Mitigating GIC Saturation in Power Transformers

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Large power transformers in high-voltage transmission systems are generally susceptible to half-cycle saturation when subjected to geomagnetically induced currents (GICs). Many passive methods for mitigating the effects of GICs have been proposed, but all of them are costly to implement and have disadvantages. This paper proposes a less costly approach wherein an open delta auxiliary winding is located next to the core. The new winding is fed by an adjustable current source. For transformers already equipped with a closed-delta winding, this location allows the use of a very moderately rated auxiliary winding and controlled current source. Half-cycle transformer saturation can be avoided by adjusting the current source to cancel the magnetomotive force generated by the GIC flowing through the high-voltage windings.

Key words: half-cycle saturation, geomagnetic induced currents, solid-state power conversion, phase-controlled rectifier, auxiliary transformer winding

1. Introduction

The earth is constantly bombarded by a stream of charged particles from the sun, known as the solar wind. When disturbances occur in the sun's outer layer ionized particles are propelled outwards in the form of a shock wave. These shock waves travel away from the sun at speeds of 500 to 1,000 kilometres per second and compress the earth's magnetic field when they collide with it some 48 to 134 hours later. At the time of compression the charged particles are diverted towards the earth's polar regions, where they form east west currents around the so called auroral oval high in the atmosphere.¹⁾ These charged particles then generate observable terrestrial and atmospheric phenomena, such as induced potential differences along the earth's surface and the aurora borealis, respectively.

The high-altitude currents, generated by the motion of the charged particles, change rapidly in response to variations in the solar wind. These changes in current result in temporal variations in the earth's magnetic field and therefore induced potential differences over the earth's surface. Ordinarily these induced voltages cause a current to flow along the earth's surface.¹⁾ However the presence of transmission lines, grounded through

transformer neutrals, provides an alternative path for currents. The magnitude of these currents depends on a variety of factors, including the location, length, orientation, and resistance of the line, the resistance of transformer windings, the earth resistivity as well as the grounding resistance of transformer stations. The induced potentials are generally more worrisome at higher latitudes such as in the northern United States, Canada, and Scandinavia because these regions are closest to the north magnetic pole where the interaction between the earth's magnetic field and charged particles from the sun is strongest. Also in northern countries, the problem is more severe because the ground is composed of a thick layer of high resistivity igneous rock. Regions further south are also susceptible to the affects of magnetic storms but only during periods of intense activity.²⁾

The presence of severe GIC in the windings of high voltage transformers may lead to half cycle saturation. The half cycle saturation turns the transformer into a large reactive power consumer leading to voltage depression, and also into a harmonic current generator. The harmonics can lead to the following problems.³⁾

- overloading of capacitor banks
- possible maloperation of relays
- resonance in harmonic filters at HV dc converter terminals, distortion in the ac voltage, and the subsequent loss of dc power transmission

Under very severe circumstances the system may lose stability, as was the case for Hydro Quebec, on March 13, 1989.⁴⁾

In this paper we begin by briefly describing an appropriate means of modelling GIC using a circuit based model. This is followed by a description of known passive methods for mitigating the effects of geomagnetically induced currents in transformers. We then propose an alternative active method of addressing the GIC problem, which would overcome the disadvantages of the passive methods and which would also be less costly to implement. Simulation results are then shown to demonstrate the viability of the new approach.

2. Model Development

Figure 1 illustrates a simplified grounding scheme

Fig. 1 Grounding configuration for the high-voltage transmission line transformers.

Fig. 2 Low frequency equivalent circuit model showing the flux density B of the time varying earth's magnetic field linking the loop created by the transformer, the transmission line, and earth return.

Fig. 3a Kenora GIC neutral current over a three-hour interval on February 21, 1994.

Fig. 3b Fast Fourier transform of the signal shown in Fig. 3a.

for a high voltage transmission line. At 500 kV and above transformers are usually constructed of three single phase transformers, rather than a three phase core-type structure, and are therefore more susceptible to half cycle saturation arising as a result of GIC.⁵⁾ Figure 2 illustrates how the voltage is induced around the closed loop comprised of the transmission line and the earth return path, where R_{trans1} and R_{trans2} refer to the winding resistances of the respective transformers, R_{line} refers to the transmission line resistance, and R_{earth} refers to the grounding resistance of the terminating stations plus the earth-return (Carson) resistance. A typical GIC disturbance measured by Ontario Hydro, and its spectrum, are shown in Fig. 3a and 3b, respectively. These figures provide an indication of the signal bandwidth which is present. Note that a step function has somewhat similar spectral characteristics. When the transformer includes a delta-connected winding, its shielding will further emphasize these low frequencies. For simulations, the circuit in Fig. 2 can be replaced by an equivalent Thevenin voltage and resistance. Appropriate broadband Thevenin sources can be inferred from records of earth surface potentials or dc currents in transformer neutrals.⁶⁾ In this study, a simple step voltage was used to demonstrate the viability of the proposed method.

