Geomagnetically Induced Current-Monitoring Method Based on High Voltage Wires for Transformers

CHUN-HUI GAO1, HE GAO1, WEN-LIN LIU2, HAI-PENG SHI1, SI-TONG YAN1, AND QIAN-RAN ZHANG1

1State Grid East Inner Mongolia Electric Power Research Institute, Huhhot 010020, China
2Beijing Tianhe Benan Electric Power Technology Company Ltd., Beijing 102206, China

Corresponding author: Wen-Lin Liu (13901259607@139.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 51577060, and in part by the State Grid Inner Mongolia Eastern Electric Power Company Ltd., Program under Grant 526604200001.

ABSTRACT Hall sensors have a relatively low withstand voltage but have been used at the neutral point of transformers to monitor geomagnetically induced currents (GICs). However, when introduced into monitoring devices via sensor wiring, high voltages at the transformer neutral point can lead to damage to electronic components and increase the risk of serious power grid accidents. For monitoring GICs from the neutral point of the transformer, this paper proposes a transformer GIC monitoring method based on high-voltage wire equipotentials and a transformer GIC power (GIC-Q) algorithm based on the proportional coefficient K value method. A transformer monitoring device based on the proposed methods was tested at a 500 kV substation in China. In addition, we verified the accuracy of the proposed method and validity of the monitoring data produced using geomagnetic disturbance data with a Kp-index of 4 from the Man Zhouli Geomagnetic Observatory Station.

INDEX TERMS Calculation method, geomagnetic storm, GIC monitoring, high voltage wire, reactive disturbance.

I. INTRODUCTION
Quasi-DC geomagnetically induced currents (GICs) with a frequency of 0.0001–0.01 Hz are generated in a power system because of magnetic storms [1]. This type of quasi-DC GIC infringes on the transformer and causes harmful interference, such as temperature rise, secondary harmonics, and reactive power disturbance [2]. Excessive temperature rise may damage the transformer while reactive power disturbance disrupts the power balance, causing local voltage drops, and the chain reaction results in a blackout [2], [3]. After the Quebec power outage on March 13, 1989 [3], the North American Electric Reliability Council (NERC) and the American Electric Power Research Institute (EPRI) organized GIC research projects, including GIC monitoring and governance technology research [4], [5]. However, owing to the large scale of the power grid, large investment, and difficulty of GIC defense, defense against geomagnetic storm grid disasters has been assessed as a difficult problem for modern society [6].

EPRI developed the SUNBURST monitoring system [7], which used Hall sensors to collect the GIC of transformers and provided several measured data for the study of GIC and its secondary interference. China has developed a similar monitoring system [8] that uses Hall sensors to collect the GIC at the neutral point of the transformer. The neutral point requires access equipment with high withstand voltages, whereas the withstand voltage of the Hall sensor and its monitoring device are low. Therefore, the monitoring devices developed have a few applications in the power grid of China. As the conductor cross-sections for the 1000 kV grid transmission line [9] increases, monitoring the grid GIC and its secondary reactive power are issues to be addressed.

To address the problem of using a Hall sensor to monitor the GIC at the neutral point of the transformer, we developed a GIC monitoring method and device based on a high-voltage wire by using an algorithm of GIC transformer reactive power loss based on the proportional coefficient K value in [10] and [11]. The developed monitoring device
and system were applied to a power grid. We utilized the geomagnetic disturbance (GMD) data of the geomagnetic storm on October 1, 2021, to verify the effectiveness of the GIC collection method and monitoring device.

II. GIC AND SECONDARY INTERFERENCE MECHANISM OF POWER GRID

Geomagnetic storms, which are caused by intense solar activity, produce GMDs that generate geoelectric fields in the earth. These geoelectric fields then induce GICs in circuits comprising transmission lines and transformers grounded at both ends and the earth.

The mechanism by which GICs alter transformer behavior and thus cause harmful system interference is illustrated in Fig. 1. When a GIC occurs, the transformer operating point shifts upward, resulting in half-wave saturation of the transformer core. This saturation distorts the excitation current waveform from a sine wave to peak wave, resulting in an increase in harmonics and the reactive power loss as well as subsequent temperature increase. Of these, this study focused on monitoring the change in reactive power loss caused by GICs.

