Prepared Testimony of John G. Kappenman
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Introduction

I would like to thank the FERC for the opportunity to provide comments today on this important topic area. In my comments, I will lay out the basis of some of the work done by many different government departments and agencies to estimate GMD Risk, but I would like to summarize it briefly up front. The conclusion of all the studies has been: the risks are serious. And let me say, it is certainly not hard to reach that conclusion. There has been extensive modeling and model validation, but even without modeling, just using simple extrapolations from measured data, you can reach the same conclusion. Measured data that NERC has been reluctant to gather and ask for from the power industry as well.

The real question here is, how did a small group of NERC authors, after pulling the draft task force report away from the full task force, reach discrete, definitive, positive conclusions in the few weeks they had to rewrite the draft, in seclusion? With hundreds of different transformer designs in the US transformer fleet and with transformers in all ages and conditions, nothing definitive could be said without extensive data collection on all those transformers, and without developing and exercising detailed finite element thermal and electrical models on every transformer type. And yet, the NERC report includes a well-publicized, very specific assertion, that the US fleet is, essentially, not seriously vulnerable. Where is the data? Where are the models? Where did this rosy conclusion come from? I assume, for example, NERC would not make the ridiculous claim they are basing such a broad and discrete, optimistic conclusion for the entire highly design and age variant US fleet on, for example, a single general model of one notional transformer design? So what is the basis for their conclusion? Whatever it is, no one I know was able to find it in their report.

Overview of Prior US Government Analysis

I have been a principal investigator on this topic area for many years and held Senior Engineering Management positions with a Midwestern electric utility company. I have both research and practical experience on the analysis of this problem for the US bulk power system.

I have conducted research studies on this problem for the US Congressional EMP Commission, for FEMA under US Presidential Executive Order 13407, for the US National Academy of Sciences, and for Joint FERC/DOD/DHS/DOE studies under Oak Ridge National Laboratory. I also was one of the authors of the 2010 Joint DOE/NERC High Impact/Low Frequency (HILF) Report on this subject area.

All of my investigations have depended significantly on data and mathematical modeling validated by data to derive estimates of the potential impacts to the bulk electric power grid. This has allowed for detailed forensic analysis of small contemporary storms and for analysis for severe geomagnetic disturbance events which have historically occurred before but have not yet been experienced by the present day bulk power system.

The data that was used in these studies consisted of the following:

- From ~1980 forward all digital one-minute or shorter cadence data from all available geomagnetic observatories around the world for each major geomagnetic storm.
- Other recorded observations of contemporary and historically important storms.
- Observations of Geomagnetically Induced Current (GIC) flows that have become publicly available.
- Data on behaviors of transformers and other bulk power system components that have been exposed to GIC flows including staged tests which I personally conducted, tests performed by others, and in-situ observations made by myself and many others.
- Data on equipment and system failures due to contemporary storm events

While all of my studies have depended on both real-world data and mathematical modeling, the NERC Geomagnetic Disturbance (GMD) Task Force used a different investigative process. The GMD Task Force collected minimal data on real-world data and did not present the results of any electric grid modeling. Instead, the GMD Task Force relied on discussion groups of engineers.

More importantly all of the studies I have performed are in agreement with studies and analysis that can be more simply and empirically determined by undisputed data and impacts that were observed in other storm events. When examining real-world data, no modeling is required to understand directly observed effects of geomagnetic disturbance on the electric grid. Here are some facts:

- Fact – The March 1989 solar storm caused the blackout of the Quebec Grid.
- Fact – A large nuclear plant transformer was also destroyed by the March 1989 Storm at the Salem New Jersey nuclear plant.
- Fact – A large number and rate of failures of other nuclear power plant transformers was observed in the 24 months after the March 1989 storm.
- Fact – NERC's own report of the March 1989 storm noted widespread and unprecedented impacts to the US and North American power grid that nearly lead to a large scale blackout across major portions of the US.
- Fact – Measured data has shown that storms with impulsive disturbance levels that are 4 to 10 times larger than those that impacted the North American grid in March 1989 have occurred before
- Fact – The only US electric power company to openly report transformer impacts of that storm (Allegheny Power), reported that deleterious impacts causing loss-of-life to transformer insulation on 36% of their EHV transformer infrastructure just from the March 13, 1989 geomagnetic storm.
    - Many of the affected transformers did not fit the design profile that transformer experts would be considered at high risk of GIC damage, rather they were 3 Leg Core type design.

