MHD-EMP (E3) Assessment of the US Power Grid

GIC and Transformer Thermal Assessment

NERC Joint OC-PC Webinar
July 25, 2017

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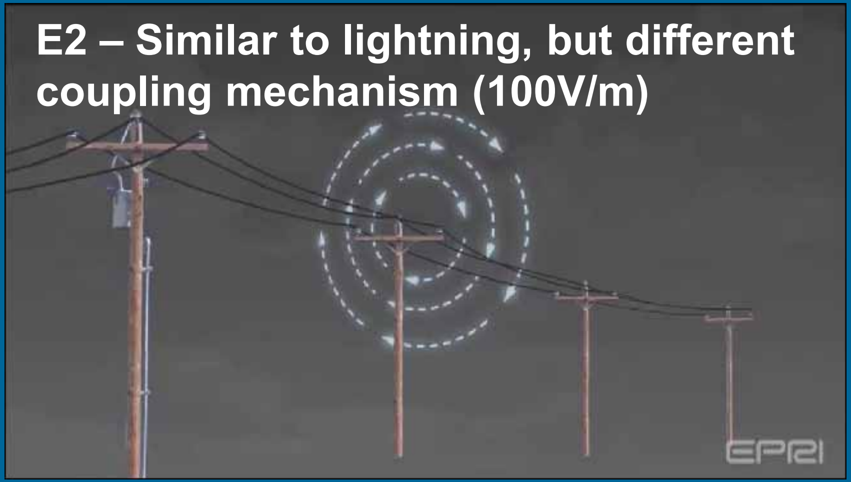
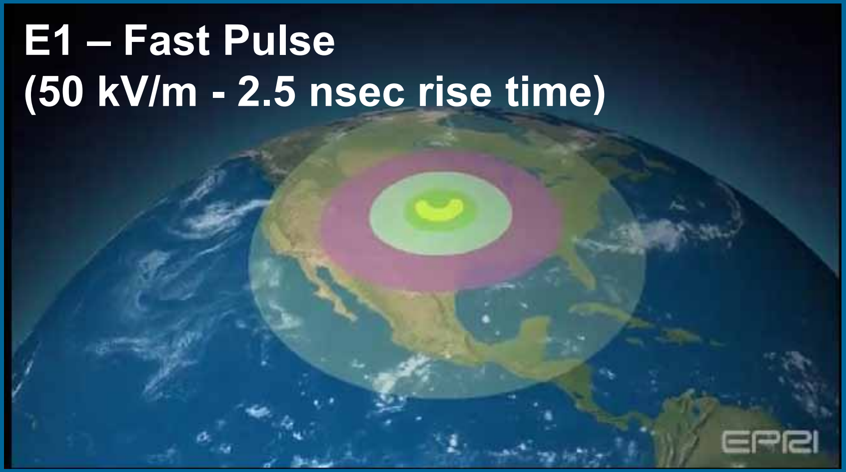
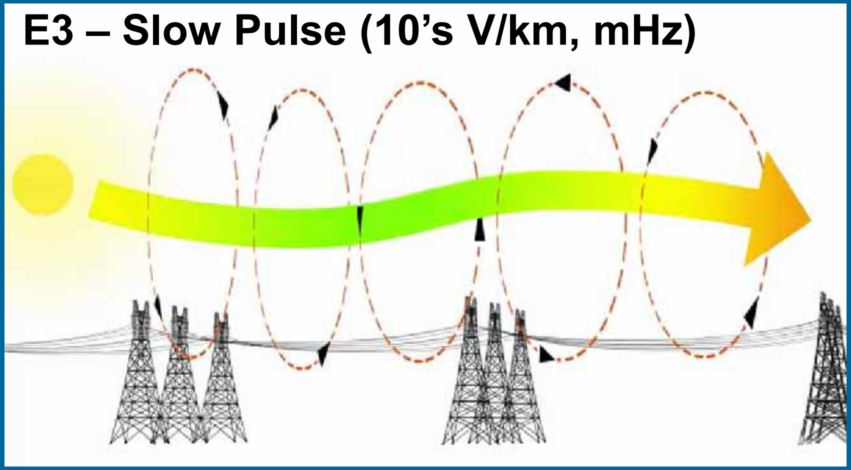
High-altitude Electromagnetic Pulse (HEMP)







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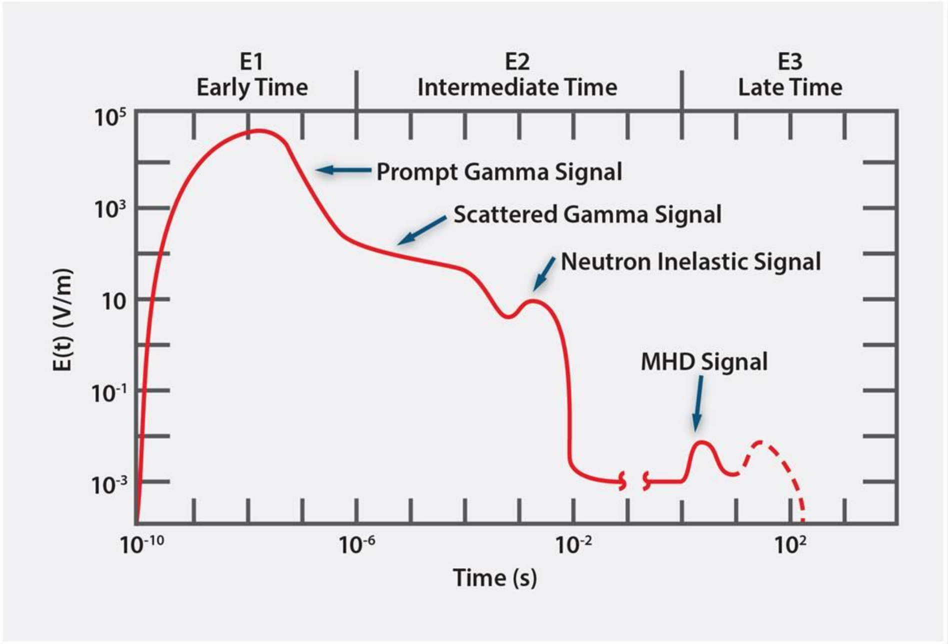
Potential Impacts of HEMP on Bulk-Power System