The magnetic flux of the saturated transformer core is nonlinear to the excitation current. The current with a 90° lag voltage increases the inductive reactive power consumed by the core. This increase in reactive power is the cause of the grid disruptions detailed in Section I.

Therefore, this paper proposes to calculate transformer reactive power loss while monitoring GIC, to provide transformer reactive power loss variation data for power grid operation and dispatching.

III. GIC ACQUISITION DEVICE AND MONITORING SYSTEM

The principle of the monitoring device based on high-voltage wires is illustrated in Fig. 2. The sampling clip on the branch wire collects the voltage signal on the wire, which is 1 m long. The voltage signal is sent through the sampling signal line to the signal processing part for processing. A denoising processing method [12], [13] is first applied to the voltage signal, which is then processed into a current signal according to Ohm’s law (i.e., the monitored GIC). The signal processing part is placed inside an iron-casing box, which is installed via two spacers on the two-split wire on the 500 kV side of the transformer. The signal processing component of the monitoring device is powered by the inductive power extraction component.

The monitoring device in the literature [8] is based on the transformer neutral point and Hall sensor, whereas the monitoring device illustrated in Fig. 2 is based on the equipotential and self-power supply of 500 kV wires. The Hall sensor set on the grounded flat steel at the neutral point of the transformer is replaced by the sampling clip, and the 220 V power supply from the transformer terminal box is replaced by an inductive power supply part. Therefore, the high-voltage–damage monitoring device at the neutral point of the transformer and the risk of the high-voltage neutral point entering the low-voltage (220 V) power supply system are eliminated.

The composition of the monitoring system is illustrated in Fig. 3. The signal filtering and processing, clock synchronization, and wireless communication modules of the signal processing part are similar to those in [8]. These modules are used for processing signals collected by the sampling sensing part, realize synchronization with the background monitoring terminal clock, and transmit GIC monitoring data, respectively. The three modules in the signal processing part
use advanced technology, which has been applied in the early stages. For the circuit and processing algorithm of the signal processing part, please refer to the detailed introduction in the literature [8].

### IV. GIC REACTIVE POWER ALGORITHM FOR TRANSFORMER

To provide GIC reactive power data for power grid safety analysis, this study proposed the use of monitored GIC data to calculate the reactive power loss of the transformer. In 1991, Walling et al. first discovered that the GIC reactive power loss of a transformer varies linearly with GIC [14]. In 2001, Dong et al. calculated the relationship between GIC reactive power and GIC of 500 kV single-phase, 230 kV three-phase shell, 230 kV three-phase three-column, and 525 kV three-phase five-column transformers using a simplified \( \phi-I \) magnetization curve and field circuit model [10]. Considering the operating voltage, the reactive power increment is expressed as:

\[
Q_{\text{Loss}} = U_{\text{pu}} K I_{\text{GIC}},
\]

(1)

where \( Q_{\text{Loss}} \) is the GIC reactive power increment of the transformer, Mvar; \( U_{\text{pu}} \) is the unit value of the voltage at the actual operating terminal of the transformer; \( K \) is the GIC reactive power loss coefficient, Mvar/A; \( I_{\text{GIC}} \) is the GIC flowing through each phase winding of the transformer, A. The \( K \) values for the transformers summarized by the research group in this study are listed in Table 1.

| Core structure                      | \( K \)   |
|------------------------------------|-----------|
| Single-phase transformer           | 1.18      |
| Three-phase shell transformer      | 0.33      |
| Three-phase three-leg core         | 0.29      |
| transformer                        |           |
| Three-phase five-column core       | 0.66      |
| transformer                        |           |

