Updated Late-Time High-Altitude Electromagnetic Pulse (E3 HEMP) Transformer Thermal Assessment

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Technical Update, February 2022

EPRI Project Manager

R. Horton

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Principal Investigators
R. Horton
B. Schenkman
A. Greenwood

The following organization, under contract to EPRI, provided technical support:

Texas A&M University
301 Wisenbaker Engineering Building
College Station, TX 77843-3128

Principal Investigator
A. Birchfield

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ABSTRACT

The late-time component of high-altitude electromagnetic pulse (E3 HEMP) can induce low frequency, geomagnetically induced currents (GIC) in transmission lines and power transformers that have grounded-wye winding connections. The flow of GIC in transformer windings is of particular interest because it can cause part-cycle saturation of transformer cores leading to additional reactive power absorption, additional hotspot heating in windings, and structural parts and emission of harmonic currents. Bulk-power system impacts from E3 HEMP can range from voltage collapse to transformer overheating and possible damage.

The Electric Power Research Institute (EPRI) previously studied the potential for E3 HEMP to cause voltage collapse and transformer damage and has communicated those results in a series of publicly available reports. The focus of this study is to reassess the potential impacts of E3 HEMP on transformer hotspot heating using an additional E3 HEMP environment comprising waveform and amplitude data provided by the U.S. Department of Energy and spatial component provided by the EMP Commission. Additional transformer thermal models that were not available at the time of previous EPRI studies were also used in this updated assessment. Prior study results were updated to include the new transformer thermal models, and updated results from those prior studies are also compared with the latest results to provide additional context.

Keywords

Geomagnetically induced current
GIC
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PRIMARY AUDIENCE: Asset owners and operators of the U.S. bulk-power system

SECONDARY AUDIENCE: Regulators, state and federal entities, and other stakeholders

KEY RESEARCH QUESTION

The key research question addressed was to determine whether a high-altitude electromagnetic pulse (HEMP) E3 environment comprising waveform and amplitude data provided in the January 11, 2021, U.S. Department of Energy (DOE) memo and spatial component provided by the EMP Commission is more severe than E3 HEMP environments previously used in Electric Power Research Institute (EPRI) transformer thermal assessments. Additional transformer thermal models that were not available during previous EPRI studies were also used in this updated assessment.

RESEARCH OVERVIEW

The focus of this study was to reassess the potential impacts of E3 HEMP on transformer hotspot heating using new E3 HEMP environment data and transformer thermal models that were not available at the time of previous EPRI studies. Prior study results using a high-fidelity E3 HEMP environment provided by Los Alamos National Laboratory were also updated to include the new transformer thermal models.

The same 11 notional target locations used in EPRI's February 2017 and April 2019 E3 HEMP transformer thermal assessments were reevaluated using the new E3 HEMP environment. The E3 HEMP environment consisted of an E3B temporal component (E-field peak amplitude and waveform) that was provided in the January 11, 2021, DOE memo and a spatial component (E-field direction and magnitude based on geographic location) that was derived from an EMP Commission report published in 2018 (The spatial component was not included in the January 11, 2021, memo so an alternative data source was required). Two threat levels were considered: 1) existing threat (25 V/km) and 2) potential future threat (50 V/km).

In the transformer thermal assessment, total hotspot temperatures in transformer windings and structural parts due to part-cycle saturation caused by geomagnetically induced current (GIC) flow and an assumed loading condition were calculated using the E3 HEMP environment. To provide a worst-case scenario for transformer hotspot heating, it was assumed that the system remained stable throughout the duration of the HEMP event. The resulting time-domain GIC flows for each transformer included in the interconnection-scale model were then used as input to 89 different transformer thermal models to provide a broad range of potential impacts. The maximum peak temperature from the 89 models was compared, for each transformer, with temperature limits derived from IEEE Std. C57.163 to determine the expected number of transformers at potential risk of thermal damage. Results from the current study as well as prior studies are provided for comparison. Additionally, assessment results from the April 2019 study using a high-fidelity E3B environment (35 V/km) provided by Los Alamos National Laboratory (LANL) were updated to include 84 additional transformer thermal models (89 total thermal models) that were not available at the time of the previous study.

KEY FINDINGS

- The potential impact of the new E3B environments (25 V/km and 50 V/km) on transformer hotspot heating was found to be less severe than the LANL E3B environment (35 V/km) used in the 2019 EPRI study. The worst-case location using the new E3B environment at 50 V/km resulted in 8 transformers being at potential risk of thermal damage, while the same study using the LANL E3B environment identified 49 transformers being at potential risk of damage.
- An analysis of the updated results using the LANL E3B environment with the additional transformer thermal models showed that the increase risk of thermal damage as compared with the 2019 study (five total thermal models) was the result of a single autotransformer design. When this single model was removed (88 total thermal models vs. 89), the expected number of transformers at potential risk of thermal damage was similar to the results of the April 2019 study.
- The number of transformers at potential risk of thermal damage from the LANL E3B environment was found to be approximately 6 times higher (49 vs. 8) than the DOE/EMP Commission environment even though the new environment had a 42% higher E-field amplitude (50 V/km vs. 35 V/km). This disparity is due to differences in the temporal and spatial aspects of the two environments. The LANL E3B environment covers a much larger geographic area, and its spatial component is time varying. Thus, the spatial component of E3B can be as important, if not more, than the temporal component.
- Transformers that are in good operating condition are less likely to experience thermal impacts from hotspot heating due to E3 HEMP as compared with transformers that are in poor operating condition. Thus, proper transformer maintenance is a recommended best practice to help mitigate the effects of transformer hotspot heating on system performance.
- Future E3 HEMP environments that are developed for industry use in bulk-power system assessments should include both temporal and spatial components.

WHY THIS MATTERS

Understanding the potential impact of E3 HEMP on bulk-power system transformers is a critical component in assessing the duration that a HEMP attack could degrade the power grid. Additionally, it provides stakeholders with information that can be used to support investment decisions over the next 30–50 years. This research provides the potential impact of various E3 HEMP environments to bulk-power system transformers using high-fidelity power system analytics and a large database of transformer thermal models.

HOW TO APPLY RESULTS

The results of this study agree with earlier works, which indicate that the immediate failure of a significant number (hundreds) of large power transformers from E3 HEMP is unlikely. The assessment provides a measure of the overall risk of E3 HEMP to bulk-power system transformers in aggregate, but it does not provide the risk of specific transformers as this requires a more detailed analysis by the asset owner. Additionally, the potential impact of transformer damage on the performance of the bulk-power system was not evaluated.

