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CIGRE US National Committee
2018 Grid of the Future Symposium

Comparison of Measured and Simulated Geomagnetically Induced Currents in TVA using Different Conductivity Structures and Network Parameters

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SUMMARY

The impacts of geomagnetic disturbances (GMD) and geomagnetically induced currents (GIC) on power grids are well known by now. GMD monitoring is seeing a rise, with the deployment of 1) GIC measuring devices in transformer neutrals, and 2) magnetometers to bridge the gaps in the existing coverage. Concurrently, modeling of GMDs in power system simulations is becoming increasingly important especially for risk assessment. While the modeling has come a long way, there are still several uncertainties in the process. Some of these include the ground conductivity, and parameters related to the power system model itself. One way of reducing the uncertainties and improving the models is through validation. When a significant enough GMD event occurs (which is not that frequent), measurements such as magnetic fields and GIC neutral currents can be used in validating different models used in the overall GIC calculations, from the input B to the output i.e. the GICs. The goal of this paper is to briefly describe this procedure of validation for an actual event and footprint using available measurements and models. In particular, we compare GIC measurements from transformers in TVA taken during a June 2015 GMD storm and compare them to GICs simulated using models. We vary parameters such as the ground conductivity model (1D layered earth vs 3D electromagnetic transfer function based), and network-related ones such as how many substations are included in the analysis, etc. The goal of these comparisons is to provide an idea about the sensitivity of the GICs to these parameters, recognizing that results may vary across systems and events. This will help determine the aspects of the models or parameters that may need to be modified in order to improve GIC estimates. Another important goal is to provide some example results of simulated vs measured GICs for reference purposes, since they are lacking in current literature. The ultimate idea is to motivate more such validation studies by demonstrating current simulation capabilities, and highlight the importance of measurements and data for the same.

KEYWORDS

Geomagnetically Induced Currents, Geomagnetic Disturbances, GIC, GMD, Comparison, Validation, Ground Conductivity, Electric Field, 1D, 3D.

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I. Introduction

Geomagnetically induced currents (GICs), caused by geomagnetic disturbances (GMDs) have the potential to impact power systems in several ways. The two major impacts are 1) damage to transformers due to heating, and 2) harmonics leading to a loss of reactive power support devices accompanied by increase in reactive power losses in transformers. The latter can cause a system voltage collapse. To prepare for these events, studies need to be performed on power system models to ensure the grid may be able to withstand them, and if not, what measures can be taken. This concern has led to the creation of transmission planning standards, TPL-007-1 [1] and TPL-007-2 [2], of which the former is already in effect.

The key element of both these standards is to perform studies on system GMD models to see if the results fall within certain limits. Hence, a lot depends on the accuracy of the underlying system models used, which contain unconventional data such as substation locations and grounding resistances, transformer winding resistance and so on. They are unconventional because they are not used in load flow and other typical studies, and hence such data have not been collected in decades, or ever in some cases. In some instances, parameter values are still not available, and defaults are used. The defaults may work for winding dc resistances since they are estimated from the ac power flow case, which mostly have been entered based on the original transformer name plate or test report data. However, they do not work well for grounding resistances [3], and having the actual values is very important for correct GIC estimates.

Another aspect of these standards is the network applicability. In terms of voltage level, only the 200 kV and higher voltage network needs to be included in the GMD model (in other words, transformers with a high side wye-grounded winding above 200 kV). Furthermore, the planning guide [4] mentions that neighbouring areas can be approximated by including two or more key buses into the adjoining network. It is true that GICs tend to concentrate on higher voltage lines as they have lower resistance. But not including the lower voltage network may not necessarily have any advantages, since GIC calculations are fast even for very large systems. It might be the case that the substation data on the lower voltage or neighbouring substations may not be available, which is where this approximation may be helpful, and also from the point of view of collecting new data and what to prioritize.

Last, it is known that the electric field induced in a region during a GMD depends on the deep earth conductivity at that location. The layered-earth 1D model from [5] has been adopted in these standards. For the actual study, a benchmark electric field and a slight variation has been proposed, both time series and peak snapshot, which makes use of these 1D models. Electric fields can also be calculated using 3D EMTFs (electromagnetic transfer functions) available from NSF Earthscope [6].

In short, the key aspects of an overall power system GMD model such as the power system network properties and the conductivity model may have approximations and uncertainties associated with them. This paper assesses the impacts of these parameters on modeled GICs by validating them against GICs measured during a GMD event that occurred in June 2015. We make use of GIC measurements available from transformer neutrals in TVA. The GMD event is recreated by using the magnetic field measurements [7] taken during that event from the nearest available magnetic observatory which is located at Fredericksburg, VA (FRD).

The rest of the paper is organized as follows. Section II describes the properties of the network model we varied in the paper, i.e. using an off-line (planning) or online (real-time) power system model, and the number of substations included in the simulation in terms of the maximum nominal voltage level and neighbouring areas. It also briefly describes the two different conductivity models applied in the paper, 1D layered earth and 3D EMTFs. Section III contains results of the different studies comparing measured and simulated GICs with all the parametric variations. Section IV concludes the paper, summarizing the key findings and directions for future work.

