IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 13, 2020, accepted March 26, 2020, date of publication March 30, 2020, date of current version April 17, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2984262

A Mitigation Method Based on the Principle of GIC-Even Distribution in Whole Power Grids

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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 The geomagnetically induced currents (GIC) caused by geomagnetic storms can inflict the anomalous operation of power systems, damaging electrical equipment, or even resulting in a large-area blackout of power systems. Therefore, to reduce the impact of GIC and avoid severe disasters has been a major challenge for the development of large-scale power grids. Considering the fact that geoelectric field may have random orientation in mid-low-latitude areas, this paper employs GIC-Benchmark model, to calculate the GIC of East-China 1000kV ultra-high voltage (UHV) and 500kV extra-high voltage (EHV) power grids under a uniform geoelectric-field of 1V/km. We further analyze the characteristics and the pattern of GIC in UHV power grid and identify high-risk nodes which can be vulnerable to GIC encroachment. Then we propose installing additional resistors in the transformer neutral points of high-risk nodes to even the GIC distribution in whole networks, and make the theoretical calculation of GIC in East-China 1000kV power grid after installation. The results show that the principle of GIC-even distribution can reduce edge effect remarkably, which works well in mid-to-low- latitude areas at least, thus we expect to avoid space weather disaster in power grids with power operation scheduling and other mitigation methods.

INDEX TERMS Geomagnetically induced currents, EHV power grid, UHV power grid, GIC-even distribution.

I. INTRODUCTION

The geomagnetic disturbances (GMD) are stronger near terrestrial auroral zones, and the induced geoelectric field in east-west direction is remarkable. Therefore, in high-latitude areas, GIC are relatively larger in eastward transmission lines [1]. However, in mid-low-latitude areas, northward component of the geoelectric field can be larger than eastward component [2]–[3], GMD will not only cause GIC in eastward transmission lines, but also considerable GIC in northward lines. In addition, with recently added 1000 kV ultra-high voltage (UHV) power grid in China's power system in 2009, transmission lines in a 1000 kV power grid now adopt the 500-mm^2 eight-bundle conductors. Small DC resistances per unit length of such transmission lines can increase the potential risk of large GIC generated in China's UHV power grid in the future [4]. The results show that GIC impact on power system security is inevitable during the development of large-scale power grid, for which the latitude of the power grid is almost irrelevant. Now, preventing the power grid from GMD disasters has been a critical task in China's power grid construction and operation, which is well concerned by electrical and other related departments.

Apart from geomagnetic storms, grounding current of DC electrode in converter stations has similar effects in China's ±500 kV high-voltage DC network and ±800 kV ultra-high voltage DC power transmission systems, but only in a more limited area [5]. Since data from monitors in ±800 kV Xizhe converter transformer neutrals reached 210 A [6], the state grid corporation of China installed capacitor blocking devices in Xizhe converter station and nearby transformers neutrals in 2015. However, the larger GIC eventually flow to the transformer neutrals around those without bias suppression devices [6]. Reference [7] proposed a solution by optimizing topological structure of the converter stations connected to the grid to reduce the effect of the DC current. Therefore, it is unsuited to adopt capacitors blocking devices to mitigate GIC [8]. According to the facts that GIC are relatively small in mid-low-latitude areas and the solutions to converter stations' DC-bias in [7], we propose a mitigation method based on the

The associate editor coordinating the review of this manuscript and approving it for publication was Md Apel Mahmud.

TABLE 1. Coordinates of substations.

	Substation	Voltage (kV)	latitude	longitude
1	Wannan	1 000	31.0582	118.5664
2	Huainan	1 000	32.6255	116.9999
3	Nanjing	1 000	32.0602	118.7969
4	Taizhou	1 000	32.4558	119.9231
5	Suzhou	1 000	31.2989	120.5853
6	Shanghai	1 000	31.2304	121.4737
7	Zhebei	1 000	30.7597	119.7934
8	Zhezhong	1 000	29.0791	119.6474
9	Zhenan	1 000	27.9942	120.6994
10	Fuzhou	1 000	26.0746	119.1018
11	Wuhu	500	31.3649	118.4742
12	Long	500	32.1995	118.7134
13	Yandu	500	33.3377	120.1550
14	Feng	500	32.4826	119.9269
15	Shipai	500	31.5060	120.9095
16	Huang	500	31.2723	121.2126
17	Lian	500	31.0068	121.0456
18	Miao	500	30.5425	119.9774
19	Ping	500	30.3675	119.9755
20	Han	500	30.8943	120.0868
21	Qiaosi	500	30.3494	120.2961
22	Lanting	500	29.9242	120.4935
23	Fengyi	500	28.5339	119.1799

principle of GIC-even-distribution in whole power networks, expecting to avoid severe accidents as much as possible.