3. Passive GIC Mitigation

Measures proposed to mitigate the effects of geomagnetic storms in transmission systems have for the most part assumed the use of passive devices. These devices are placed in series with transformer neutral leads and could include elements such as capacitors and polarizing cells.

3.1 Neutral capacitor

A capacitor placed between the neutral of the transformer and ground inherently blocks the flow of GIC and allows some ac neutral current to flow, but introduces a new set of serious risks. In particular, a capacitive element in close proximity to the transformer can result in the generation of very high ferroresonant voltages.³⁾ Also, the transformer neutral may be subjected to currents of 50 kA or more due to single-line-to-ground faults on the system. These large neutral currents will produce overvoltages which are damaging to the capacitor, transformer, and system surge arrestors. The overvoltages could possibly be eliminated using crow-bar type sparkgaps or thyristors, but this adds additional complexity.

3.2 Series compensation

Capacitors placed in series with each line will completely block the flow of GIC along a transmission line. However adding series capacitors in HV transmission lines just to mitigate GIC is usually uneconomic. Thus

Fig. 4 Three-phase diagram of the studied system, modeled by using EMT.
Note: The geomagnetic effect is represented by a Thevenin source V_{geom} .

this method has not been seriously considered.⁷⁾

3.3 Polarizing cells

Polarizing cells usually contain two nickel electrodes in a sodium hydroxide electrolyte. If the dc voltage exceeds 1.8 V, the cell will be in the conducting state and dc current can increase by thousands of amperes without significantly increasing the dc voltage drop across the cell. This is similar to a diode with a forward drop of 1.8 V.⁸⁾ The polarizing cell has been considered as a possible neutral blocking element in that it can be placed between the neutral lead of the transformer and earth ground without disturbing the ac characteristics of the power system. The major limitation of presently available polarizing cells is their low dc voltage blocking capability. A large number of cells in series may be required, depending on the spectrum of the GIC and the frequency-dependent shielding caused by the delta transformer windings.

4. Active GIC Mitigation

The fundamental problem caused by GIC in power transformer windings is half-cycle saturation, or a flux shift caused by the quasi direct current in the windings. This shift can be nullified by injecting into a new auxiliary winding a current proportional to the quasi dc neutral current, taking the turns ratio into account. The thermal rating of the auxiliary winding needed for GIC compensation can be shown to be relatively modest, only about 10 kW for a 800 MW generator step-up transformer. By locating this winding internal to another closed-delta winding in the transformer, the new winding will be shielded from system faults. Various current sources can be considered and in this paper we explore the use of a phase-controlled rectifier as shown in Fig. 4. Under balanced conditions, the open

Note: L_o is the zero sequence line inductance per phase
 R_{line} is the line resistance per phase
The L_{mag} nonlinearity is approximated by Fig. 6

Fig. 5 Zero sequence model of the circuit under consideration.

Fig. 6 Magnetizing characteristics of the saturable reactor.

Fig. 7 Transformer exciting current obtained by using the EMTP simulation program.

delta auxiliary appears as a constant resistance load when viewed from the two connection points of the current source. Thus the converter would have to supply a load voltage equal to the total voltage drop across the three auxiliary windings. The required bipolar capability can be accomplished by placing two phase controlled rectifiers back to back.⁹⁾ The selection of a turns ratio between the new auxiliary winding and the high voltage winding would be determined by the current rating of the silicon controlled rectifier switches. The required power rating of the converter would be determined by the total losses in the open delta auxiliary winding.

5. Simulation Results

The transformer model used for the simulation is shown in Fig. 5.⁵⁾ The characteristic for the saturable magnetizing branch is shown in Fig. 6. The complete system diagram is shown in Fig. 4. The main problem when simulating the real circuit with an applied dc voltage is the time required for the direct current in the transformer to reach a steady state value, due to the shielding effect of the delta winding. To reduce the transient time of simulation to establish half cycle saturation, the step voltage source was increased. The simulation was performed with the Alternative Transient Program ATP, one DOS version of EMTP (*i.e.*, The Electromagnetics Transient Program).¹⁰⁾ Figure 7 shows the transformer magnetizing current prior to the initiation of GIC (*i.e.*, <100 ms), at the onset of half cycle saturation (*i.e.*, at 200 ms) and at the time the counter magnetomotive force is applied (*i.e.*, at 500 ms), followed by the return to an unsaturated state.

6. Conclusions

Large power transformers in high voltage transmission systems are generally susceptible to half cycle saturation when subjected to Geomagnetically Induced Currents (GIC). Many passive methods of mitigating the effects of GIC have been proposed in the past. All of them, however, are costly to implement and have some serious drawbacks. This paper has proposed a new method of actively mitigating transformer saturation employing a transformer with one additional new auxiliary open delta winding. The basic operating principle is to inject a controllable bipolar quasi dc current into the new winding. The magnetomotive force created by the quasi dc current is adjusted so as to cancel the magnetomotive force created by the GIC flowing through the grounded star connected high voltage transformer winding. The proposed method of mitigating GIC has been successfully simulated and should be relatively inexpensive to implement.

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