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Impact of Shunt Reactor Bank Switching on Transformer Neutral Geomagnetically Induced Current (GIC) Monitoring

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SUMMARY

This paper presents the results of simulations of observed DC neutral current transients on a 765/345 kV autotransformer bank associated with the switching of a shunt reactor on the 345 kV bus. These transients were observed by a recently installed GIC monitor on the neutral of the transformer bank and the simulations were carried out to study their association with the shunt reactor switching. The shunt reactor is rated at 250 Mvar, three phase, and is connected to the 345 kV bus by a circuit breaker. Key observations include:

- The switching of inductive devices inherently produces electrical transients. These transients are seen in both the voltage and current and can result in a decaying DC component in the current.

- The DC current produced is a function of the point on the voltage wave that each circuit breaker pole closes. Due to the phases being 120 degrees electrically apart, the DC current in each phase will typically be different (different point on wave closing points).

- The DC currents will flow in each phase (they are typically not the same in each phase due to system imbalances, etc.), add in nearby neutral connections of transformers with wye-grounded windings, and appear as a DC current transient to any device monitoring DC current in the transformers' neutrals.

KEYWORDS

GIC, reactor switching transients, DC neutral current, PSCAD/EMTDC

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I. Introduction

The following describes simulations conducted to investigate reactor bank switching at AEP's Breed 345 kV station and observed DC neutral current transients on the 765/345 kV autotransformer bank #1 at the nearby Sullivan station (see Figure 1). The DC current transients were observed during shunt reactor bank switching after the installation of a geomagnetically induced current (GIC) monitor on the neutral of Transformer #1. This monitor records DC current in the neutral of the transformer bank which, theoretically, if no DC current sources exist on the transmission system, should be the current induced by the Earth's geomagnetic field. This monitor has been recording DC neutral current transients coinciding with the Breed 345 kV reactor bank being switched online. The simulations were conducted in order to investigate the relationship of these transients with reactor bank switching and to potentially rule out any geomagnetic source.

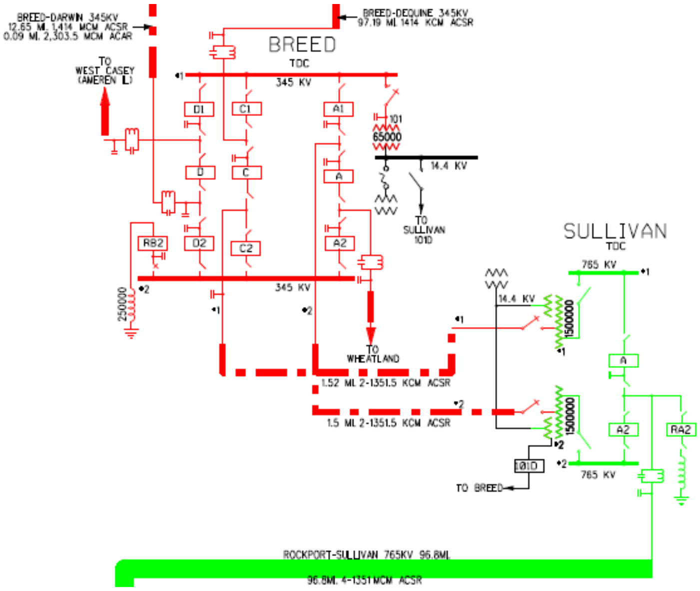
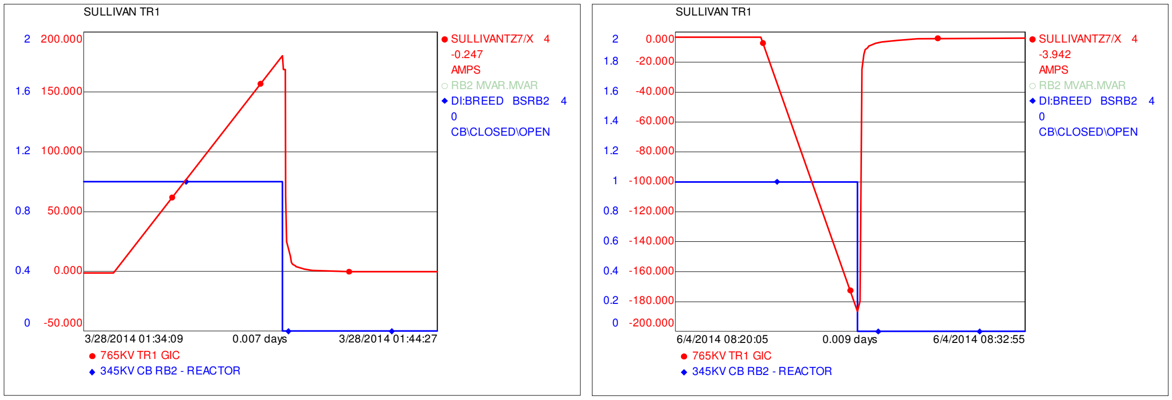