EPRI CONTACT: Randy Horton, Senior Program Manager, rhorton@epri.com

PROGRAM: Substations, P37

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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1 INTRODUCTION

Background and Motivation for this Research

The late-time component of high-altitude electromagnetic pulse, E3 HEMP, can induce low frequency, geomagnetically induced currents (GIC) in transmission lines, and power transformers that have grounded-wye winding connections. The flow of GIC in transformer windings results in part-cycle saturation leading to additional reactive power absorption, additional hotspot heating in windings, and structural parts and emission of harmonic currents. Bulk-power system impacts from E3 HEMP can range from volage collapse to transformer overheating and possible damage.

The Electric Power Research Institute (EPRI) has previously studied the potential for E3 HEMP to cause voltage collapse and transformer damage and has communicated those results in a series of publicly available reports [1–3]. Since the completion of those studies, two important updates have occurred. First, the U.S. Department of Energy (DOE) released a memo on January 11, 2021 [4], that provides waveform and E-field amplitude specifications for an E3 HEMP environment. Second, ongoing EPRI research has developed 84 additional transformer thermal models since the time of the initial studies. Thus, the focus of this study was to reassess the potential impacts of E3 HEMP on transformer hotspot heating using the new E3 HEMP environment and additional transformer thermal models that are now available. Additionally, the study documented in EPRI report 3002014979 [3] was re-run using the additional thermal models to evaluate the potential impacts that these models may have on the results of the prior study.

Objective

The objective of this study was to update prior transformer thermal assessments of the U.S. transformer fleet using an E3 HEMP environment provided in the January 11, 2021, DOE memo and additional transformer thermal models that were not available at the time of prior studies. The results of the current assessment were compared with the results from prior EPRI studies to improve the understanding of how the system would respond to different E3 HEMP environments.

Scope

The scope of this study was restricted to assessing the potential thermal impacts of E3 HEMP on large power transformers located within the contiguous United States (CONUS), which includes the Eastern Interconnection (MMWG), the Western Interconnection (WECC), and the Texas Interconnection (ERCOT). Using readily available data and state-of-the-art modeling and analysis techniques, the number of transformers that would be expected to be at potential risk of thermal damage caused by the GIC generated by E3 HEMP from a single, high-altitude burst over the CONUS was estimated. The study evaluated the same 11 notional target locations used in prior EPRI studies [1–3].

Report Organization

The remainder of this report is organized as follows:

- Section 2 provides a description of the E3 HEMP environment that was used in the assessment.
- Section 3 describes the approach used to calculate GIC flows and transformer hotspot temperatures due to part-cycle saturation.
- Section 4 describes the methodology used to perform the transformer assessment.
- Section 5 provides a list of technical references that are cited throughout the report.
- Appendix A provides a technical basis for excluding E3A HEMP in transformer thermal assessments.

2
E3 HEMP ENVIRONMENT AND GIC CALCULATION PROCEDURE

The following sections describe the E3 HEMP environment and GIC calculation approach that were used in this study.

E3 HEMP Environment

The late-time component of E3 HEMP comprises two components: E3A or blast component and E3B or heave component. For this study, only the E3B component was evaluated as it is the component capable of generating GIC flows lasting for hundreds of seconds, which can result in significant hotspot heating in transformers. The technical basis for excluding E3A in transformer thermal assessments is provided in Appendix A.

In order to perform E3 HEMP assessments on a continental scale, the environment must include: 1) a temporal component, a waveform and maximum peak geoelectric (E-field) level on the ground; and 2) a spatial component that describes how the E-field amplitude and direction vary with geographic location.

The DOE E3 HEMP environment [4] includes only the temporal component and so the spatial component was derived from additional sources that included a 2018 EMP Commission report [5] and private communication with a Commission representative [6].

Temporal Component

The E3B waveform provided in the DOE memo [4] is defined for t > 0 as

$$E_{3b}(t) = -\alpha t^2 e^{-t/\gamma} \frac{\beta^3 t - 3\beta^3 \gamma + t^4}{\gamma(\beta^3 + t^3)^2} \qquad \textbf{Eq. 2-1}$$

where, $\alpha = 13 \times 10^5$, $\beta = 200$, and $\gamma = 20$.

The 50 V/km peak E-field, defined by Equation 2-1, is for possible future threats and is based on a ground conductivity of 1E-03 S/m for a mid-latitude CONUS location of 40°N. Current assessed threats have a peak E-field of 25 V/km [4].

For this study, the waveform described in Equation 2-1 was normalized and used as the temporal component at each location on the ground. The normalized waveform is shown in Figure 2-1.

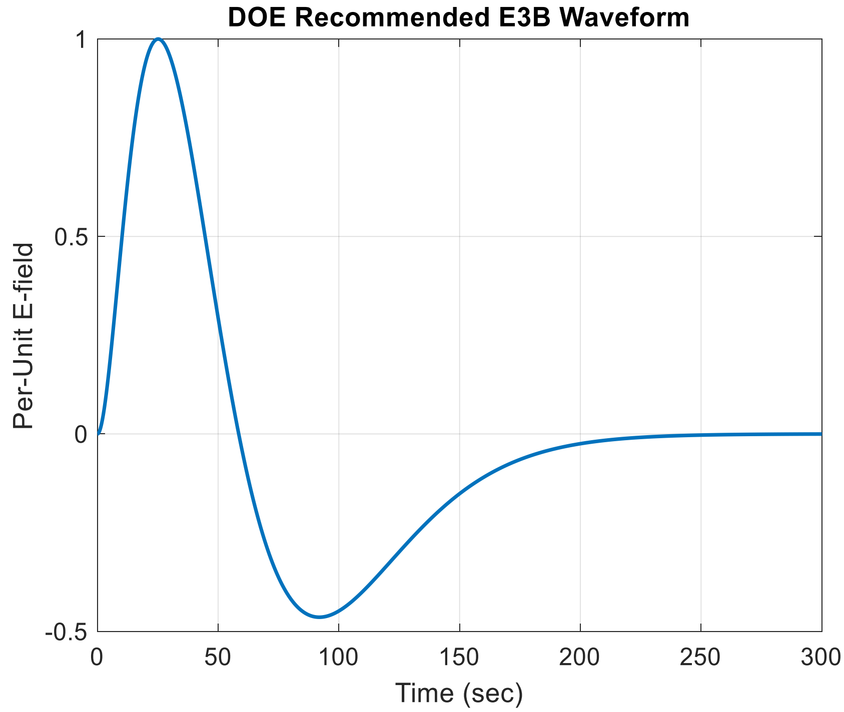

Figure 2-1
DOE recommended E3B HEMP waveform

Spatial Component

The spatial component of the E3B field was obtained from a Commission report [5] and personal communication [6] and is shown in Figure 2-2. The percent amplitudes shown in Figure 2-2 represent the percent of the peak E-field level at each geographic location shown. The direction of the E-field vectors provided and shown in Figure 2-2 remains constant throughout the simulation. This is in contrast to the LANL E3B environment where the direction and amplitude of the E-field vectors are time-varying. See Figure 2-9 of EPRI report 3002014979 [3] as an example.