II. Parameters Considered

A. Type of Model: Planning vs Real-Time

Two types of network models were available to study this GMD event. First a planning i.e. an offline model was used to represent the TVA footprint, and its neighbours as needed. While this may be useful for studying benchmark events, it does not provide a realistic representation of the system as it was during the time the GMD event occurred. To address this, a real-time model of the TVA footprint from June 22nd, 2015 was obtained. This would at least be more topologically similar to the actual system conditions than the planning case. Such “online” models are derived from the EMS, and are state estimator snapshots which can then be saved as power flow cases in either full topology (i.e. node breaker) or bus branch form as needed. A bus-branch model was sufficient for this study, and was used. All the results shown here make use of the actual TVA model, both planning and real-time, which is a part of the larger Eastern Interconnect model. Names of substations, transformers, and other system elements have not been disclosed in the paper to maintain confidentiality.

B. Number of Substations

In the initial planning model, locations for 47 500-kV substations were made available, with buses mapped into them. This location data was later mapped into the real-time model as well. All of these belonged to the TVA region. Since GIC calculations need location data to estimate the length and orientation of transmission lines using which the GMD-induced dc voltages are calculated, and to determine where the transformers are located, it means that only this part of the network was included in the analysis. The TVA region also contains about a dozen 230 kV substations, while remaining ~1000 substations are 161 kV and below. To consider the effect of varying number of substations and hence different sizes/ extent of the region of study, two conditions were analysed. First is using the network defined by the 47 substation locations only, which we refer to as the “minimized” (min) network in this paper. The second condition is where we also included all the remaining substations at all voltage levels within TVA plus the substations in the areas connected to TVA by tie lines, as much as was available to us. We refer to this as the extended or maximized (max) network.

C. Deep Earth Conductivity:1D Layered Earth vs 3D EMTF

The last impact we consider is that of the type of deep earth conductivity model used to derive the electric field from the measured magnetic field. There are papers such as [8] which discuss some of the underlying properties, and the differences between the responses from these models in detail; here the key points are summarized. The 1D regions are broader and spread out over larger areas, whereas 3D electric fields tend to have a lot of local variation and at times intensification and/or field rotations. For the 1D model, the electric field is always orthogonal to the magnetic field, whereas this is not necessary for the 3D-derived electric field. The biggest concern over 1D is that since they cover such large regions, they may not be accurately modelling some of the local conductivity features, whereas 3D transfer functions being available every 70 km or so may be providing that information. That being said, 1D regions are supposed to represent the average response over a region, which is also seen in GIC estimates using the model [8].

III. Simulations and Results

A. Procedure

Irrespective of the type of models used, the overall GIC calculation procedure remains the same. To perform validation using an event, one needs to start with the magnetic field, B, driving the changes measured during the storm. This data is typically available at 1 sec, 10 sec, or 1 min cadence. Ideally the magnetometer(s) should be located as close to the study footprint as possible. In our case, FRD observatory is located ~600 miles from Nashville, TN which is approximately near the center of the TVA footprint. The nearest substation is as close as roughly 300 miles whereas the farthest is more than a 1000 miles from FRD. Hence, the B may not be quite accurate for this region; it was used since it was the closest available source for that event. Then, the electric field is calculated using the desired conductivity model. In case of the 3D EMTFs, a much more finely varying electric field is obtained, while for the 1D it can be quite consistent across a larger region. In addition to spatial variation, these electric fields are also calculated over a time series to allow for comparison of time series GICs. We used electric field data sampled at 10 sec in the following analysis.

For easier data handling of such spatio-temporally varying electric fields, the study footprint was divided into a grid of points, separated by 0.5 × 0.5 degree latitude and longitude. The Ex (northward) and Ey (eastward) components were defined at each such geographic point, at timepoint. The 3D electric fields are highly non-uniform in nature. However the GICs can be solved following the commonly known methodologies, such as in [9]. The transmission lines are divided into segments and the GMD-induced dc voltage is calculated by integrating the electric field over the length of each line. The only approximation made in this case is that a straight line path is assumed between two substations since the geographic routes of the lines are not known in the model (yet).

Unlike the shorter 15 minute comparisons done in [10] to analyze just the first peak of the storm, in this paper we looked at a two hour window to capture multiple peaks and assess the simulations and models over a longer time frame. The GIC measurements used here are from monitors installed in transformer neutrals; these monitors are part of the network of 13 EPRI Sunburst detectors at TVA. The storm began on June 22nd 2015, while the first peak in the GIC measurements was observed just after 18:30 UTC. The next high activity period began at around 19:45 and went on till around 20:20 UTC. We compare the magnitudes of the measured GICs (transformer three-phase neutral currents) to those of the simulated ones. The original measured data does contain both positive and negative values, but comparing magnitudes allows us to compare the strength of the GICs more consistently, and not let the comparisons get affected by the localized field rotations, especially in the case of 3D electric fields. Those will be addressed in future research.

