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A Novel Ice-related Disaster Regional Mapping Method for Electric Networks Based on Grey Clustering Theory and Field Incident Records

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Abstract: A novel ice-related disaster regional mapping method is proposed, which combines previous galloping and atmospheric icing mapping methods with historical data of observed ice-related incidents (galloping, ice shedding, and overloads). This research is an attempt to consider together the meteorological parameters, terrain factors and transmission lines configuration as a whole, which are at risk of causing power line outages and damage. The Grey fixed-weight clustering method is adapted to analyze the meteorological factors resulting in galloping. Then, terrain parameters and transmission lines configuration are used to amend the results of Grey clustering. In addition, field ice-related incident records are used to determine the galloping grades directly. Using both qualitative and quantitative results of the analysis method, four ice-related regions are defined: light galloping, medium galloping, heavy galloping and heavy icing regions. A 220-kV line section is used as a case study, which shows the effectiveness and consistency of the new method. Finally, an initial ice-region map of China's Yunnan province is presented, which may be of great use for operating and maintenance of transmission lines in service, and for the design and routing of new lines. Also, this research can provide a useful reference for other electric power networks in regions prone to atmospheric icing.

1 Introduction

A novel ice-related disaster regional mapping method is proposed which combines information on the occurrence and degree of severity of the primary types of ice-related disasters threatening the mechanical security of overhead transmission lines, due to conductor galloping episodes and overloading induced by heavy atmospheric icing and ice shedding. The mapping method combines information on observations of heavy atmospheric icing and galloping, leading to the designation of four categories to characterize the risks associated with the mechanical security of electric networks: 1) the light galloping region, 2) the medium galloping region, 3) the heavy galloping region, and 4) the heavy icing region. Such a mapping tool brings two significant benefits to electric power utilities. On one hand, it can be used to set preventive maintenance priorities of exposed lines in terms of anti-galloping or anti-icing measures, and to design different line monitoring schemes and maintenance and repair plans, to optimize costs and continuity of service. On the other hand, it provides useful information for the design of new transmission line corridors, which can help to avoid inasmuch as feasible the regions prone to ice-related disasters, or help to plan proper strengthening measures in advance for lines which will have to go across these regions (Lin Li et al., 2012).

For galloping mapping, Shao Demin et al. (1996) considered ten meteorological parameters using the Grey clustering method, which proved quite effective. However, their method has essentially led to meteorological regional divisions, for its lack of comprehensive consideration of other relevant factors responsible for galloping. Ma Jianguo (1999 & 2002) and Fu Fengren et al. (2010) put forward a different mapping method based on observations of galloping incidents (galloping frequency of occurrence), which is significant for lines in service with sufficient incident records, while it cannot be extrapolated to newly-built lines or to assist in designing new projects. Tao Baozhen et al. (2010) suggested a combined approach considering both meteorological and topography factors, but its success was quite limited because it could not yield specific criteria with broad application. Gao Zhi et al. (2010) proposed a mapping method based on the freezing rain frequency which can be only used for the Hebei province in China. A galloping coefficient method was proposed by Tu Ming et al. (2011), which included a computational model making use of statistical data of meteorology and terrain factors. However, the accuracy of the method is hampered by the lack of statistical data for the vast majority of the Chinese electrical grid. The method shows great potential and will require a huge investment in data collection. In the proposed method, the authors make use of previous recent research (Lin Li et al., 2012) and account for specific galloping mechanisms, meteorological parameters, terrain factors and line configuration.

Icing maps are more straightforward to obtain and most researchers (Lichun Shu et.al, 2009, Lisha Ouyang et al., 2010, Shaoyi Zhou, 2010, Wenbo Pang et al., 2012) took the historical operating records and meteorological factors as their main indicators, and concluded to four regions in China, i.e., the non-iced region, the light ice-coated region (with an average ice thickness of 0-10 mm, accumulated on conductors), the medium ice-coated region (10-20 mm), and the heavy ice-coated region (above 20mm). Yi Lu et al. (2011) put forward a more comprehensive mapping technique which also includes information on the occurrence of tower collapses and line breakages attributed to atmospheric icing, reported galloping incidents, and flashovers caused by icing and wet snow. However, it mainly relied on historical data on galloping, and failed to include a specific criterion for tower collapse and line flashover. Besides, as violent galloping events may also trigger tower collapses and line breakages, it is difficult to appreciate whether the indicators are truly independent.

