Risk assessment framework of geomagnetic storm disaster in long-distance UHV transmission system

Jiang Lin, WU Weili
YiLi Normal University, YiNing XinJiang,835000
wwllxm@163.com

Abstract. Based on the reference geomagnetic field waveform issued by NERC, a fault assessment framework of geomagnetic storm disaster in 750 kV UHV transmission system in China is established. Six factors are considered: geomagnetic latitude, earth conductivity, transformer GIC reactive response, transformer GIC thermal effect, geomagnetic field waveform and wide area geomagnetic storm effect. The research results can provide useful reference for the vulnerability assessment of geomagnetic storms in power system.

1. Introduction
The geomagnetic disturbance comes from the energy released by solar activity. The induced geoelectric field, as the external power source, has caused the damage of the power transformer and the regional blackout accident when it is driven to generate the geomagnetic induction current (GIC) in the power system. The larger the amplitude of the geoelectric field, the greater the GIC is generated by the drive, and the greater the harm to the power system will be. In addition, the study also shows that long-distance and high-voltage power systems are more vulnerable to geomagnetic storms. Therefore, it is necessary to assess the risk of geomagnetic storms in China's cross regional UHV power systems.

Geomagnetic storm disaster is defined as a low probability and high risk event [1], and a large number of countries and regions also pay attention to geomagnetic observation and vigorously carry out [2]. However, the factors those determine the amplitude of induced geoelectric field are not only the geomagnetic disturbance, but also the geoelectric conductivity. However, the progress of this part of work is limited, and the grid data acquisition of geoelectric conductivity is still difficult For example, although we have obtained the large-scale geoelectric conductivity [3], it still cannot meet the needs of geoelectric field calculation. In order to solve the accuracy problem of the geoelectric conductivity model, many literatures often use the conductivity data of the same type of geoelectric component area or plate to replace [4,5]. However, with the deepening of the research on geomagnetic storm disturbance, NERC proposed the related work of studying standard geomagnetic disturbance events [6], defined the geomagnetic field waveform standard, and provided the idea of studying geomagnetic storm fault in power system.

The 750 kV UHV transmission system in China spans thousands of kilometers and adopts the autotransformer, which is easy to be attacked by the geomagnetic storm. In order to avoid the system fault caused by the geomagnetic storm disturbance, it is necessary to estimate the risk of geomagnetic storm disturbance in advance. In view of this, taking the reference geomagnetic disturbance proposed by NERC as the premise, six factors influencing the fault risk are combined to form the risk assessment framework of long-distance UHV transmission system geomagnetic fault, which is expected to provide
useful reference for the defense and early warning of transmission system security risks brought by extreme weather in China.

2. GMD Model
The peak geoelectric field depends on the geomagnetic field waveshape and the local earth conductivity.

2.1. Benchmark GMD waveform
The benchmark GMD event is defined by NERC for geomagnetic latitude of 60° and it must be scaled to account for regional differences based on geomagnetic latitude. The scaling factor is defined as

\[ \alpha = 0.001 \cdot e^{0.115 \cdot L} \]  

where \( L \) is the geomagnetic latitude in degrees, and \( 0.1 \leq \alpha \leq 1.0 \). This scaling factor \( \alpha \) has been obtained from a large number of global geomagnetic field observations of all major geomagnetic storms since the late 1980s and can be approximated with the empirical expression as Table 1.

| Geomagnetic Latitude(°) | Scaling Factor(\( \alpha \)) |
|--------------------------|-----------------------------|
| \( \leq 40 \)           | 0.10                        |
| 45                       | 0.2                         |
| 50                       | 0.3                         |
| 54                       | 0.5                         |
| 56                       | 0.6                         |
| 57                       | 0.7                         |
| 58                       | 0.8                         |
| 59                       | 0.9                         |
| \( \geq 60 \)           | 1.0                         |

2.2. Geoelectric field model
The reference geoelectric field amplitude was determined through statistical analysis using the plane wave method. The statistical analysis resulted in a conservative peak geoelectric field amplitude of approximately 8 V/km. The frequency of occurrence of this benchmark GMD event is estimated to be approximately 1 in 100 years.