Figure 1 – AEP's Breed and Sullivan stations

The remainder of this paper is organized as follows – section II discusses the observed transformer DC current transients, section III discusses the basics of reactor bank switching transients, Section IV discusses the PSCAD/EMTDC model utilized for the simulations, section V presents simulation results and discussion of those results, and section VI presents concluding remarks.

II. Observed GIC Monitor Transients

Figure 2 shows two examples of the DC current transient recorded by the GIC monitor on Sullivan Transformer #1 when the Breed 345 kV reactor bank switches online. The red curves in the figure are the currents recorded by the GIC monitor while the blue curves are the Breed reactor breaker status where a value of '1' indicates the breaker is open and conversely, a value of '0' indicates that it is closed.



(a) (b)

Figure 2 – (a) Sullivan Transformer #1 GIC current and Breed reactor breaker status for a positive DC current transient (b) Sullivan Transformer #1 GIC current and Breed reactor breaker status for a negative DC current transient

These data come from AEP's SCADA system data historian and have been modified by the historian's archiving algorithm (swinging door compression) so that not all sampled points are saved. As a result, the data do not have uniform sample rates and exhibit linear trends (such as ramps in the data for fast changes) that are products of the archiving algorithm.

Readily observed from these data is the relationship between the recorded DC current and reactor bank switching. The current reaches its positive or negative peak very quickly after the reactor bank breaker closes. Also observed from these data, is the exponential decay of the current from its peak value (positive or negative) to its approximate pre-transient value. This is indicative of an inductive type of response.

Certain questions arise based upon these observed transients. Is this a real phenomenon and not the product of the monitoring system? If the transients are real, what about reactor bank switching causes them? If real, can this phenomenon be reproduced in simulation? The work reported in this paper attempts to answer these questions.

III. Reactor Bank Switching [1]

Before discussing the simulations described above, it is informative to study the transient response of a simple RL circuit which describes the switching of a shunt connected reactor with an ideal source. Consider the circuit shown in Figure 3

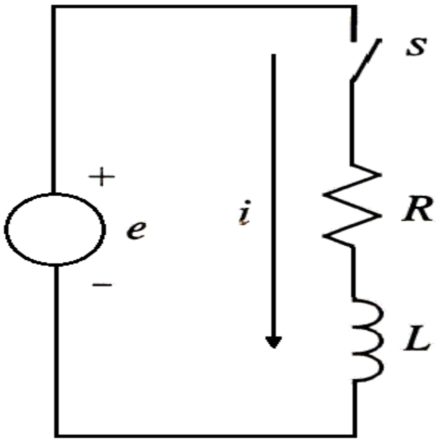


Figure 3 – Simple RL circuit for understanding the basics of reactor switching

e in Figure 3 is the source voltage and is given by the following:

$$e = E_m \sin(\omega t + \alpha) \qquad (1)$$

If the switch S is closed at time t_s, the current *i* is given by

$$e = L\frac{di}{dt} + Ri \qquad (2)$$

Solving (2) for *i*,

$$i = Ke^{-\frac{R}{L}(t-t_s)} + \frac{E_m}{Z}\sin(\omega t + \alpha - \varphi) \qquad (3)$$