In this research, the authors are motivated by the necessity to combine the regional mapping of galloping zones and ice-coated regions, and to consider the main types of ice-related disasters globally. There is also a clear advantage to combine both qualitative and quantitative analyses when considering meteorological parameters, terrain factors and line configurations.

Acknowledging the current lack of meteorological and terrain data on the Chinese territory, the Grey fixed-weight clustering method is used, which is known for its efficiency in quantifying the uncertainty of complex systems with small samples and poor information (Sifeng Liu, & Yi Lin, 2010). Grey clustering is employed to grade the regions with partial meteorological data, especially for the regions with no transmission lines. For the in-service lines, a combination of historical incident records and Grey clustering is used to determine the four ice-related regions of light, medium or heavy galloping, and heavy icing.

A 220-kV line section is used as a case study, which shows the effectiveness and consistency of the new proposed method. Finally, a preliminary ice-related disasters regional map of China’s Yunnan province is presented.

2 Ice-related Disaster Regional Mapping Method

Conductor galloping is an aeroelastic instability phenomenon resulting from the combined action of meteorological factors (wind direction and velocity, turbulence, and ice thickness), topographical parameters (ground surface roughness, line proximity to large bodies of water, presence of hills and valleys), and line configuration (single or bundled conductors, conductor diameter and construction type, natural frequency, stiffness and damping) (P. Yu et al. 1993, J. Wang & J.L. Lilien 1998, Yinglong Guo et al. 2003). It is proposed to use the Grey fixed-weight clustering method to analyze the meteorological factors which are more uncertain than the terrain and line parameters. Then, the terrain parameters and data on transmission line configuration are used to amend the results obtained from Grey clustering. In addition, the field ice-related incident records are used to determine the galloping grades directly whenever available.

Sudden ice-shedding and overloads are the main potential sources of disasters for heavy ice-coated regions (defined with an average ice thickness in excess of 20 mm), as they may cause conductor breakages, fittings failure, flashovers and tower collapses (Jamaleddine et al. 1993, McClure et al. 2003, Kálmán 2007). Galloping, however, occurs mainly in regions with an average ice thickness of 3- 20 mm.

The procedure of the proposed method is as follows:

Step 1 Define the regions with more than 3 reported occurrences of galloping during the past 10 years, as heavy galloping regions. Keep the heavy ice-coated regions as they are currently defined in icing maps.

Step 2 Use Grey fixed-weight clustering to define the other regions of galloping grading.

Firstly, three meteorological parameters deemed as the most significant are selected as clustering factors: ice thickness, wind speed, and the angle between the perennial (dominant) wind direction and the line.

Statistical data from previous studies (Dingbao Chen 1988, Yinglong Guo et al. 2003) indicate that galloping often occurs in a wind speed range of 4 m/s to 20 m/s, with a representative average ice thickness varying from 3 to 20 mm, and when the angle between the incident wind direction and the galloping lines is in the range of 45° to 90°. Lines in flat terrain and those with bundled conductors are more prone to galloping than others.

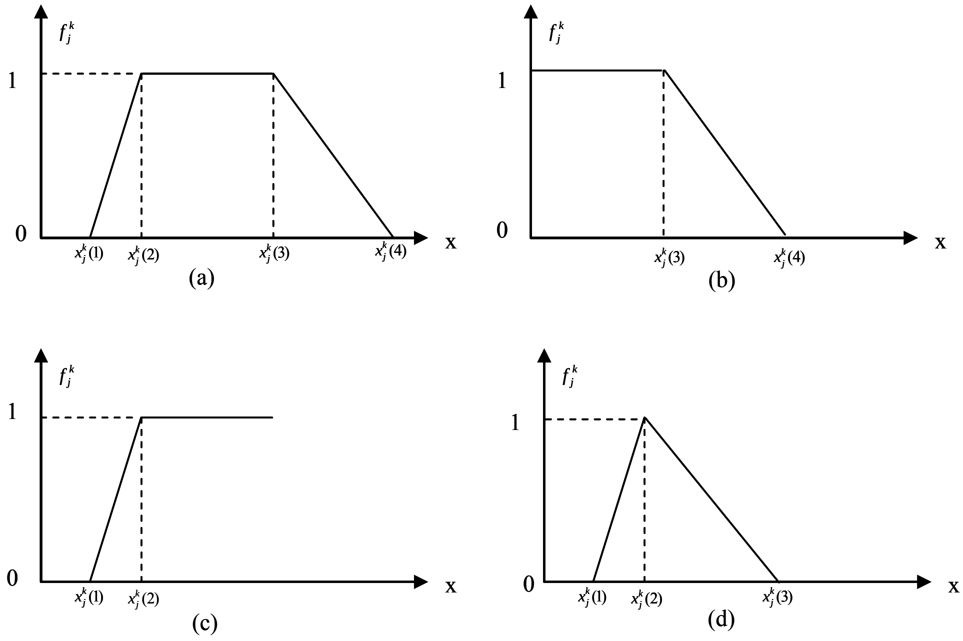
The specific procedure for galloping grading is as follows:

1) Define the galloping grading criteria and galloping subclasses, the Grey clustering indices, and the whitenization weight functions. The values used in the study are presented in Table 1 and below.