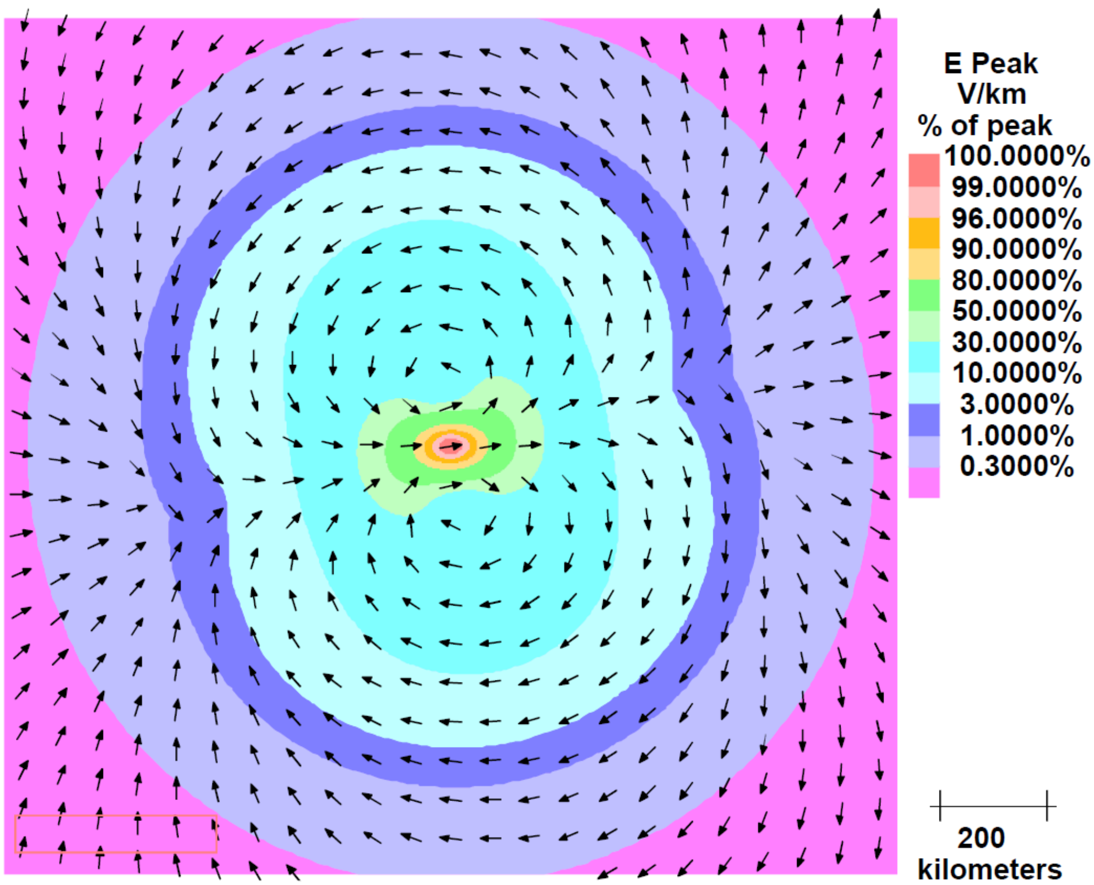

Figure 2-2
Spatial component (E-field scaling and direction) of the E3B environment [5, 6]

A notional laydown of the E3B environment is shown in Figure 2-3 to provide context to the geographic coverage this E3B environment provides. The values associated with the contour lines correspond to the peak E-field level at those locations. The peak E-field covers a relatively small area (on the order of 1,000 km^2), and the E-field amplitude is significantly reduced as one moves away from the ground zero location.

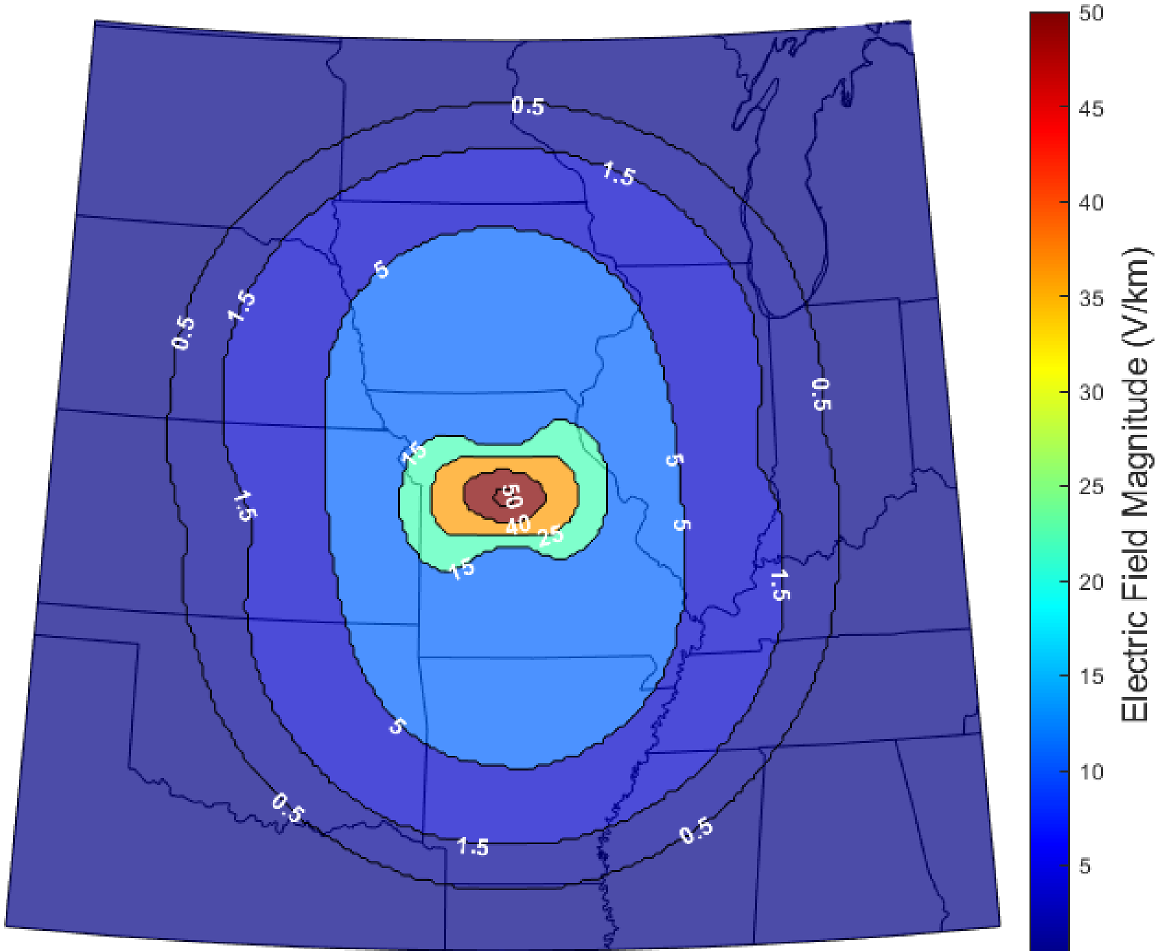

Figure 2-3
Notional laydown of the new E3B environment

3

GIC CALCULATION PROCEDURE AND THERMAL MODELING APPROACH

The following sections describe the approach used to calculate GIC flows and use them to calculate the transformer hotspot temperature due to part-cycle saturation of the transformer core.

