A Method to Assess GIC's Impact on Protection Systems

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Abstract

Geomagnetically Induced Currents (GIC) refer to currents induced by a geomagnetic disturbance or storm at the Earth's surface. One of major problems caused by GIC is that high level of GIC may cause the transformer core to be saturated. A saturated transformer will draw more reactive power from the grid and inject harmonic contents to the grid. These will impact operation and stability of power system and protections.

It is very important to know exact location where a specific protection may experience GIC so that a certain action can be taken to deal with the issue.

A simple method is proposed in this paper to assess the impact of GIC on protection system. Through this way, assessment of complicated GIC issue is converted to a fault calculation. In this paper, transformer current differential protection, capacitor bank protection, line zero sequence over-current protection and distance protection are assessed with the proposed method. According to these assessment results, different actions may be taken to address different problems each protection would experience. The benefit of this method is that we can save huge equipment investment since the assessment result would show the exact equipment with GIC issue.

1.0 Introduction

Scientists predict that a strong solar storm will peak in 2012-2013 with much higher than the previous historic record strengths. The strong storm will significantly impact electrical power transmission system including protections.

The solar flare influences electric power system by Geomagnetically Induced Currents (GIC). GIC's effects on their systems have been observed, experienced and studied in several utilities in Scandinavia, Canada, United States, and South Africa etc. The saturation of transformers caused by low frequency GIC from 0.001Hz to 0.1Hz is the root cause of the GIC's effect on power system. The saturation of the transformers will draw much higher excitation current than the excitation current under their normal operation condition. The operation reliability of relaying protection system during the GIC event is a concern of each power utility. The focus on the protections is that the protection should not trip during GIC event if no fault exists in the protected zone but trip if a fault appears in the protected zone. These effects are summarized as Figure 1.

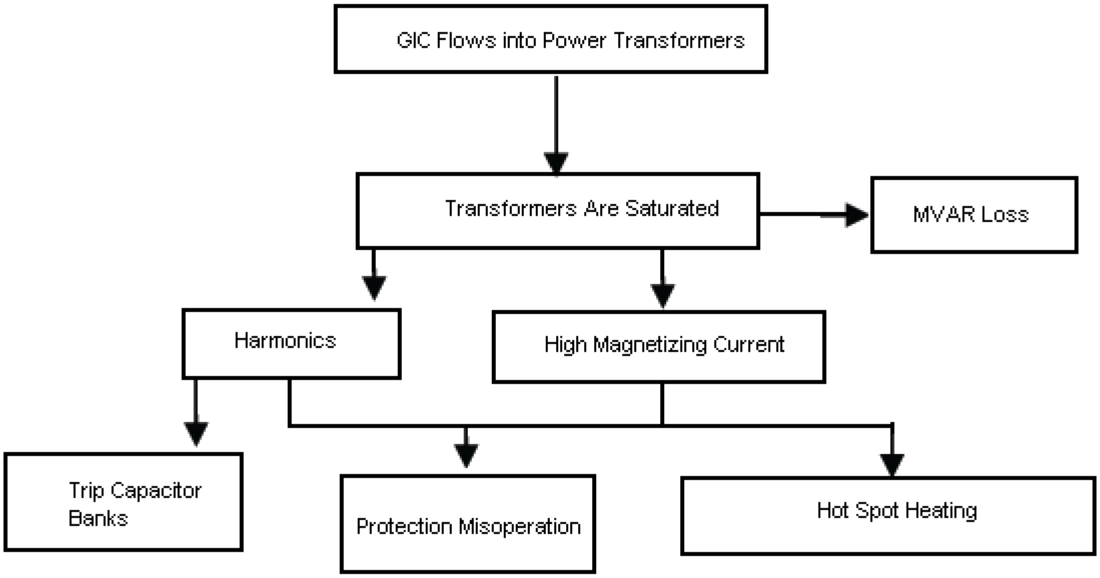


Figure 1 GIC's Effects on Power Systems

Different protection elements are affected in different ways. For example, an electromechanical over-current relay is sensitive to harmonics generated by the GIC but microprocessor-based protections are immune to harmonics since all harmonics have been removed by either analog or digital filters.

GIC's impacts on individual protection elements and CTs, and VTs have been analyzed and tested [9, 10, and 13]. However, authors of this paper have not found papers to provide a simple method to assess the GIC's effect on the protections that are in service. It is very important to know exact location where a specific protection may have a GIC issue so that a certain action can be taken to deal with the issue.

This paper proposes a method to assess the impact of GIC on protection system. With this method, assessment of a complicated GIC issue is converted to a simple fault calculation. With fault currents, voltages and impedances, protection engineers can easily assess the operational performance of any protection during GIC. According to these assessment results, different actions may be taken to address different problems. The benefit of this method is that we can save huge equipment investment since the assessment result will show the exact equipment with GIC issue.

Since saturation of power transformers due to GIC is the root cause to influence the operational performance of protection relays, the analysis and assessment start from transformer model.

2.0 Transformer Model during GIC

When a transformer is subjected to GIC, the dc current generates a dc flux offset superimposed on the normal ac flux and results in a shifted core flux, as shown in Figure 2.

If the peak of the total flux enters the saturation region of the core magnetization characteristic, the transformer is driven into half-cycle saturation. As such, the transformer magnetizing current Im_{AC}, which is small under normal symmetric excitation condition, increases to the unidirectional magnetizing current Im_{GIC}, under the GIC conditions.