I have also performed mathematical modeling of the U.S. bulk power system for the U.S. Government. All models rely on simple modeling of currents induced in a closed loops consisting of high voltage transmission lines, transformer windings, and conductive ground. The current induced in the loop is directly related to the rate of change of the magnetic field surrounding the closed loop and the resistance of the loop, a straightforward application of Faraday's Law and Ohm's Law. Because Maxwell's Equations, Faraday's Law and Ohm's Law are the most basic of physical principles, there is no lack of disclosure regarding the fundamentals of my models or the models that many others have applied to this problem.

Importantly, because publicly available GIC data can be matched with other publicly available data on magnetic fields during solar storms, it is possible to validate the theoretical models with real-world data. The currents and power grid impacts predicted by the models generally match real-world experience, as detailed in reports that have been provided.

The U.S. bulk power system is composed of thousands of transformers and transmission lines. Moreover, deep Earth ground conductivity characteristics within the United States varies considerably. Substantial time and expense was required to enumerate all significant transformers and transmission lines, and to estimate ground resistances. Also, software code had to be written to account for each of these important factors. Consistent with standard commercial practice, Metatech (the firm that I was employed by at the time of the analysis) has not disclosed proprietary data and software code. Further, there are numerous engineering and scientific papers that I and many others have published on these topics. Hence, the basic physical principles of these models are both disclosed and available to all. Even during the course of the NERC GMD Task Force several other parties were providing results from their analysis as well.

Lack of Adequate Data and Evidence Collection by NERC

Data is factual and fundamental evidence that is required to develop insights and interpretations of observed events, and to make extrapolations and validate models for more severe events that have not yet occurred on present day power grids. While NERC has emphasized "Developing additional open source tools and models to develop GMD mitigation strategies", they have not emphasized the even more important and primary action of gathering and providing data that currently exists and is readily available. This data is crucial for developing a better understanding of these important concerns.

While there are going to be both commercial proprietary models used as well as perhaps open source models, it is crucial to have data openness and transparency such that not only NERC and their members can assess the vulnerability of the grid, but so that independent experts and society as a whole can perform these evaluations. Unfortunately, this important requirement has yet to be pursued by the NERC GMDTF and is a major shortcoming of the NERC interim report. During the GMD Task Force deliberations of 2011, it became known to various Task Force participants that data existed on GIC-related (and other) transformer failures that had occurred. Requests were made to NERC to seek data and reports on GIC observations and transformer failure root cause reports, a request which NERC adamantly refused. Therefore this NERC investigation is hampered by its own unwillingness to collect the evidence which exists for the Task Force to examine.

Using the limited publicly available GIC data, I provided a report to the NERC GMD Task Force last year showing a simple method to estimate GIC flows based on this data and the underlying principles set forth by Faraday. This is a calculation method which does not even depend upon a large scale model. Rather it is a simple empirical estimating method based upon the concept of paired observation of GIC flow during a storm with the driving geomagnetic disturbance environment (dB/dt in nT/min). Using these two observations of GIC and dB/dt, it is straight forward to extrapolate to higher dB/dt levels that society is concerned with. Having this calibrated frame of reference, it is possible to do first approximation estimates of GIC flows at the same network location with simple scaling methods for storms that are larger in intensity. Importantly, these independent GIC assessment methods indicate that GIC flows are plausible that could reach several hundred Amps/phase in EHV transformers across the US electric power grid. The overall general agreement in the results of these independent analysis efforts with detailed models tends to support the findings of expected GIC flows that are plausible for severe geomagnetic storms. Therefore having access to an even more comprehensive GIC measurement data set that exists but is not in the public domain would aid in providing better assessments of the vulnerabilities and risks facing the electric grid and the public from these storm events. NERC's unwillingness to collect this data further inhibits better assessments that can be done by the Task Force and other independent experts.

Inadequate Failure Analysis for the NERC GMD Task Force

Using publicly available GIC data and modeling results, I provided a report to the NERC GMD Task Force showing the transformer-by-transformer estimates of GIC under conditions of a 5,000 nanotesla per minute solar storm. The model showed that 350 transformers would experience GIC in excess of 90 amps per phase, approximately the same amps per phase that destroyed the Salem Phase "A" transformer during the March 1989 storm.