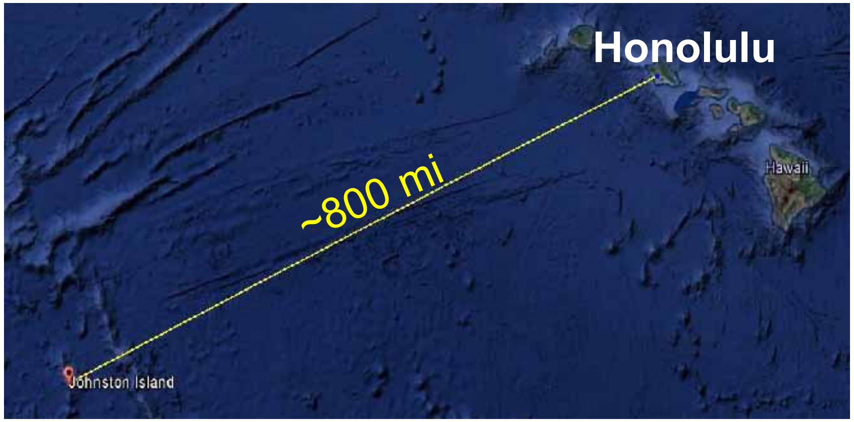
- E1 (early-time)
  - Damage to electronics
  - MV and HV insulation
- E2 (intermediate time)
  - Damage to MV insulation
- E3 (late time)
  - Voltage collapse
  - Damage to bulk-power transformers (thermal)



Historical Perspective

- The U.S. government (and others) have known about EMP for a long time.
- U.S. performed high-altitude nuclear tests in 50's and 60's to determine impacts to military infrastructure.
- Starfish Prime Test - 1.4 MT weapon detonated approximately 400 km above Johnston Atoll in the South Pacific.
- Disrupted communication systems, damaged satellites, and impacted electrical systems in Hawaii.

Starfish as viewed from Maui
July 9, 1962



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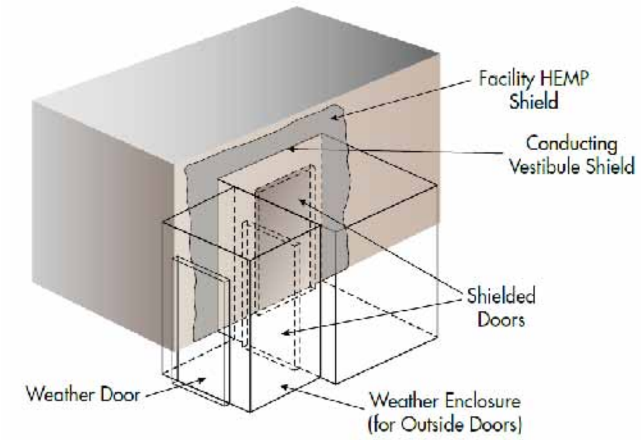
Background and Motivation for HEMP Research

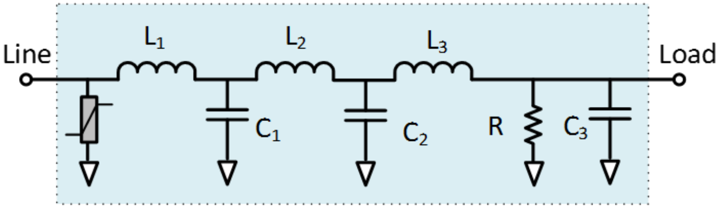
- Portrayed as a "Dooms Day" scenario in the media

- Potential for regulatory and legislative action

- MIL STD hardening options are costly and impractical in some cases

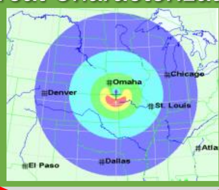


- Potential for unintended consequences



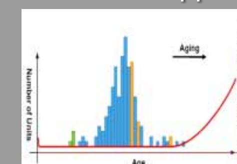
Three Year Research Plan
April 2016 – April 2019

Primary Research Focus in 2017

2016-2018
Threat Characterization


2016-2019
EMP Vulnerability


2018-2019
Trial Implementation


2018-2019
Decision Support


Impacts


2016-2019

Mitigation, Hardening and Recovery

2017-2019

2016-2019
Member and Stakeholder Communication


- Currently 58 members
- Collaborating with DOE, DOE National Labs, DoD and DHS

MHD-EMP Assessment of the Continental United States: GIC and Transformer Thermal Analysis

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

Geomagnetically Induced Current and Transformer Thermal Analysis

3002009001

CONTENTS

http://www2.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002009001

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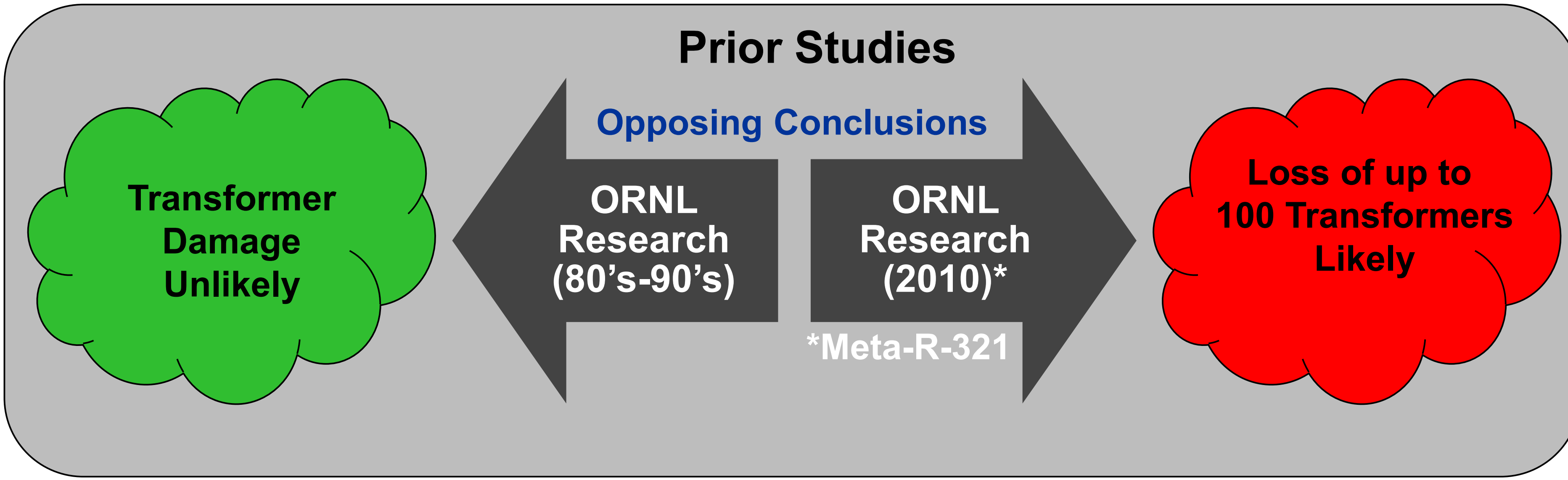
Motivation and Purpose for the E3 Assessment