GIC Calculations

The modeling approach used in this study to compute the time-domain GIC flows resulting from the E3 HEMP environment was the same as in previous studies [1–3]. A simplistic example of a single transmission line, a generator step-up (GSU) unit and an autotransformer are illustrated for discussion purposes in Figure 3-1.

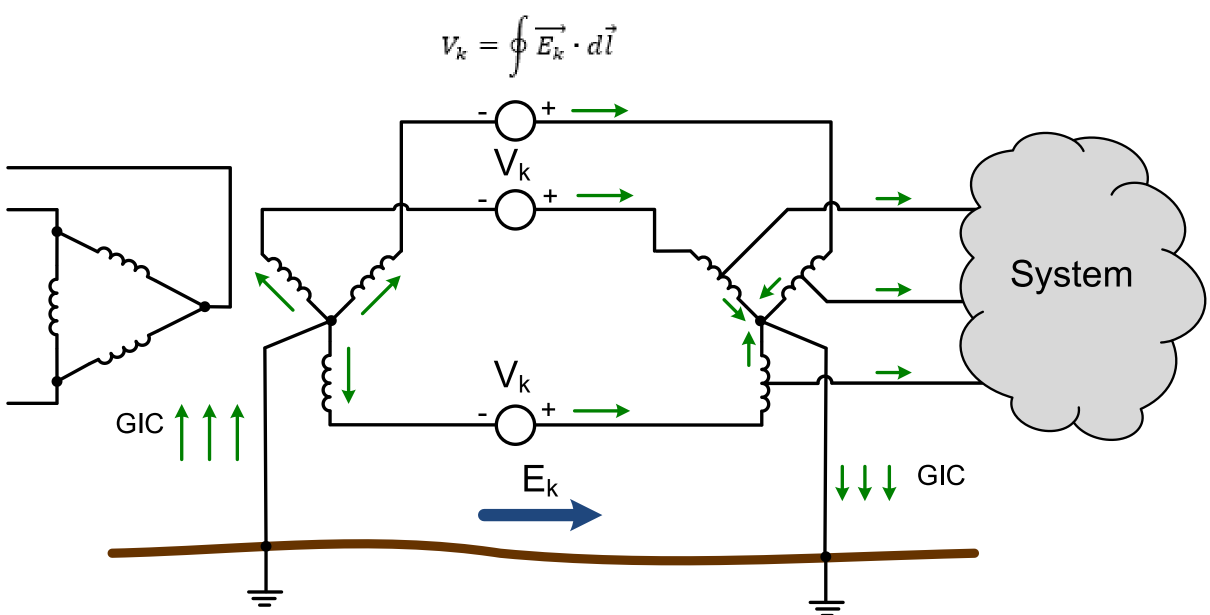

Figure 3-1
Simplified GIC calculation

The geoelectric field on the ground at the location of the transmission line, E_k, induces a voltage in the transmission line indicated by V_k. The induced voltage, in turn, drives the flow of GIC in a circuit that comprises the high-voltage GSU winding, the transmission line, and the autotransformer windings (common and series). As illustrated in Figure 3-1, the summation of the GIC flows in the common, and series windings continue into the equivalent system if the transmission line terminates into a transformer with a grounded-wye winding.

In an interconnection-scale grid where there are 10,000s of transformers and 100,000s of transmission lines over a large geographic area where the E-field is highly non-uniform, the calculation approach becomes rather complicated but can be described at a high level. The induced voltage for each transmission line, V_k, is determined by computing the path-dependent line integral of $\vec{E} \cdot d\vec{l}$. Because the E-field is non-uniform (see Figure 2-3, as an example), each transmission line is broken up into sections in order to perform the calculations. (For this study, the length of each line section was chosen to be 10 km. This length, based on past experience and engineering judgment, provides a good balance of accuracy and model complexity.) The resulting induced voltages are then combined with a very-low frequency (dc) model of the bulk-power system to compute the time-domain GIC in all transmission lines and bulk-power transformers included in the model.

To provide a direct comparison with prior studies, the power system models that were used in this study were the same as prior analyses. Specifically, the following cases shown in Table 3-1 were used in this study.

Table 3-1
Case descriptions

Interconnection	Case Description
Eastern	MMWG_2017SUM_2015Series_Final: 2015 Series, ERAG/MMWG Base Case Library; 2017 Summer Peak Load Case, Final
Western	16HS3a: Western Electricity Coordinating Council; 2016 HS3 Operating Case; October 20, 2015
Texas (ERCOT)	15DSB_2017_SUM1_Final_10152014: 15DSB-2017 Sum On-Peak Base Case—Economic—ERCOT SSWG Final

These cases include electrical models and parameters of most major ac transmission lines and transformers with nominal voltages between 69 kV and 765 kV, major high-voltage dc transmission lines, power generating stations, and loads aggregated at transmission buses. Geographic information for substations was included separately. These cases do not contain all the parameters necessary to calculate GIC flows, for example, transformer winding connections, winding resistance, or substation ground grid resistance, and so various assumptions are made. For this study, the same assumptions as previous studies were made and are documented in EPRI reports 3002009001, 3002011969, and 3002014979 [1–3].

A key assumption made in this study with regard to the power system model is that the system remains stable throughout the duration of the E3 HEMP event. Thus, GIC flows continue for the entire duration of the E3 HEMP event. Prior studies [2, 3] have demonstrated that E3 HEMP can cause voltage collapse and cascading outages. Therefore, this assumption provides a worst-case scenario for transformer hotspot heating.

