Magnetohydrodynamic Electromagnetic Pulse Assessment of the Continental U.S. Electric Grid

Voltage Stability Analysis

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ABSTRACT

The exo-atmospheric detonation of a nuclear weapon can generate a low-frequency electric field at the earth's surface. The resulting electric field, referred to as *magnetohydrodynamic electromagnetic pulse (MHD-EMP)* or *E3*, induces very low frequency currents in transmission lines and bulk power transformers. Similar to the effects from a severe geomagnetic disturbance (GMD), these geomagnetically induced currents (GICs) can cause part-cycle saturation of bulk power transformers, which can lead to adverse system impacts including voltage collapse and thermal damage in bulk power transformers.

The assessment presented in this report, which evaluated the potential for E3 to cause instability or cascading of the bulk power system, is a continuation of a previous Electric Power Research Institute (EPRI) assessment that evaluated the potential for the GICs generated by E3 to cause thermal damage to bulk power transformers. As with the previous study, a single high-altitude burst over 11 different target locations within the continental United States (CONUS) was evaluated—that is, the assessment was comprised of 11 separate studies.

The voltage stability assessment was conducted using a time-domain modeling approach to compute the GIC flows and the response of the bulk power system to those GIC flows. This modeling approach allowed for the dynamics of generators and loads to be included in the model, as well as the effects of generic impedance-based transmission line protection schemes (Zone 3) and generator ride-through capability (voltage and frequency). The effects of system topology changes due to protection system operations (lines and generators) were included in both the GIC calculations and dynamics simulations. The effects of harmonics resulting from part-cycle saturation, and the potential damage to critical electronic systems or other assets caused by the preceding E1 or E2 pulses, were beyond the scope of this study.

The results of the assessment indicate that voltage collapse due to E3 alone is possible for several of the target locations that were evaluated. Although it is difficult to precisely determine the geographic area that would be impacted by voltage collapse, for the cases that indicated voltage collapse is possible, the geographic extent of the impact was estimated to be on the order of several states or larger. None of the scenarios that were evaluated resulted in a nation-wide grid collapse.

Details of the assessment approach and final results of the study are provided. Possible E3 mitigation options are also discussed in the report.

Keywords
Bulk power system
Electromagnetic pulse (EMP)
Geomagnetic disturbance
High-altitude electromagnetic pulse (HEMP)
Magnetohydrodynamic electromagnetic pulse (MHD-EMP)

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PRIMARY AUDIENCE: Asset owners, planners, and operators of the United States bulk power system

SECONDARY AUDIENCE: Regulators as well as state and federal entities

KEY RESEARCH QUESTION

The assessment presented in this report was performed to determine the potential for instability or cascading resulting from E3 from a single, high-altitude burst over 11 notional target locations in the continental United States (CONUS). This assessment is a continuation of a previous Electric Power Research Institute (EPRI) study performed to determine the potential for E3 to cause thermal damage to bulk power transformers. Ultimately, this assessment sought to answer the following question: "If a high-altitude electromagnetic pulse (HEMP) attack occurred, and an E3 environment like the one simulated was generated, could voltage collapse occur due to the additional reactive power absorption of bulk power transformers?"

RESEARCH OVERVIEW

This research evaluated the dynamic response of the CONUS bulk power system when exposed to a notional E3 environment to determine the potential for voltage collapse resulting from the additional reactive power absorption of bulk power transformers experiencing part-cycle saturation due to the geomagnetically induced currents (GICs) generated by the E3 event. To perform the assessment, a time-domain model of the bulk power system including the dynamics of loads, generators, and protection schemes was assembled and simulated using the GICs generated by the E3 environment as the initiating event. For each of the 11 notional target scenarios that were investigated, several parameters were monitored throughout the simulation, including bus voltage and frequency, area of impact, and amount of load and generation loss that would be predicted to occur as a result of the simulated event.

As with the previous transformer thermal assessment, there were several considerations that were beyond the scope of this study. For example, this effort did not consider the potential contribution to voltage collapse that damage resulting from early-time electromagnetic pulse (E1) or intermediate-time electromagnetic pulse (E2) might have, affecting critical electronic systems (for example, protection and control systems, or generator controls), assets (for example, insulators or instrument transformers), or loads. The potential impact of harmonics resulting from part-cycle saturated transformers was also not included in the analysis.

KEY FINDINGS

- Voltage collapse due to E3 alone was found to be possible for several of the scenarios that were simulated. Although it is difficult to precisely determine the geographic area that would be impacted by voltage collapse, for the cases that experienced voltage collapse it is estimated to be regional and on the order of several states or larger, but smaller than either the Eastern or Western Interconnections. None of the scenarios that were evaluated resulted in a nation-wide grid collapse.
- The GICs predicted to be generated by the effects of the E3 environment modeled were large enough and of sufficient duration to cause part-cycle saturation of bulk power transformers over a large geographic region—for example, a significant portion of an interconnection.
- The simulations showed that the resulting transformer reactive power loss could lead to a significant reduction in system voltage, ultimately leading to loss of generation and load, and in some cases, voltage collapse.
- In 5 of the 11 target locations the simulations failed to converge numerically at some point during the 112-second simulation period due to considerable loss of generation and load. In the case of one target location that affected two interconnections, the simulations achieved numerical convergence for one of the interconnections that was affected, but not for the other. Lack of numerical convergence in these cases is an indicator of voltage collapse.
- Numerical convergence was achieved throughout the 112-second simulation period for the remaining 6 target locations. Simulation results did not indicate voltage collapse for these locations; however, for two of the target locations, the potential for localized voltage collapse was found to exist. The geographic extent of localized voltage collapse is estimated to be on the order of a single state or smaller.
- Significant loss of generation and load occurred over a large area for all 11 notional target locations that were simulated. For cases where a voltage collapse scenario was not identified, automatic generation control (AGC) and/or operation of under-frequency load shedding schemes would be required to maintain system frequency beyond the 112-second simulation period, and the inability to perform these functions could result in instability.
- Load loss in some cases also led to temporary overvoltage conditions in portions of the bulk power system. These overvoltage conditions tended to be more localized, and occurred near the end of the simulation. Automatic control actions such as overvoltage tripping of shunt capacitor banks or transformer load tap changing would be expected to reduce the system voltage in affected areas; thus, this finding was not viewed as a concern as long as such control functions have been hardened against E1 and E2, and are operable post-event.
- The modeling approach and assumptions related to bulk power system loads and generation were found to be critical components of the assessment. For example, excluding the dynamic effects of power system loads or voltage/frequency ride-through behavior of generators tended to yield results suggestive of a significantly lower impact.

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EXECUTIVE SUMMARY

WHY THIS MATTERS

A prior EPRI assessment found that the impact of E3 on bulk power transformers would be minimal due to the longer thermal time constants of windings and structural parts of typical bulk power transformers and the short duration of the E3 event. This subsequent research project focuses on another potential impact, which is voltage collapse of the bulk power system. The results of this assessment suggest that voltage collapse from E3 is possible due to transformer part-cycle saturation effects alone; however, the impacts were found to be regional and on the scale of previous voltage collapse events that have occurred in the United States.

HOW TO APPLY RESULTS

The results of this assessment can be used to help quantify the overall risk of E3 impacting the bulk power system as a whole (interconnection-level assessment), but they should not be used to identify specific areas of islanding or asset-specific mitigation measures.

Although study results indicate that regional voltage collapse from E3 is possible, the impact of E3 on the bulk power system can potentially be mitigated by reducing or blocking the flow of GICs in bulk power transformers. Mitigation could potentially be accomplished with neutral grounding resistors, capacitive blocking devices, series capacitors, or a combination of these approaches. Designing protection and control systems so that they are immune to the effects of power system harmonics, and adding automatic switching and load shedding schemes, may also help to mitigate the impact of E3 events. As with any mitigation approach, a detailed analysis of a particular system is required to determine the level of mitigation that is required. Additionally, the potential for unintended consequences should be evaluated on the system to ensure that normal power system operation is not adversely affected by the application of any GIC mitigation technologies. Because transmission operators are not currently provided with any warning of an impending HEMP attack, and voltage collapse due to E3 occurs rather quickly, manual operator actions are not expected to be timely enough to help mitigate voltage collapse.

