A Safety Evaluation Method for a Power System Influenced by a Geomagnetic Storm

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This work was supported in part by the National Natural Science Foundation of China under Grant 51577060, in part by the National High Technology Research and Development of China (863 Program) under Grant 2012AA121005, and in part by the International Science and Technology Cooperation Program under Grant 2010DFA64680.

ABSTRACT Geomagnetic storm disasters have a significant impact on the safe and stable operation of power systems. Serious geomagnetic storm disasters can lead to cascading accidents in power systems, up to and including voltage collapse accidents. Therefore, it is necessary to analyze and evaluate the operational risks of power systems under magnetic storms. Based on the mechanisms of the cascading failures caused by geomagnetic storms, the technical requirements for the power system safety assessment of geomagnetic storm disasters are analyzed, and an evaluation method is proposed. The key problems and evaluation systems to be solved are also discussed in this paper. A simulation method for the interactions between geomagnetically induced currents (GIC) and power systems is proposed, and a simulation is carried out based on MATLAB and the PowerWorld simulation software. The simulation results show that this method can accurately reflect the impact of faults on power systems and their cascading failures. The present research results provide a reference for further quantifying and preventing the power grid risks caused by magnetic storms.

INDEX TERMS Geomagnetic disturbance (GMD), geomagnetically induced currents (GIC), risk assessment, hybrid model.

I. INTRODUCTION

Regarding the consequences of the strong solar storm, it is expected that the function of satellites, energetic sources, communication and navigation systems will be disrupted, secondary effects will occur in transport, safety and emergency systems, telecommunications and other wireless and electronic devices [1]. Geomagnetic disturbances (GMD) are stronger near terrestrial auroral zones and cannot be ignored due to their impacts on power system operational risk [2], [3]. In high latitude areas, there have been blackouts caused by geomagnetic storm disasters. In March 13, 1989, the Quebec power grid in Canada was seriously affected by the strong magnetic storm (the maximum Dst of geomagnetic storms was -589 nT), resulting in the paralysis of the entire power grid, resulting in the power failure time of more than 9 hours for more than 6 million residents, and the direct economic losses amounted to tens of millions of dollars, resulting in heavy losses. During the twenty-third peak period of the solar cycle, there were several geomagnetic storm events. Many of the power grids around the world were affected by magnetic storms. For example, the Malmo in northern Sweden suffered a blackout on October 30, 2003, when the maximum value of geomagnetic storm Dst was -383 nT, making the peak value of GIC in a transformer 330A, resulting in a transmission line tripping and then large power outages. In Jiangsu, Zhejiang, Guangdong, and other areas of China, a large number of geomagnetic storm disasters have attacked the power grid, prompting reflection on the safety and defense system of the power grid [4], [23], [27], [28]. The study in [5] discusses the new challenges faced by the blackout defense system and possible solutions for extreme external disasters; the work in [5] suggests that nonelectrical information, such as meteorological and geological information, should be introduced into the defense system to increase the functionality of the blackout defense system; the study in [6] proposes a comprehensive evaluation method for the impact of meteorological events on the power grid. It is suggested in [7] that the response characteristics and disaster causing mechanisms of power grids and their equipment under magnetic storm disasters cycle, there were several geomagnetic storm events. Many of the power grids around the world were affected by magnetic storms. For example, the Malmo in northern Sweden suffered a blackout on October 30, 2003, when the maximum value of geomagnetic storm Dst was -383 nT, making the peak value of GIC in a transformer 330A, resulting in a transmission line tripping and then large power outages. In Jiangsu, Zhejiang, Guangdong, and other areas of China, a large number of geomagnetic storm disasters have attacked the power grid, prompting reflection on the safety and defense system of the power grid [4], [23], [27], [28]. The study in [5] discusses the new challenges faced by the blackout defense system and possible solutions for extreme external disasters; the work in [5] suggests that nonelectrical information, such as meteorological and geological information, should be introduced into the defense system to increase the functionality of the blackout defense system; the study in [6] proposes a comprehensive evaluation method for the impact of meteorological events on the power grid. It is suggested in [7] that the response characteristics and disaster causing mechanisms of power grids and their equipment under magnetic storm disasters
are related to space weather information and that the power outage prevention system scheme for extreme external natural disasters, which copes with space weather and meteorological disasters, should be expanded, while the impact of magnetic storms on the safety and stable operations of large-scale power grids should be analyzed.