II. CALCULATION OF GIC IN POWER GRIDS

A. RELEVANT PARAMETERS DETERMINATION

To calculate GIC, the chief problem is to determine the direction of the induced geoelectric field because of lacking precise magnetotelluric data. Reference [9] utilized precise model of earth resistivity, with data of a strong geomagnetic storm in November 2004, they calculated the geoelectric field intensity of Xinjiang area, and the largest value of the northward component was 0.8896 V/km, whereas that of the eastward component was 0.3026 V/km. Due to the characteristics of ionospheric current direction are not obvious in mid-low-latitude, in the process of geomagnetic disturbances, the direction and intensity of the earth electric field will change irregularly, and there is no certainty or any kind of pattern to the change. Therefore, according to [9], this paper proposes the geoelectric field value of 1 V/km for GIC calculation in the UHV power grid in China.

Driven by determined geoelectric field, the dc resistance of GIC flowing path is the major factor in calculating GIC. Generally, larger GIC will occur in networks with higher voltage levels when the geomagnetic storm is assumed to be the same, so the main concern for this paper is to mitigate GIC impact on 1000 kV power grid. Because the scale of 1000 kV Sanhua ac UHV power grid in [4] is too large for the necessity of the attempted calculation in this paper, we propose to use the 1000 kV power grid that has already been put into operation, which has a simple structure to illustrate the mitigation method of sharing GIC among whole power network equally. The relevant parameters in GIC calculation are shown in Table I–III [4].

TABLE 2. Resistance of transmission lines.

From	To	Voltage (kV)	Resistance (Ω/phase)
Huainan	Wannan	1 000	2.5914
Huainan	Nanjing	1 000	1.2231
Nanjing	Taizhou	1 000	1.2460
Taizhou	Suzhou	1 000	2.7596
Suzhou	Shanghai	1 000	0.4816
Wannan	Zhebei	1 000	1.1619
Zhebei	Shanghai	1 000	1.2613
Zhebei	Jinhua	1 000	1.5289
Jinhua	Zhenan	1,000	1.1084
Zhenan	Fuzhou	1,000	2.2169
Nanjing	Long	500	0.9038
Zhebei	Miao	500	1.4596
Zhebei	Han	500	0.4364
Zhebei	Qiaosi	500	0.5267
Zhebei	Ping	500	1.4596
Wannan	Wuhu	500	0.8276
Jinhua	Fengyi	500	0.3762
Jinhua	Lanting	500	1.3392
Taizhou	Yandu	500	0.7524
Taizhou	Feng	500	0.7524
Suzhou	Shipai	500	0.3009
Suzhou	Huang	500	0.3009
Shanghai	Lian	500	0.5310

TABLE 3. Parameters of GIC model for china UHV and EHV power grid.

Voltage (kV)		1000	500
Substation grounding resistance (Ω)		0.1	0.5
dc resistances of autotransformer' winding (Ω)	common winding	0.183	0.238
	series winding	0.141	0.097

B. CALCULATION OF GIC IN POWER GRID

Modeling according to the method provided in [10] and case of Benchmark in [11], we can arrive at the calculation result of GIC in 1000 kV UHV grid and 500 kV EHV grid. The results are shown in Fig. 1 and Fig. 2, where different sizes of circles and thicknesses of lines are used to represent different levels of GIC, and the hollow or solid circles represent whether GIC flow in or out of the neutral point in a substation. These two figures show GIC values in 1000 kV transformers and transmission lines under the stimulation of a 1V/km geoelectric field that is either eastward or northward, where GIC interaction with the 500 kV grid is ignored in Fig. 1.