with

$$Z = \sqrt{R^2 + \omega^2 L^2}$$

$$\varphi = \tan^{-1}\left(\frac{\omega L}{R}\right)$$

$$\alpha = voltage\ phase\ angle$$

In equation (3), K is such that the current, *i*, at $t = t_s^+$ is the same as that at $t = t_s^-$. If *i* is equal to 0 at $t = t_s^-$,

$$K = -\frac{E_m}{Z}\sin(\omega t_s + \alpha - \varphi) \qquad (4)$$

From equation (3), the current has two components: a transient, DC component and a steady-state alternating component at fundamental frequency, ω. Figure 4 provides an example of the current for switching the simple circuit in Figure 3 with a source voltage of 281.7 kV peak at 60 Hz, R equal to 1.5 ohm, and L equal to 1.263 H (this represents one phase of a three phase 250 Mvar shunt reactor bank at 345 kV rms). For our purposes, we are interested in the DC component. The presence of this component ensures that the inductor current does not change instantaneously when the switch is closed. This component decays to zero with a time constant of L/R. From equation (4), the initial magnitude of the DC component depends upon the voltage peak magnitude, the reactor impedance magnitude and angle, and the angular position on the source voltage waveform at which the switch is closed (given by $\omega t_s + \alpha$). The total reactor current is inevitably supplied among all available sources connected to the reactor bus.

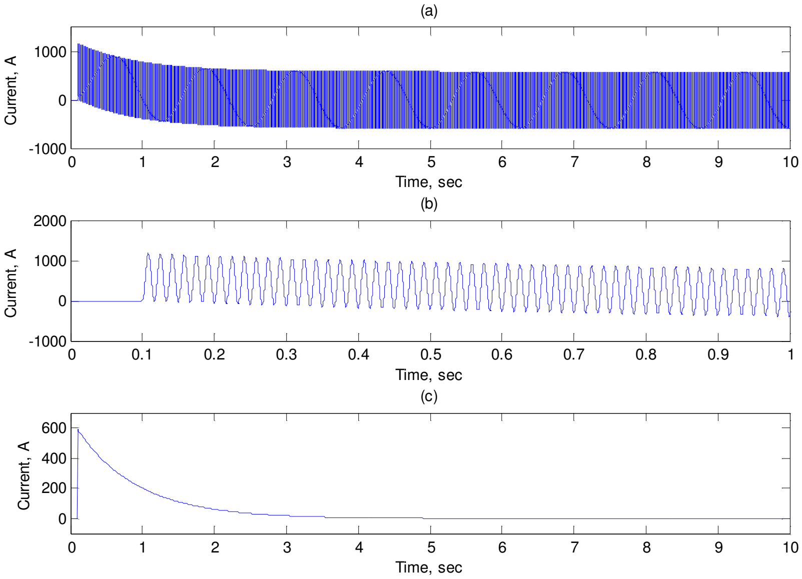


Figure 4 – (a) Total current (AC + DC) (b) Zoom in of total current around switching instant at 0.1 seconds (c) DC component of current

IV. PSCAD/EMTDC Model and Simulations

To answer the questions posed in Section II and investigate the phenomenon further, a PSCAD/EMTDC model for this system was developed. The model is shown in Figure 5. The system was modelled in detail at least one bus away from the Sullivan 765 kV and Breed 345 kV buses. Beyond this, the system was represented by its equivalent.

The reactor circuit breaker used to switch the reactor bank in and out service was modelled with a pole closing span equal to 4.16 ms. This was done in order to account for the mechanical nature of the circuit breaker and the fact that all three poles do no close at exactly the same time but are typically within the pole closing span of one another. All of the transmission lines utilized full frequency dependent models and the two Sullivan autotransformers utilized more accurate magnetic equivalent circuit models which represent core effects in the transformers more accurately.

With this model, simulations were carried out to investigate the phenomenon and its sensitivity to reactor bank switching. Additionally, to investigate the impact of reactor bank point-on-wave closing instant on transformer DC neutral current, an initial multiple run simulation was conducted in which the breaker phase A point–on–wave closing time was increased sequentially across one 60 Hz power cycle in 0.3333 ms steps. The closing times of Phases B and C were offset from the Phase A time by +/- 2.08 ms respectively to account for the breaker pole closing span. The DC neutral current in each Sullivan autotransformer was monitored and recorded in order to see how the current varied with different point-on-wave closing instances.