In [8], the geomagnetic induced current (GIC) was used as an index to measure the level of magnetic storm disasters in the power grid, while the risk that magnetic storms may affect the power grid is divided into “low”, “medium”, “high”, and “extreme” to reflect the impact of magnetic storms on the system to a certain extent. The research in [9] comprehensively analyzes the response characteristics of a large power grid in the United States under the influence of strong magnetic storms from a systematic perspective and notes that magnetic storm disasters constitute a great threat to the safe operations of the power grid. In [10], measures and methods to prevent magnetic storm disasters in the U.S. power grid are proposed and simulated. In 2012, the North American Electric Reliability Corporation (NERC) conducted a special assessment on the impact of magnetic storm disasters on power system reliability, noting that the assessment model for grid magnetic storm disasters is not perfect. In [11], [12], the influence of geomagnetic induction currents on power systems was preliminarily evaluated by combining the information for geomagnetic storm disturbances with the parameters of the power system, but no quantitative index was proposed to measure the safety of the power grid [11]. The reference [13] evaluated the GIC level in the Swiss power grid through GIC and power flow calculation.

A magnetic storm not only has the “small probability, large scope” characteristics of ice disasters and other meteorological disasters, such as freezing rain; it also presents a high risk of producing power system cluster damage and a fault chain. This makes it necessary to improve existing power system security assessments and early warning and power failure prevention systems, enhance our understanding of space weather information, and ensure that power regulation personnel create a timely prevention and control plan, evaluate power system failures and disaster processes under the influence of magnetic storm, and provide feasible early warning information and prevention plans [14]. To sum up, in the past research, there is no risk assessment model considering magnetic storm disturbance with quantitative evaluation indexes.

Combined with historical magnetic storm events, this paper will discuss the mechanisms of magnetic storm disasters, analyze the technical requirements of power system security assessment under magnetic storm disasters, and design a risk assessment framework that considers magnetic storm disturbances. This paper focuses on the key problems to be solved, establishes an integrated hybrid model of magnetic storms and power systems, achieves a hybrid simulation of magnetic storm disturbances and electrical responses (with the help of MATLAB and the PowerWorld simulator). In order to quantitatively analyze the influence of magnetic storm on power system, this paper proposes GIC reactive power loss disturbance degree index and GIC reactive power loss disturbance entropy as risk quantitative evaluation index. Define the degree index of magnetic storm disturbances to reflect the transmission, development process, and disturbance results of electrical faults under the magnetic storm disturbances. Finally, the GIC benchmark model is used as an example to verify the effectiveness of the evaluation methods and indicators and to provide a basis for the evaluation of the security risks of the power system in regions vulnerable to magnetic storms.

II. THE FAILURE MECHANISM AND RISK ASSESSMENT REQUIREMENTS OF MAGNETIC STORM INTERFENCES IN THE POWER GRID

A. FAILURE MECHANISMS OF MAGNETIC STORMS IN THE POWER GRID

According to Faraday’s law of electromagnetic induction, the Earth’s electric field is induced on the Earth’s surface. When there are multiple grounding points in the power system, due to the effect of the Earth’s electric field, the potential difference between different grounding points will drive GIC in the power system, which will flow through the neutral point and winding areas of the power transformer, leading to saturation of the half wave of the transformer core, resulting in a transformation of voltage. At the same time as damaging effects like increases in temperature and vibrations, the reactive power demands and active power loss of the system increase, resulting in an overload of the reactive power compensation device. Transformer excitation saturation will also produce rich harmonics, resulting in the misoperation of the protection device. In that case, a load transfer will increase the load pressure of the other lines and increase the failure probability [2], [25], [26].

Generally speaking, when the power system architecture, equipment, and parameters are fixed, the GIC level has a direct relationship with the intensity of the geomagnetic disturbance: The stronger the change of the geomagnetic field, the larger the geoelectric field that will be induced in the Earth. As an external source, the amplitude of the geoelectric field has a linear relationship with the GIC of the power system. Therefore, the stronger the geomagnetic disturbance, the larger the amplitude of the GIC in a specific grid.

The research shows that the reactive power loss of a power transformer caused by the winding flow of the GIC increases monotonically with the amplitude of the GIC, so the intensity of the geomagnetic disturbance will also affect the GIC’s reactive power loss of a power system [8], [11].