China began building a 1000 kV UHV power grid in 2009. In [15], a field-road coupling model was established using the design data of transformers and iron cores provided by the manufacturer; the excitation current and reactive power loss characteristics of GIC under the action were obtained. According to the GIC-\( K \) value method (the GIC reactive power loss of the transformer is proportional to the magnitude of GIC) for fitting GIC-Q loss characteristics [10], [11]; hence, the continuous increase in GIC in the range of 0–130 A was studied, and the reactive power increment coefficient \( K \) of the 1000 kV single-phase four-leg transformer group was obtained as 2.44 [15], supplemented with the missing Table 1 single-phase four-leg transformer \( K \). Under the action of GIC, the reactive power loss \( Q_m \) of the single-phase four-leg transformer is calculated by

\[
Q_m = Q_{\text{Loss}} + Q_0 = 2.44 \times I_{\text{GIC}} + 1.23,
\]

(2)

where \( Q_0 \) is the reactive power when the transformer group is not saturated, and the constant 2.44 is the magnitude of the reactive power increment proportional coefficient \( K \).

The magnetic latitude of China is relatively low, and the corresponding GMDs from geomagnetic storm are relatively weak. The risk of GIC accidents is in power grids of 500 kV and above. In response to the needs of China’s power grid GIC monitoring and evaluation, the summarized GIC reactive power characteristics of transformers of 500 kV and above are shown in Fig. 4.

It can be observed that the GIC reactive power loss of a 1000 kV single-phase four-leg transformer is the largest, which is approximately 2.07 times that of a 500 kV single-phase shell-type transformer. As the GIC value increases, the GIC reactive power increment of the single-phase transformer becomes larger than that of the three-phase transformer.

Consider China’s provincial power grid as an example: the number of transformers of 500 kV and above ranges from dozens to hundreds. The number of 500 kV transformers in developed provinces is large, but the length of transmission lines above 500 kV is short. Underdeveloped provinces have relatively long transmission lines, although the number of transformers is small. As described in Section V, theoretical calculations are used to decide whether to perform GIC monitoring or governance.

### V. RISK ASSESSMENT OF MENG DONG POWER GRID GIC

In this study, the Meng Dong power grid was used as an example to assess the risk of GIC accidents. Power grids with a GIC value of 500 kV and above are affected by factors such as geomagnetic storm intensity, geoelectricity and its structure, and power grid structure. Compared with provincial power grids in economically developed areas, the newly built 500 kV power grid in Meng Dong has the characteristics...
TABLE 2. Results of geomagnetic storm effect for several transformer substations.

| Site               | GIC/A | GIC-Q/Mvar | δU/kV |
|-------------------|-------|------------|-------|
| Bai Yinhua        | 164.14| 100.45     | 12.74 |
| Hai Bei           | 189.12| 115.61     | 10.78 |
| Hulunbui Factory  | 61.75 | 37.73      | 10.64 |
| Horqin            | 233.62| 144.41     | 12.40 |
| Aluminum City     | 121.21| 74.73      | 10.14 |
| Alatan            | 133.54| 82.71      | 10.93 |
| Qing Feng         | 82.76 | 51.38      | 14.31 |
| Ya Keshi          | 168.30| 103.9      | 13.25 |

of relatively long transmission lines with a relatively large cross section. For example, 500 kV lines supporting Zhaqing ±800 kV DC utilize 630 mm² four-split conductors. Because the line is long and the unit DC resistance of the wire is low, the GIC generated by geomagnetic storms is relatively large.

The earth and power grid model was established based on the GMD data of the geomagnetic storm on March 13, 1989 (provided by the Institute of Geophysics of China Earthquake Administration), the magnetotelluric sounding data of Meng Dong (provided by Jilin University), and the power grid data and materials of Meng Dong Electric Power Company. The GIC of 122 power plants and substations at 220 kV and above in Meng Dong Gire were calculated. The GIC reactive loss increment and bus voltage fluctuation δU were also calculated by the k-value method [16]. Among them, the 8 500 kV plants and stations with larger GIC, GIC reactive power, and δU values are shown in Table 2 [16].

The GIC in Table 2 is the maximum value of the neutral point GIC of each transformer at the plant station during the geomagnetic storm on March 13, 1989; the GIC reactive power is the maximum value of the GIC reactive power increment of each transformer; and δU is the maximum value of the bus voltage change of 500 kV caused by GIC reactive power. Table 2 shows that the GIC of the neutral point of the transformers in the 6 500 kV substations, including Bai Yinhua, Hai Bei, Horqin, Aluminum City, Alatan, and Ya Keshi exceeds 100 A. The GIC of the 500 kV Horqin station transformer is as high as 233.62 A, which exceeds the GIC of 200 A at the time of the Quebec power grid blackout on March 13, 1989.