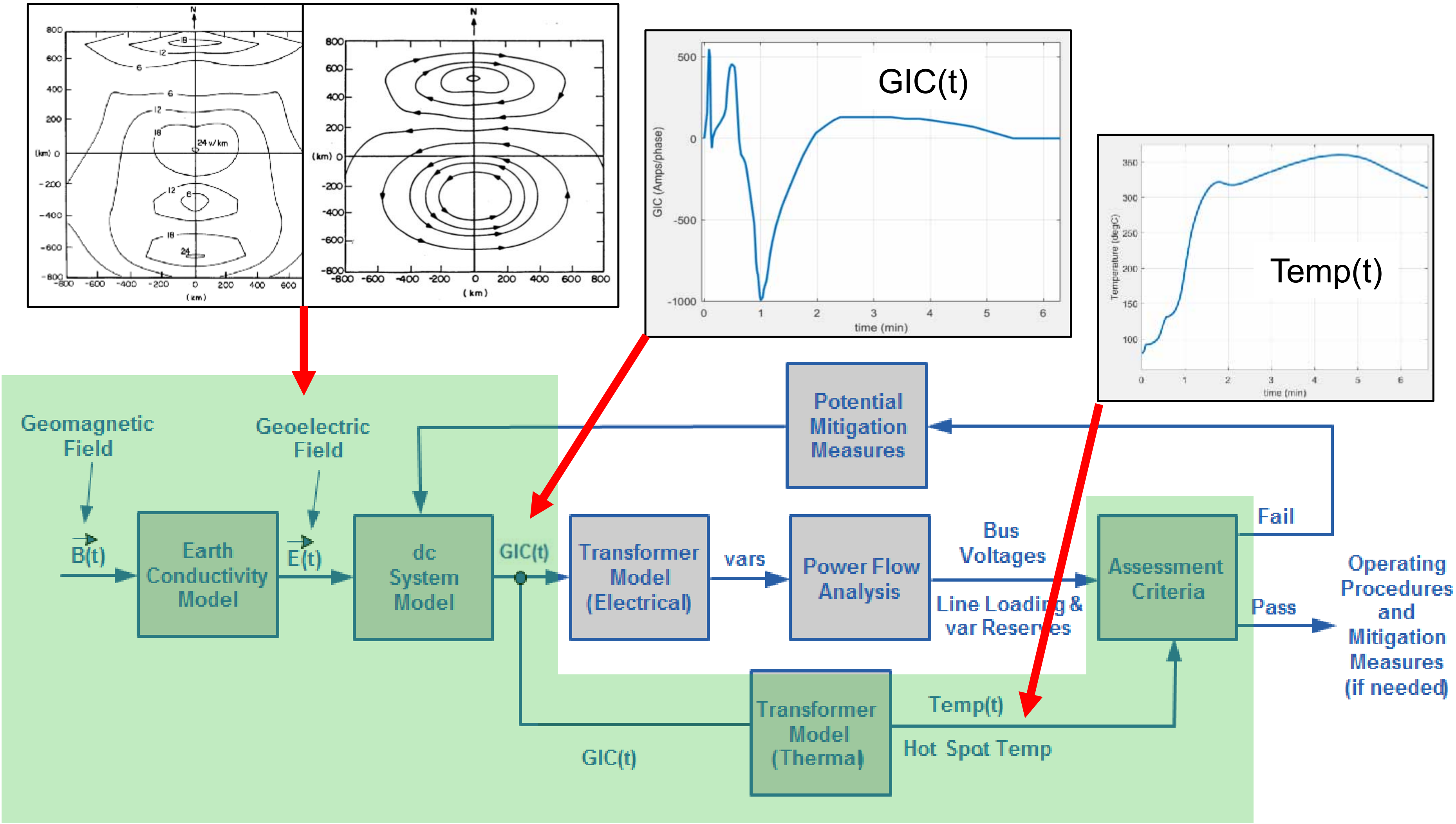
- Widespread loss of bulk-power system transformers would result in a long-term blackout.



- EPRI's analysis used the latest scientific advancements to model/assess GIC and its effects on bulk-power transformers.