Transformer Thermal Modeling

The time-domain transformer thermal modeling approach used in this study was the same as prior studies and uses a first-order differential equation to describe the thermal response of transformer windings and structural parts. The differential equation used to compute the time-domain hotspot rise due to the effective GIC flow in the transformer is provided in Equation 3-1. The derivation of Equation 3-1 is provided in EPRI report 3002009001 [1].

$$y(k+1) = K(k)\left[\left(\frac{1}{1+\frac{2\tau}{\Delta t}}\right)\left(x(k+1)+x(k)\right) - \left(\frac{1-\frac{2\tau}{\Delta t}}{1+\frac{2\tau}{\Delta t}}\right)y(k)\right] \quad \textbf{Eq. 3-1}$$

Where:

$x(k)$ and $x(k+1)$ are the *effective GIC flows* (defined as the GIC flow that causes an offset in the transformer core flux) at the current time step and the next time step, respectively (A)

$y(k)$ and $y(k+1)$ are the transformer hotspot temperature rise due to effective GIC flow at the current time step and the next time step, respectively (°C)

$K(k)$ is the asymptotic thermal response of the transformer at time-step k (°C/amp)

τ is the thermal time constant (seconds)

Δt is the time step (seconds)

The asymptotic thermal response of large power transformers experiencing part-cycle saturation has been shown to be a nonlinear function of GIC [7]. This effect can be accommodated in the model by computing K at each time step using a look-up table, denoted by $K(k)$, in Equation 3-1.

At the instant the GIC begins to flow in the transformer winding, it is assumed that the winding or structural part is in thermal equilibrium and equal to the top oil temperature. Because the time constant of the transformer oil is on the order of hours, the top oil temperature can be assumed constant during the 3- to 5-minute period associated with an E3 HEMP event. Thus, to determine the total hotspot temperature, *THS*, the hotspot rise found using Equation 3-1, is added to the top oil temperature, θ_{TO}, as shown in Equation 3-2.

$$THS = \theta_{TO} + y \quad \textbf{Eq. 3-2}$$

As with prior studies, the top oil temperature was assumed to be 80°C for all transformers [1, 3], which corresponds to approximately 92% loading if the ambient temperature is 40°C [8].

For this study, an additional 84 transformer thermal models, developed as part of EPRI's ongoing geomagnetic disturbance research [7], were also included. The models include conventional transformers, autotransformers, and GSUs. Core types include:

- Single-phase, core-form: one wound limb, two-flux return limbs (1LEG)
- Single-phase, core-form: two wound limbs (2LEG)
- Three-phase, core-form: three-wound limbs (3LEG)
- Single-phase, core-form: two-wound limbs, two-flux return limbs (4LEG)
- Three-phase, core-form: three-wound limbs, two-flux return limbs (5LEG)

Forty-two (42) different transformer designs were evaluated with two different tie bar designs each (best-case design and worst-case design), which resulted in a total of 84 additional thermal models. Parameters and details of the additional transformer thermal models that were used in this study are provided in EPRI report 3002017708 [7]. The 5 thermal models used in this 2019 study were combined with the additional 84 thermal models to yield a total of 89 thermal models that were used in the subject transformer thermal assessment.

4

TRANSFORMER THERMAL ASSESSMENT

The framework used to perform the transformer thermal assessment is illustrated in Figure 4-1.

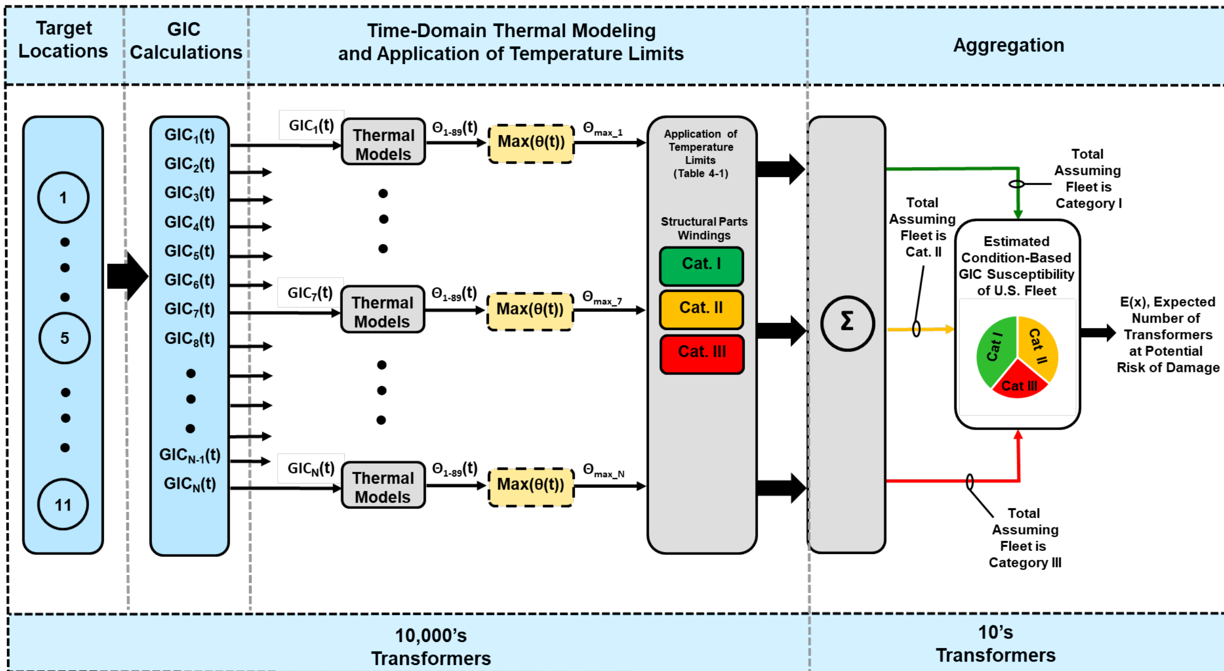

Figure 4-1
Thermal assessment process

Step 1—Identify Target Locations and Apply E3 HEMP Environment

The same 11 notional target locations across the CONUS used in previous studies were used as ground zero locations in this study. The E3B environment described in Section 2 (see Figure 2-3 as a notional target location) was centered on the ground zero location.

Step 2—Perform GIC Calculations

For each target location (single burst), the time-domain GIC flows resulting from the spatiotemporal E3B environment were computed for each transformer included in the interconnection-scale model, using the methodology described in Section 3. In general, this analysis included tens of thousands of large power transformers.

Step 3—Perform Time-Domain Transformer Thermal Calculations

The total hotspot temperature of each transformer was computed using the time-domain transformer thermal model described in Section 3. Because no information was available as to which thermal modeling parameters should be assigned to a specific transformer, the total hotspot temperature was computed using all available thermal models, and then the maximum instantaneous hotspot temperature of all the transformer thermal models was used for each transformer. An example of a hotspot calculation for a single transformer using all 89 transformer thermal models is shown in Figure 4-2.