Significantly, while NERC declined to use these model results for their GMD Task Force Report, NERC also refused to release the detailed model results to participants in the task force. NERC considers the model results are "Critical Energy Infrastructure Information" and therefore exempt from public disclosure. NERC wants to have it both ways--they discount the model results, while at the same time saying that the model results are so sensitive they cannot be released. Both efforts on the part of NERC prevent the public and other experts from being able to perform their own independent assessments.

In many cases, GIC levels much larger than 90 amps per phase GIC are being estimated across the US, leading to legitimate concerns that the electric grid is likely to experience multiple deleterious effects. These effects observed during real-world solar storms include:

- Reactive power consumption and system collapse
- Overheating and damage to transformers
- Vibration and resulting damage to transformers
- Network collapse and resulting damage to transformers
- Damage to large generators
- Damage to shunt reactors

Some of these effects have been observed with relatively small geomagnetic storms. For example, reactive power consumption caused the collapse of the Hydro-Quebec system in 1989 and a grid outage in Sweden in 2003. Transformer overheating and failure has been observed at Salem nuclear power plant in New Jersey, St. James Bay in Canada, New Zealand, and in multiple locations in South Africa. Network collapse and failure has been observed at La Grande, Canada. We also know that each major storm has produced new and unanticipated failures of electric power grids. For example, prior to the March 1989 storm, the power industry had not thought that a blackout could occur or that transformers could be damaged. As a result of the 2003 storm, we also learned that large numbers of transformers could be damaged from low-level but long duration GIC exposure.

These are the geomagnetic storm effects that we know about. During the GMD Task Force deliberations of 2011, participants uncovered new cases of probable transformer failures at Hope Creek nuclear power plant in New Jersey and Seabrook nuclear plant in New Hampshire. Task force participants requested that NERC obtain root-cause investigations reports and GIC data, but NERC management adamantly refused.

Again, participants in the NERC GMD Task Force stressed that various incidents of transformer failure are not being fully examined in respect to GIC-related root-causes. Evidence of key or contributing factors of GIC-caused transformer failures is not normally considered. And as several noted to the NERC GMD Task Force, that unless overheating caused by leakage flux established by GICs is specifically considered, which is unlikely based on current limited knowledge of the problem, GICs will not be reported as a cause or contributing factor of failures. I have provided various statistical evidence and reports to NERC showing correlations of failure rates with geomagnetic storm activity. As a number of NERC GMD Task Force participants noted, "The Real Transformer Experts are the Transformers Themselves"; therefore NERC efforts to exclude this important source of evidence is particularly troubling.

The Limitations of Transformer Models and Importance of Transformer Failure Data

Early in the NERC GMD Task Force a transformer engineer for one of the manufacturers gave a presentation claiming that only one transformer had every failed due to GIC--the Salem Phase "A" transformer during the March 1989 storm. The engineer attempted to provide alternative explanations for every other transformer failure described in official reports and peer-reviewed technical literature. For example, failures of transformers in South Africa were explained away initially as being a result of poor-lead design. I filed a report with the NERC GMD Task Force that called into question nearly all of the transformer manufacturer conclusions, showing they largely were in some instances wrong, in other instances clearly contradictory to earlier statements by these same experts, and in other instances simply did not stand up to scrutiny. In the instance of South Africa transformers, I noted the reports publicly available on these transformers showed failures other than leads. Immediately the transformer engineer claimed that failures were then due to oil-contamination (with no substantiation provided). This had also been reviewed and dismissed by the owners of those transformers. Yet this interpretation is the one that NERC has decided to endorse in their report. My report also pointed out that one power company reported 36% of their transformers sustained damage after the March 1989 storm, and that they were the only US company to publicly report their data. It should be clear that a much larger storm has the potential to cause more severe and even wider spread damage. .

Lack of Standards for GIC-Withstand and Public Risk Uncertainties

There are major disagreements with and amongst the Transformer experts on the potential assets at-risk due to severe geomagnetic storms. Simply stated, there are no standards that define "GIC-Withstand" of transformers. Historically—and even post-March 1989—no industry "GIC Withstand" standard has ever been adopted. The only standards that do exist are in regards to

Over-Excitation (which GIC certainly causes) and these standards clearly define limited levels and time durations of Over-Excitation that can be tolerated in transformers. At the highest limits of over-excitation (which is only 140%), these conditions can only be tolerated for durations as short as 10 seconds. Present design standards also confirm that for over-excitation which is as little as 110%, these conditions cannot be tolerated for long durations even when the transformer is unloaded. In fact in the 1960's, General Electric (a transformer manufacturer) and the Edison Electric Institute clearly defined a template for "GIC Withstand" based upon the already existing standards for Over-Excitation.

