Solving old problems with new technology: How to monitor and measure GIC and OPD currents

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1 INTRODUCTION

Geomagnetically-induced currents (GICs) are produced by a naturally induced geo-electric field during geomagnetic disturbances. An extreme example of this type of occurrence happened in March 1989, during one of the largest geomagnetic disturbances of the twentieth century. Rapid geomagnetic field variation during this storm led to the induction of electric currents in the Earth's crust. These currents caused wide-spread blackouts across the Canadian Hydro-Quebec power grid, resulting in the loss of electric power to more than 6 million people. If a similar storm-induced blackout had occurred in the Northeastern United States, the economic impact could have exceeded $10 billion. On average, 200 days of strong to severe geomagnetic storms that could produce GICs on the surface of the Earth can be expected during a typical 11-year cycle. However, knowing exact levels of induced currents in power grid infrastructure during a geomagnetic event requires knowledge of deep earth conductivities and transmission line design parameters. GICs are also difficult to measure as they are non-cyclical and slowly varying over time and most of the power systems architecture relies on magnetic transformers tuned for sinusoidal signals.

Another reoccurring issue in power plants is the loss of phases on auxiliary transformers. If one phase is lost, or open, motors and other components can be damaged and emergency power sources might be compromised. When these transformers are used for emergency supply the detection of this problem is difficult, as they are not usually in service. In critical infrastructure, such as nuclear power plant systems open phase conditions can be catastrophic and open-phase detection systems (OPDs) are required. These seemingly unrelated problems have some common ground. Both are difficult to efficiently monitor, detect and measure using traditional systems and if unchecked may lead to severe consequences.

However, with the use of Digital Instrument Transformers along with modern IEDs, both situations can be viably addressed. This paper describes a standalone system that uses optical current transformers in conjunction with IEC 61850 process bus enabled protection relays and DFRs to measure currents with wide dynamic range and bandwidth. The paper will present how such system can be used to monitor and measure GICs due to its ability to measure DC signals and how it may be deployed as an OPD system in critical installations, by measuring the magnetizing currents of the auxiliary transformers. Finally, a discussion on the commissioning of an actual installation and its results are presented.

2 THE OLD PROBLEMS

2.1 Geomagnetically-Induced Currents (GICs)

In times of heightened space weather, solar storms generate intensive coronal mass ejection that may hit the Earth, affecting the Earth's magnetic which is called of geomagnetic storm. During geomagnetic storms, the variation of magnetic fields will cause electrical currents (Faraday's law of induction) which will flow over conductive materials nearby, such as electric transmission lines, oil and gas pipelines and non-fiber communication cables. These electrical currents are called by Geomagnetically-Induced Currents (GICs).

More specifically in power systems, the GIC usually enters the transmission lines through ground connections of power transformers. Figure 1 illustrates the phenomenon.

