Metatech

Meta-R-322

Low-Frequency Protection Concepts for the Electric Power Grid: Geomagnetically Induced Current (GIC) and E3 HEMP Mitigation

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FOREWORD

This report deals with techniques for protecting the high voltage portion of the U.S. power grid against the effects of geomagnetically induced currents (GICs) resulting from geomagnetic storms and the late time E3 portion of high altitude electromagnetic pulse (HEMP), which is also known as MHD EMP. The basic concepts of operational modifications, blocking DC series capacitors in the lines and series resistors in the transformer neutral ground connection of wye windings and autotransformers, are introduced in Section 1, and explored in more detail in Section 2.

Section 3 examines the existing systems that have introduced series capacitors in a substantial fraction of the system, specifically the Hydro Quebec system from the mid 1990s and the WECC region in the western U.S. It is seen that series capacitors on some lines reduces the GIC currents and production of reactive power, but not by a great amount. Section 4 briefly performs a generic evaluation of the effect of neutral blocking resistors as a function of line length.

Section 5 extends this to an examination of the effects of neutral blocking resistors on the high voltage portion of the whole U.S. power grid, using a constant geo-electric field. Section 6 continues the evaluation examining the effects of placing resistors in only the highest voltage transformers (which contribute a disproportionately high fraction of the reactive power), or only on some fraction of transformers with the highest GICs. Sections 7 and 8 deal with the performance of the U.S. power grid modified with neutral blocking resistors in selected geomagnetic storm scenarios and E3 HEMP scenarios, respectively.

Section 9 deals with the system tradeoffs that result from the introduction of the neutral blocking resistors, including IEEE standards, restrictions due to existing insulation limitations and expected modifications in relay settings.

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Executive Summary

As discussed previously in reports Meta-R-321 and Meta-R-319, both E3 HEMP geomagnetic field disturbance environments and naturally occurring geomagnetic storms can cause the flow of geomagnetically-induced currents (GIC) through transformers in an exposed power grid. The GIC, if large enough, can disrupt the AC performance of the grid, causing initial blackouts and also posing the potential for permanent damage to large transformers, which can lead to restoration delays for the power grid. Because the problem has been identified and options exist for reduction, elimination, and/or management of the GIC threat, the most severe impacts to the power grid from these threat environments should be viewed as preventable.

In consideration of mitigation strategies, the options generally encompass two complimentary approaches, operational hardening and infrastructure hardening of the power system. These approaches provide an overall strategy of layered actions to counter the threats posed by a large GIC disturbance. Both approaches are complimentary, in that both act to improve the security of the grid. Yet they are also functionally independent, such that the failure to successfully enact an operational procedure does not defeat the hardening measures aimed at reducing GIC flows.

Infrastructure hardening of the power system is the more important and certain mitigation strategy and can be optimally done through the application of passive devices or circuit modifications that block or reduce the flow of GIC in a power grid. While operational modifications can also be considered, the varying state of system operation may limit the range of effectiveness and flexibility available to a system operator at any point in time. In addition, the operator may not have a complete situational awareness. As a result, infrastructure hardening will generally be more reliable in reducing GIC-based threats to the power grid. The investigation documented in this report is a conceptual engineering effort to assess the possibilities of power grid infrastructure hardening through GIC reduction strategies that can be employed. The analysis also undertook efforts to assess the degree of efficacy, relative costs, and any anticipated engineering trade-offs for the AC performance of the U.S. power network.

Prior power industry research and development has shown that various GIC blocking devices can be applied to significantly reduce or even eliminate GIC in a power grid. This report provides some perspective on the possible approaches that can be considered. Transmission line series capacitors (simple schematic shown in Figure Exe-1) applied on a limited and targeted basis do not appear to be an effective or likely economical choice for the reduction of GIC across the U.S. power grid, especially in the tightly interconnected eastern portions of the grid. Series capacitors are already heavily used in the WECC grid (~50% penetration), and the analysis provided in this report indicates that these regions continue to be vulnerable to both E3 HEMP and geomagnetic storm threats. In terms of performance, the analysis provided in this report for the WECC network estimates that already existing series capacitors in this region reduce overall GIC levels by only 12% to 22%. These series capacitors have to be applied in each of the three phases; at EHV operating voltages, higher penetrations of this type of blocking approach would be exceedingly costly.

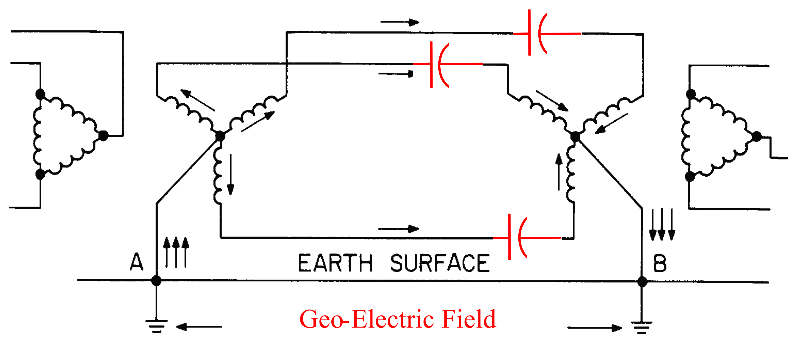

Figure Exe-1. Adding series capacitors in each phase of the transmission line will block all GIC flow in this circuit.

Two other approaches exist to block or reduce GIC flow, and both of these approaches would insert devices in the transformer neutral-to-ground connection where the GIC enters the transmission network. The first approach involves inserting a capacitive device in the transformer neutral-to-ground connection that would block all DC current flow into the power grid, and therefore completely eliminate the E3 HEMP or geomagnetic storm threat. While this is a workable concept in theory, the traditional approach for the transformer neutral capacitive devices was originally conceived in the prior solar cycle before the extremes of large geomagnetic storms or E3 threat environments were fully understood. In that prior context of smaller storms, the devices were only to be applied in a few locations to protect only a few highly exposed and vulnerable transformers rather than to apply these more broadly as is now understood necessary for sever geomagnetic storms or the E3 threat environments. Widespread application of neutral capacitor devices would bring considerable uncertainty and risk of impedance changes and ferroresonance concerns on the network. Limited application of neutral capacitors would not be effective in mitigation concerns of wide spread catastrophic damage to key EHV transformers.

The alternative transformer neutral blocking strategy considered was the global application of a simpler low-ohmic resistor in the neutral-to-ground connection point in all transformers on the power grid (simple schematic provided in Figure Exe-2). This approach would only achieve partial reduction in GIC, but levels with the trade-off being a simpler, more reliable, and overall less-expensive power grid hardening solution. The investigation indicates that practical devices using this approach can typically reduce overall GIC levels by ~60 to 70%. Transformer neutral blocking resistors also have inherent cost advantages, in that the devices can be built for lower voltage withstand and current ratings compared to in-line installation options. Also because the resistance is added in the neutral where currents are normally at or near zero, instead of in the phase, the power system would not be exposed to higher operating losses due to added resistance in each AC phase line.

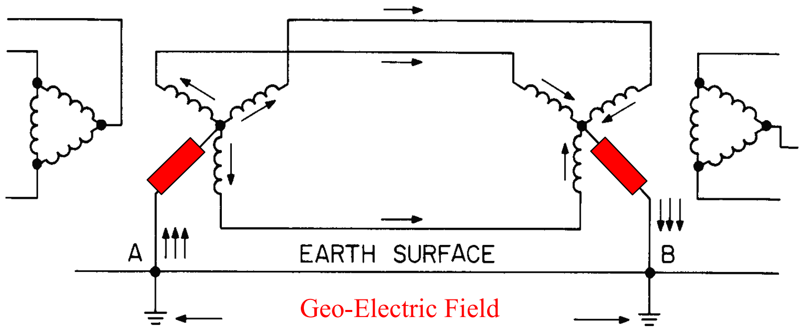

Figure Exe-2. A low-ohmic resistor in the transformer neutral ground connection at each transformer will act to significantly reduce, but not completely block, the GIC flow in the transmission line and each transformer.

Modifying the nature of the grounding of the entire U.S. EHV and HV power grid is a considerable challenge, and engineering trade-offs need to be clearly understood and mitigated. The general practice has been solid or effective grounding of these transmission networks, due to a variety of economic and reliability reasons. However, it is this practice that introduces the unintended vulnerability of these networks to GIC from E3 HEMP threat environments and from naturally occurring geomagnetic storm events.

The approach of using neutral resistors for GIC reduction does not appear to pose significant or insurmountable impediments. IEEE Guidelines were examined in regard to whether these neutral resistor devices would significantly alter the grounding effectiveness of the power grid. The screening performed in this analysis indicates that as long as low-ohmic resistors are appropriately used, they do not appear to alter the grounding coefficients of the EHV and HV networks beyond the guideline recommendations.

While this proposal is still at only a conceptual development stage, it is anticipated that installed costs per unit (per transformer) can be reasonably expected to be in the range of $40,000 to $100,000 each. The number of transformers that need to be considered for installation will require further refinement through more detailed analyses that can only be undertaken with power industry participation, but it is expected that the total number will range between 3000 to 5000 units for the entire U.S. EHV and HV power grid.

While the objective of this study was to investigate physical hardening options, it should be noted that operational mitigation methods are also possible. In previous work for the National Grid in the UK, Metatech developed and implemented a methodology to allow grid operators to respond to a short notice alarm of a geomagnetic storm and to take mitigating action based on previous computations and consideration of previous network responses.

Section 1
An Overview of GIC Blocking and Reduction Devices on Transmission Networks

Both E3 disturbance environments and naturally occurring geomagnetic storms can cause the flow of geomagnetically-induced currents (GIC) through transformers in an exposed power grid. The GIC, if large enough, can disrupt the AC performance of the grid causing initial blackouts and also poses the potential for permanent damaged to large transformers, which can lead to restoration delays for the power grid. Hardening of the power system is optimally done through the application of passive devices or circuit modifications that block or reduce the flow of GIC in a power grid. While operational modifications can also be considered, the varying state of system operation may limit the range of effectiveness and flexibility available to a system operator at any point in time. Further, the possibility of human error is substantially higher in application of any operational measure that would be needed to safely secure the network, whereas passive and permanently installed hardware modifications would be ever-present and prepared to counter the threat environment impacts no matter when they occur. Operational actions also are unlikely to provide substantial levels of GIC reduction that would be needed to limit the potential for permanent damage to the key assets such as EHV transformers and circuit breakers on the bulk transmission network.

As shown in Figure 1-1, the flow of GIC in this simple power system is due to a geo-electric field created by the E3 or geomagnetic storm environment over the length of the transmission line and transformers at each end. The flow of the GIC enters and exits the single transformer neutral-to-ground point on each transformer and the flow splits equally in each of the three phases of the transformers and transmission lines. An overview of the different GIC blocking and reduction approaches can be quickly reviewed using this simple power system circuit. For example, in Figure 1-2 the application of transmission line series capacitors is depicted. Since the capacitors block the flow of all DC currents, all GIC flow in this transmission line, and by extension the two transformers at each end of the transmission line, would also be blocked. These apparatus needs to be able to handle the rated AC current flow and rated operating voltage of the transmission line,

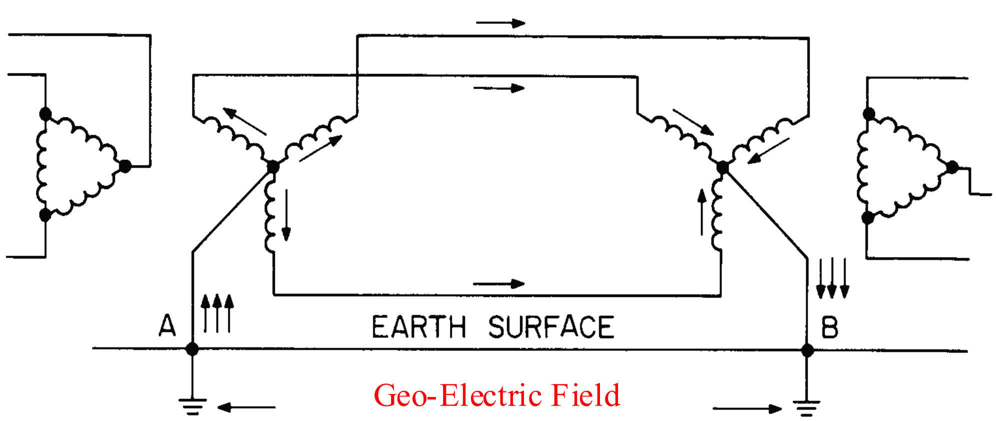

Figure 1-1. A simple GIC flow path on a single transmission line, which is terminated by a neutral-grounded transformer at each end of the line.

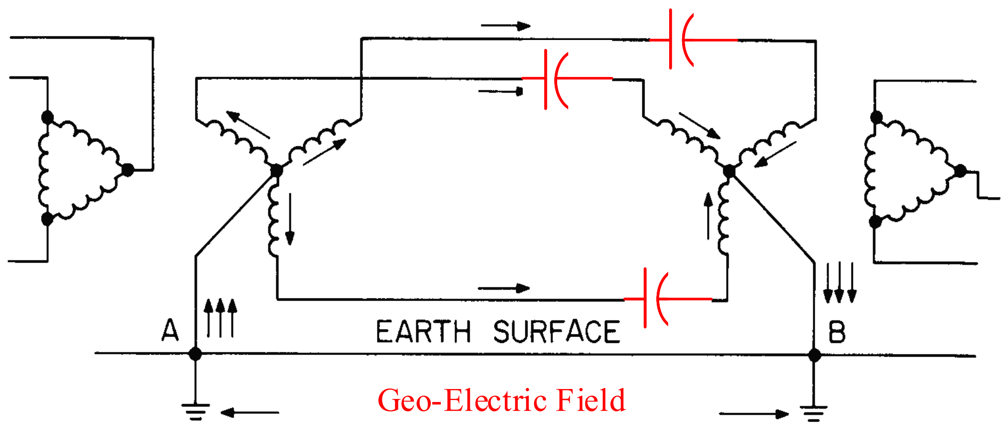

Figure 1-2. Adding series capacitors in each phase of the transmission line will block all GIC flow in this circuit and in each transformer.

which adds enormous expense when considering the 345, 500, and 765kV transmission operating voltages. An alternative to transmission line series capacitor banks is to move the capacitors to the transformer neutral-to-ground connections as shown in Figure 1-3. For this simple circuit, the application of only one of these neutral blocking devices in

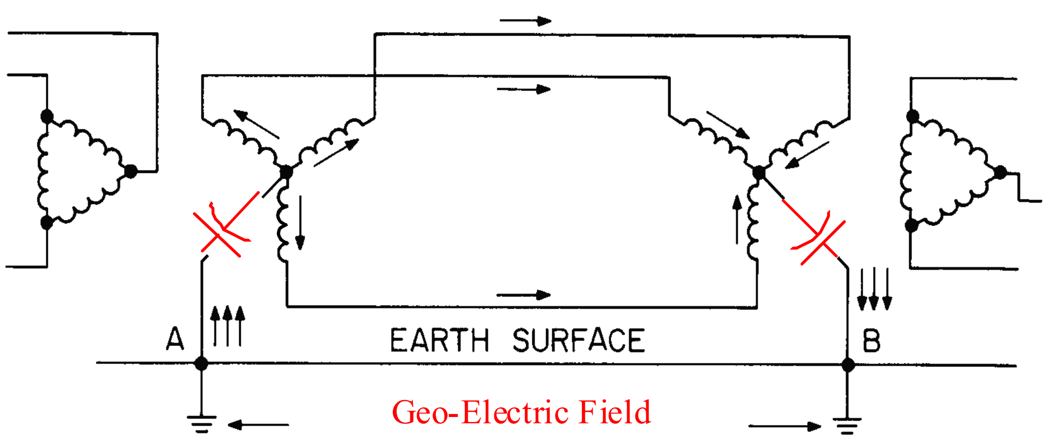

Figure 1-3. A single low-voltage capacitor in the transformer neutral ground connection at each transformer will also block the GIC flow in the transmission line and each transformer.

either of the transformers would be sufficient to block all GIC flows, however in real networks the circuit would have multiple loops and blocking throughout would be needed to block all GIC. The number, rated ampacity, and rated operating voltage of these devices are all smaller and simpler in concept and cost than those that will be needed for transmission line series capacitor application. In addition to transformer neutral blocking capacitors, it is also possible to consider the application low-ohmic resistors that would also be placed in the neutral connection. These would be applied in the same place as the neutral blocking capacitors as shown in Figure 1-4. While the flow of GIC would not be completely prevented, the addition of the neutral resistance can add significant resistive impedance to the overall transmission circuit and cause a resulting large reduction in total GIC flow.

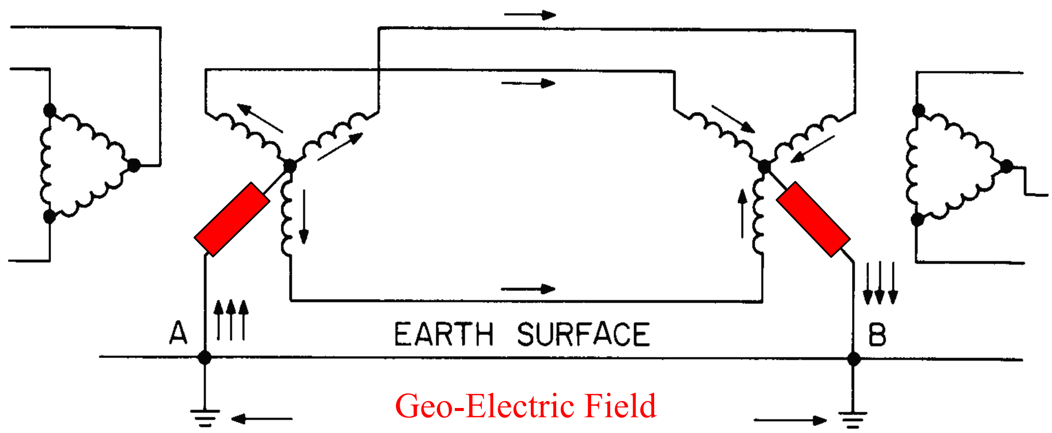

Figure 1-4. A low-ohmic resistor in the transformer neutral ground connection at each transformer will act to significantly reduce, but not completely block, the GIC flow in the transmission line and each transformer.

Because GIC accesses power systems through the multiplicity of grounded neutral leads of wye-connected transformers, the most effective point at which to place blocking or limiting devices is also in these neutral-to-ground leads. Series capacitors in transmission lines will also block GIC, while these devices are very expensive, especially at 345, 500, and 765kV voltage applications, they can also provide AC system benefits. Neutral GIC blocking devices have been actively researched since the early 1990s and several hardware versions have been successfully deployed for blocking stray DC or GIC flows into exposed transformers (Ref 1-1, 1-2). Contemporary adaptations of these blocking devices have utilized highly reliable power electronic devices for the demanding high-current, high-speed switching features of the device. These devices have gained particularly wide usage throughout the cathodic protection sector of the pipeline industry where very large AC currents can couple from nearby transmission lines into pipelines.

References

1-1 J. G. Kappenman, F. S. Prabhakara, C. R. French, T. F. Clark, H. M. Pflanz, V. D. Albertson, N. Mohan, "Mitigation of Geomagnetically-Induced and DC Stray Currents", Electric Power Research Institute Report EL-3295, December 1983.

1-2 J. G. Kappenman, S. R. Norr, G. A. Sweezy, D. L. Carlson, V. D. Albertson, J. E. Harder, B. L. Damsky, "GIC Mitigation: A Neutral Blocking/Bypass Device to Prevent the Flow of GIC in Power Systems", IEEE PES Special Publication 90TH0357-4-PWR, Special Panel Session July 17, 1990, pages 45-52.

Section 2
GIC Blocking and AC Bypass Device Design and Operation

A brief discussion and evaluation will be provided of various GIC reduction strategies that could be considered for reducing and blocking the flows of GIC (the quasi-DC current) produced from either a geomagnetic storm or the E3 portion of a HEMP threat scenario. As described more fully in reports Meta-R-319 and Meta-R-321, both severe geomagnetic storms and the E3 portion of the HEMP threat have the capacity to place very large numbers and large percentages of the U.S. EHV transformer population at-risk of permanent damage, an outcome that could significantly prolong widespread power outages caused by these events.

As noted previously, prior work in the power industry had been sponsored by EPRI and others in the power industry in the early 1980's and again in the early 1990's (Ref 1-1,1-2). These designs concepts were based upon the insertion of capacitance in the transformer neutral-to-ground connection. Because the extremes of the geomagnetic storm environments were unknown, they were therefore presumed to be no worse than those observed during the March 13-14, 1989 storm. As a result, the understanding that existed at that time was to not be concerned about the large number of transformers that we now know would be at-risk of failure, but rather only a few exposed transformers that may be at-risk. The approach at that time was to install only a very few devices to block GIC at those transformers of concern, therefore concern about widespread introduction of capacitive devices in the transformer neutral was not posed. The broader threat of damaging levels of GIC now require device conceptual designs that can be broadly applied in the power grid and that would also not introduce new and undesirable operational or engineering risks to the networks. The next few sections of this report will introduce and discuss various strategies and some of the pros and cons of each approach.

In this section, a summary will be provided of the functional approach and conceptual design for a device capable of either blocking GIC or reducing its levels compared to the normal solidly grounded power grid design. The GIC blocking device for application on bulk power systems requires a capability to block DC or GIC flows into or out of the transformer while simultaneously allowing a path for the flow of long-duration low-level AC currents and very short-duration but very high magnitude AC currents due to nearby faults on the high voltage network. The operational aspects of the capacitor–based Neutral Blocking and Bypass Device (NBBD) can be illustrated in the next few schematic diagrams. More modern adaptations of resistor-based neutral devices will also utilize many of these same design concepts. Figure 2-1 provides a simple schematic of the NBBD as it would be installed in a typical transformer neutral-to-ground connection. As outlined in the schematic, the device entails two primary circuit systems, a capacitive circuit that provides the GIC blocking and normal flow path for low-level long-duration AC currents. The other circuit system is the bypass circuit that provides the rapid and temporary bypass of the blocking capacitor under AC fault conditions. This bypass circuit provides the path to ground for the short-duration but very high magnitude AC currents that will be created during a nearby AC fault condition. Figure 2-2 provides a depiction of the flow of low-level AC currents through the GIC blocking capacitor under normal operation conditions. The AC current rating of this circuit element can be adjusted, though a typical rating of 50 amps is commonly used. Figure 2-3 provides a schematic showing the path of flow for the high-magnitude AC fault currents, which is now diverted from the blocking capacitor through the switching devices, which have high current ratings. Once the fault has been isolated from the network and AC current levels drop, the device automatically reverts to the normal GIC blocking mode of operation as illustrated in Figure 2-2. One of the drawbacks of neutral capacitor blocking devices is that the device must be bypassed at medium level voltages, in that the neutral of most large power transformers is only rated for 150kV BIL (or equivalent to 15kV distribution class voltages). This voltage stress limitation means that bypass of the capacitor would need to be done whenever AC or DC voltage stress reached these steady state levels. Since the extremes of the E3 environment as it occurs at the transformer neutral-to-ground point have not as yet been well defined, the ability to fully define the operational requirements for a neutral capacitor blocking device cannot be fully established at this time. Follow-on engineering efforts would be conducted to better define the DC voltage withstand specifications. The application of neutral resistors can be done as simple resistor devices or can also have an even simpler bypass circuit to limit excessive AC current flow conditions or high neutral voltage rise conditions. It is also expected that these devices can be applied with more robust acceptance of the extreme AC or DC voltage and current environments that would occur during large E3 threat events. Therefore, this device is also rigorously examined as part of the hardening options for the power grid.

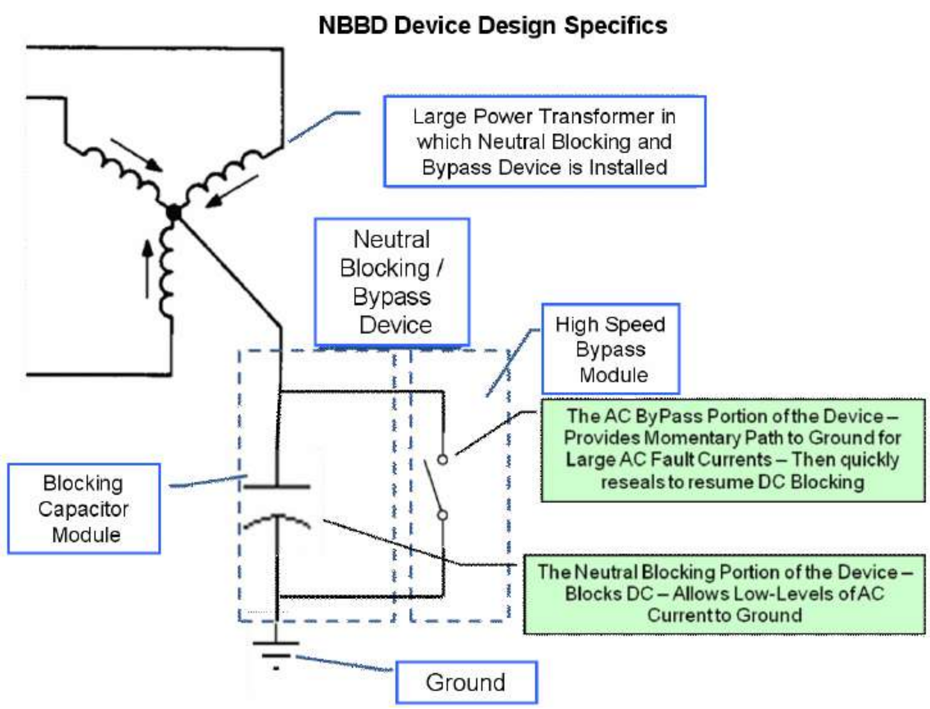

Figure 2-1. Schematic of a Neutral Blocking and Bypass Device in a transformer neutral.

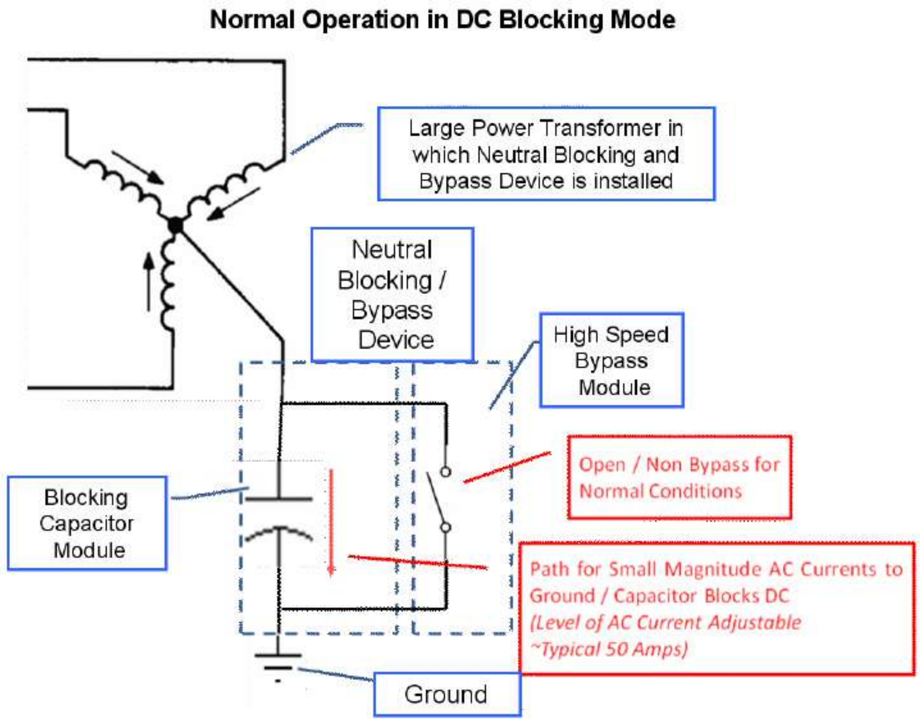

Figure 2-2. Under normal operation conditions, low-level AC currents flow through neutral capacitor. The capacitor also acts to block GIC flow into the transformer.

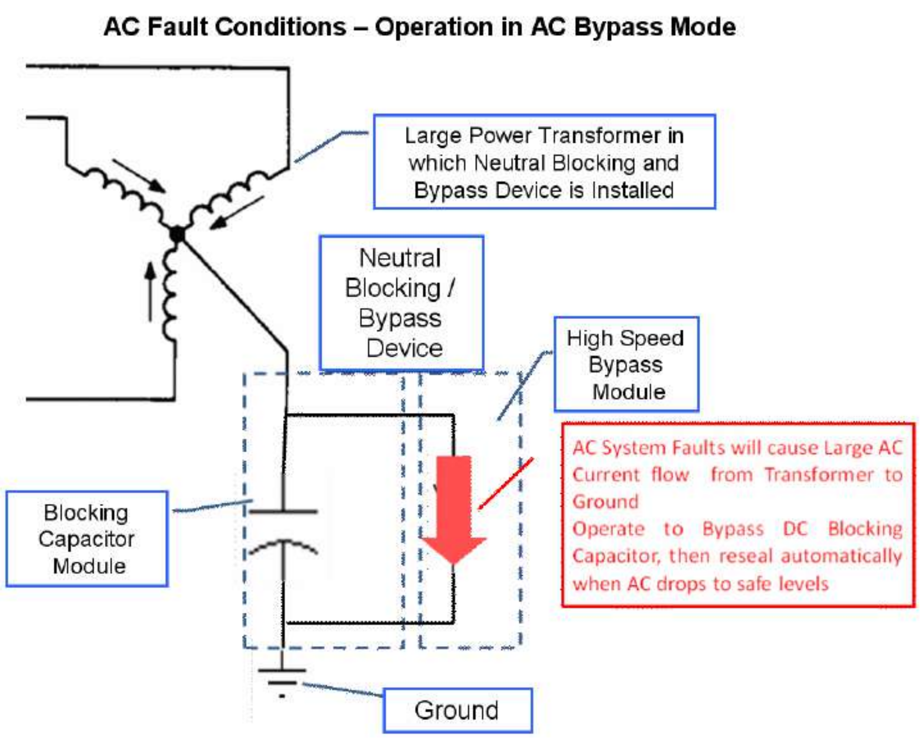

Figure 2-3. Under AC fault conditions, high magnitude AC currents flow through power-electronic bypass circuit to ground. The capacitor is temporarily bypassed.

While all these depictions of blocking devices have been illustrated for delta/wye-grounded transformer connections, a common transformer connection used on the HV and EHV transmission network in the U.S. is the autotransformer connection as shown in Figure 2-4. Unlike the delta/wye transformer, this transformer has a direct connection between the primary and secondary voltage levels. Because of this intra voltage connection between the series and common windings, a device in the transformer neutral to block GIC will only block the flow of GIC in that transformer's common winding and will not inherently block the flow of GIC in the series winding. Therefore, any neutral blocking strategy that is focused upon a single operating voltage (for example only installing blocking devices in the neutrals of all 500kV transformers only) will be relatively ineffective in preventing the flow of GIC due to the alternate path for GIC flows in the numerous autotransformer interconnections to other operating voltages across the network.

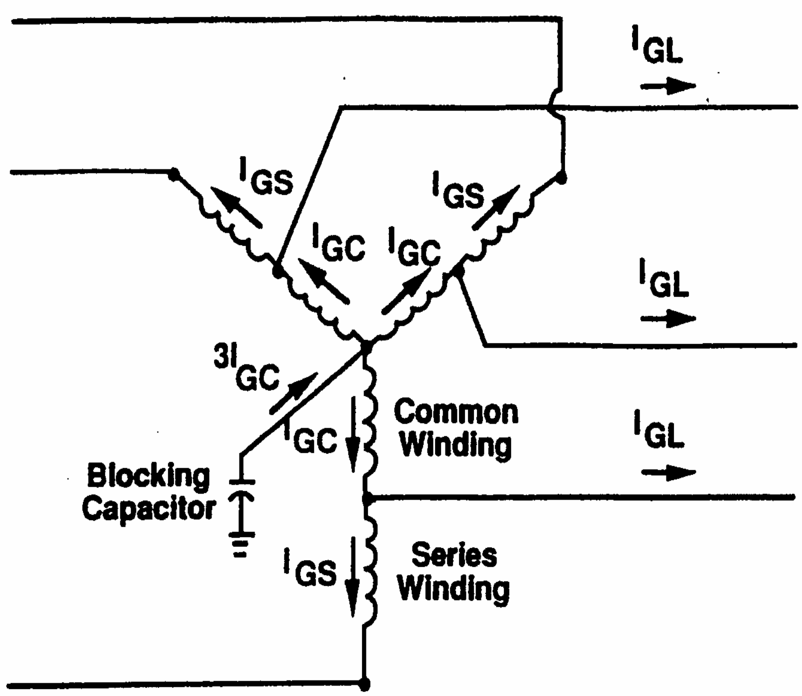

Figure 2-4. A significant portion of the EHV and HV transformer population in the U.S. power grid is of the autotransformer design. The series and common winding connections allow the flow of GIC independently in the transformer. For a neutral blocking capacitor installation, the GIC in the neutral lead and common windings of the auto-transformer will be completely blocked, while GIC can still flow in the series windings of this transformer type.

Section 3
Comparison of Series Capacitors and Neutral Blocking Resistors on a Simple Transmission Network

In order to study the most effective strategies for GIC-blocking or reduction, it is necessary to have a power network simulation tool that will depict the complex spatial and temporal geo-electric field patterns and the complex power circuit topology that will provide the approximate values of GIC flow in each transformer and transmission line in the simulation model. Various devices such as series capacitors, neutral capacitors and resistors can be simulated to study various blocking and mitigation strategies. In the mid 1990s the Hydro Quebec system completed the installation of series capacitors on a number of their 735kV transmission lines. It was intuitively recognized that these series capacitors would block the flow of GIC in the lines in which they were installed, but it was not known how effective they would be in reducing overall GIC flows and therefore reducing the threat to the system. To illustrate the GIC reduction impacts of series capacitors, a simple simulation has been undertaken of the Hydro Quebec 735kV transmission network. Figure 3-1 provides a map of the geographic layout of the 735kV transmission network in Quebec, while Figure 3-2 provides a map with color-coding to show the transmission lines where series capacitors have been added to block GIC flows. As shown in Figure 3-2, the long transmission ties from the Montreal load region north to the James Bay region and northeast to Churchill Falls region have been series compensated, which will prevent the flow of GIC on these long ~1000 km interties.

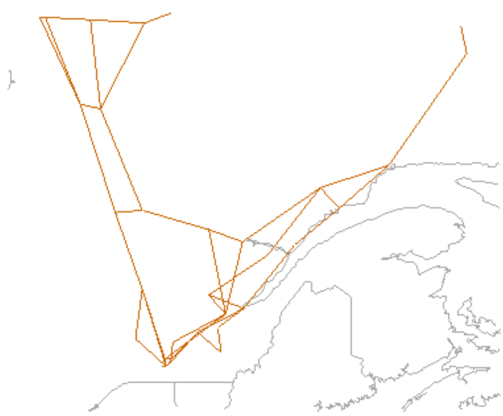

Figure 3-1. Map of the Hydro Quebec 735kV transmission system.

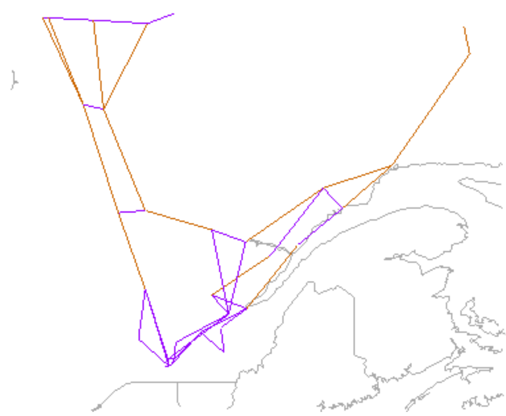

Figure 3-2. Map of the Hydro Quebec 735kV transmission system with the addition of series capacitors indicated by orange lines.

There remain a number of lines, particularly in the Montreal load region, that are not series compensated. To examine the relative GIC blocking efficacy of the transmission network, a large and uniform east-west geo-electric field is simulated for both the uncompensated and compensated transmission network configurations. Figures 3-3 and 3-4 show the pattern of GIC flows for both network configurations. As expected, the pattern of GIC flows differs substantially. By comparing the flow patterns, the GIC is reduced in many regions due to the addition of the line capacitors, but is also noticeably larger in some locations as displacement of flows to alternate circuit paths are occurring.

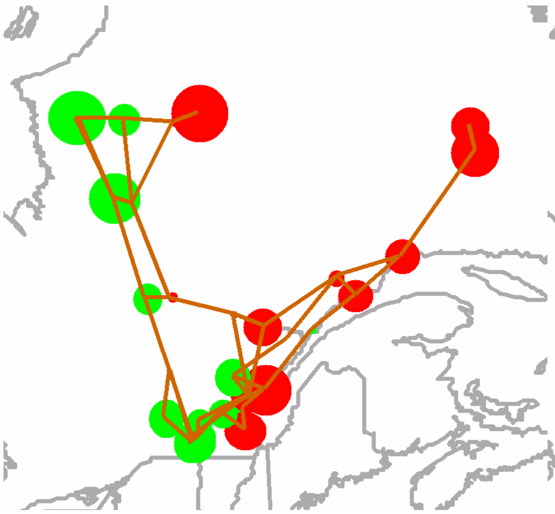

Figure 3-3. Pattern of GIC flows in Quebec 735kV network for an east-west geo-electric field with no series compensation in the transmission lines.

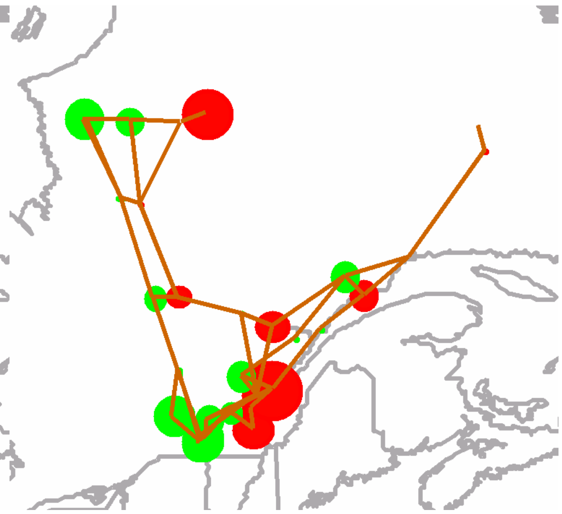

Figure 3-4. Pattern of GIC flows in Quebec 735kV network for an east-west geo-electric field with series compensation in the transmission lines.

The pattern of GIC flows both with and without the series capacitors can be more quantitatively compared by plotting the individual transformer GIC flow per phase for the normal system and series compensated system, as shown in Figure 3-5. In this comparison the normal system GIC flows in each transformer were sorted and plotted by increasing magnitude of GIC flow, as shown in the blue plot of transformer GIC flows. Using the same sorting order, the plot of altered GIC flow in each transformer is shown in the companion red line curve. At many locations, the GIC flow levels are reduced, but at other locations increases in GIC flows are evident. A more meaningful comparison can be provided from a system perspective by summing all the GIC flows in the transformers for the two network configuration conditions. Figure 3-6 provides a comparison of the sum of GIC flows, in the normal case total GIC is ~5800 amps/phase and the total GIC flow decreases to ~4100 amps/phase due to the addition of the series capacitors. This is a net ~30% reduction in GIC flows across the system.