Lastly, operational procedures designed to recover from voltage collapse resulting from E3 should consider the potential effects of E1 and E2 on critical electronic systems. The ability of E1 to damage communications systems, supervisory control and data acquisition (SCADA) systems, and protection and control is a major concern since loss of these functions can adversely affect system recovery efforts. Therefore, electromagnetic pulse (EMP) hardening of critical electronic systems within transmission control centers, black-start units, and substations included in cranking paths should be considered.

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VOLTAGE STABILITY ASSESSMENT

Background

Depending on the height of burst and weapon yield, the exo-atmospheric detonation of a nuclear weapon can generate a substantial low-frequency electric field at the earth's surface [1]. The resulting geoelectric field, referred to as *magnetohydrodynamic electromagnetic pulse (MHD-EMP)* or *E3*, induces very low frequency currents in the bulk power system. Similar to effects from a severe geomagnetic disturbance (GMD), these geomagnetically induced currents (GICs) can cause part-cycle saturation of bulk power transformers. The response of bulk power transformers experiencing part-cycle saturation includes additional reactive power absorption and generation of harmonic currents, as well as additional hot-spot heating in transformer windings and structural parts. The increase in reactive power absorption and generation of harmonic currents can lead to additional effects that include voltage collapse of the bulk power system. In fact, it has been well established that the effects of the additional reactive power absorption and harmonic currents generated by part-cycle saturated transformers were the root cause of the March 13, 1989, blackout that occurred in the Hydro-Québec service territory during a severe GMD event [2].

The following assessment was performed to determine the potential for instability or cascading resulting from E3 from a single, high-altitude burst over 11 notional target locations in the continental United States (CONUS). This assessment is a continuation of a previous EPRI study [3] performed to determine the potential for E3 to cause thermal damage to bulk power transformers.

As with the previous transformer thermal assessment [3], there were several considerations that were beyond the scope of this study. For example, this effort did not consider the potential contribution to voltage collapse that damage resulting from E1 or E2 might have, affecting critical electronic systems (for example, protection and control systems, or generator controls), assets (for example, insulators or instrument transformers), or loads. The potential impact of harmonics resulting from part-cycle saturated transformers was also not included in the analysis. Determining the precise geographic area or region that may experience voltage collapse was also beyond the scope of this study.

Overview

An assessment of the bulk power system located within the CONUS was performed to determine the potential for voltage collapse resulting from E3 created by a single, high-altitude burst over the CONUS. The notional target locations chosen for this study were the same as those used in EPRI's previous transformer thermal assessment [3]. The procedure that was followed to perform this voltage stability assessment is illustrated in Figure 1-1.

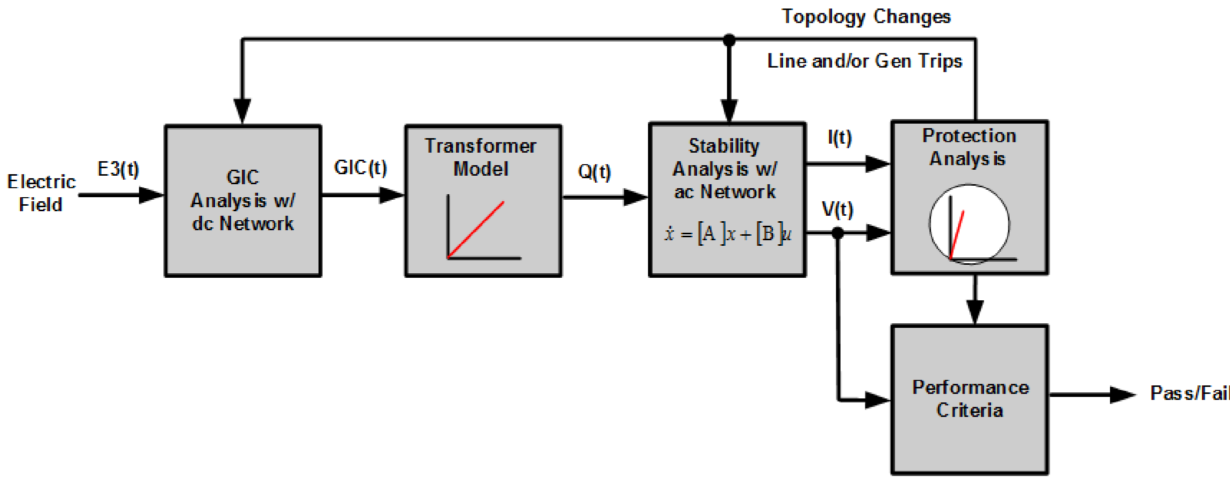

Figure 1-1
Procedure for performing voltage stability assessment of the U.S. bulk power system

The assessment procedure was as follows:

- **Step 1 – Calculate GIC Flows:** GIC calculations were performed at each time step of the simulation using the same E3 environment and dc model as described in the previous EPRI study [3]. The only modification to the GIC calculation approach presented in that study [3] was that the dc network was modified during the simulation if topological changes were initiated by protection systems (e.g., Zone 3 relay tripping of transmission lines). This allowed the GIC flows to be based on the actual system topology throughout the duration of the simulation.
- **Step 2 – Determine Reactive Power Absorption of Bulk Power Transformers Experiencing Part-Cycle Saturation:** A linear mapping of reactive power (var) absorption versus effective GIC flows in all bulk power transformers was used to estimate the amount of reactive power that was absorbed when the transformer was operating in a part-cycle saturated state. The reactive power absorption was computed at each time step.
- **Step 3 – Time-Domain Stability Analysis:** The resulting reactive power absorption provided in Step 2 was included in the ac network model as an additional constant current load located at the transformer terminals. A time-domain stability analysis was performed including these additional loads.
- **Step 4 – Time-Domain Protection Analysis:** At each time step, generator response to bus voltage at the point of generator interconnection and impedance swings as seen by the Zone 3 line relays was compared with protection settings to determine if setpoints were exceeded. At each time step, the ac and dc system models (refer to Step 1) were modified if protection operations resulted in topological changes to the system.
- **Step 5 – Analysis:** The results of stability analysis were analyzed to determine the potential for wide-scale voltage collapse.

The assessment procedure illustrated in Figure 1-1 was performed for each of the 11 notional target locations individually. In cases where the E3 environment affected multiple interconnections, each interconnection was modeled separately. To minimize simulation time and potential numerical issues associated with performing a full dynamics analysis for the full 300+ second E3 waveform, a simulation time of 112 seconds was chosen to capture the peak of the E3A and E3B waveforms as well as approximately 1 minute after the E3B peak to account for later effects of load and generation loss. A comparison of the E3 waveform that was used for this study and the full E3 waveform that was used in the transformer thermal assessment [3] is illustrated in Figure 1-2.