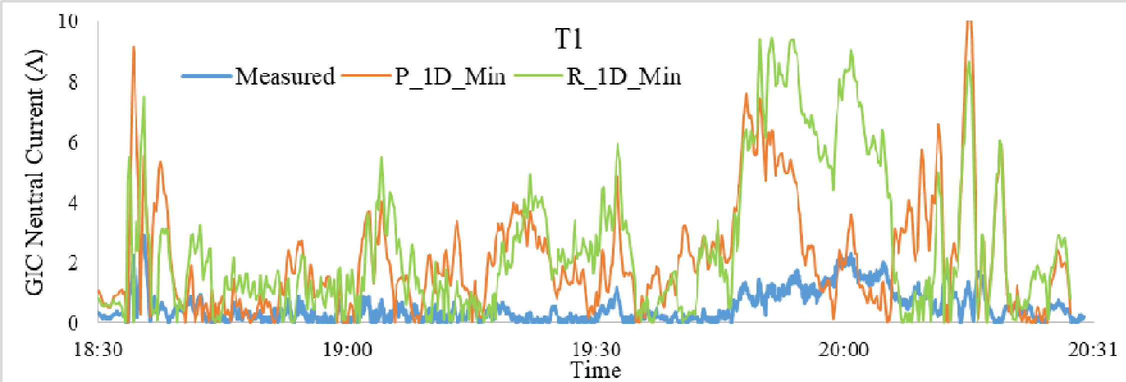
B. Network Parameter Variation

In this section, the figures showing GIC simulation results will bear a legend of the type “P_1D_Min” where the first character (here “P”) stands for the abbreviation of the model type (P for planning, and R for real-time). Similarly the second set of characters represent the earth conductivity model, and last three (“Min” or “Max”) represent the inclusion of only the 47 500-kV TVA substations, or all ~1000 TVA substations plus all substations from tie-line connected areas (first neighbours) respectively.

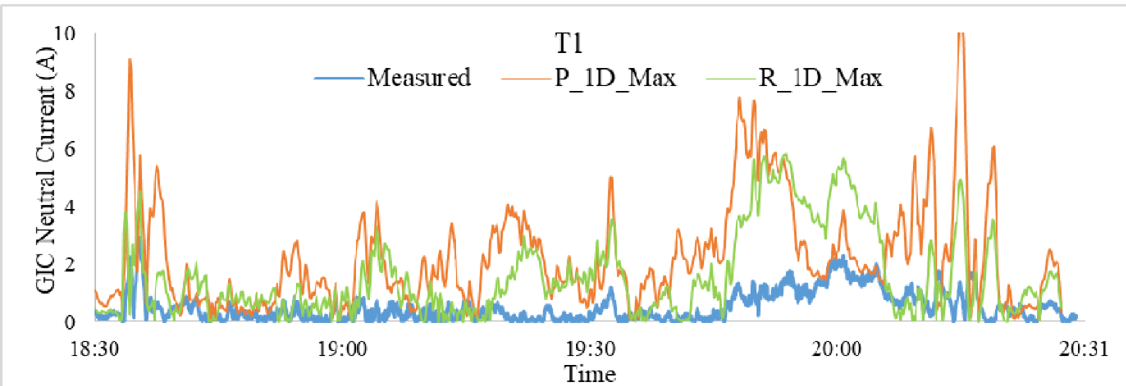
In the first set of studies, we kept the conductivity model fixed to 1D and varied the network properties such as the type of model and the number of substations (i.e. extent of the network) considered. Figure 1 shows a set of comparisons done for GICs at Transformer 1 (T1). The blue curve represent the actual measured GIC value, the orange curve is the simulated GIC using the planning model, whereas the green curve is the value calculated using the real-time model.

Comparing Figure 1(b) to 1(a) shows that for T1, the simulation results fare better compared with the measured GICs when more of the network (i.e. substations) are included. One can observe this by comparing the set of orange and green curves across these sub-figures, which represent the same model type. In the real-time model results especially, including more substations causes a reduction in the magnitude overshoots throughout, showing an improvement from 1(a) to 1(b). Finally 1(c) just reproduces the real-time model results from (a) and (b) on the same plot and shows that T1 simulated GICs are the closest to the measured values for more of the network included, in the real-time model.

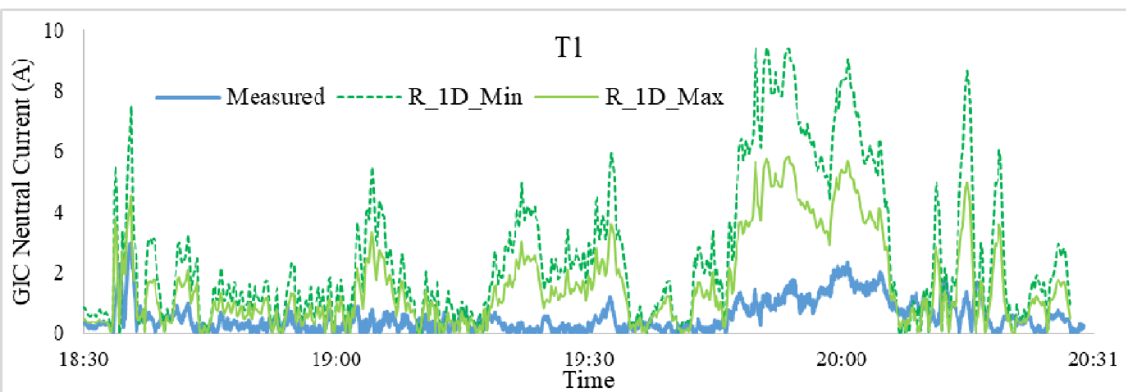
This is the most expected result for two reasons. First, the real-time model corresponds to the system and its topology when the event occurred, hence it is more likely to get the GIC distributions correct. The planning model on the other hand is an offline model and may have some devices or lines whose status did not match the real system. Second reason would be the fact that including the lower voltage network and the neighbors further improved the estimation of the GICs. This is likely if the transformer is located in a substation which is near the edge of the minimized system, and is thus influenced by its neighbors when they are included. It could also be possibly away from the edge of the minimized network, depending on the effective resistance of the lines connected to the transformer in the extended system. In Figure 1(c) we also notice that the two simulation results are just scaled versions of each other and almost perfectly correlated. We make more such hypotheses about transformer locations with respect to 1) the minimized TVA system, 2) the magnetometer further in the paper, which were confirmed by looking up the required information in our models.



