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# Towards Developing Implementable High Altitude Electromagnetic Pulse E3 Mitigation Strategies for Large-Scale Electric Grids

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*Abstract*—**Electromagnetic pulses caused by high altitude nuclear explosions (HEMPs) have the potential to severely disrupt large-scale electric grids. This paper presents some strategies that could be helpful in mitigating the impacts of the longer term HEMP E3 aspects, with a focus on techniques that could be implemented in an energy management system. These include adaptive shedding of load and generation, and transmission level switching. Several visualization techniques are also presented. The approach is shown using a 2000 bus synthetic electric grid.**

*Keywords*—**High Altitude Electromagnetic Pulses, Geomagnetically Induced Currents, Electric Grid Visualization**

## I. INTRODUCTION

The ability of electromagnetic pulses caused by high altitude nuclear explosions (HEMPs) to impact electronics and the electric grid has been known for many decades, with [1] providing an early description of an approach to quantify electric grid vulnerability. An HEMP is usually considered to cause three separate electric fields at the earth's surface, called E1, E2 and E3. Each is time and spatially varying, though with vastly difference magnitudes and durations. The E1 is the quickest, lasting less than a microsecond, with electric fields of 10's of kV per meter. The E2 has electric fields of up to 100's of volts per meter and a duration of up to several milliseconds; E2 is often considered similar to lightning. The longest, E3, has a duration of up to several minutes and field values of potentially 10's of volts per km. The E3 is typically divided into the E3a (blast) waveform, lasting a few seconds, and the E3b (heave) waveform, lasting for several minutes.

Over the last decade, roughly starting with the publication of [2] and [3], there has been increased research focusing on the HEMP E3 impacts on the electric grid, and HEMP impacts remain an electric grid reliability risk priority [4]. Since the electric grid impacts of E3 can be somewhat similar to the impacts of the naturally occurring geomagnetic disturbances (GMDs) [5] there has been some overlap in the research. Both affect the electric grid by causing changes in the earth's magnetic field, which results in slowly varying (i.e., compared to the 50 or 60 Hz electric grid frequencies) electric fields at the surface with the values of these fields highly dependent on the earth's conductivity going down hundreds of kilometers. These electric fields in turn cause quasi-dc currents known as geomagnetically induced currents (GICs), which flow in the high voltage transmission system. The GICs can then cause saturation in the transformers, resulting in harmonics, increased reactive power consumption, and potential overheating, and/or voltage collapse.

However, there are some important differences between the HEMP E3 and GMD electric grid impacts. First, because the E3 has a faster rise time and shorter duration, usually it is modeled using time-domain transient stability level simulations [6] as opposed to the power flow approach used with GMDs [7], [8]. Second, because the E3 is proceeded by the much faster E1 and E2, the potential impacts of these waveforms need to be considered, with [9] providing good coverage of some of these impacts. Third, an HEMP could occur with little or no warning time. In contrast, the solar corona mass ejections that cause GMDs can be observed on the sun at least a day ahead of time, allowing at least some warning, albeit with a substantial lack of specificity. With an HEMP an electric grid could almost instantly go from normal to "in extremis" operation [10]. Examples of other events with little or no warning time include earthquakes, physical attacks and cyber-attacks [11]. Fourth, the duration of the HEMP itself is substantially shorter than a GMD, with the HEMP over within minutes whereas a GMD could go on for days. While this does limit the potential for initial operator intervention, because of the potential of an HEMP to cause a cascading grid failure, mitigative control could still be effective. Fifth, since HEMPs have never occurred on large-scale electric grids, there is no prior experience. This contrasts with GMDs in which minor ones occur regularly, and there is some experience with more major events [12]. Last, because an HEMP would only be caused by an adversary, the time and location of the event could be planned to cause maximum damage and, as noted in [1], there could be multiple simultaneous events.

Assessing the impacts of HEMPs on electric grids and determining effective mitigation approaches is a challenging and certainly interdisciplinary problem. It is also an area of active research, with some examples of recent works in the area including [13], [14], [15], [9], [16], and [17]. The purpose of this paper is to present an approach that could be used to help develop mitigation strategies to minimize the impacts of HEMPs with a focus on techniques that could be implemented in an electric utility energy management system (EMS). The use of visualization in the development of these

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techniques is also presented. The approach is shown on a 2000 bus synthetic electric grid. The next section presents more details on the approach, with the subsequent section providing the mitigation strategies.