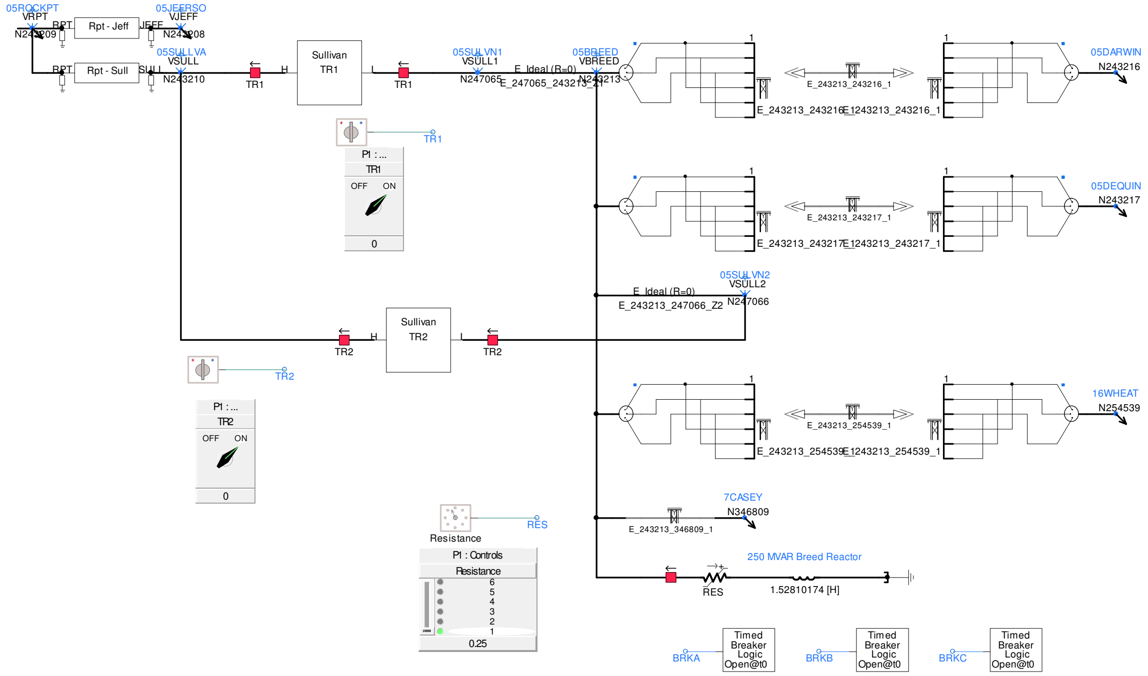


Figure 5 – PSCAD/EMTDC model

V. Simulation Results and Discussion

In this section, results from the simulations described above are presented and discussed. These results provide a better understanding of the phenomenon and the parameters that affect it.

Examining Figure 6, we get a sense for how much the point-on wave closing time of the reactor breaker impacts the DC neutral current experienced by the transformers at the Sullivan station. From Figure 6, we see that DC neutral currents in the simulations ranged from approximately 200 A into the neutrals to approximately 200 A out of the neutrals of the transformers. This is a range of approximately 400 A solely due to the instant on the voltage waveforms that the breaker poles closed. These results are not unexpected considering the discussion of reactor switching transients in Section III.