Big Picture: GIC and Transformer Thermal Assessment

11 Target Locations Across the Continental U.S.



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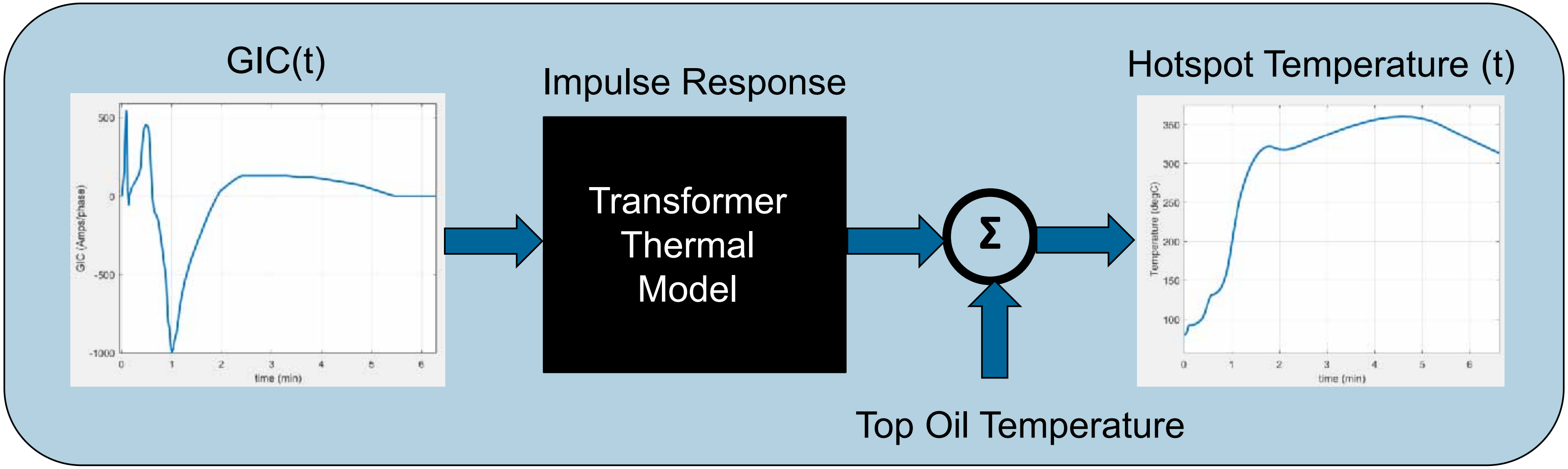
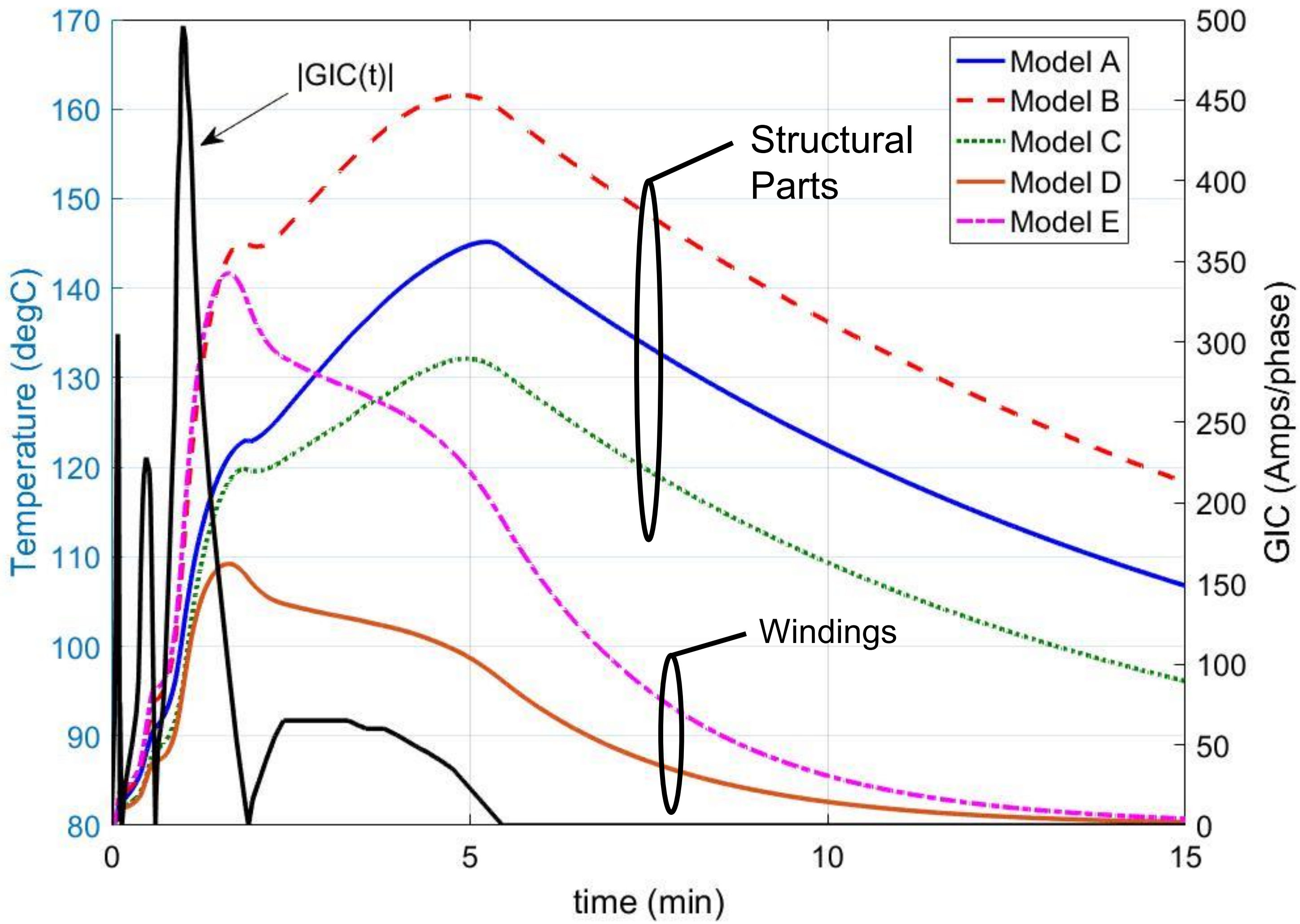
Transformer Thermal Analysis

- Time-domain thermal model was used to perform assessment.
  - Meta-R-321 assessment used GIC magnitude only as screening criteria.
- Five different conservative transformer thermal models were used to represent the U.S. transformer fleet.
- The initial (pre-event) top oil temperature of all transformers in the analysis was assumed to be 80°C regardless of pre-event loading.
- Transformers experiencing effective GIC levels less than 75 Amps/phase were assumed to be immune to thermal damage.



Example Results (Single Case)

- Example results with GIC(t) generated by MHD-EMP (E3)



Condition-Based GIC Susceptibility

- Temperature limits in IEEE C57.163 assume transformers are in new condition.

- The concept of Condition-Based GIC Susceptibility was developed to account for variability in condition of US bulk-power transformers.

- The Condition-Based GIC Susceptibility Category of a given transformer was estimated using:
  - PTX Condition Code (based on trends of dissolved gases)
  - Moisture Content in oil (transformer age was used as a proxy)

- Transformer design was accounted for in thermal models.