## II. SIMULATION APPROACH AND VISUALIZATIONS

An HEMP's impact on an electric grid depends upon a number of factors including the size and location of the blast, the earth's impedance near the blast, the electric grid including its protection system, how effectively the electric grid engineers develop mitigation strategies prior to the event, and on the automatic and human operator intervention during the event. The contribution of this paper is primarily on mitigation, and how visualization can help in developing these mitigation strategies.

The overall simulation approach used here is based on that of [6] in which the electric grid is represented with a time-domain, positive sequence model with an integration time-step of about ¼ or ½ cycle initialized from a power flow solution. Standard transient stability models are used to represent the system dynamics, such as models for synchronous machines, exciters, governors, stabilizers, and renewable generation. Some aspects of the protection system are also represented including generator over excitation limiters (OELs) [18].

Another important generator modeling consideration here is in the initial power flow to make sure that the statuses of any radial generator step-up transformers (GSUs) connected to off-line generators are correct. Since the status of such GSUs does not affect the power flow solution, it is very common to model off-line generators without opening its associated GSU. However, in an HEMP study the GSU statuses can have a significant impact on GICs and the reactive power losses.

With respect to the load, its modeling has been an area of study for decades with much of the history and current state-of-the-art given in [19] and [20]. A key load challenge in any dynamics study is the load characteristics can certainly influence the results, yet the composition of the load is constantly changing both as customers utilize different types of existing load as conditions change (e.g., day versus night or summer versus winter) and on a longer term as newer types of load are added to the system. The results presented here mostly utilize the quite detailed and now widely available composite load model (CMLD), which has about 130 parameters. An advantage of the CMLD is many utilities already customized models to represent the load at different buses and ambient conditions. The disadvantage is because of its complexity it takes longer to simulate. Hence some results are given using a much simpler static model.

Here the spatially and time-varying electric field associated with the HEMP E3 is assumed as an input. Then, during the simulation at each time step the GICs are calculated and their impact on the transformer is modeled as a reactive current load [21]. A number of different HEMP E3 waveforms exist in the literature, with examples including [22], [23], and [24]. All note that the actual waveform would be dependent upon a number of values including the type of weapon, burst height and location. For the simulations presented here an entirely fictional time and spatially varying waveform is used, roughly motivated by that of [24], with a maximum magnitude of 75 V/km, close to the 85 V/km recommended in [23].

Since an E3 would be proceeded by an E1, the power system impacts of the E1 also need to be considered with [9] providing good coverage of some of these couplings. Other references that consider E1 impacts include [25], [26], [27] and [28]. In this paper the only coupling considered is the possibility that some of the load modeled in the initial power flow would be lost almost instantaneously as a result of the E1. Hence the time-domain simulation would initialize at a non-equilibrium point due to this power imbalance. How much load is lost would depend in part on the spatial distribution of the E1, with examples of these spatial distributions provided in [29], [25] and [9].

This paper demonstrates its techniques using a 2000 bus (2K) synthetic electric grid that covers a geographic footprint equal to most of the US state of Texas [30] with a nominal frequency of 60 Hz, a total real power load of 67 GW, a reactive power load of 19 GVar, and in-service shunts of about 20 GVar. The load distribution roughly matches the population distribution of Texas. Details on the development of this grid, including its stability and GIC related models, are given in [31], [32], [33] and [34]. The oneline for this grid is shown in Figure 1 with the line color on the display used to show the transmission line's nominal voltage (orange 500 kV, purple 230 kV, and black for lower voltages), and green flow arrows superimposed on the branches to show the direction and magnitude of the real power flow. It is important to note that this grid does not in any way represent the actual Texas electric grid, with the paper's examples provided only to illustrate the associated techniques that could be applied to any electric grid. All the simulations presented here were done using PowerWorld Simulator Version 22.

