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Calculation of GIC in Bulk Power Systems

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SUMMARY

During geomagnetic disturbances, magnetic field variations drive low frequency electric currents along transmission lines and through transformer windings to ground wherever there is a path for them to flow. GIC are considered quasi-dc because of their low frequency (typically on the order of mHz) relative to the power frequency; thus, from a power system modeling perspective can be considered dc. The flow of these quasi-dc currents in transformer windings causes half-cycle saturation of transformer cores which leads to increased transformer hotspot heating, harmonic generation and reactive power loss, each of which can affect system reliability. Assessment of the geomagnetic hazard requires accurate modeling of the GIC that are expected to occur during a given geomagnetic disturbance (GMD). This paper serves as a primer for calculating geo-electric fields, developing the appropriate system model and computing GIC in bulk power systems.

KEYWORDS

Geomagnetic Disturbance, Geomagnetically Induced Currents, Geoelectric Field, Geomagnetic Field.

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INTRODUCTION

The process for computing GIC in a bulk power system comprises several steps. First, the geoelectric field must be estimated or determined from available data. Secondly, a dc model of the bulk power system must be constructed. Lastly, the resulting GIC flows are computed using circuit analysis techniques. Once the GIC flows are determined they are used as inputs to other system studies such as power flow analysis and thermal analysis of transformers.

GEOELECTRIC FIELD CALCULATIONS

The first step in computing GIC is to determine the geoelectric field that is experienced by the power system. The height to the source of the geomagnetic field is 100 km or greater so the height of the transmission lines is insignificant and the resulting electric field at the height of the transmission line can assumed to be the same as the electric field at the earth's surface. The geoelectric field can either be assumed (arbitrary magnitude and direction) or it can be computed using well-known frequency domain techniques provided that the local Earth conductivity structure and geomagnetic field are known [1]-[2]. The relationship between the geomagnetic field, earth surface impedance and the geoelectric field is described in (1),

$$E_x(\omega) = Z(\omega)H_y(\omega) \qquad\qquad E_y(\omega) = -Z(\omega)H_y(\omega) \tag{1}$$

where, $E_x(\omega)$ is the Northward geoelectric field (V/m), $E_y(\omega)$ is the Eastward geoelectric field (V/m), $H_x(\omega)$ is the Northward geomagnetic field intensity (A/m), $H_y(\omega)$ is the Eastward geomagnetic field intensity (A/m), and $Z(\omega)$ is the earth surface impedance (Ω). The relationship between the geomagnetic field intensity, $H(\omega)$, and the geomagnetic field density, $B(\omega)$, is given by $B(w) = m_0 H(w)$ where , μ_0 is the magnetic permeability of free space.

The earth surface impedance $Z(\omega)$ can be computed, as a first approximation, using a 1-D layered Earth model. Because of the low frequencies associated with GIC, skin depths can approach 1000 km. The earth surface impedance can be computed using the recursive relation provided in (4)-(6) [2]

$$Z_n = j\omega\mu_0 \left(\frac{1 - r_n e^{-2k_n d_n}}{k_n \left(1 + r_n e^{-2k_n d_n}\right)} \right) \tag{4}$$

$$r_n = \frac{1 - k_n \dfrac{Z_{n+1}}{j\omega\mu_0}}{1 + k_n \dfrac{Z_{n+1}}{j\omega\mu_0}} \tag{5}$$

where, ω is the frequency (rad/sec), μ_0 is the magnetic permeability of free space, $k_n = \sqrt{j\omega\mu_0\sigma_n}$, r_n is the thickness of layer n (m), σ_n is the conductivity of layer n ($(\Omega\text{-m})^{-1}$). For the bottom layer where there are no reflections,

$$Z_n = \frac{j\omega\mu_0}{k_n} \tag{6}$$

This 1-D model provides a representation of the changes of Earth conductivity with depth but ignores lateral variations in conductivity. The earth surface impedance behaves similar to a high-pass filter. To calculate electric fields the magnetic field data is Fourier transformed into the frequency domain. The frequency components are then multiplied by the earth surface impedance to give the electric field spectrum. An inverse Fourier transform is then used to give the electric fields in the time domain. An alternative approach is to to convolve the magnetic field data with the earth impulse response to give the electric field directly in the time domain.