(a) P = Planning, R = Real-time. 1D Conductivity Model. Minimized Network Size.



(b) Extended Network Size. Note the real-time model (green) and measured GIC correlations.



(c)

Figure 1. Measured and simulated GIC comparison at Transformer 1 (T1)

Other results showed that the response characteristics can vary greatly across the system and transformers. Figure 2 shows that the transformer T2 GICs are not so sensitive to these changes in the models; especially for the real-time model the results overlap irrespective of how much of the network we include. Similarly at T3, the simulation results are even more consistent across the different variations. This means that the neighboring network does not impact the GICs in this transformer, indicating that it could be located towards the interior parts of the system. However, as seen later, T3 is in fact at the edge of the minimized system but it is a special case in which the extended system does not add any lines to it.

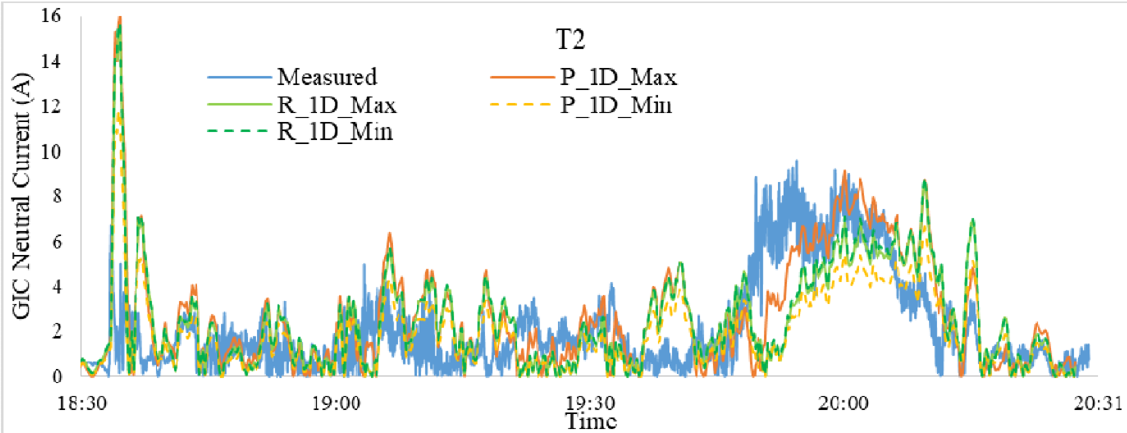


Figure 2. Measured and simulated GICs at Transformer 2. Note real-time model responses are almost identical.

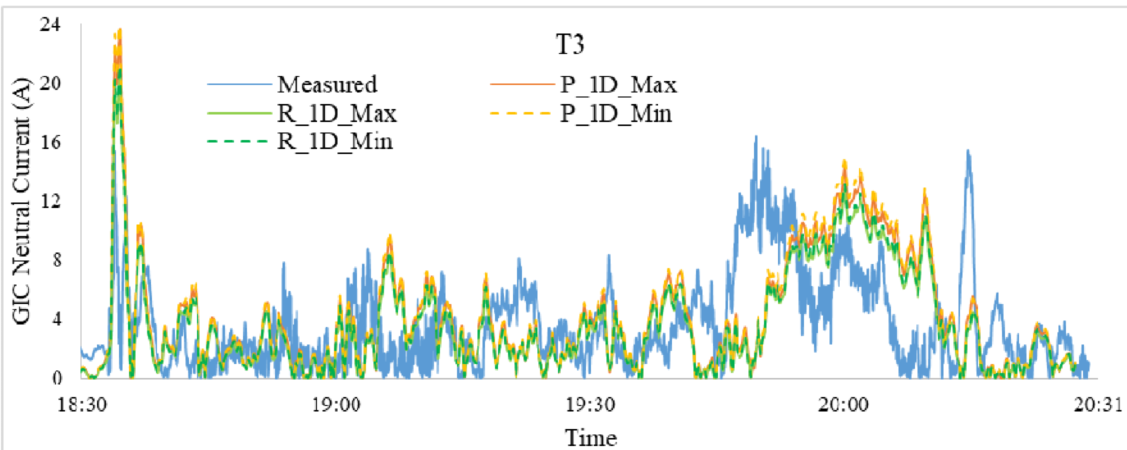


Figure 3. Measured and simulated GIC comparison at Transformer 3. All models give similar results.