In Fig. 1 and Fig. 2, like most researches, if we take the direction of geoelectric field as the reference direction in each

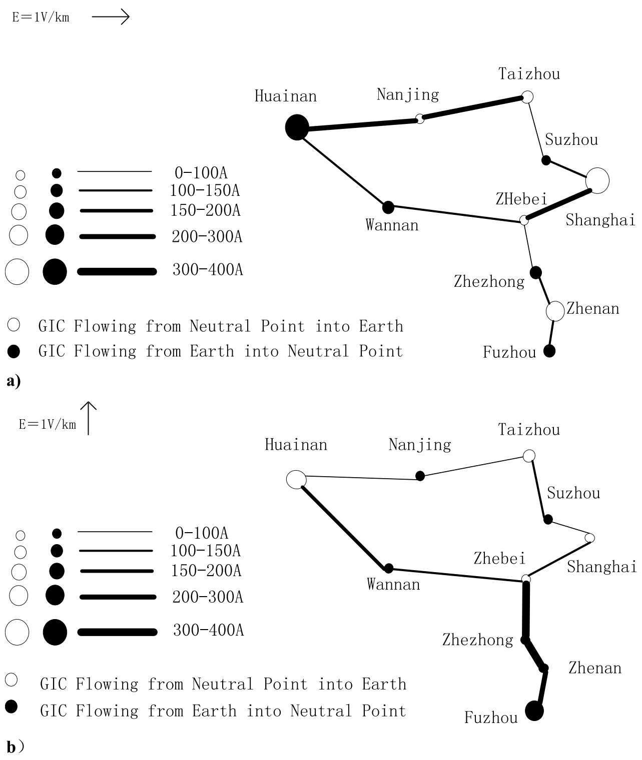

FIGURE 1. GIC in a UHV power grid under a 1V/km eastward (a) and northward (b).

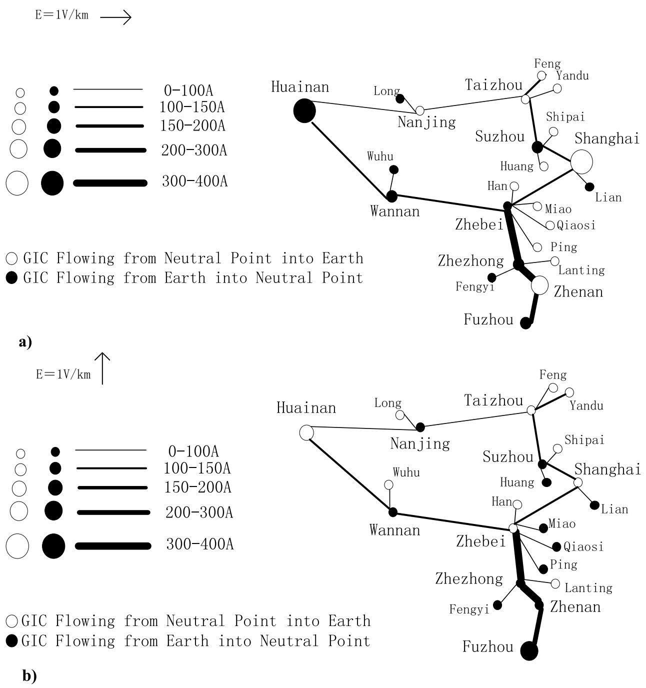

FIGURE 2. GIC in a dual-voltage grid considering both the 1000 kV and the 500 -kV systems: a) GIC in a dual-voltage grid under an eastward geoelectric field of 1 V/km, b) GIC in a dual-voltage grid under a northward geoelectric of 1 V/km. The GIC data are three-phase values.

figure, then substations in the middle of a line have relatively smaller GIC, whereas substations located at the start or end point of the direction have larger GIC [12]. In Fig. 1a, where the reference direction is pointed west to east, the Huainan and Shanghai substations have a larger GIC than everywhere else, with values of 382.9 and 375.88 A, respectively, whereas 500 -kV power grid is taken into account in Fig. 2a, these two substations with values of 383.79 and 346.62 A respectively, and we can see in Fig. 1–2 that they are located on the west and east side of the grid. As with Fig. 1b, the Huainan and Fuzhou stations have large GIC values of 206.48 and 248.82 A in their transformer neutral points, respectively, whereas in Fig. 2b these two substations with values of 200.01 and 249.28 A, respectively. They are located on the south and north sides of the grid, coinciding with the start and end points of the reference direction here. Due to 1000 kV UHV generator step-up autotransformers, however, are designed with the single-phase, four-pillar type or single-phase five-pillar type, with weak resistance to GIC, and terminal substations have GIC with values over 200 A in Fig. 1–2 are supposed to be high-risk nodes.