Figure 3 depicts the calculated frequency spectrum of the magnetizing current of a typical three-phase 500kV-750 MVA power transformer, when the transformer is subjected to the GIC magnitude of 100A observed at the neutral point of the transformer. This current corresponds to 100/3=33.3 A/phase GIC, since the geomagnetic disturbance induces the same magnitude of GIC on three phases. Due to both unsymmetrical excitation and nonlinearity of the core, the magnetizing current contains both even and odd harmonics with high magnitudes comparable with the fundamental component. The flow of the harmonics in the power system creates power loss, can overload the capacitor banks, increases the possibility of the resonance in the power system, and may cause mal-operation of the protective relays due to the distorted voltage and current signals.

Fig. 3 shows the corresponding total harmonic distortion (THD) of the magnetizing current which exceeds 200% at the lower levels of GIC and decreases at higher GIC levels. It should be noted that in practice the harmonic magnitudes are attenuated by the system impedances and capacitances and the realistic THD is smaller than that shown in Fig. 3, as presented in Table 1.

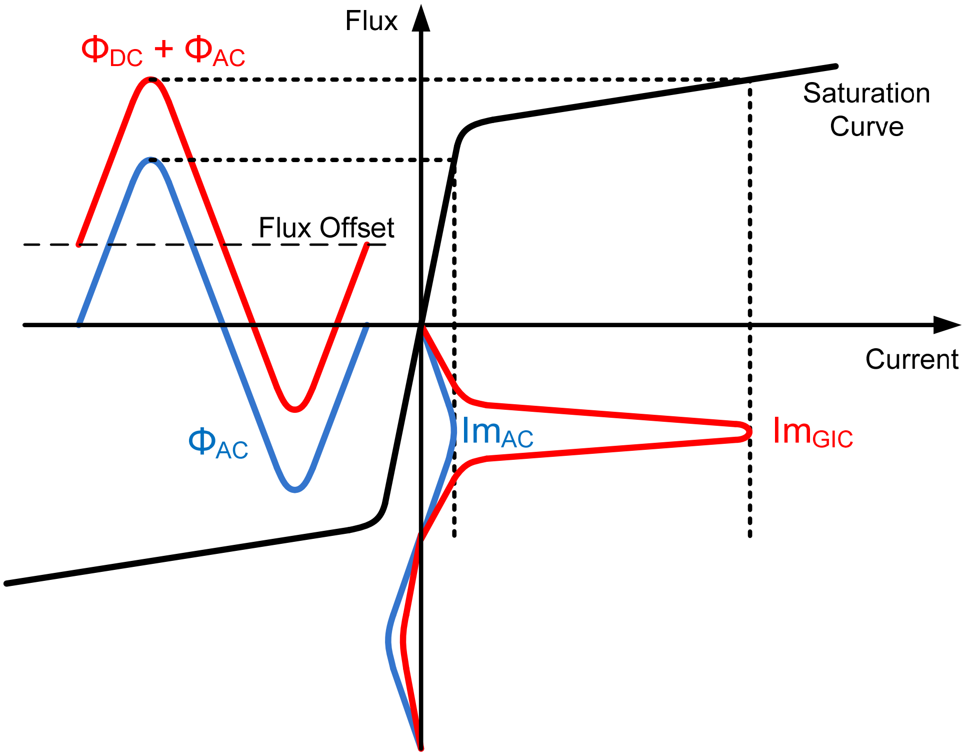


Figure 2 Half-cycle saturation of the transformer core due to GIC

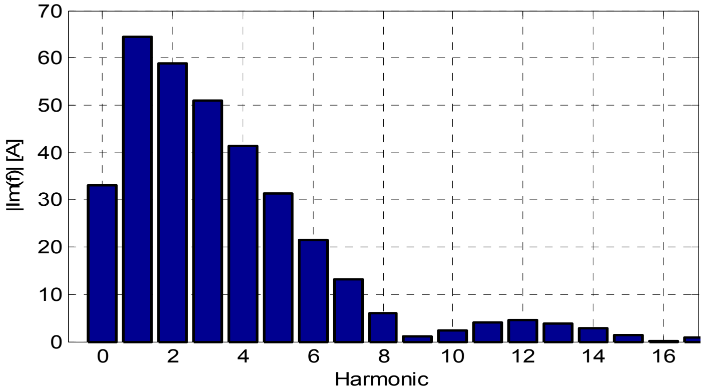


Figure 3 Harmonics of a typical 500kV transformer magnetizing current at GIC=33.3 A/phase (100A at the neutral point of the transformer)

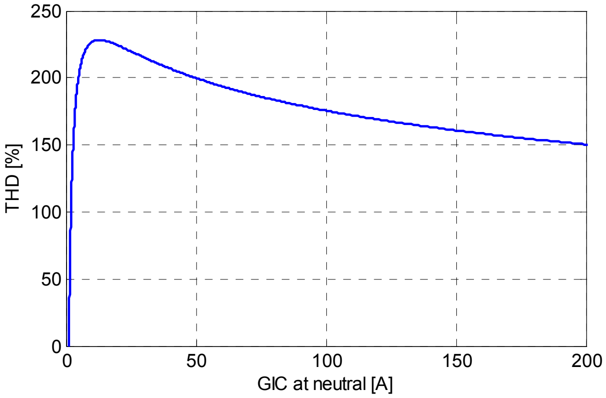


Figure 4 Total Harmonic Distortion (THD) corresponding to the frequency spectrum of Figure 3

Due to diversity in transformer core and winding configurations, different transformer types behave differently under GIC conditions. For the assessment of the protection system vulnerability to GIC, Table 1 also provides the ratio of the fundamental component of the transformer magnetizing current to the magnitude of the GIC. In Table 1, the higher possible limits are given such that the severe GIC conditions are taken into account and therefore, the relay behaviors are examined under such conditions.