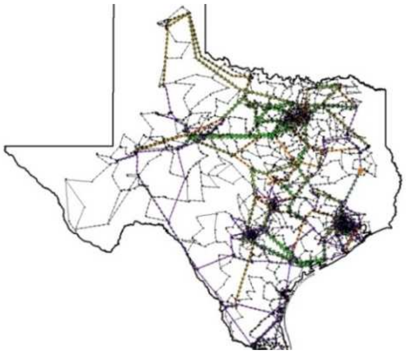

Figure 1: 2000 Bus (2K) Grid Oneline

In order to determine effective HEMP mitigations, it is important to understand how such events can affect the grid. Or as noted in [35], maintaining good electric grid simulation situational awareness (SA). However, this can be quite challenging since HEMP simulations contain all of the results associated with a standard power system dynamics study, coupled with the impacts due to the time-varying GICs. To help the paper uses several visualization techniques including grid data contouring [36], flow visualization [37], [38], geographic data views (GDVs) [39], GDV Summary Objects (GSOs), and GDV Line Summary Objects (GLSOs) [40].

As an example, Figure 2 shows the 2K grid in which the GSO approach is used to group the substations into an 8 by 8 grid in which the size of each rectangle is proportional to the load in that portion of the grid, whereas the power flow between the GSOs is shown using the GLSO approach with the green arrows showing the amount of power flowing between the GSOs. Here most of the load is on the eastern side of the grid, and there is commonly a large amount of power transfer from west to east. The contour shows the voltage variation, with a large initial scale chosen to better illustrate the later stressed conditions. Initially the grid is in the normal operating state with the figure showing the power flow solution that is used to initialize the stability simulation.

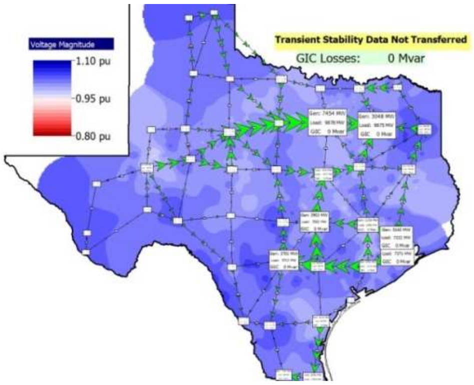

Figure 2: 2K Case Initial Load, Flow and Voltage Values

The approach is then to do time-domain simulations representing the impact of the HEMP on the grid. Here the HEMP is assumed to be centered in the northeast portion of the system. The simulation starts with optionally representing the impact of the E1 waveform, resulting in potentially lost load. Figure 3 shows an example contour of an assumed E1 load scalar scenario, here with all the loads in the non-blue region reduced (by up to 25% in this example) prior to the start of the simulation. This results in an immediate loss of about 3800 MW of load (5.6%), causing some initial power mismatches, and an increase in the system frequency over the first few seconds (shown in later figures).

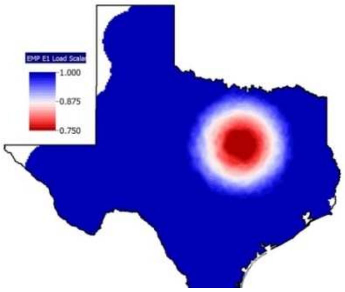

Figure 3: 2000 Bus (2K) Case Example EMP E1 Load Scalar Contour

Then, using the approach of [6], at each time step the impact of the E3 waveform is calculated. As noted earlier, here the assumed waveform is a fictional representation that is assumed to reach a maximum at about 24 seconds. Figure 4 and Figure 5 contour the resultant electric field at 15 and 25 seconds respectively for the case in which the maximum magnitude is scaled to be 75 V/km; the arrows showing the electric field's direction. The time and spatial variation is readily apparent from these figures.