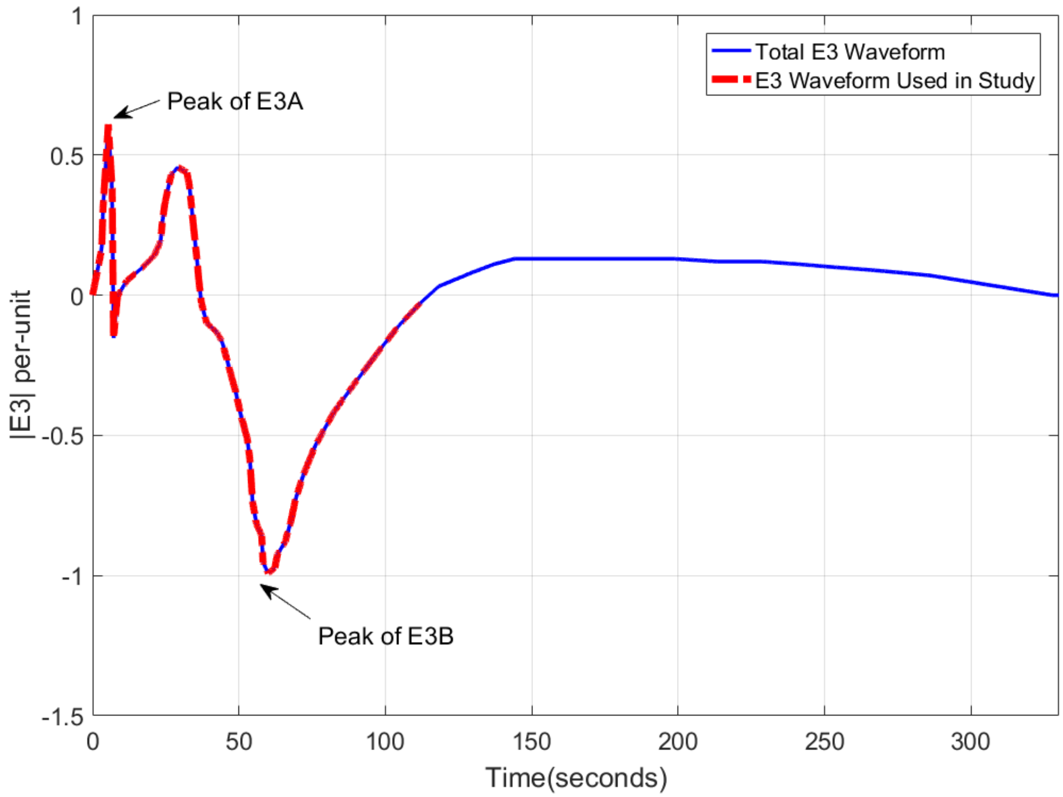

Figure 1-2
Illustration of E3 waveform used in the voltage stability study

The following section provides additional detail regarding the power system models (ac and dc) that were used to perform this assessment.

Power System Models

The modeling approach, dc network model with assumptions, and E3 environment that were used to calculate the time-series GIC flows reported in the transformer thermal assessment [3] were also used in the voltage stability analysis. For reference, the maximum geoelectric field level at the peak of the E3B wave is 24 V/km, and is located near ground zero and approximately 600 km south of ground zero [3]. Other areas experience lower geoelectric field levels. The reader may refer to pages 2-6 through 2-11 of the thermal assessment report [3] for a full description of the E3 environment that was used in this study.

The base power flow models, or cases, were taken from Federal Energy Regulatory Commission (FERC) Form 715 filings for each of the major North American synchronous interconnected power grids:

- The Eastern Interconnection
- The Western Interconnection
- The Texas Interconnection

These cases that were selected provided real and reactive power flows for summer peak conditions. They included positive sequence models of most major ac transmission lines and transformers with nominal voltages between 69 and 765 kV, major high-voltage dc (HVDC) transmission lines, power generating stations, and loads aggregated at transmission buses.

The file names and internal descriptions for each of the cases that were used in the study are as follows [3]:

- MMWG_2017SUM_2015Series_Final: 2015 Series, ERAG/MMWG Base Case Library (CEII); 2017 Summer Peak Load Case, Final
- 16HS3a: Western Electricity Coordinating Council; 2016 HS3 Operating Case; October 20, 2015
- 15DSB_2017_SUM1_Final_10152014: 15DSB-2017 Sum On-Peak Base Case - Economic - ERCOT SSWG Final - ERCOT PSSE V3340 Mod V8002

Dynamics data linked to the above cases were obtained from the Eastern Interconnection Reliability Assessment Group (ERAG), the Western Electricity Coordinating Council (WECC), and the Electric Reliability Council of Texas (ERCOT). The following subsections describe additional ac modeling details that were not included in the base power flow or dynamics data. Additional dc modeling details not included in the base power flow data and assumptions that were made are provided in the thermal assessment report [3].

Transformers

A piecewise linear function was used to model the relationship between the effective GIC flow and the increased transformer reactive power consumption. Here the values are expressed using a per-unit approach [4],

$$Q_{\mathrm{loss,pu}} = V_{\mathrm{pu}} K_{\mathrm{pu}} \, I_{\mathrm{Eff,pu}} \qquad \textbf{Eq. 1-1}$$

where $Q_{loss,pu}$ is the per-unit reactive power absorption of the transformer, K_{pu} is a per-unit scaling factor, and $I_{Eff,pu}$ is the per-unit effective GIC determined by dividing I_{Eff} by a transformer current base defined as

$$I_{base,peak} = \frac{\sqrt{2} S_{base}}{\sqrt{3} V_{base}} \qquad \textbf{Eq. 1-2}$$

where S_{base} is the nameplate rating of the transformer (VA), and V_{base} is the line-to-line voltage of the high-voltage winding (Volts). Note that with this approach, the K_{pu} values are independent of the assumed S_{base}, which makes it more suitable for large-scale analyses where specific data are not available for each transformer in the model. For this study, a K_{pu} of 1.8 was assumed for all transformers with nominal high-side voltages greater than 400 kV (all transformers at this voltage level were assumed to be single-phase), and a value of 1.5 was used for the lower-voltage transformers. The K_{pu} factor is a function of the air-core reactance of the transformer [5,6], where the 1.8 factor is representative of a transformer with an air-core reactance of approximately 0.4 per unit on nameplate ratings. Because of the linear dependence of transformer reactive power absorption on bus voltage magnitude, the additional reactive power absorption due to part-cycle saturation can be represented as a constant reactive current load [4], and this approach was utilized for this study.

Loads

Loads were represented by either the composite load model [7] or a constant impedance (Z), constant current (I), and constant power (P), or ZIP, model. A one-line diagram of the composite load model used in this study is provided in Figure 1-3.

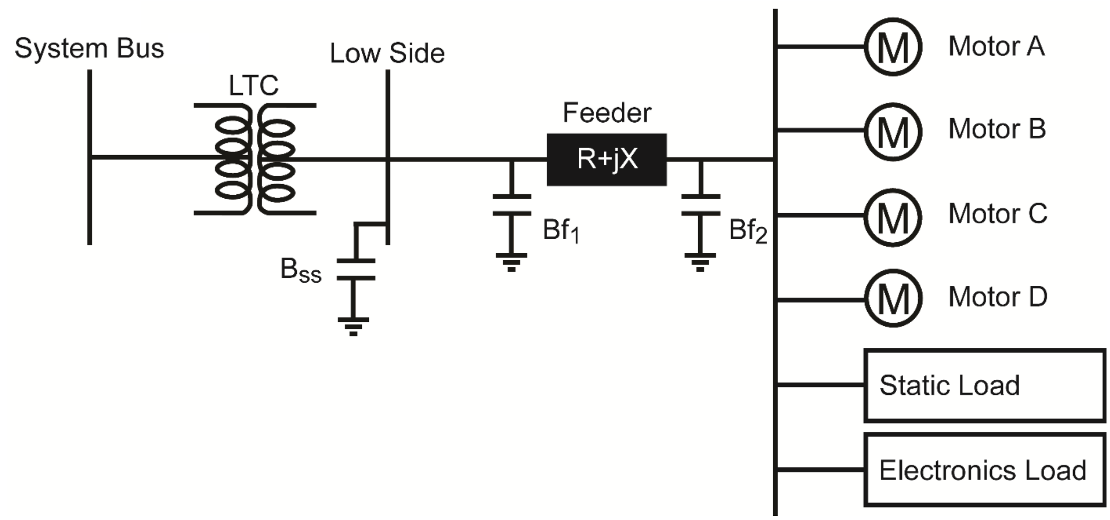

Figure 1-3
Composite load model

The composite load model illustrated in Figure 1-3 has the following components:

- **Transformer:** Step-down transformer with load tap changer (LTC) control that connects the load bus and feeder to the transmission system
- **Feeder:** Distribution feeder equivalent to connect the low-side terminals of the step-down transformer to the new loads defined below (defined as a pi-model with series impedance R + jX and shunt admittances Bf_1 and Bf_2, as shown in Figure 1-3)
- **Substation Shunt Compensation:** Shunt capacitor bank connected to the low-side terminals of the step-down transformer (shown as the shunt admittance B_{ss} in Figure 1-3)
- **Motor A:** A three-phase induction motor driving commercial air-conditioners and refrigeration, which are constant torque type loads
- **Motor B:** A three-phase induction motor driving fans, which are high-inertia loads with a load torque proportional to the square of speed

- **Motor C:** A three-phase induction motor driving pumps, which are low-inertia loads with load torque proportional to the square of speed
- **Motor D:** A single-phase induction motor driven compressor representing a residential air-conditioner
- **Static Load:** A conventional ZIP model
- **Electronics Load:** Discharge lighting

The basic parameters of the composite load model used in this study were similar across all interconnections. However, the percentages of the load makeup—for example, the percentage of Motor A, Motor B, Motor C, and Motor D—varied by control area. The EPRI Load Component Export Tool (LCET) [8] was used to develop the parameters for each control area. The dynamic response of the composite load model at a high-voltage bus during the E3 event is illustrated in Figure 1-4. In this example, the under-voltage tripping of load at approximately 55 seconds, and the corresponding impact on bus voltage, are evident.