Taking the geomagnetic storm of 29–31 October 2003 as an example, the data of seven geomagnetic stations (data source: http://www.intermagnet.org), including IQA (73°N), ABK (65°N), NUR (57°N), OTT (55°N), MMB (35°N), CTA (27°N), and HER (32.5°S) were chosen, and the data for geoelectric conductivity were taken from Quebec, Canada. The intensity of the geomagnetic disturbance was characterized.
| Geomagnetic station | $|B_{max}|$ (NT) | $|E_{max}|$ (mV/km) | GIC mean value/A | System reactive power loss/Mvar |
|---------------------|-----------------|------------------|-----------------|----------------------|
| JQA                 | 5 000           | 5 000            | 199.790         | 1 123.4              |
| ABK                 | 3 798           | 2 890            | 115.480         | 649.4                |
| NUR                 | 2 890           | 2 690            | 107.490         | 604.4                |
| OTT                 | 1 000           | 2 500            | 99.897          | 561.7                |
| MMB                 | 489             | 250              | 9.990           | 56.2                 |
| CTA                 | 398             | 249              | 9.550           | 55.9                 |
| HER                 | 380             | 249              | 9.550           | 55.9                 |

Table 1 shows that the stronger the magnetic storm disturbance, the greater the GIC and reactive loss generated in a specific power system, and thus the greater the possibility of an overload of the reactive power supply or its compensation equipment. When the reactive power of the system is seriously insufficient, in order to protect the reactive power supply and other power equipment, the relay protection action cuts off the reactive compensation device, the power supply, and a large number of loads. When the system is still unable to be balanced, the voltage collapses, causing a large-scale power outage. The generation, development, and catastrophic process of a grid fault under the influence of a magnetic storm are shown in Figure 1.

It can be seen that the GIC caused by the magnetic storm acts as an inducement to power grid disaster accidents, which causes operational system risks in two ways: (a) damage to the system equipment, especially the power transformers; (b) a large number of reactive power defects, resulting in voltage instability or even system collapse.

**B. RISK ASSESSMENT DEMANDS OF A POWER GRID UNDER A MAGNETIC STORM DISTURBANCE**

A magnetic storm disaster is a natural event with low probability, high risk, and wide range; the existing power grid fortification standard is far lower than the necessary degree of resistance to a magnetic storm disaster. If all power grids were to greatly improve their anti-magnetic-storm capabilities, the economic cost would be too high and would be difficult to achieve. More importantly, the occurrence law of a magnetic storm remains uncertain, and there is also a risk of equipment vacancy. Therefore, in addition to using different design standards according to the differences in geographical location and the Earth’s conductivity, it is also necessary to improve the antimagnetic storm standard of transformers according to the different importance levels of the transformers in the system; this is also one of the measures recommended by NERC to prevent the grid from suffering magnetic storm disasters [15].

However, in terms of economy and technology, it is not realistic to rely on planning and investment in a primary system to resist magnetic storm disasters. Therefore, it is necessary to start from a secondary system, improve existing theoretical safety assessment systems and power failure prevention systems, integrate system scheduling and space weather early warning information, establish a dynamic response model for a power grid under the interference of magnetic storms, and evaluate the state of its safety. This would be an effective method to provide early warning information and a practical scheduling scheme.

To measure the safety and stability of a power system under a magnetic storm disaster, it is necessary to simulate the formation process of electrical faults in a magnetic storm scene, analyze the safety and stability level of each physical quantity in the transient or transition process of the system after the fault, establish a unified model of geomagnetic disturbance information and electrical dynamics, implement an interactive simulation between them, and build a measurement of the threat of magnetic storm events based on the simulation results. The index and evaluation system for the power grid security degree, as well as the prevention and
control strategies, are formulated to alleviate magnetic storm disasters and reduce power outage losses.

The following key problems need to be solved when geomagnetic storm disturbances and the dynamic responses of the system are considered under a unified theoretical framework.

1) GIC MODEL OF A POWER SYSTEM

The geomagnetic induced current (GIC) is the result of the interactions between a magnetic storm and the power system. The magnitude of GIC is related to the intensity of the magnetic storm, its geoelectric structure, and the parameters and structures of the power system and its equipment. Two conditions are needed to calculate GIC: a magnetic-storm-induced Earth field and grid data. In [14], the complex image method was applied to the calculation of the Earth’s electric field. The work in [17] was the first to establish a fast calculation model for an induced Earth electric field by using the plane wave theory and the element current system. In [18], a GIC calculation model of the power system was established by using plane wave theory. The authors in [19] noted that neglecting the function of a line protection device in the calculation of GIC can produce large errors. At present, the accuracy of geomagnetic observation information is high and can make full use of this favorable condition to establish a grid GIC model combined with geomagnetic measurement information, thereby providing an important basis for accurately measuring and evaluating magnetic storm grid disasters.