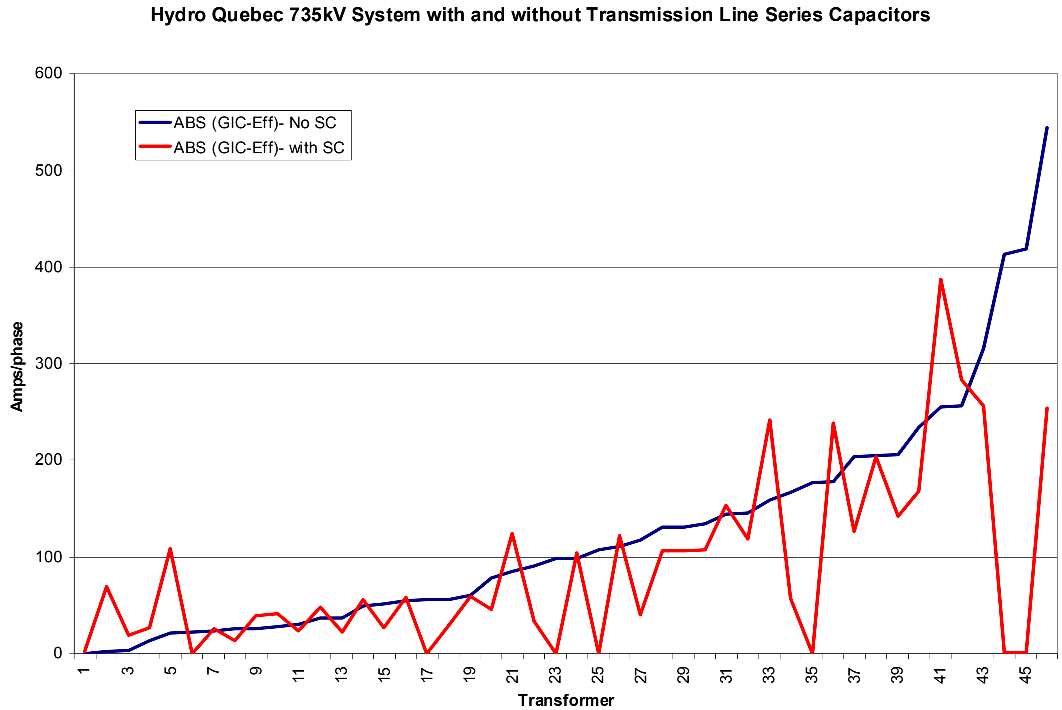

Figure 3-5. Comparison of GIC flows in each transformer for an east-west geo-electric field with and without series compensation in the transmission lines.

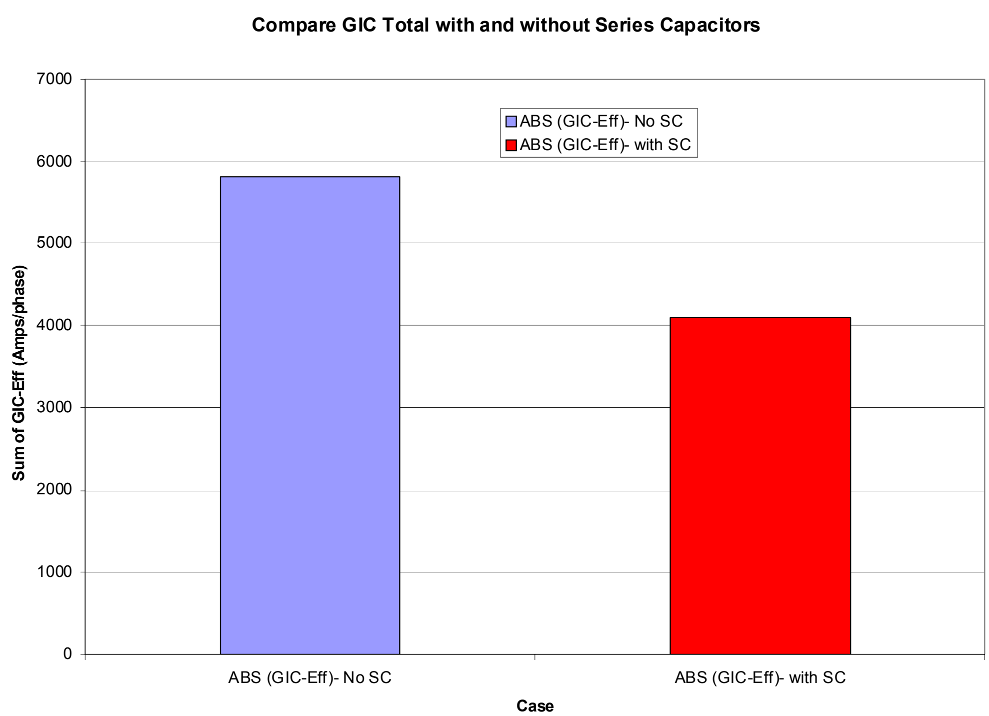

Figure 3-6. Comparison of sum of GIC flows in the network for an east-west geo-electric field with and without series compensation in the transmission lines.

These results also compare favorably with simulations of the WECC region of the U.S. model, which has ~50% of all transmission lines series compensated. Figure 3-7 provides a map of the western U.S. WECC power pool region showing the location of series compensated lines. A set of simulations was performed on the WECC region using a uniform geo-electric field, and rotating this by 360° in 10° increments. The total GIC at each increment was calculated for the normal grid design with ~50% compensation versus a grid design where all of the series capacitors were removed (bypassed). As shown in Figure 3-8, the level of GIC with series capacitors is only fractionally smaller than the grid without the series capacitors. Figure 3-9 provides a calculation of the % GIC reduction for the WECC region series capacitors, and this summary indicates GIC reductions (based upon orientation of the geo-electric field) only range from ~13% to ~22%.

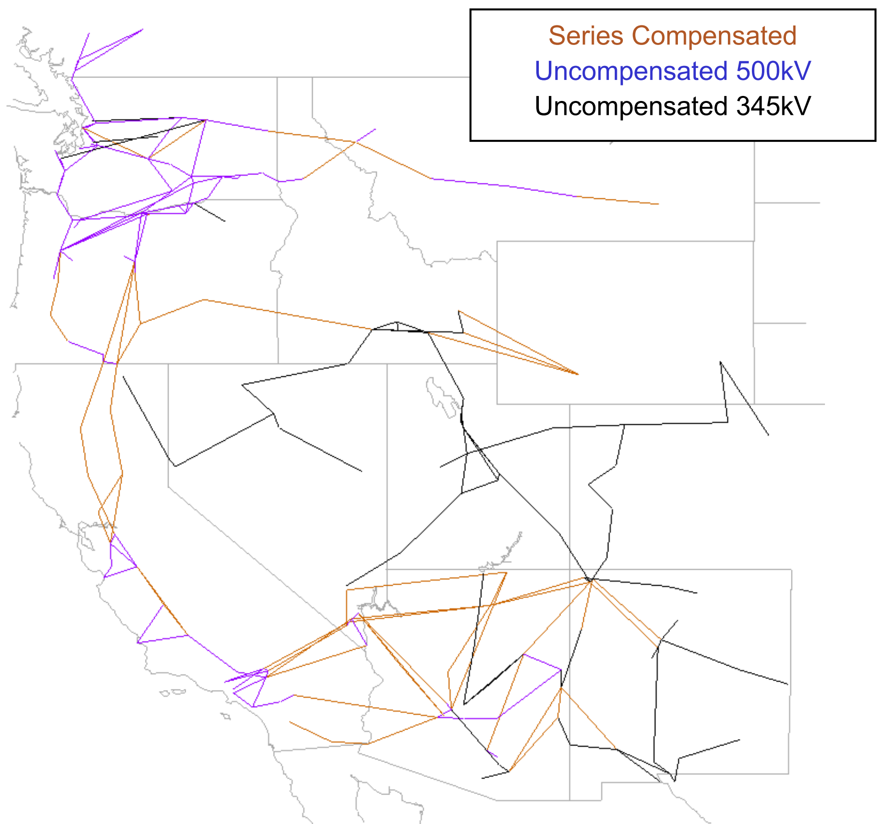

Figure 3-7. Map of western U.S. WECC region noting series compensated and uncompensated transmission lines.

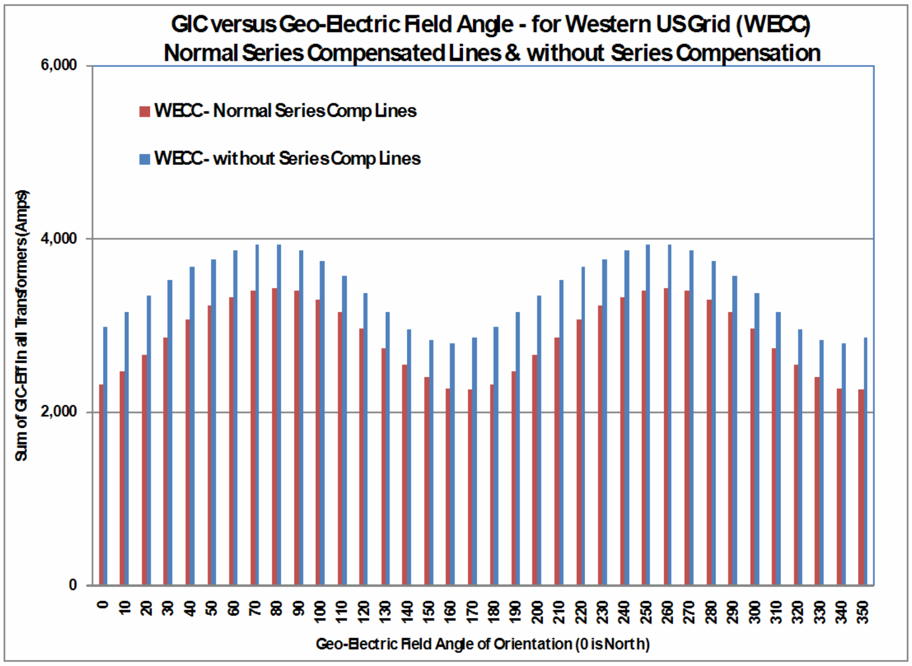

Figure 3-8. Comparison of sum of GIC flows in the WECC region for a rotating geo-electric field with and without series compensation in the transmission lines.

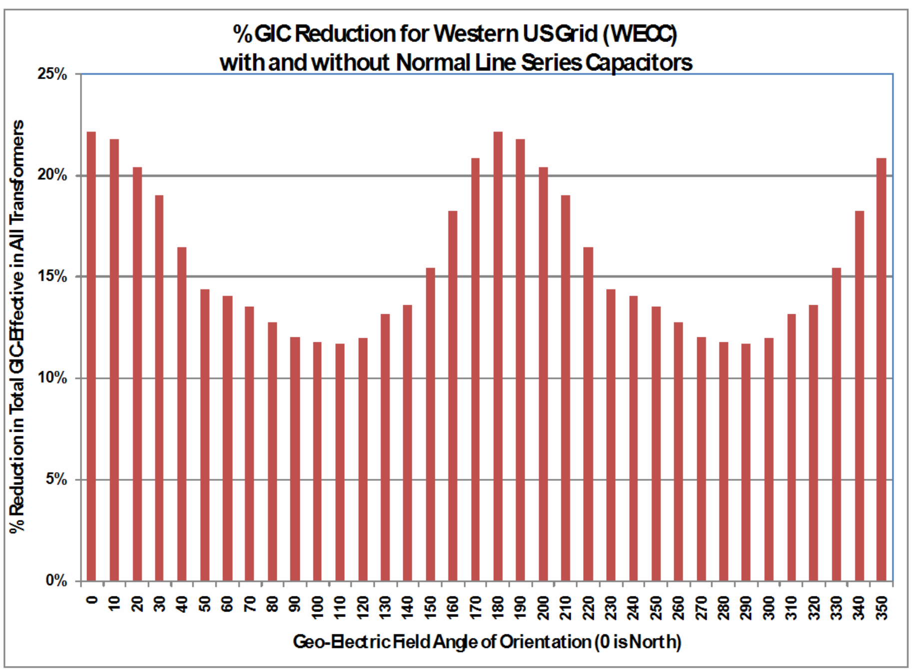

Figure 3-9. Percent GIC reduction in the western U.S. WECC region for simulations with and without series compensated transmission lines.

To provide further perspective on GIC blocking and reduction strategies, a comparison was also performed for the uncompensated Quebec transmission network with several sizes of low-ohmic neutral resistors in each of the transformers. Simulations were performed with neutral resistor sizes of 3 ohms, 5 ohms and 10 ohms in the neutral of each of the 735kV transformers. Figures 3-10, 3-11, and 3-12 provide the pattern of GIC flows for each of these neutral resistor blocking cases. As shown, the pattern of flows essentially remains the same from Figure 3-3, with no neutral resistors; with the exception of decreasing GIC magnitude at each location with increasing neutral resistor size, the pattern of GIC flow polarity remains more consistent. Figure 3-13 provides a comparison of GIC flow at each transformer for the normal conditions and for each of the different size neutral resistor scenarios. Only in a few of the locations with very low initial GIC flow conditions does the level of GIC flow increase. The reduction in GIC flow for each of these cases shows uniform levels of decrease at each location as the size of the neutral resistor increases. Figure 3-14 provides a comparison of total GIC flow with the addition of the neutral resistor cases. When even the 3 ohm neutral resistor case is compared with the normal conditions, the total GIC flow is reduced by ~68%. This indicates that a comprehensive neutral resistor strategy can provide large reductions in GIC flows.

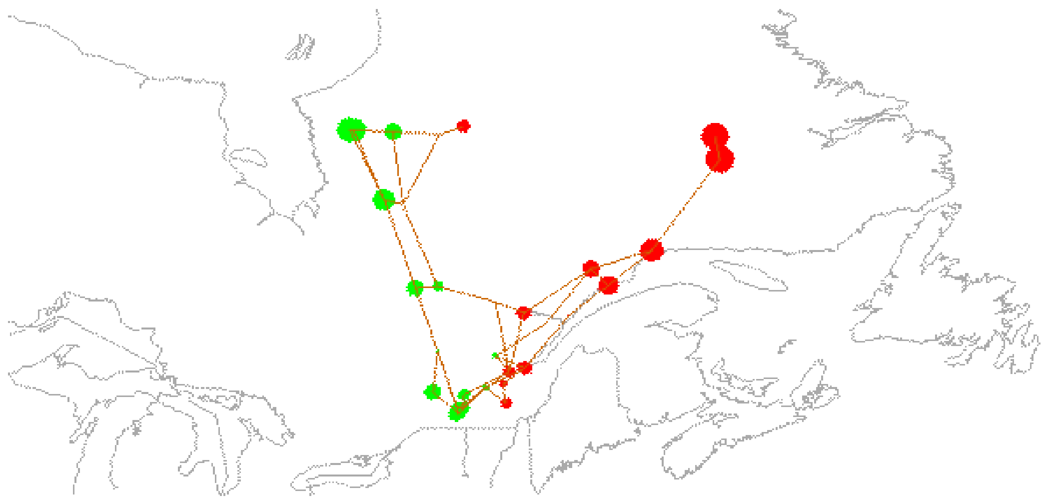

Figure 3-10. Pattern of GIC flows in Quebec 735kV network for an east-west geo-electric field and with 3 ohm transformer neutral resistors.

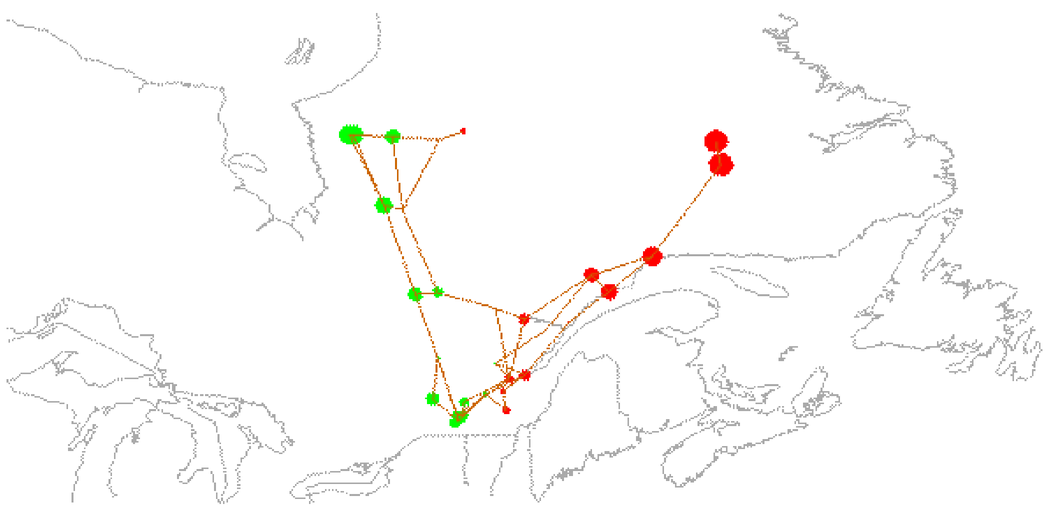

Figure 3-11. Pattern of GIC flows in Quebec 735kV network for an east-west geo-electric field and with 5 ohm transformer neutral resistors.

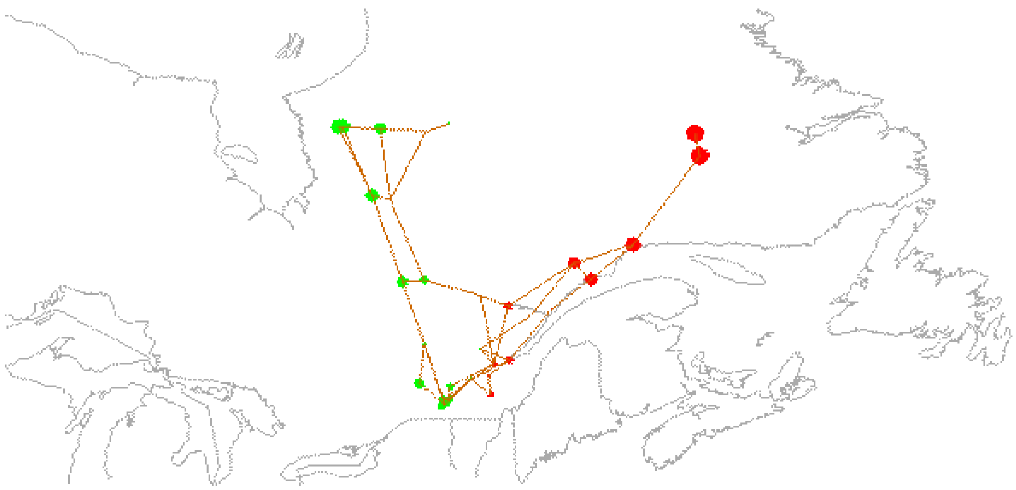

Figure 3-12. Pattern of GIC flows in Quebec 735kV network for an east-west geo-electric field and with 10 ohm transformer neutral resistors.

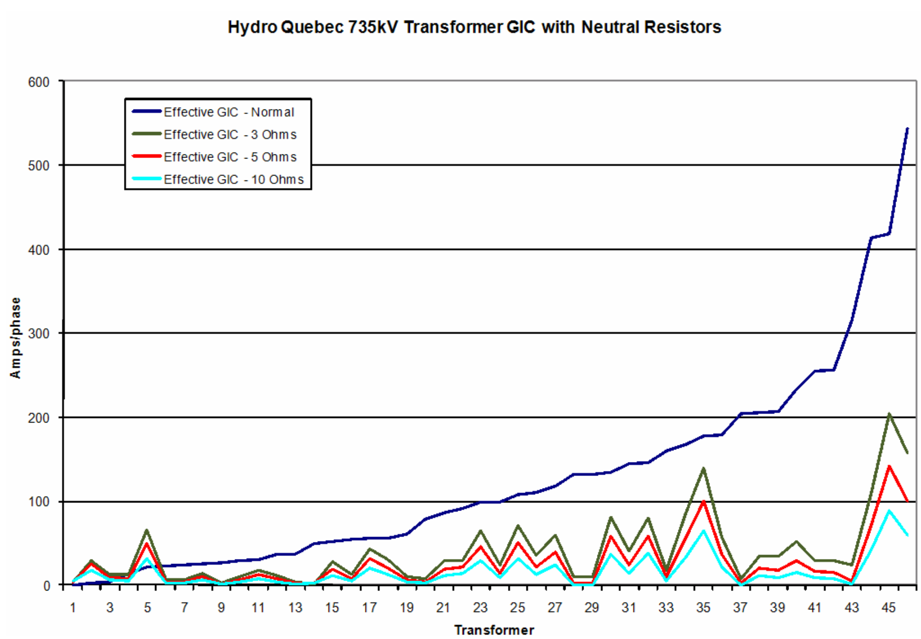

Figure 3-13. Comparison of GIC flows in each transformer for an east-west geo-electric field for normal conditions and with various size transformer neutral resistors.

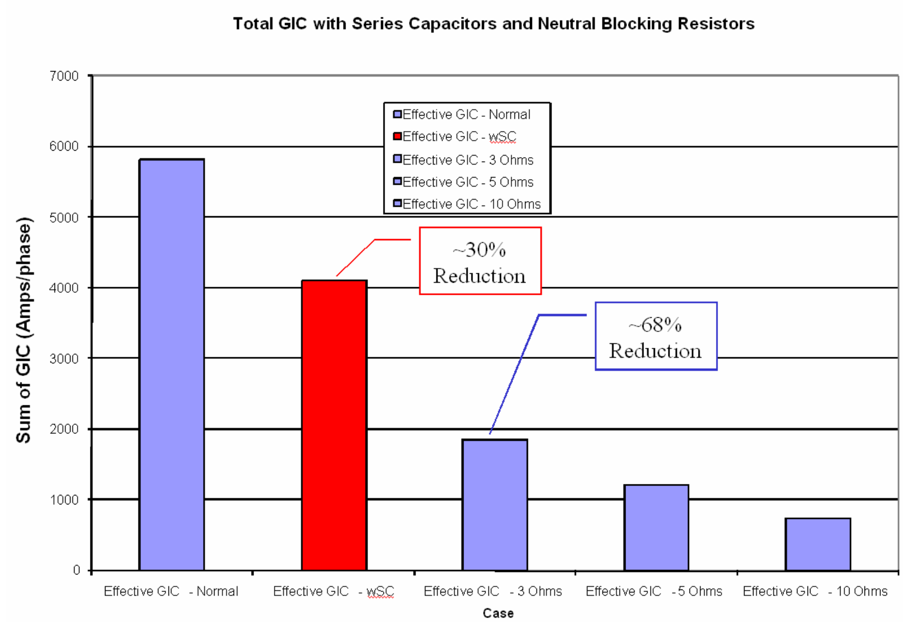

Figure 3-14. Comparison of um of GIC flows in each transformer for an east-west geo-electric field for normal conditions, series compensation (i.e. wSC), and with various size transformer neutral resistors.

Section 4
A Generic Evaluation of Neutral Blocking Resistors for GIC Reduction

The application of neutral blocking capacitors at every transformer neutral grounding location across the U.S. power grid would block all GIC flow from the E3 threat environment. However, the design and concerns about adverse interaction of such a capacitor-based blocking device technology is still not fully developed and is beyond the scope of this analysis effort. Because of these uncertainties, the GIC reduction strategies will focus upon the application of more economic and readily available technology of low-ohmic neutral resistors. As previously discussed in the application on the Hydro Quebec network, these devices provided much larger GIC flow reduction compared to the extensive application of transmission line series capacitors across the Hydro Quebec system. A more generic perspective can be developed on the application of such devices by analyzing their effectiveness in a simple circuit application. Using the simple circuit of a transmission line with a transformer at each end, previously provided in Figure 1-1, the benefits of different size neutral resistors can be illustrated by varying the length of this transmission line. Figure 4-1 provides a plot of the transformer neutral GIC for a normal line configuration and for various sizes of transformer neutral resistors, using the average line and transformer resistances for a 500kV system. In the normal line configurations and for short line lengths, the GIC levels increase at a high rate as the level of transformer resistance becomes a less significant portion of the total circuit resistance. With a transformer neutral resistance, the increase in line length produces a more linear increase in GIC levels, due to the continuing dominance of the transformer termination resistance (including the neutral resistor) in the overall circuit resistance.

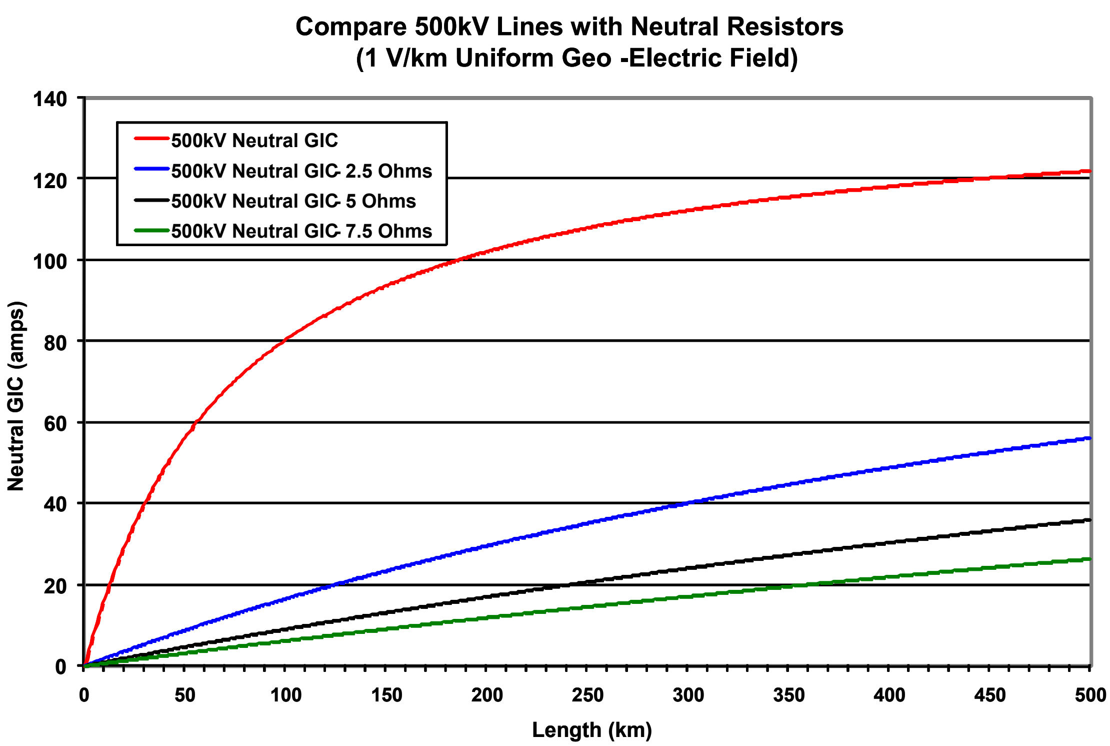

Figure 4-1. Comparison of GIC flows in the simple circuit of Figure 1-1 as line length increases, for normal conditions and with various size transformer neutral resistors.

The rate of GIC flow reduction can also be calculated as a function of circuit length as this provides further understanding of the range of effectiveness of this GIC reduction strategy for a variety of actual power network circuit topologies that will be examined in Section 5. Figure 4-2 provides a plot of the percentage GIC reduction versus line length for the various neutral resistor sizes and simulation data as supplied in Figure 4-1. As indicated by the trend line of these comparisons, the shorter the transmission line length, the greater the amount of GIC reduction. For example in the case of the 7.5 ohm neutral resistor, for a transmission line of ~75km or shorter, the amount of GIC reduction exceeded 90%. As the circuit length became very long, the amount of GIC reduction gradually and linearly decreased to a total reduction of about 83% for a 500km length transmission line. For the 2.5 ohm neutral resistor, the amount of GIC reduction was only ~54% for a 500km transmission line length. This analysis generically implies that for large networks, that have an architecture consisting of short lines between transformer termination locations, that the level of GIC reduction might be greater than for networks which have much longer average transmission line connections.

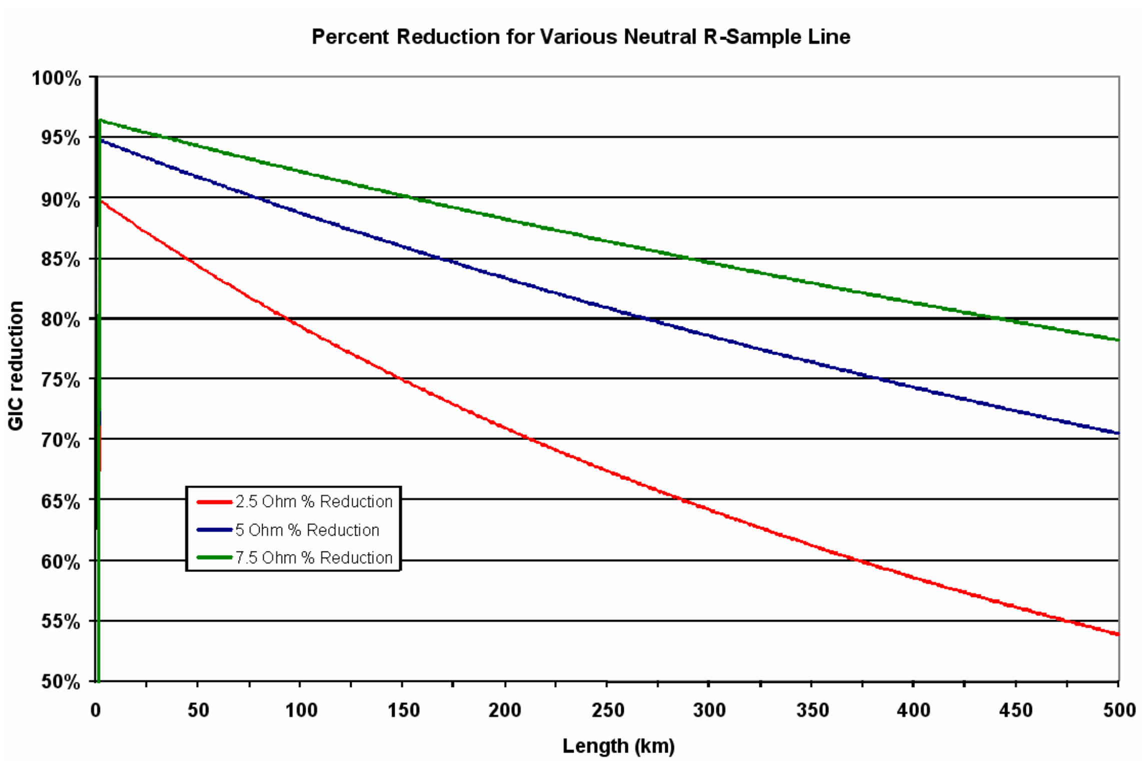

Figure 4-2. Percent reduction in GIC from Figure 4-1 due to application of neutral resistors versus line length.

Figure 4-3 provides a summary by kV rating of the average line length of transmission lines in the U.S. As shown, the average length also generally increases with kV rating. Both the size of the population of lines and the extremes in line length also need to be noted, as averages will not fully explain location specific vulnerabilities that may develop. In looking at 765kV lines, there are a U.S. population of only ~35 of these lines, with the average being 64.7 miles in length and the longest being ~175 miles long.

At 500kV, there is a much larger population, with ~445 lines. The average length is 54.1 miles with a longest un-series compensated distance of 171 miles in the U.S. eastern grid and a series compensated line of 395 miles in length in the WECC region. At 345kV, this segment has the largest population of lines with a total of ~1339 lines. As with the other rated voltages, large variations in lengths are also possible, with some un-series compensated lines of ~263 miles of length in the eastern U.S. grid and a series compensated line of ~391 miles of length in the WECC.

While this generic evaluation provides some general guidance on what to expect, region and grid specific evaluations were conducted to evaluate further the benefits of a neutral resistor blocking strategy as applied across the entire U.S. HV and EHV grid. The results of this analysis will be provided in the remaining sections of this report.

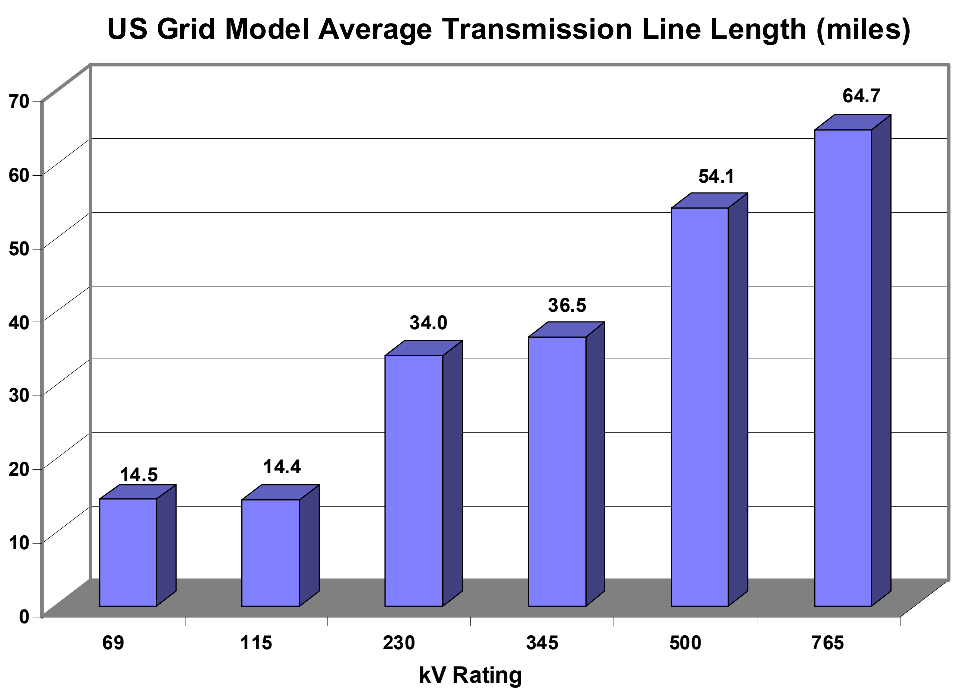

Figure 4-3. Average length of transmission lines in U.S. by kV rating.

Section 5
Static Geo-Electric Field Analysis of GIC Reduction Strategies for the U.S. Electric Power Grid

In prior analyses of the U.S. grid and impacts as reported in Meta-R-319 and Meta-R-321, the bulk transmission network representation was limited to voltages of 345kV, 500kV and 765kV. While these are the voltages where the most significant, impacts and also where the bulk of the impacts, will occur due to GIC flows, the ability to examine the efficacy of GIC blocking scenarios should include extension of the grid model to lower operating voltages. In the U.S. grid, underlying transmission voltages of 230kV, 161kV, 138kV and 115kV are also present and can at times contribute to overall GIC flows in the U.S. grid. These underlying voltages are also typically interconnected with the higher voltages (345kV and above) through autotransformer connections. As a result, they can provide a direct flow path for GIC from these underlying voltages into the 345kV and above network even when the transformers on this portion of the network have neutral blocking devices applied to them. As blocking devices are considered for the 345kV and higher voltage levels, these HV (115-230kV) transformers could act as an alternate path for GIC flow. While these HV transformers were not important in determining overall vulnerability of the U.S. grid in prior studies, they may play an important role (as an alternate GIC flow path) now that the emphasis is directed towards blocking and mitigation of E3-caused GIC flows and impacts to the U.S. grid.

Recognizing the importance of this issue, substantial efforts were made to expand the U.S. Grid Model to these underlying voltages. Since this portion of the network has a higher density and population compared with the 345kV and above, it was not feasible, given the time and monetary constraints to incorporate all of the underlying system into the full U.S. Grid Model at this time. Figure 5-1 provides a map of the existing Powercast U.S. Grid Model for all transmission at voltages of 345kV, 500kV and 765kV. In prior analysis, the major impact areas were especially noteworthy for the mid-Atlantic portion of the eastern U.S. power grid. As a result, this area was given the highest priority in expansion of the model at this time. The model requires both transformer and transmission line impedance data, but also important to this model are the geographic locations of all facilities, such as lines and substations. Impedance data for all underlying transmission voltages was obtained by Metatech from AC load flow study models. However, location is not a feature that needs to be considered in typical power flow models and as a result the GIC modeling is inherently more complex than the AC load flow. Locations can be, and in this case were, estimated from high quality transmission network maps provided by NERC; and in some cases these locations were more fully augmented by available satellite imagery of the specific substation assets. However, the NERC maps did not include detail for transmission line and substation locations below 230kV. Therefore, the additions were limited to 230kV lines and substations in the eastern U.S. area as shown in Figure 5-2. Further underlying voltage additions should be performed before final blocking and mitigation measures are carried out, but these details will allow more accurate assessment of the conceptual design options that are the focus of this analysis.

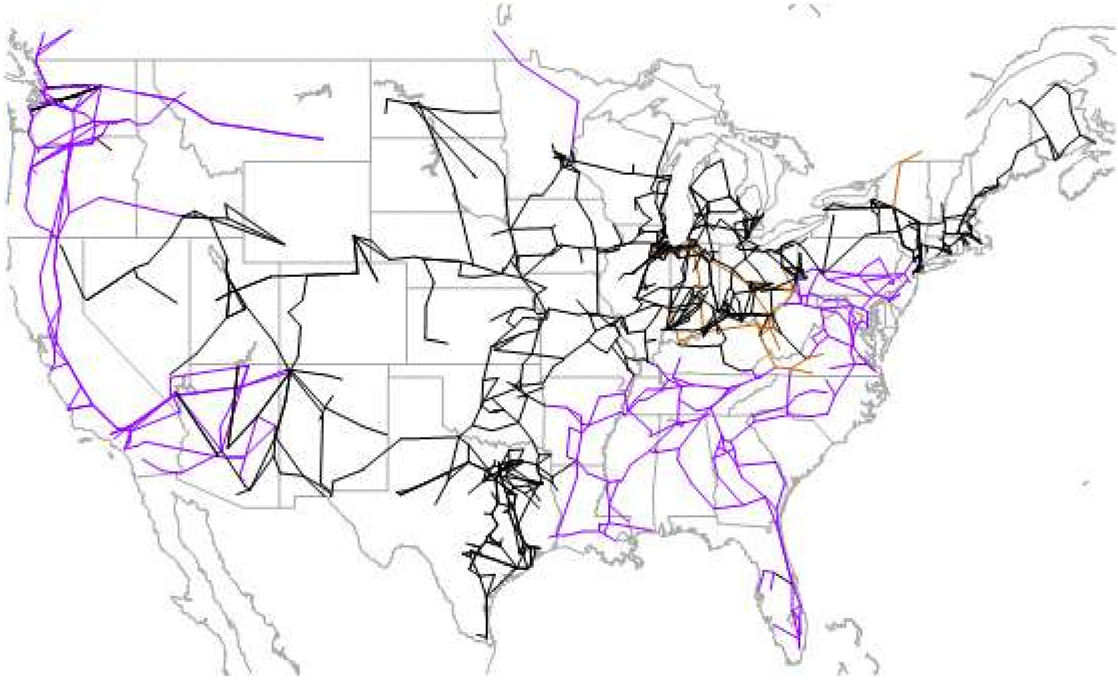

Figure 5-1. Map of U.S. high-voltage transmission network model for GIC simulation, CONUS region (orange 765kV, blue 500kV and black 345kV transmission lines).