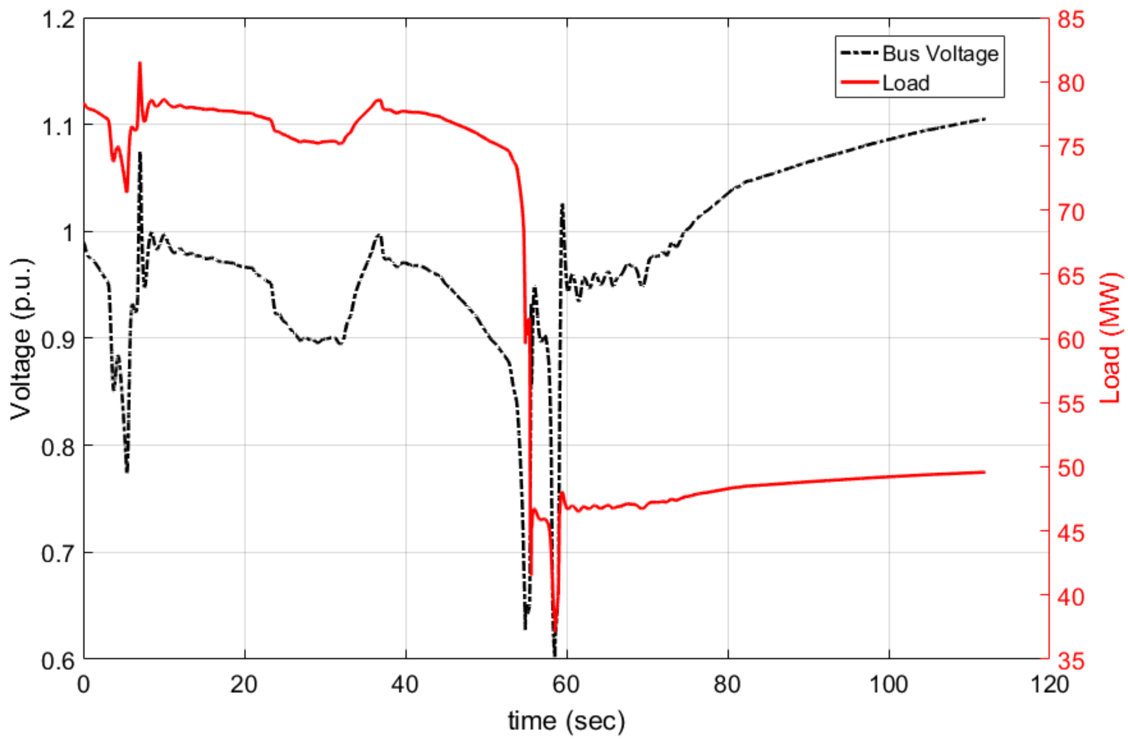

Figure 1-4
Example dynamic response of the composite load model during an E3 event

The composite load model was used as the primary load representation in the study; however, there were some exceptions. Individual loads with circuit IDs of 98, 99, or EQ were assumed to represent equivalent circuits, and were modeled with conventional ZIP load models with the real power portion of the load being modeled as a constant current and the reactive power portion of the load modeled as a constant impedance. Individual loads less than 5 MW or with a real power (P) to reactive power (Q) ratio less than 1 were also modeled using a conventional ZIP model. The breakdowns of the percentage of load modeled using the composite load model (CLM) versus a static ZIP model for the three interconnections is provided in Table 1-1.

Table 1-1
Load model distribution

Interconnection	Load Modeled with CLM		Load Modeled with ZIP Only	
	GW	% of Total	GW	% of Total
Eastern	553	84	107	16
Western	162*	94	11	6
Texas (ERCOT)	80	98	82	2

* 157 GW of this load did not include the feeder model shown in Figure 1-3.

Generators

Most faults and events analyzed in the transient stability time frame are of sufficiently short duration that over-excitation limiters (OELs) are not expected to constrain generator reactive power output. Thus, over-excitation limiter models are typically not provided for most generators included in interconnection-wide dynamic model files (*.dyr or *.dyd). However, the E3 wave is of sufficient duration (lasting approximately 5 minutes) that exciter output can be attenuated by OELs, and the event covers a large geographic region such that additional transformer reactive power losses due to part-cycle saturation can occur over a wide area. Generators without OELs modeled can respond with excessive reactive power output, providing an overly optimistic view of the system voltage response. Therefore, generic OEL models were included in this study to provide an additional level of reality and conservatism. All generators for which an OEL model was not provided in the interconnection dynamics model file were assigned the OEL4C model (refer to Figure 1-5) [9] with the following parameters:

- **Q_{ref}:** high reactive power limit, set to match the power flow limit (Q_{max})
- **T_{delay}:** the delay time between the limit being exceeded and the controller starting to act, set to 20 seconds
- **K_p:** gain for the proportional block of PI controller, set to 1
- **K_i:** gain for the integral block of PI controller, set to 1
- **V_{min}:** maximum value to change voltage reference, set to -0.2

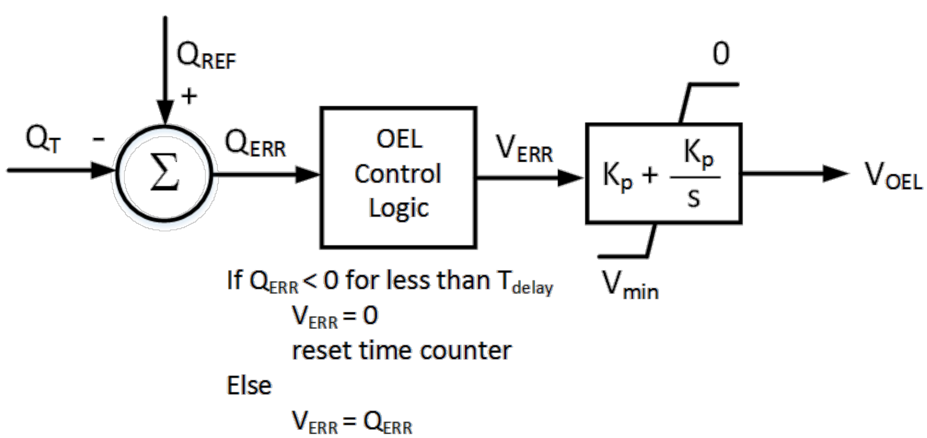

Figure 1-5
Overexcitation limiter (OEL4C)

During E3 events, the system voltage can dip below or rise above the allowable generator trip levels defined in the NERC PRC-024-2 standard [10]. These voltage levels and corresponding durations are provided in Figure 1-6 for the three U.S. interconnections.