The difference in the behavior across T1, T2 and T3 can be explained as follows. Recognizing that in a "perfect" model and simulation where there were to be no errors in the input data or parameters and the system conductivity models would accurately represent actual response, we would expect the simulated GICs to correlate with the measured GICs, and even almost match in magnitude. Hence the way in which the simulated values vary and under what modeling conditions can tell us which aspect(s) of the model need further looking into or corrections.

The very similar values of simulated GICs at T3 shows that the type and extent of system makes no difference to the results, which means any of these factors being the source of error is unlikley. Note that all these simulation outputs are driven by the basic input of the magnetic field from FRD. We noted earlier that it is located far from the system (830 miles from T1, 780 miles from T2, and 650 from T3) and could introduce errors. This may be also causing the delay in the response observed at around 19:50 UTC in T2 and T3, starting from 0 A. What is interesting is that at T2 and T3, for the magnitude of the peak of this variation between 19:50 and 20:10, the measured and simulated values match well (~9 A and ~15-16 A, respectively). This delay issue is revisited in the 3D results discussion further in the paper (i.e. could it be caused by the 1D model?). Furthermore, all the models are able to capture the timepoint of the rise to the first peak of the GIC at all transformers, although the magnitudes may be off.

A consistent observation across T1, T2, and T3 is that for the same model type (planning or real-time), the simulated GICs at each transformer are simply scaled in varying ratios when the number of substations included is changed. This again may apply to most transformers, except a few such as T5, shown in Figure 4. Here we see a good correlation between the extended real-time model and the measured GIC. However the minimized model correlation is very different. Moreover, for T1 and T5, the results are also improved when more of the network is included, while for others they are not affected much in the real-time model case implying again that T1 and T5 lie at the edge of the minimized network. The implication of these observations can be explained in two parts.

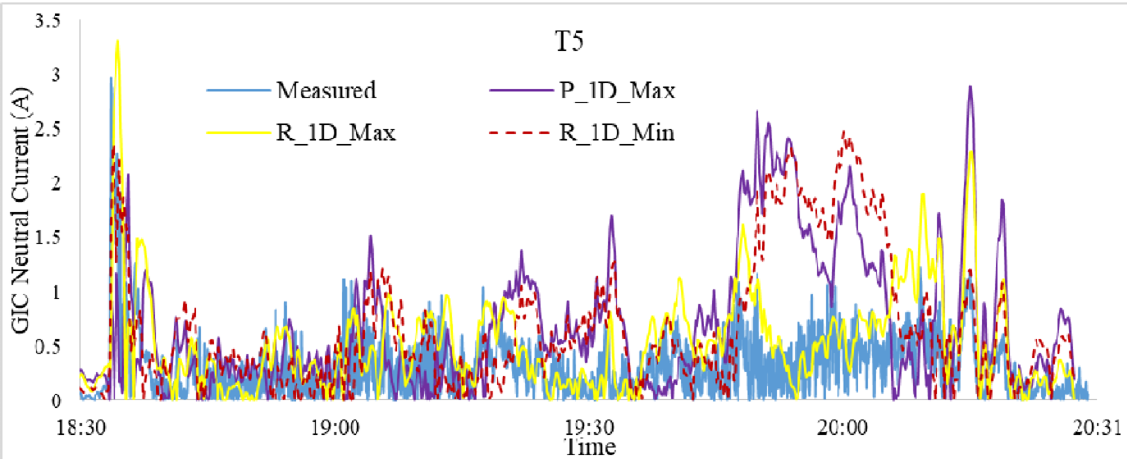


Figure 4. Measured and simulated GIC comparison at Transformer 3 (T3). Real-time model response correlates well with measurements, along with magnitude matches including first peak.

First, the scaling phenomenon for the different sized networks can be explained by the fact that the power system GIC model which takes the GMD-induced dc voltage (due to electric field) in the lines to yield actual GICs is linear. A scaling with no phase difference would indicate a difference primarily in this part of the model such as topology, resistance values etc. If there is a phase difference associated with the scaling, it means that the induced dc voltage i.e. the electric field was affected as well. For 1D conductivity, most of the TVA footprint comes under one physiographic region, hence the electric field is expected to be similar at these locations. This means that either the conductivity at T1 and T5 is incorrect, or the magnetic field driving the electric field is not acurrate. Since T1 and T5 are assumed to be located at the edge, the latter would be true if T1 is located far from and T5 is near the magnetometer. This was also confirmed by inspecting the model, and is summarized in III.D.

Comparing across the planning and real-time model, except for cases in which the model type does not affect the calculated GICs much, the real-time model performs better. In this subsection, we showed results using planning i.e. offline models just to demonstrate how they may impact the results. While for some cases the estimated GIC did not vary, for some there was a large difference across the online and offline model. For validation and event recreation, the best practice would be to use the online model since it would represent the topology of the system during the event most accurately. Figure 5 shows a good example of a well correlated measured and simulated GIC, at a different transformer T4 using a real-time model. The lack of any obvious delays indicates its possible proximity to the magnetometer used as the source of the magnetic field especially compared to T1, T2, and T3. As expected, T4 was found to be 450 miles away. This was the nearest transformer to FRD which had "usable" measurements for analysis. It will be interesting to see if the correlation as well as the magnitude improves if a nearer transformer is studied in the future. While an extended model was used here, it may not always be necessary if the results are insensitive to the size of the system. At times, it could make the results worse; this will be explored in the next section.