SYSTEM MODELING

Because GIC are very low frequency, typically 0.1 mHz -0.1 Hz, the ac network model is generally reduced to its dc equivalent [4]. The following sections describe the component models necessary for calculating GIC in a bulk power system.

A. Transformers

Power transformers are represented by their dc equivalent circuits, i.e. mutual coupling between windings and windings without physical connection to ground are excluded. An exception to this, as described later, is the series winding of an autotransformer which is always included in the model. Delta windings are not included in the model as they do not provide a path for GIC flow.

Generator Step-Up Transformers

The dc equivalent circuit of a delta grounded-wye generator step-up unit (GSU) is provided in Fig. 1 where R_{w1} i is defined as the dc resistance of the grounded-wye winding.

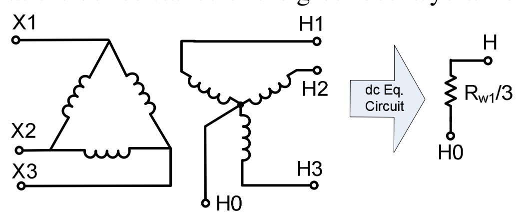

Fig. 1. Single-phase dc equivalent circuit of a GSU.

DC resistance values are best obtained from transformer test reports. However, if these are not readily available then the dc resistance of the grounded-wye winding may be estimated using positive sequence resistance data. The per-unit positive sequence resistance, R_{HX}, includes both the resistance of the high-voltage winding, R_H, and the referred value of the low voltage winding, R_X, as indicated in (7),

$$R_{HX} = \frac{R_H + n^2 R_X}{Z_{bh}} \tag{7}$$

where Z_{bh} refers to the base impedance on the high-voltage side of the transformer and n is the transformer turns ratio (V_H/V_X). The assumption is made that the high-voltage winding resistance and the referred value of the low-voltage winding are approximately equal [4]; thus, the resistance of the high voltage winding can be estimated using (8). The skin effect is typically ignored.

$$R_H = \frac{1}{2} \cdot R_{HX} \cdot Z_{bh} \tag{8}$$

Two-Winding and Three-Winding Transformers

The dc equivalent circuit of both a two-winding and three-winding transformer is provided in Fig. 2. Both winding neutral nodes (i.e. X0 and H0) are modeled explicitly. In some cases, either the X0 or H0 terminal may be ungrounded.

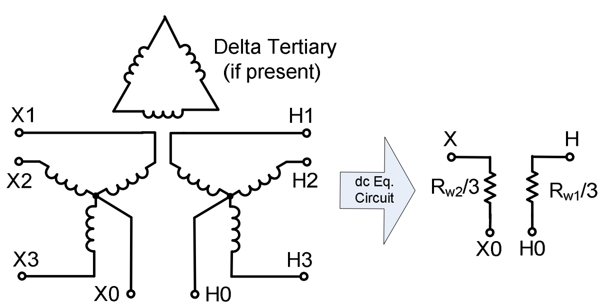

Fig. 2. Single-phase dc equivalent circuit of a two-winding or three-winding transformer.

R_{w1} and R_{w2} in Fig. 2 refer to the dc winding resistance values of the high voltage or extra-high voltage and medium voltage windings, respectively. Again, if test report data are not readily available then the dc winding resistances can be estimated using the same procedure described for GSUs.

Autotransformers

The dc equivalent circuit of an autotransformer is provided in Fig. 3.