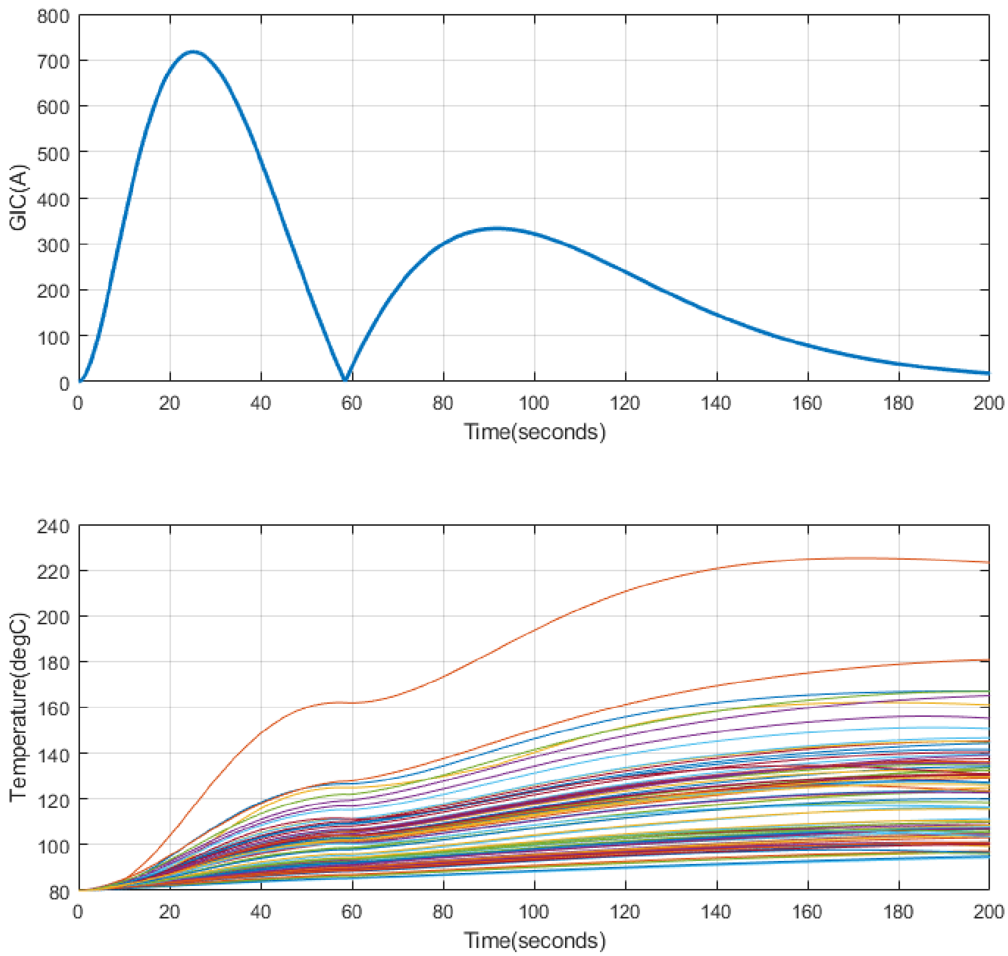

Figure 4-2
Example of hotspot calculation of transformer structural parts using all available transformer thermal models

In the example shown in Figure 4-2, the top graph plot is the GIC applied to the transformer over 200 seconds (note that the time resolution of Figure 4-2 was selected for optimal viewing; the actual simulation time was 1,000 seconds). The bottom plot is all 89 transformer thermal models and associated temperature rise based on the induced GIC. For this example, the maximum instantaneous hotspot temperature that would be used in the transformer thermal assessment would be approximately 225°C. Overall, this results in a very conservative approach for assessing the vulnerability of large power transformers to the flow of GIC.

Step 4—Apply Temperature Limits and Aggregate Results

Next, the maximum instantaneous hotspot temperatures (windings and structural parts) were evaluated against the temperature limits provided in Table 4-1. These limits were derived from IEEE Std. C57.163 [9] and an assumed transformer operating condition (GIC susceptibility categories). Temperature limits associated with each of the three operating condition categories and the corresponding percentage of U.S. transformers assumed to be in those categories are summarized in Table 4-1. Additional information regarding how these categories were identified is provided in EPRI report 3002009001 [1].

Table 4-1
Temperature limits based on the assumed transformer operating condition and percentage estimate of the U.S. transformer fleet in each category

Condition-Based Geomagnetically Induced Current Susceptibility Category	Percentage of Fleet	Hotspot Temperature Limit	
		Structural Parts (°C)	Windings (°C)
I	36%	200	180
II	25%	180	160
III	39%	160	140

The numbers of transformers that were identified as exceeding the specified temperature limits in Table 4-1 for each category (I, II, and III) were then computed. This was done by taking the maximum instantaneous hotspot temperature of each transformer and summing the number of transformers that exceeded the temperature limits assigned to each category. This calculation results in three values, and each value is the number of transformers at potential risk of thermal damage, assuming all transformers were in that specified operating condition. Using these results, Equation 4-1 was used to estimate the expected number of transformers, *E(X)*, that could be impacted including all transformer operating conditions.

$$E(X) = p_1X_1 + p_2X_2 + p_3X_3 \quad \textbf{Eq. 4-1}$$

Where:

p_1 is the probability that a given transformer is in Category I or 0.36

p_2 is the probability that a given transformer is in Category II or 0.25

p_3 is the probability that a given transformer is in Category III or 0.39

X_1 is the number of transformers exceeding the temperature limits, assuming entire transformer fleet is in Category I

X_2 is the number of transformers exceeding the temperature limits, assuming entire transformer fleet is in Category II

X_3 is the number of transformers exceeding the temperature limits, assuming entire transformer fleet is in Category III

The results of these calculations for all 11 notional target locations are provided in Table 4-2. For comparison, the results of EPRI's 2019 study [3] are also provided. The first column of Table 4-2 defines the notional target location that was evaluated. The second column shows the results from the previous EPRI study using the Los Alamos National Laboratory E3B environment, peak E-field of 35 V/km, and a limited number of transformer thermal models that were available at the time of that study [3]. The third column shows the results of the same study but supplemented with the additional 84 transformer thermal models included in the subject study. The fourth column shows the results of the same study as column 3 but assumes that all transformers are in good operating condition (Cat. I) which is equivalent to using the performance criteria described in North American Electric Reliability Corporation's white paper, TPL-007-2 [8]. The fifth column is the same as the third, but the worst-case thermal model was removed from the analysis. The sixth and seventh columns are the results of the subject study (new E3 HEMP environment) with the peak of the E3B environment being 25 V/km (current assessed threat level) and 50 V/km (potential future threat level), respectively.