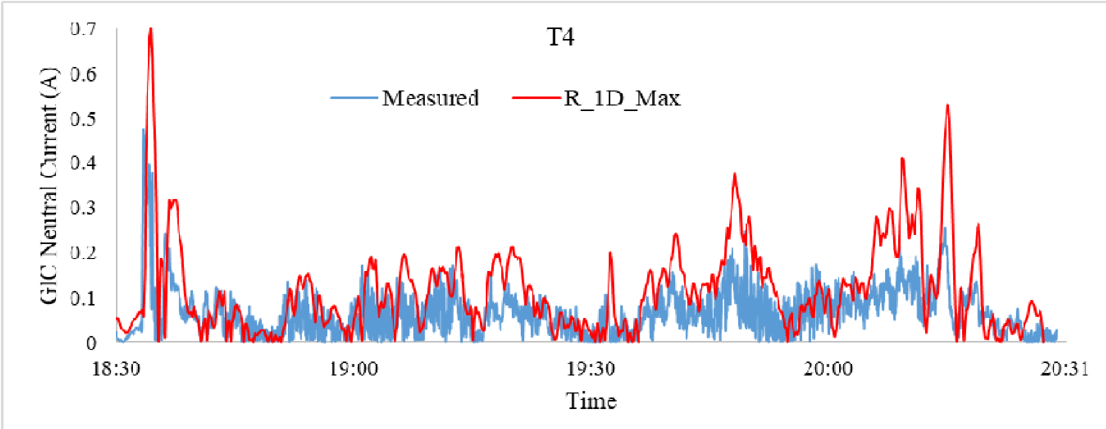
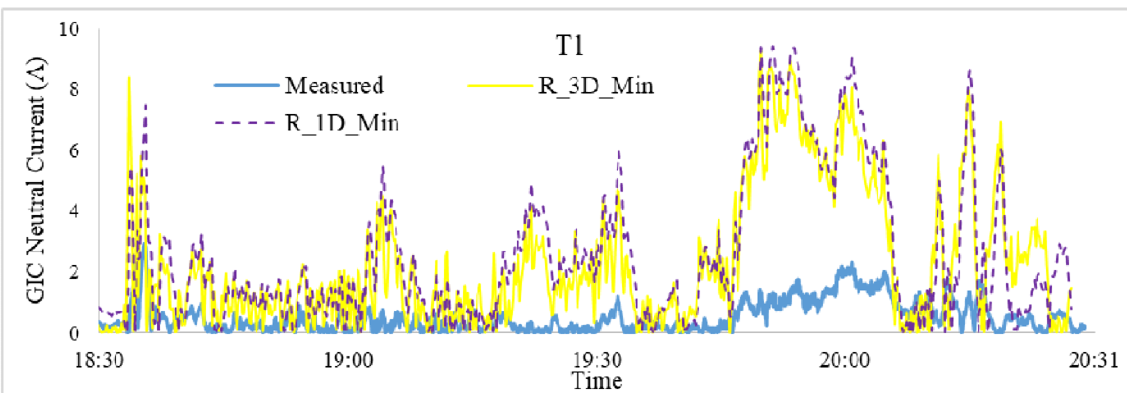


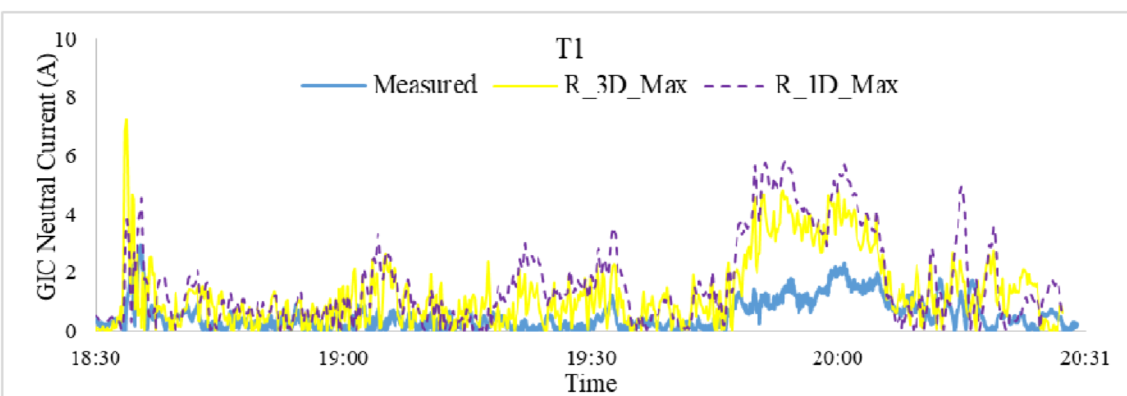
Figure 5. Measured and simulated GIC comparison at Transformer 4 (T4). Real-time, 1D conductvity model response correlates well with measurements.

C. Conductivity Model Variation

We now look at the impacts of different conductivity models and network extent. Figure 6 shows simulated GICs at T1 again, but now including the 3D conductivity model simulation results. For T1, the 1D and 3D GICs are similar in magnitude and correlated for the same network size. For the extended network both of them are slightly closer in magnitude to the measured GICs. The 3D simulated values have higher frequency content, as also seen in the subsequent figures. Given the insensitivity to the type of conductivity model coupled with observations from the previous section, we can imply that T1 is too far away from the magnetometer to be reasonably reproduce the current.