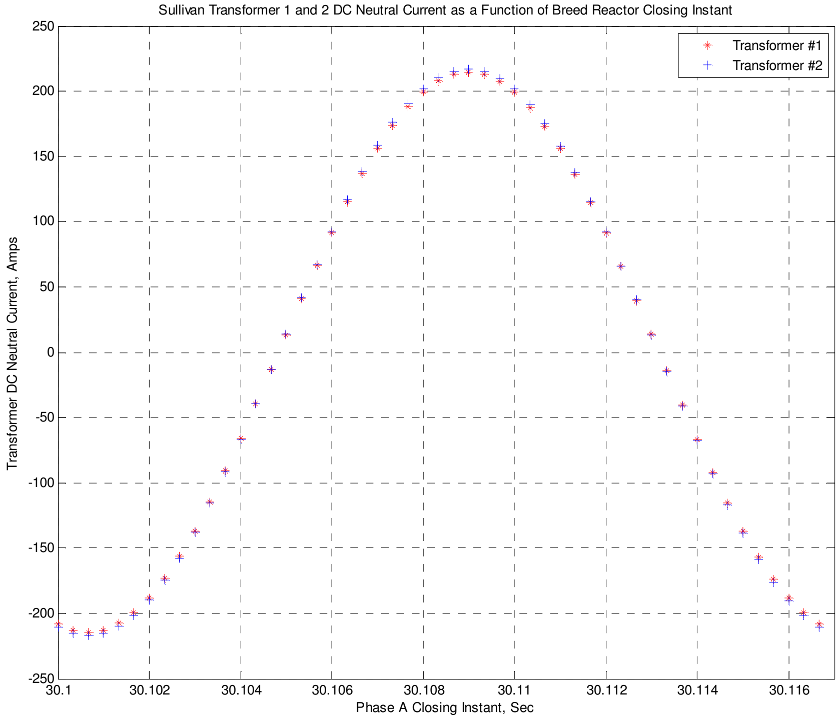


Figure 6 - Sullivan Transformers 1 and 2 DC neutral current as a function of Breed reactor closing instant

Figure 7 shows the transformers' DC neutral current for the switching instant that produced the maximum positive peak current. The simulated response in this figure matches closely the observed DC current transient shown in Figure 2 (a). This provides an indication that these observed DC transients do represent a real phenomenon related to reactor bank switching and that it is possible to recreate this phenomenon through simulation.

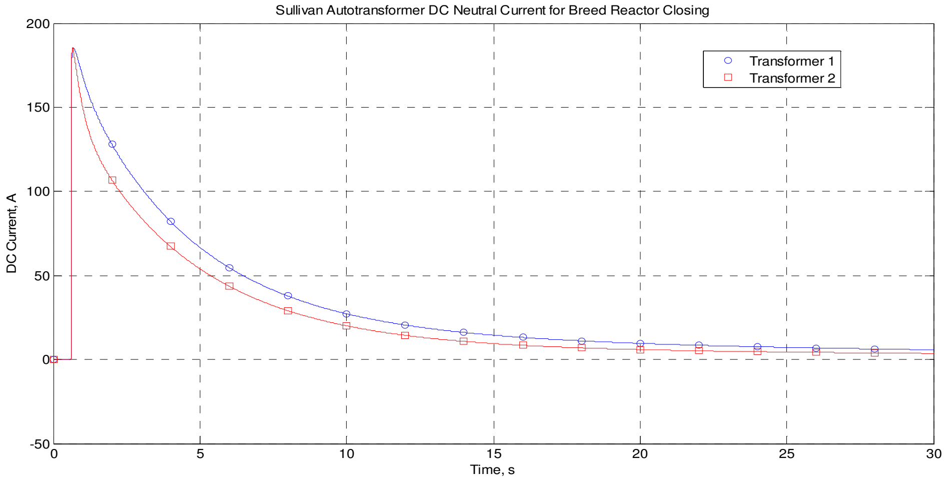
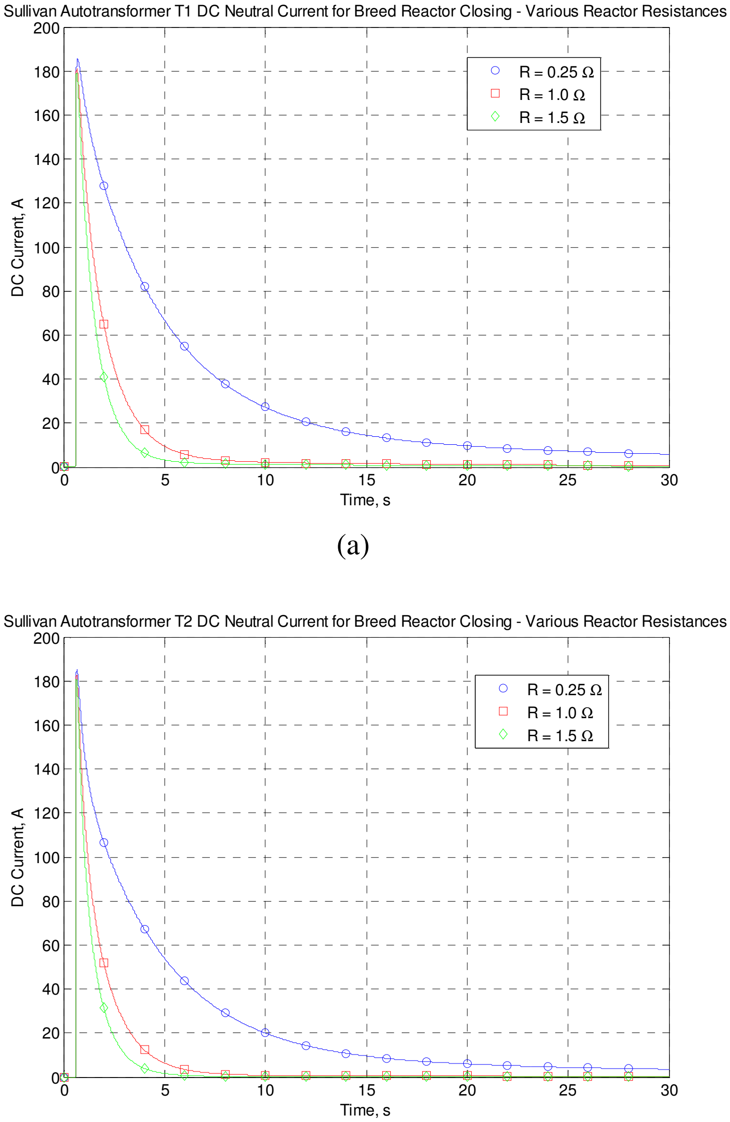