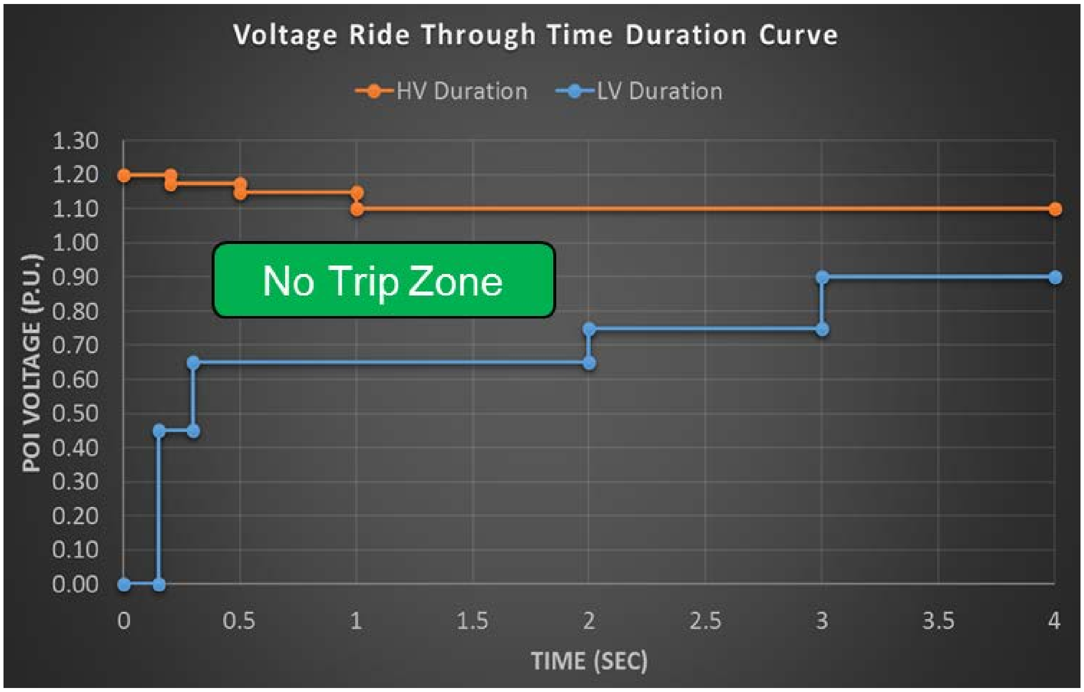

Figure 1-6
Voltage ride-through time duration curve from NERC PRC-024-2

To include the effects of potential generator tripping during periods of high or low voltage, generator ride-through capability as defined in NERC PRC-024-2 [10] was modeled at the point of interconnection (POI) using voltage relays. During the simulations, if the bus voltage at the POI was within the “no trip zone” shown in Figure 1-6, it was assumed that the generator would not trip. If the bus voltage at the POI was outside the no trip zone, the generator was tripped off-line during the simulation. It should be noted that the PRC-024-2 standard applies to ride-through requirements of interconnection relaying, and may not capture all undervoltage conditions at plant auxiliary buses that could result in tripping. This approach is consistent with modeling best practices of large-scale events such as the one evaluated in this study.

Frequency ride-through was found to be an important aspect of this study. Frequency ride-through was also assumed to meet the requirements provided in NERC PRC-024-2 [10]. The over-frequency and under-frequency ride-through capability that was included in the model is shown in Figures 1-7 through 1-9, for the Eastern Interconnection, the Western Interconnection, and the Texas Interconnection, respectively.

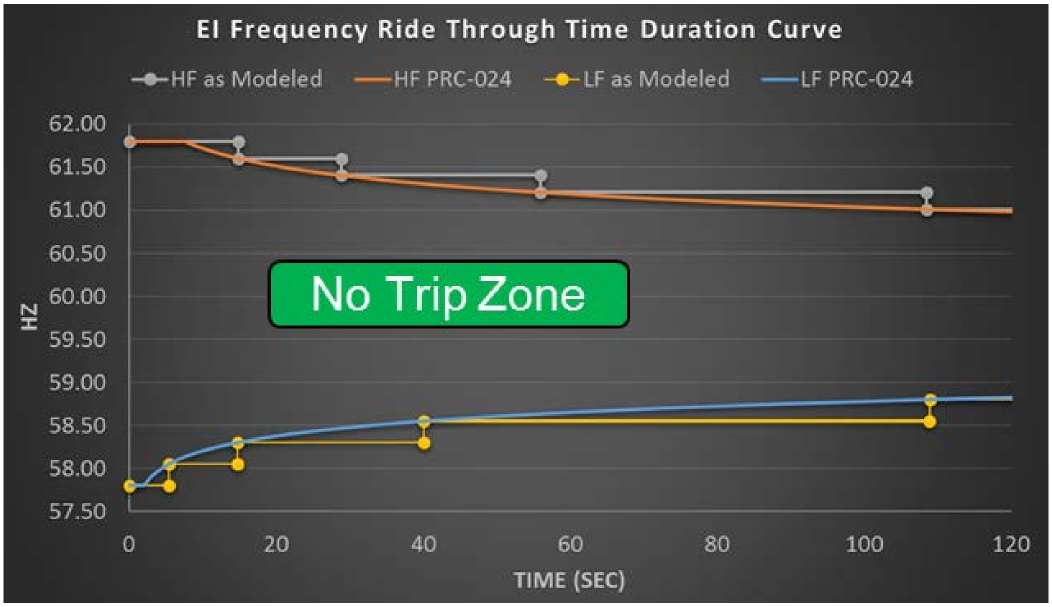

Figure 1-7
Eastern Interconnection frequency ride-through time duration curve from NERC PRC-024-2

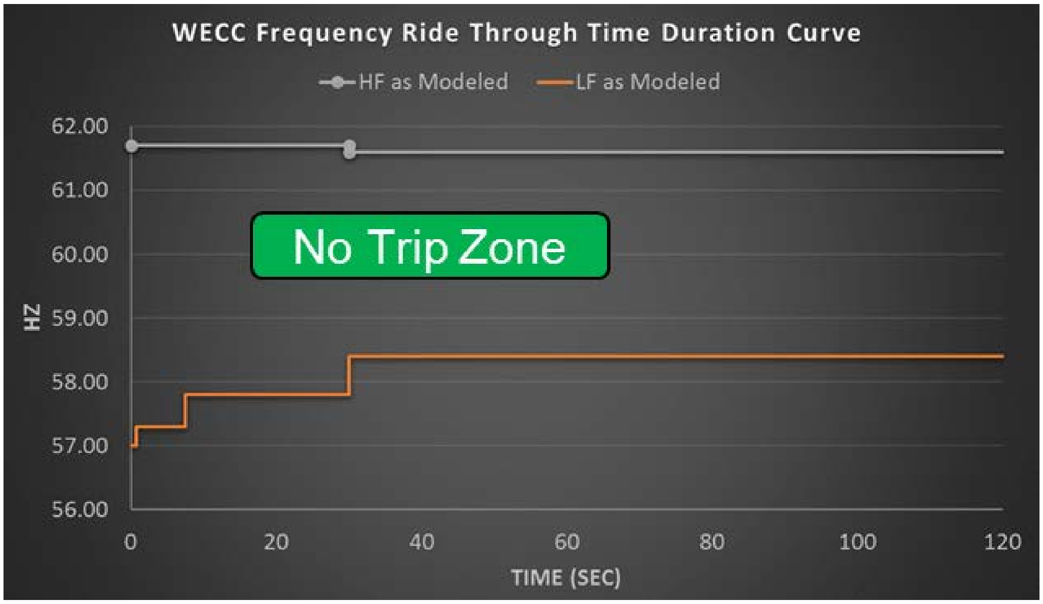

Figure 1-8
Western Interconnection frequency ride-through time duration curve from NERC PRC-024-2

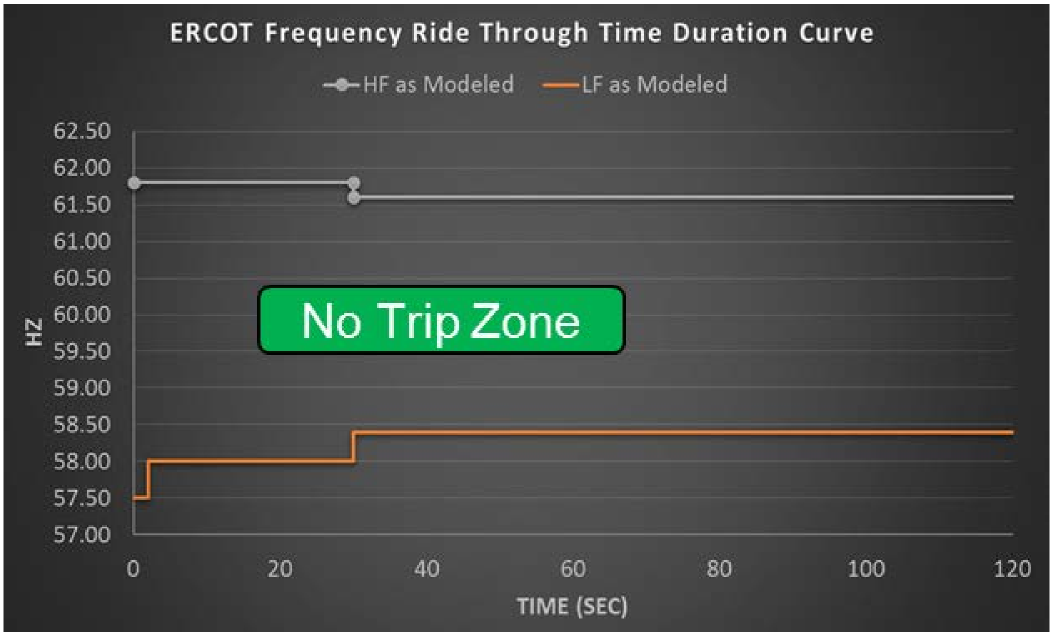

Figure 1-9
ERCOT Interconnection frequency ride-through time duration curve from NERC PRC-024-2

As shown in Figure 1-7, a stair-step characteristic was used as a proxy to map the logarithmic ride-through characteristic provided in PRC-024-2 [10].