Performance Criteria

Condition-based GIC Susceptibility Categories

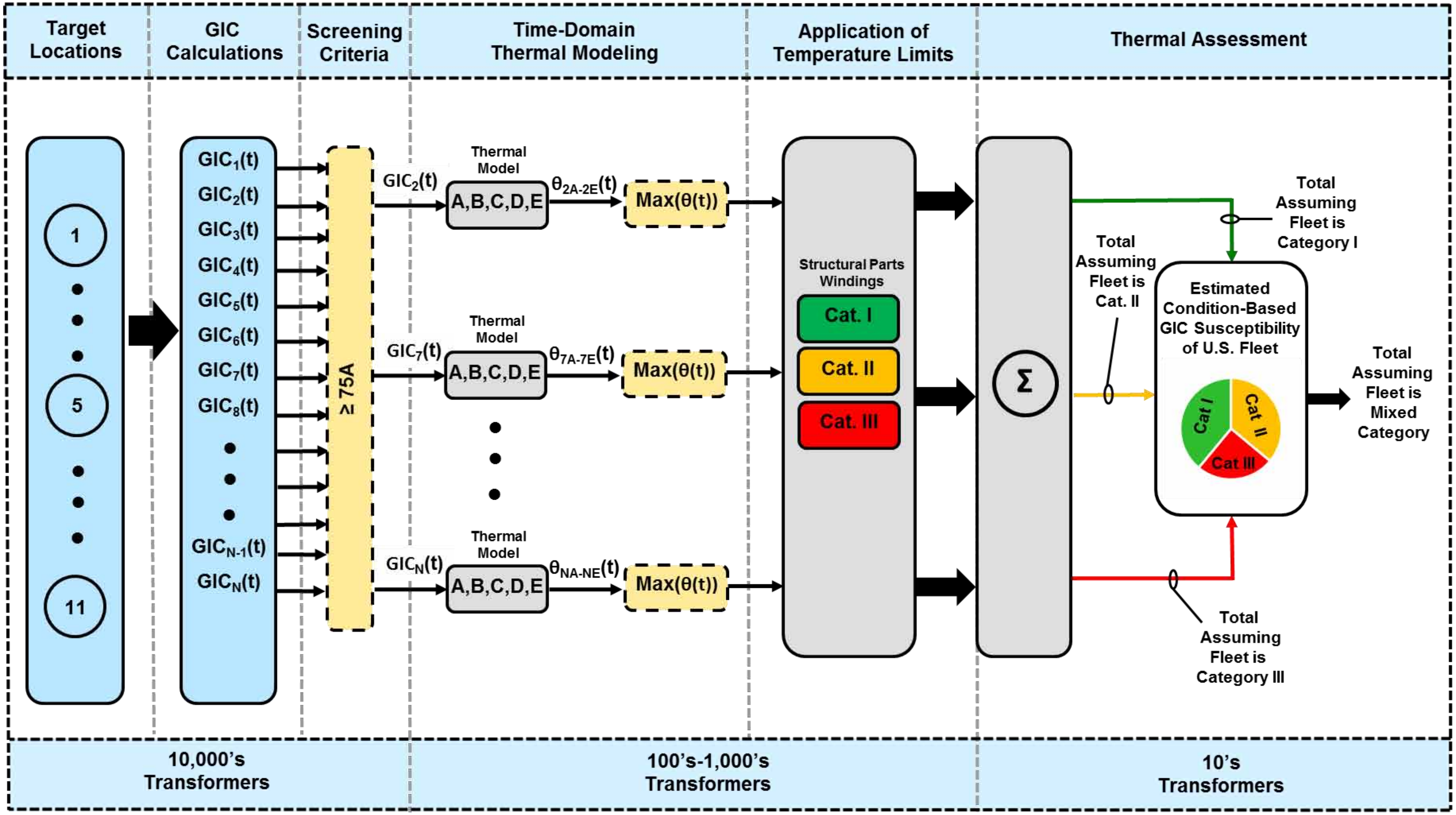
Parameter	Condition-Based GIC Susceptibility Category		
	I	II	III
Age	0–25	25–40	>40
Power Transformer Expert (PTX) software Abnormal Condition Code	1	2–3	4–5

Conservative Temperature Limits

Condition-based GIC Susceptibility Category	Hotspot Temperature Limit	
	Structural Parts (°C)	Windings (°C)
I	180	160
II	160	140
III	140	120

For comparison, IEEE C57.163 limits are 200°C for structural parts and 180°C cellulose insulation (windings).

Transformer Thermal Assessment Process



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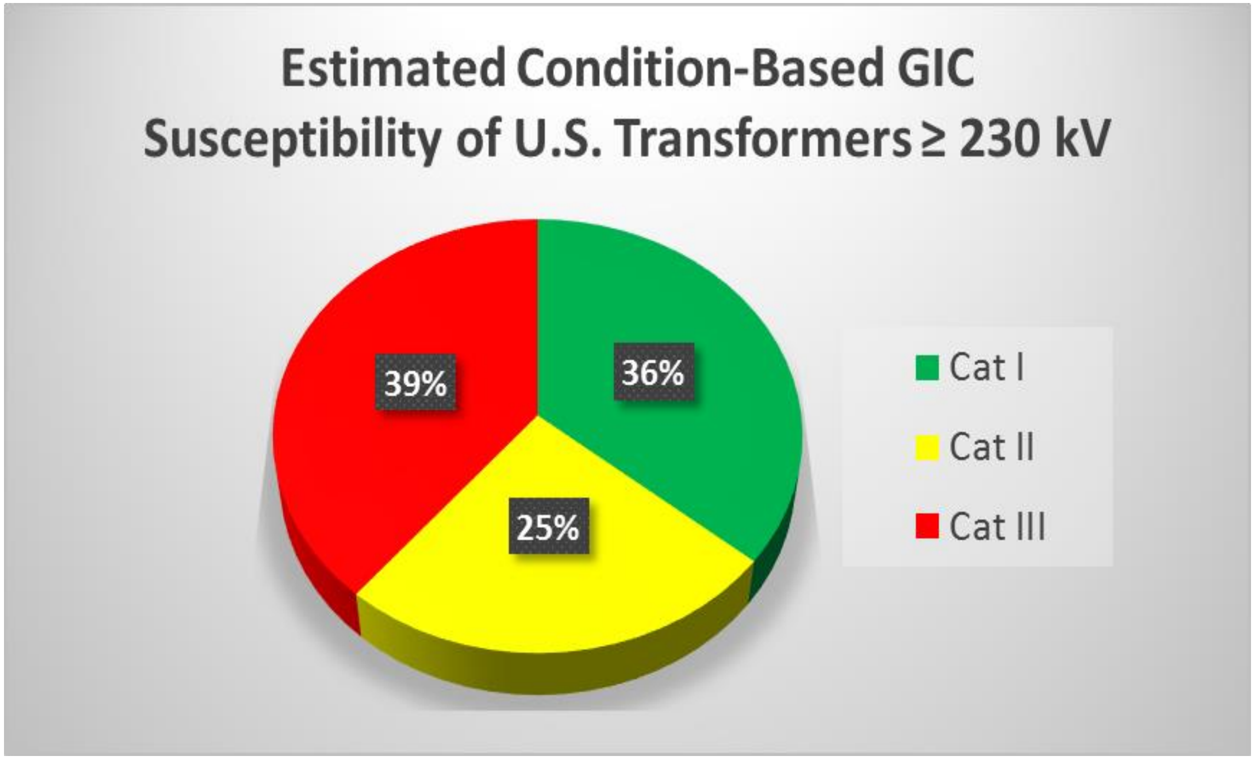
Step 1: Broad Category Assessment