Further studies and analyses of results in Fig. 2 indicate that, once considering the influence of GIC in the 500 kV system

on GIC at the 1000 kV substations, which makes some 1000 kV substations' GIC become larger whereas others become smaller. Of those, when the 500 kV network is taken into account, under the eastward electric filed, the GIC in the neutral of the Suzhou station increases from 36.3 A to 108.34 A, i.e. by 72.04 A; and Zhebei station's increases from 0.58 A to 59.64 A, i.e. by 59.04 A; whereas GIC flowing through Taizhou station decreases from 126.37 A to 81.74 A, i.e. by 44.63 A, and Shanghai station's deceases from 375.89 A to 346.62 A, i.e. by 29.27 A. Under the northward electric field, the GIC in the neutral of the Suzhou station decreases from 139.83 A to 36.29 A, i.e. by 103.54 A; whereas GIC flowing through Zhebei station increases from 72.42 A to 98.37 A, i.e. by 29.95 A; and Wannan station's increases from 31.82 A to 56.64 A, i.e. by 24.82 A, Nanjing station's increases from 74.09 A to 94.36 A, i.e. by 20.27 A. Thus it can be seen that although the 500 kV power grid do have an influence on 1000 kV power grid, the 1000 kV power grid GIC still take the lead, which is also the focus of this paper.

III. CALCULATION OF GIC-EVEN DISTRIBUTION

A. PRINCIPLE OF GIC-EVEN DISTRIBUTION

These results show that whether considering 500 kV power grid or not, substations located at the start or end of power grid have large GIC is the primary characteristic of 1000 kV power grid. Based on this, and the fact that power grid protection technology and anti-interference capability are comprehensive currently, we propose a principle of GIC-even distribution, then take appropriate measures to soften GIC impacts on power grid. To minimize accident risks caused by geomagnetic storms in power grid, there are two main measures including operational and hardening measures, such as adding resistors into the neutral of transformers and arranging

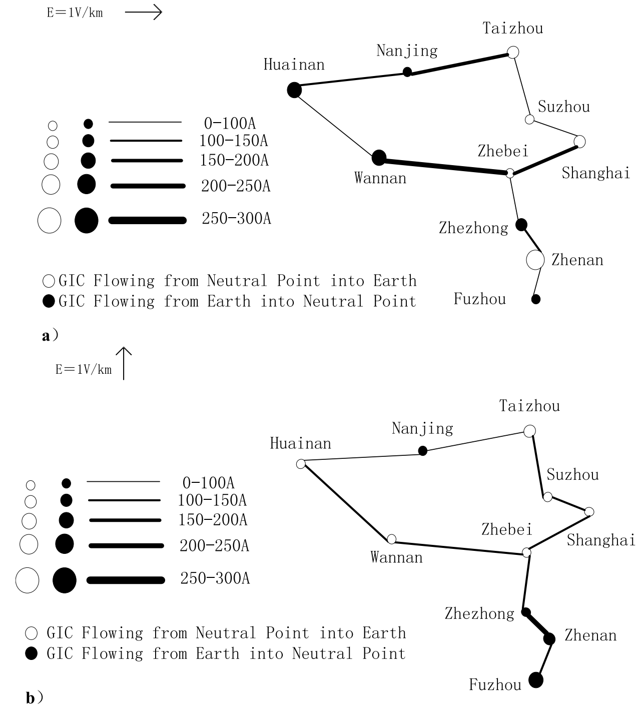

FIGURE 3. GIC in a UHV power grid after adding a series resistor under a 1V/km eastward (a) and northward (b).

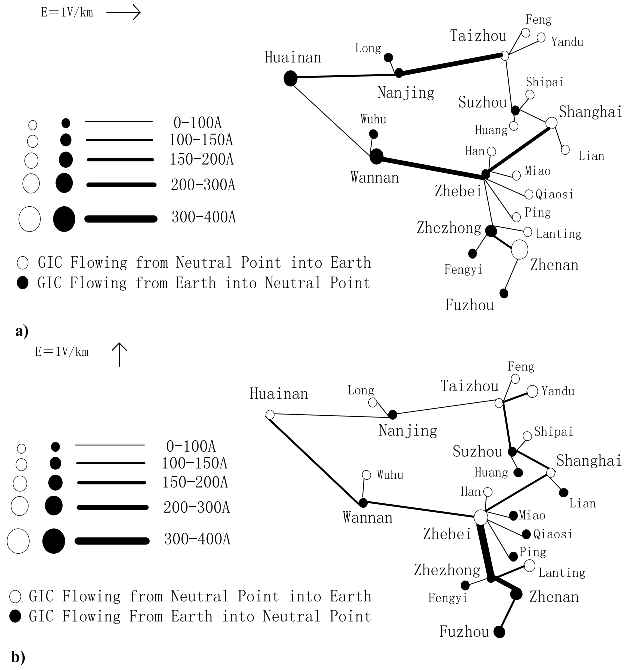

FIGURE 4. GIC in a dual-voltage grid considering both the 1000 kV and the 500 kV systems after adding a series resistor under a 1V/km eastward (a) and northward (b).