Table1: Galloping Regions Grading Criterion by Using Grey Fixed-weight Clustering Method

	Light Galloping Region (k=1)	Medium Galloping Region (k=2)	Heavy Galloping Region (k=3)
Ice thickness on conductors (j_1) (mm)	0-5	20-30	5-20
Wind Speed (j_2) (m/s)	0-4	Above 20	4-20
Angle between perennial wind direction and line (j_3) (°)	0-45	45-65	65-90

The typical form of a whitenization weight function, $f_j^k(\bullet)$ (j is the criterion; k represents the subclass), is shown in Figure 1 (a), where, $x_j^k(1), x_j^k(2), x_j^k(3), x_j^k(4)$ are designated as the turning points. This whitenization weight function can be written as $f_j^k[x_j^k(1), x_j^k(2), x_j^k(3), x_j^k(4)]$. Different forms are obtained if there are no first and second turning points (Figure 1 (b)), or no third and fourth turning points (Figure 1 (c)), or if the second and third turning points coincide (Figure 1 (d)); then $f_j^k(\bullet)$ are referred to as a whitenization weight function of lower measure, upper measure, and middle measure, and are denoted as $f_j^k[-,-,x_j^k(3),x_j^k(4)]$, $f_j^k[x_j^k(1),x_j^k(2),-,-]$, and $f_j^k[x_j^k(1),x_j^k(2),-,x_j^k(4)]$, respectively. (Sifeng Liu, & Yi Lin, 2010)



(a) (b) (c) (d)

Figure 1: Different Types of Whitenization Weight Functions

In this study, the whitenization weight functions, $f_j^k(\bullet)$ (j = 1,2,3; k = 1,2,3), are determined by analyzing data from previous research, as follows:

[1]

$$
\begin{aligned}
&f_1^1[-,-,5,15]; \qquad f_1^2[15,25,-,-]; \qquad f_1^3[5,15,-,25];\\
&f_2^1[-,-,4,12]; \qquad f_2^2[12,20,-,-]; \qquad f_2^3[4,12,-,20];\\
&f_3^1[-,-,45,55]; \qquad f_3^2[45,55,-,65]; \qquad f_3^3[55,65,-,-];
\end{aligned}
$$

and the values of $f_j^k(\bullet)$, (j = 1,2,3; k = 1,2,3), can be obtained through the following equations,

[2]

$$
f_1^1(x)=\begin{cases}1 & 0\le x\le 5\\ -(x-15)/10 & 5<x\le 15\end{cases}; \qquad f_2^1(x)=\begin{cases}1 & 0\le x\le 4\\ -(x-12)/8 & 4<x\le 12\end{cases};
$$

$$
f_1^2(x)=\begin{cases}(x-15)/10 & 15<x\le 25\\ 1 & 25<x\end{cases}; \qquad f_2^2(x)=\begin{cases}(x-12)/8 & 12<x\le 20\\ 1 & 20<x\end{cases};
$$

$$
f_1^3(x)=\begin{cases}(x-15)/10 & 5<x\le 15\\ -(x-25)/10 & 15<x\le 25\end{cases}; \qquad f_2^3(x)=\begin{cases}(x-4)/8 & 4<x\le 12\\ -(x-20)/8 & 12<x\le 20\end{cases};
$$

$$f_3^1(x)=\begin{cases}1 & 0\le x\le 45\\ -(x-55)/10 & 45<x\le 55\end{cases};$$

$$f_3^2(x)=\begin{cases}(x-45)/10 & 45<x\le 55\\ -(x-65)/10 & 55<x\le 65\end{cases};$$

$$f_3^3(x)=\begin{cases}(x-55)/10 & 55<x\le 65\\ 1 & 65<x\end{cases};$$

2) Calculate the clustering weights of the three galloping indices.