- Assessment was performed assuming every transformer in the CONUS was Category I, Category II or Category III.
- Provided "book ends" to analysis.

		Total Number of Transformers Exceeding Temperature Limits Based on Assumed Condition-Based GIC Susceptibility Category of Entire Transformer Fleet		
Target Location	Number of Transformers with GIC_{eff} ≥75 Amps/Phase	Category I	Category II	Category III
1	1897	0	2	22
2	1872	2	4	15
3	1938	1	4	22
4	1912	2	6	19
5	1812	0	5	21
6	2435	0	3	15
7	689	0	2	10
8	692	0	1	7
9	675	2	3	11
10	2382	1	4	23
11	1965	3	6	28

Step 2: Estimate the Condition-Based GIC Susceptibility Category of U.S. Bulk-Power Transformers

- The condition-based GIC susceptibility category distribution of the U.S. fleet was estimated from 1,451 230 kV and above transformers contained in the EPRI database.



Step 3: Estimate the Expected Number of Transformers to be at Risk of Potential Thermal Damage

- Expected number of transformers at potential risk of thermal damage.

$$E(X) = \sum_{j=1}^{K} p_j X_j$$

$$= 0.36 \cdot X_1 + 0.25 \cdot X_2 + 0.39 \cdot X_3$$

where,

E is expected number of transformers to be at risk of thermal damage;

X_1 is the number of transformers exceeding the temperature limits assuming all transformers are in Category I;

X_2 is the number of transformers exceeding the temperature limits assuming all transformers are in Category II;

X_3 is the number of transformers exceeding the temperature limits assuming all transformers are in Category III.

Assessment Results

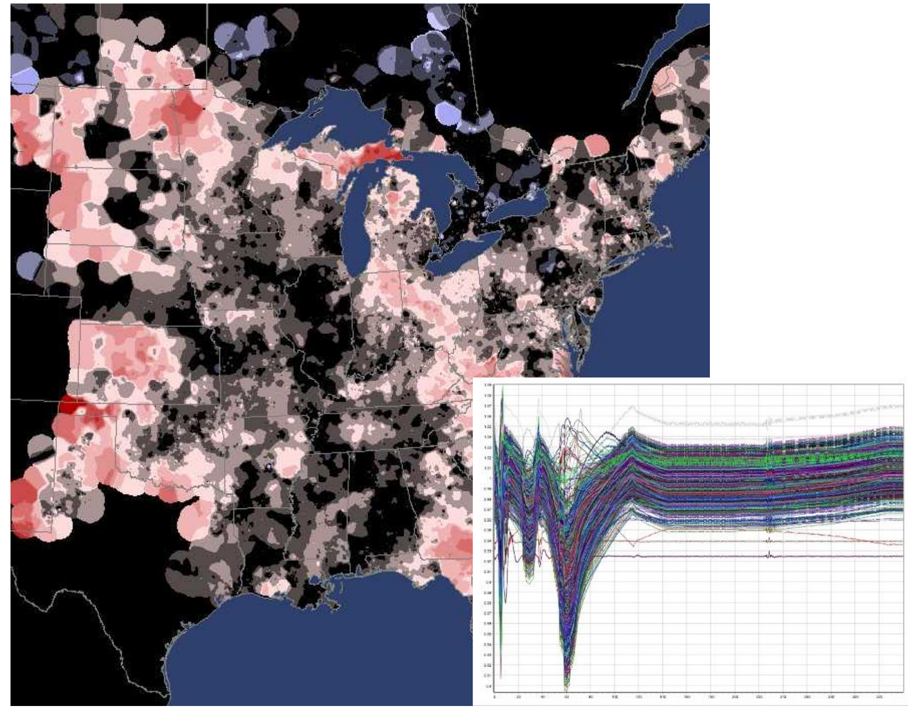
- Expected number of transformers to be at risk of thermal damage ranged from 3 to 14 depending on target location.

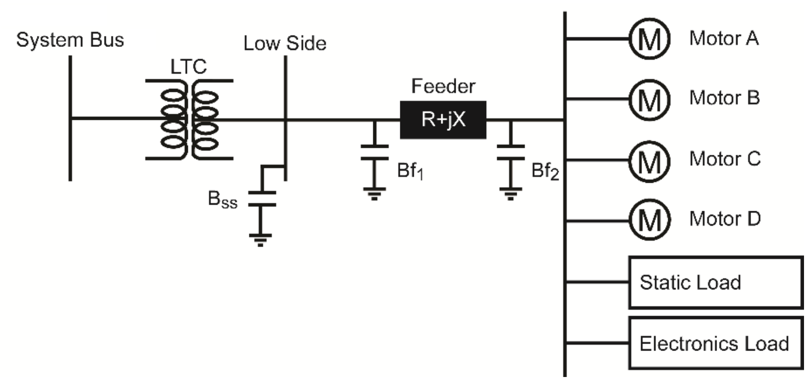
E(x)