Table 1 Fundamental magnetizing current increase and the harmonic distortion under GIC conditions

Transformer core type	Ratio of per phase magnetizing current I_1/I_{GIC}	THD (%)	
		@ low GIC	@ high GIC
Single-phase transformers bank	1.4 - 2	190	140
5-limb or shell-type	1.14	170	130
3-limb	1.14	170	130

In the table, “@ low GIC” stands for the conditions in which the GIC level is not much higher than the transformer knee point current, e.g., 5A/phase GIC, whereas “@ high GIC” corresponds to the THD at a high GIC levels, e.g. 16.7A/phase or higher. As the GIC magnitude increases, the magnitude of THD decreases. For simplification purpose, THD value “@high GIC” can be used for the analysis a high GIC condition.

The transformer behaviors during GIC conditions are as follows:

Transformer bank consisting of single-phase transformers: Extensive analyses have shown that the transformer banks consisting of three single-phase transformers are the most vulnerable type to GIC. A small amount of GIC is enough to drive the transformer core into saturation. Under balanced system voltage, when the transformers are subjected to GIC all three units equally saturate and produce the same odd and even current harmonics. While the phase current includes both even and odd harmonics, the neutral current of the transformer bank mainly consists of the dc current (GIC) and triplen harmonics (such as 3rd, 6th, 9th,harmonics). However, if the system ac voltage becomes unbalanced, the neutral current contains all frequency components.

Five-limb and shell-type cores three-phase transformers: Five-limb and shell-type cores represent almost similar behaviors under GIC and therefore these transformers are included in the same category in Table 1. These transformers are less prone to GIC as compared with single-phase units and represent lower saturation level. As such, the rate of increase of magnetizing current and the THD level is also lower. Unlike single phase units, in five-limb and shell-type transformers, even under balanced voltage conditions, the neutral current (zero sequence) includes dc and all even and odd harmonics. The middle phase draws less (can reach 60%) fundamental frequency magnetizing current with respect to the outer phases but with higher THD.

Three-limb three-phase transformers: the behavior of this type under GIC conditions is the most complicated one and the assessment of three-limb core saturation needs additional parameters which are not usually provided by the manufacturers or the transformer test sheets. In general, this type is the least vulnerable transformer type to GIC. However, to take a conservative worst case scenario and take into account a severe GIC and saturation conditions, the parameters of Table 1 for this transformer type are given the same as five-limb core transformers.

The modern microprocessor (IED) and solid-state protective relays make decision based on fundamental components of the current/voltage signals, whereas the electromechanical relays are based on the r.m.s. values of the measured voltage/current signals. In Table 1, the given ratio of the fundamental frequency magnetizing current to the GIC current can be directly used for IED relays. However, the r.m.s. current I_{rms} for electromechanical relays, can be deduced from the following equation, based on the given *THD* and the associated fundamental frequency current I_1.

$$I_{rms} = I_1\sqrt{1+THD^2} \tag{1}$$

3.0 Assessment of GIC's Influence on Protection Systems

The model described above is based on an infinite power system with a certain value of GIC input. In a real power system, in additional to the transformer's parameters, the magnetizing current drawn by a saturated transformer also is determined by system's parameters. According to Figure 2, the magnitude of the magnetizing current is a function of magnetic flux in the transformer core. The magnetic flux is proportional to the voltage applied on the transformer. The voltage at the terminal of the transformer also is related to the current from the grid. When GIC are injected into a transformer, its magnetizing current increases. The increase of the current normally causes the voltage to drop down. The voltage down will pull the magnetizing current back to a stable level, which is lower than the level if the transformer is supplied by an infinite system. Therefore, in addition to magnitude of GIC, the GIC's effect on the power system depends on transformer parameters, system configuration, and transformer's location.

The analysis on the impact of GIC on protections in service is different from analysis on individual relay in a lab. For example, if two transformers with same parameters are connected to the grid at different locations with different equivalent system impedances, the magnetizing currents of each transformer caused by GIC shall be different. Therefore, the influence of GIC should be analyzed by connecting the transformer into a real grid.

A current differential protection of a transformer is set with a threshold value to avoid misoperation due to all types of measurement errors. The threshold value normally is around 15%-40% of the rating current of the transformer. The magnetizing or excitation current of a power transformer is a leakage of a current differential protection. The magnetizing current in primary normally is at few amperes, which is much lower than the pickup threshold setting.

A transformer will draw high magnetizing current due to GIC. According to analysis in the part 2.0 on transformer model, 1 ampere of GIC will roughly generate 2 amperes of the fundamental component of magnetizing current if a rated voltage is applied on the transformer. For a certain value of GIC, when the applied voltage increases or decreases, the generated fundamental magnetizing current is higher or lower. For an applied voltage on the transformer, when GIC increases or decreases, the generated fundamental magnetizing current increases or decreases accordingly.

A complete transformer model shall include its magnetizing impedance and leakage impedances. The latter are linear impedances but the former is non-linear impedance. For most application on short circuit studies, the magnetizing impedances of transformers are input with a linear element or not required since their value usually are very large.

However, GIC may cause the transformer into deep saturation. At this saturation, the equivalent magnetizing impedance is much lower than its normal value. It is proper to consider the effect of the magnetizing impedance in transformer model when assessing GIC's effect.