A fuzzy consistent matrix is used in determining the clustering weight values of the galloping indices, to avoid assigning these values directly by subjective experience (Zhixin Tang, 2010). The researchers or line engineers need to set the priorities and importance order of the indices, and then, a fuzzy preferential relation matrix, B, is obtained:

[3] $\mathrm{B}=\left(\mathrm{b}_{\mathrm{ij}}\right)_{m\times m}$

Where, B is the fuzzy precedence relation matrix. b_{ij} is the precedence relation coefficient of clustering indices j_{i} and j_{j} .when j_{i} is superior to j_{j} , b_{ij} =1; when j_{i} has the same importance as j_{j} , b_{ij} =0.5, and otherwise, b_{ij} =0 . m is the number of the indices， and equals 3 in the paper.

In this study, the importance order is $\mathrm{j}_1<\mathrm{j}_2<\mathrm{j}_3$. Then, the fuzzy consistent matrix, R, is given in [4]

[4] $\mathrm{R}=\left(\mathrm{r}_{\mathrm{ij}}\right)_{m\times m}=\left[\left[\sum_{\mathrm{k=1}}^{\mathrm{m}}\mathrm{b}_{\mathrm{ik}}-\sum_{\mathrm{k=1}}^{\mathrm{m}}\mathrm{b}_{\mathrm{jk}}\right]/2\mathrm{m}+0.5\right]_{m\times m}$.

A square root method is employed to compute the clustering weight values of these indices,

[5] $\eta_{\mathrm{j}}=\overline{\eta_{\mathrm{j}}}/\sum_{\mathrm{k=1}}^{\mathrm{m}}\overline{\eta_{\mathrm{k}}}\qquad \overline{\eta_{\mathrm{j}}}=\left(\prod_{\mathrm{i=1}}^{\mathrm{m}}\mathrm{r}_{\mathrm{ij}}\right)^{1/\mathrm{m}}$

Where η_{j} is the weight of clustering index j, $\overline{\eta_{\mathrm{j}}}$ is the initial value of η_{j} .

Finally, the weights obtained are η_1 = 0.211 for ice thickness, η_2 = 0.335 for wind velocity, and η_3 = 0.454 for the angle between wind direction and the line.

3) Compute the Grey fixed-weight coefficients

[6] $\sigma_i^k=\sum_{j=1}^{m}f_j^k(x_{ij})\cdot\eta_j$, (i=1,2,3; k=1,2,3)

Where σ_i^k is the weight clustering coefficient for object i to belong to the kth grey class; whitenization weight function $f_j^k(x_{ij})$ is obtained in Equation 1 and η_j is the weight of clustering obtained in Equation 5; and x_{ij} is the observed data value of object i with respect to criterion j.

(4) Determine the Grey clustering results. If $\max\limits_{1\le k\le s}\{\sigma_i^k\}=\sigma_i^{k^*}$, the region i can be graded to the k*th galloping subclass.

Step 3 Amend the Grey clustering results using the terrain factors and line configuration data.

Studies have shown that lines with certain configurations, for example with bundled conductors, are at a higher risk of galloping than those using single conductors (Q. Zhang et al., 2000). Besides, galloping is more likely to occur in areas with particular topographic features (Yinglong Guo et al., 2003). Long spans of bundled conductors in flat terrain, which are prone to galloping, may have been graded into the light galloping region using the Grey clustering method, while it would be wise to increase their galloping region risk (to medium galloping region).The regions with one or two galloping incidents records during the past 10 years can be dealt with in the same way.

Step 4 Continuously improve the regional mapping as more information becomes available.

More meteorological data, topography information and field incidents records are needed to refine the ice-related regions map, especially for regions with micro-meteorological and micro-topographical conditions. So, a sustained effort in data collecting is necessary, and the map should be revised every several years.

3 Case Study

A 220-kV line section example is presented as a case-study to illustrate the proposed method and show its effectiveness.

This line section is from the gantry to the first angle tower (double circuit with double-bundled conductors), located in the 220-kV Haidong substation, in China’s Yunnan province.

This station is located on a low-lying platform between mountains; there is a lake nearby, which makes this region a typical micro-topographical area, prone to strong laminar winds, and the angle of attack of the perennial wind direction and the line is about 90°, as shown in Figure 2.

Two wind-related faults were observed in this section, in October 2010 and in January 2011, shortly after the line was put into operation in September 2010. Another possible explanation for the faults is that there is a change of the conductor arrangements from horizontal at the gantry to vertical at the angle tower, which results in a reduction of phase-to-phase clearances towards the middle part of the span.