		Total Number of Transformers Exceeding Temperature Limits Based on Assumed Condition-Based GIC Susceptibility of Entire Transformer Fleet			
Target Location	**Number of Transformers with GIC_{eff} ≥75 Amps/Phase**	**Category I**	**Category II**	**Category III**	**Mixed Category (I:36%, II:25%, III:39%)**
1	1897	0	2	22	9
2	1872	2	4	15	8
3	1938	1	4	22	10
4	1912	2	6	19	10
5	1812	0	5	21	9
6	2435	0	3	15	7
7	689	0	2	10	4
8	692	0	1	7	3
9	675	2	3	11	6
10	2382	1	4	23	10
11	1965	3	6	28	14

What's Next? Voltage Stability Analysis

- Evaluating the potential impacts of E3 on voltage stability.
- Using same E3 environment that was used in transformer thermal assessment.
- Performing time-domain analysis; load and machine dynamics are included.
  - Composite load model
  - Overexcitation Limiters
  - Relay models (PRC-023)
  - Generator voltage/frequency ride-through capability (PRC-024)
- Results expected by Q3 2017





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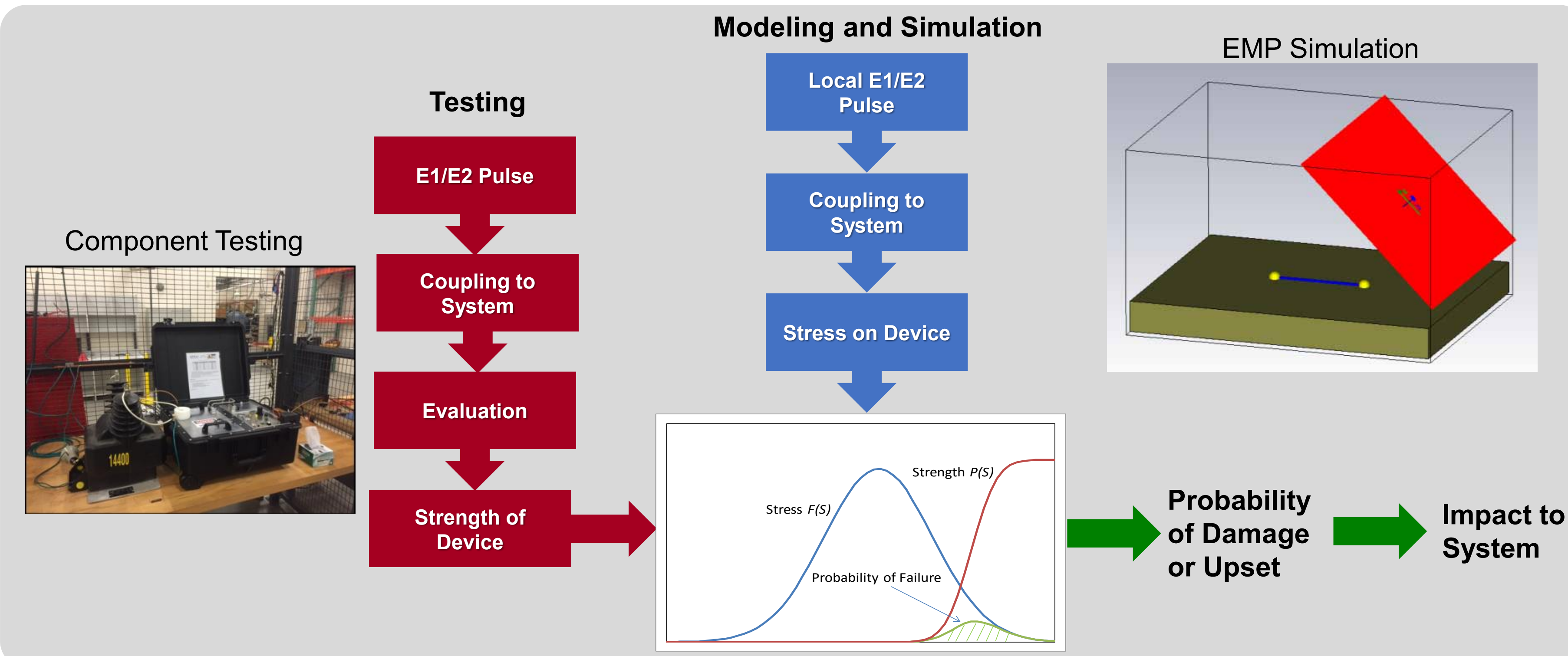
What's Next? E1/E2 Threat Assessment

- Testing to determine E1/E2 threshold levels of components **(Strength)**.
- Modeling to determine surge levels that components might be exposed **(Stress)**.
- Analysis to determine the **Probability of Damage or Upset** of components.
- Analysis to determine Impact of damage or upset of components on overall bulk-power system.