Magnetizing impedance of a transformer is nonlinear. It is not realistic to build a short circuit fault database including all power transformers with nonlinear models. If a protection does not have any issue under high GIC event, there is not any protection under low GIC condition. If a protection does not have a GIC issue under lower GIC, we still need to know whether it will work properly under a heavy GIC condition. Therefore, it is enough that protection engineers assess the operational performance of the protections under the high GIC event. If we replace the transformer's magnetizing branch with linear impedance under a certain value of GIC, the assessment of GIC effect can be done by conducting a fault through a certain value of impedance, which is used to model a transformer magnetizing impedance. If so, a complicated GIC event will be converted into a simple fault study.

We can model this GIC issue by paralleling one branch of impedance between the transformer terminal and neutral. Since GIC only flows into a grounded transformer, the paralleled impedance should be a neutral-grounded configuration. The characteristics of the magnetizing impedance determine that the impedance almost is a pure inductance. As description above, if one ampere of GIC flows into a transformer from its one winding, a roughly 2 amperes of fundament content of the magnetizing current will be generated if a rated voltage is applied on the transformer. For a 500kV transformer, if GIC is 66.6 amperes per phase or 200 amperes at the transformer neutral, it is equivalent to insert an inductance with a value as below,

$$Zm = \frac{500kV/\sqrt{3}}{66.6A \times 2} = 2167\Omega$$

To assess the operation behavior protection during GIC, we prefer to use a higher magnetizing current, therefore, we use $Zm = 2000\Omega$ for fault calculations. This value corresponds to a magnetizing current under 500kV

$$Igic = \frac{500kV/\sqrt{3}}{2000 \times 2} = 72A/\,phase$$

200 amperes at neutral or 66.6 amperes per phase is commonly considered very high magnitude of GIC to cause some serious problem.

If there are several transformers in one station, magnetizing impedance of each transformer suffering GIC shall be dealt with similar method as above. These new added impedances should be connected in parallel. The final impedance will be

$$Zm = 2000/N$$

At 220kV level, the ratio of the magnetizing current to GIC is same as the ratio at 500kV with 1.4-2.0. We still choose 2.0 to assess the GIC's effect. The impedance for calculating the magnetizing current will be

$$Zm = \frac{220kV/\sqrt{3}}{66.6A \times 2} = 954\Omega$$

We choose $Zm = 900\Omega$ for fault calculations. For more than one transformer in a parallel, the final impedance for GIC assessment will be

$$Zm = 900/N$$

Since GIC is a space weather event caused by solar storm, it may make multiple transformers at different stations to be saturated with different saturation degrees. Protection engineers only want to know the operational behavior of the protections under the worst case scenario. Following will describe assessment methods for different kinds of protection. Since all GIC issues of protections are caused by the transformer saturation, we will begin from transformer differential protection.

.3.1 GIC’s Impact on Transformer Current Differential Protections

The current differential protection of a transformer consists of three parts: a) pickup element; b) percentage differential element; and c) the second harmonics restraint element as shown in Figure 5.

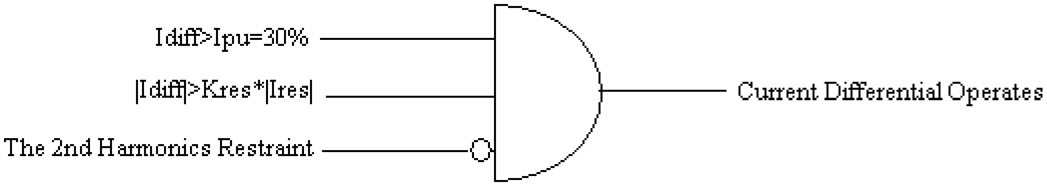


Figure 5 Operational Principle of Current Differential Protection

3.1.1Pickup Element

For current differential protection, both load current and external fault current are through current. They don’t contribute the differential current. Therefore, the current differential protection of a transformer will not be caused to pick up or operate due to saturation of other transformers.

Magnetizing current increment due to the transformer core saturation caused by GIC will increase the differential current. For example, for a 500kV-750MVA three-phase transformer, the pickup threshold value of the current differential protection is set with 30% of the transformer rating current, that is,

$$Ipu750 = 30\% \times \frac{750MVA}{\sqrt{3} \times 500kV} = 260 amperes$$

This value corresponds to 130 amperes of GIC per phase or 390 amperes at transformer neutral. It almost is 2 times higher than the highest GIC value. Therefore, GIC will not cause this differential protection to operate if it is set with 30% of the transformer rated current.

Similarly, for a 500kV-360MVA transformer, its pick threshold is set with 30% of the rated current, that is,

$$Ipu360 = 30\% \times \frac{360MVA}{\sqrt{3} \times 500kV} = 124amperes$$

This value corresponds to 62 amperes of GIC per phase or 186 amperes at transformer neutral. It is below the maximum GIC record value. There, the 200amperes of GIC will cause the differential protection to pick up.

From the analysis above, we can see that the differential protection for a larger transformer is more stable than the differential protection for a smaller transformer.

3.1.2Second Harmonics Restraint Element

The magnitude of the magnetizing current caused by GIC determines that the transformer core operates at the lower part of the saturation region of B-H curve, within which there is high percentage of the harmonic content. Since GIC is a quasi-DC component, there are high even orders of harmonics including the second harmonics. When a transformer is energized, the magnetizing inrush current is normally 8-20 times of the rating current. For the inrush condition, magnetizing flux in the transformer core is on the high part of the B-H curve. The magnetizing current caused by GIC is normally lower than the rating current of the transformer. At the low part of the B-_ curve, the ratio of the second harmonics to the fundament content in the magnetizing current is higher than at the high part. Since at the high part, the second harmonics can normally restrain the fundament component in the magnetizing current, at the low part of the B-H curve, the second harmonics is high enough to restrain the fundamental component. The differential protection will not operate during GIC.