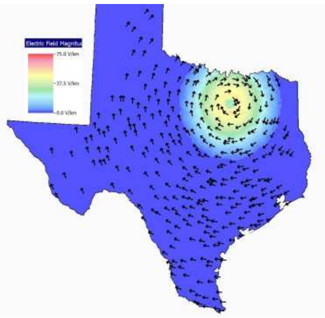

Figure 4: 2K Case Example EMP E3 Waveform at 15 Seconds

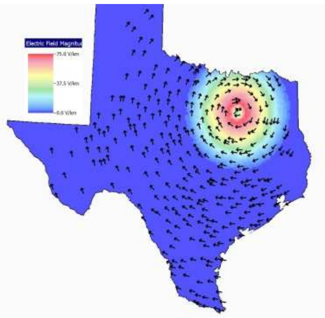

Figure 5: 2K Bus Case Example EMP E3 Waveform at 25 Seconds

The impact of the HEMP on the grid, and whether any mitigation measures are needed, is then obtained by considering the simulation results, here leveraging the techniques presented in [35]. As an example of a less impactful event, Figure 6 shows the time variation for all 2000 bus per unit voltage magnitudes and Figure 7 the variation in the bus frequencies for an HEMP scenario in which the maximum electric field is scaled to be 30 V/km and the maximum HEMP induced reactive power losses are 26.6 Gvar, occurring at about 25 seconds. Figure 8 repeats the values from Figure 2, except at time of 25 seconds. The yellow arrows are used to visualize the flow of the GICs, with the direction of the GICs primarily driven by the electric field's direction; because of the clockwise circulating electric field, the GICs in the northeast portion of the system are likewise circulating. Aside from the assumed E1 loss of 3800 MW load, which causes the initial frequency increase seen in the first few seconds of Figure 7, the grid recovers.

As the amount of the assumed field is increased, the grid becomes increasingly stressed, with Figures 9 and 10 repeat the previous scenario except now with the maximum field set to 60 V/km and the grid actually on the verge of a cascading voltage collapse. Trying to increase the value above this, at least without mitigation, is not possible. To consider the impact of the load model, Figure 11 repeats this scenario except using a very simple model for the load consisting of constant current for the real power and constant impedance for the reactive power. This comparison both shows that the detailed CMLD does make a difference, but that a still reasonable approximation can be done with a static model.

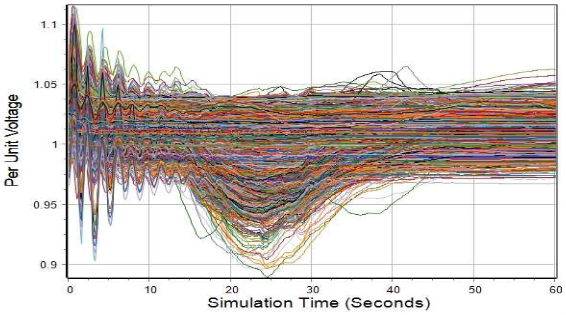

Figure 6: 2K Case Bus Voltage Magnitudes for 30 V/km Maximum Scenario

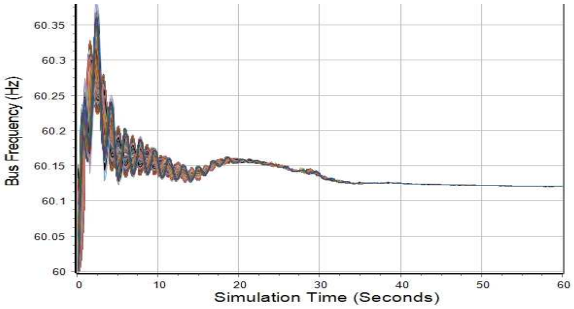

Figure 7: 2K Case Bus Frequencies for 30 V/km Maximum Scenario

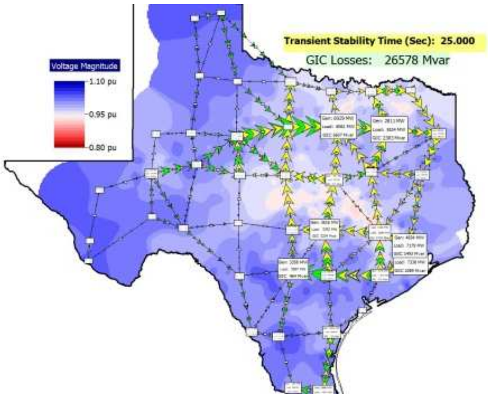

Figure 8: 2K Case Loads, Flows and Voltage Contour at 25 Seconds

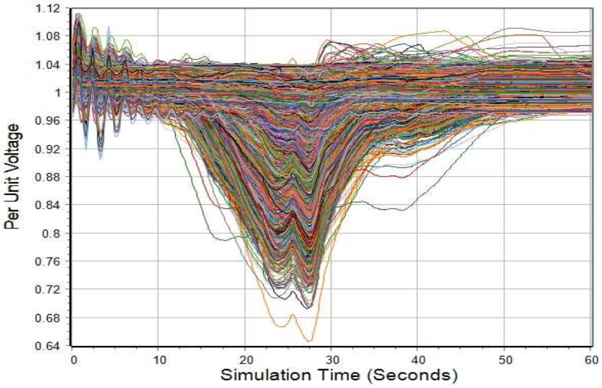

Figure 9: 2K Case Bus Voltage Magnitudes for 60 V/km Maximum Scenario

## III. MITIGATION STRATEGIES AND FUTURE DIRECTIONS

Like other aspects of electric grid protection, any HEMP mitigation strategy needs to strike a balance between cost and benefit. However, HEMPs do present unique challenges in trying to achieve this balance. Still, as has been shown in the previous section, HEMPs at field values less than the 85 V/km recommended in [23] could causes a rapid voltage collapse that might affect an entire interconnect. Hence mitigation measures should at least be studied.