operating mode to weaken the flow of the GIC in networks. Because arranging operating mode is a more complex problem, this paper hereby as a starter, begins this investigation with the method of installing additional resistors into the neutral of high-risk substations to even the distribution of GIC in networks.

B. VALUE OF ADDITIONAL RESISTORS

In order to ensure the effectiveness and reliability of transformer neutral grounding, resistors added in the neutral of transformers should be as small as possible, which can control the flow of the GIC in transformer neutral points within a certain range. According to the experience of UHV engineering in China, especially high-low-end test of UHVDC transmission project, choosing dc resistances of 0.65 ohms and 0.7 ohms, respectively for 1000 kV and 500 kV power grids at neutral point is relatively reasonable. Taking the Huainan power grid in south China as an example, we then verified this modeling and simulation method using MATLAB. After optimum calculations by MATLAB, we arrive at the optimal value of additional resistors of 0.65 Ω in series with the original earthing resistance at 1000 kV terminal substations Shanghai, Huainan, Fuzhou (in Fig. 1), and the value should be 0.7 Ω when 500 kV grid is considered, these values also meet the standard in code for design of AC electrical installations [13].

C. CALCULATION OF GIC-EVEN DISTRIBUTION

Following the method mentioned above, calculation results after adding a series resistor at Huainan, Shanghai, Fuzhou stations are shown in Fig. 3–4. As shown by calculation, after adding a series resistor at edge stations, the GIC in the neutral of Huainan, Shanghai, Fuzhou 1000 kV stations decrease drastically, whereas GIC flowing through other stations' increase or decrease, respectively. Of those, in Fig. 3a, under the eastward electric filed, the GIC in the neutral of the Huainan station decreases from 382.9 A to 164.84 A, i.e. by 218.06 A, and Shanghai station's decreases from 375.88 A to 128.35 A, i.e. by 257.53 A, when 500 kV power grid is taken into account in Fig. 4a, GIC flowing through in Huainan station decreases from 383.79 A to 157.59 A, i.e. by 226.2 A; and Shanghai station's decreases from 346.62 A to 97.43 A, i.e. by 249.19 A. Under the northward electric field, in Fig. 3b, the flow of the GIC at Huainan station decreases from 206.48A to 89.58 A, i.e. by 116.90 A, and Fuzhou station's decreases from 248.82 A to 151.34 A, i.e. by 97.48 A; whereas 500 kV power grid is taken into account in Fig. 4b, GIC flowing through Huainan station decreases from 200.01 A to 82.17 A, i.e. by 117.84 A, and Fuzhou station's decreases from 249.28 A to 147.15 A, i.e. by 102.13 A. As we can see, after adding a series resistor at high-risk nodes, GIC flowing through high-risk nodes almost all dropped to below 200 A, though some substations' GIC become a bit larger, they are still below 150 A.

The calculation results in Fig. 3–4 also show that after in series additional resistors at terminal stations, the direction and magnitude of the GIC flowing through some substations are changed. A comparison between Fig. 1 and Fig. 3, under the eastward electric field, the direction of the GIC flowing through Nanjing station changes from neutral point into earth to earth into neutral point, the value of GIC changes from

35.26 A to -70.28 A, whereas 500 kV power grid is taken into account in Fig. 2 and Fig. 4, the value changes from 30.55 A to -69.11 A. And Suzhou station's changes from earth into neutral point to neutral point into earth, and the value of GIC changes from -36.3 A to 95.54 A. Under the northward electric field, the direction of the GIC flowing through Wannan and Suzhou station changes from earth into neutral point to neutral point into earth, and the values of GIC change from -31.816 A to 0.157 A and from -15.084 A to 1.101 A, respectively.