(a) 1D and 3D conductivity based electric field response using real-time, minimized model.



(b)

Figure 6. Measured and simulated GIC comparison at T1 for different conductivity models

For T2 and T3 in Figures 7 and 8, the minimized network response is very similar to the extended network, hence it is not included again in Figure 8. At T2, the 3D response does not lag the measured GIC, as was the case with the 1D results. The magnitudes are better represented by the 1D model compared to the 3D model, especially for the latter half of the storm. In terms of the delay, there could be certain characteristics of the 3D model response i.e. its transfer function at this particular location or close by that the 1D is not able to capture in this case. The delays are gone with 3D conductivity at T2, but not at T1 and T3. Also note the local intensification of the magnitude at T2 caused by the 3D model. Hence it is more likely that there are some very local features of the 3D model near T2 that help replicate the GICs in phase, but not in magnitude. This explanation would also be more consistent with the reasoning of the previous section that the B input may not be appropriate at T2 due to its distance.

The delay still exists at T3, and the 1D and 3D models have similar correlations but the 3D intensifies the magnitude, bringer it closer to the measurements. This is an example of the intensification being helpful and the GIC differences consisting of scaling (i.e. dependence on system size), with little to no phase difference. The 1D model is closer to the first peak of the measured GIC, while the 3D response is closer to the magnitude of the "local peak" at around 20:15 UTC; at this point both the models and the measurement are well lined up.

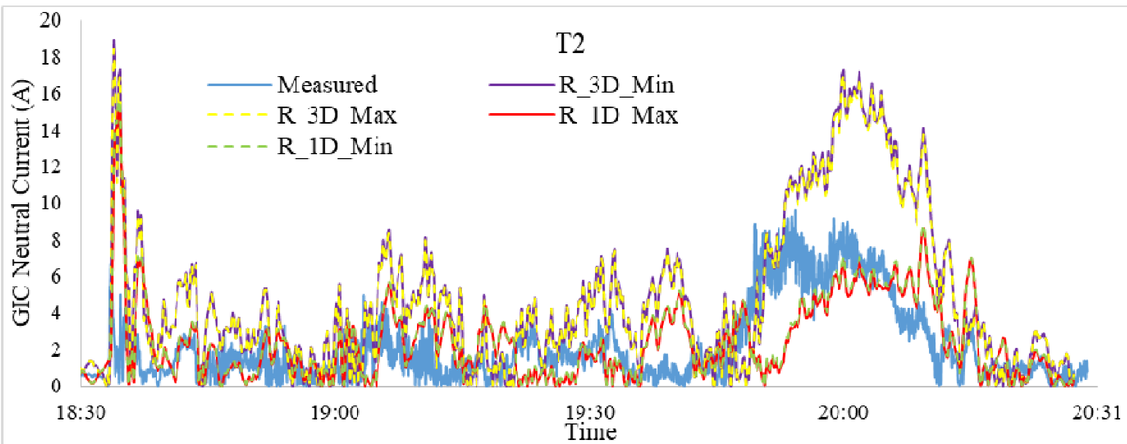


Figure 7. Measured and simulated GICs at T2 for different conductivity models. Note the 3D response is not delayed between 19:45 and 20:00 as in case of 1D. Magnitudes are represented better by the 1D model.

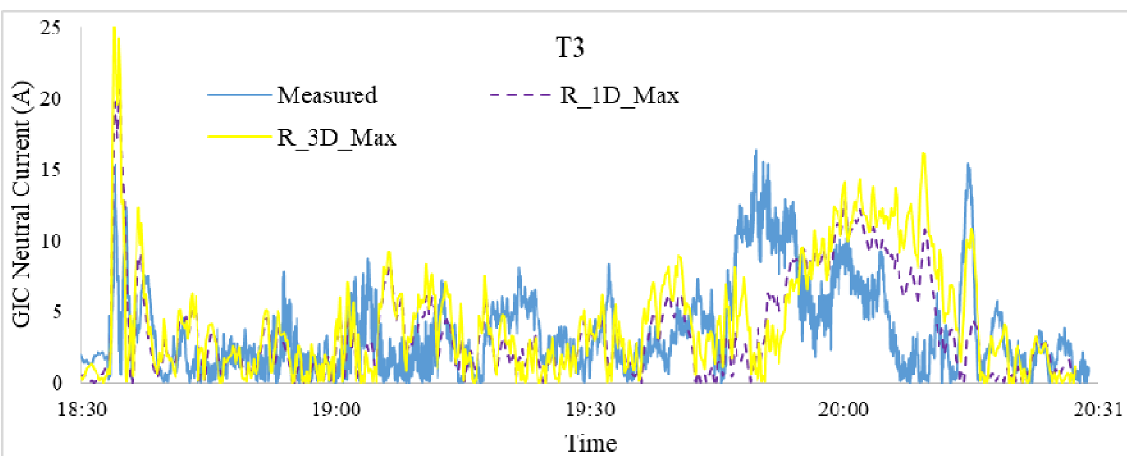


Figure 8. Measured and simulated GIC comparison at T3. 1D and 3D response is similar.