According to the information on the Earth’s electric field, the Earth’s potential difference at both ends of the line can be approximately calculated by formula (1):

\[ U_i = E_{Ni}L_{Ni} + E_{EI}L_{EI} \]  

(1)

where \( E_{Ni} \) and \( E_{EI} \) are the north and east geoelectric field amplitudes (V/km, \( L_{Ni} \), and \( L_{EI} \), respectively) for the transmission lines in the north and east of the projection (km). The equivalent effect of the geoelectric field is shown in Figure 2.

In Figure 2, \( R_1 \) and \( R_2 \) are DC resistances of line 1 and line 2 respectively; \( R_{01} \), \( R_{02} \), and \( R_{03} \) are DC resistances of substation 1, 2, and 3 respectively; \( I_{GIC12} \) and \( I_{GIC23} \) are GIC flowing through transmission lines 1-2 and 2-3; \( I_{GICi} \) represent GIC flowing through substation; \( U_i (i \in 1,2) \) can be calculated according to formula (1). After equivalent, the GIC can be calculated by the DC model.

2) SIMULATION OF A TRANSFORMER FAULT UNDER THE ACTION OF GIC

The analysis of the magnetic storm disaster in the power grid shows that the power transformer is the primary object of the magnetic storm disaster. GIC flowing in the transformers make excitation saturation, temperature rise and vibration of transformer abnormal. Meanwhile, the reactive power loss increases sharply. The harmonic effect and the influence of load capacity should be simulated with a transformer model, which is also necessary to analyze the risk of magnetic storm disasters in the power grid [20], [21]. Transformer reactive power loss model is shown in formula (2) and (3).

\[ Q_{GIC} = U_k K_{GIC} \]  

(2)

\[ U_k = \frac{UU_e}{500} \]  

(3)

\( K \in [1\sim1.18, 0.33\sim0.5, 0.29, 0.66\sim0.7] \) Mvar/A, is the reactive coefficient obtained by experiment, which corresponds to 500 kV single-phase transformer, three phase shell transformer, three phase three pole core transformer and three phase five pole core transformer respectively. \( U_k \) is the voltage coefficient of the transformer, \( U \) is the actual operation voltage of the transformer, and \( U_e \) is the rated voltage of the transformer.

3) MAGNETIC STORM–ELECTRICAL HYBRID SIMULATION

The excitation saturation of the power transformer under the action of GIC, the establishment of a model to describe the distribution and satisfaction of its increased reactive power demands in the system, and the model of the effects of harmonics on the protection device are involved in the process of combining magnetic storm information with the power system and are also the keys to quantitatively evaluating the system’s operation risk. At present, studies on the hybrid simulation model that integrate information on magnetic storms with the parameters of the power system are rare. Most power system simulation software does not support the injection of disturbance information for a magnetic storm, so it is necessary to establish a hybrid model featuring magnetic storms and an electric system by combining the GIC and the transformer—as well as the reactive power and the harmonic wave it generates—within the electric dynamic model, to reproduce the successive failure process of the power system caused by magnetic storms and the GIC and thus lay the foundation for proper safety assessment of the power grid. Large-scale transmission systems are widely distributed, and their operational safety is very high, so it is impossible to carry out a magnetic storm disturbance test in the actual power grid. Therefore, it is necessary to show the detailed evolutionary process of GIC generation, transformer excitation saturation, and the grid faults caused by the GIC simulation. To develop all the programs, we could readily
design a good general framework, but the overall workload is too large, making timely development difficult. Instead, we relied upon the help of an existing software platform and customization of the required module program. At present, the software used to define GIC calculation modules on a platform is the PowerWorld simulator (hereafter referred to as PowerWorld) developed by the Department of electrical and computer engineering of the University of Illinois. The induced Earth field of a magnetic storm can be calculated by the MATLAB software, and their data interface modules can be defined, allowing a hybrid simulation of magnetic storm disturbances and electrical dynamics to be realized by MATLAB and PowerWorld. PowerWorld is a highly visual type of powerful system simulation software. It is famous for providing powerful multi-functional modules, offering three-dimensional visualization, and having a friendly user interface. It has a transient simulation function and provides macro command programming, customizable application program interface functions, and allows user programming to achieve any complex custom function. The combination of MATLAB and PowerWorld can meet the requirements of a hybrid simulation of magnetic storm disturbances and electrical systems [22].

