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GIC Flow Characteristics and Mitigation

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SUMMARY

The geomagnetically induced current (GIC) is a quasi-DC current which can cause transformer saturation and reactive power losses. Based on the analysis of GIC flow characteristics in power grid, this paper has introduced two novel concepts which are System Edge and GIC Active Circuit for determining the most vulnerable spots in power system under the threat of GIC in all conditions. With these two concepts, the performance of series capacitor and transformer neutral blocking as GIC mitigation strategies have been evaluated. This paper has demonstrated that blocking line-GIC may elevate the transformer effective GIC and blocking GIC at transformer neutral point could shift GIC related problems to neighboring areas.

KEYWORDS

GIC, transformer neutral blocking, series capacitor, effective GIC

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1. Introduction

The North American Electric Reliability Corporation (NERC) has issued TPL-007-1 standards to address the transmission system planned performance during geomagnetic disturbances [1]. The standards require responsible entities to perform the vulnerability assessment based on the benchmark GMD event which is defined by geoelectric field magnitude and angle. According to NERC Benchmark GMD Whitepaper [2], the regional geoelectric field peak amplitude is calculated by:

$$\text{Epeak} = 8 \times \alpha \times \beta \text{ (V/km)} \tag{1}$$

In equation (1) α is the scaling factor for geomagnetic latitude and β is the scaling factor for earth conductivity. For steady-state GIC and load flow analysis, the angle of the geoelectric field is assumed to be variable. However, the orientation is uniform throughout the system.

Based on the vulnerability assessment result, the TPL-007-1 standard requires responsible entities to develop corrective action plans to meet the performance requirements. These plans include but are not limited to installation, modification, retirement or removal of transmission and generation facilities, protection systems, operation procedures and demand-side new technologies. AEP has investigated possible approaches and found they are able to mitigate the threat locally but at the same time often create new problems in nearby areas. In this paper two new concepts called System Edge and GIC Active Circuit are introduced to study the characteristic of GIC flow in the power grid. The performance of two popular mitigation strategies, neutral blocking and series capacitor are also evaluated using these two concepts with respect to the change of GIC flow pattern before and after installing these equipment. The GIC flow in this paper is assumed to have a uniform geoelectric field orientation which is in accordance with the NERC whitepaper.

2. Effective GIC

One of the important geomagnetic effects on power systems is transformer saturation, which leads to harmonics and reactive power losses [3]. The concept of effective GIC is used to measure the severity of GIC impact on transformers. By its definition, effective GIC is calculated as the summation of transformer high voltage side and low voltage side GICs with the consideration of winding ratios to represent the overall impact to the transformer.

$$I_{E-GIC} = \frac{\alpha_t I_H + I_L}{\alpha_t} = I_H + (I_N / 3 - I_H) V_X / V_H \tag{2}$$

In equation (2), I_H is the per phase DC current injected into transformer high side, I_L is the per phase DC current injected into transformer low side, I_N is the neutral DC current (3-phase), α_t is the transformer turns ratio, $\alpha_t = V_H/V_X$, V_H is the rated voltage at the HV terminals and V_X is the rated voltage at the LV terminals.

In this paper, the change of GIC flow characteristics is measured by effective GIC values. The mitigation strategies are also evaluated with respect to their abilities to reduce transformer effective GIC.

3. GIC Flow Characteristic

3.1. System Edge

Transformers at the system boundary often exhibit high effective GIC [5]. A hypothetical system showed in Figure 1 is used to demonstrate this phenomenon. The system consists of four substations on the same latitude connected by three straight transmission lines. Thus, with uniform geoelectric orientation, GICs flow in the same direction in the three transmission lines. The four transformers in Figure 1 are defined as two-winding, Wye grounded–delta connections and there is no GIC flow on the transformer low side. The effective GIC is the GIC entering the transformer high side terminals. By drawing the three GICs, it can be noticed that GIC1 and GIC2 flow in opposite directions as transformer 2. Also, GIC2 and GIC3 flow in opposite directions as at transformer 3. By Kirchhoff's Voltage Law, GICs would neutralize each other at opposite directions. The resulted effective values for these two transformers are |GIC1 – GIC2| and |GIC2 – GIC3|. Meanwhile, for transformer 1 and 4, which are at the system boundary, each transformer only carries one GIC flow that indicates their effective GICs are |GIC 1| and |GIC 3| respectively. It can be noticed that the effective GIC of transformers connected by transmission lines on both sides is smaller than that of transformers at the end of a radial topology.