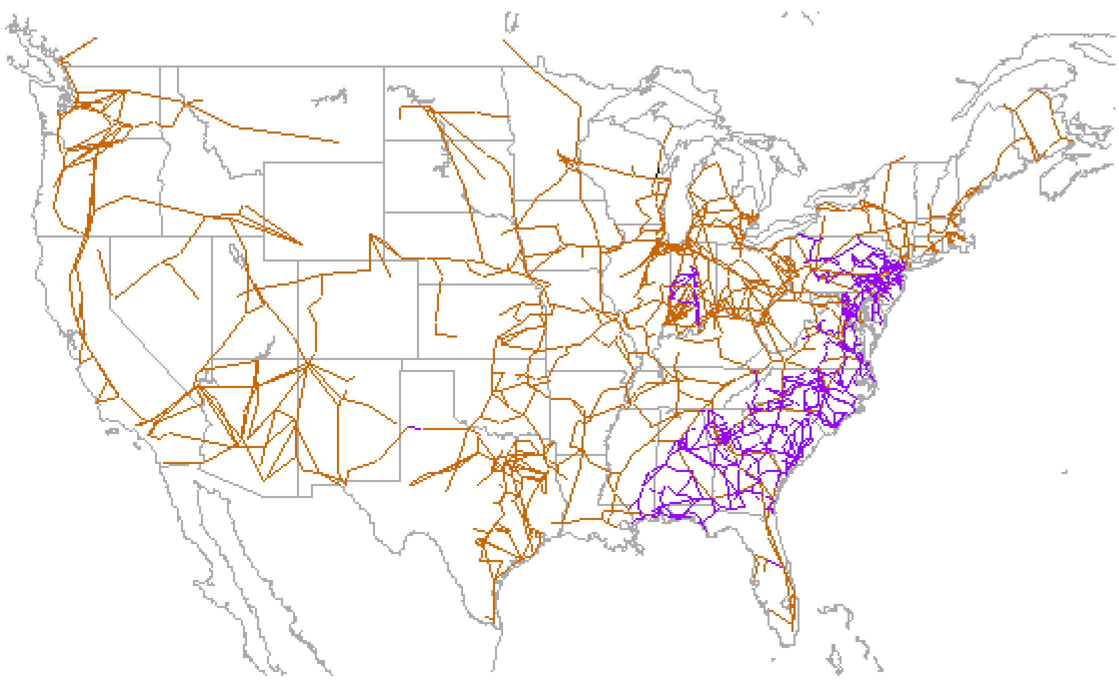

Figure 5-2. Map of U.S. high-voltage transmission network model for GIC simulation, CONUS region with 230kV additions marked in purple.

These specific 230kV assets included in the U.S. Grid Model constitute ~50% of all 230kV facilities within the eastern grid and ~33% of all 230kV facilities in the U.S. In terms of size, the model now includes a count of 1,388 transformers of 230kV primary voltage rating versus 1,572 transformers of 345kV rating. In total, the 230kV+ model includes ~3,550 transformers spanning 765kV, 500kV, 345kV and now 230kV.

In prior analyses of the U.S. grid and impacts, specific geomagnetic storm and E3 threat scenarios were simulated to quantify the potential impacts that they pose to the U.S. grid. These threat scenarios were generally geographically localized compared the entire U.S. grid infrastructure, and also had complex geo-electric field orientations and experienced local enhancements due to the influence of the ground conductivity conditions which also vary from region to region.

In order to simplify the analysis of blocking device efficacy, it is desirable to develop a comprehensive screening approach that removes extraneous variables for the initial screening of mitigation option evaluation. While the various mitigation and blocking options will also be tested against these specific threat scenarios and all local variables, it is more revealing and useful to do preliminary evaluation of blocking strategies using a more uniform geo-electric field condition that can be applied simultaneously across the entire U.S. grid infrastructure. In particular, it is desirable to test these blocking strategies using a uniform geo-electric field (1 V/km), which is applied across the U.S. The flow in particular lines and transformers is also heavily influenced by the orientation of the geo-electric field. For example a 1 V/km geo-electric field, which is perfectly aligned with a transmission line and the terminating transformers at each end, will result in maximum GIC flow on these sets of facilities. Likewise, a field orthogonal to these assets will result in minimal GIC flows. The U.S. grid presents a complex network topology, therefore no one geo-electric field provides an adequate test for the coupling effects of the geo-electric field for present grid design or variations in blocking strategies that are being examined in this analysis effort. In order to examine the impact of geo-electric field variations, the static geo-electric field will be rotated a full 360°, in 10° increments.

This same approach also allows for a summary evaluation of the impact on GIC flows and MVAR increases that the addition of the 230kV facilities will cause in the U.S. Grid Model. Figure 5-3 provides a plot of total GIC flow (as measured by the sum of the absolute value of GIC-Effective per phase) in all transformers in the U.S. grid for the 345kV+ grid model (includes only 345kV, 500kV, and 765kV assets) versus the U.S. Grid Model with the 230kV details added, for a static 1 V/km geo-electric field across the U.S. that is rotated. As shown, the peak GIC levels for both model cases occur at a 90° and 270° angles (east-west or west-east orientation) at a level of just over 16,000 amps for the 230kV+ model versus ~13,000 amps for the 345kV+ model. Minimum GIC levels occur at 0° and 180° (north-south) orientations. Depending upon the angle, this is a 14% to 21% increase in overall GIC flows with the addition of the 230kV assets.

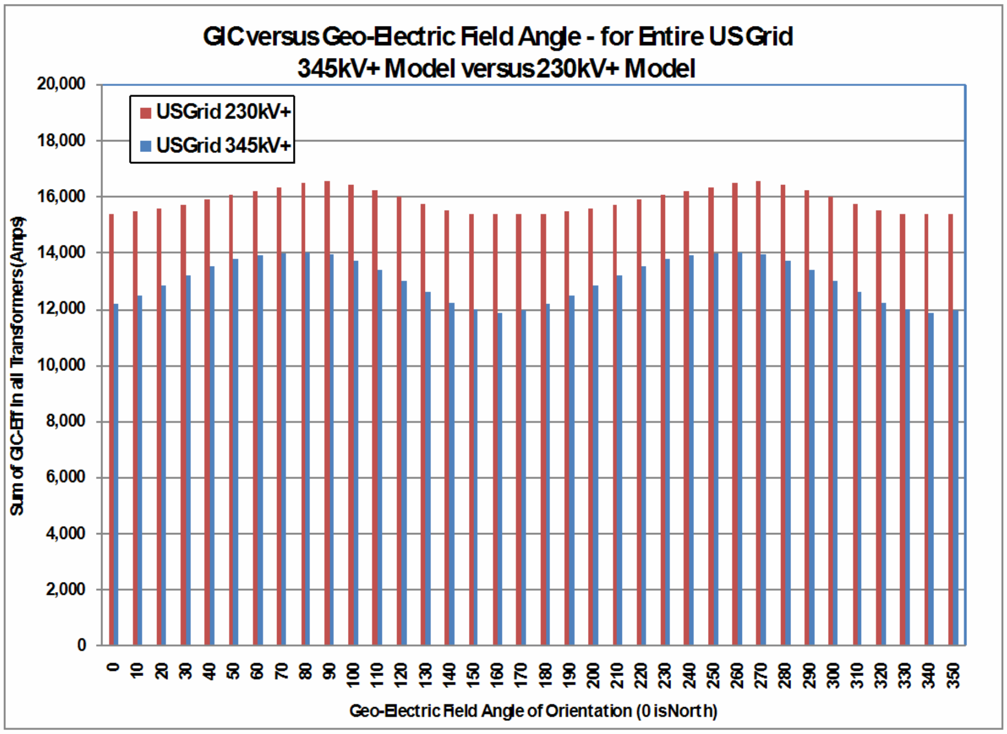

Figure 5-3. Total GIC flow in U.S. power grid for 345kV+ model and for 230kV+ model for 360 degree rotation in 1 V/km geo-electric field.

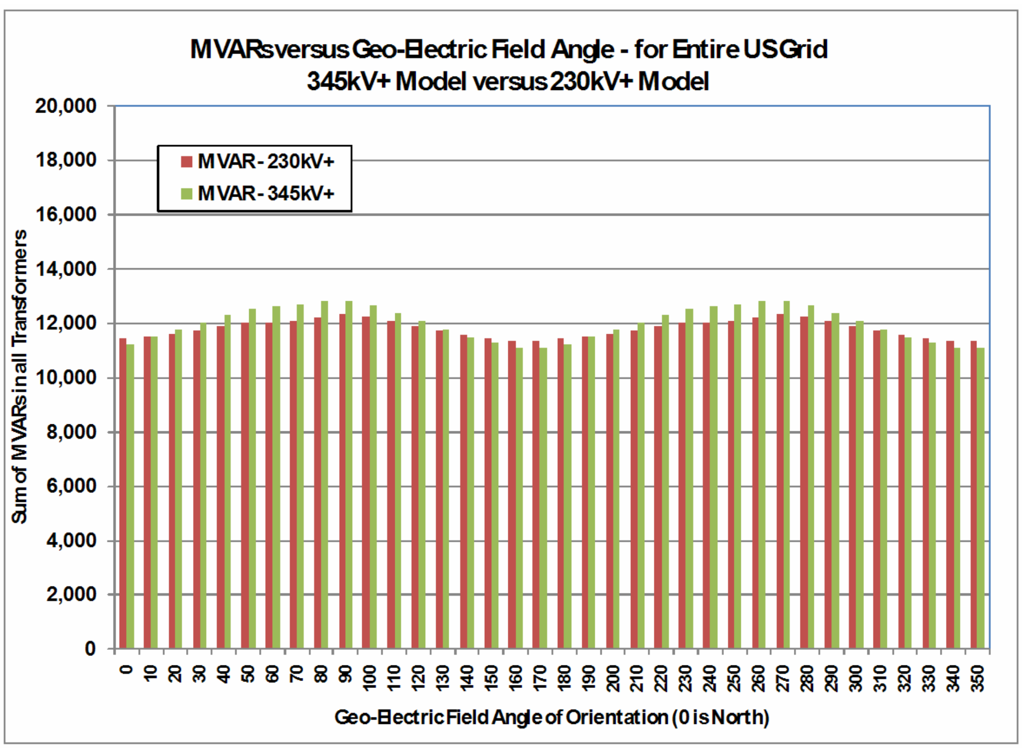

Figure 5-4. Total MVAR increase in U.S. power grid for 345kV+ model compared to 230kV+ model for 360 degree rotation in 1 V/km geo-electric field.

The impact of the 230kV additions can also be examined in respect to increased MVAR demands due to the GIC. Figure 5-4 provides a comparison of the increased MVAR demands for the 345kV+ and 230kV+ models. As this comparison illustrates, there is a negligible overall impact on MVAR demand levels between the two models. At some angles, there is even a slight decrease in overall MVAR demands. This occurs due to slight reductions in GIC in higher kV rated transformers due to the inclusion of the additional GIC flow path in the 230kV transformers added to the model. These 230kV transformers produce significantly decreased MVAR demands for each amp of GIC compared to the higher kV rated transformers. The eastern 230kV grid is considered in all of the following calculations in this document.

These attributes can be more fully summarized by examining the totals of GIC flow and MVAR increase for each voltage rating. Figure 5-5 provides a breakout by kV rating of the total GIC flows and MVAR increases the GIC causes in each of these kV ratings. As shown, the largest GIC flows occur in the 345kV transformers, while the second largest is in the 230kV transformers, this is logical in that they represent larger total lines miles than for either the 500 or 765kV facilities. MVAR increases due to GIC flow increase as a function of kV rating and from increased GIC flows. As a result, the 500kV transformers produce the largest cumulative MVAR increase, even though they do not have the highest cumulative GIC flows. In a similar point of comparison, it should be noted that while the 230kV transformers have cumulative large GIC flows, the level of MVAR increase in these transformers is the smallest of all kV rating classes. These transformers also tend to act as a GIC collecting network – passing GIC directly onto upper kV rating transformers because of the large number of autotransformer connections which provide enhanced GIC flows paths directly from one voltage level to another. While the 765kV rating cumulative levels are small, it is only because of the relatively small number of these assets in the U.S. grid. To provide further perspective on the relative size of GIC flows to each kV rating class, Figure 5-6 provides an analysis of the average GIC flows for transformers by kV rating. As shown, the highest kV rated transformers also have the highest average GIC flow. This is primarily due to reduced DC resistances per unit at the higher kV ratings, resulting in a larger GIC level for the same geo-electric field.

Previous investigations indicated that GIC levels have been increasing over time due to design factors that have acted to reduce DC resistances in the power grid. The addition of DC resistance to reduce GIC levels in any of the transformer and transmission line phases is highly undesirable because this would cause significant increase in AC current losses. However, AC systems are operated as 3-phase balanced and as a result, little if any AC current flow normally occurs in the neutral-to-ground connection. As a result, the transformer neutral-to-ground point would be an optimal point to introduce added resistance for the purpose of impeding the DC GIC flow, while causing minimal impacts to AC system operating efficiencies. Hence the primary means of mitigating GIC flows, which will be examined, are based upon the concept of adding low ohmic resistance in the transformer neutral-to-ground locations. Figure 5-7 provides a calculation of GIC flows for a 2.5 ohm neutral resistor addition in all transformer neutral-to-ground locations in the U.S. Grid Model (including the newly added 230kV transformers). As shown, the

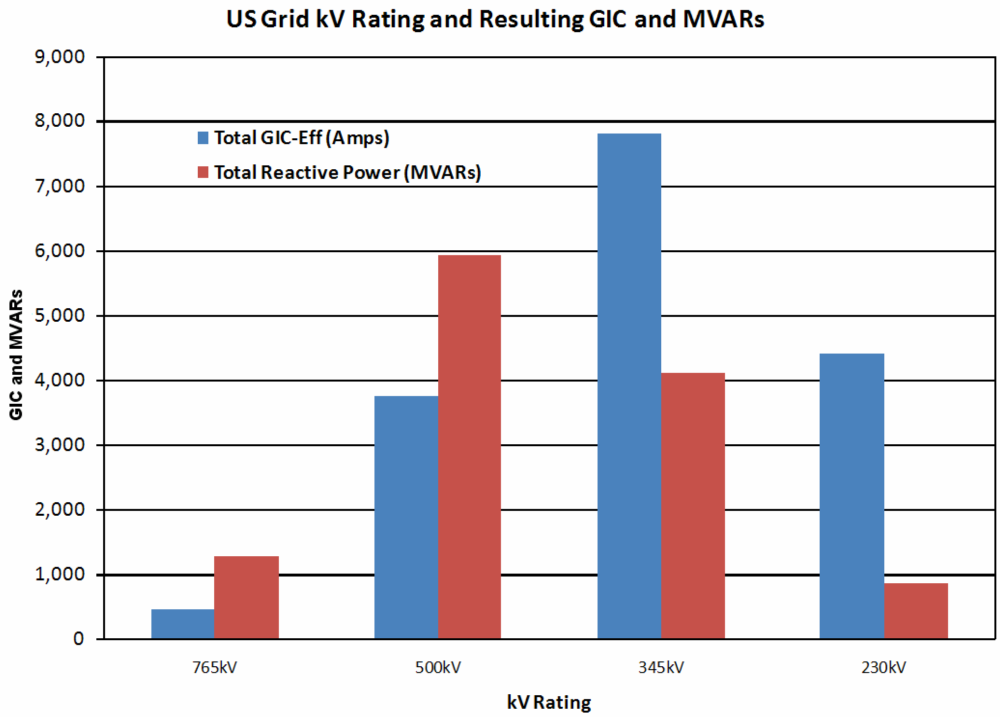

Figure 5-5. Total GIC flow and increased reactive power losses (MVARs) in U.S. power grid at 90° geo-electric field orientation (east-west) by kV rating for a 1 V/km geo-electric field.

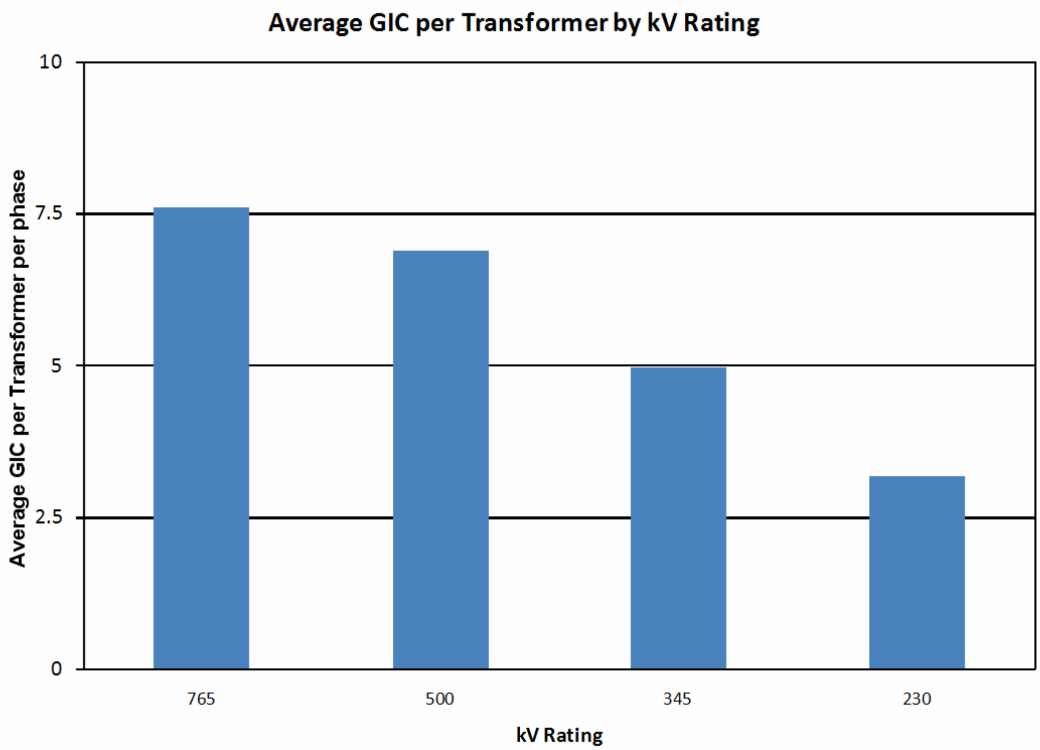

Figure 5-6. Average GIC flow in U.S. power grid at 90° geo-electric field orientation (east-west) by kV rating for a 1 V/km geo-electric field.

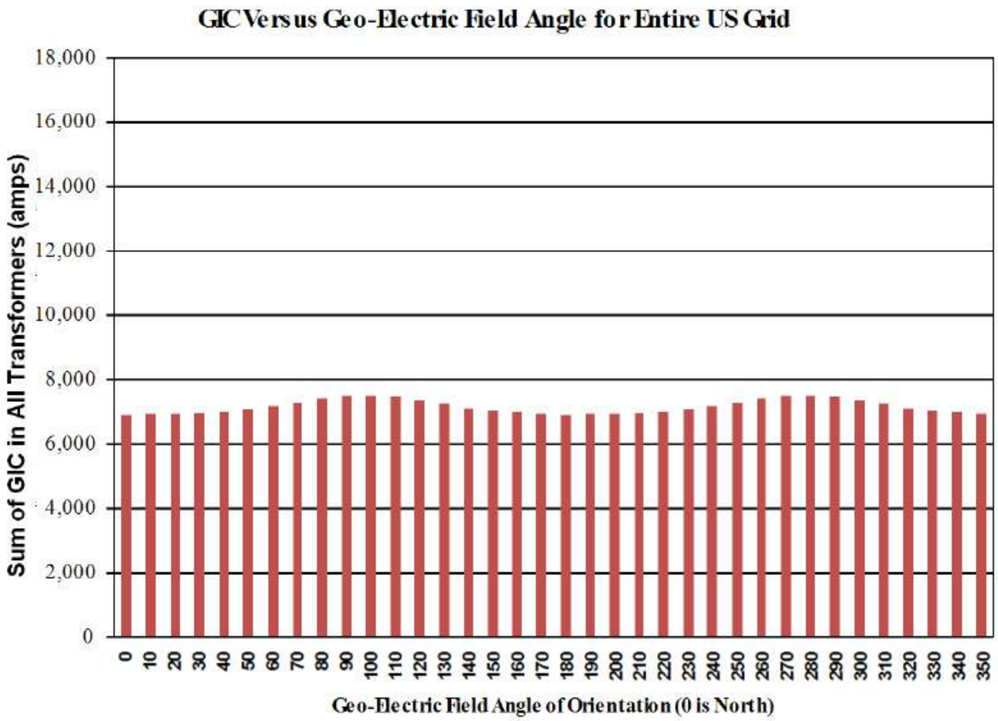

Figure 5-7. Total GIC flow in U.S. power grid with the addition of 2.5 ohms resistors in all transformer neutrals.

peak GIC levels are reduced to ~7,500 amps, which is a ~55% reduction from the levels for the normal grid design shown in Figure 5-3 (for the 230kV+ model). Simulations were also performed for 5 ohm and 7.5 ohm neutral resistors, and the GIC sum results are shown respectively in Figures 5-8 and 5-9 for each case. As the neutral resistor size increases, the amount of GIC also continues to decrease. GIC totals less than 5,000 amps are observed for all orientations for the 7.5 ohm case. It should be noted that the addition of neutral resistors in all cases resulted in a slight shift in peak geo-electric field angle, which has shifted from a 90° angle to a 100° angle. Figure 5-10 provides a comparison plot of the % GIC reduction for all three of these resistor sizes. The GIC reductions, as shown here, range from the mid 50% range to the low 70% range for all geo-electric field orientations.

In all of the previous simulations, neutral resistors were applied in all transformers, yet as previously discussed in Figure 5-6, the 230kV transformers have much lower average GIC levels than at the higher kV ratings. In order to examine for mitigation scenarios that might be nearly as effective, yet cheaper and requiring fewer neutral resistor devices, a simulation was performed with only 2.5 ohm neutral resistors applied at all transformers rated 345kV and higher, and leaving all 230kV transformer neutrals unaltered. Figure 5-11 provides a summary of the GIC flow totals for this simulation. For perspective, the results shown here can be directly compared to those provided in Figure 5-7, which had resistors in all transformer neutrals (including the 230kV transformers). GIC levels with 2.5 ohm resistors in the neutral only of 345kV+ transformers reach the level of ~10,000 amps, which is generally ~3,000 amps higher

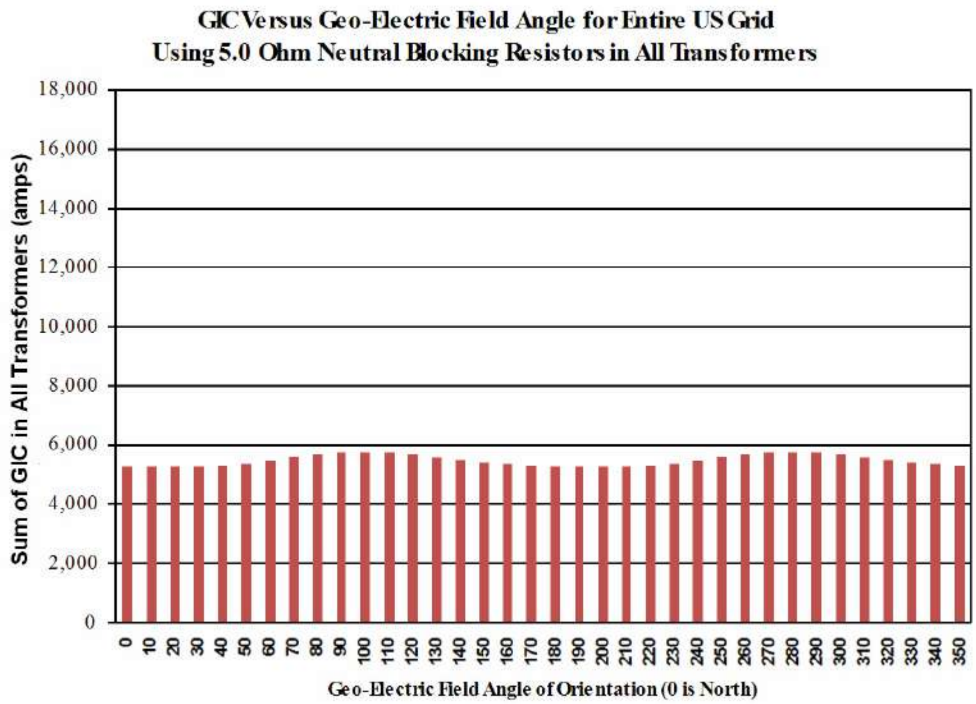

Figure 5-8. Total GIC flow in U.S. power grid with the addition of 5 ohms resistors in all transformer neutrals.

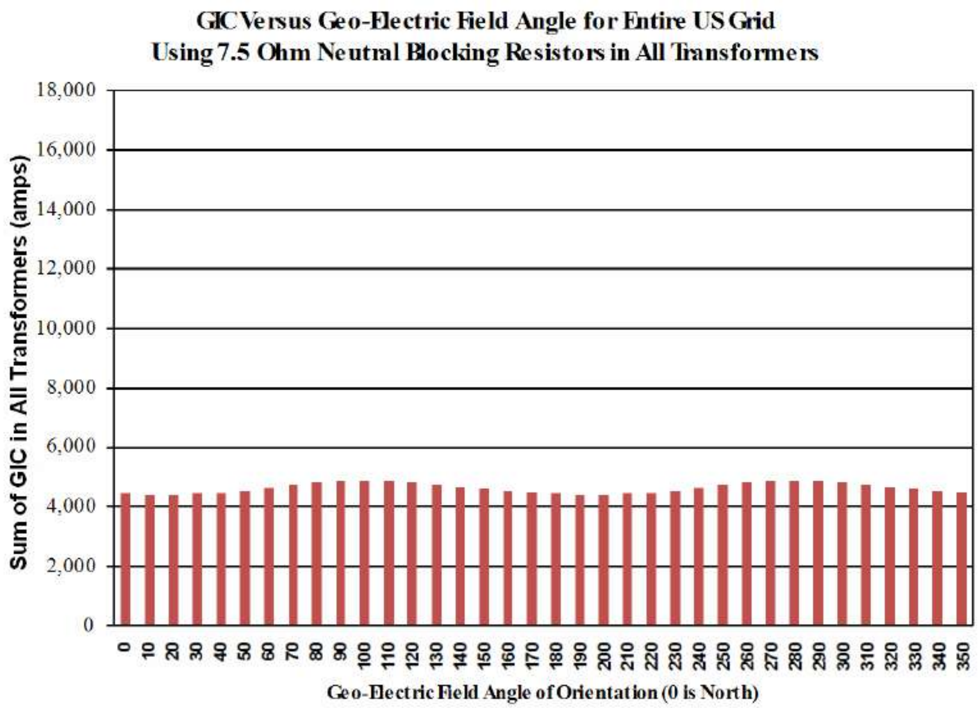

Figure 5-9. Total GIC flow in U.S. power grid with the addition of 7.5 ohms resistors in all transformer neutrals.

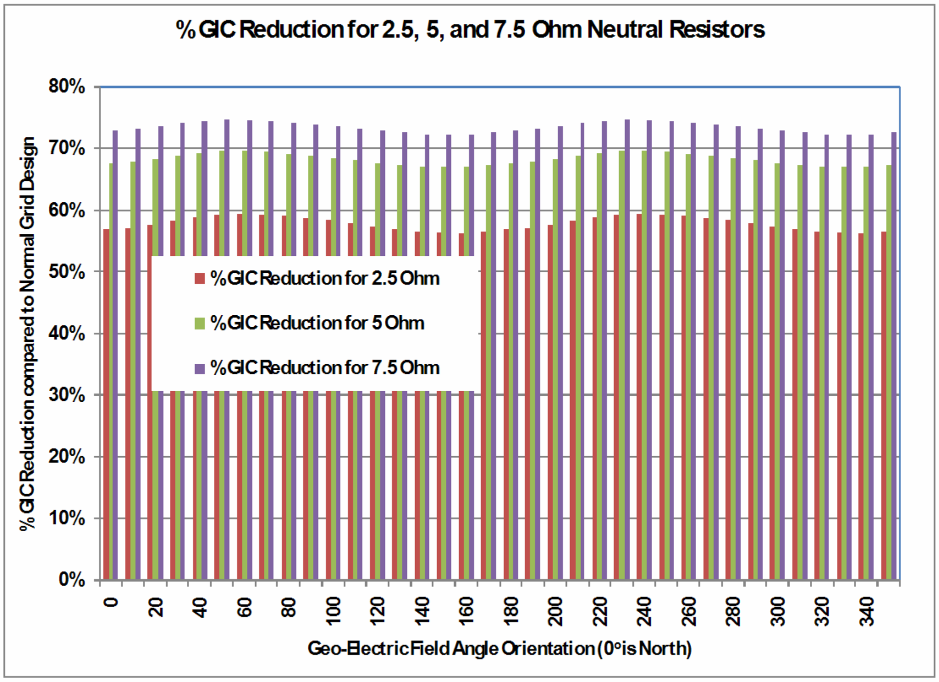

Figure 5-10. Percent GIC reduction in U.S. power grid with the addition of 2.5, 5, & 7.5 ohms resistors in all transformer neutrals.

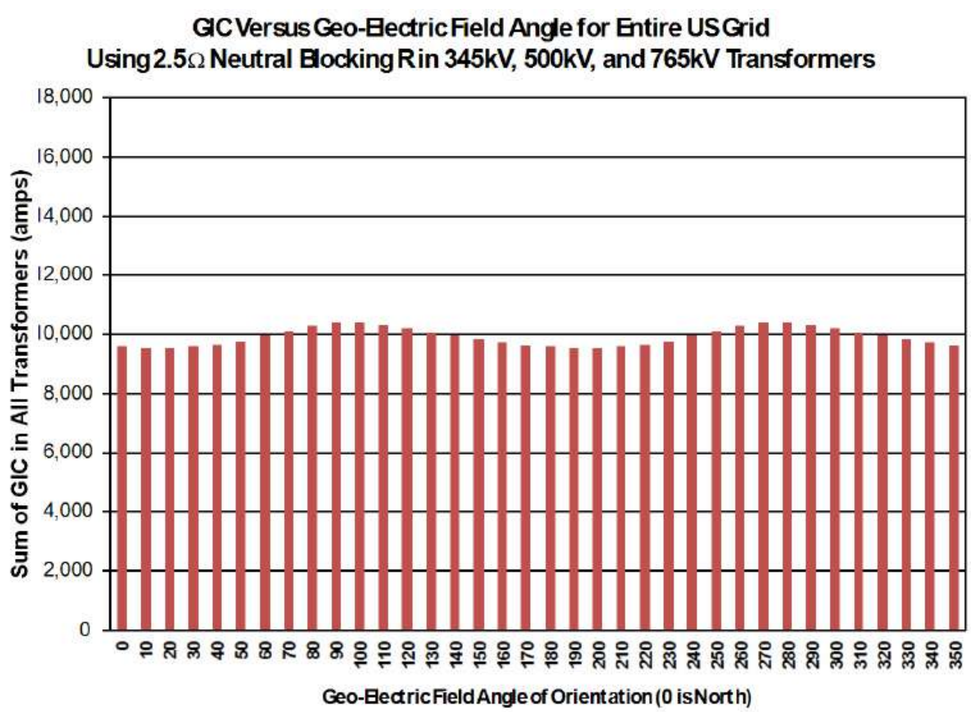

Figure 5-11. Total GIC flow in U.S. power grid with the addition of 2.5 ohm resistors in only the 345kV, 500kV & 765kV transformer neutrals. Neutral resistance in 230kV transformers is unchanged.

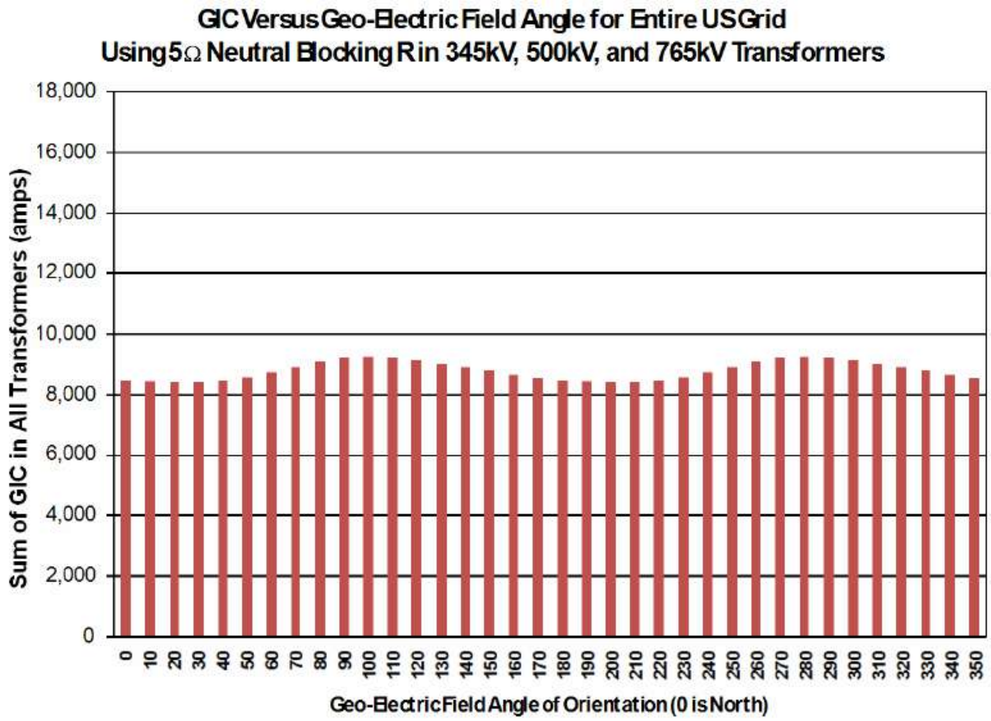

Figure 5-12. Total GIC flow in U.S. power grid with the addition of 5 ohm resistors in only the 345kV, 500kV & 765kV transformer neutrals. Neutral resistance in 230kV transformers is unchanged.

than shown in Figure 5-7. A similar simulation was performed with 5 ohm resistors in only the neutral of 345kV+ transformers, and GIC totals are given in Figure 5-12. GIC levels for this case range between ~8,000 and ~9,000 amps, and when compared to the case with all transformers with 5 ohm resistors (Figure 5-8), the GIC levels are ~3,000 amps higher for this case as well. A similar performance gap is also the case for 7.5 ohm resistors in only the 345kV+ transformers (Figure 5-13) when compared to the case with all transformers with 7.5 ohm resistors (Figure 5-9).

An additional simulation was performed using the concept of utilizing blocking capacitors instead of resistors in the transformer neutral-to-ground connection. The capacitors will completely block the flow of all GIC, unlike resistors which will only reduce GIC flows. As in the prior simulations, these devices were only applied in the 345kV, 500kV, and 765kV rated transformers (all 230kV transformer neutrals remained unblocked) and the GIC flow totals for this case are provided in Figure 5-14. While neutral blocking capacitors have better GIC flow blocking capability, there are numerous technical problems with such a wide scale application of these devices as conceived in this case. These technical problems would primarily be concerns with how neutral capacitors could adversely impact many other AC system operations. Because of these technical problems, neutral capacitors are not being recommended. However, this simulation will help identify the true GIC contributions that the 230kV system can provide to the interconnected higher kV rated networks. As shown in Figure 5-14, GIC flows still total from ~5,200 to ~6,100 amps. In comparison from the analysis previously provided in Figure 5-4 on the 230kV+ model, the contribution from the 230kV network

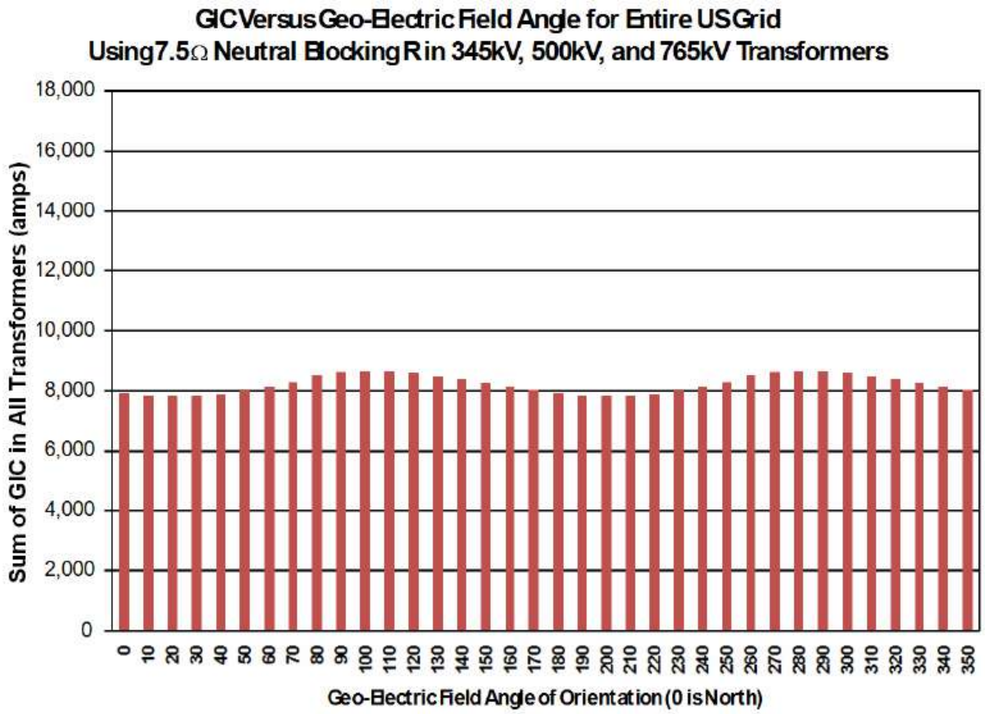

Figure 5-13. Total GIC flow in U.S. power grid with the addition of 7.5 ohm resistors in only the 345kV, 500kV & 765kV transformer neutrals. Neutral resistance in 230kV transformers is unchanged.

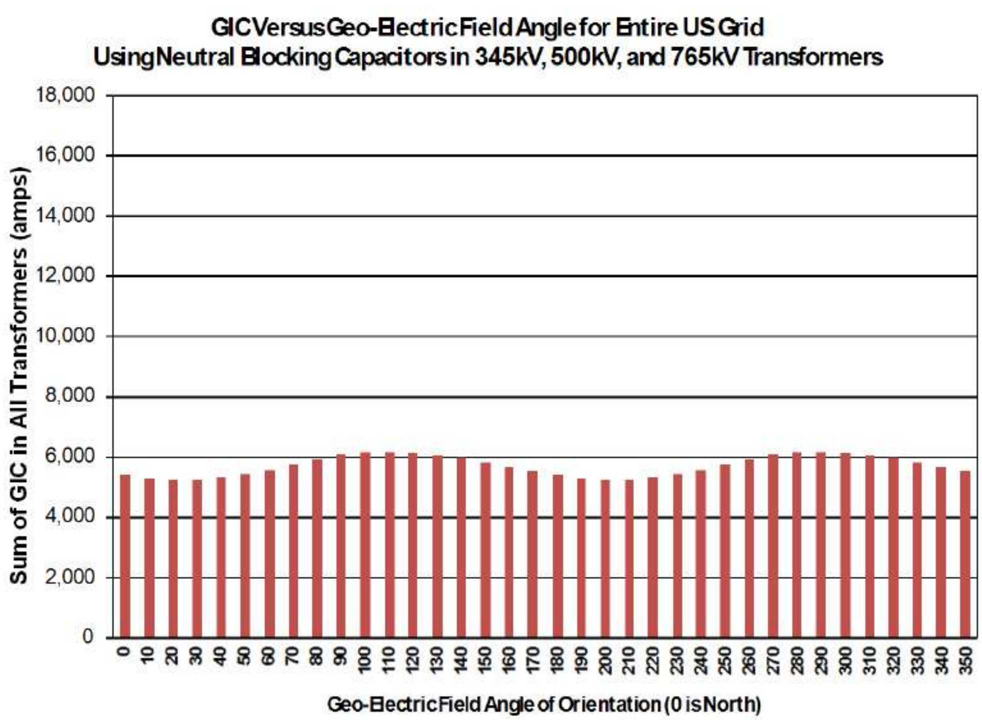

Figure 5-14. Total GIC flow in U.S. power grid with the addition of neutral blocking capacitors in only the 345kV, 500kV & 765kV transformer neutrals. Neutral resistance in 230kV transformers is unchanged.

has actually increased compared to the normal grid configuration. Further, the total GIC flows for the neutral capacitor case and the neutral resistor cases (Figures 5-11 through 5-14), the GICs are all quite high compared to the cases with the simpler neutral resistors at all locations (Figures 5-7 through 5-9). These scenarios suggest a more detailed analysis is necessary to find optimization approaches that could reduce the numbers of locations where neutral blocking devices are needed.