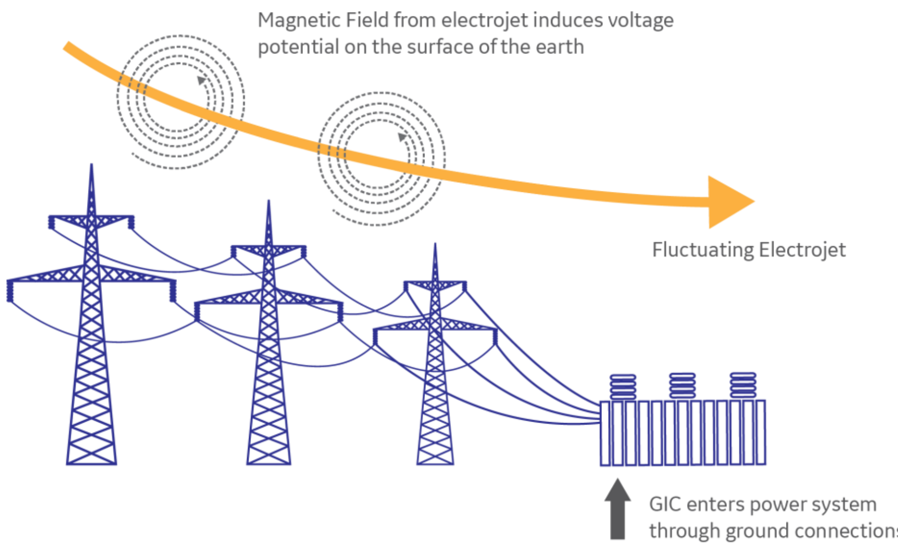

Figure 1 - Geomagnetically-Induced Currents in Power Grids

GICs of tens to hundreds of amperes have been already recorded, and often they are defined as quasi direct current (DC). Although the occurrence of GICs is more common in higher latitudes, it has been recorded in mid and low latitude after weather storms over the last decade.

In power systems, although some power transformers may be susceptible to immediate or cumulative winding damage due to high winding circulating currents if exposed to high levels of GIC, the major problem is the half-cycle saturation of transformers cores, which leads to increased transformer hotspot heating, harmonic generation, and reactive power absorption – each of which can affect system reliability. On March 1989, the province of Quebec in Canada experienced severe geomagnetic storm causing a collapse in the Hydro-Québec power grid. In a matter of seconds, the protective relays tripped in a cascading sequence of events, leaving more than six million people without power for hours, with significant economic loss.

With the continued growth of high voltage power networks and the interconnective of systems, power systems are more susceptible to GICs, and to understand and mitigate the risks, to measure and monitor the quasi-DC currents in power grids becomes necessary.

2.2 Open Phase Detection (OPD)

A power generation plant has certain safety equipment (e.g., cooling pumps) that must operate continuously. The safety equipment is usually powered by the plant itself, but in certain situations (whether in maintenance or fault situations) the plant power may not be available, and the power is tapped from the grid to run the safety equipment. Either way, the power from the plant or grid runs through step-down transformer to the safety equipment. Lastly, backup diesel generators may be employed to power the safety equipment if both the plant and grid power are unavailable.

But, what happens if an open phase condition exists on the high side of the step-down transformer mentioned? While the transformer is unconnected to any load (e.g., the safety equipment), the installed protection devices may not be able to detect a broken line feeding its high side due to the tendency of the transformer to rebalance itself through induction, and the resulting current flows remain quite small. It may be only after the load is connected that the power is discovered to be "bad" (e.g., the transformer is powered by only two phases on the high side). Such conditions can quickly degrade the safety equipment motors. A critical purpose of the OPD system is thus to detect that the step-down transformer is not properly energized on its high side before any attempt is made to use it as a power source.

Open-phase Detection (OPD) is of prime concern in the nuclear industry. Events at several nuclear power plants have shown that the open-phases on the HV side of a transformer may be difficult to detect by existing plant instrumentation and electrical protection schemes. If an open-phase condition is not quickly detected and the transformer not isolated from the system, tripping of critical motor driven loads and loss of plant safety systems can occur. Breaker poles failing to close, a broken conductor, failure of a transformer bushing or line insulator, a loose connection or a blown fuse can all lead to an open-phase condition.

3 THE NEW TECHNOLOGY

3.1 Optical Current Transformers (OCT)

Optical Current Transformers (OCT's – here of fiber construction) have properties that differ significantly from conventional iron core CTs, as the measurement principle is quite different between then. For the purposes of this paper, it will be considered an OCT based on the Faraday's effect, which establish the interaction between a magnetic field and the light – or the rotation of polarized light.

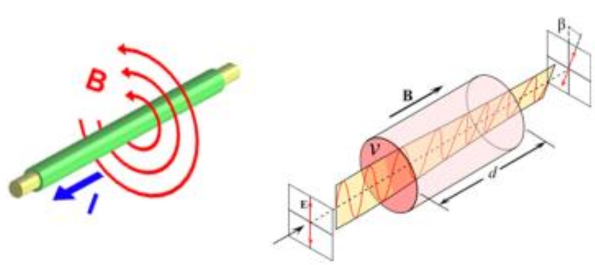

Figure 2 – Rotation of light based on the Faraday's effect.