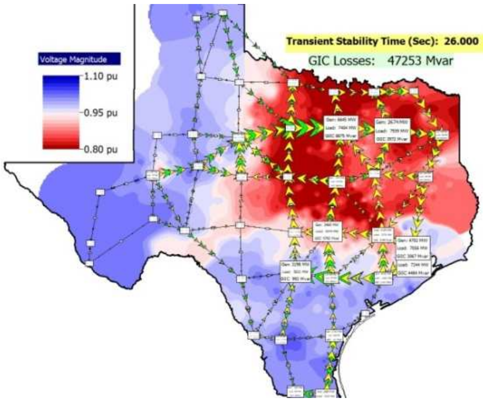

Figure 10: 2K Case Loads, Flows and Voltages at 26 Seconds at 60 V/km

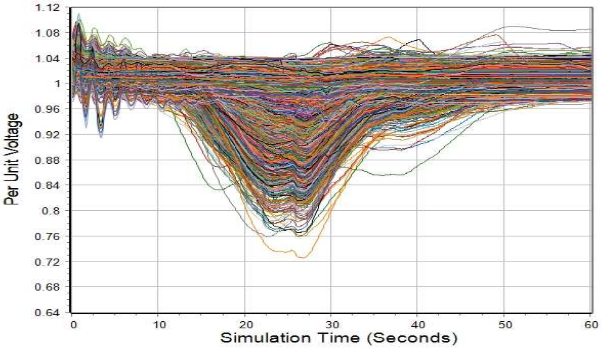

Figure 11: 2K Case Bus Voltage Magnitudes with Simplified Load Model

The mitigation strategies presented here are based on the following assumptions. First, the HEMP would occur with no warning. That is, the system state could be instantly changed from normal to the "in extremis" of [10] in which "heroic actions" are needed to contain the disruption. Second, given the unique characteristics of an HEMP including the resultant harmonics, an automatic system could be setup to reliably detect within seconds that an HEMP has occurred. Future control actions could then be premised on this knowledge. Third, given the time frame human operator intervention cannot be assumed and a state estimator solution would not be available to do any significant system-wide analysis during the event. Fourth, measurements from SCADA and/or PMUs would be available so many individual component values would be known. Fifth, because of a time frame of seconds, as opposed to cycles, automatic mitigation actions could be implemented at the control center (EMS) level as opposed to only in substation relays. Sixth, as demonstrated in this paper, HEMP simulations could be available to engineers to allow system specific mitigation strategies to be developed. While these strategies might involve adaptive islanding [41], [42], the remainder of this section shows how even simple and EMS implementable "rules of thumb" could be helpful.

The overall approach used to develop the mitigation strategies is to combine simulations with the ability to consider control actions using a power flow initialized at some point in the simulation using the approach of [43] that includes the GICs and their reactive power impacts. Since the voltage collapse is ultimately driven by too much reactive power consumption, the mitigation strategies can be divided into two categories. The first are those that directly impact reactive power consumption such as shedding load, while the second are those that change the system topology to modify the GICs and their associated reactive power losses. Like any power system protection system, the challenge with these strategies is to quickly decide on the amount of "heroic" action that is actually needed. This requires performing a variety of different off-line studies considering many different HEMP scenarios. The particular mitigations could be quite system specific; the next section gives some initial general guidance, with a demonstration with the 2K grid.

For load shed the challenge is to quickly outage sufficient load in the locations most impacted by the HEMP. Interestingly, the ability of the grid to withstand the simulated E3 event is actually quite dependent on the amount of load that is assumed lost as a result of the E1. This is because this load is lost quickly and in the locations that are, in general, most impacted by the HEMP. While having load permanently damaged as a result of the E1 is certainly not desirable, this is a silver lining, particularly if such load has protection devices that prevent permanent damage yet temporarily fail open, and do not attempt to reclose for at least several minutes. For the remaining load a potentially useful approach is once the HEMP is detected to quickly open non-critical loads when their voltage magnitude falls below a potentially quite high setpoint (e.g., 0.75 per unit) and/or when the rate of change of voltage magnitude is sufficiently negative.