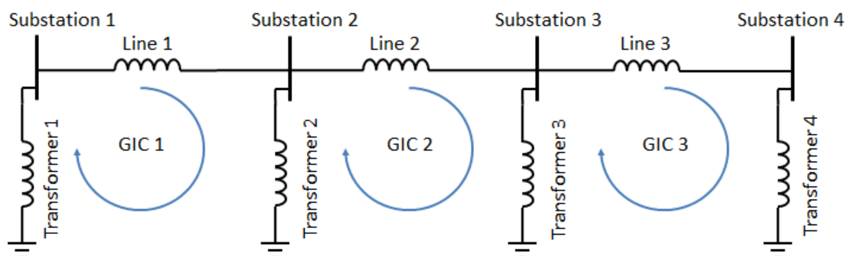

Figure 1. GIC flow in a single phase circuit

The simulation results confirmed that transformers at the System Edge always exhibit high levels of effective GIC. In the AEP East system interconnection, all transformers violating the 75A threshold specified by the TPL-001-1 standard are at the System Edge.

Reference [6] has demonstrated that the transformer neutral blocking device is not an efficient approach to reduce both the overall system GIC level and the individual transformer's effective GIC. The behavior of GIC at System Edge can be used to explain this further. Firstly, installing blockings device at the System Edge could eliminate GIC generated by the transmission line immediately connecting to it and possibly reduce effective GIC on that transformer. However, it creates another System Edge at the neighboring substation, which means more effective GIC could be observed there. In Figure 1, if the neutral blocking device is installed at Transformer 1, the flow path of GIC1 is blocked. This would result in 0 effective GIC at Transformer1. However, the effective GIC of transformer 2 would increase from |GIC1 – GIC2| to |-GIC2|. Blocking Transformer 1 has mitigated the problem for Transformer 1 but makes Transformer 2 more vulnerable. Secondly, if the blocking device is not installed at the System Edge, it would not eliminate GIC generation but force it to go to other places. Using the system in Figure 1 as an example, if the neutral blocking device is installed at Transformer 2, it will reduce the effective GIC of Transformer 2 to zero. Meanwhile, Transformer1 and Transformer3 could experience GIC flow generated by both Line1 and Line2. Although it is not simple summation, the effective GIC for the new topology can be approximated as |GIC1 + GIC2| and |GIC1 + GIC2 – GIC3| for transformer 1 and 3 respectively, which are not a reduction compared with the original system configuration.

3.2. GIC Active Circuit

The above section has discussed the simplest topology where only two circuits connecting to a substation and all substations are on the same latitude. In reality, a substation can have multiple outlets and be located anywhere relative to other substations. In this paper, the concept GIC Active Circuit is introduced to assess the severity of effective GIC with different possible system configurations.

The simplest scenario would be a substation connected by only one transmission line as shown in Figure 2 below. This configuration is similar to the System Edge concept in section 3.1. Since there is only one circuit feeding GIC to the substation, it can be said that the substation has one Active Circuit.

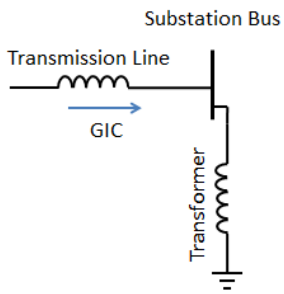

Figure 2. Example of one GIC Active Circuit

For two transmission lines connecting to a substation, according to their physical orientations, there will be three possible scenarios: (a) the two circuits are in the same quadrant, (b) the two circuits are in quadrants next to each other or (c) the two circuits are in opposite quadrants. Figure 3 illustrate these three scenarios.