Section 6
Optimization of GIC Reduction Strategies

As noted in Section 5, the application of GIC blocking devices in only the highest kV rated transformers does not produce the most optimal GIC reduction strategy. In order to examine further where the GIC flows are occurring, a summary of the GIC flow in each transformer can be summarized as shown in Figure 6-1. Here the GIC flow in each of the ~3,500 transformers included in the 230 kV+ model is shown in order from the smallest to the largest GIC levels for the 1 V/km geo-electric field orientation of 90°. As shown in this summary, there is a wide variation in GIC levels, essentially from ~0 amps to over 60 amps/phase. It would be expected that at any particular angle of geo-electric field orientation, that GIC flow could be minimum for some assets while also at a maximum level in other assets, and that this ranking would change with the alteration in geo-electric field orientation as well. Therefore, in order to test for the participation of GIC flow in transformers at all geo-electric field orientations, the GIC was summed at each location over an entire 180 degree rotation of the geo-electric field. Figure 6-2 provides this summary using the same type of low to high GIC ordering. As shown, this summation of GIC flows also indicates that there is a wide variation in GIC flows for individual transformers and that a large number of transformer appear to have very low levels of participation in GIC flows at all geo-electric field orientations. This indicates that they have limited GIC flow at all geo-electric field angles and provide a preliminary signal that these particular locations may not be necessary to include in any or all blocking strategies for inclusion of neutral resistors or blocking devices.

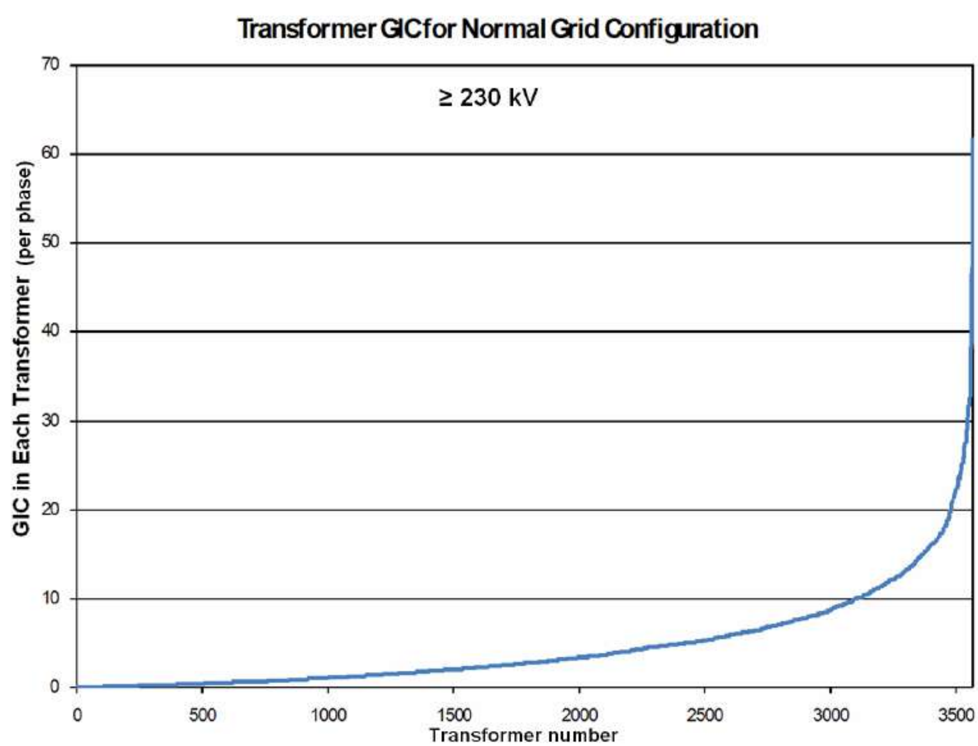

Figure 6-1. GIC flow in each transformer from lowest to highest GIC/phase for geo-electric field orientation of 90°.

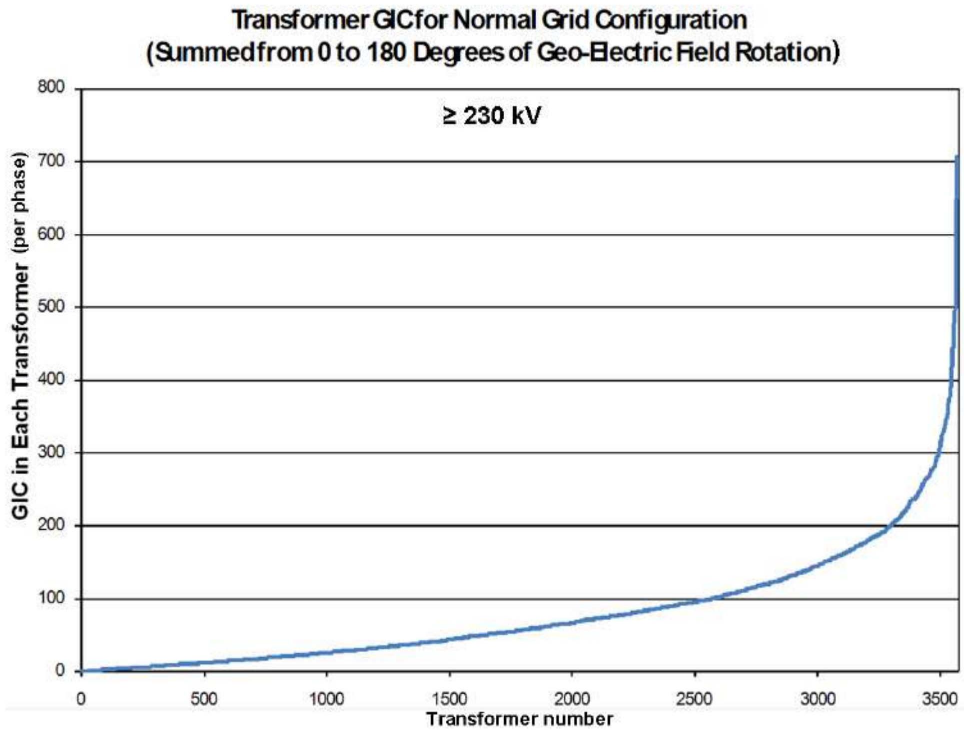

Figure 6-2. Sum of GIC flow in each transformer from lowest to highest GIC/phase over an entire 180° of geo-electric field orientation.

Further analysis can be performed by reviewing the GIC flows for some of the previous GIC simulations and blocking strategies. Figure 6-3 provides a comparison plot of GIC flows in individual transformers both for the normal or present grid design and for the GIC blocking strategy of using 2.5 ohm resistors in all transformer neutral-to-ground connections. As illustrated in this comparison, at many locations the addition of the 2.5 ohm resistors produced substantial drops in GIC flows compared to the normal grid design. In addition to the many locations where GIC was reduced, there are also a number of locations where the GIC increased above levels of the GIC for the normal grid design. Figure 6-4 provides a comparison plot similar to that shown in Figure 6-3, except that instead of 2.5 ohm neutral resistors, 5 ohm neutral resistors are utilized. Again this comparison illustrates, in general, even lower overall levels of GIC flows at most transformers, although it is the case again, for some locations the GIC levels have actually increased. In many cases the transformers that exhibit GIC flow increases are auto-transformers in the network where sharp flow reversals have occurred due to the addition of the neutral resistors. Figures 6-5 and 6-6 illustrate the before (normal grid design case) and the after (5 ohm neutral resistor case) GIC flows in a 765/500kV autotransformer. Under normal grid design, the pattern of flows (Figure 6-5) in the autotransformer resulted in a GIC-Effective of only 1.6 amps per phase, even though neutral-to-ground current totaled ~-33 amps. The low GIC-Effective occurs because the flows of GIC in the common and series windings in each phase of the autotransformer nearly cancel each other out (when adjusted for the voltage rating of each winding). As shown in Figure 6-6, the addition of the 5 ohm neutral resistor drops the neutral current

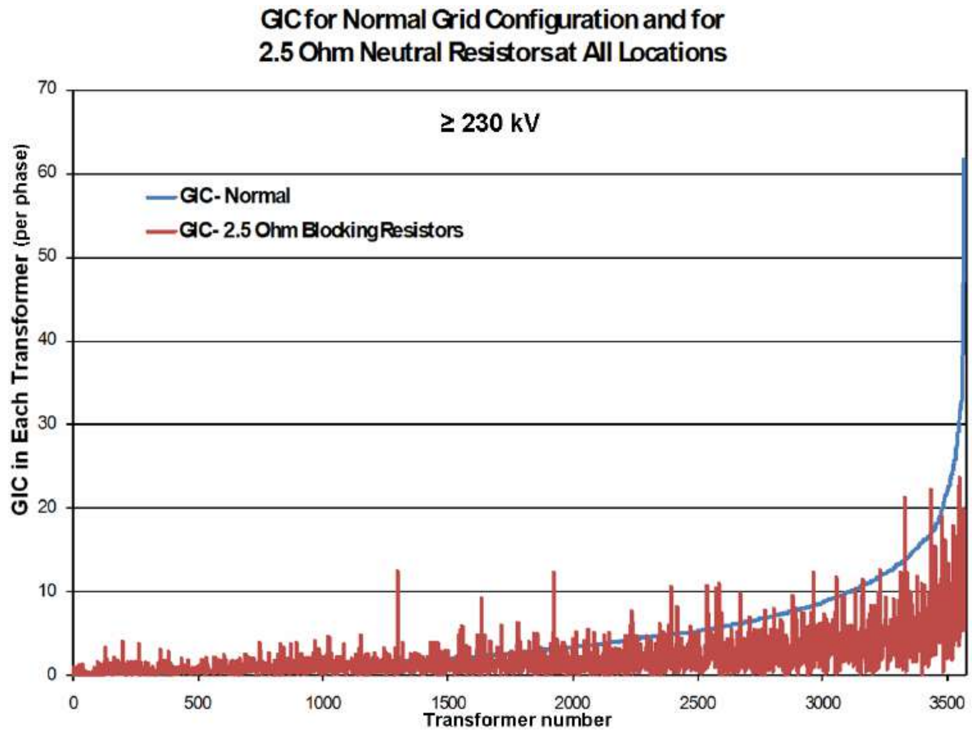

Figure 6-3. Comparison of GIC flow in each transformer for normal grid design compared to case with 2.5 ohm neutral resistors for 90° geo-electric field orientation.

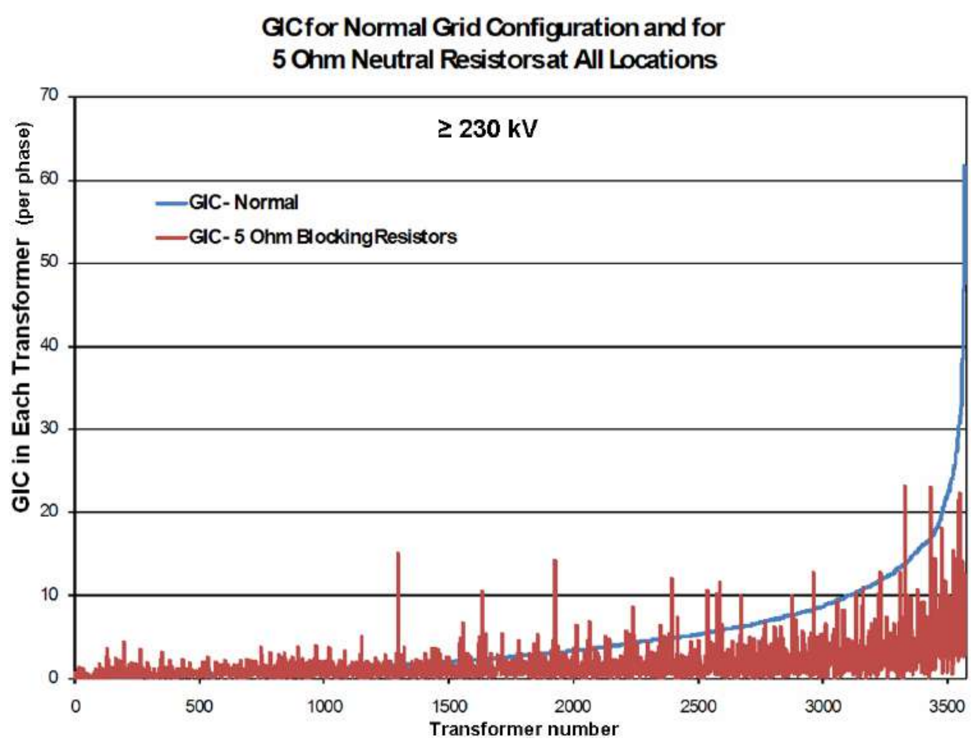

Figure 6-4. Comparison of GIC flow in each transformer for normal grid design compared to case with 5 ohm neutral resistors for 90° geo-electric field orientation.

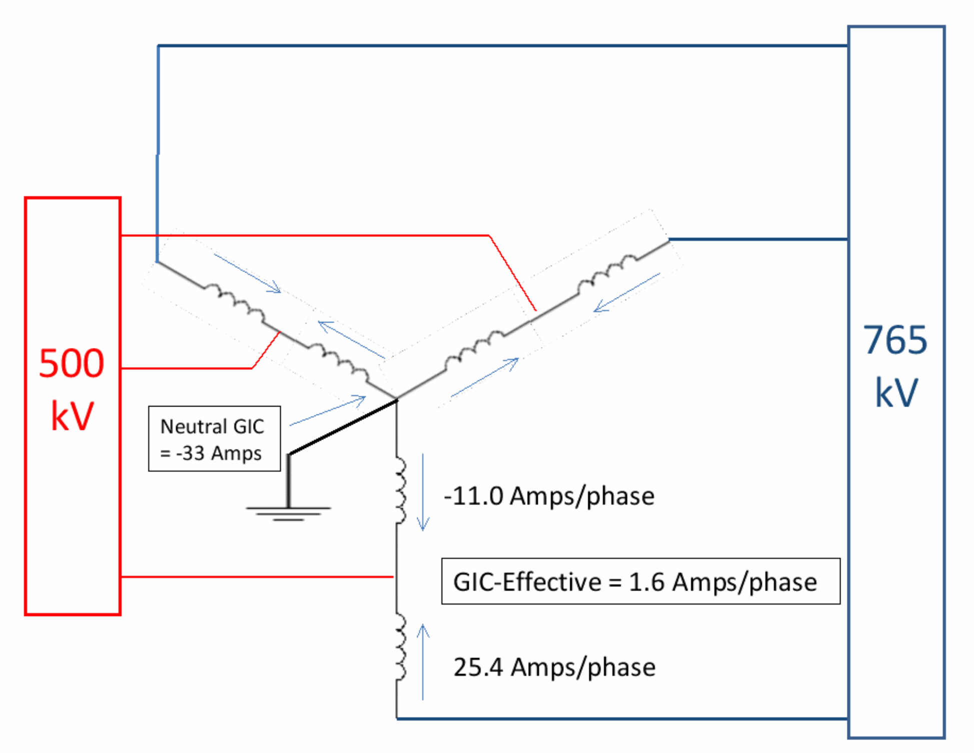

Figure 6-5. Pattern of three-phase GIC flow in each winding of a 765/500kV autotransformer for normal grid design.

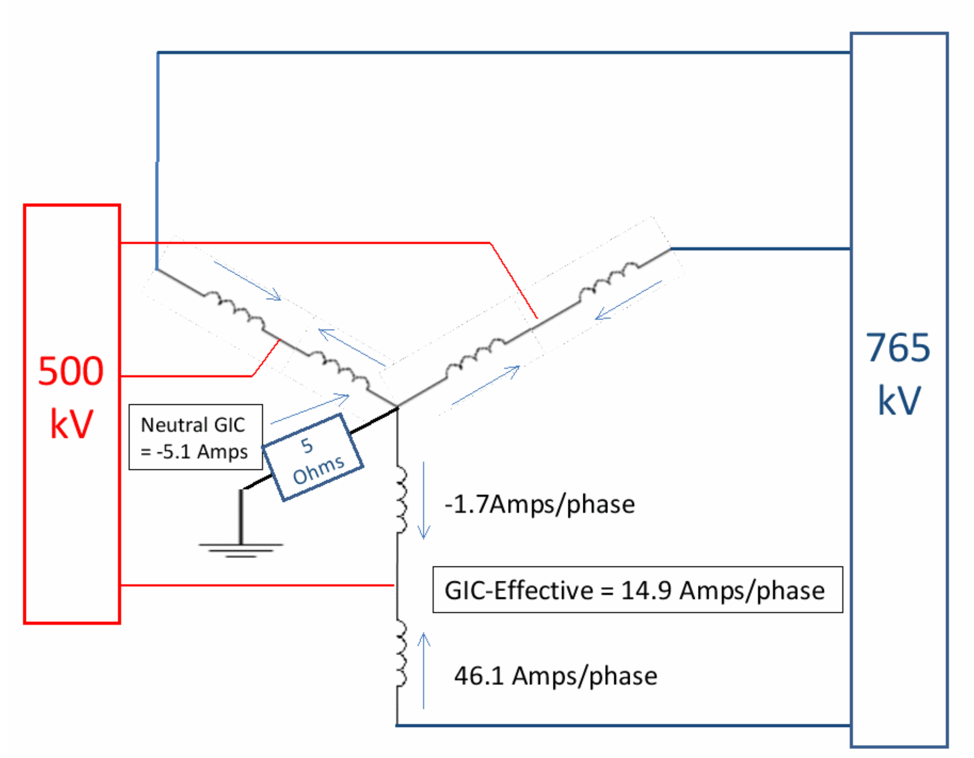

Figure 6-6. Pattern of three-phase GIC flow in each winding of a 765/500kV autotransformer for 5 ohm neutral resistor case.

significantly from -33 amps to only -5.1 amps. This also drops the per phase GIC flow in each common winding significantly, since the neutral current divided by three is the common winding GIC (i.e. -1.7 amps per phase in this case). In addition, the pattern of GIC flows has been altered throughout the network and now causes a larger GIC flow per phase on the series winding of the autotransformer – 46 amps per phase compared to only 25.4 amps per phase in Figure 6-5. This results in the GIC-Effective increasing from 1.6 amps to 14.9 amps, a nearly tenfold increase at this particular location. While the neutral resistor is successful in reducing the GIC flow in the common winding, it is not able to control the GIC flows, which might actually increase in the series windings. Many of the locations that experience GIC flow increases follow this pattern of flow changes in autotransformers as the most common mechanism for GIC increases.

Figure 6-7 is similar to Figures 6-3 and 6-4 in that it provides a similar comparison of the normal grid design GIC flow in each transformer compared to the case with 7.5 ohms neutral resistors. In examining Figures 6-3, 6-4, and now 6-7, it is clear that in most cases the GIC levels decrease at many locations, and those locations that have had low GIC's in the normal grid design also generally have low GIC levels in each of the neutral resistor design cases as well.

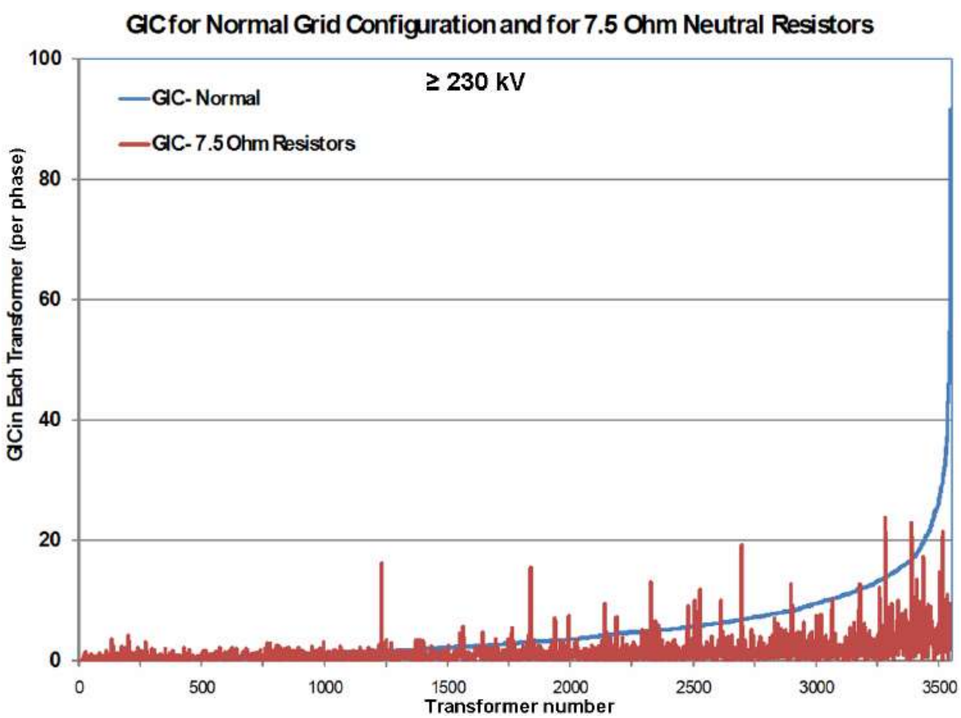

Figure 6-7. Comparison of GIC flow in each transformer for normal grid design compared to case with 7.5 ohm neutral resistors for 90° geo-electric field orientation.

An examination of the characteristics of the transformers with consistently low GIC flows provides some perspectives. Figure 6-8 shows the MVA ratings of the low GIC flow transformers (the lowest 25% of transformers ranked by GIC flow) and the number of units at each MVA rating. This indicates that most of the low GIC participating transformers generally have the smaller MVA ratings in size. Figure 6-9 provides a breakout by kV rating of the number of transformers for each of the major kV rating classes. As illustrated, using just the number of transformers alone, the 230kV and 345kV units are the most numerous. However, when looking at the results by percentage of population for each kV Class (Figure 6-10), the weighting is more uniform across the major kV rating classes. This indicates that all transformer kV rating classes potentially have units that may not need to have GIC reduction strategies applied. Locations of the low flow transformers are shown in Figure 6-11. This indicates that these low GIC participation transformers are quite uniformly distributed geographically as well.

As described in Section 5, several GIC reduction scenarios were examined. Exploiting the just-described locations that exhibit low GIC participation, several additional optimization strategies can be developed based upon only installing GIC reduction resistors in the transformer neutrals of the locations experiencing the largest GIC levels for all orientations of the geo-electric field. Figure 6-12 provides a summary of total GIC levels at each geo-electric orientation with the GIC reduction strategy of using 5 ohm neutral resistors in only the top 50% of all GIC transformers. In comparing this to Figure 5-3 (normal grid and no resistors), GIC levels using this approach are substantially reduced. Figure 6-13 provides a comparison summary of the GIC flows in each individual transformer for the normal grid design and for the strategy where 5 ohm resistors are only applied in the top 50% of GIC flow transformers. While overall GIC levels are reduced, as summarized in Figure 6-12, GIC flows are significantly shifted from the top 50% to some of the transformers in the bottom 50% of GIC flows, as illustrated in Figure 6-13. Figure 6-14 provides a GIC summary for 5 ohm resistors installed in the top 75% of GIC flow transformer locations, under normal conditions. The same results are shown in Figure 6-15, along with a comparison of GIC flows for the normal grid design.

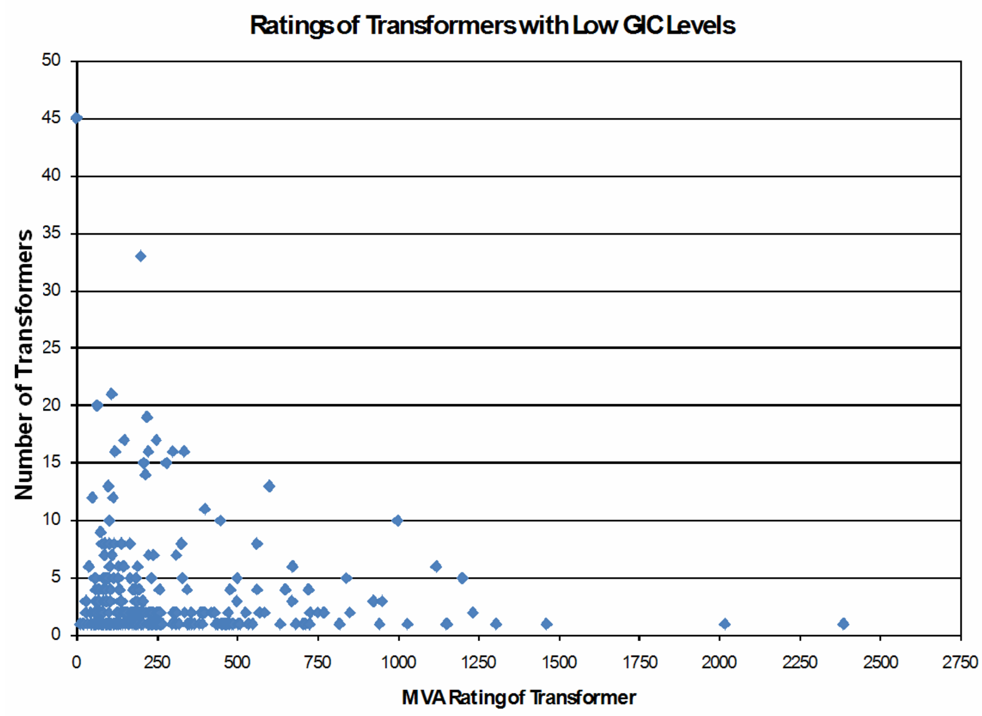

Figure 6-8. MVA ratings of low GIC flow transformers for normal grid design (lowest 25% of transformers as measured by GIC flows).

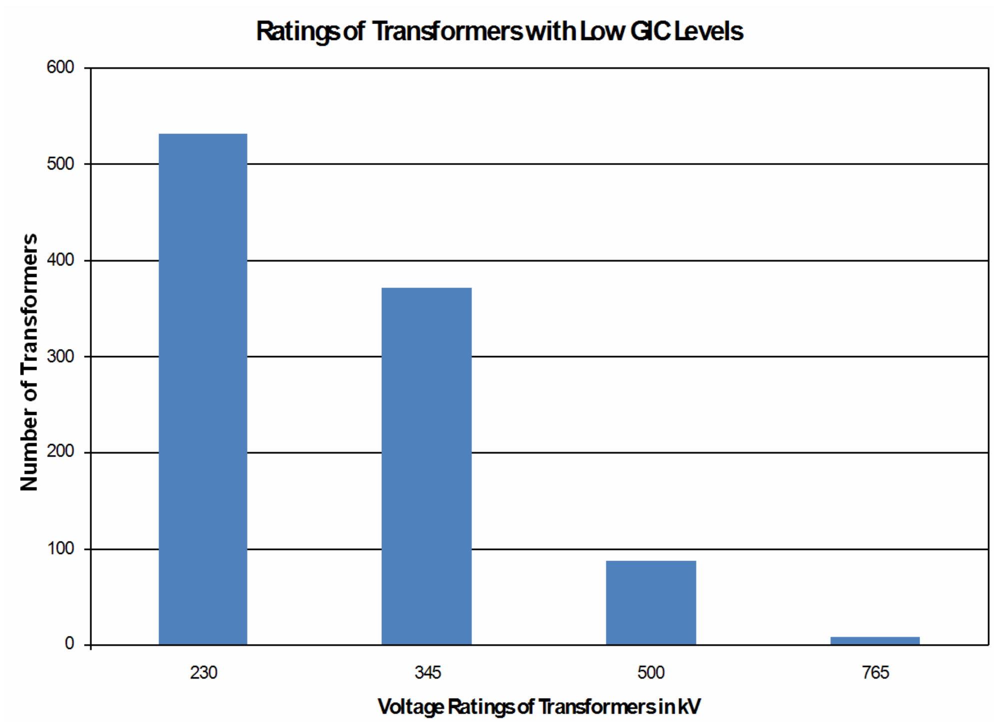

Figure 6-9. Voltage ratings of transformers with low GIC flow for normal grid design.

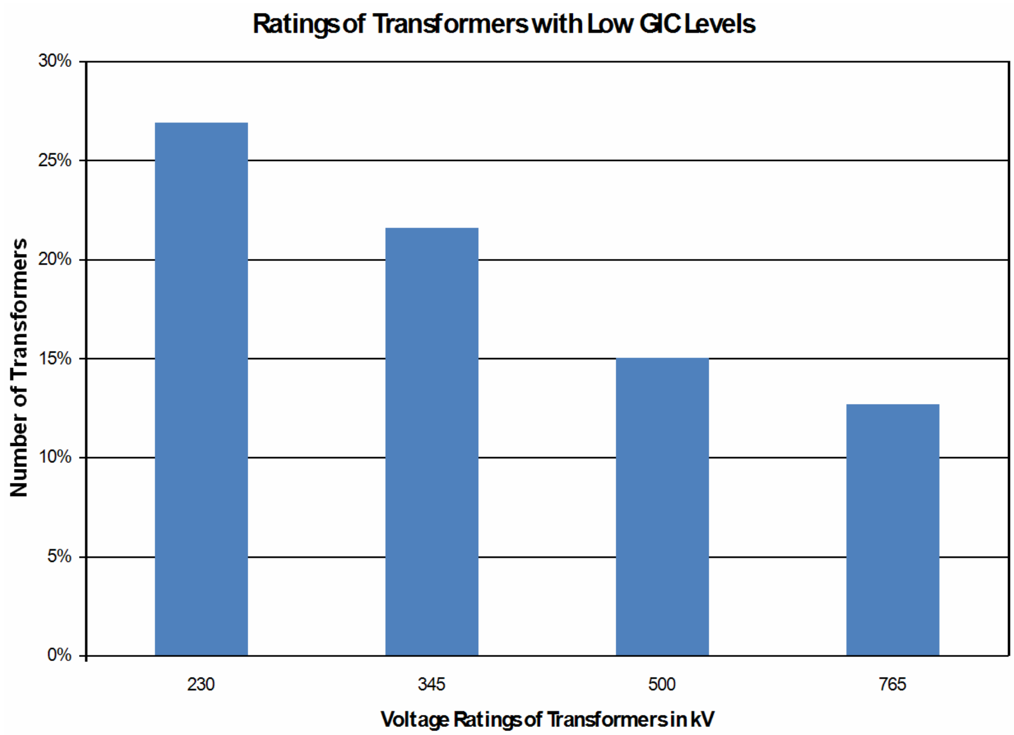

Figure 6-10. Percent of transformers with low GIC flow by kV rating for normal grid design

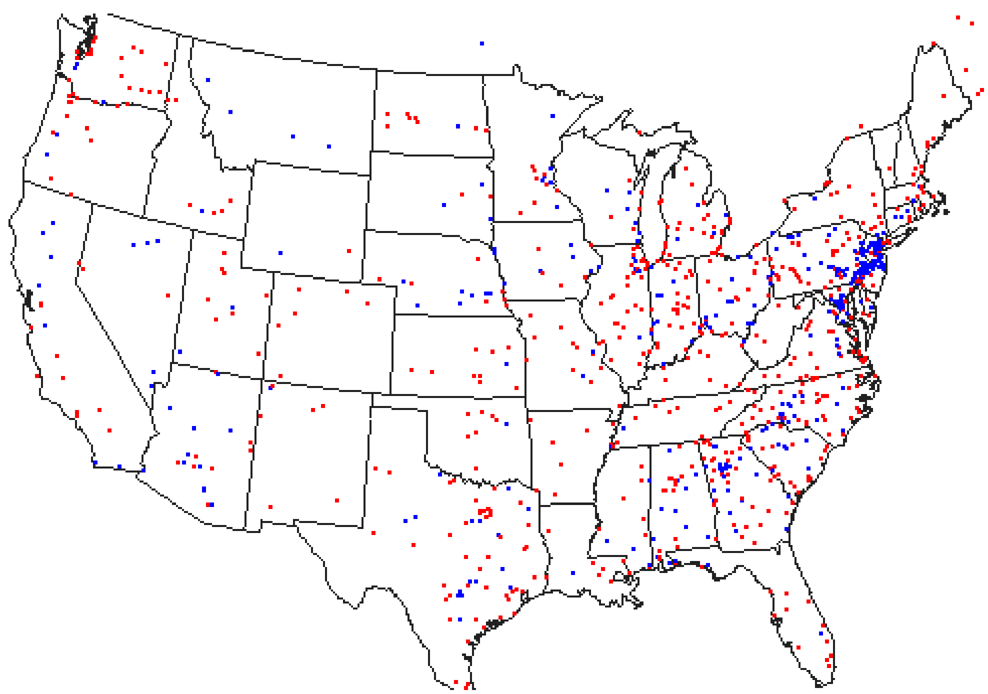

Figure 6-11. Location of transformers with low GIC flow for normal grid design. Red dots indicated location of transformers within upper 75% of GIC flow while blue dots indicate location of bottom 25% of GIC flow transformers.

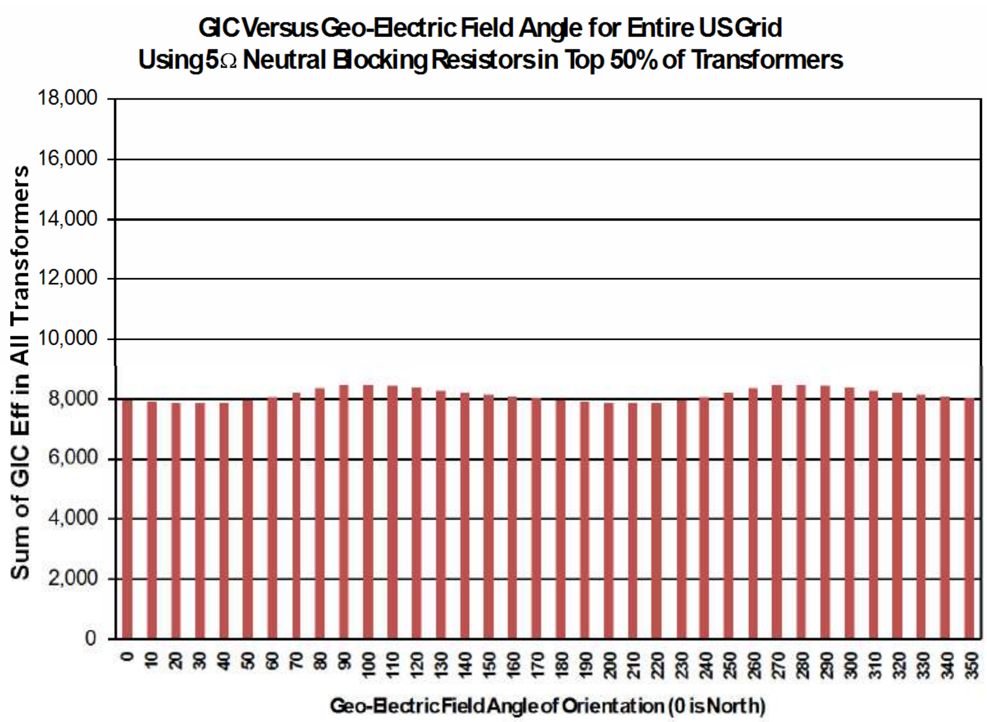

Figure 6-12. Total GIC flow in U.S. power grid for U.S. Grid Model with the addition of 5 ohm neutral blocking resistors in only the top 50% of GIC transformer neutrals.

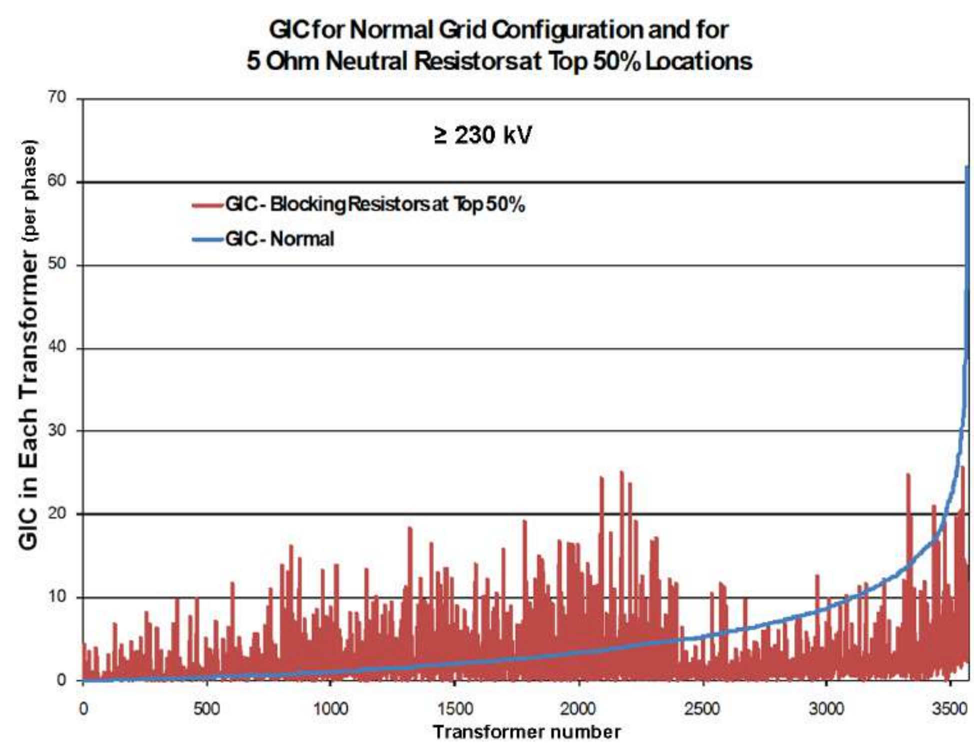

Figure 6-13. Comparison of GIC flow in each transformer for normal grid design compared to case with 5 ohm neutral resistors in only the top 50% of GIC transformers, for 90^{o} geo-electric field orientation.

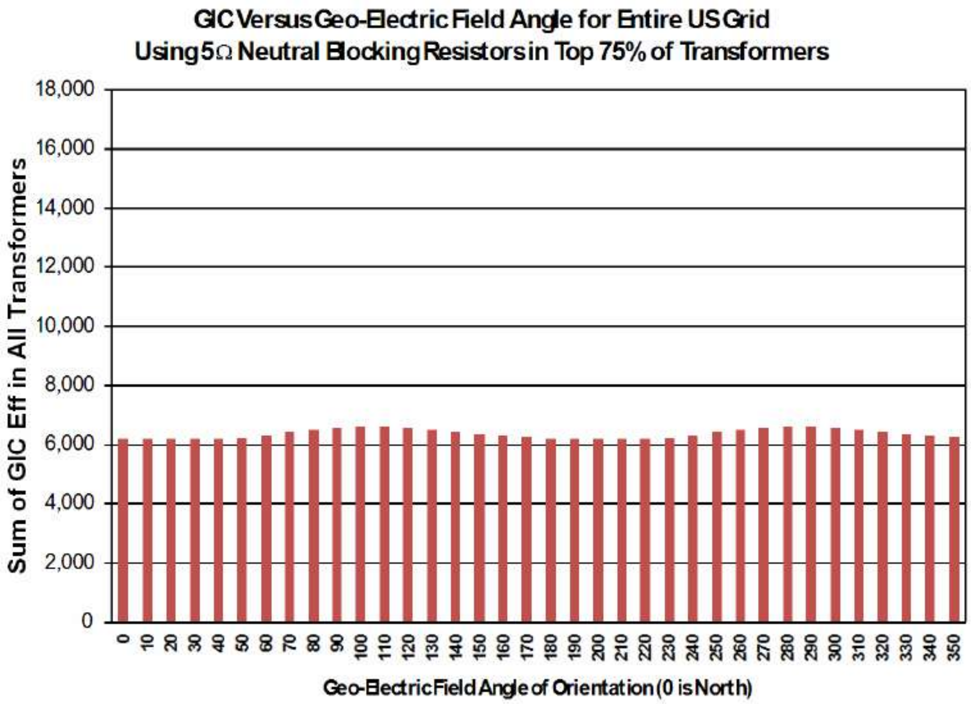

Figure 6-14. Total GIC flow in U.S. power grid for U.S. Grid Model with the addition of 5 ohm neutral blocking resistors in only the top 75% of GIC transformer neutrals.