IV. ANALYSIS OF GIC-EVEN DISTRIBUTION

A. EFFECTS OF GIC-EVEN DISTRIBUTION

Accordingly with [14]–[16], in Fig. 5 and Fig. 6, we can compare GIC-even distribution effect at ten 1000 kV stations before and after in series with additional resistors at Huainan, Shanghai and Fuzhou stations. Fig. 5 shows earthing GIC at ten 1000 kV stations when the geoelectric field is 1 V/km and points to the east and north. The blue solid line demonstrates the "without resistors" situation whereas the "with resistors at three stations" case is depicted by the red dashed line. The asterisks mark the particular three high-risk stations having a resistor. Fig. 6 is the same as Fig. 5 except taking account into 500 kV power grid. And a negative value means GIC flows from earth into neutral point whereas a positive value means GIC flows from neutral point into earth.

As shown in Fig. 5–6, whether considering 500 kV power grid or not, after adding a series resistor at three high-risk substations, GIC flowing through ten 1000 kV stations are all controlled in a low level, though the direction and magnitude of GIC changed at some stations, the values of GIC at ten 1000 kV stations are below 150 A on the whole. This indicates that, in series with additional resistors at three terminal stations can distribute the GIC that flowing in transformers' neutrals of whole power network equally, which can eliminate edge effect and reduce accident risk caused by GIC.

In our example, the alleviation effects of GIC at Zhenan 1000 kV substation is not as desired, whose value of GIC still lingers around 200 A under an eastward electric field. The main reasons are as follows: (1) after adding a series resistor, the direction and magnitude of GIC changed at some stations. Based on Kirchhoff's current law, which states that the sum of GIC flowing from neutral points into earth equals the sum of GIC flowing from earth into neutral points, and because the direction of GIC at most stations is from earth into neutral point, whereas the direction of GIC at Zhenan station is from neutral point into earth , so Zhenan station has a larger value of GIC;(2) transmission lines directly connected with Zhenan station in the direction of the electric field, both flowing either to or from this station; thus making their sum large under the eastward electric field.

Once considering 500 kV power grid, the value of additional resistors increases by 0.05 Ω, after adding a series resistor at 3 edge stations in dual-voltage grid, under the eastward and northward electric field, the GIC in the neutral of most 500 kV stations have a slight increase but are still below 100A, only under the northward electric field, the GIC of Yandu and Lanting 500 kV stations with a value between 100 A and 150 A. Therefore, adding a series resistor at edge stations almost has no impact on 500 kV power grid. In addition, in dual-voltage grid, the GIC of 1000 kV stations is a bit smaller than single-voltage grid's, that is 500 kV power grid can help to spread the GIC distribution in whole power grid, which means the impact of 500 kV power grid on 1000 kV power grid should not be ignored.

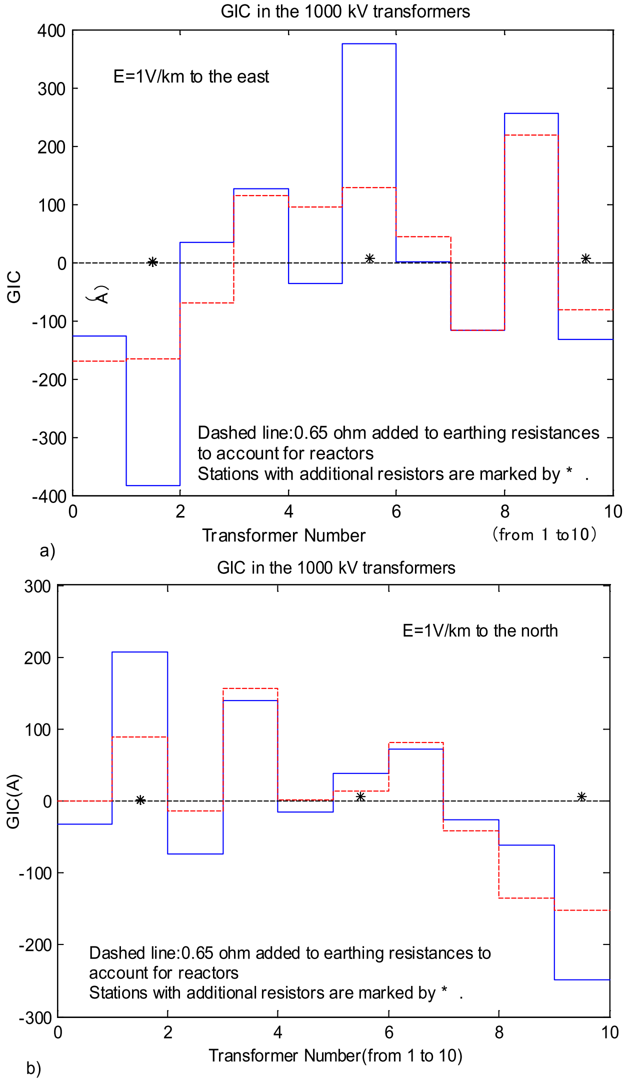

FIGURE 5. GIC at 1000 kV substations before and after adding a series resistor, under a 1V/km eastward (a) and northward (b).