Line Relays

The potential tripping of Zone 3 distance relays due to impedance swings during the E3 event was also included in this study. For each transmission line included in the model, a Zone 3 distance relay was included in the model. The reach of the relay was assumed to be the maximum allowable by NERC PRC-023 [11], which is equivalent to 150% of the line rating at 0.85 per-unit voltage and a power factor angle of 30 degrees. The line ratings were obtained from the power flow models for each interconnection. The Zone 3 reach was determined by

$$Z_R = \frac{Z_{30}}{\cos(\alpha - 30°)} \qquad \textbf{Eq. 1-3}$$

where

$$Z_{30} = \frac{0.85 \cdot V_{LL}}{\sqrt{3} \cdot 1.5 \cdot I_{rat}} \qquad \textbf{Eq. 1-4}$$

V_{LL} is the line-to-line voltage (V), I_{rat} is the rated line current (Amps), and α is the line angle (degrees), which for this study was assumed to be equal to the angle of maximum torque (AMT). The relay “reach” in terms of the percentage of the protected line was determined using the positive sequence line impedance provided in the power flow case. The resulting relay reach (mho characteristic) is illustrated in Figure 1-10.

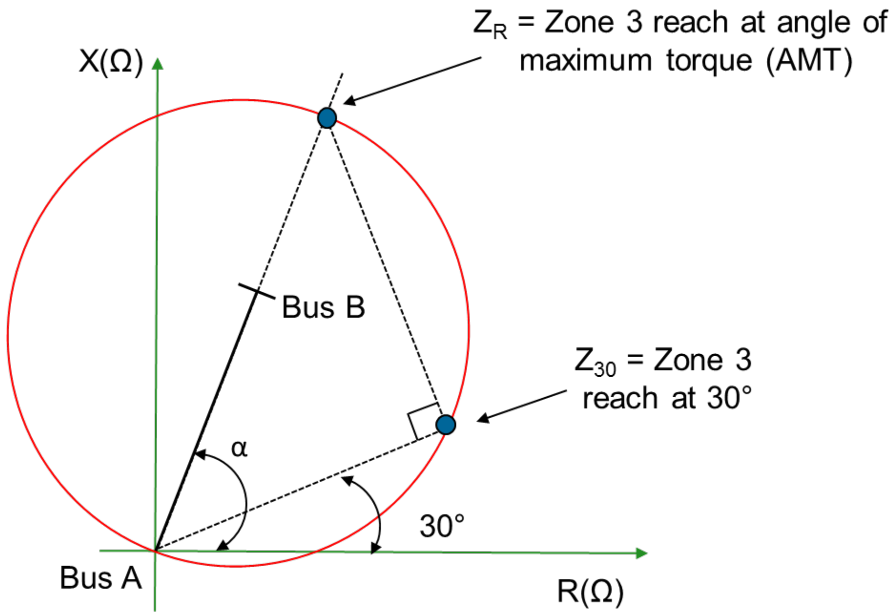

Figure 1-10
Zone 3 relay characteristic

A time delay of 60 cycles (1 second) was used to determine if a tripping action was required.

Performance Criteria

For purposes of this study, the term *voltage collapse* was defined as a condition where the voltage profile in a significant part of the power system following the E3 event was found to be unacceptably low. Thus, the primary goal of the assessment was to estimate, using detailed simulation results and engineering judgement, whether or not a significant portion of the system could experience voltage levels that were low enough to disrupt the normal operation of the bulk power system, potentially leading to a total loss of power in a given area.

For each of the 11 notional target scenarios that were investigated, several parameters were monitored, including bus voltage and frequency, area of impact, and amount of load and generation loss that occurred during the 112-second simulation period. The bus voltage and frequency for an example scenario are shown in Figures 1-11 and 1-12, respectively. The results shown in these figures are for the small areas (one north and one south of ground zero) where the geoelectric field is at a maximum—that is, 24 V/km peak during E3B. The y-axis of Figure 1-11 represents the per-unit bus voltage, and the x-axis represents time (seconds). The y-axis of Figure 1-12 represents the bus frequency (Hz), and the x-axis represents time (seconds).