4) QUANTITATIVE ASSESSMENT AND CONTROL DECISION FOR POWER GRID SECURITY UNDER A MAGNETIC STORM DISASTER

Different intensities of magnetic storm disasters will cause different degrees of physical damage and security and stability threat to the power grid. At present, there is no perfect method or model to quantify the influential degree of a power grid under a given magnetic storm, making it difficult to develop a prevention and emergency control scheme. Therefore, it is necessary to quantify the risk of power grid operations under the disturbance of a magnetic storm, determine the high-risk areas of a system magnetic storm disaster, and focus on the installation of preventive measures and the development of an emergency scheduling scheme to minimize the losses caused by the magnetic storm. The influence degree of the magnetic storm on the power system can be measured from two perspectives: the degree of magnetic storm disturbances and their influence on the power system security. The degree index of magnetic storm disturbances should reflect the level and distribution of the reactive power disturbances of the power system caused by the magnetic storm; the degree index of the influence of the magnetic storm on the security of the power system should reflect the information on the voltage and network loss of the power system caused by the magnetic storm disturbance. To quantify the impact of magnetic storms on power systems, the following risk indicators are defined.

- Disturbance index of GIC reactive loss

\[ D_Q = \frac{\sum_{i=1}^{T} Q_{Tlossi} + \sum_{j=1}^{L} Q_{Llossj}}{Q_S} \]  

(4)

\[ T \] and \( L \) are the number of transformers and lines respectively; \( Q_{Tlossi} \) and \( Q_{Llossj} \) are the reactive loss of transformers and lines due to GIC respectively; \( Q_S \) is the sum of the reactive power of all reactive power sources. \( D_Q \) is the index representing that the magnetic storms disturb the reactive power of the power system. The larger the value is, the greater the influence of the magnetic storm on the reactive power of the power system is.

- Disturbance entropy of GIC reactive loss

\[ \mu_t = |Q_{GICt} / Q_{GICmax}| \quad (t = 1, 2, \ldots, T) \]  

(5)

\( \mu_t \) is the reactive loss ratio, \( Q_{GICt} \) is GIC reactive power loss of transformer \( t \), \( Q_{GICmax} \) is the maximum GIC reactive loss generated in transformers. Given \( n \) continuous intervals, \([0, u], [u, 2u], \ldots, [(n - 1)u, nu]\), the disturbance entropy of GIC can be defined as follows,

\[ H_{QGIC} = -C \sum_{k=1}^{n} \frac{l(k)}{T} \log \frac{l(k)}{T} \]  

(6)

\( l(k) \) is the number of transformers in the \( k \) interval, \( C \) is constant. The minimum value of \( H_{QGIC} \) is 0 and the maximum value is \( Cl_{gn} \). The larger the value of \( H_{QGIC} \) is, the more uneven the distribution of reactive power disturbance is. A few transformers are likely to have large reactive power loss, even if \( D_Q \) is small, the voltage of individual nodes may be unstable. The smaller the value of \( H_{QGIC} \) is, the smaller the degree of reactive power loss disturbance of each transformer is, and when \( D_Q \) is large, it is easy to cause a cluster disturbance of reactive power loss.

In order to evaluate the risks to the safe operation of the power system produced by magnetic storm disasters, it is necessary to combine comprehensive information, such as the intensity of the magnetic storm, the Earth conditions of the area where the system is located, the structure and parameters of the system's grid structure, and the electrical equipment. In addition, to quantitatively estimate the severity of a disaster caused by a magnetic storm (such as the outage scale or outage probability), a disaster chain model for the magnetic storm power grid must be constructed. A geomagnetic storm induced geoelectric field is the result of the direct action of a geomagnetic storm on the Earth’s surface and also the source of the GIC driving the power system. This field can be used as the key link between the geomagnetic storm and a power grid disaster, whereby forming a complete disaster chain for the geomagnetic storm power grid. On this basis, a risk assessment model for a power system magnetic storm disaster was preliminarily constructed, as shown in Figure 3.

In Figure 3, the geomagnetic storm disaster information module is used to obtain the geomagnetic disturbance intensity, occurrence time, orientation, and other information. There is an interface between the evaluation system and the space weather forecast system used to receive the geomagnetic storm prediction information. At present, China’s space weather warning center has been able to effectively predict magnetic storms. The geotectonic information module collects the geodetic sounding data and constructs an
Earth conductivity model. The geomagnetic storm disaster information module and the geotectonic information module can be replaced by a geoelectric field detection module when conditions permit (i.e., allowing direct measurement of the grounding electric field of the power system), but the existing power grid rarely adds grounding electric field monitoring equipment at the grounding point, so it is still necessary to calculate the grounding electric field.

The power system structure and parameter module provide the system electrical parameters needed to calculate the GIC. The GIC calculation module has two functions: calculating the induced Earth electric field of the magnetic storm and, on this basis, integrating the GIC calculation model of the system. The results are input into the information of the transformer fault simulation module. The first mock exam module of the transformer fault is based on the GIC, transformer structure, parameters, and voltage level and calculates the reactive power loss and harmonic effect of the transformer. The transformer’s load capability is investigated as the input information for the next module.