B. THE FEASIBILITY OF ADDING SHARING ADDITIONAL RESISTORS

On the condition of no short circuit fault, in general, the additional resistors have no obvious influence on the effectiveness of transformer neutral grounding. The above analysis reveals that, adding a series resistor at 3 high-risk stations can reduce the GIC in whole networks effectively, therefore,

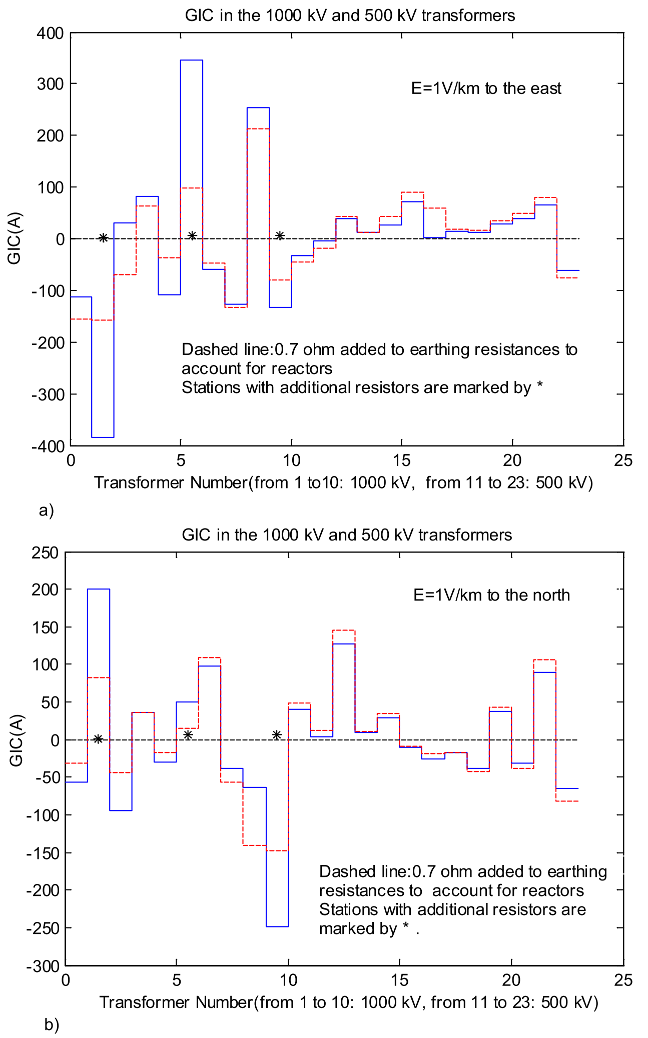

FIGURE 6. GIC at 1000 kV and 500 kV substations in a dual-voltage grid before and after adding a series resistor: a) GIC in the neutral of 1000 kV and 500 kV substations under an eastward geoelectric field of 1 V/km, b) GIC in the neutral of 1000 kV and 500 kV substations under a northward geoelectric field of 1 V/km. The GIC data are three-phase values.

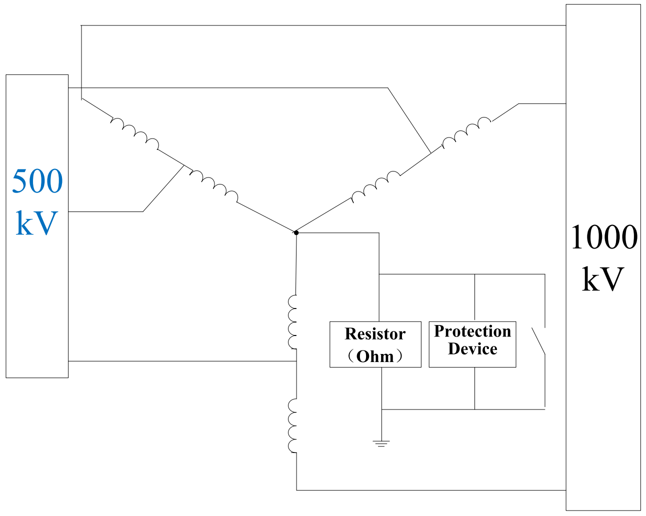

FIGURE 7. Diagram of the technology realizing of neutral device.