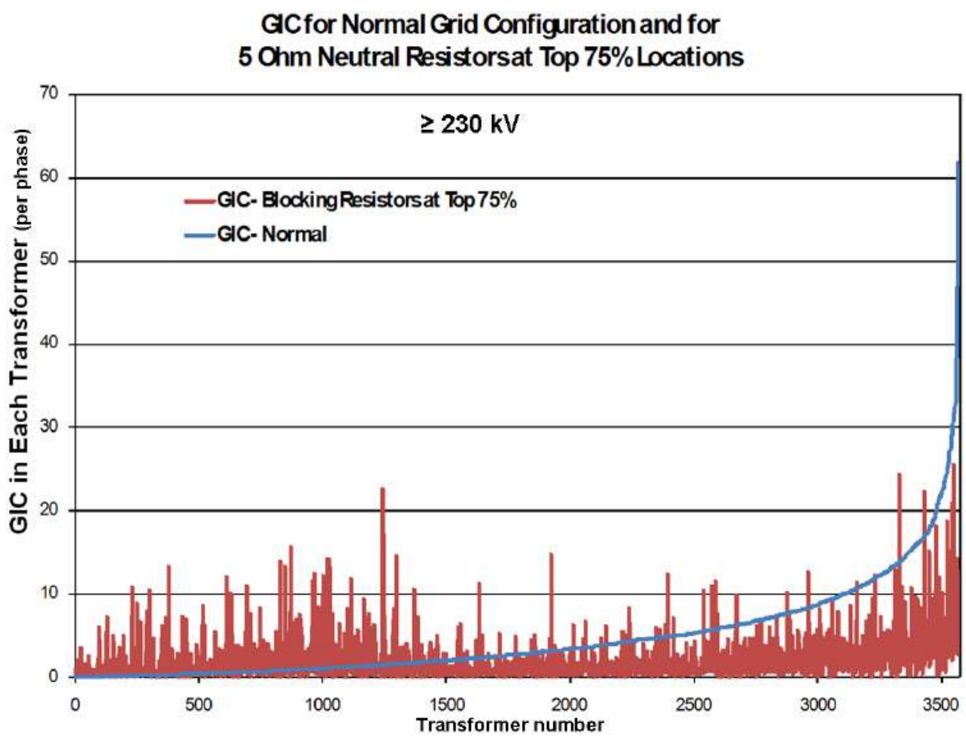

Figure 6-15. Comparison of GIC flow in each transformer for normal grid design compared to case with 5 ohm neutral resistors in only the top 75% of GIC transformers, for 90^{o} geo-electric field orientation.

A similar set of simulations have been performed for 2.5 ohm neutral resistors that are installed in only the top 50% and top 75% of GIC locations. Figure 6-16 provides the summary for the 2.5 ohm resistors in the top 50% of locations while Figure 6-17 provides the GIC summary for the top 75% of locations. As expected from previous trends, the GIC levels are reduced further by the application of 5 ohm resistors relative to the 2.5 ohm resistors.

Further perspective can be provided by summarizing the percentage reduction in GIC levels for both the 2.5 ohm and 5 ohm strategies that have been described in both Section 5 and this section. Figure 6-18 provides a comparison in the reduction in GIC flow in U.S. power grid for U.S. Grid Model with the addition of 2.5 ohm neutral blocking resistors in all and as well in only the top 75% of GIC transformer neutrals. This comparison illustrates that by including the 2.5 ohm resistors in all locations generally provides a ~54% to 56% reduction in GIC levels compared to the normal grid design. In comparison, installing resistors in only the top 75% of locations produces nearly similar levels of GIC reduction, with GIC reduction in the ~50% to ~52% reduction range. These GIC reduction levels are within a few percentage points of the design case with resistors at all locations. This indicates that by choosing not to add 2.5 ohm resistors at the low-GIC participation locations, the levels of GIC reduction remain at similar levels overall. Figure 6-19 provides a comparison summary of GIC reduction for the 5 ohm resistors installed in all locations and in the top 75% of GIC locations. Again, the two 5 ohm GIC reduction design options produce higher levels of GIC reduction compared to the 2.5 ohm resistor options, with reductions generally in the ~60% range. Also both design options have relative levels of GIC reduction that are within a few percentage points of performance in GIC reduction. These results indicate that optimization can both reduce the hardening costs while producing relatively similar levels of GIC reduction.

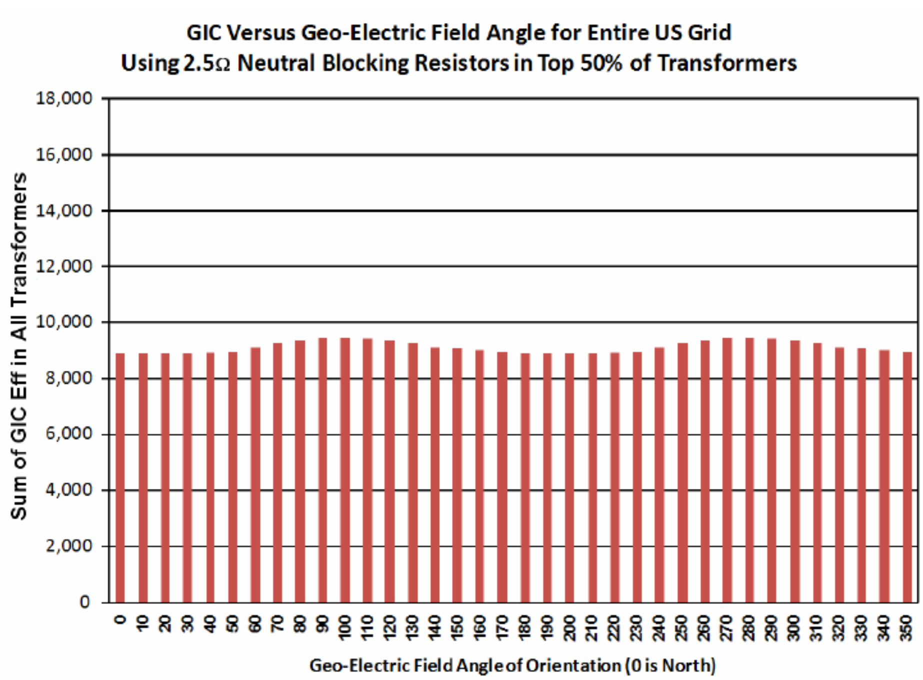

Figure 6-16. Total GIC flow in U.S. power grid for U.S. Grid Model with the addition of 2.5 ohm neutral blocking resistors in only the top 50% of GIC transformer neutrals.

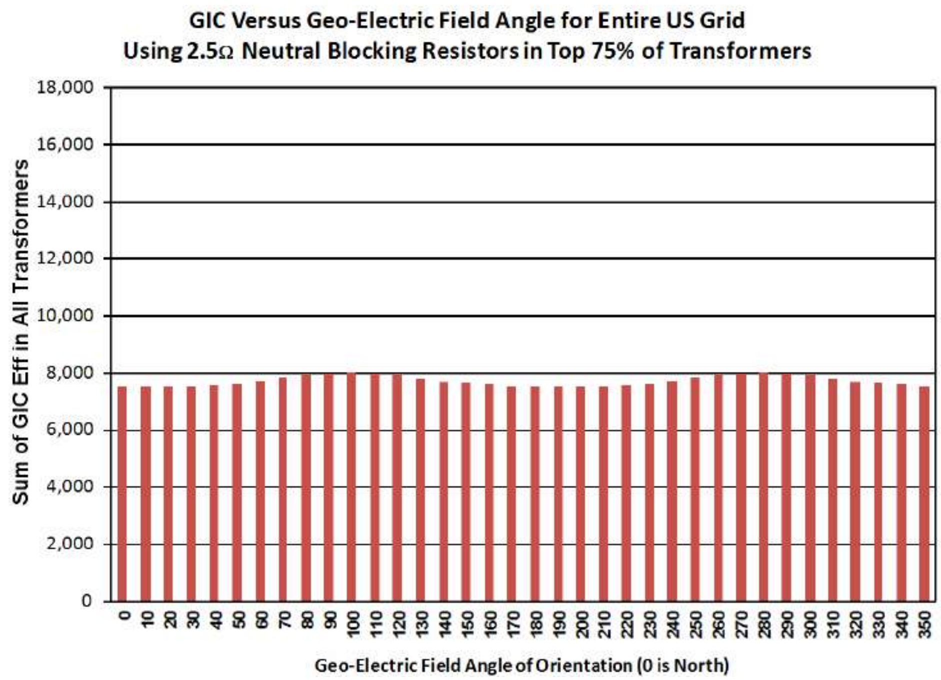

Figure 6-17. Total GIC flow in U.S. power grid for U.S. Grid Model with the addition of 2.5 ohm neutral blocking resistors in only the top 75% of GIC transformer neutrals.

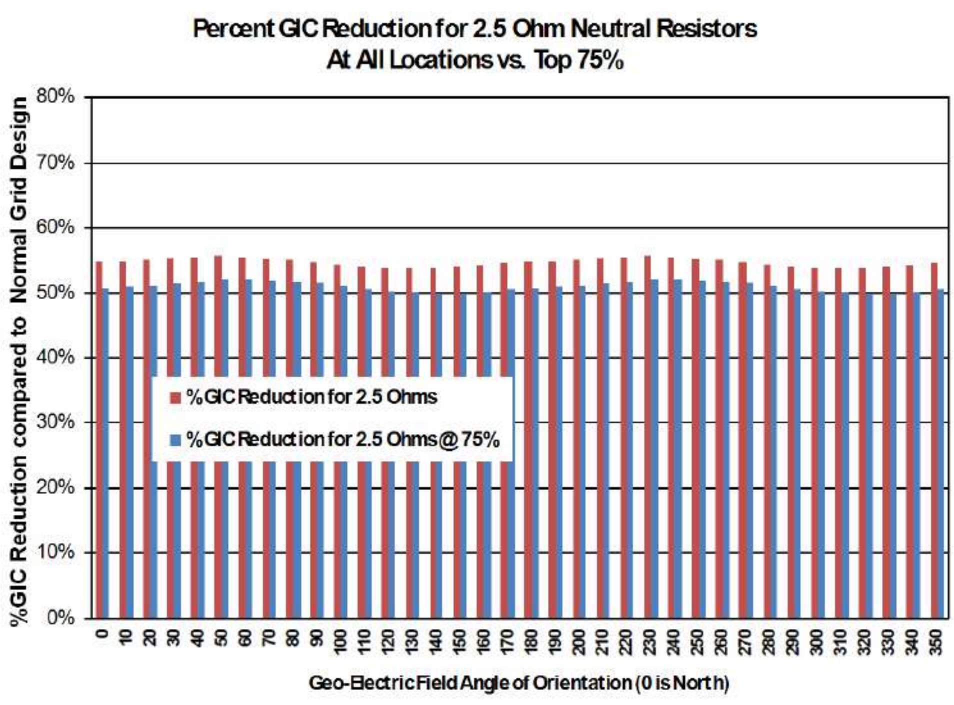

Figure 6-18. Reduction in GIC flow in U.S. power grid for U.S. Grid Model with the addition of 2.5 ohm neutral blocking resistors in all and in only the top 75% of GIC transformer neutrals.

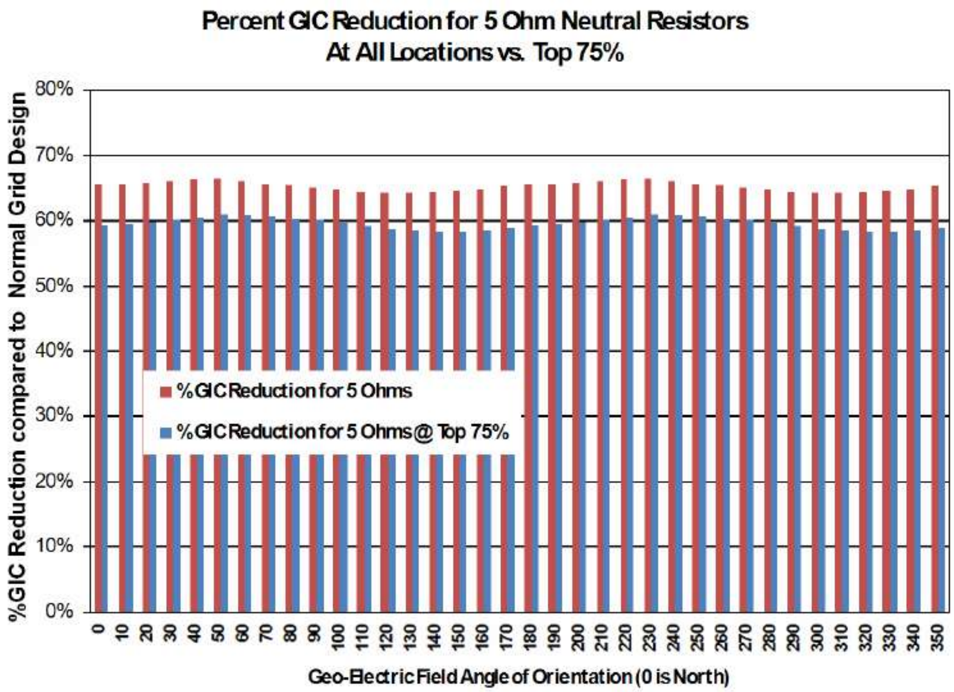

Figure 6-19. Reduction GIC flow in U.S. power grid for U.S. Grid Model with the addition of 5 ohm neutral blocking resistors in only the top 75% of GIC transformer neutrals.

Section 7
Evaluation of GIC Reduction Strategies for Geomagnetic Storm Scenarios

GIC reduction strategies have been evaluated and have also undergone limited optimization in their overall design in Sections 5 and 6 of this report. These evaluation methods involved uniform 1 V/km geo-electric fields applied simultaneously over the entire U.S. grid. Real geomagnetic storms and E3 threat scenarios will produce much more spatially complex geo-electric field patterns and with geo-electric field intensities that can be significantly higher than those used in Sections 5 and 6 for screening purposes. These real events can also have a more regionally intense impact. Therefore, these events provide a good check opportunity to further evaluate the efficacy of the GIC reduction strategies that have been developed.

Since geomagnetic storms have occurred on numerous occasions and their potential impacts are much better understood than those associated with E3 threat scenarios, the GIC reduction scenarios are tested against several storm events. For the first simulation, a time-step simulation was developed from actual observed disturbance conditions during the March 13-14, 1989 Superstorm that caused widespread disturbances to the North American power grid. For this storm, the time interval from 21:20-22:30UT on March 13, 1989 was selected, as this period of storm intensification caused the greatest number of observed impacts in the U.S. grid. The substorm activity during this time interval produced some of the largest and most wide-spread impacts observed across the U.S. power grid, as a large number of events were reported across the entire continent, even as far south as Los Angeles. The power system problems were caused by a more complex pattern of storm intensification during this time interval than prior intervals in the March 13-14, 1989 storm. Also, the disturbance regions expanded to mid-latitude locations over the U.S., which exposed large portions of the U.S. grid to moderately intense disturbance conditions. The geomagnetic disturbance conditions at time 22:00 UT is shown in Figure 7-1. At this time, there was both a large westward electrojet extending from Europe to the center of the North American continent, and also a large eastward electrojet from the eastern U.S. through the Pacific Northwest. It is also evident that these disturbance regions were very dynamic, as they significantly expanded in area over the time interval shown. The environment was particularly harsh because of the lower latitude position of the eastward electrojet. The disturbance region exposed a large fraction of the U.S. grid, causing the large number of power system events reported.

The storm impacts can be assessed further by reviewing the geo-electric field conditions and estimated GIC flows across the U.S. power grid at key times. Figure 7-2 shows the conditions at time 21:44 UT; at this time an intense geo-electric field extends from the Mid-Atlantic region into the upper Midwest. Voltage regulation problems were reported in Wisconsin, along with a number of problem reports in the Pennsylvania and New Jersey regions. Figure 7-3 shows the conditions at time 21:57 UT, the intense geo-electric field extends from the Mid-Atlantic/New England regions to the Pacific Northwest. This triggered a large number of problems all across the U.S., as noted in the figure.

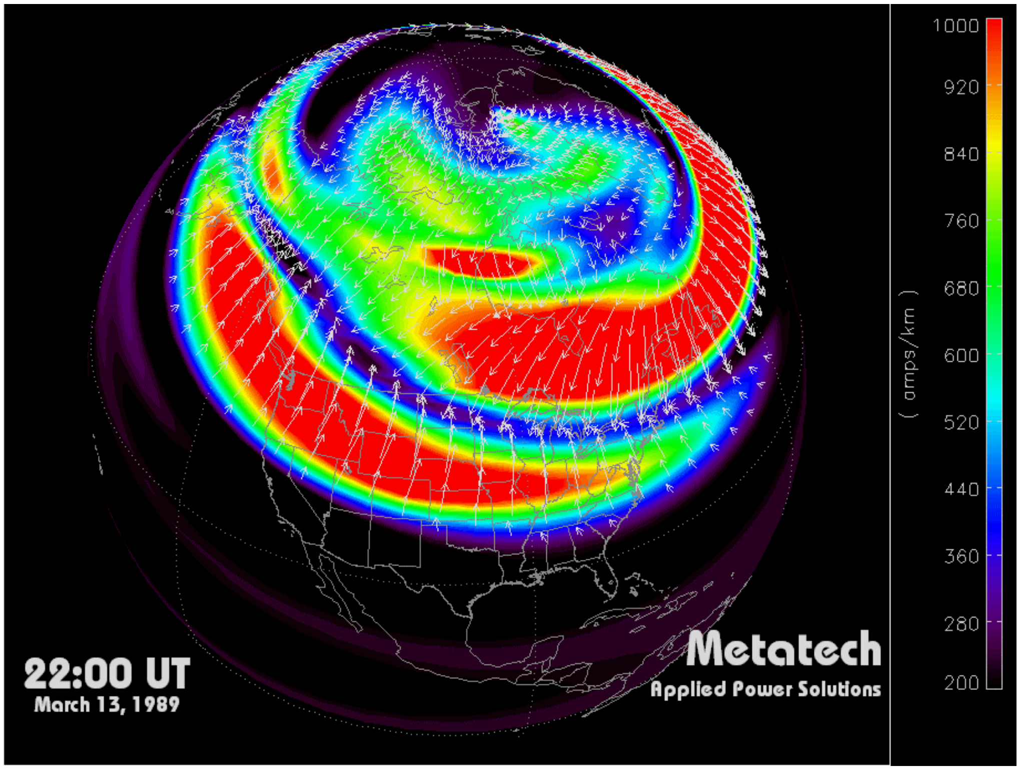

Figure 7-1. Geomagnetic field disturbance conditions simulated at 22:00UT, March 13, 1989.

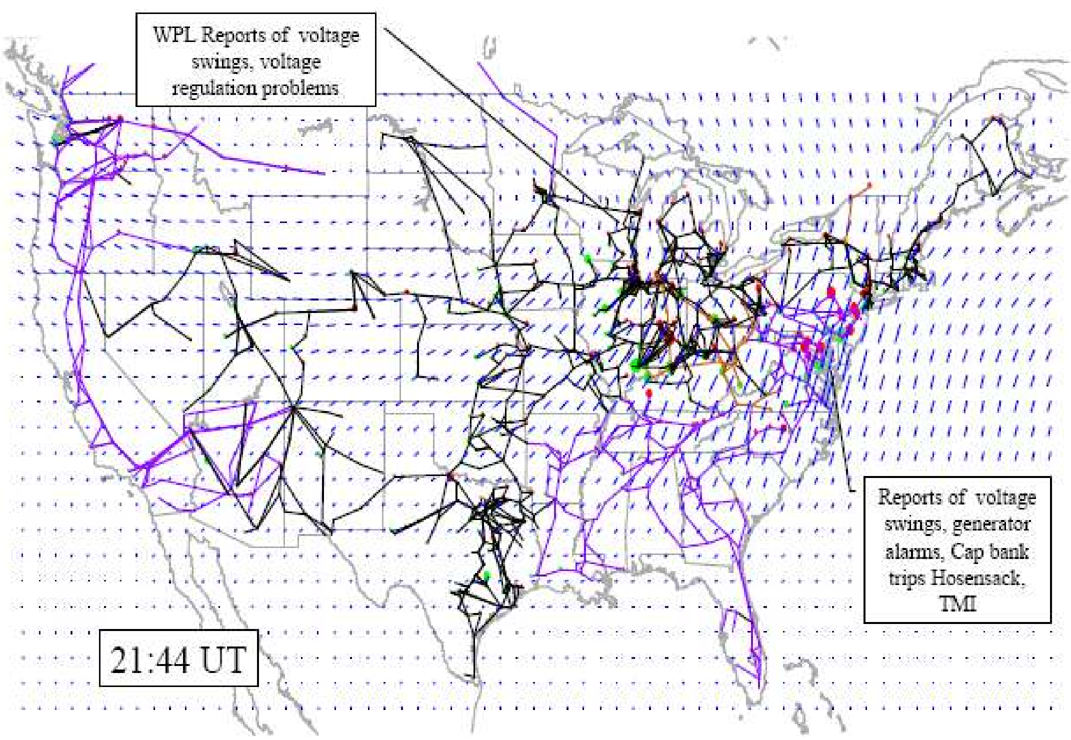

Figure 7-2. Simulation of U.S. power grid conditions at 21:44UT on March 13, 1989.

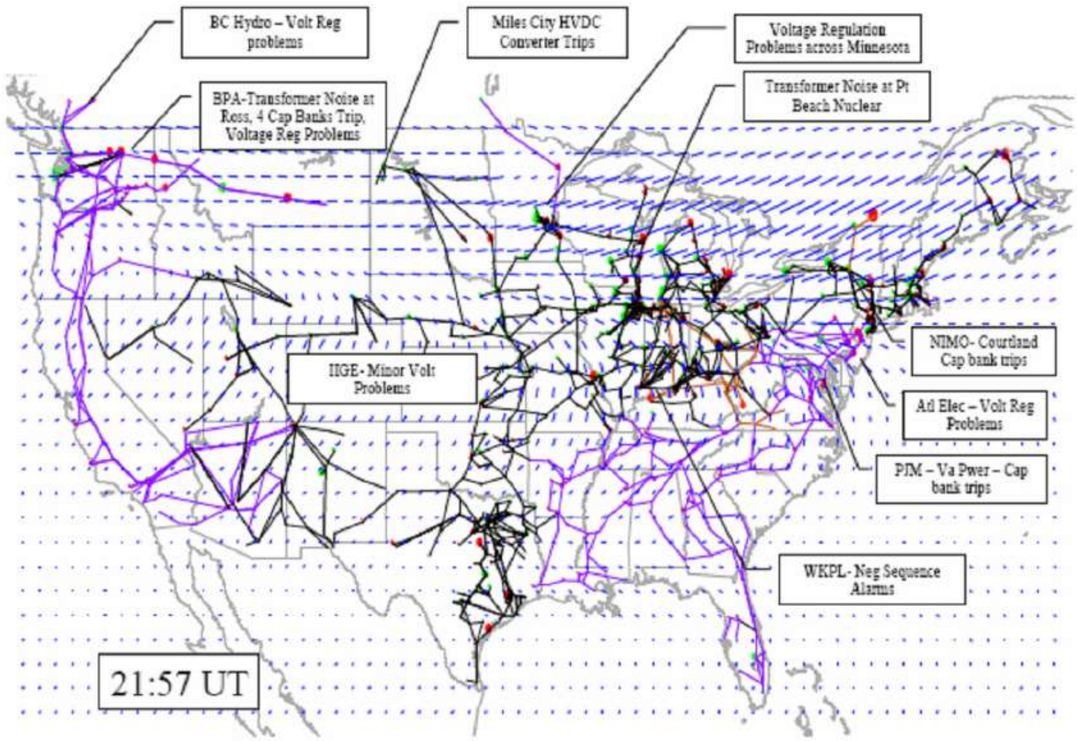

Figure 7-3. Simulation of U.S. power grid conditions at 21:57UT on March 13, 1989.

Using this important storm time interval, three simulations were performed utilizing the U.S. power grid model. The first simulation was the grid model with the normal or present system design, while two additional simulations were made to examine two GIC reduction strategies with 5 ohm resistors at all locations and 5 ohm resistors only in the top 75% GIC locations. Figure 7-4 provides a time step summary of the total GIC observed in the power grid model for these three simulations. As shown in this figure, the highest GIC levels occur for the present grid design, while both of the 5 ohm resistor strategies produce significant reduction in GIC levels. Figure 7-5 provides a summary, over the time interval, of the GIC reduction percentage (compared to normal) for the two 5 ohm resistor plans that have been evaluated. Both provide GIC reductions that are generally greater than 60%, though as in the previous analysis, the differences between the two options are within a few percent. A more relevant metric for examining power grid impacts (rather than GIC) is the impact that GIC causes to system operations due to increased reactive power demands. Figure 7-6 provides a similar time period summary as shown in Figure 7-4, only for increased reactive power (in MVARs) for the three simulation cases. As with the GIC levels, this summary illustrates that both GIC reduction design options provide significant reductions in MVAR levels.

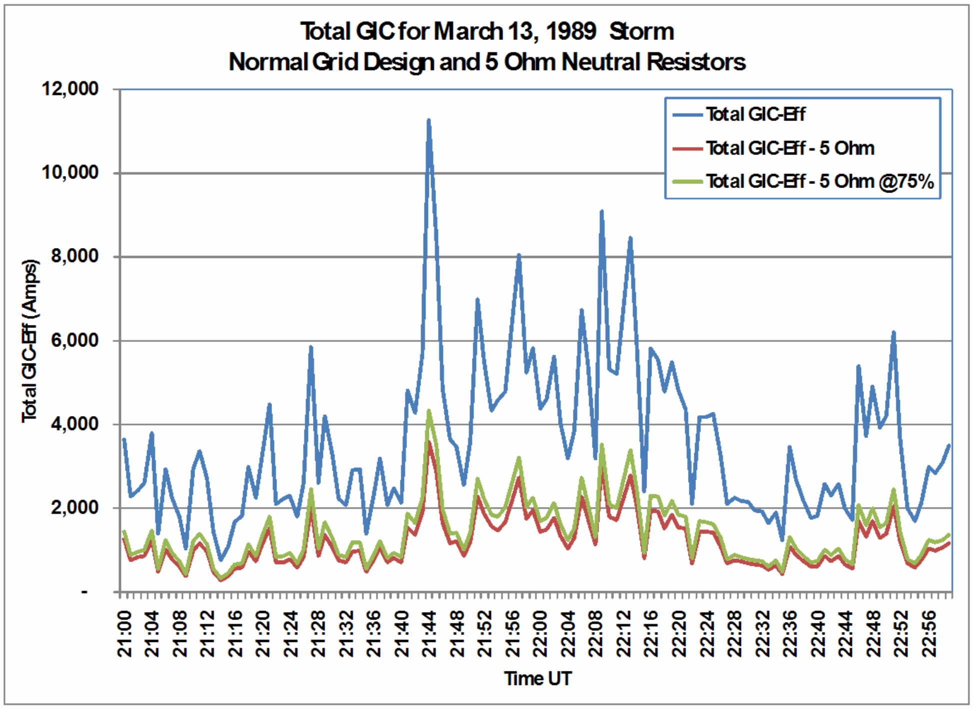

Figure 7-4. Summary of simulated GIC levels in the U.S. grid for storm interval on March 13, 1989, comparing normal design with two 5 ohm resistor GIC reduction designs.

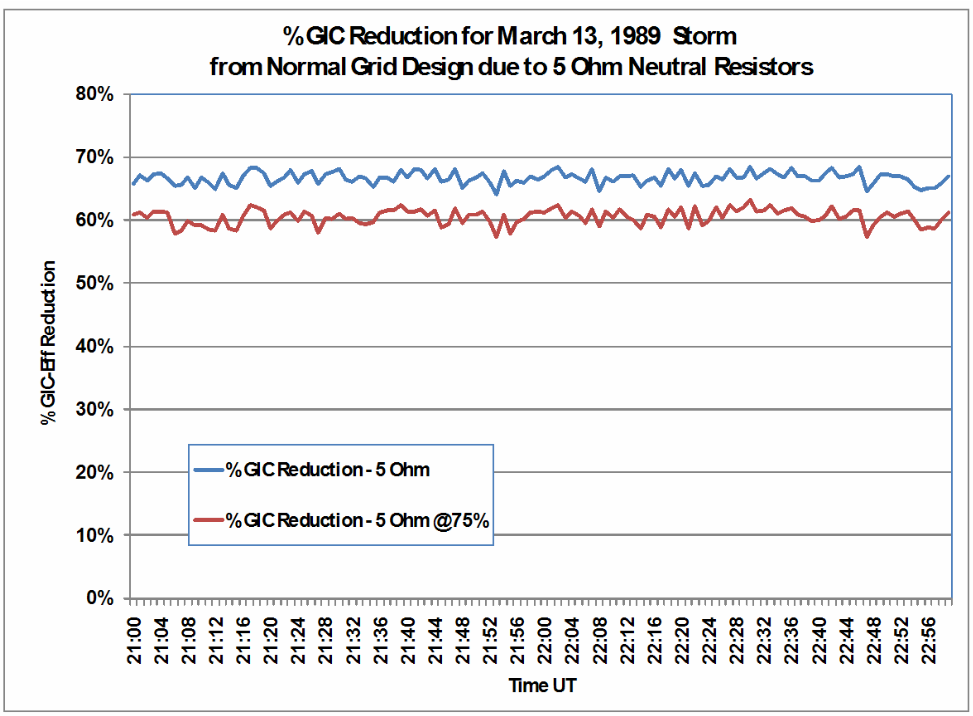

Figure 7-5. Summary of GIC reduction levels in the U.S. grid for storm interval on March 13, 1989, for the two 5 ohm GIC reduction designs.

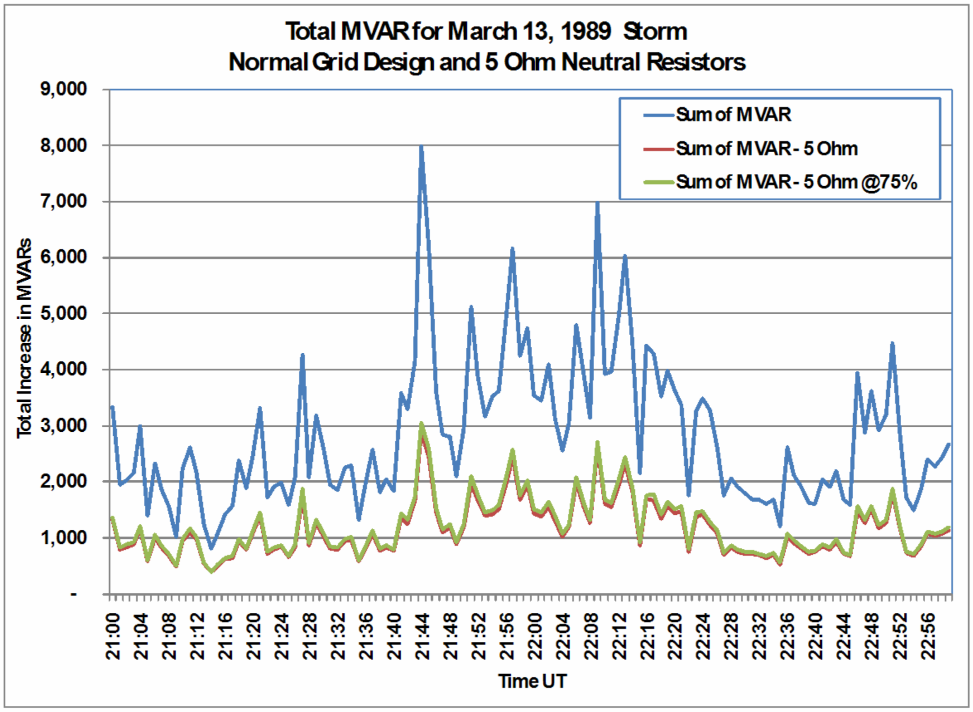

Figure 7-6. Summary of simulated increase MVAR levels in the U.S. grid for storm interval on March 13, 1989, using normal design and two 5 ohm resistor GIC reduction designs.

What is also apparent in this summary is that there is very little difference between the two design options in their overall efficacy in reducing the MVAR increases. This is further confirmed in Figure 7-7, which provides a summary of the MVAR reduction percentage at all times for the two design options. MVAR reduction efficacy is closer for both design options because a large number of the low GIC participating transformers (bottom 25%) are in lower kV rated transformers, which produce less MVAR response for GIC flows. Since GIC is being reduced the most in the top 75% of transformers in both cases at the higher kV rated transformers (which produce the most MVAR increases) that causes the two design plans to have very similar comparative performance than for measures of GIC alone.

Impulsive geomagnetic field disturbances provide the most useful metric of the geomagnetic storm environment for electric power grids and other ground-based infrastructures that can be impacted by GIC. Significant power grid impacts in present day networks have been observed at relatively low levels of intensity. For example, the Quebec grid blackout during the March 13-14, 1989 storm occurred at a peak intensity of 480 nT/min and permanent damage to large power transformers have occurred at even lower intensity levels. As noted in Meta-R-319, an analysis of both contemporary and historic storm data and records indicates dBh/dt impulsive disturbances larger than 2000 nT/min have been observed on at least three occasions since 1972 at latitudes of concern for power grid infrastructures in the U.S. In extreme scenarios, available data suggests that disturbance levels as high as 5000 nT/min may have occurred during the great geomagnetic storm of May 1921, an intensity ~10 times larger than the disturbance levels associated with the major impacts observed on North American power grids in March 1989. In order to evaluate these extreme geomagnetic disturbance conditions, a series of simulations were performed on the U.S. grid for normal design and for the two 5 ohm GIC reduction strategies using the 4800 nT/min disturbance conditions located at a geomagnetic latitude of 50° north across the North American continent.

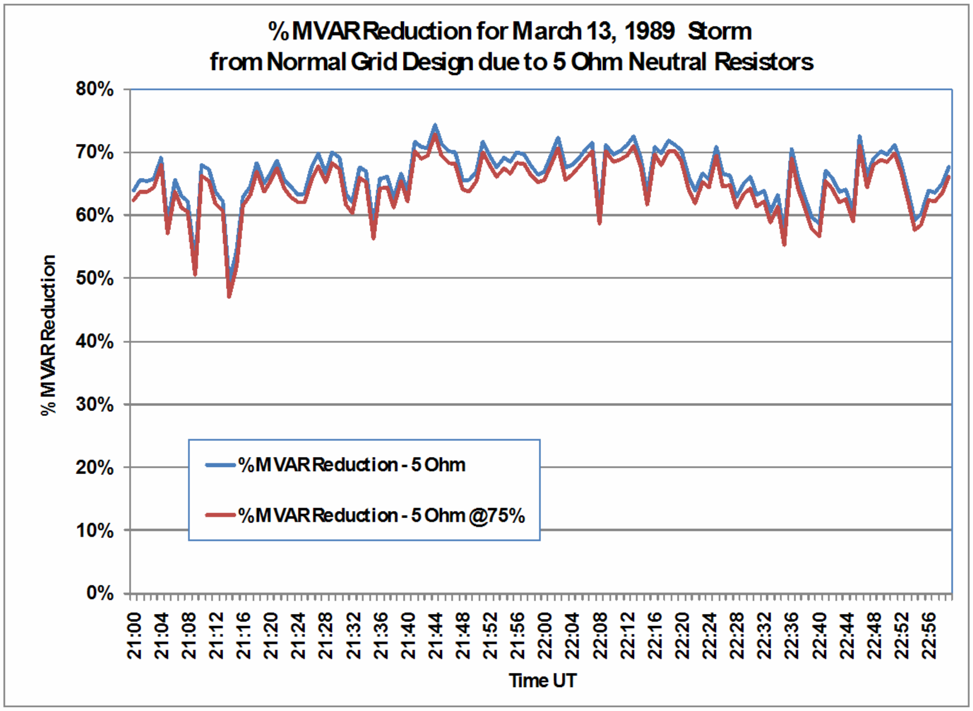

Figure 7-7. Summary of MVAR reduction levels in the U.S. grid for storm interval on March 13, 1989 for the two 5 ohm GIC reduction designs.

Figure 7-8 provides a plot of the GIC levels estimated for the severe geomagnetic storm threat environment reaching a peak of 4800 nT/min. This can be compared to Figures 7-9 and 7-10, which provide a similar plot of the GIC levels for the grid design cases of the two GIC reduction strategies using 5 ohm neutral resistors. Both indicate substantial reduction in GIC levels across the impacted areas of the U.S. Figure 7-11 provides a more detailed quantification of these three cases and the overall efficacy of the two 5 ohm GIC reduction designs. In this comparison chart, the total GIC and MVAR levels are provided for the three cases. It is again noteworthy in comparing the two 5 ohm design cases that while there is some differences in GIC levels between the two, there is much smaller differences between the two designs when it comes to MVAR's, which provides the best measure of impact to the power grid. Figure 7-12 provides a summary of both design cases in respect to the percent reduction in GIC levels and MVAR levels. This comparison indicates both design options provide ~60% reductions in both of these important metrics and that percent MVAR reductions are virtually identical for the two design options. This again indicates that both the design options produce nearly comparable net benefit to the power grid as measured by MVARs.

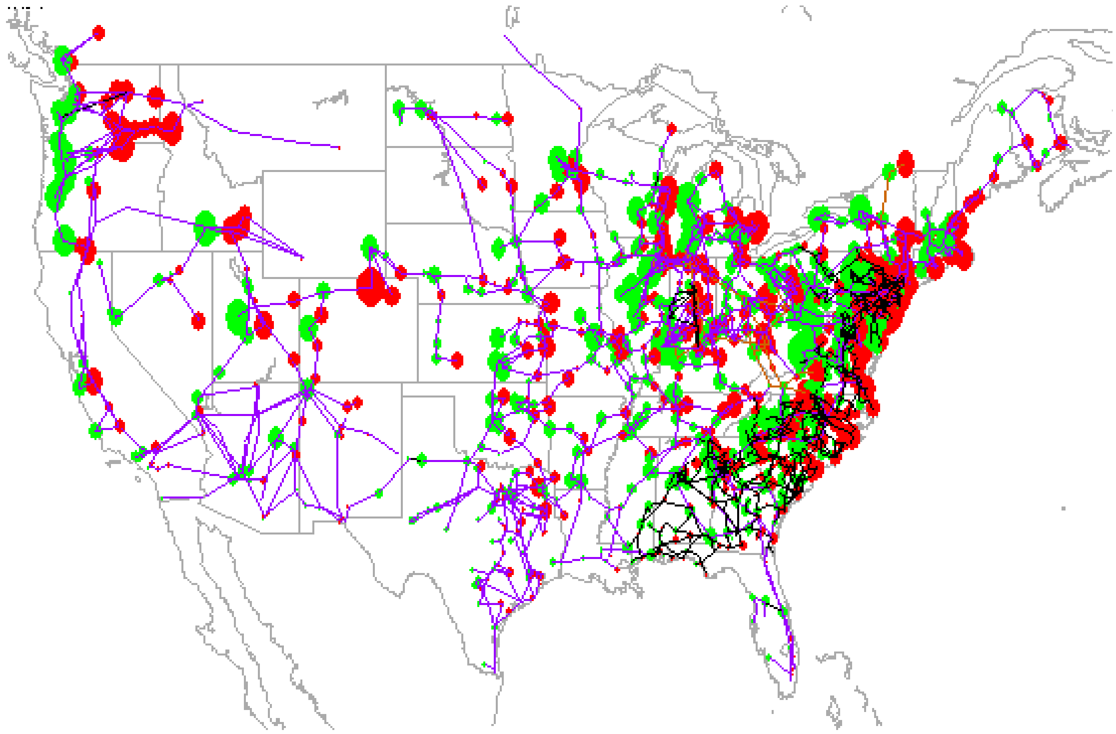

Figure 7-8. Simulation of U.S. power grid conditions for a 4800 nT/min geomagnetic storm threat centered at 50^{o} latitude.

