Uncertainty of Geomagnetically Induced Current in Xinjiang 750kV Planned Power Grid Based on Polynomial Chaos Expansion

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Abstract. Geomagnetically inducted current (GIC) can cause DC bias of the transformer. The derivative effect of DC bias may threaten the safety of power equipment and power grid. To study the GIC uncertainty caused by the grid parameters variation is of great significance for the assessment and defense of GIC during magnetic storm. Based on the polynomial chaos expansion (PCE) method, the chaos polynomial expansion of GIC is constructed assuming the line impedance, transformer impedance and grounding impedance in the power grid as input variables. For planned Xinjiang power grid in 2020, the uncertainty analysis for the GIC of substations flowing into the earth is carried out by using the derived polynomial chaos expansions. The 95% confidence interval, mean and variance statistics of the GIC are obtained. Comparison between PCE method and Monte Carlo (MC) method shows the validity and the efficiency of the PCE method.

1. Introduction
Geomagnetic disturbances (GMD) caused by solar activity can seriously affect the operation of the power system. As stated in[1], as early as the 1940s, GMD interfered with grid operation. The basic mechanism of the interference is that the Earth's magnetic field changes caused by GMD induce an electric field on the ground; the induced electric field generates geomagnetically induced current (GIC) in the transmission line, the transformer grounded at the neutral point, and the earth-made circuit. The GIC of 0.0001~0.01Hz will lead to the half-wave saturation, abnormal vibration and increased noise of the transformer iron core, as well as a series of hazards such as increased harmonic current and misoperation of protective devices in the power grid, and even collapse of the power system in serious cases.

As the voltage level increases, the transmission line is often used to reduce the corona loss on the surface of the conductor. The resistance of the unit length line decreases rapidly with the increase of the voltage level. The unit length resistance of the ultra-high voltage transmission line is only half of the 500kV line, the transmission distance is longer and the construction scale is larger. Compared with the existing 500kV main grid, the GIC level in the 750kV grid will be higher. In addition, due to the large transmission capacity, the transformer in the 750kV ultra-high voltage power grid generally adopts the structure of three single-phase auto-transformer transformers. In this transformer, Dc bias is often not cancelled out as it is in the three-phase three-column or the three-phase five-column transformer, so the resistance to GIC is lower[2].
The existing GIC calculation models are all deterministic models, that is, each parameter in the model is a certain value. Although such calculation results have certain reference significance, they are quite different from the real situation. The regional temperature difference between day and night in Xinjiang 750kV power grid planning area is large, and the climate of four seasons is variable, which makes the power grid parameters fluctuate to some extent. In addition, the temperature change of the power grid operation itself will also cause the change of power grid parameters. These factors will cause grid parameters have certain fluctuations. In addition, the temperature changes of the grid operation itself will also cause changes in grid parameters. Therefore, it is necessary to study the uncertainty of GIC caused by changes in grid parameters.

In this paper, an uncertain quantization method for geomagnetic induced current based on Polynomial Chaos Expansion (PCE) is proposed. Based on the Xinjiang 750kV grid planning, this paper considers the unit length resistance of the transmission line, the equivalent DC resistance of the transformer and the grounding resistance of the substation as three-dimensional random input variables, and projects the objective function on a set of orthogonal polynomial substrates, which is a set of contains a uncertain parameters of orthogonal polynomial approximation function, thus using the polynomial to output the results were statistically analysed. Compared with the Monte Carlo(MC) method, and the calculation results can obtain meaningful statistical information in the probability distribution of GIC and the upper and lower bounds of the confidence quickly, which provides an important reference for the GIC disaster risk assessment of the power grid.

2. Polynomial Chaos Expansion of GIC

2.1. GIC Calculation Method Brief

The frequency of GIC is 0.000 1~0.01 Hz, which can be regarded as quasi-direct current. Therefore, GIC can be solved by circuit method in the network model of the power grid. The GIC(I, in ampere)along power transmission lines from the standard matrix equation in Lehtinen and Pirjola(1985):

\[
I = (1 + YZ)^{-1}J
\]

Where \(Z\) is the impedance matrix, \(Y\) is the network admittance matrix and \(I\) is the identity matrix. \(J\) is the ‘perfect-earthning current’.