Nearly all of the transformers in-service in the US Bulk Power System were not purchased with any specific design considerations that take into account GIC exposure or withstand. Therefore these transformers will continue to be a large population of existing transformers with a "Design Basis" that may not provide adequate "GIC-Withstand." As an alternative, the application of existing transformer over-excitation standards as a surrogate would suggest generally low GIC withstands in existing transformers on this "Design Basis" approach. Using this method it is also clear that these GIC Withstand levels will be greatly exceeded in a number of transformers for severe storm scenarios with the potential for wide spread damage to the grid and raises the spectre of serious risks for the American public of long duration electric grid outages. It should be noted that these are the standards that the transformer experts themselves have defined and standardized.

Available transformer observations, failure data, and staged tests of transformers also confirm that as GIC levels increase in a transformer, internal heating and deleterious effects also increase. Present transformer thermal models do not reliably predict where and how much heating will occur in a transformer due to the presence of GIC. Thermal models also do not have the ability to predict other internal problems that have been observed in actual transformers from GIC exposure. Reports of deleterious effects from discharging have been reported but would not be represented in current thermal transformer models. Other failure modes of transformers such a gas bubbling and dielectric failure associated with that mode are also not captured in models. The temperature levels of 200oC advocated by NERC in their report are too high to protect against this mode of failure. Vecchio, a transformer thermal modeling expert, noted in his Chapter on Transformer Thermal Modeling, an important concern on modeling limitations as follows:

> *"A cautionary note must be sounded before too literal a use is made of this procedure. Gas bubbles can start to form in the oil next to the insulation when the insulation temperature reaches about 140°C. These bubbles can lead to dielectric breakdown which could end the transformer's life, rendering the calculations inapplicable."*

I must conclude, therefore, that NERC reliance upon these modeling methods understates the real risks to the public. The NERC model that was noted in their report also has not been vetted by the GMD Task Force or various subject matter experts and was only presented in the final draft of their report. It should not be viewed as anything that would supplant the already existing over-excitation standards either. Therefore there is considerable additional uncertainty about the capability of this model beyond what has previously been noted about such transformer modeling limitations. Further it was also clearly noted by the NEC GMD Task Force participants that there was enormous diversity in transformer design, such that a single transformer model could not be reliably applied to make broad and sweeping conclusions about all transformers from one model as performed by NERC in their report. This would be analogous to depending upon one bridge inspection to determine that all other US bridges were safe. This should not be accepted by the FERC or the American public as a prudent and adequate safety procedure.

Other factors that need to be considered but are not in the NERC report include transformer design changes post-1972 that have lowered excitation current levels and act to drive transformers into Over-Excitation at very low levels of GIC, increasing their vulnerability. This new risk vector applies to many of the newer transformers in the present day system and acts to make them vulnerable not only to brief severe GIC events, but also to low level but long duration GIC events. That means that other storm processes such as long duration recurrent storms, which are more common, could pose a risk as well. The degree of this penetration of these new risk aspects is not publicly available.

Age and Condition of U.S. Transformer Fleet and Public Risk Uncertainties

Age and condition of transformers is also a serious concern for the US bulk power system in the face of this threat. The Age and Condition of the US Transformer fleet has been independently reported as the bulk of the transformers are near 35-40 years old, very near their end-of-life. Transformer experts such as Prevost also notes that; *"In the final quartile of transformer life. Failure probability can increase by 5 to 10 times the normal system failure rate over prior life of transformers."* This means that a severe storm is likely to cause a larger number of failures than previous studies had been able to estimate. This characteristic of decaying GIC Withstand with age/condition of the transformer also implies new risk aspects that are not yet understood by the industry or the public. This essentially is equivalent allowing flood dikes to erode with age, even though the risk remains the same for the 1-in-100 year flood that the dikes were constructed to withstand. Unfortunately, we have witnessed several levee failures in recent years due to this kind of neglect. This should never be tolerated as an acceptable public policy for that risk, yet this is also the case for GIC Withstand of the bulk power system. All of the above information was also disclosed to the NERC GMD Task Force.