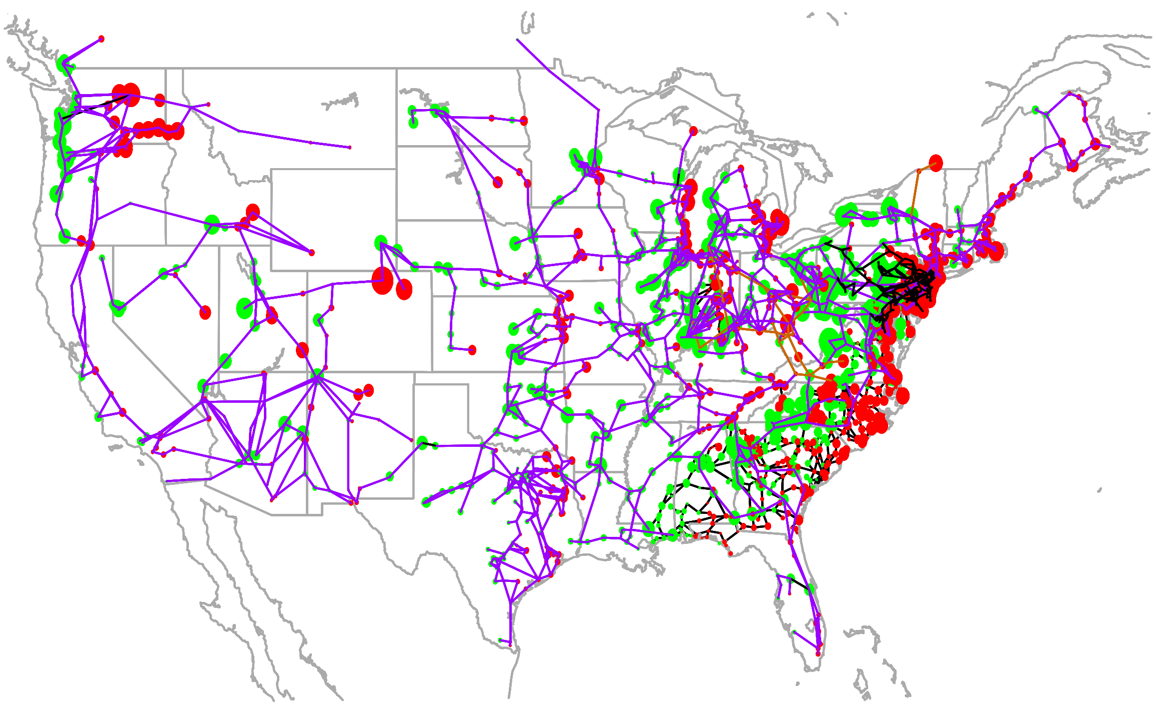

Figure 7-9. Simulation of U.S. power grid conditions for a 4800 nT/min geomagnetic storm threat with the addition of 5 ohm neutral resistors in all transformers.

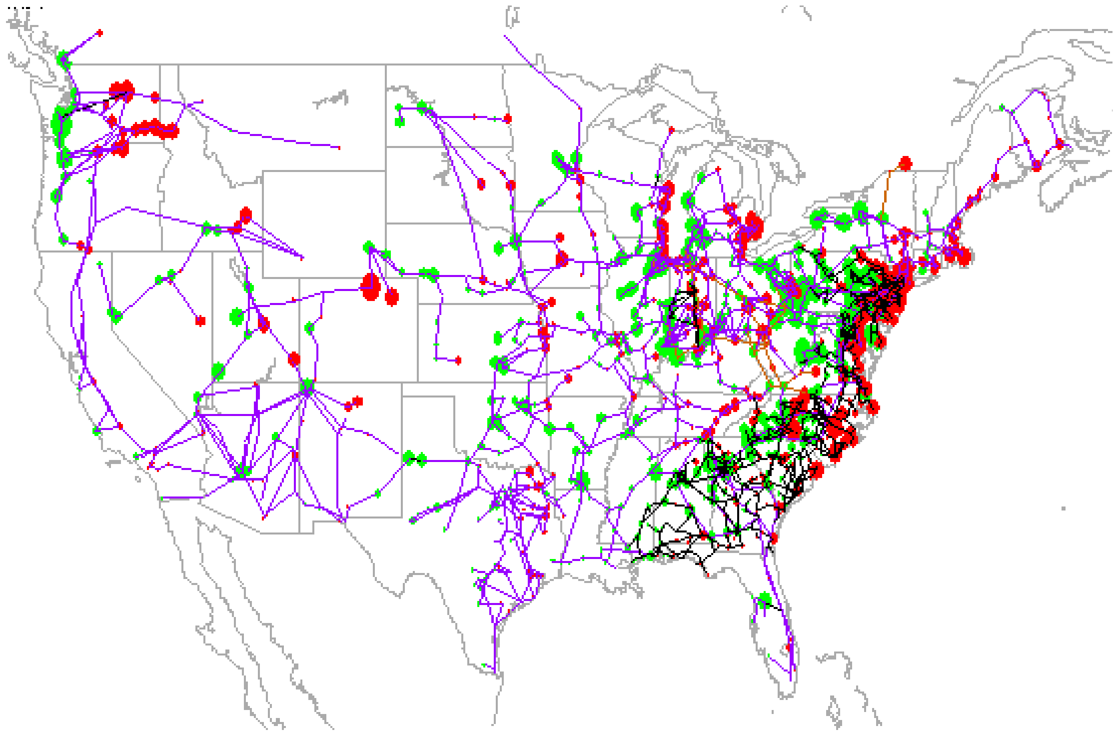

Figure 7-10. Simulation of U.S. power grid conditions for a 4800 nT/min geomagnetic storm threat with the addition of 5 ohm neutral resistors in only the top 75% of transformers.

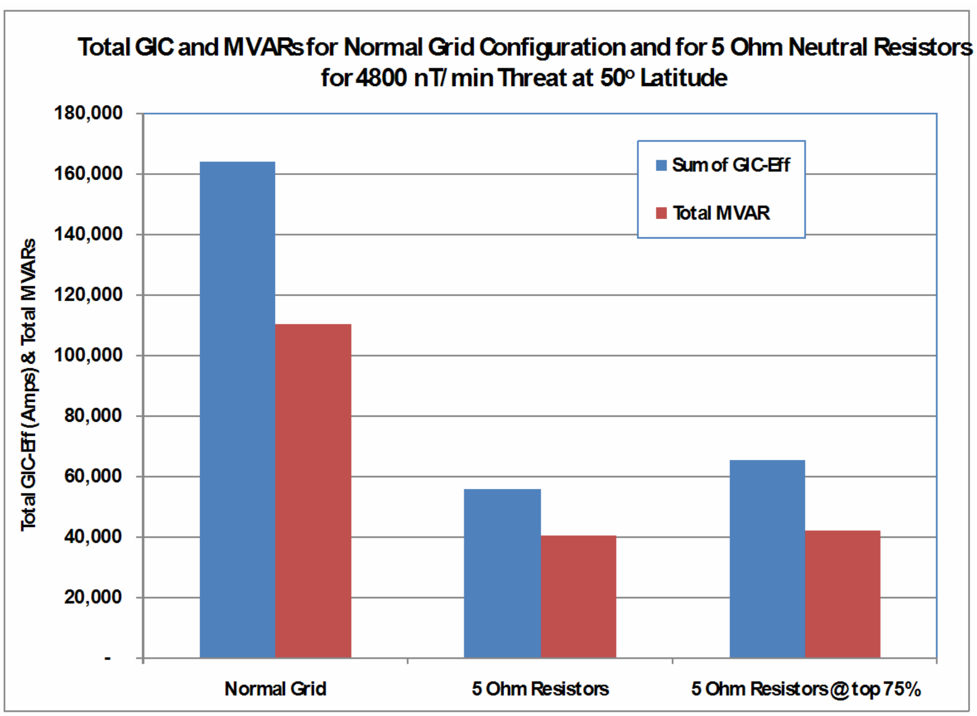

Figure 7-11. Comparison summary of GIC and MVAR levels for a 4800 nT/min geomagnetic storm threat. Comparison is provided between normal grid design and the two 5 ohm resistor GIC reduction designs.

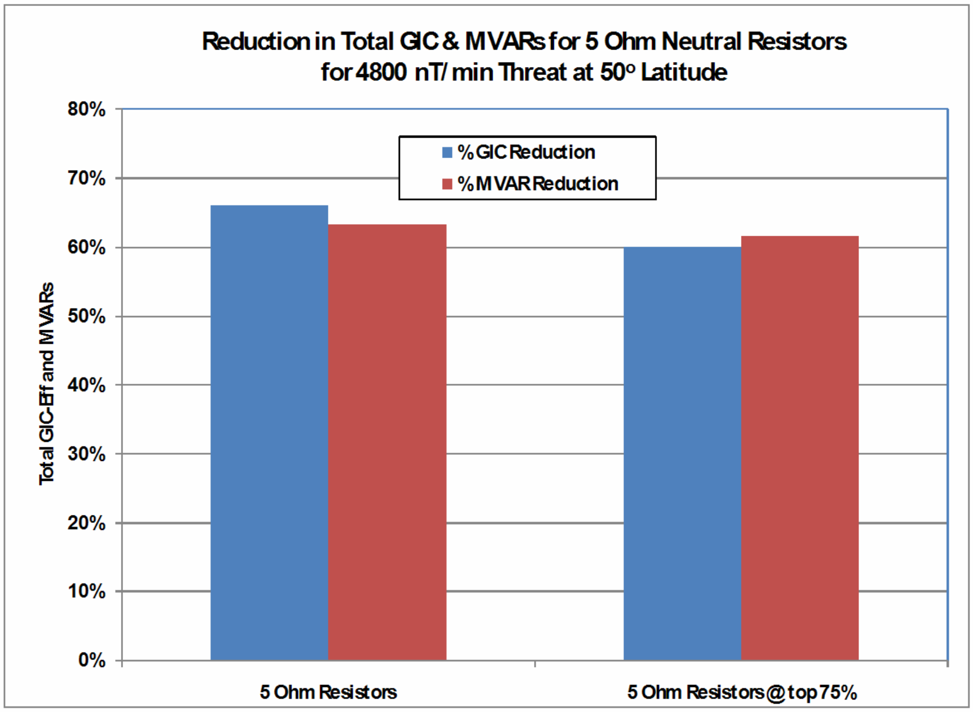

Figure 7-12. Summary of GIC and MVAR reduction percentage for a 4800 nT/min geomagnetic storm threat. Comparison is provided between normal grid design and the two 5 ohm resistor GIC reduction designs.

An especially important measure of comparison that can also be identified is the potential for regions of power grid blackout due to the geomagnetic storm threat environment. Using the previously developed disturbance energy metric, a summary by state-level can be developed that provides the estimated regions of initial power system collapse due to the storm disturbance peak. As in prior estimates, it is important to note that initial blackout spreading beyond the areas depicted is possible due to the dynamics of cascading or progressive collapse that can occur in the tightly networked power grid. Therefore these estimates should be viewed as likely best-case estimates rather than worst-case estimates of blackout regions.

For the 4800 nT/min threat environment and normal grid design, Figure 7-13 provides a plot again of the GIC level in each transformer and shows in shading the states that are likely to experience initial power grid collapse due to the large levels of GIC and resulting MVAR increases. As shown in this figure, most of the region from Illinois eastward through the Mid-Atlantic States as well as a significant portion of the south are estimated to have levels that would threaten power grid collapse. While Kentucky was not included in these initial estimates, the disturbance levels observed here are very close to the threshold used to estimate collapse. In addition, three states in the Pacific Northwest region are also estimated for initial blackout of the power grid as well.

Figures 7-14 and 7-15 provide a similar summary of GIC and estimated blackout regions for the two 5 ohm GIC reduction strategies. Both indicate that these design strategies provide substantial reductions in the regions of expected power grid blackout compared to the normal grid design case of Figure 7-13, and both design strategies produce identical results in this regard.

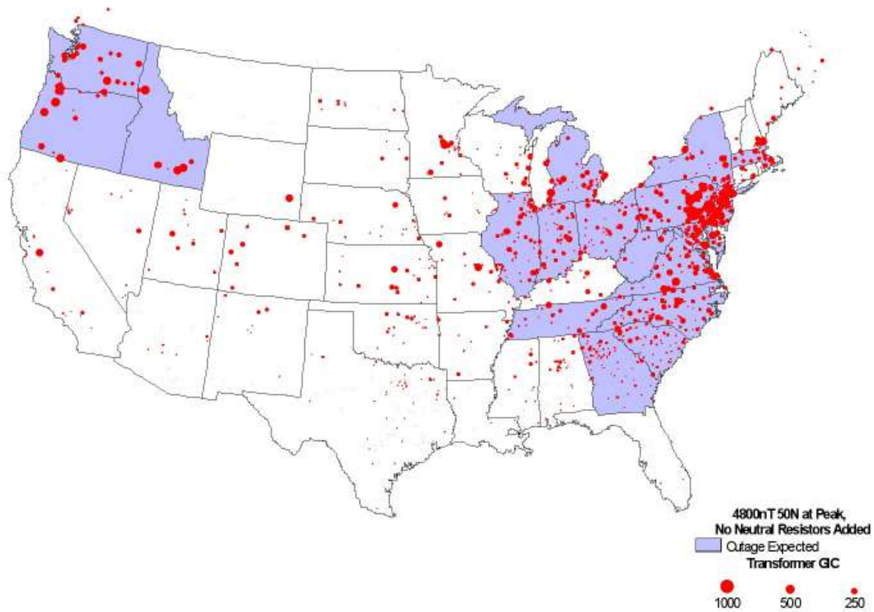

Figure 7-13. Map of GIC levels in transformers and estimated regions of power grid outage for a 4800 nT/min geomagnetic storm threat with the normal grid design.

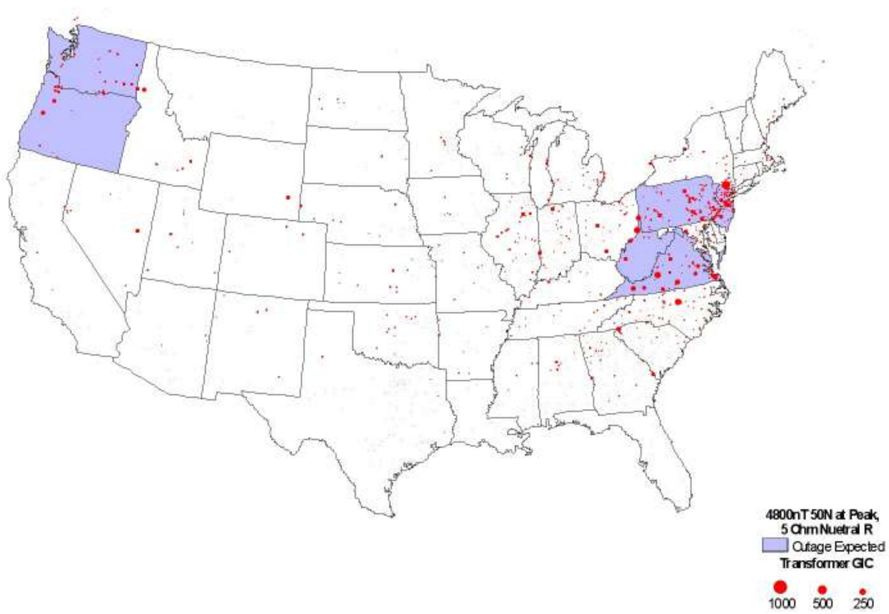

Figure 7-14. Map of GIC levels in transformers and estimated regions of power grid outage for a 4800 nT/min geomagnetic storm threat with 5 ohm resistors in all transformers.

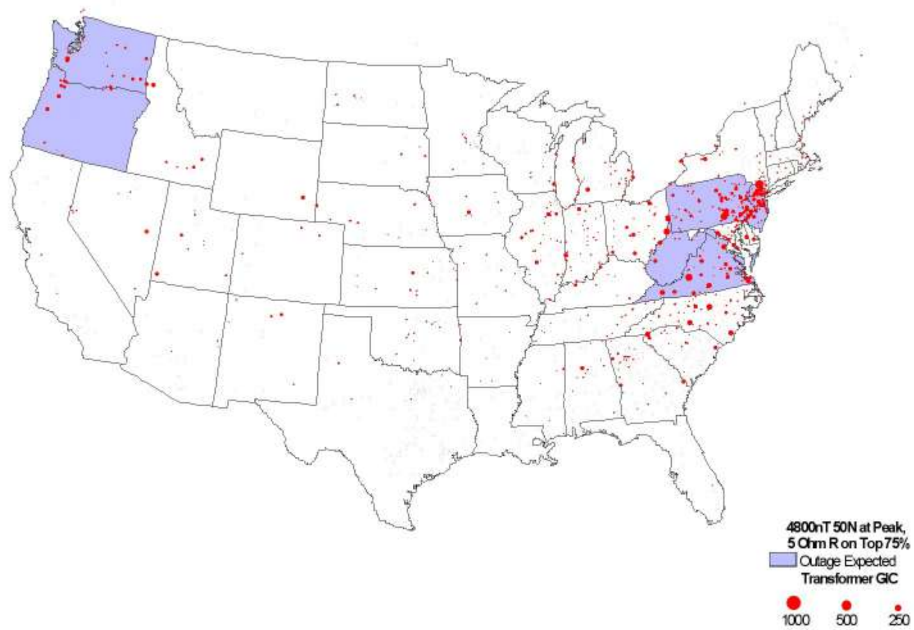

Figure 7-15. Map of GIC levels in transformers and estimated regions of power grid outage for a 4800 nT/min geomagnetic storm threat with 5 ohm resistors in top 75% of transformers.

A more in-depth analysis of the levels of GIC for this threat environment is provided in Figure 7-16 for the normal grid design with the 4800 nT/min disturbance. The peak GIC flows of all transformers is provided in this chart. As shown, these GIC levels are quite high compared to earlier results provided in Sections 5 and 6, which were only simulated with a uniform 1 V/km geo-electric field. As this is a much more severe disturbance environment, there are several hundred transformers with GIC in excess of 90 amps per phase. This raises important concerns about levels of failure and permanent damage that may occur to these transformers. Figures 7-17 and 7-18 provide comparison plots of GIC levels in all transformers for the normal grid case with the two 5 ohm GIC reduction strategies. As shown in these plots, both 5 ohm strategies reduce GIC flows at most locations with high GIC levels, while shifting GIC flows to other locations which already had low GIC flows.

The difficult aspect of this threat is the determination of permanent damage to power grid transformers and how that would act to impede the restoration process. At sufficiently high enough levels of GIC, transformer damage is the most likely outcome, although other key assets on the grid are also at risk. In particular, transformers experience excessive levels of internal heating brought on by stray flux when GICs cause the transformer's magnetic core to saturate and to spill flux outside the normal core steel magnetic circuit. Previous well-documented cases have noted heating failures that caused melting and burn-through of large-amperage copper windings and leads in these transformers. These multi-ton apparatus generally cannot be repaired in the field. If transformers are damaged in this manner, they need to be replaced with new units, which

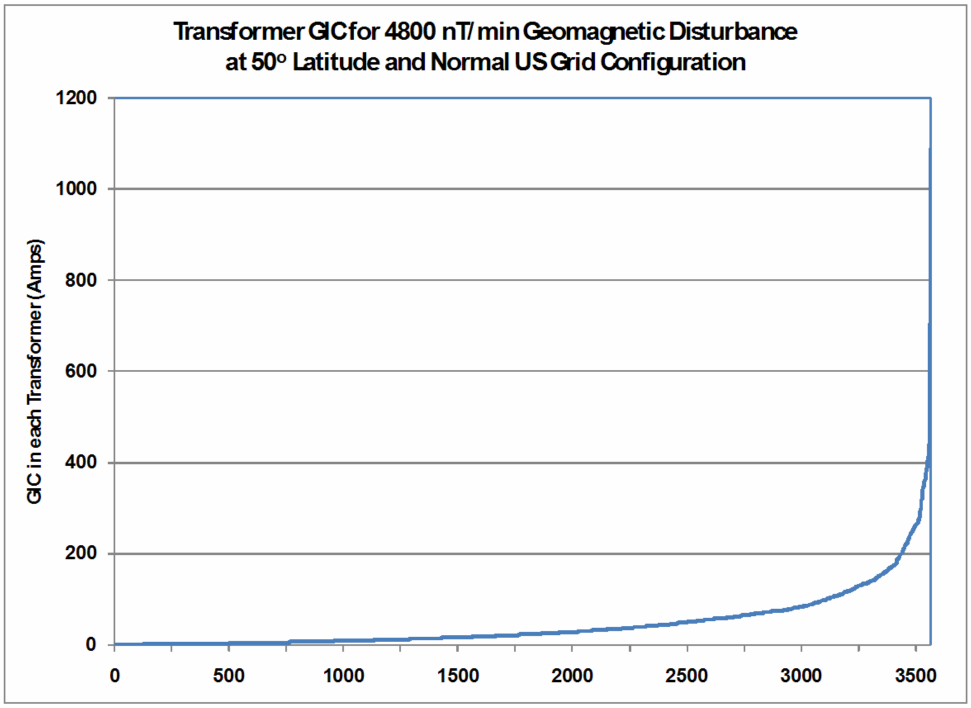

Figure 7-16. GIC flow in each transformer for normal grid design for the 4800 nT/min geomagnetic disturbance threat environment.

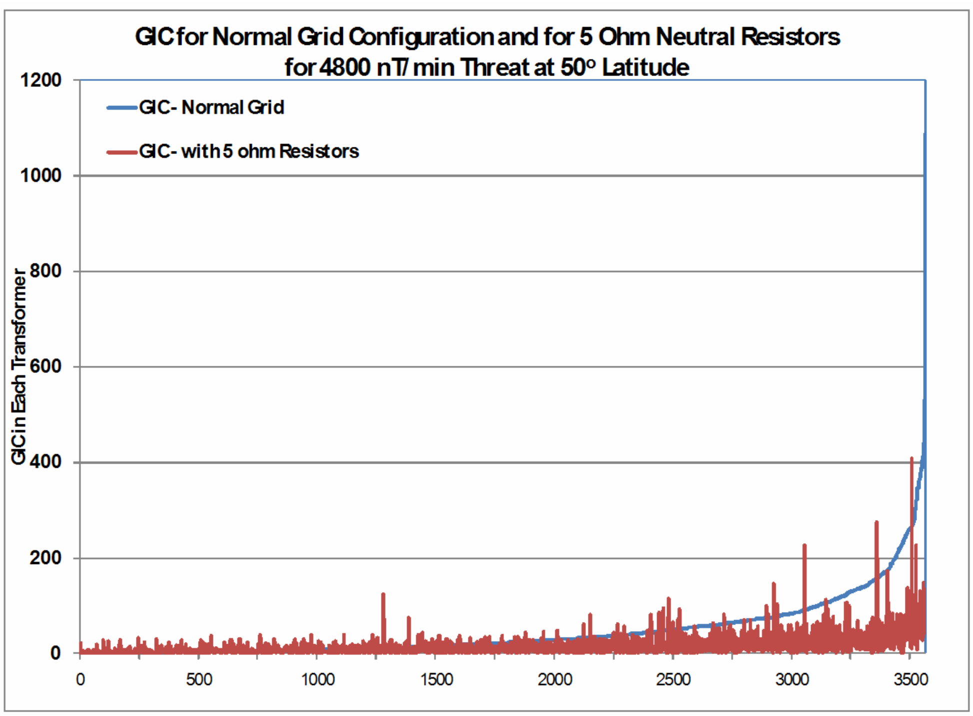

Figure 7-17. Comparison of GIC flow in each transformer for normal grid design compared to case with 5 ohm neutral resistors in all transformers for the 4800 nT/min geomagnetic disturbance threat environment.

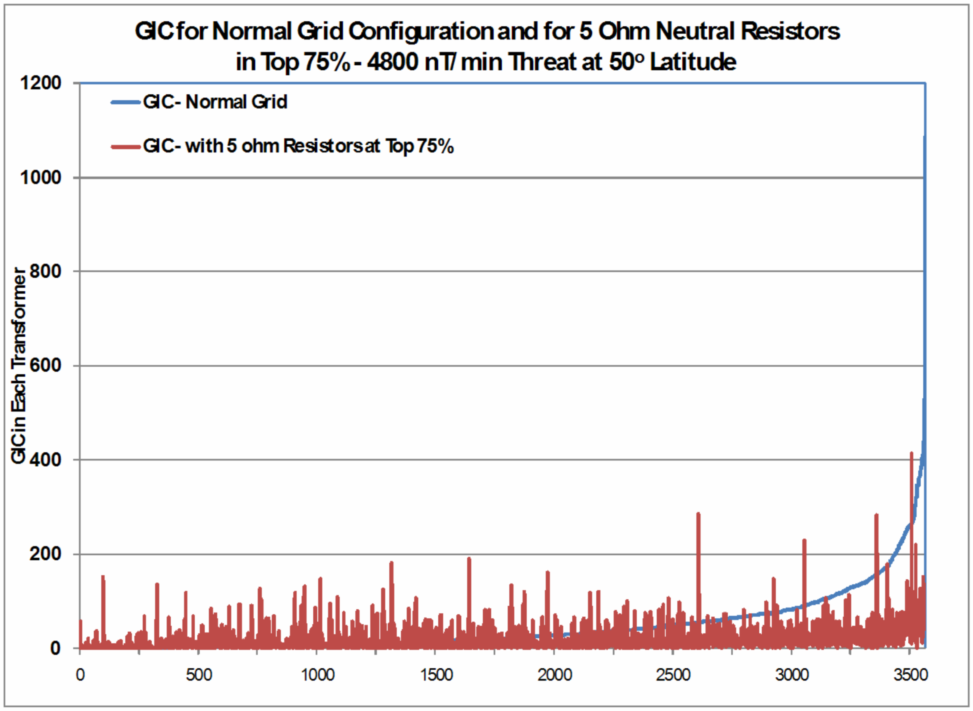

Figure 7-18. Comparison of GIC flow in each transformer for normal grid design compared to case with 5 ohm neutral resistors in only the top 75% of transformers for the 4800 nT/min geomagnetic disturbance threat environment.

have manufacture lead times of 12 months or more in the world market. In addition, each transformer design (even from the same manufacturer) can contain numerous subtle design variations. These variations complicate the calculation of how and at what density the stray flux can impinge on internal structures in the transformer. Therefore, the ability to assess existing transformer vulnerability or even to design new transformers to be tolerant of saturated operation is not readily achievable. Again, the experience from contemporary space weather events is revealing and potentially paints an ominous outcome for historically large storms that are yet to occur on today's infrastructure.

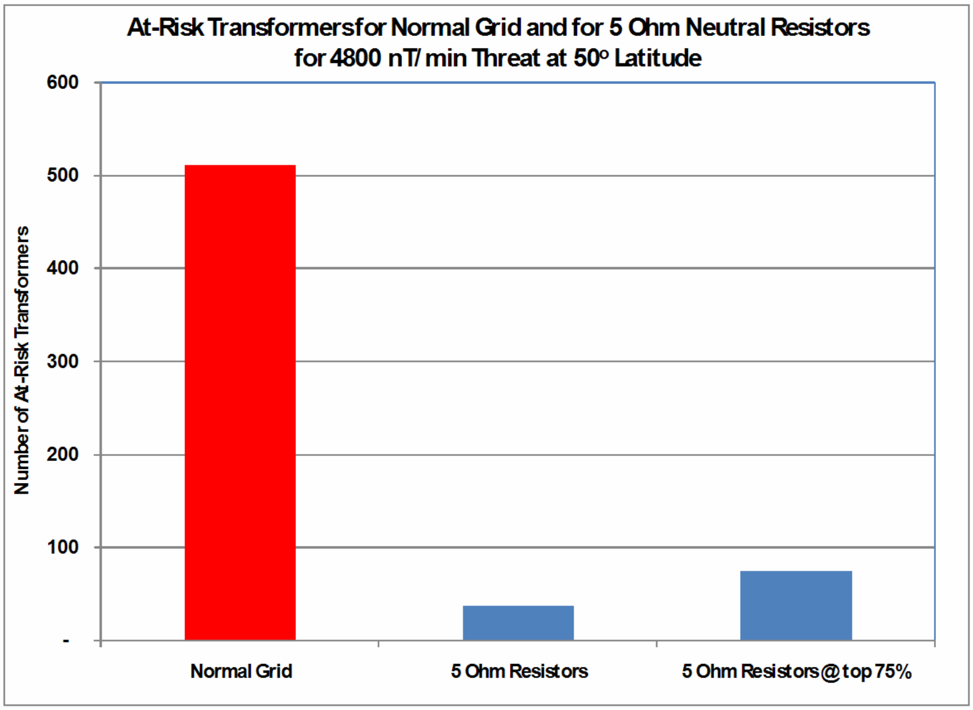

Figure 7-19. Comparison of at-risk transformers for normal grid design and the two 5 ohm GIC reduction strategies for the 4800 nT/min geomagnetic disturbance threat environment.

Using a 90 amps/phase GIC threshold, an analysis can be provided of the at-risk transformers that could sustain permanent damage due to the high levels of GIC flows. Figure 7-19 provides a comparison of the number of at-risk transformers for the three 4800 nT/min simulations comparing the normal grid design with the two 5 ohm GIC reduction designs. As shown, for the normal grid design over 500 transformers would be considered to be at-risk for this storm scenario. For the 5 ohm resistor in all transformers strategy, the number of at-risk transformers drops to only 37 units, a 93% decrease in at-risk transformers. The design with 5 ohm resistor in only the top 75% of transformers reduced the at-risk units to 75 transformers, an 85% reduction from the normal design case.

To provide further context on the importance of the at-risk transformers and how these could act to impair the function of the EHV network and ultimately the ability to provide restoration of the power supply to impacted areas, a map provides an estimate of “percent loss” of EHV transformation capacity by state for the same 4800 nT/min threat environment for the normal grid design case in Figure 7-20. As shown, some of the most heavily impacted states experience more than a third loss of capacity; such large scale damage would likely lead to prolonged restoration and/or long term chronic shortages of electric energy supply capability to the impacted regions. Figures 7-21 and 7-22 provide maps of the geographic estimate of impaired EHV transmission capacity for the two 5 ohm GIC reduction designs. A significant reduction in the degree of impairment is evident for both 5 ohm GIC reduction scenarios compared to the normal grid design estimates. While there are significant reductions in at-risk transformers, New Jersey still retains nearly 49% impaired capacity in both GIC reduction cases. This is of concern for that region and suggests that more extensive remedial design approaches may be warranted. However, all other regions have limited impaired capacity and would not be expected to experience as significant recovery problems.

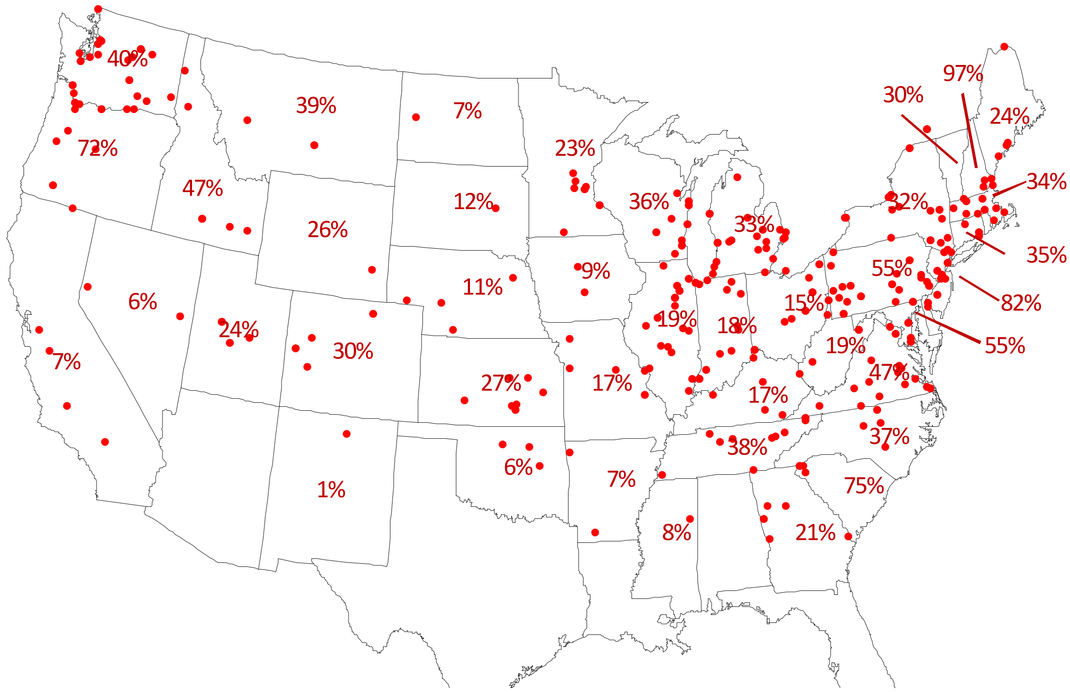

Figure 7-20. Map showing the at-risk EHV transformer capacity by state (345kV and above) for the normal grid design and 4800 nT/min disturbance scenario. Rregions with high percentages could experience long duration outages

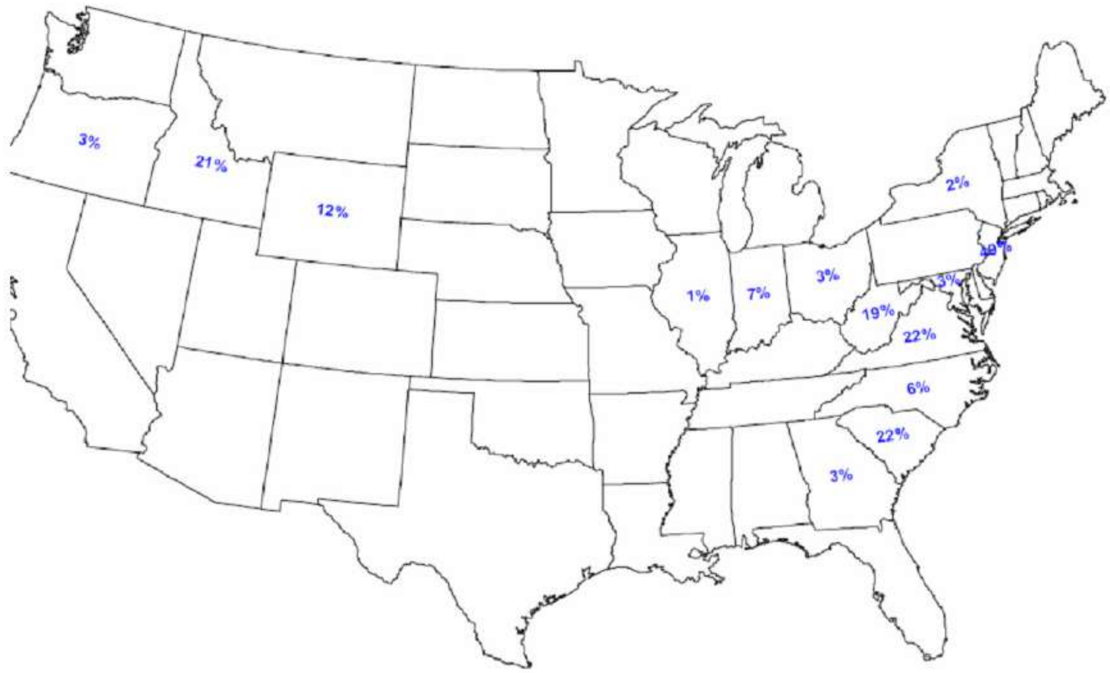

Figure 7-21. Map showing the at-risk EHV transformer capacity by state (345kV and above) for 5 ohm resistors at all transformers design and 4800 nT/min disturbance scenario.

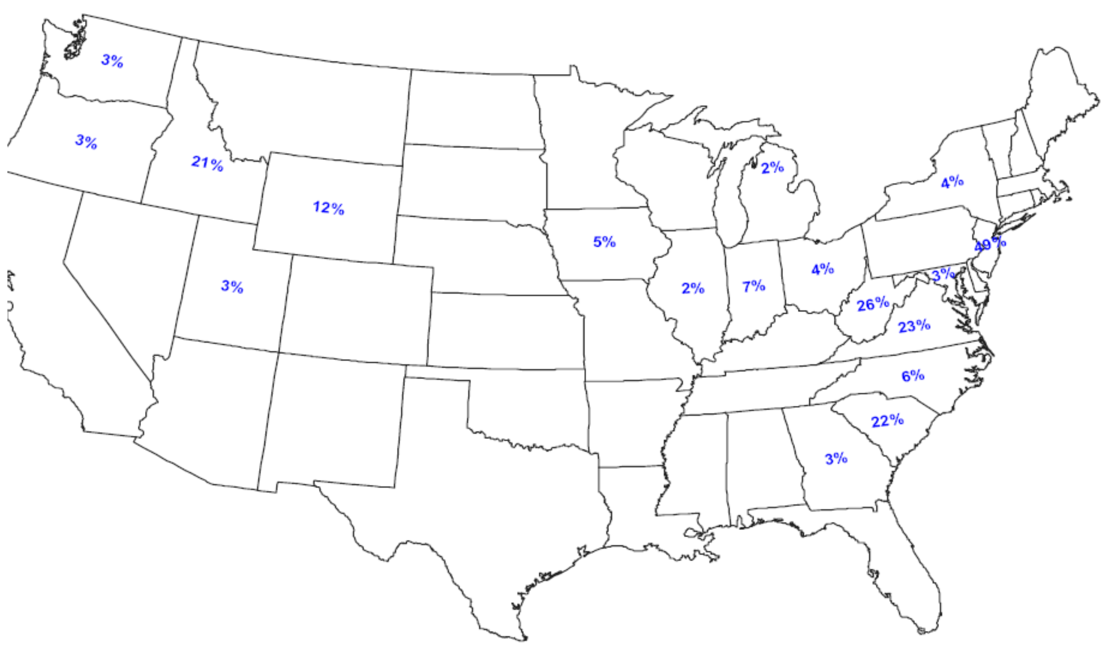

Figure 7-22. Map showing the at-risk EHV transformer capacity by state (345kV and above) for 5 ohm resistors at only top 75% of all transformers design and 4800 nT/min disturbance scenario.

Section 8
Evaluation of GIC Reduction Strategies for E3 Heave Disturbance Scenarios

A high altitude EMP burst can produce broad and intense regional geomagnetic field disturbances in a fashion similar to that associated with severe geomagnetic storms. These E3 Heave threat scenarios will subsequently produce large GIC flows in the exposed portions of the U.S. power grid and produce similar potential for impacts to reliable operation of the grid as discussed in Section 7. As in Section 7, a series of simulations and analyses were carried out to examine the impact due to the large E3-caused GIC currents that will occur in the electric power infrastructure and the power grid infrastructure's ability to be restored following this type of intentional attack. In addition, analysis is provided for the efficacy of neutral blocking resistors as a means to reduce GIC levels and therefore to mitigate some of the consequences of these threat scenarios.

Four specific E3 threat cases are used in this analysis. These consist of a high altitude detonation centered over the New York region called "NY Device D"; a scenario of a high altitude detonation over the Los Angeles area called "LA Device D"; and two cases based upon a scenario of a high altitude detonation over approximately Columbus Ohio. The first one is a medium yield device called "Case 12D" and the second is a large yield device called "Case 16D". The New York and Los Angeles focused cases were particularly selected to examine the possible damage and restoration potential for such attacks over large population regions where high–density of critical power and telecommunications infrastructure is present. The detonation, because of its proximity to these coastal metropolitan areas, will expend a significant portion of the E3 threat environment over the oceans near these regions. Therefore, a scenario was also selected with the burst over the Midwestern portions of the U.S., where all significant portions of the E3 threat environment energy would illuminate a larger area of U.S.-based infrastructures with lesser degree expended over the ocean regions. Hence the selection of the Columbus, Ohio region for Cases 12D and 16D, as these two bursts have the potential to provide one of the broadest possible laydowns of E3–HEMP on the power grid infrastructure in the U.S. For perspective, the E3 pattern for the Case 16D is provided in Figure 8-1.