2.2. Polynomial Chaos Expansion of GIC

Due to the uncertainty of the grid parameters, the GIC calculations also show randomness. If these uncertain random parameters are represented by the set \(\xi = \{\xi_1, \xi_2, \cdots, \xi_n\}\), then according to the principle of the polynomial chaotic expansion shown in Fig. 1, the chaotic polynomial expansion of GIC is as follows:

\[
I = \sum_{i=0}^{P} \alpha_i \psi_i(\xi)
\]

Where \(\alpha_i (i = 0, 1, 2, \cdots)\) is the chaotic polynomial expansion coefficient, \(\psi_i(\xi)\) is the multidimensional orthogonal polynomial basis (in this case, the model parameters are consistent with the uniform distribution, see Table 1), and \(P+1\) is the number of expansion terms. Where P is determined by the number \(n\) of variables and the highest order \(d\) of the polynomial in the expansion[3],

\[
P = \frac{(n + d)!}{n!d!} - 1
\]

It can be seen from the construction process of the polynomial chaotic expansion that the constructed model is determined by the orthogonal polynomial base and its corresponding coefficients. Once the distribution type of the input parameters is determined, the orthogonal polynomial base can be obtained quickly, so the accuracy of the corresponding coefficients is directly related to the accuracy of the constructed model.
Table 1 Three-dimensional orthogonal polynomial base (full-scale)

| i | Order | $\psi_i(\xi_1,\xi_2)$ |
|---|-------|------------------------|
| 0 | 0     | 1                      |
| 1 | 1     | $\xi_1$                |
| 2 | 1     | $\xi_2$                |
| 3 |       | $\xi_3$                |
| 4 |       | $\xi_1\xi_2$          |
| 5 |       | $\xi_1\xi_3$          |
| 6 |       | $\xi_2\xi_3$          |
| 7 | 2     | $3\xi_1^2/2-1/2$      |
| 8 |       | $3\xi_2^2/2-1/2$      |
| 9 |       | $3\xi_3^2/2-1/2$      |

2.3. Determination of coefficient

It can be seen from the previous section that the accuracy of the coefficients corresponding to the orthogonal polynomial base directly determines the calculation accuracy of the constructed model. Based on the one-dimensional Gaussian integral, the traditional full-factor numerical integral projection method is used to ensure the calculation accuracy. Under the premise, the coefficient calculation efficiency is greatly improved.

Based on the properties of the orthogonal polynomial, you can multiply both sides of equation (2) by $\psi_j(\xi)$, and then expect the two sides of the equation. The simplified result is:

$$
\alpha_i = \frac{\langle I, \psi_i(\xi) \rangle}{\langle \psi_i(\xi), \psi_i(\xi) \rangle} (i = 0, 1, \cdots, P)
$$

(4)

The molecular $\langle \psi_i(\xi), \psi_j(\xi) \rangle$ can be directly integrated, and the expression of I in the denominator is complicated and difficult to display (only discrete values). The numerical integration (multidimensional integral) expression using the full factor numerical integration method is as shown in (9):

$$
\langle I(\xi), \psi_i(\xi) \rangle = \sum_{j=1}^{N} I(\xi_j) \cdot \psi_i(\xi_j) \cdot W_j
$$

(5)

Where N is the number of samples and $W_j$ is the weight of the sample[4].

Fig.1 Process of polynomial chaos expansion

3. Quantitative results of uncertainty in GIC in Xinjiang Power Grid

The Xinjiang 750kV planning grid (Figure 2) has a wide geographical distribution, long transmission lines, and small unit length resistance. At the same time, due to the structure of the three single-phase transformers used in 750kV, its resistance to bias current is low. Therefore, it is necessary to carry out calculation analysis. The uncertainty of the GIC application in the Xinjiang 750kV planning grid is
quantified. On the one hand, it can verify the correctness of the algorithm, and on the other hand, it provides a reference for the governance of GIC.

Fig.2 Geographic view of Xinjiang planned grid in 2020

3.1. Grid Parameters
In the GIC calculation process, since the GIC is equivalent to quasi-direct current, only the DC parameters of each component in the power grid are considered\(^5\). The specific parameters are shown in Table 2:

| Parameter                          | Numerical size          |
|------------------------------------|-------------------------|
| Line unit length resistance \(R_l\) | 0.01205\(\Omega/km\)    |
| Transformer equivalent DC resistance \(R_x\) | 0.3\(\Omega\)    |
| Substation grounding resistance \(R_d\) | 0.3\(\Omega\)    |

In practical applications, the DC resistance of the transmission line is usually found in the product manual. The resistance value usually found in the product manual is 20°C, and the actual operating temperature of the transmission line is often different from 20°C. In the GIC calculation process, the uncertainty of the transmission line resistance should be considered. Similarly, the uncertainty of the transformer equivalent DC resistance and the substation grounding resistance should also be taken into account. This paper assumes that the DC resistance of the above three components obeys a uniform distribution within ±10% of specific parameters, and analysing the influence of the simultaneous change of three parameters on the uncertainty of the grid GIC.