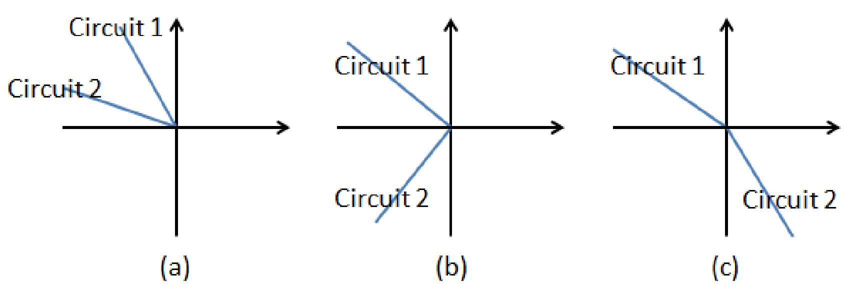

Figure 3. Position of transmission lines

For Figure 3 (a) and (b), since GICs generated by the two circuits have the same orientation, when they reach the substation, the only outlet is through the transformer to the ground. The resulted effective GIC at the substation transformer is the summation of two individual line GICs. Considering the concept of System Edge discussed in section 3a, substations with circuits orientated as in Figure 3(a) and (b) are equal to the System Edge with double-circuit connection. The effective GIC under these configurations will be higher than a substation connecting to only one conductor. Since in (a) and (b) there are two circuits feeding GIC, the number of GIC Active Circuits is counted as two. On the other hand, in figure 3 (c), GICs generated by two circuits are flowing opposite directions, which neutralize each other. There is no active circuit feeding GIC to the transformer. Therefore the number of GIC Active Circuit is counted as zero. Comparing with Figure 1, Figure 3 (a) and (b) are similar to substation 1 and 4 and (c) is similar to Substation 2 and 3.

In reality, a substation could have more than two connections. The concept of GIC Active Circuit can be extended to a more general form, which has more than two circuits connecting to the substation. Firstly, circuits could be divided into four quadrants. If there are two circuits in opposite quadrants, the two are marked as "inactive". After all matching pairs are marked out, the number of remaining circuits will be the number of GIC Active Circuits.

The number of GIC Active Circuits provides an overall estimation of the severity of effective GIC. The orientation of the electromagnetic field does not matter since the GIC of two circuits flowing opposite directions will always neutralize each other. During a geomagnetic disturbance event, only GIC Active Circuits contribute to the effective GIC of transformers. More GIC Active Circuits at a substation means that a higher effective GIC could be observed at transformers in that substation.

4. Existing Mitigation Strategies

According to NERC Geomagnetic Induced Current (GIC) Mitigation System Summary for White Paper [4], there are two major categories of mitigation strategies for GIC related problems. The first is line blocking using series capacitor banks [7] and the second is transformer neutral blocking, [8] and[9]. The performance of these two major strategies with System Edge and GIC Active Circuit concepts is analyzed in this paper.

4.1. Series Capacitor Banks

The main purpose of series capacitor banks is series compensation for transmission lines. GIC blocking is a byproduct due to the nature of the capacitor. Series capacitor banks can eliminate GIC flow on transmission lines. However, this does not mean it can always reduce effective GIC which is more important to the susceptibility of the power system.

Taking AEP's 345kV substation K as an example, (Figure 4), there are three circuits attached to substation K. Two of them go to substation A and S in the north and the third circuit goes to substation M in the south. If the series capacitor bank is installed on the transmission line K-M at substation K side, by using the GIC Active Circuit concept, without the series capacitor, the number of GIC Active Circuit is 1. Either K-S or K-A circuit can be the opposite pair of K-M circuit. When the series capacitor on the K-M circuit is in service, it blocks GIC path to substation M. Thus, substation K becomes the System Edge and the number of GIC Active Circuit for substation K has increased to 2. Although the series capacitor bank has eliminated GIC generated by circuit K-M, with 2 GIC Active Circuits, the effective GIC at substation K would be elevated dramatically. Simulations substantiate this conclusion. With 140 degree geoelectric field orientation and 3.52V/km intensity, the effective GIC has increased from 28.72A to 82.72A with the series capacitor bank switched on. Alternatively, if the series capacitor bank is installed on K-A or K-S circuit, the resulted GIC Active circuit will becomes 0 indicating smaller effective GIC at substation K. Table 1 has listed the effective GIC of the 345-138 kV transformer at substation K with series capacitor bank placement at each individual circuit. With the installation on K-A or K-S circuits, the effective GIC has reduced to at least 50% of its original level. Values in Table 2 are obtained with a 90 degree geoelectric field orientation. They also suggest the same conclusion. Because blocking circuit K-M could increase the number of GIC Active Circuits at substation K from 1 to 2, the blocking device on circuit K-M does not help to alleviate the GIC problem but intensifies it.

Table 1. Transformer effective GIC per phase (Amps, 140 degree orientation)

	Series capacitor on circuit K-A	Series capacitor on circuit K-S	Series capacitor on circuit K-M
Out of service	28.72	28.72	28.72
In service	6.26	13.28	82.72

Table 2. Transformer effective GIC per phase (Amps, 90 degree orientation)

	Series capacitor on circuit K-A	Series capacitor on circuit K-S	Series capacitor on circuit K-M
Out of service	16.17	16.17	16.17
In service	11.67	4.71	57.57

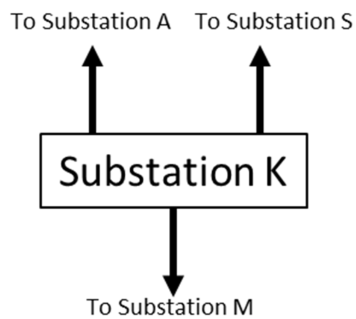

Figure 4. Substation K and its topology

By changing GIC flow pattern, the series capacitor influences transformer effective GIC values. The DC blocking feature may adversely affect GIC mitigation when the placement increases the number of GIC Active circuits.