Figure 8-2 provides a comparison plot indicating the level of MVAR impacts that each of these 4 threat scenarios would pose to the U.S. grid. Also shown for each of the 4 threats are 3 variations in grid design, those being the normal or present grid design and the two GIC reduction designs: 5 ohm resistors in all transformers and 5 ohm resistors in only the top 75% of transformers. From this comparison, the two worst threats are the Case 16D and the NY DevD scenarios. All of the threats would be expected to produce regional blackouts of the power grid, but the greatest impacts will occur for the largest two threat scenarios. It is also evident from this comparison that each of the two GIC reduction designs achieves significant reductions in MVAR increases through reducing the levels of GIC flowing in the grid. Both of the GIC reduction designs also indicate very similar efficacies in the ability to reduce MVAR levels, therefore they will cause nearly the same end result in reducing areas of initial blackout and other related impacts.

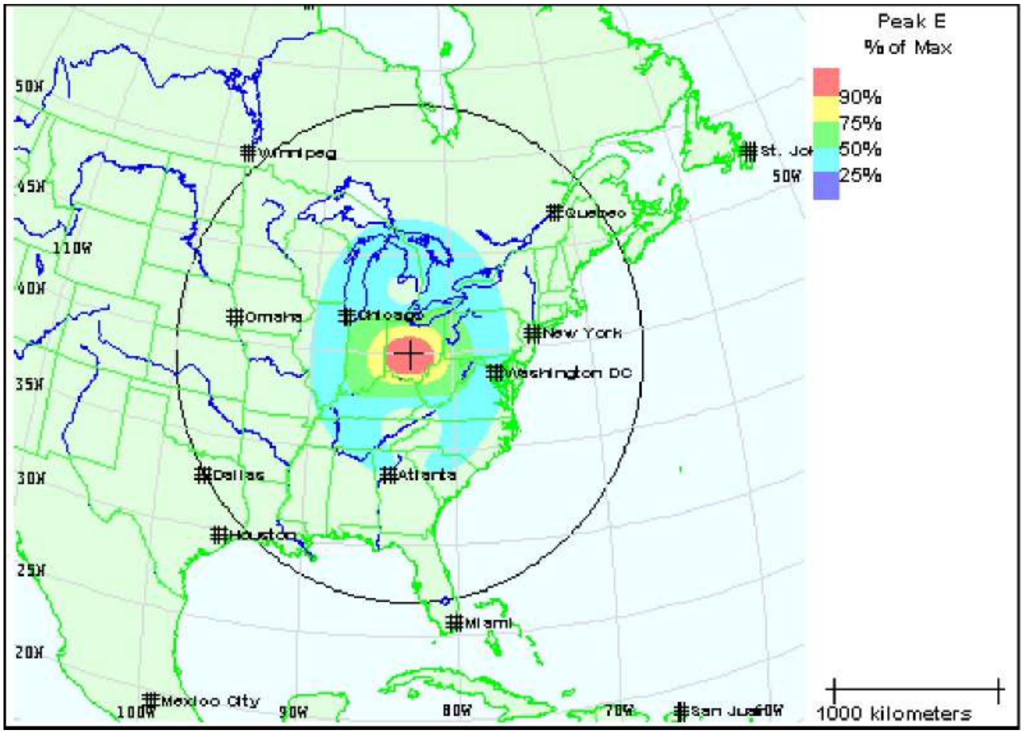

Figure 8-1. Case 16D, E3 Heave field pattern.

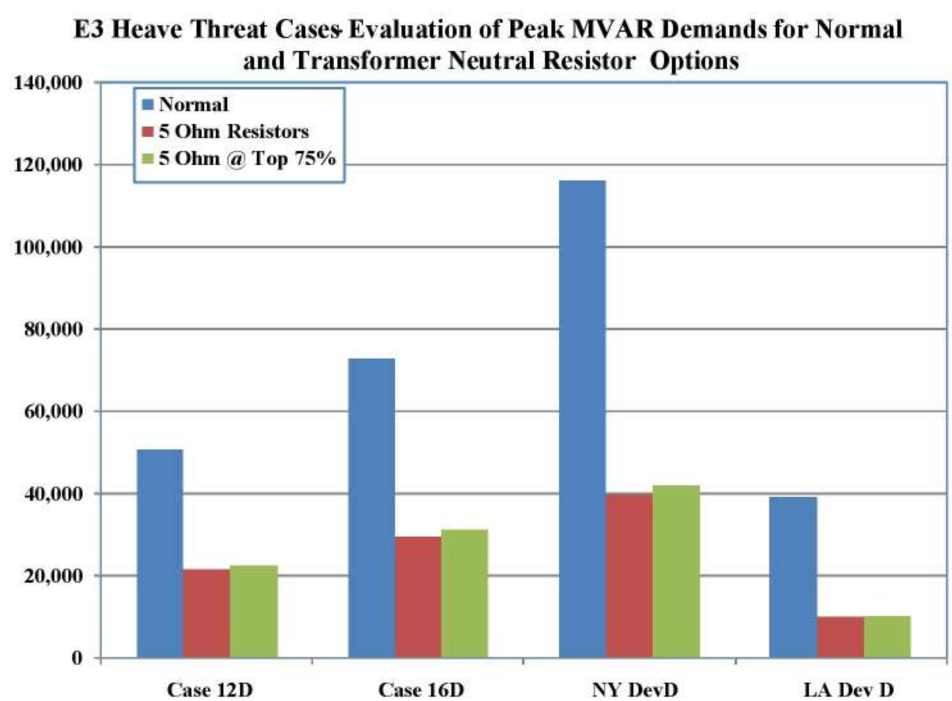

Figure 8-2. Comparison summary of MVAR levels for E3 threat scenarios. Comparison is provided between normal grid design and the two 5 ohm resistor GIC reduction designs.

The two worst E3 threat scenarios will be discussed in more detail. Figure 8-3 provides a map of the peak GIC flows in all transformers for Case 16D and the normal grid design. Shown in shaded areas are the states that have been estimated to experience power grid blackout, for Case 16D for normal power grid design. As shown by this estimate, the blackout has been estimated to extend from Illinois to the Mid-Atlantic east coast and south through Georgia. While the estimated disturbance energy did not reach the blackout threshold for South Carolina, it was only a few percent under the threshold. In addition, all other areas surrounding South Carolina are estimated to have disturbance energies sufficient to cause initial blackout and so it is plausible that South Carolina and perhaps other regional neighboring states will experience initial power grid collapse through uncontrolled cascading effects subsequent to the E3 threat environment. In contrast, Figure 8-4 provides the same GIC and state impact summary for Case 16D, only for the GIC reduction design of 5 ohm resistors in all transformer neutrals. This summary illustrates both significant reductions in GIC level but also in the estimated extent of the initial power grid blackout that is likely to occur. In this case, the number of states estimated to have an initial power grid blackout drops from a total of 11 to only 4. Figure 8-5 provides a similar Case 16D threat summary for the GIC reduction strategy of 5 ohms resistors in only the top 75% of transformers. In this case, both the GIC levels and the impacted regions are very similar to the previous case, with states estimated to have initial blackout dropping from a total 11 states to a total of only 5 states.

Figure 8-6 provides a map of the peak GIC flows in all transformers and shown in shaded areas are the states that have been estimated to experience power grid blackout for the NY DevD threat scenario for normal power grid design. As shown by this estimate, the blackout has been estimated to extend from North Carolina to Ohio and across the Mid-Atlantic east coast and into the southern New England region. While the estimated disturbance energy did not reach the threshold for Connecticut or the upper New England states, these regions were only a few percent under the threshold. In addition, all other areas surrounding them are estimated to have disturbance energies sufficient to cause initial blackout, therefore it is plausible that these states and perhaps other regional neighboring states may experience initial power grid collapse through uncontrolled cascading effects subsequent to the E3 threat environment. In comparing the GIC flows from the NY DevD threat with the Case 16D threat (Figure 8-3), it is apparent that larger GIC flows are occurring in some of the locations under the maximum burst area for the NY DevD threat scenario. This is likely due to a combination of factors, a denser grid network in this region of the U.S. compared to the Ohio Valley area for Case 16D and some influences of higher geo-electric field response due to the profile of the deep-earth conductivity of this region versus the Ohio Valley region.

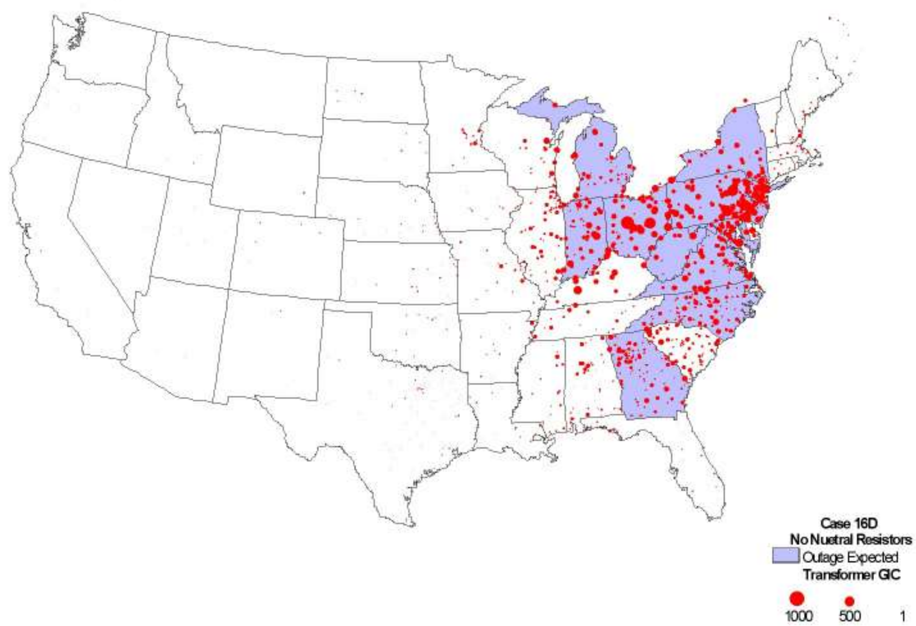

Figure 8-3. Map of GIC levels in transformers and estimated regions of power grid outage for a Case 16D threat with the normal grid design.

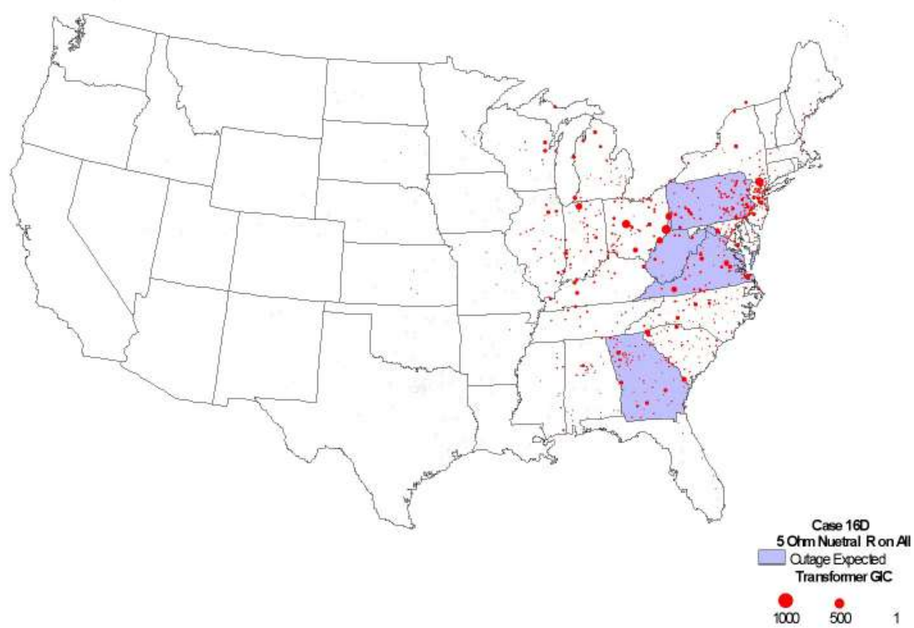

Figure 8-4. Map of GIC level in transformers and the estimated regions of power grid outage for a Case 16D threat with a GIC reduction design consisting of 5 ohm resistors in all transformers

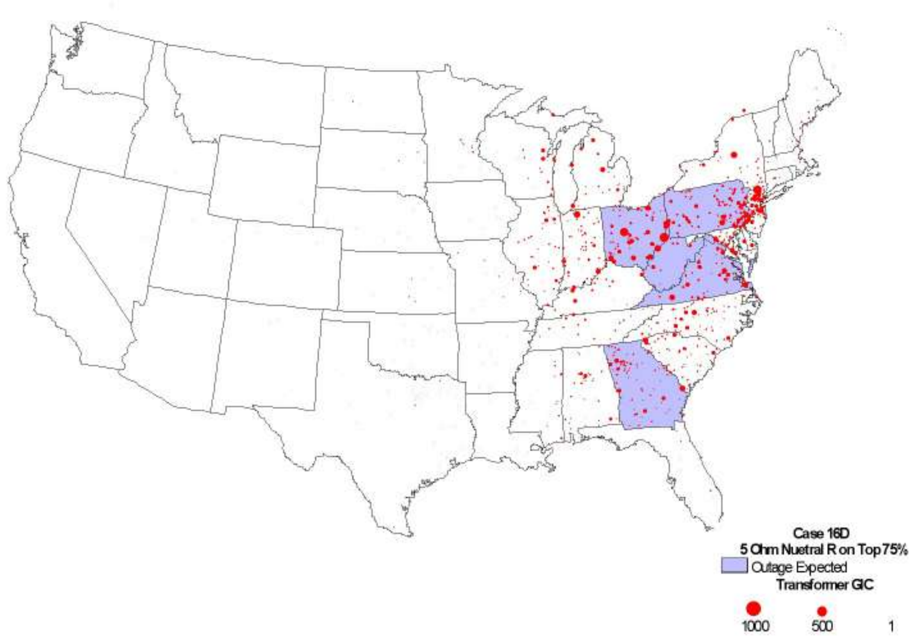

Figure 8-5. Map of GIC level in transformers and the estimated regions of power grid outage for a Case 16D threat with a GIC reduction design consisting of 5 ohm resistors in 75% of transformers.

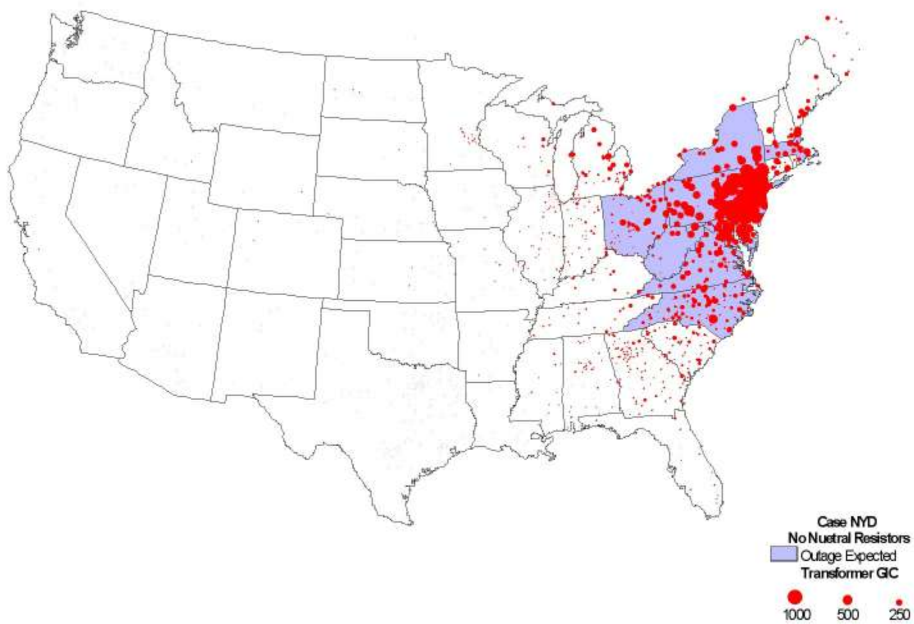

Figure 8-6. Map of GIC levels in transformers and the estimated regions of power grid outage for a NY DevD threat with the normal grid design.

Figure 8-7 provides the same GIC and state impact summary for the NY DevD threat only for the GIC reduction design of 5 ohm resistors in all transformer neutrals. This summary illustrates both significant reductions in GIC levels but also in the estimated extent of the initial power grid blackout that is likely to occur. In this case, the number of states estimated to have an initial power grid blackout drops from a total of 9 to only 6. Figure 8-8 provides a similar NY DevD threat summary for the GIC reduction strategy of 5 ohm resistors in only the top 75% of transformers. Both the GIC levels and the impacted regions are very similar to the prior design option, with states estimated to have initial blackout dropping from a total 9 states to a total of only 6 states.

To provide further perspective on the extent of the large GIC current levels observed for the NY DevD threat scenario, Figure 8-9 provides a comparison plot of the GIC flow in all transformers for the normal grid design as well as for the GIC reduction design of 5 ohm resistors in all transformers. Figure 8-10 provides a similar comparison plot for normal grid design GIC flows and GIC flows for the GIC reduction design of 5 ohm resistors in only the top 75% of transformers. When comparing these GIC flow levels with those for the 4800 nT/min geomagnetic storm threat (Figure 7-16), the NY DevD threat produces levels of GIC at a number of locations that are as much as three times larger. These GIC flow levels also provide the basic information needed to make estimates of the possible permanent loss of exposed EHV transformers for the impacted regions for the NY DevD threat as well as all the other E3 threat environments that were simulated. This determination of at-risk transformers provides the best means to estimate the difficulties in restoration of the power grid after the initial blackout. A greater number of at-risk transformers identified for each scenario will indicate a higher degree of potential permanent damage to the network and indicate a higher degree of impaired power grid infrastructure. As previously noted, the degree of impairment to the transmission network infrastructure raises concerns about a longer and more problematic recovery of the network.

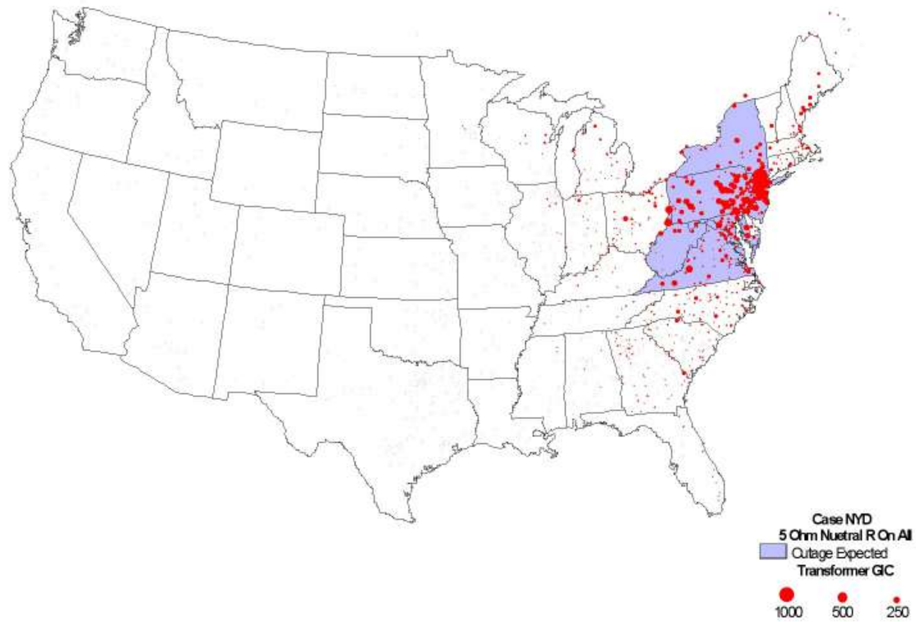

Figure 8-7. Map of GIC level in transformers and the estimated regions of power grid outage for a NY DevD threat with a GIC reduction design consisting of 5 ohm resistors in all transformers.

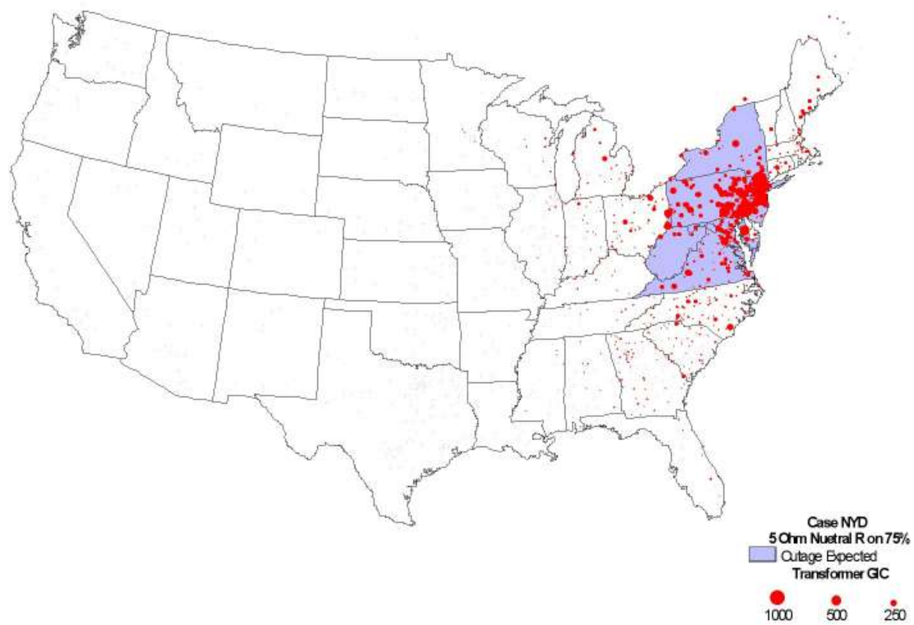

Figure 8-8. Map of GIC level in transformers and the estimated regions of power grid outage for a NY DevD threat with a GIC reduction design consisting of 5 ohm resistors in 75% of all transformers.

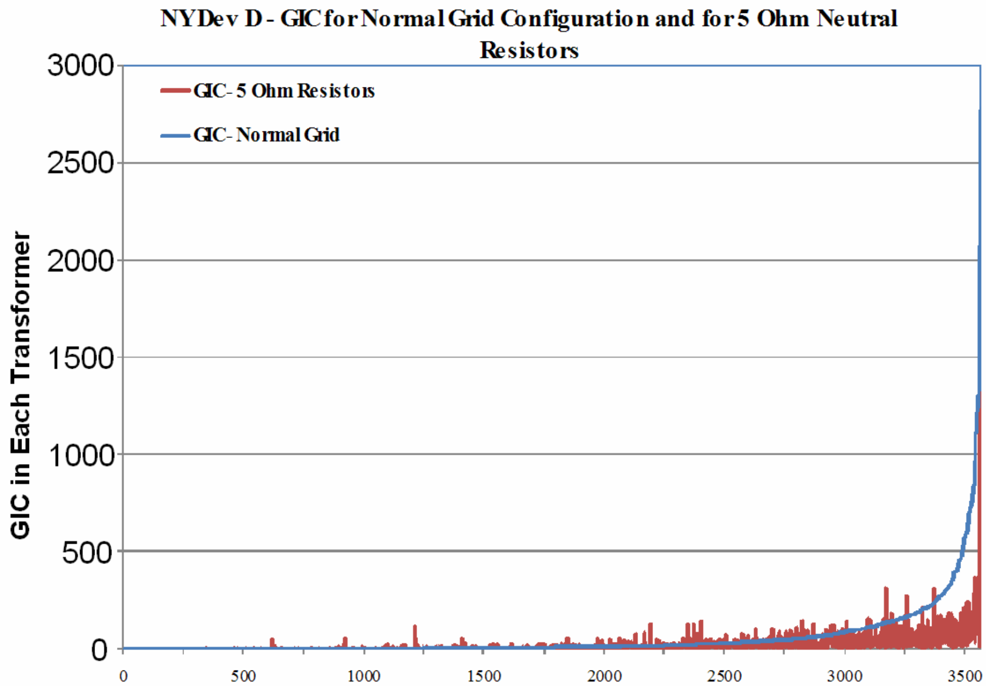

Figure 8-9. Comparison of GIC flow in each transformer for normal grid design compared to case with 5 ohm neutral resistors in all transformers for the NY DevD threat environment.

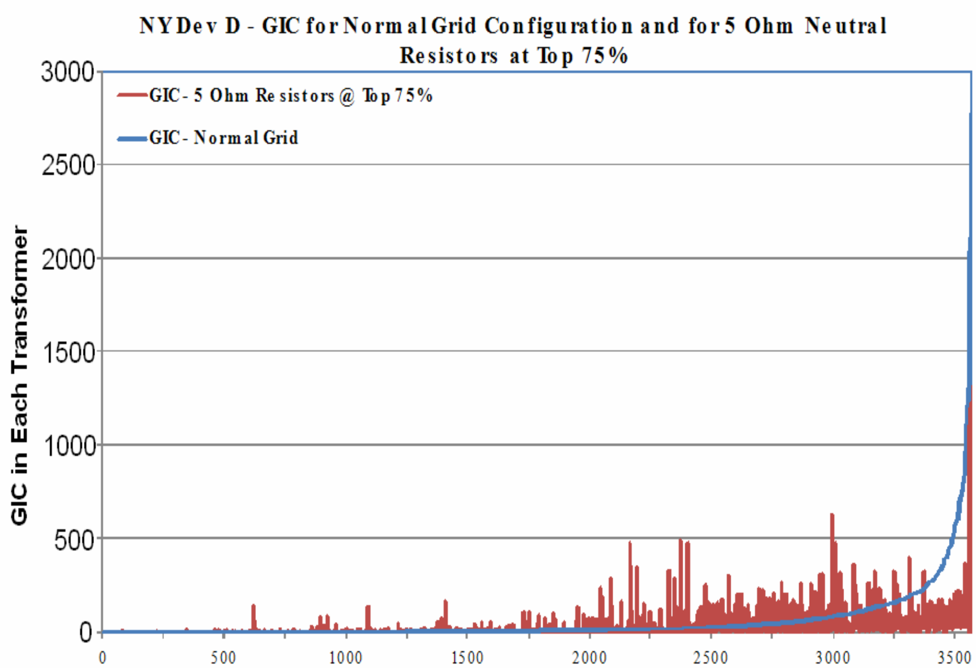

Figure 8-10. Comparison of GIC flow in each transformer for normal grid design compared to case with 5 ohm neutral resistors in only the top 75% of all transformers for the NY DevD threat environment.

Figure 8-11 provides a summary on the number of transformers that would be considered at-risk due to high levels of GIC for all four E3 threat scenarios. This summary provides the at-risk transformer count for the normal or present grid design as well as for the two GIC reduction strategies using 5 ohm neutral resistors. As shown in all cases the number of at-risk transformers decreases significantly compared to normal grid configuration for the two 5 ohm GIC reduction strategies. The top two threat scenarios of Cases 16D and NY DevD produce the largest number of at-risk transformers. Cases 16D and NY DevD respectively have over 300 and 500 transformers at-risk for the normal grid design. While for Case 16D, the two GIC reduction strategies reduce the number of at-risk transformers below 50 total units, for the NY DevD scenario the number of at-risk units is still over 200 for both of the GIC reduction strategies. To examine the potential implications of the large number of at-risk transformers for the NY DevD threat on a more regional basis, Figure 8-12 provides a map of the percentage of at-risk EHV transformer capacity (345kV and higher) for each state for the normal grid design. A higher percentage of at-risk transformers indicates a greater degree of impairment in the grid, and the more difficulty in restoring normal electric service to all end-users. Some of the most heavily impacted states are Maryland, with 100% of EHV transformers considered to be at-risk, and Pennsylvania and New York, with at-risk levels of 70% and 67%.

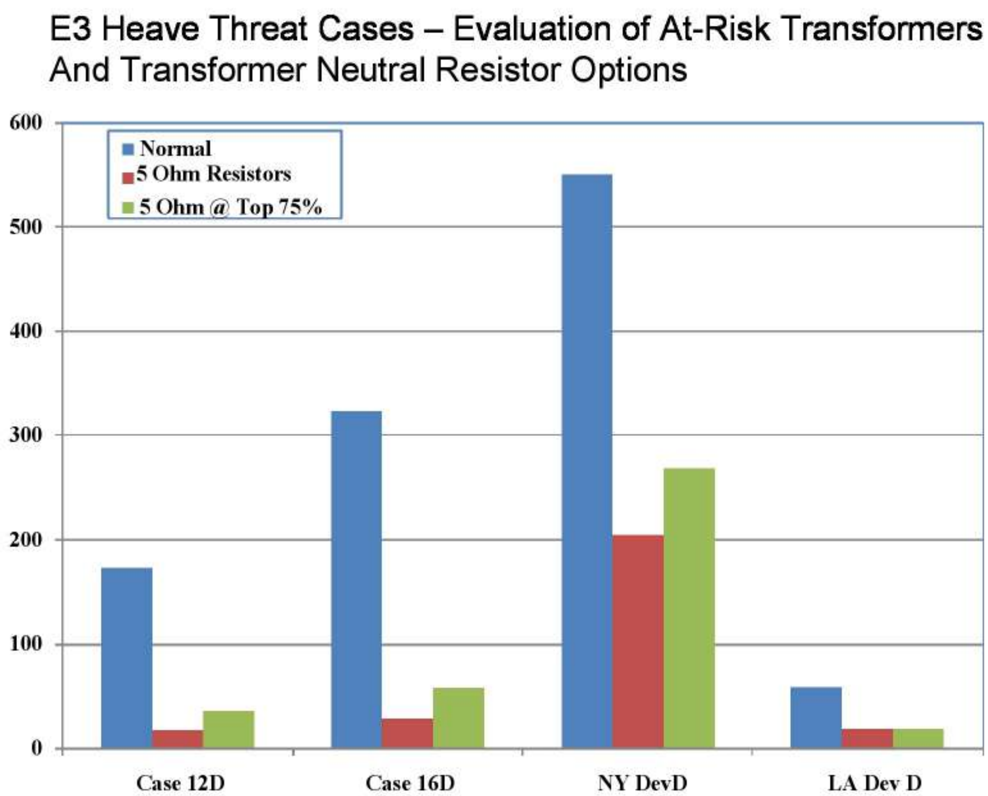

Figure 8-11. Comparison of at-risk transformers for normal grid design and the two 5 ohm GIC reduction strategies for the four E3 disturbance threat environments.

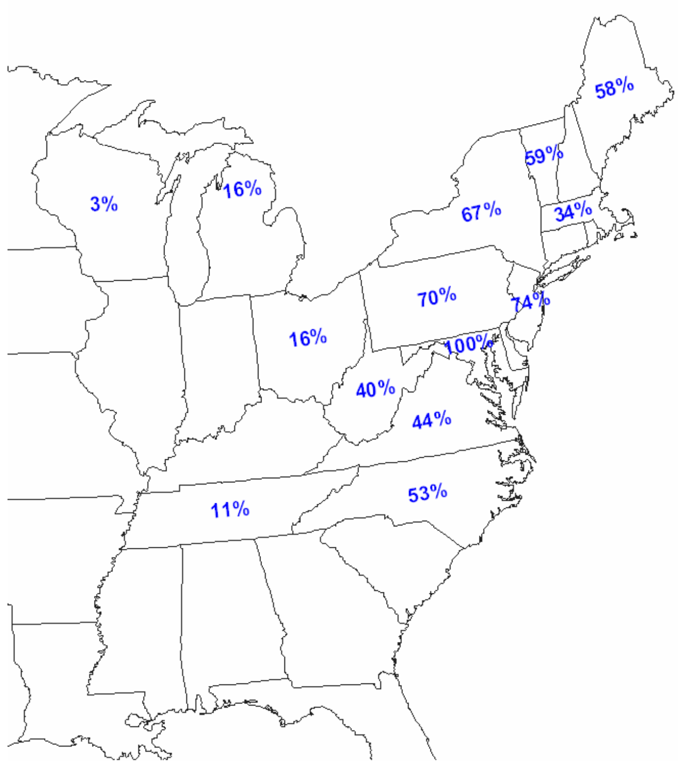

Figure 8-12. Case NY DevD – map showing the at-risk EHV transformer capacity by state (345kV and above) for normal grid design.

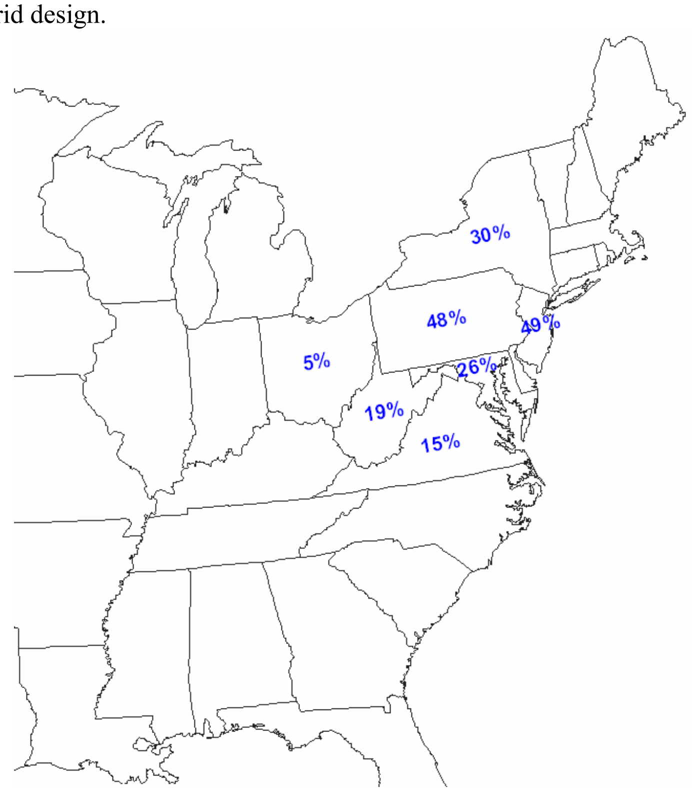

Figure 8-13. Case NY DevD – map showing the at-risk EHV transformer capacity by state (345kV and above) for 5 ohm resistor in all transformers.

Figure 8-13 provides a similar regional map of the percentage at-risk EHV transformer capacity for the NY DevD threat, only with the GIC reduction strategy of adding 5 ohm resistors in all transformer neutrals. While the percentage at-risk levels are lower in all states, some very high absolute levels of capacity at-risk still remains in Pennsylvania and New Jersey, with 48% and 49% still considered at-risk. Figure 8-14 provides a comparison plot showing the GIC levels in the at-risk transformers for the NY DevD threat for both normal grid design and for the GIC reduction design of 5 ohm neutral resistors. This graphic illustrates that while a large number of at-risk transformers remain for the 5 ohm design, the overall levels of GIC are reduced substantially from the normal grid design case. For the normal grid design case, the 551 at-risk transformers had an average GIC of 293 amps/phase. In comparison, for the 5 ohm design case, 205 at-risk transformers had an average GIC of only 151 amps/phase. While the scope of this investigation is limited, it is plausible that other operational measures combined with the 5 ohm resistors could produce further reductions in the at-risk transformers. Also additional iterations of blocking device application can be considered in the more focused engineering phases of the blocking device implementations, which are beyond the scope of this analysis effort. For example a small number of neutral blocking capacitors deployed with blocking resistors at all other locations may be able to further reduce the at-risk transformer assets.

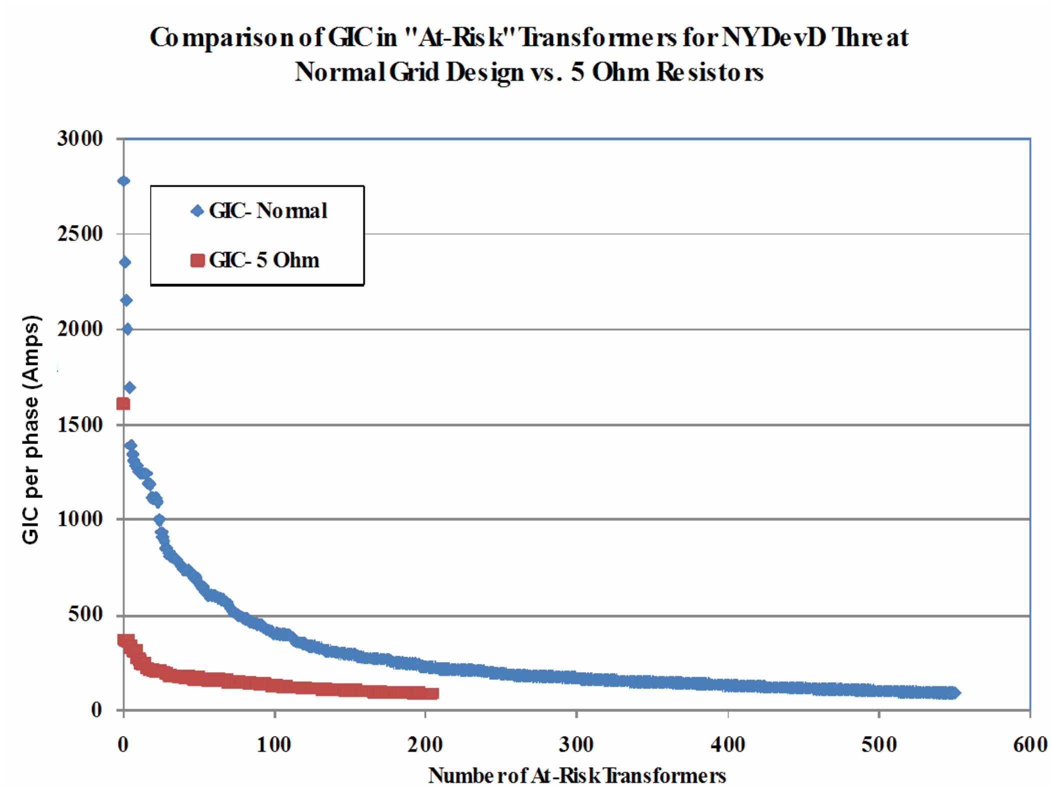

Figure 8-14. Comparison plot of GIC levels in at-risk transformers for NY DevD threat for normal grid design and for 5 ohm resistor in all transformers.

Figures 8-15 and 8-16 show comparable maps of the percentage of at-risk EHV transformer capacity, by state, for the Case 16D E3 threat environment. As previously mentioned, the state-specific impacts of Case 16D are smaller than for Case NY DevD and the primary concern is that Case 16D does have a slightly larger U.S. footprint compared to the NY DevD threat scenario. In Figure 8-15, the Case 16D threat has been examined for the normal grid design and as shown some of the most heavily impacted states with high at-risk levels are New Jersey with 74%, South Carolina with 69% and Pennsylvania with 50%. In Figure 8-16 these at-risk levels are all dramatically reduced with the addition of the 5 ohm resistors. The peak at-risk level is now South Carolina with only 22%, while New Jersey has dropped to only 14% and Pennsylvania no longer has any EHV transformers considered at-risk.