adding a series resistor is a great way to prevent power grids from disasters caused by GIC, which does little impact on the effectiveness of transformer neutral grounding compared with adding a series resistor, what's more, installing capacitors in series has low requirement of device's switching on-off time and better operation economic efficiency. This paper proposes a 1000 kV GIC mitigation device showed in Fig. 7, which can switch on-off by adopting automatic way or dispatching command. On the one hand, with the data of real-time monitoring of GIC in transformer neutral points and the Phasor Measurement Units (PMU) data through Wide Area Measurement System (WAMS) which is used widely in power system, it is easy to analyze abnormal reactive power of transformers and other disturbances derived from GIC. On the other hand, there are many effective satellite observation methods to study solar activity, though we can not predict the time that disastrous Coronal Mass Ejections (CME) reach to the earth precisely, the methods to judge the harmfulness of CME accident have already existed. Therefore, it would not be difficult to configure several neutral devices at high-risk stations for disaster prevention, and it is believed that the technical realization of the device in Fig. 7 is not difficult.

V. CONCLUSION AND DISCUSSION

For the 1000kV UHV power grid, due to the lower impedance of the transmission line, the GIC flowing through the loop system composed of transmission line, ground and transformer will be larger when the magnetic storm occurs.

In extreme cases, the geoelectric field is assumed as uniform 1 V/km, and the maximum GIC can reach 380 A. Therefore, the purpose of this paper is to explore a mitigation method which can reduce the GIC in UHV transmission system and ensure the safe and stable operation of the power grid. Based on the principle of uniform distribution, the reasonable arrangement of resistors at the neutral point of transformers is the main problem needed to be solved in this paper. This paper addresses the problem that the value of GIC will reach 380 A in 1000 kV power grid. We study the disaster prevention effect of adding a series resistor in the neutral points of transformers at 3 high-risk substations, the main conclusions and discussions are summarized as follows.

1) The results show that, adding a series resistor in the neutral points of three high-risk substations not only can eliminate edge effect, but also can balance the GIC flowing through transformers of whole network to values of almost all below 200 A, which proves that in series with appropriate resistors at very few stations can change the distribution of GIC and improve the regulation of the GIC in power grid.
2) This paper uses the value of GIC of 200 A as the threshold value of security, one reason for this is on

basis of the fact that the calculation result of Quebec accident in 1989 is over 200 A [17], the second is the ability of resisting geomagnetic storm disaster has greatly improved with the development of protection devices and WAMS technology, the third is though the value of DC current in the neutral point of ±800 kV Xizhe converter substation reached 210 A, but there is no malfunction or abnormal phenomenon spotted in the single-phase four-pillar transformer protection. Therefore, it is reasonable to believe that the current power grid has the ability to resist the threat of 200 A GIC. Due to the fact that converter transformer is a type of high impedance transformer, which is different from 1000 kV AC transformer absolutely, so further studies should focus on the ability to resist GIC of 1000 kV single-phase four-pillar and five-pillar transfromer.

3) Our study is based on the geomagnetic storm in November 2004, so one question that remains to be discussed is whether it is typical enough for a GMD in China. Reference [18] shows the reason why GIC flowing through power grid have relatively large values, that is, two CMEs which drive the geomagnetic storm are both full-halo-coronal and their explosive positions are in the heliographic center toward the west, as well as the contribution of two fast initial velocities of CME, and compared with other parameters, the velocity of CME contributes greater. Though this geomagnetic storm is not the strongest in recent years, it still produced large GIC in power grid. GIC effects caused by storms occur more frequently at high latitudes. However, during extreme geomagnetic storms (such as the Carrington event), the auroral oval considerably moves equatorward. In this case, the auroral electrojets could affect mid- and low-latitude regions such as those in China. Such effects are relatively rare [19]. On the other hand, interplanetary shocks can drive GICs at mid and low latitudes as a result of the magnetopause current compression. Although shock-associated GICs are weaker than storm-associated GICs, the former occur more often. As a result, they can cause overtime, long-term degradation of power grid equipment [20]–[21]. Since our research team mainly engages in power system technology, we will continue to study the characteristics of GIC with different incentives in the power grid. The mitigation method of GIC-even distribution among whole power grid proposed in this paper is universally applicable to mid-low-latitude power grids.

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