Table 4-2
Estimated number of transformers at potential risk of damage

Target Location	LANL E3B Env. and Original Thermal Models (35 V/km)	LANL E3B Env. and All Thermal Models (35 V/km)	LANL E3B Env. and All Thermal Models— All Transf. in Cat. I (35 V/km)	LANL E3B Env. and All Thermal Models Except T24D2 (35 V/km)	DOE/EMP Comm. E3B Env. and All Thermal Models (25 V/km)	DOE/EMP Comm. E3B Env. and All Thermal Models (50 V/km)
1	21	44	11	21	0	4
2	17	40	7	17	1	4
3	18	49	3	19	0	3
4	5	23	2	5	0	5
5	11	24	6	11	0	8
6	8	24	1	8	0	2
7	3	15	1	3	0	3
8	12	21	0	13	0	2
9	5	13	5	5	1	5
10	10	29	4	10	0	5
11	17	44	1	18	1	4

Discussion

Transformer thermal assessment results using an E3 HEMP environment consisting of a temporal component (E-field peak amplitude and waveform) provided in the January 11, 2021, DOE memo [4] and a spatial component (E-field direction and magnitude based on geographic location) derived from a 2018 EMP Commission report show that the potential transformer damage from E3 HEMP from a single weapon detonation is expected to be minimal. The worst-case location using the new E3 HEMP environment at 50 V/km resulted in eight transformers being at potential risk of thermal damage.

The potential impact of the new E3B environments (25 V/km and 50 V/km) on transformer hotspot heating was found to be less severe than that of the LANL E3B environment (35 V/km) used in the 2019 EPRI study [3]. The worst-case location using the LANL E3B environment and the same set of thermal models yielded a worst-case scenario of 49 transformers as compared with 8 using the new E3B environment.

The inclusion of the additional 84 transformer thermal models increased the number of transformers at potential risk of thermal damage as compared with results from prior EPRI studies (column 2 vs. 3 in Table 4-2). The analysis of the results showed that the increase was caused by a single autotransformer design. When this single model was removed (88 total thermal models vs. 89), the expected number of transformers at potential risk of thermal damage was similar to the results of the April 2019 study [3] (column 2 vs. 5 in Table 4-2).

The number of transformers at potential risk of thermal damage from the LANL E3B environment was found to be approximately 6 times higher (49 vs. 8) than that of the DOE/EMP Commission environment even though the new E3B environment had a 42% higher E-field amplitude (50 V/km vs. 35 V/km). This disparity is due to differences in the temporal and spatial aspects of the two environments. The LANL E3B environment covers a much larger geographic area, and its spatial component is time-varying. Thus, the spatial component of E3B can be as important, if not more, than the temporal component.

Comparing the results of column 4 with columns 2, 3, and 5, transformers that are in good operating condition are less likely to experience thermal impacts from hotspot heating due to E3B as compared with transformers that are in poor operating condition. Thus, proper transformer maintenance is a recommended best practice to help mitigate the effects of transformer hotspot heating from E3B on system performance.

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A

TECHNICAL JUSTIFICATION FOR EXCLUDING E3A IN TRANSFORMER THERMAL ASSESSMENTS

The per-unit E3A temporal component defined in the DOE memo [4] is shown in Figure A-1.

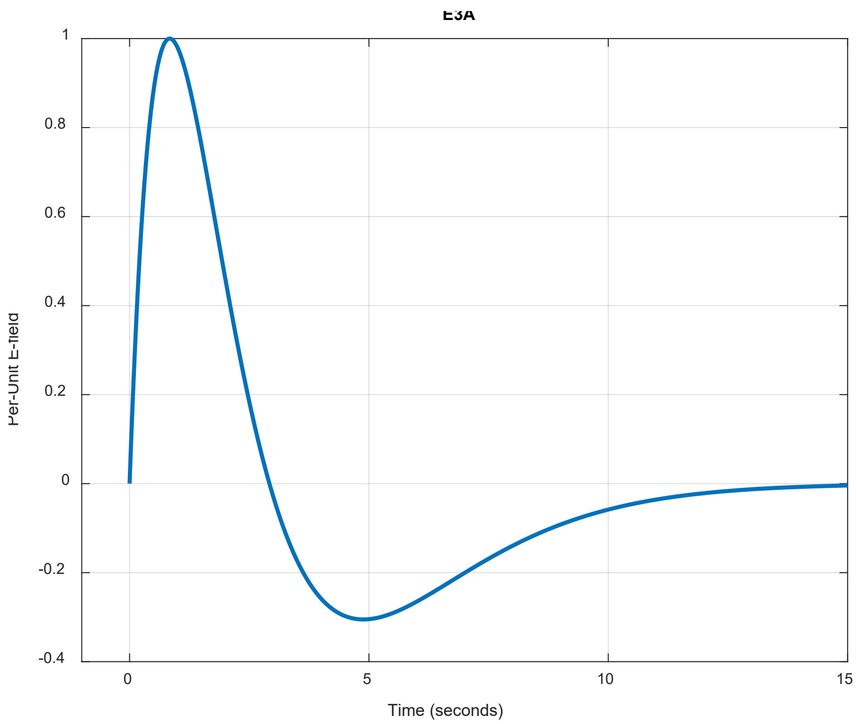

Figure A-1
E3A E-field waveform defined in the DOE memo [4]

The peak E-field for E3A is defined in the DOE memo as 40 kV/m for existing threats and 80 kV/m for potential future threats [4]. As shown in Figure A-1, the E3A field is of very short duration, lasting approximately 12 seconds.

The geographic area that is exposed to E3A fields of magnitude that is significant enough to disrupt the power grid is located to the extreme north of the ground zero location. For example, Figure A-2, taken from Metatech's report Meta-R-321 [10], illustrates the peak E-field caused by E3A. Here, it can be seen that the largest E-field occurs approximately 2,500 km north of the ground zero location. Thus, other weapon effects from E1 HEMP, E2 HEMP, and E3B HEMP are significantly reduced.

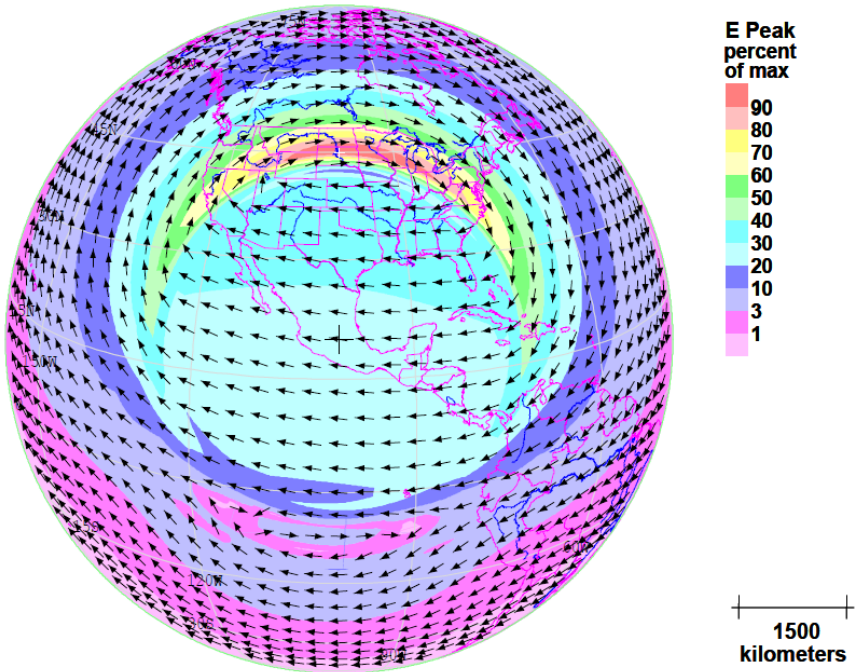

Figure A-2
Example of the E-field created by E3A HEMP [10]