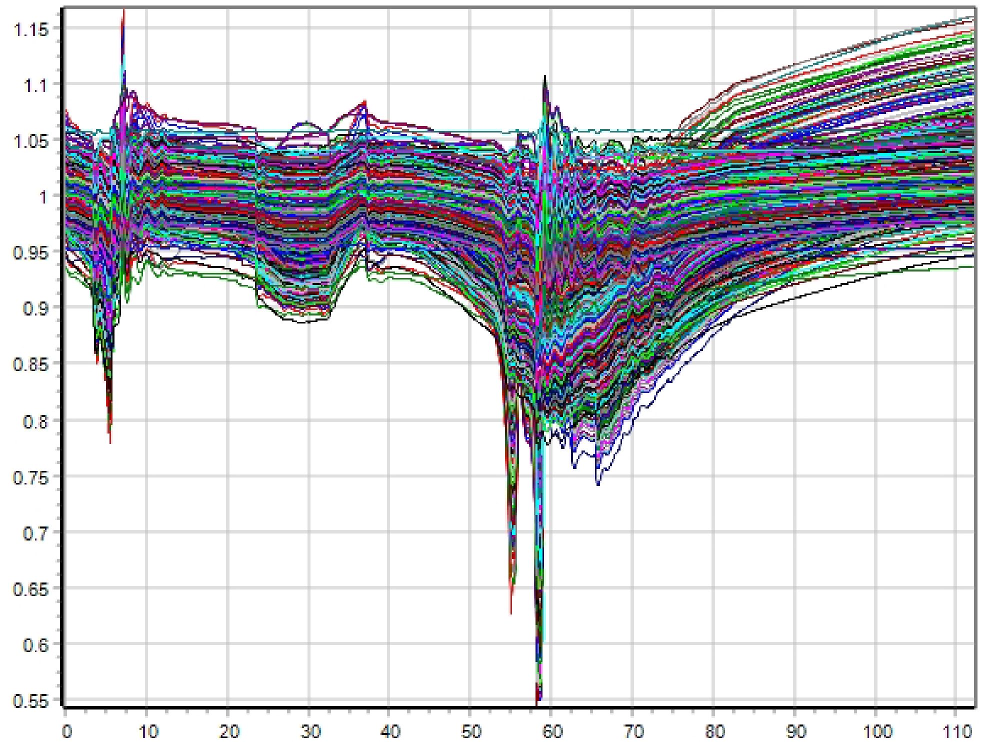

Figure 1-11
Per-unit bus voltages as a function of time

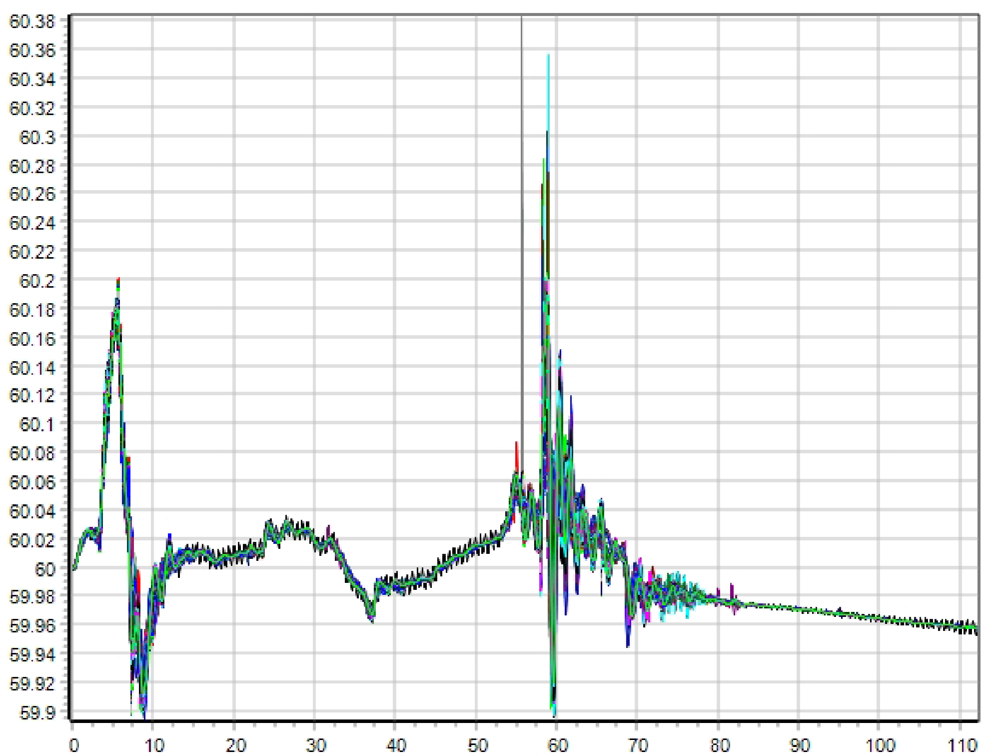

Figure 1-12
Bus frequencies as a function of time

The geographic extent of the voltage excursions for this scenario is illustrated in Figure 1-13. Figure 1-13 represents a “snapshot” of the voltage deviation at each bus in the system from its initial value (i.e., the value at the beginning of the simulation) at the peak of the E3B waveform (t = 60 seconds).

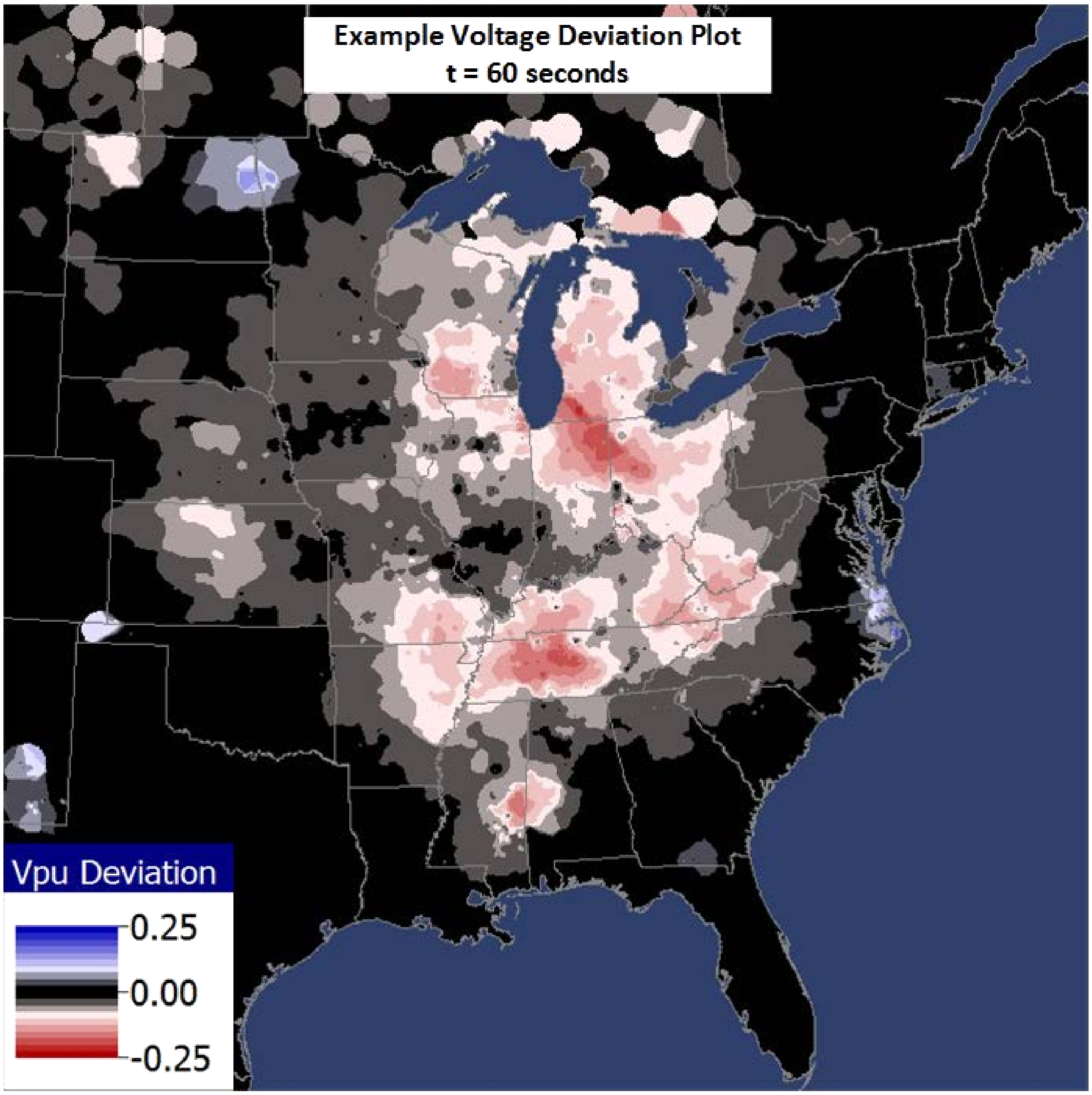

Figure 1-13
Example area of bus voltage deviation in per-unit from the initial value at t = 60 seconds

As a part of the assessment, the total generation that was tripped, the total load that was tripped, and whether or not the simulation failed to converge numerically were captured during each simulation.

When the simulation failed to converge numerically, the cases were investigated to ensure that the lack of convergence was the result of system instability and not data or modeling errors. Thus, for the purposes of this assessment, lack of numerical convergence was indicative of a potential voltage collapse scenario. All simulation results—for example, the amount of generation and load that was tripped during the simulation, plots of the system frequency and bus voltage as a function of time (refer to Figures 1-11 and 1-12), and wide-area views of system voltage deviation (refer to Figure 1-13)—and engineering judgement were used to estimate the potential for voltage collapse to occur. This information and engineering judgement were also used to estimate the geographical area that might experience voltage collapse due to the additional reactive power absorption of bulk power transformers. The use of engineering judgment in wide-scale assessments such as this is consistent with prior studies sponsored by the U.S. government, for example Meta-R-321 [12].

Assessment Results

The assessment results for the 11 notional target locations are provided in Table 1-2. The results provided in Table 1-2 for a given target location are the amount of generation and load that was tripped during the simulation, how long the simulation ran, and whether or not the simulation achieved numerical convergence throughout the simulation period. An indication of whether or not voltage collapse was predicted to occur is also included in Table 1-2. As previously mentioned, the 11 target locations shown in Table 1-2 should be viewed as 11 separate and distinct studies. Results from individual target locations should not be combined.

Table 1-2
Results of voltage stability analysis

Target Location	Interconnection	Generation Tripped (MW)	Load Tripped (MW)	Simulation Time (Sec)	Simulation Converged (Yes/No)	Voltage Collapse (Yes/No)
L01	A	12,001	5,440	112	Yes	No*
L02	A	11,066	5,598	112	Yes	No*
L03	A	27,543	13,654	112	Yes	Localized Possible**
L04	A	11,767	22,083	61.05	No	Yes
L05	A	50,729	60,303	60.87	No	Yes
L06	A	25,864	13,000	112	Yes	Localized Possible**
L07	A	15,320	8,309	112	Yes	No*
L07	B	81,149	25,715	8.33	No	Yes
L08	B	81,149	25,709	8.33	No	Yes
L09	C	5,789	4,852	112	Yes	No*
L10	C	8,162	5,317	112	Yes	No*
L11	C	10,482	9,749	56.5	No	Yes

* Automatic generation control (AGC) and/or operation of under-frequency load shedding schemes would be necessary to maintain system frequency beyond the 112-second simulation period, and the inability to perform these functions could result in instability.
** Simulation results indicate bus voltages would eventually recover, but a large area (the size of a state or more) experienced significant voltage depression (0.5 per-unit or less) at the peak of the E3B. Localized voltage collapse is possible.