The high GIC of the transformer in the Horqin station severely saturates the magnetic bias of the transformer at the station, causing risks of GIC accidents. The reactive power of GIC is 144.41 Mvar and δU is 12.40 kV. The GIC of Horqin station has been treated. Compared with Horqin station, the basis for GIC treatment at the Bai Yinhua, Hai Bei, and Yakeshi stations based on theoretical calculations is not sufficient. Therefore, GIC monitoring of transformers in the Meng Dong power grid is proposed to verify the effectiveness of the research group’s calculation results and monitoring device.

VI. APPLICATION AND DEMONSTRATION OF MONITORING DEVICE

On September 26, 2021, at the Alatan station (48.7° N, 116.8° E), a power outage maintenance opportunity of transformer #1 was used to install the device on the B-phase of its 500 kV incoming line. After the commissioning of the device, GIC data for several small and medium-sized geomagnetic storms since October 1, 2021, were obtained. Among them, the intensity of the geomagnetic storm on October 1, 2021, was the smallest, with a Kp index of 4. In this study, we verified the effectiveness of the device using the fluxgate magnetometer H-component observations at the Man Zhouli geomagnetic station (49.4° N, 117.3° E) during the same geomagnetic storm.

The GIC of the grid depends on the rate of change in the horizontal component (H) of the GMD. Using
the GMD second H component data (obtained from the Meridian Engineering Data Center website) of the Man Zhouli geomagnetic station on October 1, 2021, the first-order derivative of H (dH/dt) was obtained and compared with both the B-phase GIC second data of transformer #1 at Alatan station and the GIC reactive power data calculated according to (1); curves obtained from the processed data are shown in Fig. 5. Fig. 5(a) shows the GMD horizontal component change rate curve of the Man Zhouli geomagnetic station, Fig. 5(b) shows the B-phase GIC curve of the 500 kV side of transformer #1 at Alatan station, and Fig. 5(c) shows the GIC reactive power loss increment curve of transformer #1 of Alatan station. The Spearman correlation coefficient of data (a) and (b) in Fig. 5 is 0.91, indicating a high correlation.

The magnitude of the GIC of the geomagnetic storm on October 1, 2021, is smaller than that of the GIC of the geomagnetic storm on March 13, 1989, as shown in Table 2. The GIC and GIC-Q second data were used to evaluate the stability of the power grid. The maximum values of the second data of GIC and GIC reactive power monitored by the device were 2 A and 4 Mvar, respectively; the values are considered not risky to grid security. This is consistent with the detection of geomagnetic storm GICs with a Kp index of 4 by the device in this study, which demonstrates the accuracy of the GIC monitoring device and its effectiveness in monitoring small geomagnetic storm GICs.

The GIC temperature rise is a cause of transformer damage. In 2017, the NERC issued the evaluation criteria for the GIC’s temperature rise effect [17]. The standard recommends that the risk of GIC accidents can be evaluated with two - and five-minute GIC magnitudes, depending on the transformer type and conditions, such as GIC magnitudes and duration [17]. However, if the sampling rate of the monitoring device is assumed as two minutes, some valid data will be lost. It is feasible to use the GIC second data collected by the device in this study, convert it to two minutes or five minutes, and then study the GIC temperature rise effect.

VII. DISCUSSION AND CONCLUSION

(1) The GIC was collected from the neutral point of the transformer in [8], and a 220 V power supply was connected from the terminal box of the transformer to supply power to the Hall sensor. The inductive power extraction technology adopted in this study supplies power to the signal processing part of the monitoring device, which can eliminate the risk of connecting the high voltage of the transformer neutral point to the terminal box. The monitoring method in this study is safer and more reliable, although it requires the installation of monitoring devices with the help of transformer outage opportunities.