Figure 7 - Sullivan autotransformer DC neutral current for Breed reactor closing

One thing to keep in mind is that the response shown in Figure 7 is dependent on the equivalent network resistance and inductance at the point of application of the shunt reactor bank and also on the resistances and inductances of the reactors comprising the bank. These values help determine the peak DC current magnitude and associated time constant for the decay of this component. Figure 8 provides some examples of the responses obtained by changing the resistances of the reactors in the bank.


Sullivan Autotransformer T1 DC Neutral Current for Breed Reactor Closing - Various Reactor Resistances

(a)

Sullivan Autotransformer T2 DC Neutral Current for Breed Reactor Closing - Various Reactor Resistances

(b)

Figure 8 – (a) Sullivan Autotransformer T1 DC neutral current for various reactor resistance values (b) Sullivan Autotransformer T2 DC neutral current for various reactor resistance values

Confirming these transients as real phenomena related to reactor bank switching, allows for the capability of distinguishing them from actual GIC events. This is important so that the associated current peaks, which can be quite high, are not incorrectly categorized as GIC. Doing so could lead to applying unnecessary and expensive mitigation.

VI. Conclusion

Switching of reactors inherently produces electrical transients. These transients are seen in both the voltage and current and can result in a decaying DC component in the current. The DC current produced is a function of the point on the voltage wave that each circuit breaker pole closes and the resistances and inductances of the system and the reactors themselves. Due to the three electrical phases being 120 degrees electrically apart, the DC current in each phase will typically be different (different point on wave closing points). These currents will flow in each phase, add in nearby neutral connections of transformers with wye-grounded windings, and appear as a DC current transient to any device monitoring DC current in the transformers' neutrals.

For systems which utilize switched shunt reactors, any GIC monitoring on transformers within the same or nearby substations will need to take this phenomenon into consideration when analysing any peak currents within the monitored data. Doing so will allow for the distinguishing of reactor switching related events and ones actually produced by geomagnetic activity.

BIBLIOGRAPHY

[1] Kundar, P. (1994). *Power System Stability and Control.* McGraw-Hill, Inc.