The final conclusion on is that the second harmonics restraint characteristic ensures that the differential protection does not loss its security no matter whether or not the pickup element or the percentage differential element operates.

3.2 GIC’s Influence on Line Distance Protections

According to 3.0, the model of a saturated transformer should include its magnetizing impedance. For a 500kV transformer, the saturated magnetizing impedance is around 2000 Ω. It is equivalent to be a 4000km of transmission line. A distance relay can not react on so high fault impedance. If there are multiple transformers in one station, the simulated impedance will be reduced, but, it still too high for a distance to operate. Therefore, a distance protection will not lose its security due to GIC.

3.3 GIC’s Influence on Capacitor-Bank Protections

3.3.1 Voltage across Capacitor Bank

The saturation of some transformers caused by GIC is equivalent to addition of the some inductive branches within the power grid. The inductive branches will draw reactive power.

The direct effect of the inductive elements is to pull node voltages down. The static capacitor banks at stations are used to provide the reactive power to compensate the loss of the reactive power. The output of the reactive power supplied by the capacitor banks is proportional to the square of the bus voltage. The low voltage will sharply reduce the output of the reactive power of the capacitor bank. The decrease of the reactive output will further pull the voltage down.

This part assesses the voltage across the capacitor bank by assuming that all transformers at local station and other stations are in saturation. The saturation of each transformer is simulated by adding the paralleled inductance with the transformer as its magnetizing impedance.

Since it is not feasible to assess the capacitor bank voltage by adding parallel impedance for all transformers within entire grid, the impedance only is installed for the local transformers and transformers at surrounding stations. The effect of the saturated transformers at other stations without direct connection with the local station where the capacitor bank is located will be represented with by reducing the impedance value to one third of its original magnetizing impedance of each transformer at local or surrounding stations. It is equivalent to triple the amount of the saturated transformers near the capacitors.

According to the description on the simulation method, the magnetizing impedance of each 220kV saturated transformer will be simulated with a 300Ω instead of 900Ω. The assessment is conducted with a short-circuit program. The program calculates the fundamental contents of voltages and currents. The harmonics will be analyzed separately.

Following example demonstrates the detail procedure of the assessment for a capacitor bank as shown in Figure 3.6.

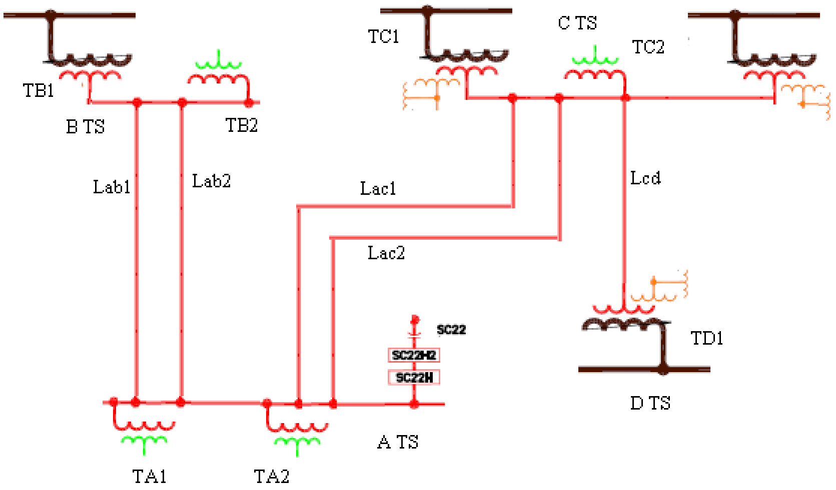


Figure 6 an Example to Assess Capacitor Voltage

The saturation of a transformer is simulated with one inductance paralleled with the transformer. The inductance will be 300Ω at 220kV bus for each transformer. If there is more than one transformer at the bus, the inductance value will be reduced accordingly

$$Zm = 300\Omega / N$$

In Figure 6, a capacitor bank SC22 is located at A TS. There are other neighboring stations B, C TS connected with A TS. D TS is connected with C TS with a transmission line but without direct connection with A TS.