The hybrid simulation consists of two parts: a magnetic disturbance electrical information conversion module and a conventional time domain simulation module. The magnetic disturbance electrical information conversion module converts the equivalent result of the magnetic storm disturbance, the transformer reactive power loss, and the transformer fault risk into an electrical disturbance and adds them to the system operation simulation, analyzes the electrical information (such as the power flow transfer after a transformer fault, reactive power loss, and the false operation probability of a protection device caused by harmonics), and inputs these electrical data into the conventional power system time domain simulation module. The first mock trial will calculate the dynamic process of the system and input the result to the next module. The risk assessment module comprehensively evaluates the time response of the generator’s reactive power, bus voltage, and other physical quantities and divides the high-risk area and overall safety level of the system. According to the results of the risk assessment, the early warning and emergency plan module optimizes and adjusts the key equipment in the high risk area according to the division results of that high risk area and adds compensation devices to the equipment with serious reactive power shortages in the simulation or adjusts the parameter setting values of the protection devices that have a high probability of misoperation and severe consequences in their disturbance.

### III. PRELIMINARY REALIZATION OF A HYBRID SIMULATION AND RISK ASSESSMENT OF MAGNETIC STORM DISTURBANCES AND ELECTRICITY

Taking the GIC standard test system shown in Figure 4 as an example, the safety risk assessment idea for a power system under a magnetic storm disturbance is illustrated. The voltage level and load parameters of this system have been marked in the figure: Node 1 is the balance node, the Earth’s conductivity for the area is shown in Table 2, the initial power flow and line capacity are shown in Table 3, and the other parameters are provided in the literature [21].

In Table 2, conductivity 1, conductivity 2, and conductivity 3, respectively, represent the Earth’s conductivity at region 1, region 2, and region 3, as shown in Figure 3.

| Thickness/km | Conductivity 1/(S/km) | Thickness/km | Conductivity 2/(S/km) | Thickness/km | Conductivity 3/(S/km) |
|--------------|------------------------|--------------|------------------------|--------------|------------------------|
| 0–25         | 2.500 0                | 0–10         | 0.500 00               | 0–20         | 0.001                  |
| 25–50        | 0.002 1                | 10–25        | 0.002 50               | 20–50        | 0.005                  |
| >100         | 0.002 1                | >50          | 0.000 33               | >50          | 0.020                  |

**FIGURE 3. Power system geomagnetic storm risk assessment model.**

**FIGURE 4. Single-line diagram of the GIC benchmark case.**
TABLE 3. Line and transformer initial operation parameters.

| Starting point | End point | Branch type | Active power/MW | Reactive power/Mvar | Limited capacity/MVA | Percentage of restricted capacity/% |
|---------------|----------|-------------|-----------------|---------------------|----------------------|-------------------------------------|
| 1             | 2        | T           | 779             | 95                  | 1 644.5              | 0.48                                |
| 2             | 3        | L           | 808.4           | 72.4                | 2 000                | 0.41                                |
| 3             | 4        | T           | 197.7           | –11.9               | 2 000                | 0.10                                |
| 3             | 4        | T           | 197.5           | –19.7               | 2 000                | 0.10                                |
| 3             | 4        | T           | 197.7           | –11.9               | 2 000                | 0.10                                |
| 3             | 4        | T           | 197.5           | –19.8               | 2 000                | 0.10                                |
| 4             | 6        | L           | –327.3          | –203.5              | 2 000                | 0.19                                |
| 4             | 5        | L           | –167.8          | –18.4               | 2 000                | 0.08                                |
| 4             | 5        | L           | –167.8          | –106.1              | 2 000                | 0.10                                |
| 5             | 21       | S           | –753.6          | –228.3              | 2 000                | 0.39                                |
| 5             | 6        | L           | –420.8          | –174.2              | 2 000                | 21.6                                |
| 6             | 11       | L           | –229.5          | –26                 | 2 000                | 0.12                                |
| 6             | 8        | T           | –899.1          | –7.8                | 2 000                | 0.45                                |
| 6             | 7        | T           | –899.1          | –7.8                | 2 000                | 0.45                                |
| 11            | 12       | L           | –991.2          | 49.1                | 1 200                | 0.83                                |
| 12            | 14       | T           | –499.8          | 39.8                | 750                  | 0.67                                |
| 12            | 13       | T           | –499.8          | 39.8                | 750                  | 0.67                                |
| 15            | 6        | L           | –485.1          | –212.3              | 2 000                | 0.26                                |
| 15            | 6        | L           | –485.1          | –212.3              | 2 000                | 0.26                                |
| 15            | 4        | L           | 47              | –150.6              | 2 000                | 0.08                                |
| 16            | 20       | L           | –81.8           | –60                 | 2 000                | 0.05                                |
| 16            | 17       | L           | –695            | 24.3                | 2 000                | 0.35                                |
| 16            | 15       | T           | 138.4           | 20.3                | 2 000                | 0.07                                |
| 16            | 15       | T           | 138.4           | 20.3                | 2 000                | 0.07                                |
| 17            | 20       | L           | 454.9           | –7.4                | 2 000                | 0.23                                |
| 17            | 2        | L           | 30.4            | –3                  | 2 000                | 0.02                                |
| 18            | 17       | T           | 600             | 129.7               | 1 644.5              | 0.37                                |
| 19            | 17       | T           | 600             | 129.7               | 1 644.5              | 0.37                                |
| 20            | 5        | T           | 180.9           | 3.1                 | 2 000                | 0.09                                |
| 20            | 5        | T           | 180.9           | 3.1                 | 2 000                | 0.09                                |
| 21            | 11       | L           | –753.6          | –167                | 2 000                | 0.39                                |