The second general mitigation strategies focus on changing the system GICs. The general guidance is to use a combination of selectively removing portions of the transmission system that are helping to create the GICs, and by (mostly) increasing the resistance of the grid in the locations most impacted by the E3. The desired result is lower and less concentrated GICs, resulting in lower and less concentrated reactive power losses. An example of an EMS implementable control that could modify the grid's GIC resistance is to open generators and their GSUs when certain criteria are met (i.e., an HEMP is occurring, low voltage, high frequency, overall reactive power flowing into the GSU). This removes paths to ground, increasing the overall resistance, and moving the GICs away from the HEMP center. An example of the first approach would be to use off-line studies to identify pockets in the transmission system that could be opened, perhaps with attached loads, and then to determine the triggers that could be used to implement the control (e.g., HEMP occurring, higher system frequencies, low voltages, etc.). Figures 12 to 14 show the results of such strategies on the 2K system, increasing the ability of the grid to withstand fields up to almost 75 V/km. In the figures the vertical lines correspond to tripped devices. Figure 15 shows a power flow snapshot, created using the approach of [43], to help develop this mitigation.

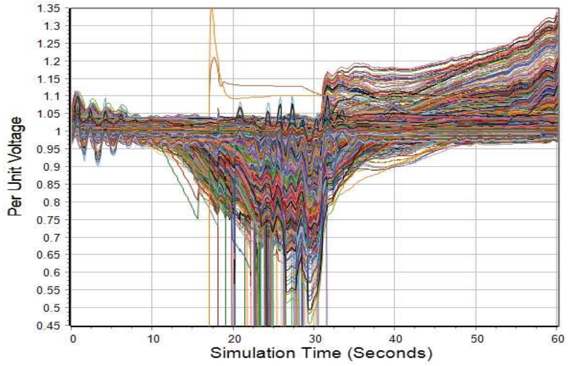

Figure 12: 2K Case Bus Voltage Magnitudes for a 75 V/km Max. Scenario

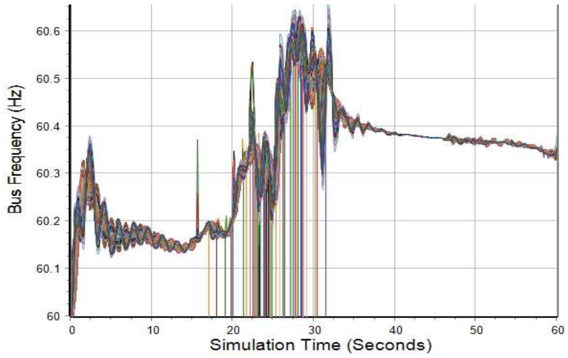

Figure 13: 2K Case Bus Frequencies for a 75 V/km Max. Scenario

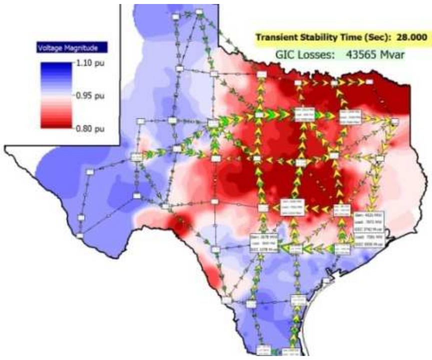

Figure 14: 2K Case Bus Frequencies for a 75 V/km Max. Scenario

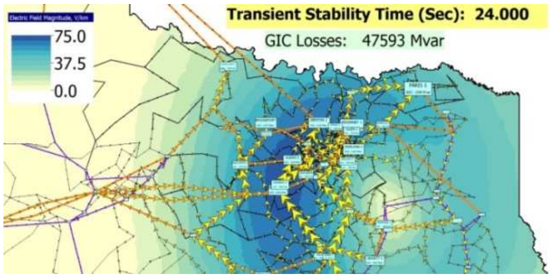

Figure 15: 2K Case Bus Frequencies for a 75 V/km Max. Scenario

Directions for future work including improved strategies for developing mitigations, demonstrations with larger grids, and more robust simulation algorithms for stressed operation.

## IV. ACKOWLEDGEMENTS

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