Grid Collapse Scenario and Damage Concerns

NERC also draws the conclusion that grid collapse is the most likely scenario. As noted in the following press statements;

> *"One of the major findings, I think, of the report is that given that the science I've described ... we believe it is much more likely that the grid would suffer voltage collapse and failure due to a shortage of what we call reactive power that supports the voltage on the grid," Cauley told reporters. "But the consequences of that kind of failure mode is that it is much less likely that large equipment, transformers, would be permanently damaged and would be unavailable to put the lights back on."*

These statements are particularly troubling in that NERC presumes that grid collapse under a severe GMD event would not have potential for widespread and catastrophic damage caused by GIC to key Bulk Power System apparatus. However, I have provided reports to NERC that do not draw that conclusion and point to other equipment damage modes that could be activated under such a scenario. In fact in this report provided to the GMD Task Force, the following concerns of damage due to grid collapse in the presence of large GICs were noted;

> *Breakers are not rated for DC current interruption, so how they would react is highly uncertain, but available data suggests that such duty may be a source for collateral damage concerns. One of the arguments that has been advanced is that network collapse due to a severe geomagnetic storm would act to self-protect transformers from damage posed by GIC exposure. This "self-protect" theory may not be a valid premise. Breaker operation in the presence of high GIC levels could cause damage to the breakers themselves or cause other adjacent apparatus to become damaged during this collapse. It is plausible that the damage posed by the collapse under high GIC conditions could result in an even greater extent of equipment damage, than previously considered.*

NERC has either ignored or overlooked this area of concern.

Conclusions

The bulk power system is the nation's most important critical infrastructure and unlike other threats, a severe geomagnetic storms can impose a near simultaneous nationwide crippling threat to this vital infrastructure. The power industry should be required to follow other sectors of society in the development and adherence to design and operation practices which safeguard the public from reasonable risk and are backed by independent oversight. This requires that the bulk power system and its equipment have a well-defined performance envelope and that the system always be operated to stay within the performance envelope. These requirements are usually backed by "force of law" underpinnings. As described for this threat, there remain great uncertainties about the safe operating envelope of the bulk power system and its equipment. None of the safeguards that the public usually requires of infrastructure operators in this regard are in place for the bulk power system.

The release of NERC's report where they attempt to draw broad conclusions that equipment damage cannot occur, essentially constitutes little more than efforts on their part to "normalize deviancy" while allowing these risks to continue to remain or even escalate. This is a process that does not always end well, as NASA and space shuttle operators have shown twice before in demonstrating that even small performance deviations such as the performance of O-Rings or the impact of three pound snowballs and disregarding their seriousness can have on the performance of complex systems.

There are also many other deficiencies at present in tracking and understanding present and future risk issues by NERC. In all other respects, design codes for high winds, ice loading on structures, seismic and pollution are all generally underpinned by force of law requirements, but are clearly lacking for geomagnetic storm threats. There are still no recommendations yet coming from NERC for design codes that take this threat into consideration. It has been the historical lack of design codes that have allowed the infrastructure to grow more vulnerable and to the point where it is perhaps the largest systemic risk and natural disaster risk that society faces. NERC and industry self-assessment and regulation have been the incumbents that have allowed decades of inattention to and miss-calculation of the risks posed by this threat. They have presided over this enormous migration of risk into the power grid and to society as well.

There have never been any requirements by the NERC and the electric industry to monitor for GIC and where it has been observed, very little of this information has been made publicly available. There are no requirements to report failures of transformers or apparatus that may have been damaged due to these events or their root-causes or allow independent teams to do those types of inquiries. In an era where blackbox recorders are required on every airplane and are now being instituted on every new car on the road; this is a startling incongruence, in that all of society has a ticket for the ride when a widespread electric grid blackout occurs.

I have tried to outline a few of the efforts used in the many US government studies which reach findings of grave risks. So the issue is not models – different, well-validated models have been used, and the same general conclusion – that the grid is seriously at risk -- can be reached without models, just using simple data extrapolation.

The real question here is; how did the NERC report manage to do what no previous study achieved, and in record time, in the few weeks the report writers had after it was pulled out of the hands of the task force? How did they reach a discrete, specific conclusion that hundreds of different transformer types and ages will withstand a severe GMD event? At a minimum, making very definitive claims for the nation's full transformer fleet would require extensive data collection and analysis. Where is the data? It certainly is not in the NERC report.

I hope to see a more extensive investigation into how such a critical report could have been so misdirected. The risk we are considering today is not any ordinary risk – we are considering a risk that could constitute a serious threat to the continuity of the United States as we know it -- a subject which should have merited the finest and most extensive documentary data collection, modeling, juried review and proof in modern times.

This concludes my testimony.