The Faraday's effect does not depend on the variation of the magnetic field over time, meaning the sensor is susceptive to DC currents as well as AC. Furthermore, the total rotation angle of the linearly polarized light or the excess phase shift of the circularly polarized light in a fiber encircling a conductor is linearly proportional to the current flowing in that conductor.

Such particularities of current fiber sensors based means the OCTs have measurement advantages over conventional iron core CTs which include orders of magnitude wider dynamic range, no saturation, and much larger frequency response including DC. Additionally, OCTs do not tap into the power of the energized line and require no oil insulation, thus making them inherently safer devices. On the negative side, OCTs come at a higher cost than their conventional CT counterparts at lower voltage applications and they exhibit a small additive zero-mean white noise component (typically 0.1 to 1 A rms) to the measurement that is absent from iron core CTs.

3.2 IEC 61850-9-2LE for Relays and DFRs

As a Digital Instrument Transformer (DIT), the secondary of an OCT is digital enabling differently optimized architectures for distributing their data to other devices, such as protective relays and digital fault recorders (DFRs).

In the past few years, there are a growing number of devices that can accept IEC 61850-9-2LE. This IEC standard defines that the analog current and voltage measurements are digitalized in sampled values (SV), and transmitted through the network in standardized messages, called as process bus.

As a single device can support more than one stream of sampled values (each stream has 4 analog signals), the IEC 61850-9-2LE is a good choice when transmitting multiple analog data over a single (Ethernet) cable. For the purposes of this paper, the IEC 61850-9-2LE is supported by the protective relay and DFR used for practical tests.

4 HOW TO MONITOR AND MEASURE GIC AND OPD CURRENTS

Because of the wide dynamic range (including DC) of the OCT, the optical current sensor can be used to detect both GIC and OPD currents. Although a single architecture could be illustrated for both GIC and OPD monitoring, this paper will cover each application separately. However, even using a single architecture would require different sensors for each purpose, as in OPD the magnetizing currents must be detected, and for monitoring the GIC the ground currents shall be measured.

4.1 Measuring and Monitoring GIC currents

As power transformers are the mostly likely entering of GIC in the power system, the ground connection of power transformers must be measured using fiber optic sensors in order to capture the GIC currents. The fiber optic CTs shall be installed in a IP66 cabinet to ensure protection against dust and water given the place where the sensors are installed.

As illustrated in figure 3, the Earth connection from each power transformer is measured using an OCT, which is connected to the OCT Electronics (that can measure up to three OCTs). The figure also illustrates the measurement from the 3-Phases of power transformer in the high side, which is designated to monitor the three phase currents and the possibility of a half-cycle saturation that may result from GICs.

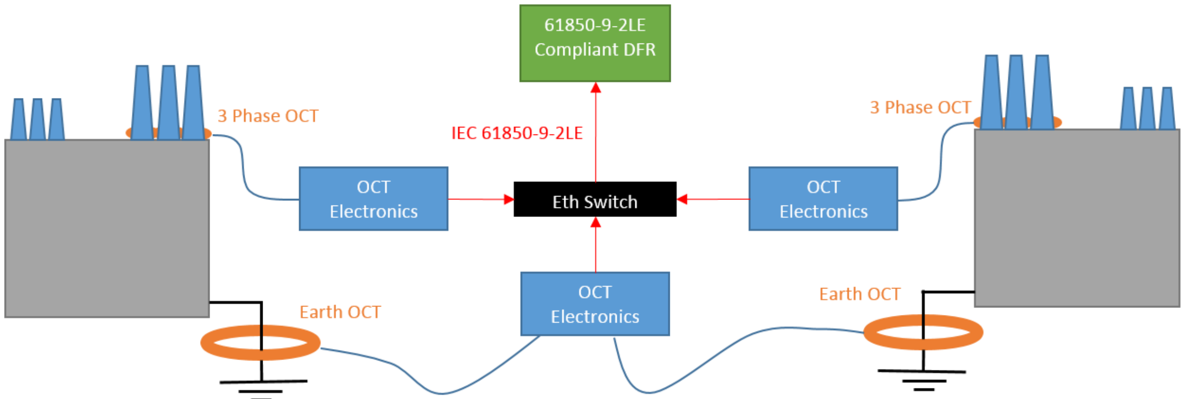

Figure 3 – Measurement and monitoring of GIC for power transformers.