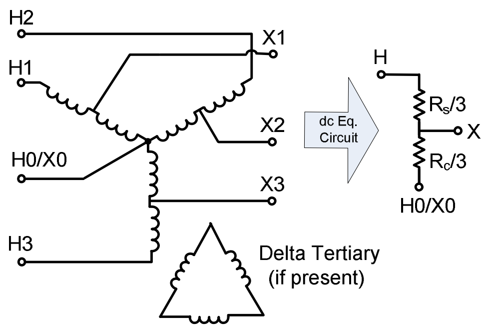

Fig. 3. Single-phase dc equivalent circuit of a two-winding or three-winding autotransformer.

R_s and R_c are defined as the dc resistance of the series and common windings, respectively. The dc resistance of the series and common windings can be estimated using (9) and (10), where R_{HX} is the per-unit positive sequence resistance, and $n = V_H/V_X$ or the ratio of the line-to-ground voltages of the H and X terminals,

$$R_s = \frac{1}{2} \cdot R_{HX} \cdot Z_{bh} \tag{9}$$

$$R_c = \frac{1}{2} \cdot \frac{R_{HX} \cdot Z_{bh}}{(n-1)^2} \tag{10}$$

B. Substation Ground Grid and GIC Blocking Devices

The resistance of the substation ground grid to remote Earth must be included in the model. The 60 Hz ac resistance is typically used since it is approximately equivalent to the dc resistance. Note there is only a single substation ground resistance value for each substation; thus, it is connected to a common neutral bus with R_{gnd} as the resistance to remote Earth of the substation ground grid.

C. Transmission Line Models

Changes in magnetic field density, *B*, with respect to time result in an induced electric field as explained in section II. The driver of GIC is the electric field integrated along the length of each transmission line which can be represented by a voltage source:

$$V_{dc} = \oint \vec{E} \circ d\vec{l} \tag{12}$$

where, $\vec{E}$ is the geoelectric field at the location of the transmission line, and $d\vec{l}$ is the incremental line segment length including direction. If the geoelectric field is assumed uniform in the geographical area of the transmission line, then only the coordinates of the end points of the line are important, regardless of routing twists and turns. The resulting incremental length vector $d\vec{l}$, becomes $\vec{L}$. Both $\vec{E}$ and $\vec{L}$ can be resolved into their x and y coordinates. Thus, (12) can be approximated by (13)

$$\vec{E} \circ \vec{L} = E_x L_x + E_y L_y \tag{13}$$

where, E_x and E_y are the northward and eastward geoelectric fields (V/m), respectively, and L_x and L_y are the northward and eastward distances (m), respectively. To obtain accurate values for the distance between substations (and to be consistent with substation latitudes and longitudes obtained from GPS measurements) it is necessary to take into account the non-spherical shape of the earth as shown in [5].

D. Shunt Devices

The bulk power system generally uses two types of shunt elements to help control system voltage: shunt capacitors and shunt reactors. Shunt capacitors present very high impedance to the flow of GIC, and are consequently excluded in the analysis. Shunt reactors, on the other hand, present low impedance to the flow of GIC, and; therefore, must be included in the analysis. The dc model of a grounded-wye shunt reactor is the same as that of a grounded-wye winding of a GSU. If dc winding resistance values are unknown, they can be estimated using an assumed X/R ratio.

E. Series Devices

Series capacitors are used in the bulk power system to re-direct power flow and improve system stability. Series capacitors present very high impedance to the flow of GIC. This effect can be included in the model by adding a very large resistance (e.g. 1 MΩ) in series with the nominal dc resistance of the line or removing the line from the model completely.

GIC CALCULATIONS

The example system depicted in Fig. 4 will be used to illustrate the process of computing GIC in a bulk power system.

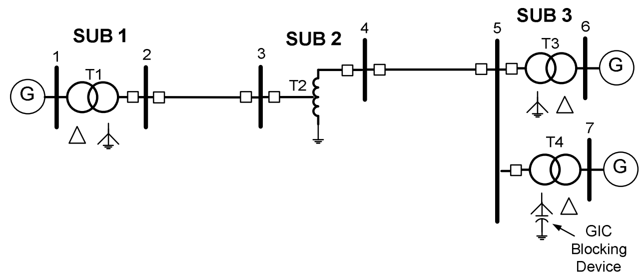

Fig. 4. Example system used to illustrate the procedure of computing GIC in a bulk power system.