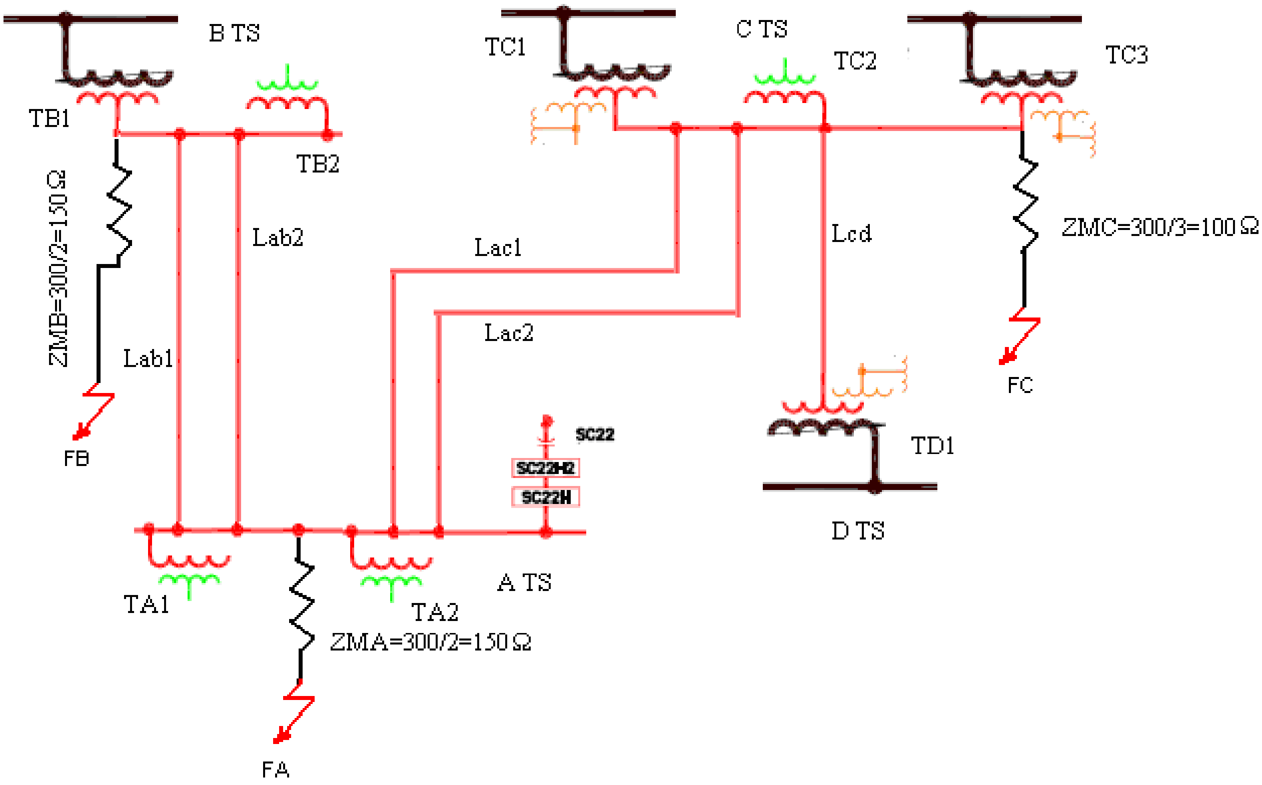


Figure 7 Simulating the saturation of transformers at Different Stations

3.3.2 Current into Capacitor Bank

The saturation of transformers due to GIC will generate high magnetizing current including the fundamental and harmonic contents. The magnetizing current will distribute within entire grid. The distribution of the magnetizing current depends on system configuration and impedance of each element.

A capacitor bank is a low impedance sink for harmonic content. Its distribution is different from distribution of the fundamental content. When some nearby transformers are driven into saturation by GIC, the current into the capacitor bank consists of the fundamental and harmonic contents. The fundamental content is proportional to the fundamental voltage across the bank. It can be calculated with a short circuit program. Harmonics can be estimated as below.

The RMS value of the total current determines the heat effect inside the capacitor bank. The fuse and electromechanical over-current protections react on the RMS value of the current. The high RMS value of the current will blow the fuse or make the over-current protection operate. Both will further pull the voltage down.

If the normal voltage across the capacitor bank is U1 before the transformers are saturated and U2 is the voltage after the transformers are saturated, the fundamental current into the bank when the transformers are saturated will be

$$I_{2\,fdm} = U_2 \cdot \omega C \qquad (2)$$

Before the saturation of the transformers, the current through the bank is

$$I_{1\,fdm} = U_1 \cdot \omega C \qquad (3)$$

The difference between two currents is caused by the saturation, that is, the appearance of the magnetizing current due to GIC. Therefore, the difference of two currents is a portion of the total magnetizing current from all saturated transformers in the grid.

Since impedances of both lines and capacitor banks are frequency-dependent, it is difficult to determine the distribution factor of the harmonics from the saturated transformers caused by GIC. Following simplified assessment on the current into the capacitor bank utilizes the calculation on the voltage across the bank.

As the frequency increases, the impedance of capacitor bank decreases and the impedances of lines increase. It appears that the THD of current into the capacitor bank should be higher than that of currents from the saturated transformers.

In Hydro One’s grid, all capacitor banks have floating neutral. However, all zero sequence components including the third and sixth harmonics will not flow into the capacitor bank. Therefore, we can not simply conclude that the RMS value into capacitor banks definitely exceed its rated value.

In the harmonic contents of the magnetizing current of the saturated transformers, the lower frequency components have higher magnitude than the higher frequency components, for example, the second and fourth harmonics have much higher magnitude than the fifth and the seventh harmonics. At the lower frequency range, the impedance of the capacitor bank is usually the higher than most of line impedances close to the capacitor bank. Percentage of the harmonic current to capacitor bank may be lower than the percentage to the lines.

At higher frequency range, as the line impedances increase and the impedance of the capacitor bank decreases. The contribution of the high frequency harmonics from other stations may reduce as the increase of the frequency. Even though the more harmonics with higher frequency from local station flow into the bank, the percentage of the harmonics will not be significantly high since the magnitude of the higher frequency harmonics is usually lower.