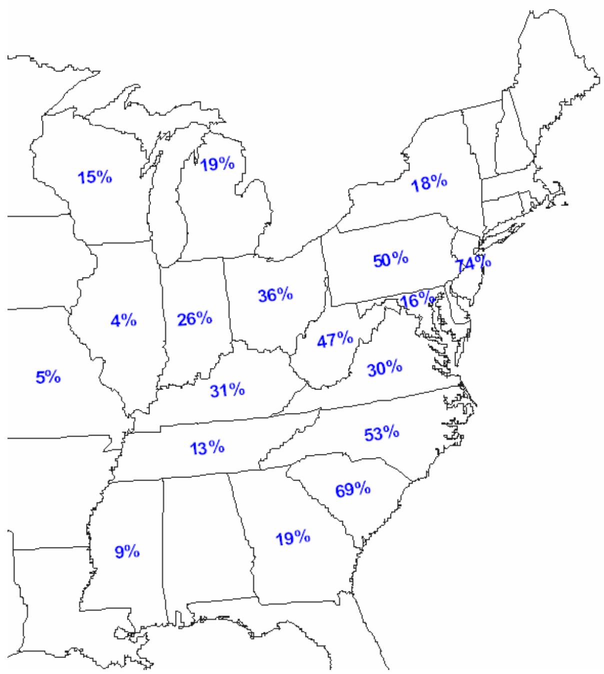

Figure 8-15. Case 16D – map showing the at-risk EHV transformer capacity by state (345kV and above) for normal grid design.

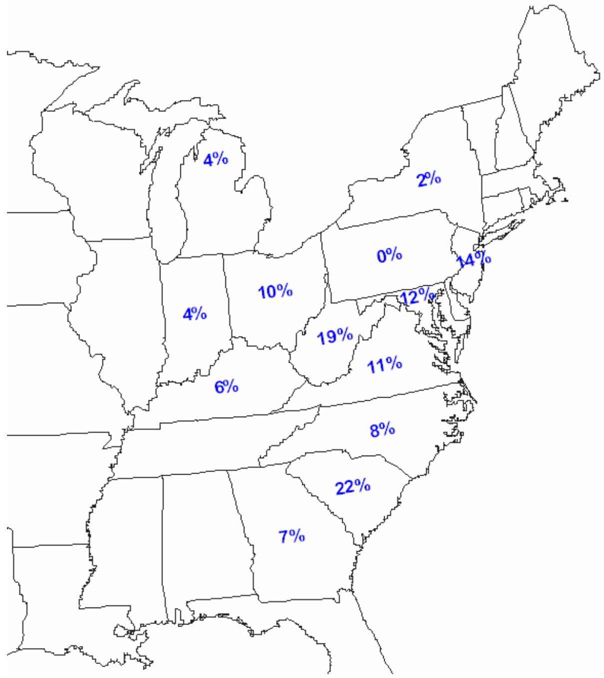

Figure 8-16. Case 16D – map showing the at-risk EHV transformer capacity by state (345kV and above) for 5 ohm resistor design.

Section 9
Engineering Concerns and AC System Performance Trade-Offs Due to Transformer Neutral Resistors

The U.S. EHV and HV Transmission Networks (i.e. 115kV and higher) have traditionally been grounded three phase systems. These transmission networks have numerous transformers configured as grounded-wye transformers (for example, as shown in Figure 1-1). In addition, the transformation steps from one transmission voltage level to another (for instance 230kV to 500kV) are generally performed using autotransformers (for example as shown in Figure 2-4), which is the most economic design for these applications. The utilization of neutral resistors for the purpose of reducing GIC flows will alter the design configuration and, as a result, engineering trade-offs should be expected. Preliminary analysis of these tradeoffs has been conducted.

Using transformers for grounding purposes on the power grid provides a number of benefits to improve AC operation and design economics of the HV and EHV transmission networks. Two primary benefits of effective grounding of the transmission network are: 1) The ability to control overvoltages and surge protection requirements, and 2) Improving the sensitivity, operating time, and selectivity of ground fault relaying.

Grounding resistors or reactors have been utilized on power grids, with the most common application being within the grounding systems of large rotating machinery such as generators and motor with loads applied at lower voltages (22kV or lower). The IEEE has provided guidelines such as the "Guide for the Application of Neutral Grounding in Electrical Utility Systems" under IEEE Standards C62.92.1-5-2000. These guidelines address applications for transmission networks (HV/EHV) as well as distribution and generation systems. In regards to the HV and EHV transmission networks, the general practice has been solid or effective grounding of the transmission networks for the above stated reasons and benefits. However, it is this practice which introduces the unintended vulnerability of these networks to GIC from E3 threat environments and from naturally occurring geomagnetic storm events.

There have been exceptions to this practice on a very limited scale. The Finnish grid utilizes impedance grounding (~150 ohms reactive) on ~50% of all transformer locations; this is needed due to the inability to achieve reasonably low resistance grounding in difficult soil/surface rock conditions. In another case, the Quebec grid has applied capacitive grounding in the neutral of several large transformers in the James Bay region for the purpose of blocking GIC flows into a select few transformers. However, the Quebec EHV transmission system as a whole is effectively grounded and GIC is blocked at only a few of the plausible GIC entry points into the network.

Because of the overriding desire to maintain effective grounding of the transmission network for control of overvoltages and improved relaying, low ohmic resistors were the only options explored in depth in this analysis. As previously discussed, these resistor sizes ranged from 2.5 to 7.5 ohms. In addition to helping maintain reasonable levels of effective grounding, these resistors can also be manufactured from materials such as cast iron, which provides durable and inexpensive design. A number of suppliers of these devices already exist in the world market, and the entry thresholds are relatively low for new suppliers to enter this market. In the application anticipated in this analysis, it is expected that installed costs for each transformer 5 ohm neutral resistor can likely be accomplished for a total cost in the range of ~$20,000 to $40,000 per unit. This cost estimate is based upon only limited auxiliaries for the passive device (no control, status communication, or power supply to the device and no elaborate switching or bypass devices). Added costs to undertake modification of legacy network relay and protection systems for the HV and EHV network are also not assumed or included in the per-unit costs. As will be described in following discussion in this section, these assumptions appear at this time to be reasonable and prudent, but further detailed analysis of these concerns should be undertaken as implementation efforts progress to more formal engineering design, testing and validation stages.

Most HV and EHV transformers provide a nominal amount of insulation and overvoltage withstand in the transformer neutral-to-ground connection of grounded-wye transformers. The general level of insulation withstand is usually classed as a 150kV BIL, which allows continuous voltage operation up to approximately 15kV. A resistor placed in the transformer neutral-to-ground connection will cause a DC voltage rise at the transformer neutral as DC currents flow through this connection to ground. As the level of DC current increases, so does the DC voltage rise at this connection point. The transformer neutral current levels were analyzed for the three worst case threat scenarios examined in Sections 7 and 8, those being the NY DevD and Case 16d E3 threats as well as the 4800 nT/min geomagnetic storm threat. Figures 9-1, 9-2 and 9-3 provide respectively the neutral current levels for the normal grid design and for the design option of 5 ohm resistors for the three threat scenarios of NY DevD, Case 16d and for the 4800 nT/min geomagnetic storm. As shown in these figures, while normal design can allow very large transformer neutral GIC to flow (for instance over 8000 amps for NY DevD), the maximum levels of GIC are generally limited to ~1000 amps in the worst case for each of the 5 ohm design strategies. These ~1000 amp GIC neutral current maximum levels, when applied against the 5 ohm neutral resistors, indicate that the maximum DC voltage rise at the transformer neutral point would generally be no larger than ~5000 VDC. This will combine with AC currents that will also be flowing in the neutral-to-ground connection to produce an overall combined AC-DC voltage rise at the neutral connection. However, with only a 5 kV DC rise, this allows considerable margin for large AC currents of as much as ~2000 amps-peak as well before threatening the voltage withstand of the transformer neutral insulation levels.

It is also possible to consider the addition of surge arrester augmentation with the neutral resistors as an additional safeguard against undesired voltage excursions at the transformer neutral. Metal oxide arresters rated for 150kV BIL insulation coordination protection could be readily added in shunt to the resistors as a bypass of the resistor under high voltage conditions. These would require some further study to make certain that they would not inadvertently compromise the GIC reduction purposes of the neutral resistor. Mechanical or power electronic bypass and insertion devices could also be considered which would allow even further adaptability to ensure AC performance while also enhancing GIC reduction options. Cost considerations and reliability issues would be greater for these more complex approaches when compared to the very simple passive resistor options that have been the focus of this analysis.

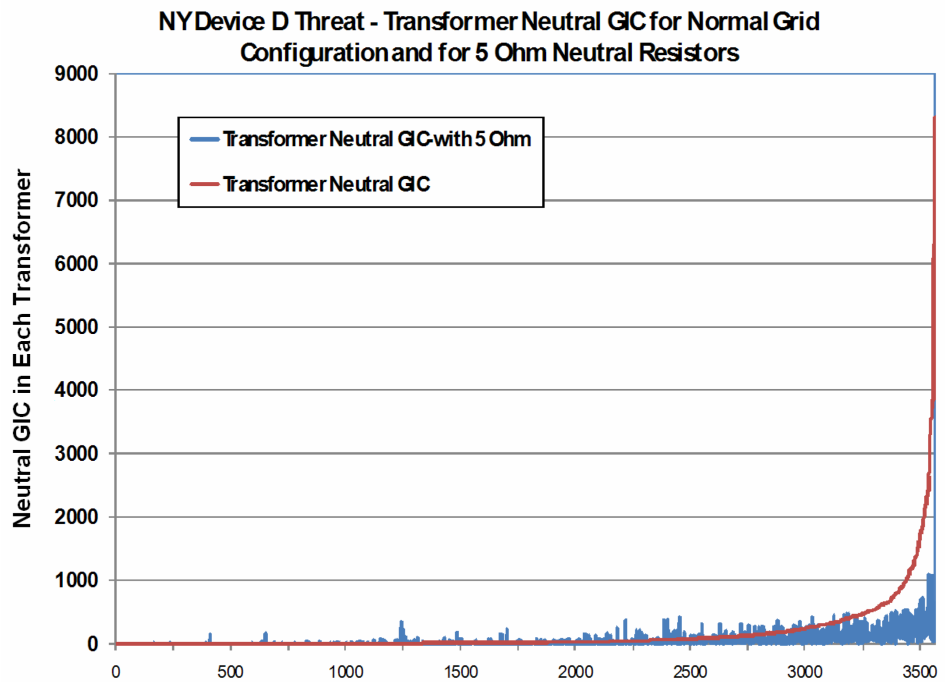

Figure 9-1. Transformer neutral-to-ground GIC currents for Case NY DevD – currents for normal grid design compared to 5 ohm resistor design.

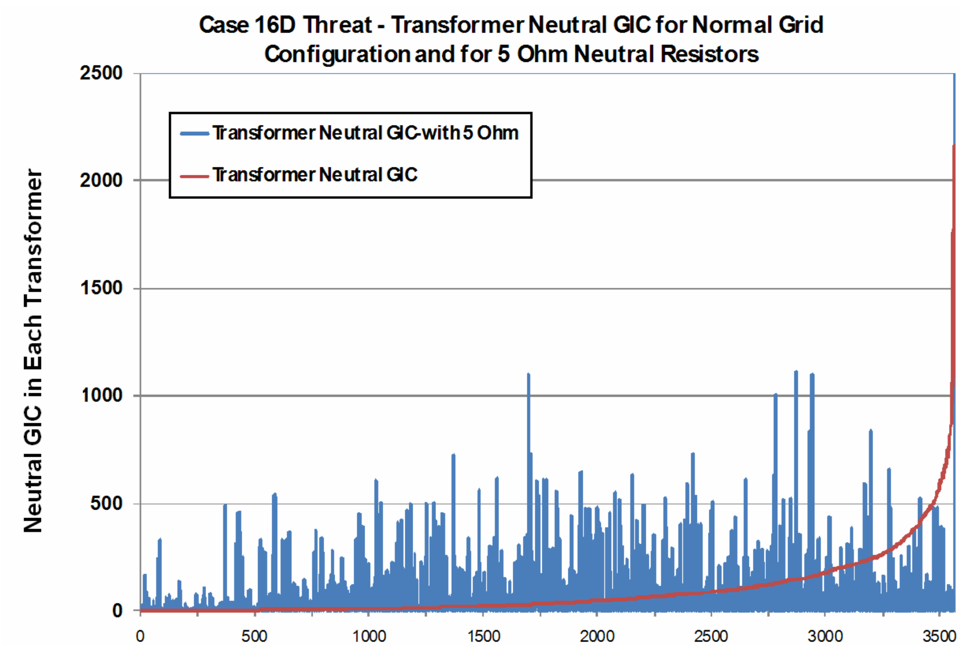

Figure 9-2. Transformer neutral-to-ground GIC currents for Case 16D – currents for normal grid design compared to 5 ohm resistor design.

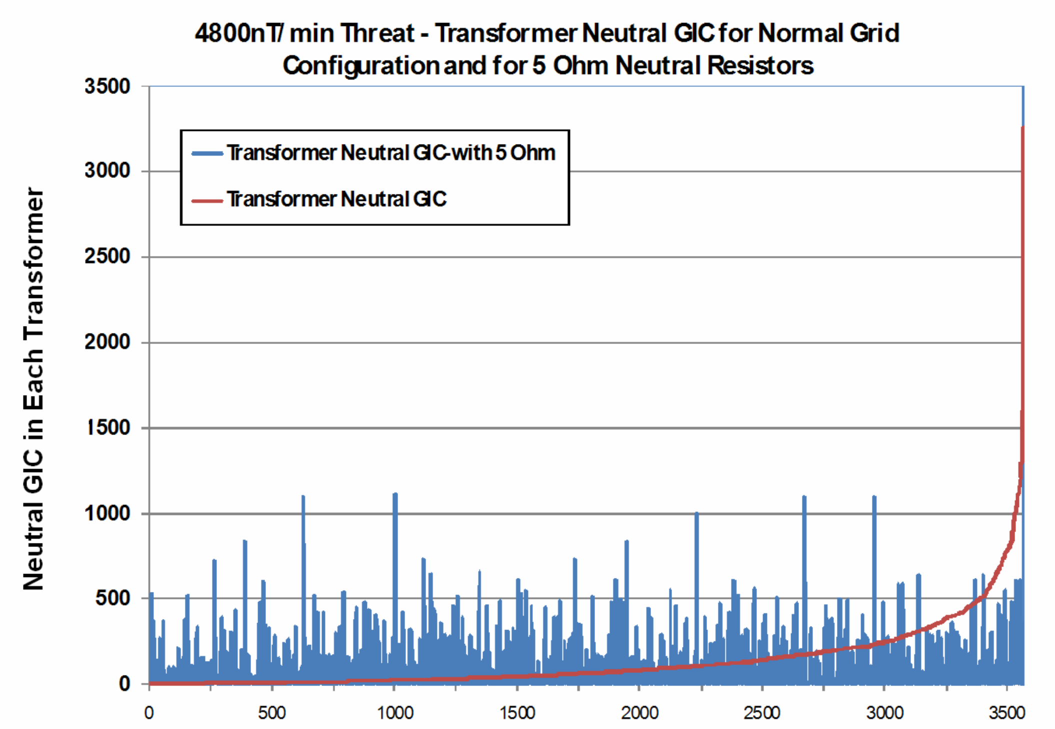

Figure 9-3. Transformer neutral-to-ground GIC currents for 4800 nT/min – currents for normal grid design compared to 5 ohm resistor design.

While Figures 9-1 through 9-3 provide reassurance about voltage rise above safe transformer BIL levels, IEEE Standard C62.92.1-2000 Table 1 provides interpretative guidelines on characteristics of grounding to determine the potential for impacts to other AC performance concerns such as sensitivity to ground faults and phase overvoltages and surge protection. A copy of Table 1 from this standard is shown in Figure 9-4 and this provides several helpful ratio tests that can be used to determine the grounding effectiveness or coefficient of grounding for the system. Class A of Table 1 (text in Red) provides the symmetrical component ratio guidelines for effectively grounded systems, which is the class that is desired for HV and EHV transmission networks.

For purposes of this analysis, only a 5 ohm neutral resistor will be considered. This is because this size resistor performs better than a 2.5 ohm resistor in reducing GIC flows and that it would have less impact on effective grounding and AC performance when compared to the 7.5 ohm resistor option. To understand the impact that a 5 ohm neutral resistor would have upon overall positive and negative sequence X and R levels in the interconnected network, perspective should be provided on normal levels of circuit impedance that will occur due to existing transformers and transmission lines in the network. Figures 9-5 and 9-6 provide plots respectively of the reactive impedance (X in ohms) for 500/230kV autotransformers versus MVA size (Figure 9-5) and for 500kV GSU (generator step-up) transformer impedance versus MVA size (Figure 9-6). As these two comparison plots indicate the impedance in transformers is substantial on the network and even the largest of transformers will generally have impedance levels sufficiently larger than the proposed 5 ohm neutral resistors. Therefore these already

Grounding classes and means	Ratios of symmetrical component			Percent fault current Note (2)	Per unit transient LG voltage Note (3)	Reference
	X_0 / X_1	R_0 / X_1	R_0 / X_0			
A. Effectively—Note (4)						
1. Effective	0—3	0—1	—	> 60	≤ 2	[B3]
2. Very Effective	0—1	0—0.1	—	> 95	< 1.5	
B. Noneffectively						
1. Inductance						
Low inductance	3—10	0—1	—	> 25	< 2.3	[B3]
High inductance	> 10		< 2	< 25	≤ 2.73	[B3]
2. Resistance						
Low resistance	0—10		≥ 2	< 25	< 2.5	
High resistance—Note (8)		>100	≤ (-1)	< 1	≤ 2.73	[B7],[B17]
3. Inductance and resistance	> 10	—	> 2	< 10	≤ 2.73	
4. Resonant—Note (5)		—	—	< 1	≤ 2.73	
5. Ungrounded capacitance						
Range A—Note (6)	—∞ to —40	—	—	< 8	≤ 3	[B6],[B20]
Range B—Note (7)	—40 to 0	—	—	> 8	> 3	[B6],[B20]

Figure 9-4. Table 1 from IEEE Standard C62.92.1-2000, ratio tests to examine grounding effectiveness.

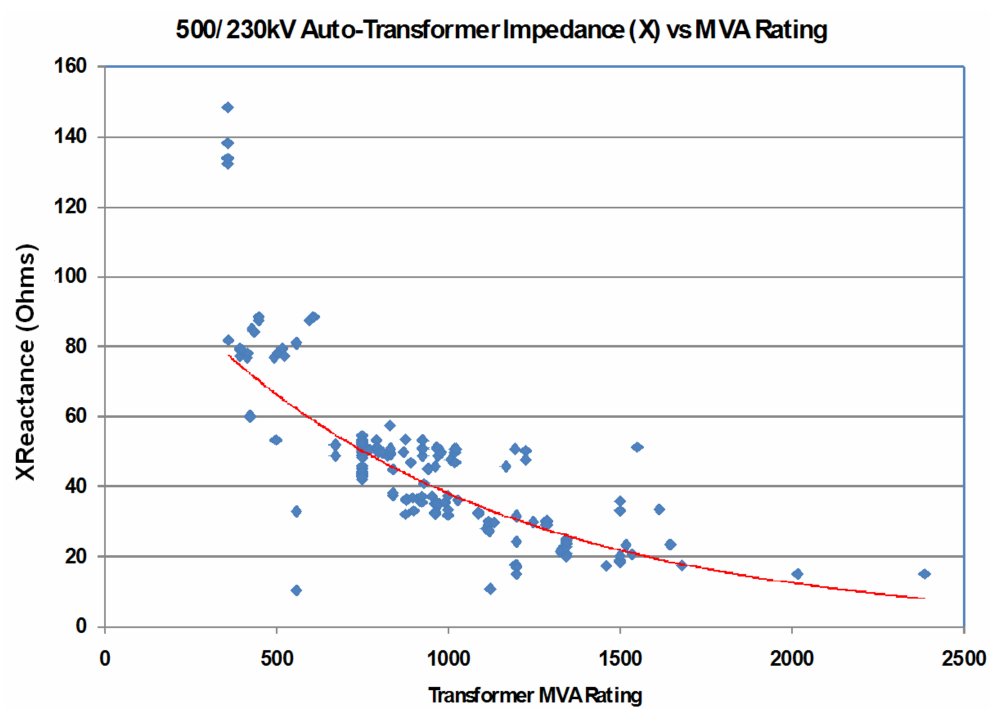

Figure 9-5. 500/230kV autotransformer reactive impedance vs. MVA rating. Fit curve added in red.

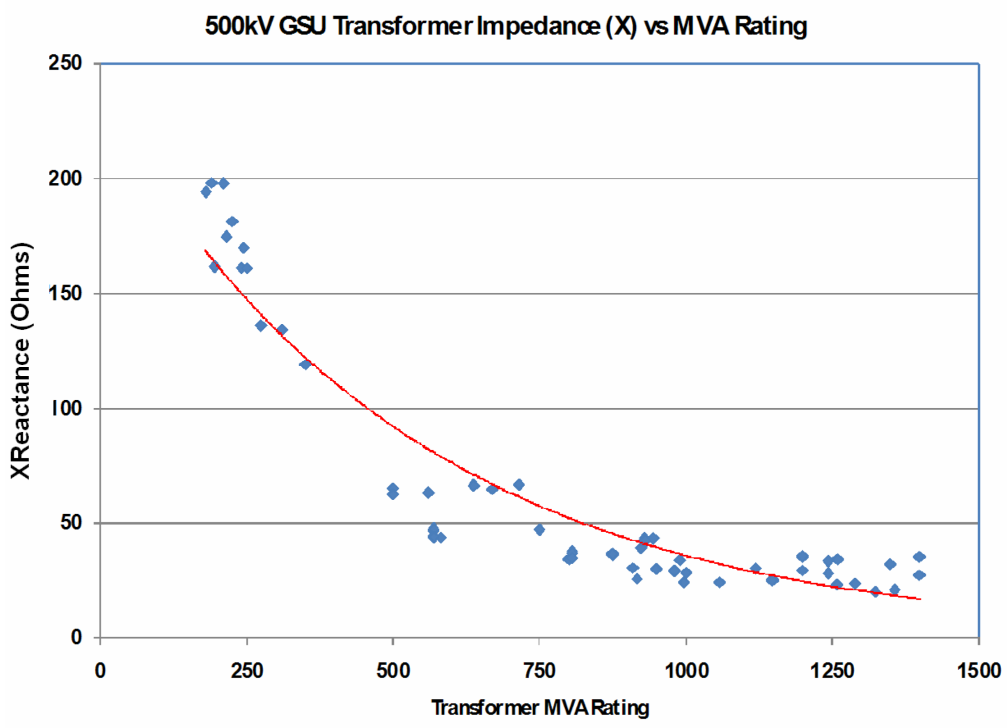

Figure 9-6. 500kV GSU transformer reactive impedance vs. MVA rating. Fit curve added in red.

existing impedances will continue to exert the most influence over fault current levels. Figure 9-7 provides a plot of 500kV transmission line reactance (X in ohms) versus length of the line. Here again even for relatively short lines, the line impedance is generally larger than the neutral resistance that is being introduced to the network. Figures 9-8 and 9-9 show the relationship between transmission line resistance (in ohms) and line length for respectively 500kV and 345kV transmission lines. For longer lines, even values of R (resistance) for these assets can be a significant factor in overall circuit impedance. The overall circuit impedance is relevant from the perspective of maintaining similar levels of AC fault conditions so that only minor changes need to be considered in relay settings to accommodate the addition of neutral resistors in the transmission network transformers. These comparison plots generally indicate that transformer and transmission line reactive impedance (X) is the largest impedance factor in the network and that as long as only low-ohmic neutral resistors are considered, impacts on AC fault current levels, and therefore impacts on relay selectivity and performance, will be minimal.

Using the network R and X values for 500kV transformers only, an examination can be undertaken to examine the coefficients of grounding for the network with the addition of 5 ohm neutral resistors. The first coefficient ratio that will be examined is the estimated zero to positive sequence reactances (X_0/X_1) as noted in the IEEE guideline Table 1 (Figure 9-4). Because the IEEE guideline indicates that a low-ohmic resistor will have a ~20% parasitic reactance as well, this level of neutral-to-ground impedance (X) has been

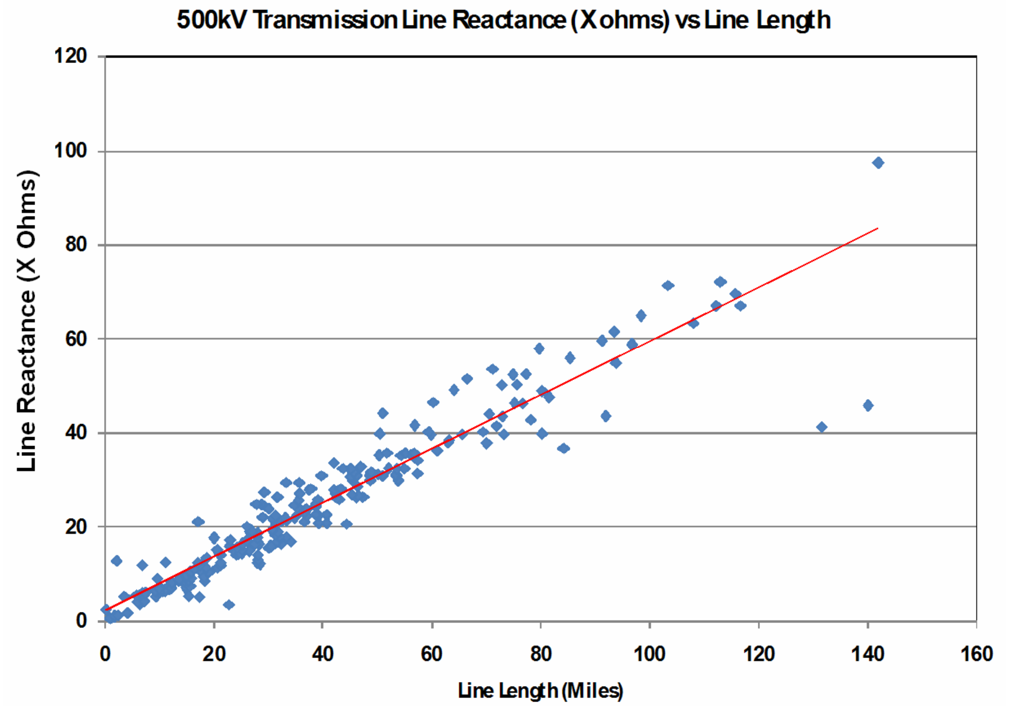

Figure 9-7. 500kV transmission line reactive impedance vs. line length. Fit curve added in red.

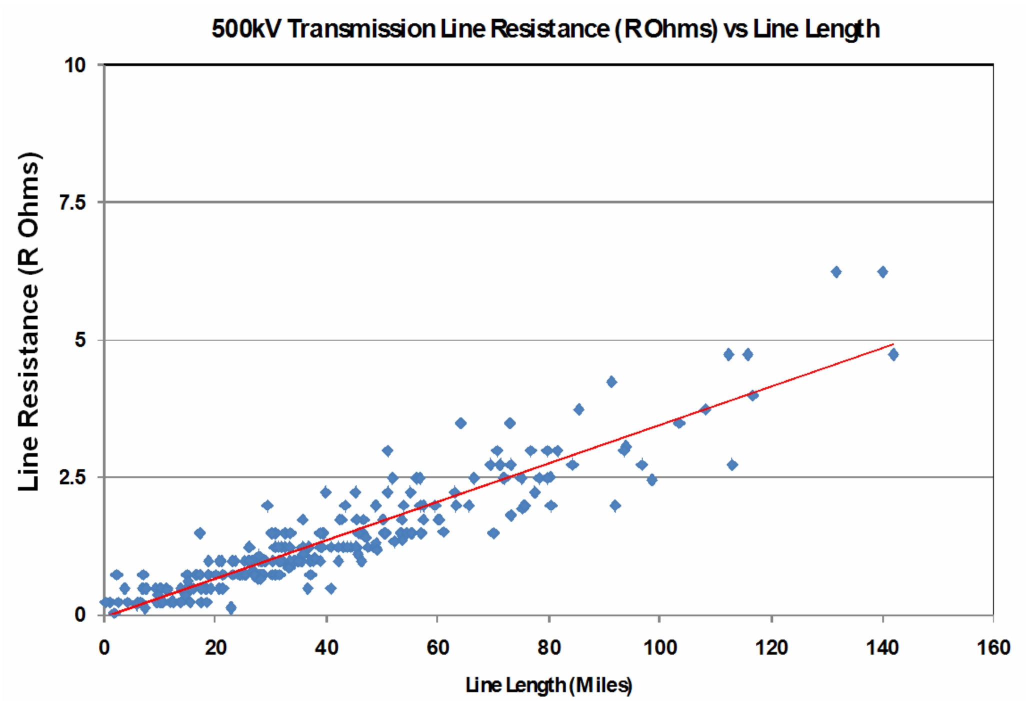

Figure 9-8. 500kV transmission line resistance vs. line length. Fit curve added in red.

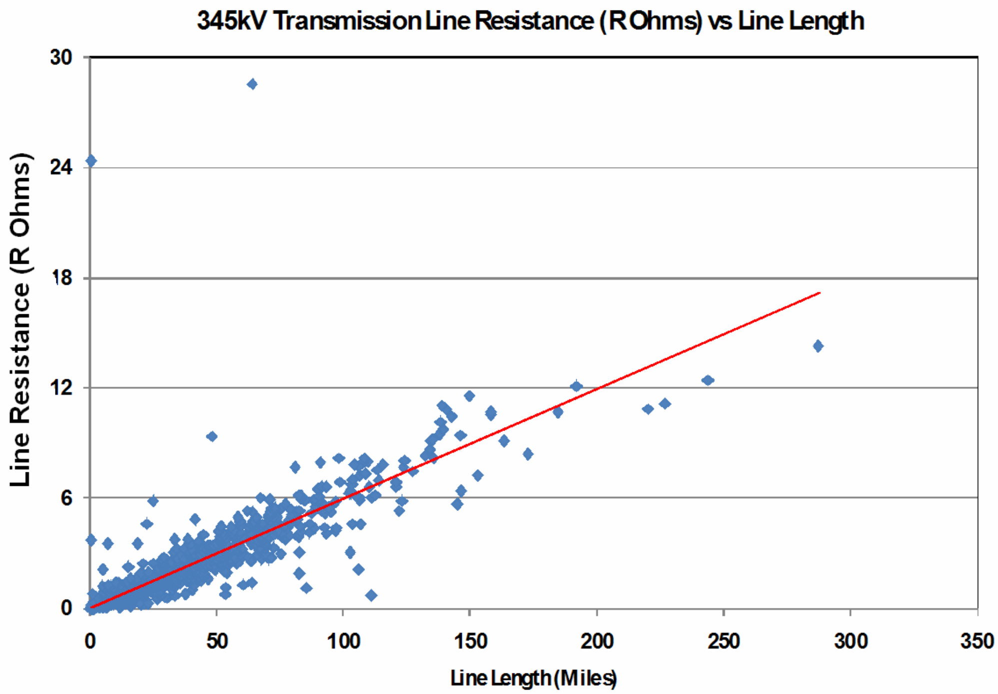

Figure 9-9. 345kV transmission line reactive impedance vs. line length. Fit curve added in red.

added for the 5 ohm resistors in the calculation of the zero sequence impedances (X_0). Figure 9-10 provides the calculation of X_0/X_1 ratio versus the MVA rating of the 500/230kV autotransformers. From the Table 1 Class A grounding guidelines, a ratio from 0-1 is considered very effective grounding while a ratio of 0-3 is considered to be effectively grounded. The results of this analysis indicate that only minor change from nominal ratio of 1 occurs due to the addition of the neutral resistor for this ratio. Because only the autotransformer impedances are considered and no added line or network impedances are included, this calculation likely overstates the degree of impact on the grounding ratio. This grounding coefficient ratio would be even more favorable using the higher impedance GSU transformers, or including transmission line impedances as well in the calculation.

The R_0/X_1 ratio (zero sequence resistance to positive impedance ratio) is another ratio highlighted in Table 1 of the IEEE guideline for evaluating the grounding effectiveness. For effective grounding, this ratio should generally fall between 0 and 1. Figure 9-11 provides the R_0/X_1 ratio for 500/230kV autotransformers for both normal grid design and for the GIC reduction design with 5 ohm neutral resistance in each transformer. As this figure shows, in only a few exceptions does the ratio exceed 1 when the 5 ohm neutral resistor design is evaluated. Again, these ratios would be more favorable if additional network impedances were included. The same ratio calculation is provided in Figure 9-12 for 500kV GSU transformers. Because these transformers have generally higher impedance values, the ratio levels in most cases are even lower than for autotransformers. As the Table 1 guideline indicates, this should act to maintain adequate fault current levels as well as limit the level of transient overvoltages on the network.

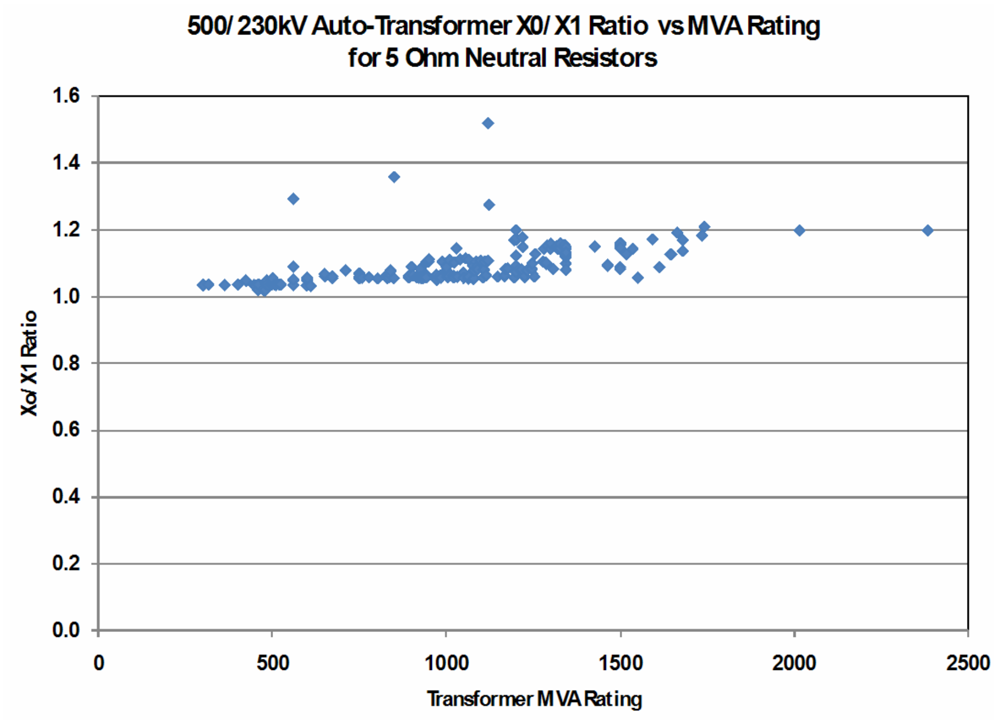

Figure 9-10. X_0/X_1 ratio for 500/230kV autotransformers.

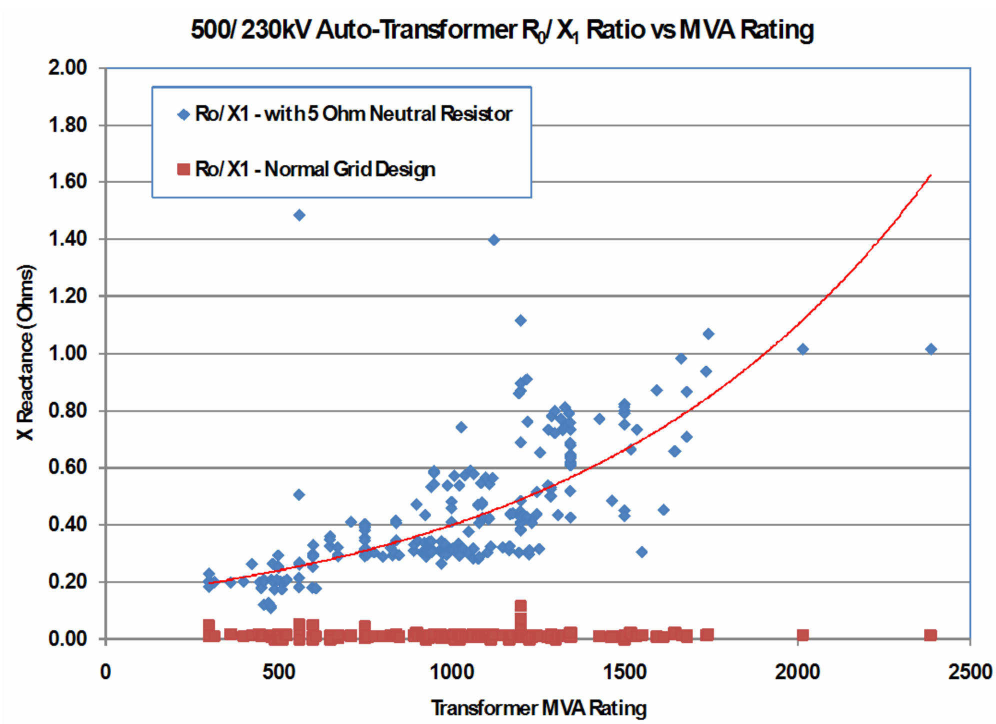

Figure 9-11. R_0/X_1 ratio for 500/230kV autotransformers. Fit curve added in red.

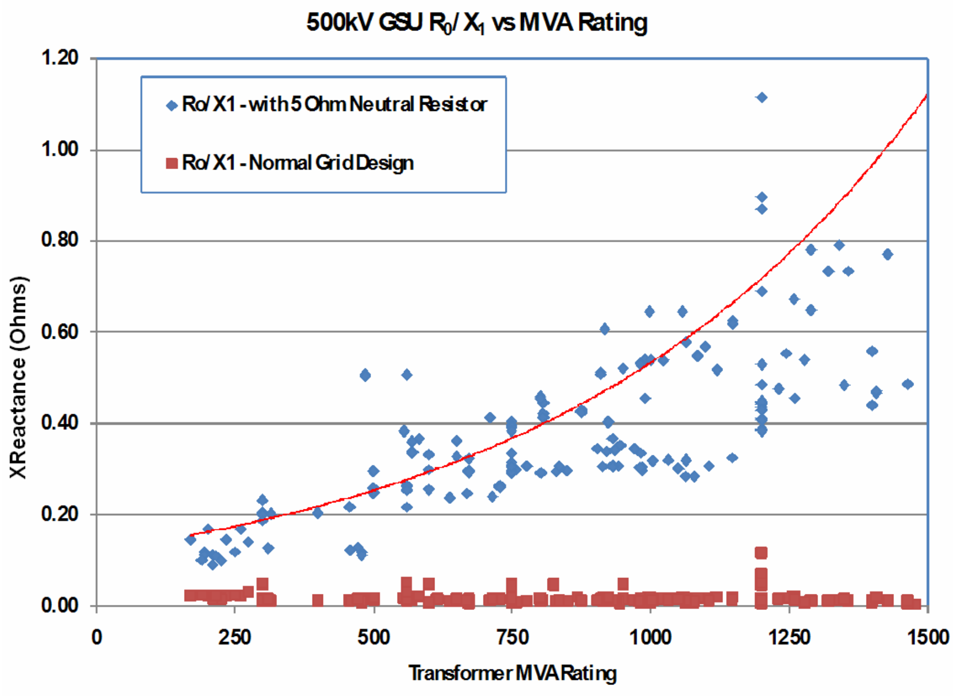

Figure 9-12. R_0/X_1 ratio for 500 kV GSU transformers. Fit curve added in red.

As design validation and testing stages are considered, for the GIC reduction designs, more detailed AC simulator analysis should also be considered for large scale network modeling to verify that these design options do not produce harmful impacts to normal network AC operation. Also as previously noted in prior Sections 5-8, favorable GIC reduction was achieved in all cases without including neutral resistors in all locations (the top 75% design). As noted, these low GIC participation transformers are evenly dispersed throughout the network. Not adding resistance at the remaining 25% of transformers will provide a large pool of solidly ground neutrals in the network to maintain various aspects of the grounding coefficient ratios that would act to further minimize relay protection impacts or transient overvoltage increases. These helpful factors were not included in the above discussed analysis and would suggest even further improvements when they are evaluated in a more detailed analysis.