2
MITIGATION AND RECOVERY

Mitigation Options

The results of the study indicate that regional voltage collapse from E3 is possible; however, the impact of E3 on the bulk power system can potentially be mitigated by reducing or blocking the flow of GIC in bulk power transformers. Mitigation could potentially be accomplished with neutral grounding resistors, capacitive blocking devices, series capacitors, or a combination of these approaches [13,14]. Designing protection and control systems so that they are immune to power system harmonics, and adding automatic switching and load shedding schemes, may also improve resiliency to E3 events [14]. Because transmission operators are not currently provided with any warning of an impending HEMP attack, and voltage collapse occurs rather quickly, manual operator actions are not expected to be timely enough to mitigate voltage collapse.

As with any mitigation approach, a detailed analysis of a specific system is required to determine the level of mitigation that is required, and this step was beyond the scope of this study. The potential for unintended consequences should be evaluated to ensure that normal power system operation is not affected by the application of any GIC reduction technology. The reader is referred to other EPRI reports [13,14] for additional detail regarding the application of GIC reduction and blocking technologies in the bulk power system.

Recovery From E3-Induced Voltage Collapse

Part of the efforts to improve HEMP resiliency of a particular system may include recovery efforts in lieu of or in addition to installing devices to reduce or block the flow of GICs in bulk power transformers and thus minimize the impact of E3 on the system. However, operational procedures designed to recover from voltage collapse resulting from E3 should consider the potential damaging effects of E1 and E2 on critical electronic systems such as communications systems, supervisory control and data acquisition (SCADA), and protection and control systems. Damage to these systems is the primary concern, since loss of these functions can potentially affect system recovery. EMP hardening of critical electronic systems within transmission control centers, black-start units, and substations included in cranking paths is recommended. Until cost-effective hardening options have been identified and/or developed for use in bulk power system applications, the reader is referred to the report *HEMP Protection of Substation Control Houses* [15] for guidance on hardening substation assets against the effects of E1 and E2.

3
SUMMARY AND FUTURE WORK

Summary

A detailed time-domain stability assessment of the CONUS was performed to determine the potential for wide-scale voltage collapse resulting from E3 generated by a single, high-altitude nuclear burst over the CONUS. Ultimately, the assessment sought to answer the following question: "If a HEMP attack occurred, and an E3 environment similar to the one modeled was generated, would voltage collapse occur due to the additional reactive power absorption of bulk power transformers?"

To assess the potential for voltage collapse resulting from E3, the same 11 notional target locations selected for EPRI's previously conducted transformer thermal assessment [3] were evaluated. As with the transformer thermal assessment [3], there were several considerations that were beyond the scope of the assessment. For example, potential damage resulting from E1, and the effects of harmonic currents, were not included due to limitations in modeling and simulation.

The following observations and conclusions can be made from evaluating the simulation results, including those provided in Table 1-2.

- The GICs generated by the E3 environment that was simulated are large enough and of sufficient duration to cause part-cycle saturation of bulk power transformers over a large geographic region. For example, the geographic region associated with the E3 environment used in this study was on the order of 1,600 km x 1,600 km, so the effects of part-cycle saturation (for example, increased reactive power absorption of bulk power transformers) were observed in the simulation results over significant portions of an interconnection. However, it is important to note that while increased reactive power absorption of bulk power transformers was observed over an interconnection-scale area, the voltage collapse region was estimated to be much smaller (see additional observations below).
- The resulting transformer reactive power loss leads to a significant reduction in system voltage, ultimately leading to loss of generation and load, and in some cases voltage collapse. Loss of load in some cases also led to temporary overvoltage conditions in portions of the bulk power system (refer to Figure 1-11 for an example). These overvoltage conditions tended to be more localized, and occurred near the end of the simulation period. Overvoltage tripping of shunt devices such as capacitor banks or transformer load tap changing was not included in the model, and it is expected that these effects would reduce bus voltages in the affected areas to levels that would not be of concern from a transmission asset damage perspective.

- In 5 of the 11 target locations (L04, L05, L07, L08, and L11) the simulations failed to achieve numerical convergence at some point during the 112-second simulation period due to considerable loss of generation and load. Such a result is indicative of voltage collapse. In the case of L07, which affected two interconnections, the simulations converged for one interconnection, but not the other. Although it is difficult to precisely determine the geographic area that would be impacted by voltage collapse, for the cases that experienced voltage collapse it is estimated to be regional and on the order of several states or larger, but smaller than the Eastern or Western Interconnections.
- Numerical convergence was achieved throughout the 112-second simulation period for the remaining 6 target locations. Simulation results did not indicate voltage collapse for these locations; however, for two of the target locations (L03 and L06), the potential for localized voltage collapse was found to exist. The geographic extent of localized voltage collapse is estimated to be on the order of a single state or smaller.
- Significant loss of generation and load occurred over a wide area in all 11 cases.
- For the cases shown in Table 1-2 that did not indicate voltage collapse would occur, namely L01, L02, L07 (one of two interconnections), L09, and L10, there was a significant generation/load imbalance that existed at the end of the simulation. In each case, the amount of generation tripped exceeded the amount of load that was tripped, and this effect (negative df/dt as illustrated in Figure 1-12) was found to be evident in all of the system frequency plots (not provided in this report). Automatic generation control (AGC) and/or response of under-frequency load shedding would be required to maintain system frequency beyond the 112-second simulation period, and the inability to perform these functions could result in instability. Evaluating the potential effects of load/generation imbalance beyond the simulation period was beyond the scope of this study.
- The modeling approach and assumptions related to bulk power system loads and generation were found to be critical components of the assessment. Because of the short duration and extreme nature of the E3 environment that was simulated, the time-domain modeling approach that was used in this study was found to be superior to the steady-state power flow techniques that are often used in geomagnetic disturbance (GMD) assessments. Similar to simulations performed to determine the potential impacts of fault-induced delayed voltage recovery (FIDVR), the dynamic behavior of connected loads was found to be an important aspect of the power system model. Thus, the addition of the composite load model and the assumptions made in that load model had a considerable impact on the results of the assessment. Lastly, the inclusion of under/overvoltage and frequency ride-through capability for generators was also found to have considerable impact on the results of the assessment. Excluding these features from the model tended to yield results suggestive of a significantly lower impact.

Future Work

There are currently two principal gaps with regard to modeling the effects of HEMP on the bulk power system. First, software tools capable of modeling the combined effects of E1, E2, and E3 do not currently exist in a commercially available format. Tools exist to model the effects of E1 and E2 on small subsystems (e.g., a single transmission substation), but the impacts are not easily “rolled up” into a larger bulk power system modeling framework so that the potential impacts of damage to critical electronics and other systems that may occur prior to the onset of the E3 pulse can be included in the assessment. Additionally, the ability to consider all the potential effects of E3 (e.g., harmonics) on an interconnection scale is extremely limited. Research efforts are currently underway to improve the ability to model the combined effects of E1, E2, and E3 on an interconnection level including the effects of harmonic currents generated during the E3 portion of the HEMP environment.

The results of this assessment are based on several modeling assumptions that are described in this report and in the transformer thermal assessment report [3]. Of the modeling assumptions made, the E3 environment [16,17] that was used in both studies has the greatest level of uncertainty. While EPRI's work is based upon the best E3 environment information that is publicly available, further research could be enhanced with an updated library of unclassified E3 environments (spatial and temporal characteristics of the resulting geoelectric field) that consider, to the extent possible, present-day nuclear stockpile information, and advancements in geoelectric field calculations—for example, layered earth conductivity models and coastal effects.

4
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