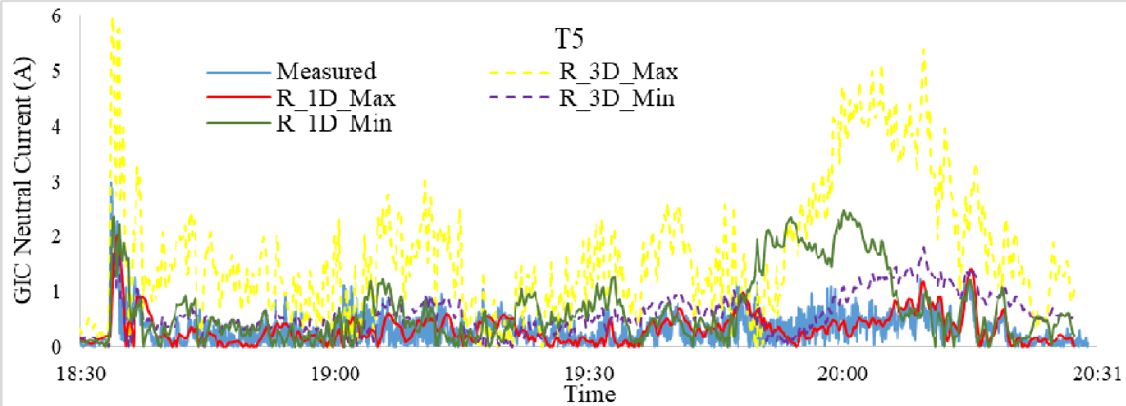


Figure 9. Measured and simulated GIC comparison at T5. 1D is well correlated with the measurements, 3D overestimates the GICs.

For T5 in Figure 9, the 1D response of the extended network covers the average of the variation in the measurements. For the minimized network's 1D response represented by the green curve, there is a slight overestimation of the GIC. In several examples so far, the minimized network response for both 1D and 3D models has typically shown higher GICs than the extended network as well as the measured values (see Figures 1, 4, and 6). Intuitively one can think of this as the concentration of GICs occurring on a subsystem. Or in other words, a larger network would have the dissipation of GICs occurring into the neighboring substations.

Figure 9 however shows an anomalous behaviour, in that the maximized network's 3D response grossly overestimates the GICs compared to the minimized network's GICs. Again there are no correlations among the different simulated values similar to Figure 4. Recall from that discussion that T5 and T1 are supposedly located near the edge of the minimized network. And unlike the 1D case where the conductivity values were the same, in the 3D case the electric fields at T1 and T5 will be most likely very different. Also for the 1D maximized case, the GIC results at T5 were good. Since the 3D results for the same model are so different, and much worse than the minimized model it is likely that there are electric field intensifications similar to the ones discussed before in the extended region that are getting induced in the lines there, inducing more voltage and hence causing more GICs to flow. If the 1D model also produced such results, it would mean that some network parameters in the extended network were incorrect, e.g. an unrealistically long, low resistance line nearby inducing a large dc voltage and GIC. Since this is not the case, we can pin-point the error source to the 3D conductivity in the extended region near T5.

D. Transformer Properties and Results Summary

In this section we summarize the key observations made about each transformer through the different studies.

Transformer	**Number of substation hops to the nearest minimized network edge**	**Results improve with extended network? (Yes/No/ Unchanged)**	**Distance from FRD (miles)**	**Comments**
T1	Two	Y	830	Min network peak almost twice the max network peak GIC
T2	Four	U	780	Perceivable delay in GICs(1D), not in 3D
T3	Zero	U	650	Perceivable delay in GICs
T5	One	Y(1D), N(3D)	600	Local field intensifications in extended region inducing large GICs

The best correlation results among all the transformers were obtained at T4, which happened to be closest to the Fredericksburg magnetometer from all the transformers analyzed. However, a detailed comparison for different model types was not performed or shown here since the measured GICs were very low (~ 0.5 A peak compared to at least ~2 A peak and much larger for other transformers). In subsequent studies we plan to monitor this and similar/nearer to FRD stations to see if 1) larger currents are observed so that they can be utilized in the validation process with sufficient confidence, and 2) if the correlations improve with the distance and by how much. The latter may help decide the distance thresholds for magnetometer data that can be used for a certain transformer.

IV. Concluding Remarks

To summarize, this paper provided some results on recreating a GMD event in the TVA footprint, and validating simulated GICs with transformer measurements. Overall, we do see that simulations are able to replicate actually recorded GIC variations reasonably well, demonstrating the capabilities of GMD modeling. The paper also highlights the need for continuing GMD model validation by showing that there is room for improvement in the results, and how sensitive GIC simulations are to different aspects of the model. Transformers were shown to be affected by 1) the conductivity model, 2) the extent of the network included around them, 3) both, or 4) neither. Hence, these factors need to be taken into consideration while collecting data or modeling the system around them for studies. Ongoing and future work is looking into acquiring data from a much closer magnetic observatory to see how the results improve. There is also a need to validate more events, and across more footprints to make more generalizable conclusions about these parameters and their impacts on transformer GICs, or derive say some functions depending on region specific quantities such as latitude and conductivity. There is a growing need to increase the observability of GICs and magnetic fields in order to produce better validation results, as well as to provide GMD situational awareness.

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