3.2. Grid GIC Uncertainty Quantification
In the strong magnetic storm incident from November 9 to 10, 2004, the GIC measured data of the power grid proved that the GMD ground electric field in China can reach 1V/km level, so the induced electric field in this paper takes 1V/km in the north-south direction and the east-west direction.

According to the chaotic polynomial expansion flowchart shown in Figure 1, on the basis of the traditional GIC calculation model, \(R_l\), \(R_x\), and \(R_d\) are used as input variables. Since all three obey the uniform distribution, the three-dimensional Legendre orthogonal polynomial is adopted. As a basis, the method proposed in Section 2.3 is used to solve the coefficients corresponding to the orthogonal bases, and the GIC about the \(R_l\), \(R_x\), and \(R_d\) chaotic polynomial expansions of the substation flowing into the earth in the power grid is constructed. In this paper, the results of the traditional model 10000 sampling point of the MC method are taken as reference. The GIC \(I_1\) of the Hetian substation
flowing into the earth is taken as an example. The comparison of the chaotic polynomial expansion calculations constructed by the two solution coefficients is shown in Fig. 3.

Fig.3 Comparison of effects of Parameters on I1 by PC and MC method

It can be seen from the figure that the calculation results of the chaotic polynomial expansion are basically consistent with the MC calculation results, which can prove the validity of the polynomial chaotic expansion method for the grid GIC calculation. In addition, in order to better compare the accuracy of the PCE method, based on the chaotic polynomial expansion, the mean and standard deviation of GIC are calculated by equations (6) and (7) according to the definition of both expectation and variance.

\[
E[I(\xi)] = \sum_{\Omega} \sum_{i} \alpha_i \psi_i(\xi) \rho(\xi) d\xi = \alpha_0
\]

\[
STDEV[I(\xi)] = \sqrt{\sum_{i=1}^{m} \alpha_i^2 \langle \psi_i^2 \rangle}
\]

Table 3 gives the statistical information estimation of the GIC flowing into the earth in the Hetian substation. It can be seen from Table 3 that the calculation accuracy of the PCE method can reach very good requirements, both the mean error and the standard deviation error are within 1%; The number of times is significantly less than the MC method.

| Method         | Mean (A)    | Standard deviation (A) | Number of solves |
|----------------|-------------|------------------------|------------------|
| MC 10000       | 307.0635    | 11.97                  | 10000            |
| PCE 2nd order  | 307.0626    | 11.988                 | 27               |

At the same time, Figure 4 shows the CDF curve of the Hetian substation flowing into the earth GIC (I1). It can be seen from Figure 4 that the range of I1 varies from 285.9 to 330.0A at the 95% confidence level.

Fig.4 Confidence interval of I1 by second-order PC method
Under the same circumstances, the uncertainty of the grid parameters causes the uncertainty of the uncertainty of other substations flowing into the GIC in Xinjiang grid as shown in Figure 5.

![GIC statistics of substations flowing into the earth in three-dimensional variables](image)

Fig.5 GIC statistics of substations flowing into the earth in three-dimensional variables

It can be seen from the uncertain quantitative information in the figure that the 95% confidence upper and lower boundary difference of GIC flowing into the earth from the Hetian substation in Xinjiang 750kV planning grid caused by the uncertainty of grid parameters is as high as 45A. Other substations have fluctuated in the GIC flowing into the earth under the influence of parameters. It can be seen that the influence of parameter uncertainty on the grid GIC cannot be ignored.

4. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) The PCE method can accurately and effectively reflect the uncertainty of GIC caused by parameter changes, and the calculation efficiency is significantly higher than the MC method.

(2) With the expansion of the grid scale, the advantages of the PCE method will be more prominent. Due to the uncertainty of ±10% change of grid parameters, the change of GIC in the grid of the Hetian substation into the earth is as high as 45A, so the influence of grid parameters on the grid GIC cannot be ignored.

Acknowledgments

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