The OCT electronics receive the raw optical signals from the sensing rings, calculate the individual phase/neutral currents and then packet the sampled values, feeding the IEC 61850-9-2LE process bus. The DFR receives such sampled values and continuously monitors each analog value, and once a DC level threshold is crossed (as configured) the DFR registers COMTRADE waveforms (including DC offset and harmonics) of all phases and neutral currents. The trigger may also set a digital output, alarming the supervisory there is a condition of GICs.

4.2 Measuring and Monitoring OPD currents

With a wide dynamic range, the same OCT sensor can be used to detect both the magnetizing currents flowing into an unloaded power transformer as well as the currents flowing into it when it is loaded, including fault currents. Since detection of an open phase condition in an unloaded transformer is generally more difficult than in a loaded transformer, this paper will limit the description of OPD currents to unloaded power transformers.

In order to detect an open phase condition on an unloaded transformer, the high side current sensors must be able to measure the excitation currents within an uncertainty of a few milliamps, given that the differences between the measured currents and the expected "fingerprint" of an OPD can be as low as a few tens of milliamps.

Figure 4 shows a block diagram of the OPD system. OCT sensing rings are placed over the bushing on each phase of the high side of the power transformer. The optical signals from each of the sensors is detected in the OCT electronics and converted to digital signals representing the individual phase currents. These currents are then processed and sent to a process bus relay via an optical Ethernet link. The relay makes the determination of the open phase condition. When an open phase condition is detected, the relay then triggers an annunciation alarm for plant operations, as well as a process bus compliant digital fault recorder, which also receives its data via Ethernet link from the OCT electronics.

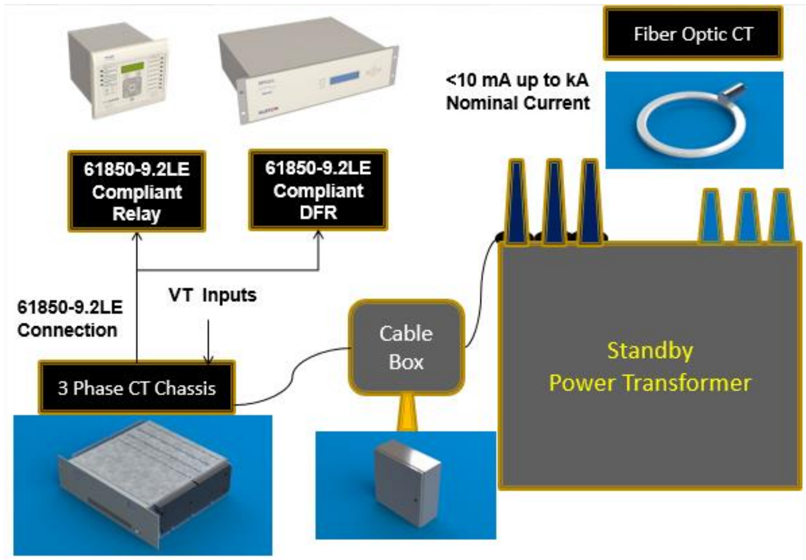

Figure 4 – Measurement and monitoring of OPD currents.

To illustrate the function of the OPD system and the analysis of the data, we present test results here obtained from two particular cases, each for an unloaded wye-wye transformer. But first, Figure 5 shows the unloaded transformer "fingerprint". As can be seen, the phase B magnetization current magnitude is less than that of phases A and C, and the phase angles of A and C have been pulled towards that of B. These conditions are fully expected from the core form construction of the transformer.