First, the geoelectric field that the system is exposed to must be either computed or estimated. Once the geoelectric field has been determined, the single-phase dc equivalent circuit can be assembled as shown in Fig. 5 . It is important to recognize that the primary "driving force" behind GIC flow is the induced voltage *in the transmission lines*, [6]. GIC can be determined by converting the circuit of Fig. 5 into its Norton equivalent and solving

$$\tilde{I} = [G]\tilde{V} \tag{14}$$

where, $[G]$ is the conductance matrix, $\tilde{V}$ is a vector of the dc node voltages, and $\tilde{I}$ is a vector of Norton Equivalent currents. A Norton Equivalent of the circuit shown in Fig. 5 is provided in Fig. 60.

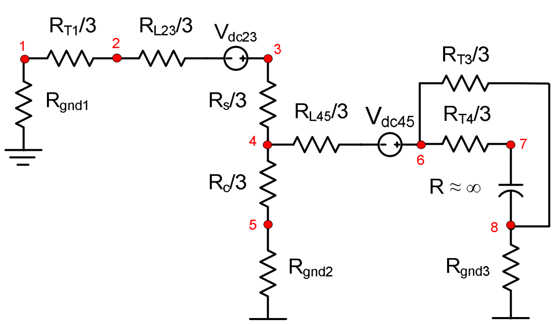

Fig. 5 Single-phase dc equivalent circuit of example system.

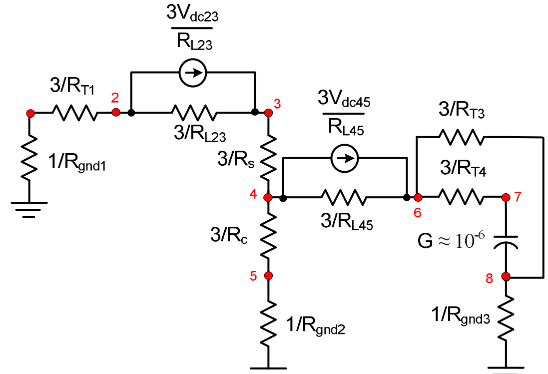

Fig. 6 Norton Equivalent of the dc equivalent circuit provided in Fig. 5.

Once [G] and $\tilde{I}$ are assembled, the dc node voltages can be computed from (15),

$$\tilde{V} = [G]^{-1} \tilde{I} \qquad (15).$$

Once the dc node voltages have been determined, the GIC flows in each element can be computed. The GIC flow in the transmission line, I_{Lij}, can be computed using (16),

$$I_{Lij} = (V_i - V_j) G_{ij} + I_{Nij} \qquad (16),$$

where, V_i and V_j are the dc node voltages at bus i and j, respectively, G_{ij} is the transmission line conductance between busses i and j, and I_{Nij} is the Norton Equivalent current of the transmission line connected between buses i and j.

Another important feature of the single-phase dc modeling technique is that the resulting GIC flows are total "three-phase" quantities. For example, the GIC flow computed using (16) is the summation of all three phases. If per-phase values are required, the computed values must be divided by 3. The same holds true for transformers. The exception is the GIC flow in the substation ground grid. The GIC that is computed is the actual GIC flow into the grid, and does not require further modification.

Because of matrix sparsity, a direct solution to (15) is not practical for realistic systems due to the large number of buses involved. As a result, sparse matrix techniques such as those presented in [7] are generally used [8].

CONCLUSIONS

Techniques are available for calculating the geo-electric fields produced during geomagnetic disturbances and modelling the GIC that flow in bulk power systems. These can be used to calculate the GIC produced during historically large events as part of assessing the geomagnetic hazard to power systems. The calculations can also be made using online geomagnetic data to provide real-time GIC simulations as part of situational awareness systems for power system operators.

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