Due to the resistor-inductor time constant of a typical power system, it can take 1–2 seconds for the voltage induced by a geomagnetic field to cause part-cycle saturation in large power transformers [11], as shown in Figure A-3. This provides a natural filtering effect during the initial seconds of the E3A event.

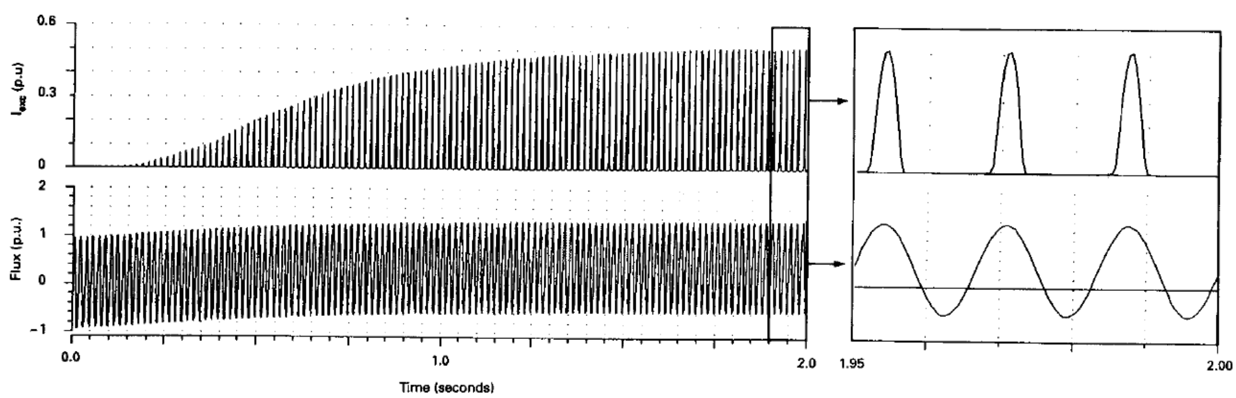

Figure A-3
Transformer flux and exciting current response to step dc voltage [11]

The second thing that minimizes the impact of E3A on transformer hotspot heating is the thermal time constants of transformer windings and structural parts. To further illustrate the potential impacts of E3A, a uniform, eastward E-field of 80 V/km was applied to the three U.S. interconnections. Table A-1 shows the maximum peak GIC resulting from these calculations.

Table A-1
Maximum GIC for a constant 80 V/km E3A E-field

Interconnection	Maximum Effective GIC (A/phase)
Eastern	3,667
Western	4,551
Texas (ERCOT)	3,079

Figure A-4 shows the response of all of the thermal models to a GIC value of 5000-A peak. Note that the GIC flow shown in Figure A-4 occurs instantaneously and ignores the 1- to 2-second time delay discussed previously. Because of the short duration of the E3A event, even a GIC flow of 5000 A does not cause the maximum instantaneous hotspot temperature to exceed any of the temperature limits provided in Figure A-4.

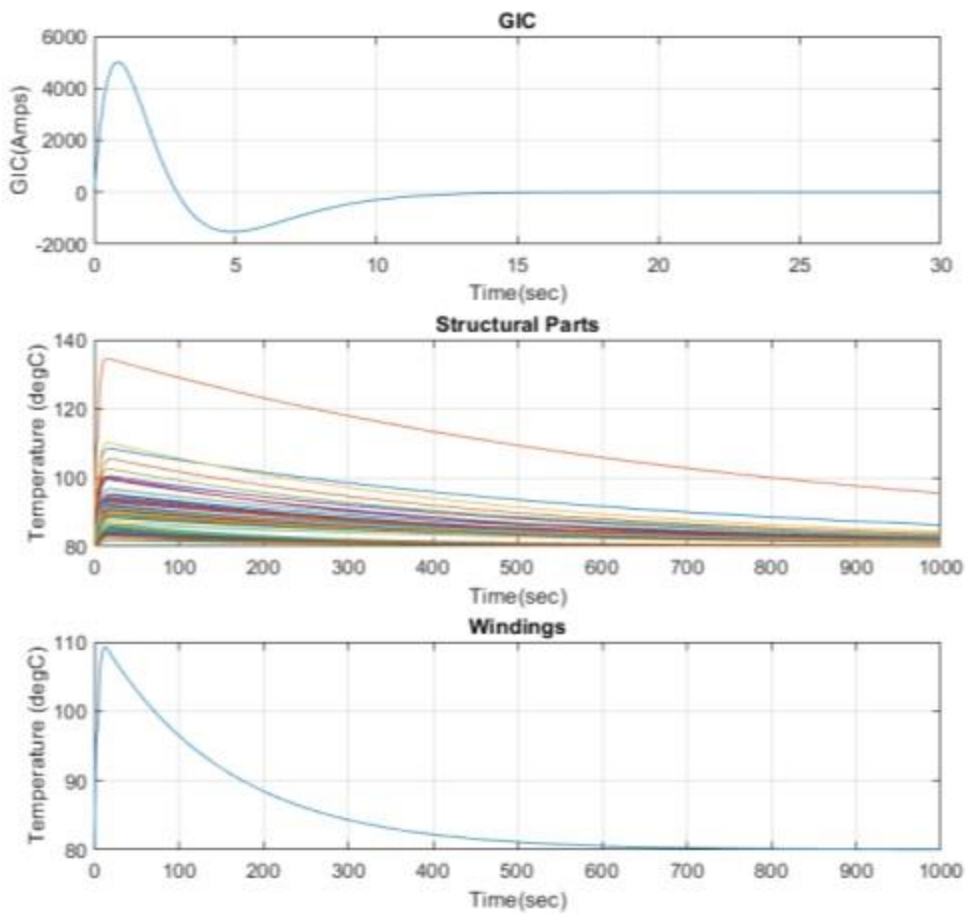

Figure A-4
Calculated hotspot temperatures using all thermal models and E3A-induced GIC flow

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EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com