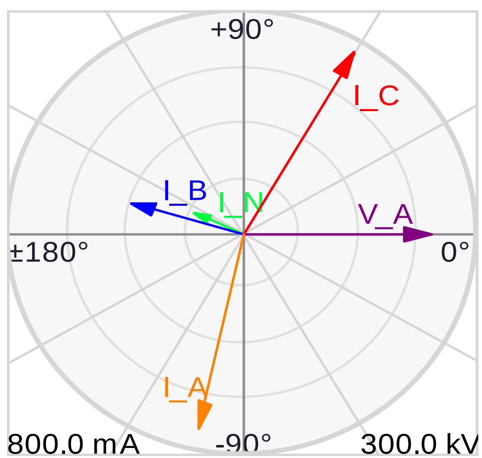

Figure 5 – The phase current in a normally, excited wye-wye transformer.

The next fingerprint analysis, as shown in Figure 6, considers there is a single phase open, in this case phase C. It is interesting to note here that the C phase current, though very much reduced in amplitude, did not go precisely to zero when it was opened. This is explained by the fact that there is capacitive coupling between the phases over the 120 meters of line between the transformer and the opened phase. It is important here to note that for open phase conditions occurring far from the transformer, it is not sufficient to simply look for a reduced phase current to detect an open phase. A fuller treatment of the fingerprint analysis is required.

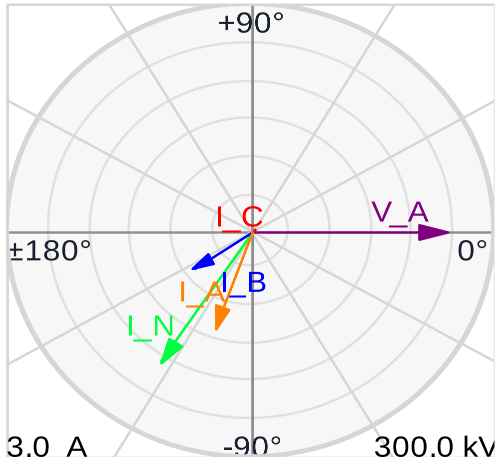

Figure 6 – The phase current of excited wye-wye transformer, with Phase C open.

Lastly, the Figure 7 illustrates the fingerprint when the Phase B and C are opened. Note that again, the C and B phases currents are not zero, although they are very close to it. And as expected, the phase A current and the neutral current are similar, due to phase A to neutral is the only path available for the magnetizing current.

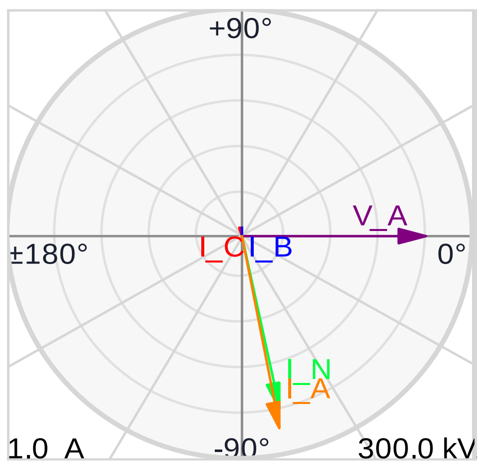

Figure 7 – The phase current of excited wye-wye transformer, with Phase B and C open.

5 CONCLUSIONS

In the past, when only conventional current transformers were available and communications depended exclusively in analogue and digital I/O systems, power systems used to face problems which were difficult to solve. To measure a DC levels along with AC in high amplitudes was not something to be considered, as well as not to have an accurate measurement over a wide range when compared to the nominal value.

With the advances of technology, Optical Current Transformers (OCTs) are a reality nowadays with accurate measurement and reliable structure. Along with it, the digital communication gives the possibility to a massive data processing and differently optimized architectures for distributing data to other devices. In this paper, it was demonstrated how the 61850 process bus devices with optical CTs may be used for the measurement and monitoring of open phase conditions and geomagnetic-inducted currents.

6 REFERENCES

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