4.2. Transformer neutral blocking.

Transformer neutral blocking devices are capacitors or resistors installed at transformer neutral-ground connections to completely cease or reduce the GIC flow through transformer windings. Various studies have pointed out that the blocking device could shift the problem to surrounding areas [10]. This paper uses AEP East interconnection to demonstrate the impact of neutral blocking devices. In Figure 5, the neutral blocking device is installed at the 765-345 kV transformer at substation 1. The transformer effective GICs at substation 2, 3 and 4 listed in Table 3 are measured before and after neutral blocking device in service.

It can be found from Table 3 that after blocking the neutral point of the transformer at substation 1, transformers at neighboring substations have a significant increase in their effective GICs. Especially in substation 3, the effective GIC is four times more than the value before neutral blocking.

Table 3. Impact of Neutral Blocking Device (Amp)

	Substation 2	Substation 3	Substation 4
Effective GIC (Amp) Before Neutral Blocking	TF1 = 59.050 TF2 = 97.230	13.651	TF1 = 11.304 TF2 = 11.274
Effective GIC (Amp) After Neutral Blocking	TF1 = 63.651 TF2 = 104.92	64.780	TF1 = 21.759 TF2 = 21.702

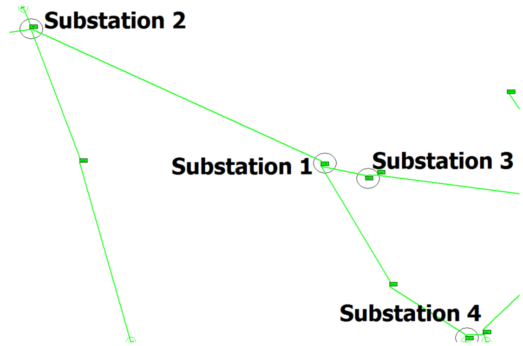

Figure 5. Transformer Neutral Blocking

The concept of GIC Active Circuit can be used to explain this phenomenon. When the neutral point has been blocked, GIC has lost the path to return to ground. From the stand point of GIC flow, the circuits from substation 1 to substation 2 and from substation 1 to substation 3 have been combined into a very long line. A longer circuit in the electromagnetic field means higher GIC current. The circuit at the opposite side of substation 3 is too short to counter the GIC generated by the new circuit. Essentially, the neutral blocking device at substation 1 changed the number of GIC Active Circuit at substation 3 from zero to one. This results in large amount of GIC flowing through the transformer at substation 3 and causes a significant elevation in effective GIC. For mitigating the GIC problem at substation 1, the neutral blocking device has shifted the problem to substations 2, 3 and 4.

In an AEP system, most of the EHV transformers are auto transformers. Neutral blocking devices are only able to block GIC in the common winding, but not the series winding. Auto transformers still exhibit effective GIC with neutral blocking devices installed. Meanwhile, it still elevates effective GIC levels in surrounding areas. The only way to guarantee the performance of neutral blocking is to install them for all transformers. However, in order to be compatible with various operating conditions, the neutral blocking devices need to meet a set of criteria such as maximum fault current up to 30,000 amps and 200 amp AC neutral imbalance current [1]. To deploy neutral blocking devices in a large scale will be an expensive option.

5. Conclusions

The concepts of System Edge and GIC Active Circuit have been introduced in this paper to study the GIC flow characteristics in the power grid and evaluate popular mitigation strategies. The two concepts disclosed the hidden nature of GIC flow in the power grid. It has been proven that improper placement of series capacitor banks can add an adverse effect during a GMD event. Also, the effect of transformer neutral blocking is limited, because only transformers equipped with neutral blocking device are protected. For auto transformers, neutral blocking can not completely eliminate the effective GIC at the local transformer and usually shifts GIC to nearby transformers.

At this time, the concept of GIC Active Circuits is still incomplete. The length of the transmission lines not considered. The substation could have a very short circuit on one side and a very long circuit on the other side. GICs generated by these two circuits are not cancelled. Moreover, the earth conductivity is also not taken into consideration. Therefore, the length ratio required to achieve significant GIC cancellation needs further investigation.

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