The regional geoelectric field peak amplitude, \( E_{\text{peak}} \), to be used in calculating GIC, can be calculated by 8 V/km using the following relationship

\[ E_{\text{peak}} = 8 \times \alpha \times \beta \text{(V/km)} \]  

The intensity of a GMD event depends on geographical considerations such as geomagnetic latitude and local earth conductivity. Scaling factors \( \alpha \) for geomagnetic latitude take into consideration that the intensity of a GMD event varies according to latitude-based geographical location. Scaling factors \( \beta \) for earth conductivity take into account that the induced geoelectric field depends on earth conductivity, and that different parts of the continent have different earth conductivity and deep earth structure.

3. Framework of fault risk assessment of geomagnetic storm disaster

3.1. GIC thermal effect
The solar energy will change the global surface geomagnetic field, but the impact of GMD on the power system can be considered separately within several hundred kilometers. The induced waveform of geoelectric field includes two aspects: instantaneous amplitude and duration of geoelectric field, which drives the amplitude and timing waveform of GIC. In terms of time, there are two aspects of GIC’s effect on the transformer. Because both the thermal time constant and the peak time of GIC are within a few minutes, whether the winding heating and thermal effect are instantaneous depends on the thermal time constant of the transformer. The thermal effect of structural component GIC may appear in the power transformer, which can be defined as follows:
In the formula, $T_{GIC\_effect}$ is the representative temperature rise of transformer under the action of GIC; $\gamma_i$ is the temperature effect coefficient of transformer caused by different GIC amplitudes, it needs to be obtained through experiments, $GIC_{t_i}$ is the amplitude of section I of M amplitude sections, and $\Delta t_i$ is the duration of section I GIC amplitude.

In addition to the thermal effect of GIC, GIC will also cause the reactive power loss effect of the transformer. $K$ factor algorithm can be used and no longer be given details.

### 3.2. Risk assessment framework of geomagnetic storm in power system

The framework of fault risk assessment under GMD disturbance of long-distance transmission system is constructed as follows:

![Risk assessment framework of long-distance EHV transmission system](image)

**Fig. 1** Risk assessment framework of long-distance EHV transmission system

### 4. Case analysis

There are 21 substations in a planned 750kV EHV transmission system in China. The geographical wiring is shown in Figure 2. In the figure, each substation has two autotransformers running in parallel, including the high, medium and low voltage sides of each transformer, with a total of 30 transformer bus nodes.

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According to the factory parameters of the autotransformer in the system, the neutral point of the autotransformer is continuously connected with a 20A GIC, and the temperature rise curve of the metal part of the transformer is shown in Figure 2.

Figure 4 shows the temperature rise effect of the transformer after different GIC actions last for 20 minutes.

Apply standard GMD disturbance waveform to 750kV system as shown in Figure 1, as shown in Figure 5.
Considering the uncertainty of GMD direction, after traversing all directions, the result of maximum reactive power loss in corresponding direction of each transformer is shown in Figure 6.

According to the GIC of each substation, assuming the ambient temperature is 20 °C, the heating effect of transformer is calculated. The 750kV transformer in the system comes from the same transformer manufacturer, ignoring the parameter error in the production process. The calculation results are as follows.
Based on the above analysis, it can be seen that during the disturbance of geomagnetic storm, the reactive power loss and the temperature rise of transformer winding generated by bus nodes 11, 12, 13 and 30 in 750kV system are very obvious, and the corresponding substations are 8, 10, 12 and 21, which shows that these four substations are very sensitive to GMD, so they need to pay more attention to the prevention of geomagnetic storm.

5. Conclusion
Aiming at the long-distance EHV transmission system, a power system fault risk framework based on standard GMD is proposed. By analyzing a 750kV Transmission System, GMD simulation and fault risk analysis are carried out. According to the simulation results of reactive power loss and temperature rise of transformer, the GMD sensitive station is determined. The research method can provide reference for early warning and prevention of GMD risk.

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