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Conclusions

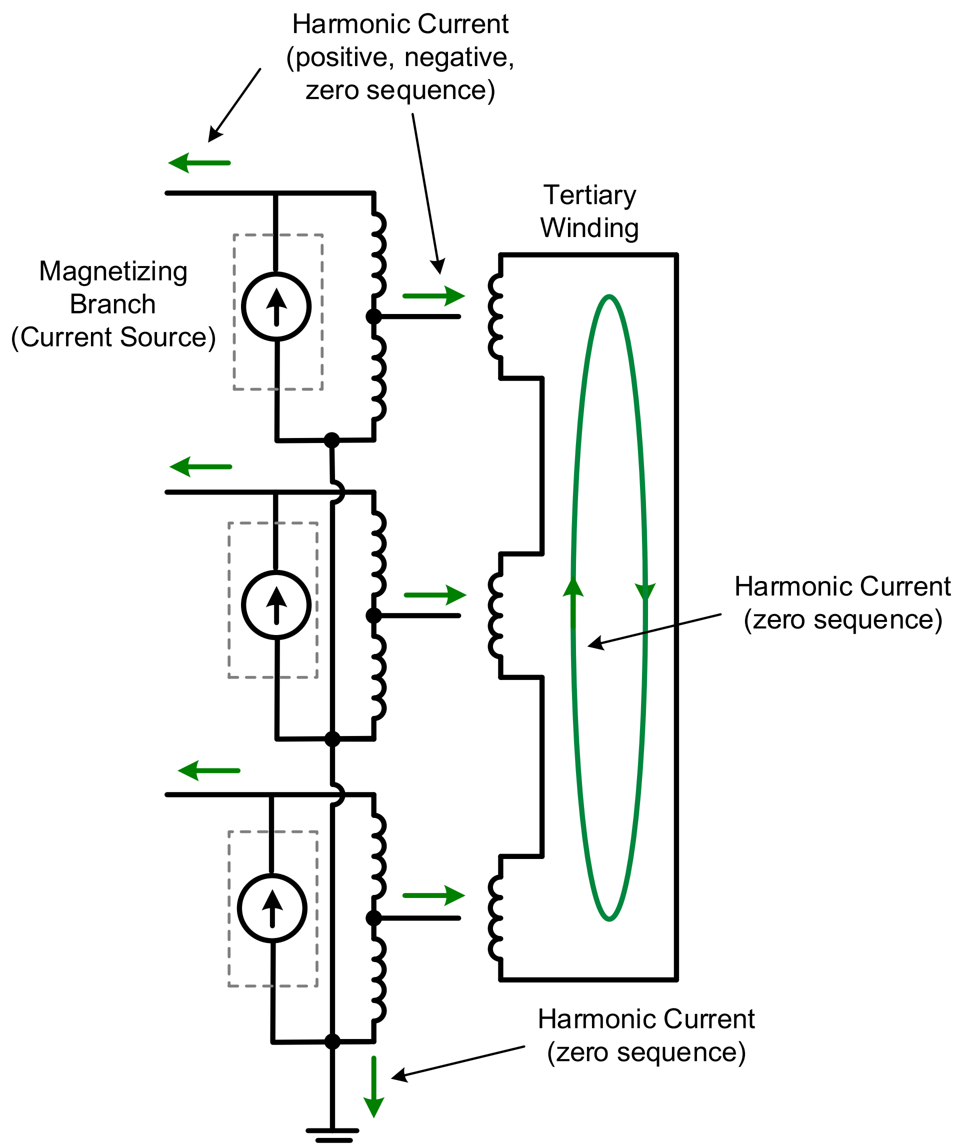
- The potential effects of HEMP are real, but there are still a lot of open research questions that need to be addressed.
- The potential for transformer damage from E3 exists, but study results indicate the quantity would be limited and manageable.
- The potential for voltage collapse and wide-scale blackouts due to E3 is real, and still under investigation.
- Research needs to be completed before hardening measures based on MIL standards are employed widely for substation electronics; cost-effective solutions are needed.
- This is a complex engineering problem; building consensus and collaboration takes a great deal of time, effort and knowledge.

Together…Shaping the Future of Electricity

Appendix

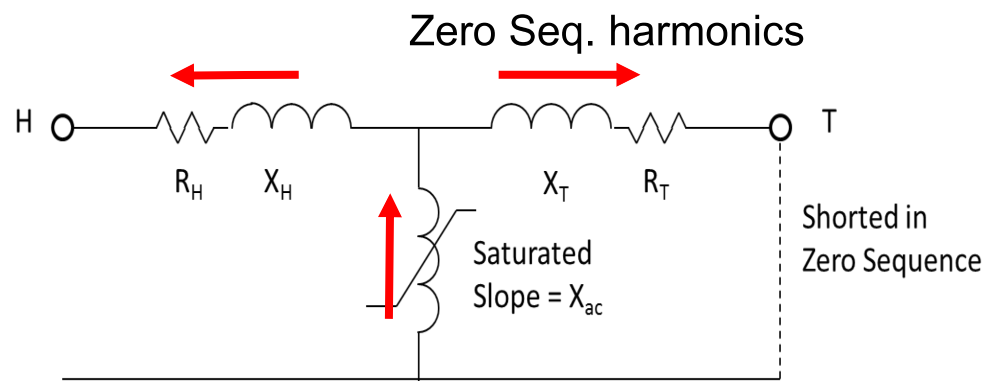
Analysis of Autotransformer Delta Tertiary Windings

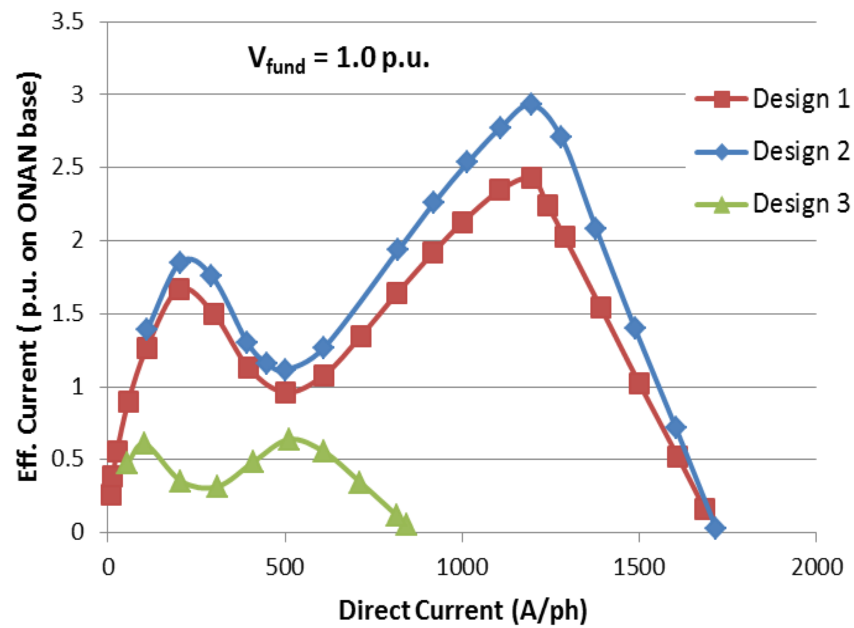
- Part-cycle saturation causes transformers to become harmonic current sources.
- The harmonic currents are “injected” into the system with some portion being absorbed by the tertiary winding.
- Circulating harmonic currents can increase hotspot heating.



Analysis of Autotransformer Delta Tertiary Windings

- The magnitudes and spectral contents of the delta currents were evaluated using an adaptation of IEEE C57.110.
- The harmonic currents were related to an equivalent fundamental-frequency current that can be compared with IEEE C57.109 damage curves.
- Analysis was applied to three different designs of a 230/115 kV 240 MVA autotransformer with 42 MVA 13.2 kV tertiary.
- Results indicate that for the transformer evaluated, circulating harmonic currents are not an issue for E3 events.





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