Figure 2: 220-kV Haidong Transformer Station

The data of the October 2010 incident was provided by the local power bureau. The incident conditions were: no ice accumulation, wind speed of 17 m/s, and the angle of wind direction and line about 90°. The Grey clustering method is used to determine the galloping region grading result for this section.

Firstly, the whitenization weight functions are defined as,

$$f_1^1(0)=1;\qquad f_1^2(0)=0;\qquad f_1^3(0)=0;$$

[7] $f_2^1(17)=0;\qquad f_2^2(17)=0.625;\qquad f_2^3(17)=0.375;$

$$f_3^1(90)=0;\qquad f_3^2(90)=0;\qquad f_3^3(90)=1;$$

Then, the Grey clustering coefficients are calculated by using equation [6], and $\sigma_1^1=0.211$, $\sigma_1^2=0.209$, $\sigma_1^3=0.580$, i.e. σ_1^3 is the maximum clustering coefficient for this region. So, this region should be defined as heavy galloping region.

According to the historical incidents records, this region should be graded as heavy galloping since two faults were observed within a half year. This shows the results from the Grey clustering method are consistent with the results based on the field incidents records.

A preliminary ice-related disaster regional map of China’s Yunnan province is presented in Figure 3, based on the proposed method. The map is incomplete and needs to be refined with more data. The band regions (line corridors) on the map are typically related to some incidents records. The fragmentary regions (in blue, for ice-coated regions) are correlated to hilly terrain and the presence of mountains.

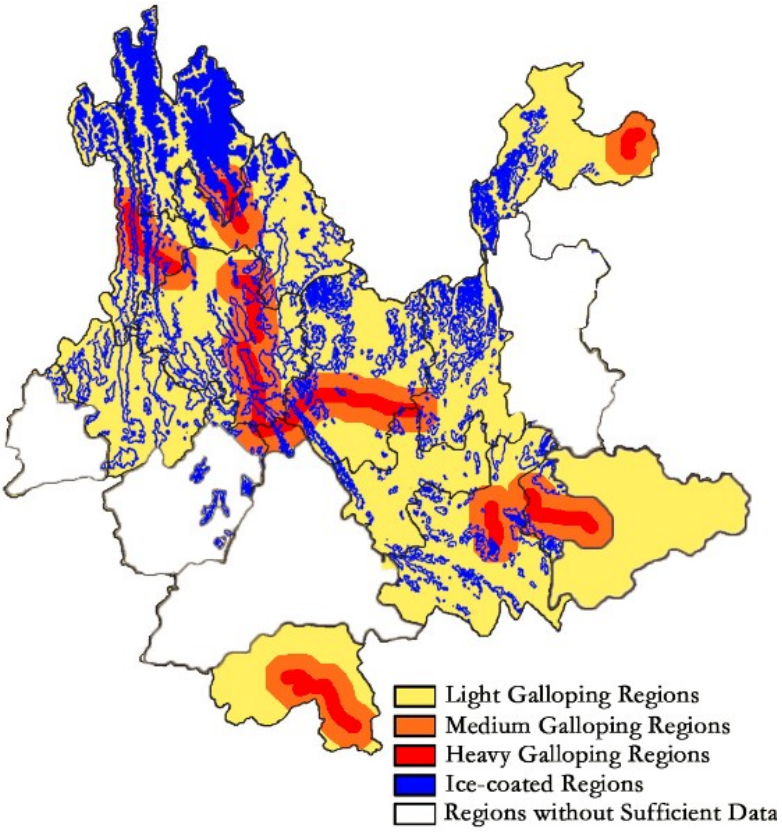


Figure 3: Ice-related Disasters Regional Map of China's Yunnan Province

4 Conclusions

A new and integrated ice-related disasters regional mapping method is proposed to offer the electric power industry a helpful tool for disaster mitigation. This kind of map is an improvement over traditional icing maps or galloping maps because it combines the information on the main types of disasters caused by icing (galloping, ice-shedding, and overloads). Grey clustering analysis of the main meteorological factors and the use of historical line incident records provide a first good quantitative solution for the mapping, while the use of terrain factors and line configuration data allows for amending the calculated results. The combination of the two provides a good balance between the necessity of quantifying the mapping indicators and dealing with insufficient data. Further studies should address the quantitative relations of terrain factors and line configuration to galloping, as including them into Grey clustering would be a significant improvement. Also, more effort should be put on meteorological data collection to get more refined and practical regional mapping results.

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