In Table 3, L, T, and S represent the line, transformer, and series capacitor, respectively. The verification steps are as follows.

**A. GIC CALCULATION**

The regional geoelectric field is calculated according to the data for 8 November 2004 (data source: http://www.intermagnet.org), as shown in Figure 5.

According to the information of the Earth’s electric field, the potential difference at both ends of the line can be approximately calculated by formula (1). Numerical simulations are carried out with MATLAB software. The calculated GIC are shown in Table 4.

**B. ANALYSIS OF THE TRANSFORMER UNDER THE ACTION OF GIC**

The reactive loss of transformer caused by GIC is obtained from formula (2). The numerical simulations are also carried out with MATLAB software, and the results are shown in Table 4.

The reactive power loss due to GIC also goes through the transformer. The process of excitation saturation, which takes a few seconds or less, is related to the design of the transformer. In addition, the harmonics caused by excitation saturation are related to the GIC level, transformer type, parameters, etc. The analysis method is similar to that of the DC bias caused by DC grounding the electrode current, which is limited to space and will not be described in detail [22].

Due to the short acting time of the magnetic storm (1–2 min), the temperature increase of the transformer has hysteresis characteristics; a short-term magnetic storm will not directly overheat the transformer and cause permanent damage. Therefore, we intend neither to establish an accurate transient model for the temperature increase of a transformer nor to consider a case featuring the permanent damage of a transformer. Only a load capacity model for a transformer under the action of GIC is proposed (Figure 6).

Figure 6 shows that the load capacity of the transformer decreases with an increase of GIC. When GIC > 90 A, the load of the transformer should be reduced to 9.39% of the load before the disturbance. Otherwise, the transformer
faces the risk of permanent failure. According to the benchmark model shown in Figure 4, the node 6 - node 7 is the transformer T6, the node 6 - node 8 is the transformer T7, the node 15 - node 16 are the transformers T5 and T15. It can be seen from Table 4 that the windings of the T6, T7, T5, and T15 transformers exceed over 90 A, indicating a high operational risk.

### C. HYBRID SIMULATION OF MAGNETIC STORM AND ELECTRICITY

Numerical simulation is performed with PowerWorldScript software. Assumptions: ① The duration of the magnetic storm is 2 min, and the intensity and direction of the magnetic storm remains unchanged; ② the system operates normally before the disturbance of the magnetic storm, and the initial state is shown in Table 2; ③ the probability of maloperation of the protection device is 0.03 due to the influence of harmonics, ignoring the influence of harmonics on other equipment; ④ the load capacity of the transformer is affected by GIC, and the load faces constant impedance. The simulation results show that the parallel capacitors connected to nodes 4 and 16 are overloaded, and the voltages of nodes 3, 4, 5, 15, 16, 20, and 21 are out of limit, where the voltages of nodes 4 and 16 are all lower than 0.75 pu.; after the protective device trips, lines 11–12 are overloaded, and the voltages of generator G4 and G5 are all lower than 0.92 pu.; lines 11–12 are tripped, and generators G4 and G5 are all lower than 0.92 pu. After a series of power flow transfers and protection device actions, the system finally experiences voltage collapse.

