process.

B. Ice failure modeled by VUMAT

The shear deformation of the ice is negligible when its thickness is small, so only the tensile failure criterion is applied to identify the failure of the ice element. To describe the porous elastic constitutive relation of the ice proposed in [7] and delete the failure element in the numerical simulation process, the user material subroutine VUMAT of ABAQUS software is developed in the FORTRAN language. The stresses at each integration point of the ice elements are updated in each incremental step by means of VUMAT. The element is considered as 'dead' in the following analysis and its mass and stiffness contributions are removed from the model if its axial stress exceeds the tensile strength of ice.

IV. RESULTS AND DISCUSSION

A. The effect of number of spans

In order to study the effect of the number of adjacent spans on the rate of de-icing of the line section, a three-span line section with 200m span length is compared to two line sections, a section with one 200m span and the other one with five 200m spans. In this case, the ice thickness is set to be 10mm and the upward impulsive load is applied at the point 6m from the left end of the mid span. The results of the numerical simulations under different number of spans are listed in Table 2. It is shown that the rate of de-icing after loading is influenced obviously by the adjacent spans, and the rate of de-icing of the loading span is the highest. For multi-span line section, the energy is transferred to the adjacent spans by the swing of suspension insulator strings after loading, and the more the number of the adjacent spans are, the less the energy dissipated to de-ice on the loading span. At the same time, the energy dissipation due to damping of the iced lines in the process of de-icing increases with the number of spans. Therefore, larger impulsive load is needed to arrive enough rate of de-icing for multi-span transmission lines.

Table 2: The rate of de-icing in the cases of different number of spans

Shock load amplitude (KN)	Rate of de-icing (%)								
	isolated span	Three spans			Five spans				
		Span 1	Span 2	Span 3	Span 1	Span 2	Span 3	Span 4	Span 5
5	42.1	16	21.7	0	10.8	0	12.7	0	0
6	60	29.8	50.9	8.8	13.3	0	44	0	15.5
7	87.3	36.4	66.3	13.1	24.8	0	69.9	5.3	36.3
8	100	29.2	84.7	33.7	18.3	24.9	73.6	2.4	34.2
9	100	37.5	100	54.2	32.3	37	96.1	28.9	53.1
10	100	49.5	100	68.7	41	56.4	99.5	48.1	44.7

B. The effect of amplitude of shock load

To investigate the effect of amplitude of shock load on the rate of de-icing, a three-span line section with 200m span length and 10mm ice thickness is numerically analyzed. The impulsive load is applied at the point 6m from the left end of the middle span. The variation of the rate of de-icing of different spans with the amplitude of shock load is shown in Fig.2. It is observed that the rate of de-icing increases with the amplitude of shock load, and the rate of de-icing of the span, on which load is applied, is higher than that of any other span.

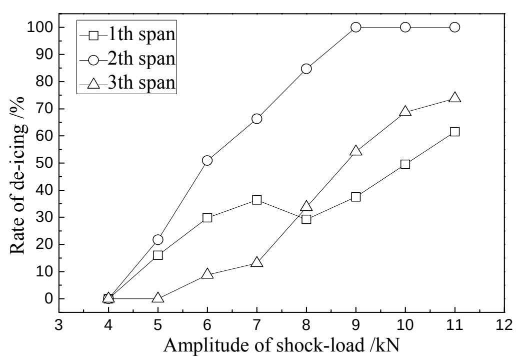

Fig 2: Rate of de-icing varies with amplitude of shock load

C. Effect of span length

The three-span line section models with different span lengths are used to study the effect of span length on the rate of de-icing, and in this case the ice thickness is set to be 10mm and the amplitude of shock load is 8kN. The rates of de-icing of the lines with different span lengths are listed in Table 3. It is obvious that the rate of de-icing decreases with the span length. Therefore, to achieve better results for de-icing, larger shock load should be applied on long span transmission.

Table 3: The rate of de-icing in different span length

Span length(m)	Rate of de-icing (%)		
	Span 1	Span 2	Span 3
200	29.2	84.7	33.7
300	15.7	62.2	23
400	8.3	24.5	15.2
500	0	3	10.2

D. Effect of ice thickness

The three-span line section with 200m span length accreted ice with different thickness under the action of impulsive load with amplitude of 8kN are numerically simulated. The rate of de-icing of the line section in the case of different ice thickness is listed in Table 4. It is discovered that the smaller the thickness of the accreted ice is, the higher the rate of de-icing. Moreover, the rate of de-icing of the loading span is higher than that of any other span. It is suggested that de-icing be carried out as early as possible in practice.

Table 4: The rate of de-icing in different ice thickness

Ice thickness (mm)	Rate of de-icing (%)		
	1th span	2th span	3th span
5	57.5	100	68.5
10	29.2	84.7	33.7
15	33.4	66.7	21.8
20	33.8	41.8	2.2

V. CONCLUSIONS

The numerical simulation method of de-icing process of iced multi-span transmission lines under shock load is presented. The results of parameter study indicate that the process of de-icing of transmission line after loading is influenced obviously by the number of spans, the span length and the ice thickness. The smaller the number of spans, the thickness of the accreted ice and the span length are, the higher the rate of de-icing; and the larger the amplitude of shock load is, the larger the rate of de-icing. The obtained results provide a theoretical foundation for the development of mechanical de-icing technology of iced transmission lines.

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