(2) In this study, the sampling part of the monitoring device uses the resistance of the high-voltage wire for GIC collection, instead of the Hall sensor at the neutral point of the transformer in [8], which can avoid the risk of the neutral point monitoring high-voltage system and the low-voltage system being mixed, as well as eliminate the zero-drift error that exists in the Hall sensor collecting small GICs.

(3) The monitored GICs were employed to calculate the reactive power loss, which can provide measured data for studying the influence of the GIC reactive power loss of the power grid and thus solve the problem of monitoring the GIC reactive power loss of the transformer.

(4) For a single-phase autotransformer, the GIC in (1) and (2) is that which flows through the series winding. Therefore, compared with the neutral point monitoring method, collecting the GIC from the high-voltage wire and calculating its reactive power loss can prevent the error caused by the low-voltage grid GIC in the common windings of the autotransformer and can accurately calculate the GIC reactive power.

(5) With the development and construction of 750 kV and 1000 kV power grids in China, an increasing number of transmission lines have adopted 400 mm² 6-split wire and 500 mm² 8-split wire in the power grid. The GIC of China’s power grid is becoming increasingly large and complex; thus, it is important to monitor the GIC and obtain the GIC reactive power data. The need for governance and prevention of GIC accidents is also becoming more urgent. The next step is to study the voltage fluctuation of GIC reactive power and the stability of GIC voltage fluctuation by using GIC reactive power data.

REFERENCES

[1] C.-M. Liu, L.-G. Liu, and R. Pirjola, “Geomagnetically induced currents in the high-voltage power grid in China,” IEEE Trans. Power Del., vol. 24, no. 4, pp. 2368–2374, Oct. 2009, doi: 10.1109/TPWRD.2009.2028490.

[2] J. G. Kappernann, “Geomagnetic storms and their impact on power systems,” IEEE Power Eng. Rev., vol. 16, no. 5, p. 5, May 1996, doi: 10.1109/6.48847.

[3] J. G. Kappernann and V. D. Albertson, “Bracing for the geomagnetic storms,” IEEE Spectr., vol. 27, no. 3, pp. 27–33, Mar. 1990, doi: 10.1109/6.48847.

[4] L. Bolduc, P. Langlois, D. Boteler, and R. Pirjola, “A study of geoelectromagnetic disturbances in Quebec. I. General results,” IEEE Trans. Power Del., vol. 13, no. 4, pp. 1251–1256, Oct. 1998, doi: 10.1109/61.714492.

[5] A. Rezaei-Zare, “Behavior of single-phase transformers under geomagnetically induced current conditions,” IEEE Trans. Power Del., vol. 29, no. 2, pp. 916–925, Apr. 2014, doi: 10.1109/TPWRD.2013.2281516.

[6] National Research Council of the National Academies. Severe Space Weather Events:Understanding Societal and Economic Impacts, Nat. Academies Press, 2006.

[7] R. L. Lescher, J. W. Potter, and R. T. Byerly, “SUNBURST—A network of GIC monitoring systems,” IEEE Trans. Power Del., vol. 9, no. 1, pp. 128–137, Jan. 1994, doi: 10.1109/61.277687.

[8] Y. Wang, C.-M. Liu, L.-G. Liu, and Y.-Q. Yan, “An online monitoring system of geomagnetically induced current in power grid,” Autom. Electr. Power Syst., vol. 33, no. 15, pp. 112–115, Aug. 2009, doi: 10.1109/TPWRD.2009.2028490.

[9] L.-G. Liu, K. Wei, and X.-N. Ge, “GIC in future large-scale power grids: An analysis of the problem,” IEEE Electr. Mag., vol. 3, no. 4, pp. 52–59, Dec. 2015, doi: 10.1109/MELE.2015.2480677.

[10] Y. Dong, Y. Liu, and J. G. Kappernann, “Comparative analysis of exciting current harmonics and reactive power consumption from GIC saturated transformers,” in Proc. IEEE Power Eng. Soc. Winter Meeting. Conf., Jan. 2001, pp. 318–322, doi: 10.1109/PESW.2001.975055.
[11] L. Marti, J. Berge, and R. K. Varma, “Determination of geomagnetically induced current flow in a transformer from reactive power absorption,” *IEEE Trans. Power Del.*, vol. 28, no. 3, pp. 1280–1288, Jul. 2013, doi: 10.1109/TPWRD.2012.2219885.