Therefore, after considering all factors discussed above, the harmonics in the magnetizing current also is distributed in similar proportion. In order to cover all calculation errors including model limitation, we choose 2.5 instead of 1.9 as new THD of current through capacitor bank. Therefore, the harmonic current will be

$$I_{2hrm} = (I_{1fdm} - I_{2fdm}) \cdot 2.5$$

Or

$$I_{2hrm} = (U_2 - U_1) \cdot \omega C \cdot 2.5 \tag{4}$$

In order to keep the capacitor bank from being damaged by high RMS value of the current,

$$I_{RMS} = \sqrt{I^2_{2fmd} + I^2_{2hrm}}$$

$$= \sqrt{((U_2) \cdot \omega C)^2 + ((U_2 - U_1) \cdot \omega C \cdot 2.5)^2} < 1.35Un \cdot \omega C$$

Or

$$\sqrt{U_2{}^2 + 6.25(U_2 - U_1)^2} < 1.35Un \tag{5}$$

If $U1 = 1.136Un = 1.136 \times 220kV = 250kV$ from (5),

$$0.67Un < U2 < 1.29In$$

Since GIC always cause the voltage low, therefore,

$$0.67Un < U2 < 1.0Un \tag{6}$$

It shows that the RMS value of the total current through the capacitor bank will not exceed its maximum current limit if the voltage is above 67% of the rated voltage.

The assessment shows that the voltage across the capacitor bank will not reach so low level when the transformers are driven into saturation by GIC. Therefore, the GIC will not cause fuses in capacitor cans to blow or over-current protection to operate.

3.4 GIC's Influence on Zero-Sequence Over-Current Protections

A zero sequence over-current element usually is used to clear a high resistance ground fault or open phase condition. Saturation of transformers due to GIC will generate zero sequence current flowing within entire grid. The zero sequence current may impact on the zero sequence over-current protections Since GIC may last up to several minutes or hours, it is necessary to examine the operational performance of both instantaneous and the timed over-current elements. As the timed elements have lower pickup threshold value than the instantaneous elements, we will mainly focus on the timed elements.

3.4.1 Transformer Symmetrical Saturation (Three Phases)

Transformer symmetrical saturation stands for three legs of the transformer cores in same saturation degree. For symmetrical saturation, a comprehensive analysis on three phases of magnetizing current provides the following conclusions:

1. The fundamental content in the zero sequence current under all of the three phases of saturation of the transformer has been eliminated since the fundamental components in each of the three phases are $120°$ apart in the positive sequence order and of the same magnitude.
2. The second, fourth and fifth harmonics have been removed since they are balanced and $120°$ apart in each phase.
3. The third and sixth harmonics may exist in each phase of the magnetizing current. The magnitude depends on the saturation degree of the transformer core. For a single-phase transformer is 190% at low GIC and 140% at high GIC. Since the total current consists of the positive, negative and zero sequences contents. The 3rd and 6th are main contents in the zero sequence current. In fact, in each phase of current, the 2nd and 4th harmonics are higher than the 3rd and the 6th harmonics; therefore, it is safe to say that the RMS of the zero sequence current is equal to the magnitude of the fundamental content in the phase current.
4. Since the impedances of all lines and transformers have linear relation with frequency of the harmonics at same ratio, the distribution factors of the zero sequence contents of harmonics are same as those of fundamental components.

Because an electromechanical relay operates on the RMS value basis, the harmonic contents in the zero sequence current will make the RMS value be greater than the fundamental value as (1). Therefore, the old electromechanical over-current relays are sensitive to harmonics caused by GIC.

Since the harmonics have been removed with analog or digital filters for microprocessor-based (IED), the symmetrical saturation of a transformer does not generate zero sequence current output in IED relays, that is, IED-based zero sequence over-current protection will not be affected by GIC.

3.4.2 Transformer Asymmetrical Saturation

A large capacity of 500kV generally consists of 3 single-phase transformers. Due to difference of material of cores among 3 single-phase transformers, the 3 single-phase transformers may experience different degrees of saturation or asymmetrical saturation degree. Unlike symmetrical saturation of a transformer, an asymmetrical saturated transformer will draw an imbalanced current with both the fundamental and harmonic contents. The fundamental content of the current may influence all types of zero sequence over-current relays.

It is not reasonable to assume that one leg of the core is in full saturation while other two legs of the core are not in saturation since GIC into each phase is same. Therefore, the saturation degree must be carefully assessed.

There are following possible saturation conditions:

1) Two phases are not in saturation while one phase is in saturation but degree is not deep or in half deep saturation;

2) One phase is in deep saturation while other two phases are in saturation but degrees are not deep or in half deep saturation;
3) One phase is in saturation but degree is not deep or in half deep saturation while other two phases are in deep saturation
4) One phase is not in saturation while other two phases are in saturation but degrees are not deep or in half deep saturation.

In order to simplify the calculation, we assume there are two saturation statuses: deep saturation or full saturation and half deep saturation. For a full or deep saturation, we use 200 amperes of GIC at neutral. It is equivalent to add a 2000Ω at 500kV or 900Ω at 220kV of inductance to calculate a fault. For a half deep saturation, we use 100 amperes of GIC at neutral. It is equivalent to add a 4000Ω at 500kV or 1800Ω at 220kV of inductance to calculate a fault.