Figures 7 and 8 show the reactive power curve of the generator output and the process of partial node voltage collapse under the given model. It can be seen in Figure 7 that during the process of the transformer reactive power loss increasing due to the disturbance of the magnetic storm, the reactive power of the generator suddenly increases in an attempt to balance the increased reactive power demand. However, because the reactive power cannot be transmitted over a long distance, the system still operates under a relative...
According to formula (4) to formula (6), take MAGNETIC STORM ON POWER GRID SECURITY attack. The weak link of the power grid under a magnetic storm attack. The nodes involved in successive failures indicate the consequences of power system failures under any magnetic storm. File programming can be used to simulate the processes and greatly. Indeed, combining MATLAB and PowerWorldScript with different intensities, parameters, and structures may vary temper responses. The simulation results of the system models the power system’s equipment parameters, actions, and system responses. The result of the interactions between the magnetic storm and a magnetic storm is shown in Figure 7-8.

As mentioned before, the process of voltage collapse is the result of the interactions between the magnetic storm and the power system’s equipment parameters, actions, and system responses. The simulation results of the system models with different intensities, parameters, and structures may vary greatly. Indeed, combining MATLAB and PowerWorldScript file programming can be used to simulate the processes and consequences of power system failures under any magnetic storm attack. The nodes involved in successive failures indicate the weak link of the power grid under a magnetic storm attack.

D. PRELIMINARY RISK ASSESSMENT OF THE IMPACT OF MAGNETIC STORM ON POWER GRID SECURITY

According to formula (4) to formula (6), take $C = 1$ and $n = 10$, set 10 continuous intervals $[0, 0.1]$, $[0.1, 0.2]$, ..., $[0.9, 1]$. As shown in Table 5, the $D_Q$ and $H_{QGIC}$ are 0.278 and 0.5546 respectively through the hybrid simulation of magnetic storm and electricity. According to the evaluation results, in 10 consecutive intervals, due to the large value of $H_{QGIC}$, the GIC effect of the benchmark model is characterized by uneven distribution of reactive power disturbance, large reactive power loss of individual transformer, and small value of $D_Q$, so the reactive power disturbance clustering effect of each transformer in the benchmark model should be weak. The traditional method mainly relies on the calculation of GIC in power grid to realize the impact assessment of geomagnetic storms, and the method proposed in this paper can effectively reveal the characteristics of reactive power disturbance under the influence of geomagnetic storms by constructing quantitative evaluation indexes. Because the evaluation index is more flexible, the method proposed in this paper is more extensive and adaptive than the traditional method.

The above analysis is carried out when the level and direction of a geomagnetic storm have been determined. Considering the uncertainty of the direction of the induced geoelectric field, it is also necessary to analyze the status of the system under a geomagnetic disturbance from different directions, in order to determine the most high-risk equipment and the nodes or areas most susceptible to geomagnetic storm disturbances in the system.

In addition, the development and endpoints of successive faults will be affected by factors such as the intensity of the magnetic storm, the system parameter settings, and the system scale. In order to reflect the risk of safe operation for a power system under the influence of a magnetic storm more comprehensively and to avoid the large-area power outage accidents caused by magnetic storms, it is also necessary to formulate a risk index of the system’s dynamic operation responses and a corresponding defense scheme, which will also be part of future work.

IV. CONCLUSIONS

Magnetic storms have caused great damage to national power systems in high latitude areas and also pose an ongoing threat to the safe operation of high-voltage transformers in China. We can effectively avoid possible grid accidents if information on magnetic storm disturbance is included in the risk assessment and defense system of the power system. The disaster degree of the power grid under magnetic storm is affected by many factors, and the security requirements of the power grid are very high. It is difficult to carry out physical experiments of the magnetic storm scene during system operation, which increases the difficulty of evaluation.

Based on a discussion of the mechanism and characteristics of magnetic storms, in this paper we analyzed the demands of evaluating power grid operation risk under the disturbance of magnetic storms, pointed out the key problems of evaluation and their solutions, constructed a risk evaluation framework

| C | n | $H_{QGIC}^{max}$ | $H_{QGIC}^{min}$ | $D_Q$ | $H_{QGIC}$ |
|---|---|-----------------|-----------------|------|-------------|
| 1 | 10 | 0               | 1               | 0.278| 0.5546      |
for power systems considering magnetic storms, designed the functions of each module and their exchange parameters, established a simplified hybrid integrated model of a geoelectric field GIC power system, and put forward a new integrated model of a geoelectric field GIC power system. With the help of MATLAB and PowerWorld, hybrid simulation and risk assessment of the power system under the disturbance of magnetic storms were realized. The example shows that the model can reflect the influence of magnetic storm events on the power system and the propagation process of faults under the given parameters of the power grid.

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