[12] T. Yang, K. J. Zhao, G. Y. Liu, and J. H. Tian, “Calculation and analysis on surface electric field intensity of bundled conductors for UHVAC transmission lines,” *High Voltage App.*, vol. 51, no. 12, pp. 6–13, Dec. 2015, doi: 10.13296/j.1001-1609.hva.2015.12.002.

[13] Y. Gong, J. Hao, and L. Jiang, “Efficient analytical method for the coupling to penetrated transmission line in multiple enclosures based on electromagnetic topology,” *IET Sci., Meas. Technol.*, vol. 12, no. 3, pp. 335–342, May 2018, doi: 10.1049/iet-smt.2017.0363.

[14] R. A. Walling and A. H. Khan, “Characteristics of transformer exciting-current during geomagnetic disturbances,” *IEEE Trans. Power Del.*, vol. 6, no. 4, pp. 1707–1714, Oct. 1991, doi: 10.1109/61.97710.

[15] L. Liu, K. J. Zhao, G. Y. Liu, and J. H. Tian, “Calculation for reactive power loss of single-phase four limbs UHV main transformer due to geomantically induced currents with parameter K,” *High Voltage Eng.*, vol. 43, no. 7, pp. 2340–2348, Jul. 2017, doi: 10.13335/j.1003-6520.hve.20170628032.

[16] H. Li et al., “Risk assessment of east inner Mongolia power grid accident based on geomagnetic storm in March 1989,” *Power Syst. Technol.*, vol. 44, no. 11, pp. 4427–4434, Dec. 2019, doi: 10.13335/j.1000-3673.pst.2019.2269.

[17] *Transformer Thermal Impact Assessment White Paper TPL-007-2—Transmission System Planned Performance for Geomagnetic Disturbance Events*, North Amer. Electr. Rel. Council. Oct. 2017.

**CHUN-HUI GAO** was born in Inner Mongolia, China, in January 1987. He received the bachelor’s degree from the Changchun University of Technology, in 2001. He is currently working as a Senior Engineer with the Electric Power Research Institute, State Grid Inner Mongolia Eastern Electric Power Company Ltd. His research interests include electrical system analysis, power system equipment status evaluation, and dc magnetic bias management of power systems.

**HE GAO** was born in Heilongjiang, China, in December 1990. He received the master’s degree from the Harbin Institute of Technology, in 2017. He currently works with the Electric Power Research Institute, State Grid Inner Mongolia Eastern Electric Power Company Ltd. His research interests include the stability analysis of electrical systems and dc magnetic bias management of power systems.

**WEN-LIN LIU** was born in Changchun, China, in 1981. He received the bachelor’s degree from Université Paris-Sud, France, in 2007. He currently works with Beijing Tianhe Benan Electric Power Technology Company Ltd., mainly engaged in the monitoring, analysis, and management of geomagnetic storms and grounding pole electromagnetic interference.

**HAI-PENG SHI** was born in Inner Mongolia, China, in October 1986. He received the master’s degree from North China Electric Power University, in 2012, where he is currently pursuing the Ph.D. degree. He is also working at the State Grid East Inner Mongolia Electric Power Research Institute, where he is a Senior Engineer. His research interests include power system stability analysis, power system equipment condition evaluation, dc magnetic bias prediction, and the treatment of power systems.

**SI-TONG YAN** was born in Inner Mongolia, China, in February 1996. She received the bachelor’s degree from North China Electric Power University, in 2017. She is currently working as an Engineer with the State Grid East Inner Mongolia Electric Power Research Institute. Her research interests include electrical system analysis and dc bias magnetic control in power systems.

**QIAN-RAN ZHANG** was born in Inner Mongolia, China, in February 1992. She received the master’s degree from the Shenyang Institute of Engineering, in 2016. She works as an Engineer with the State Grid East Inner Mongolia Electric Power Research Institute. Her research interests include the stability analysis of electrical systems and dc magnetic bias management of power systems.

---

**VOLUME 10, 2022**

---

**IEEE Access**