For full saturation, if there are multiple transformers at same station, the inductance for a fault study at a 500kV bus will be

$$Zm = 2000\Omega / N \tag{7}$$

And at a 220kV bus,

$$Zm = 900\Omega / N \tag{8}$$

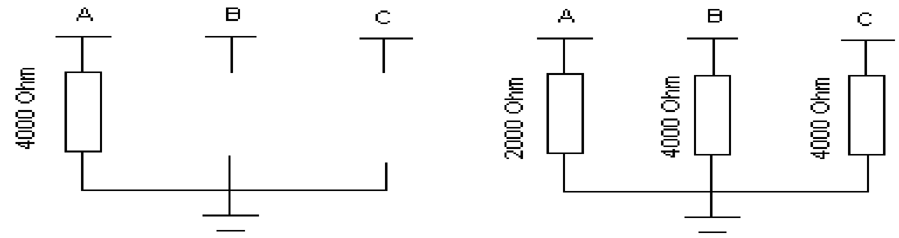
For half saturation, if there are multiple transformers at same station, the inductance for a fault study at a 500kV bus will be

$$Zm = 4000\Omega / N \tag{9}$$

And at a 220kV bus,

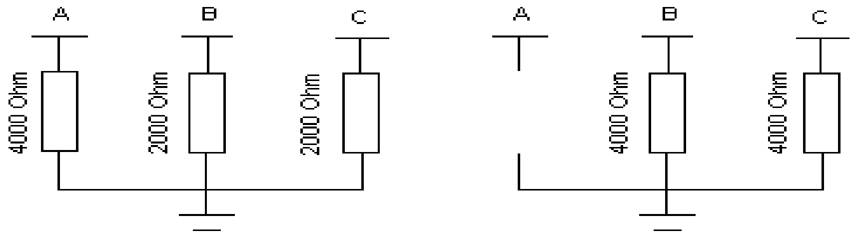
$$Zm = 1800\Omega / N \tag{10}$$

Four different saturation conditions can be simulated with following fault network.



(a) One Phase in Half Saturation
Two Phase No Saturation

(b) One Phase in Full Saturation
Two Phases in Half Saturation



(c) One Phase in Half Saturation
Two Phases in Full Saturation

(d) One Phase No Saturation
Two Phases in Full Saturation

Figure 8 Fault Branch for Asymmetrical Saturation Models

With the fault networks in Figure 8, we can conduct a fault to check the zero sequence flowing along specific line to assess whether the zero sequence over-current protection is influenced by GIC.

4.0 Applications and Conclusions

An assessment method of GIC’s impact on protection systems has been proposed. The method uses a simplified transformer model to simulate a saturated transformer.

1) The proposed method can easily be used to assess GIC effect on protection systems by some commercial fault study program.
2) This method can assess both asymmetrical and symmetrical saturation condition for multiple transformers.
3) The assessment result can provide a technical support for the decision to mitigate GIC impact on protection systems.
4) The proposed method can benefit power utilities on saving capital investment since the result can show which protection may experience GIC issue.

In order to avoid serious power blackout during GIC event, all 220kV and 500kV transformer protections, line protections in Hydro One’s grid have been assessed by proposed method. The assessment result shows that most protections will not lose their security. Some old electromechanical zero sequence over-current relays may operate if GIC current is very high. If these relays are replaced with new IED protections, the problem will not exist. The replacement of the old electromechanical relays is in progress.

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6.0 Biographies

Fenghai Sui received his Bachelor's degree from Northeast Electric Power Engineering Institute in China in 1984 and M. Sc degree in from Xi'an JiaoTong University in China in 1987, both in electrical power engineering. Since then, he had worked in Nanjing Automation Research Institute (NARI) in China for 13 years on development and design of microprocessor-based protections. From 1996, he was a senior protection development engineer.

Fenghai joined in Hydro One Networks Inc. in 2006. Currently, he is a senior network management engineer in Hydro One Networks Inc, Toronto, ON. He is a senior IEEE member and a member of IEEE/PES.

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Afshin Rezaei-Zare (M'08, SM'10) obtained his B.Sc., M.Sc., with honor from The University of Tehran, Iran, in 1998 and 2000, respectively. He obtained his Ph.D. degree under supervision from the University of Tehran and the University of Toronto, Canada, in 2007. From 2007 to 2009, he was a Post-Doctoral Fellow with the Center for Applied Power Engineering (CAPE), ECE Department, University of Toronto, Canada. Since 2010, He has been with the Department of Special Studies and Professional Development, Hydro One Networks Inc., Toronto, Canada. His research interests include the development of new models for the Electromagnetic Transient Programs, Analysis of Electromagnetic Transients in T&D Power Systems and Apparatus, Numerical Solution Techniques, Modeling and Analysis of Power Transformers, and High Voltage Phenomena.

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Miroslav Kostic received his dipl. ing. degree in Power Systems from University of Belgrade in 1984. He has held positions in engineering, project management and management at transmission utility Elektroistok in Krusevac, Serbia, Westinghouse and Eaton Electrical in Toronto, Canada, ABB in Baden, Switzerland. He has provided training in the protective relaying in Canada and USA and presented at IEEE conference in Montreal. Miroslav Currently is P&C Planning Manager for Transmission at Hydro One Networks Inc. in Toronto, ON.

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Pankajkumar Sharma received his bachelor of electrical engineering in 1985 from Saurashtra University, Gujarat, India. He began his 25-year professional career in power systems when he joined Gujarat State Electricity Board in India, where he worked for 17 years. As a divisional manager in the transmission department, Pankaj commissioned and operated a number of EHV transformer switching stations and transmission lines. In 2002, he joined Canadian Electrical Services as a design engineer with a focus on optimizing transformer windings and minimizing core-copper losses. For a short period, Pankaj worked at Toronto Hydro as a project manager. In 2006, he joined Hydro One Networks Inc., where he is currently a sustainment manager in the protection and control department and is responsible for the adequacy of the protection and control at substations. Pankajkumar is also accountable for technical interconnection requirements for distribution generation.

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