INL/MIS-24-77052-Revision-0

2024.03.13 Bushing Subcommittee presentation on Transformer Bushing Seismic Resilience: Design, Hazard, & Prevention Analysis

March 2024

Jon Bender, Bjorn C Vaagensmith, Chandrakanth Bolisetti

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2024.03.13 Bushing Subcommittee

Transformer Bushing Seismic Resilience

Design, Hazard, & Prevention Analysis

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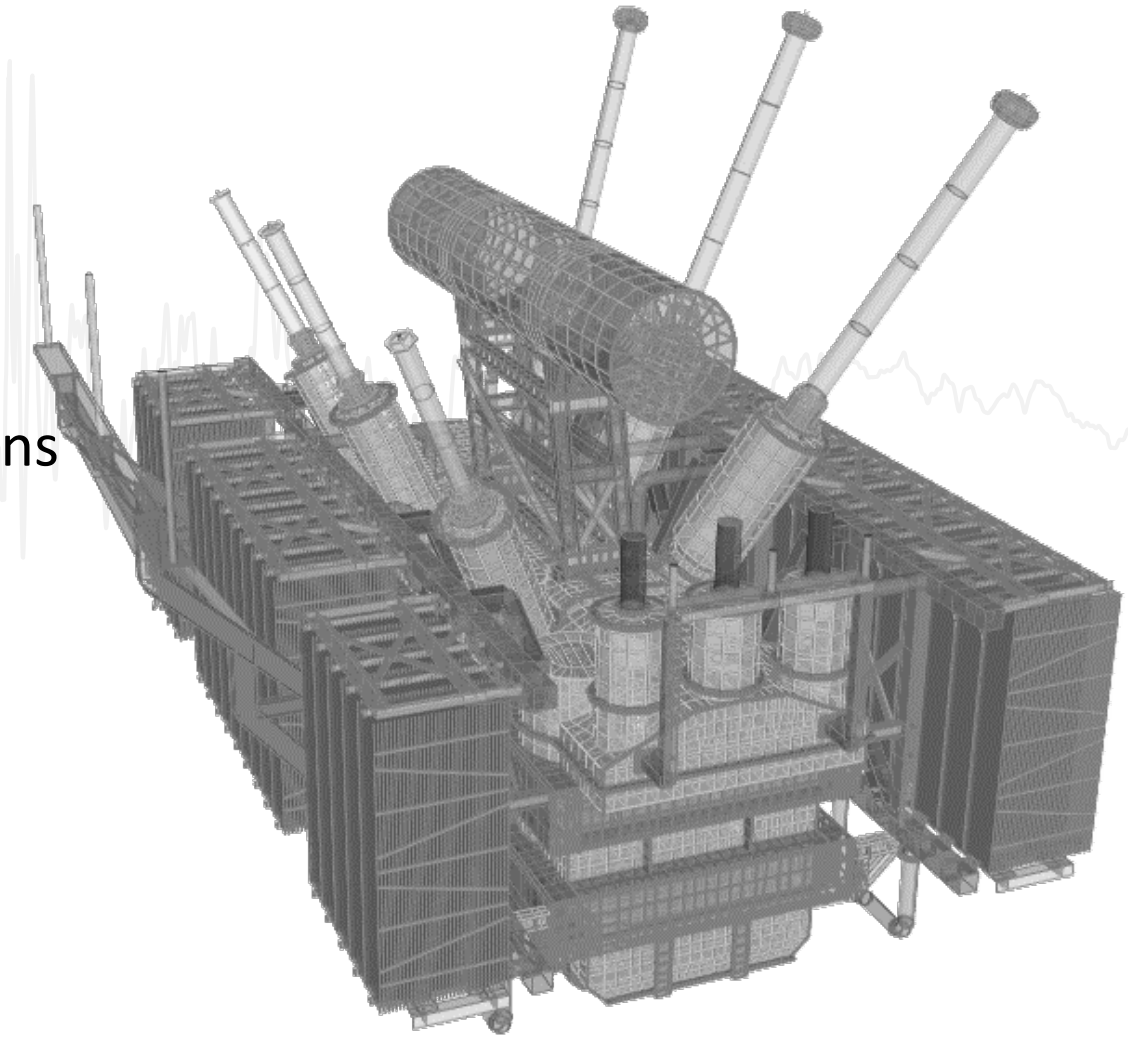
Overview

- Transformer Bushing Seismic Resilience – Scope and Scale Investigation
  - Background
  - Parametric Study
  - Seismic Grid Simulation
  - Preliminary Results
- Next Steps
  - Transformer Design Recommendations
  - Physical Experimentation
  - Bushing Protection



Support

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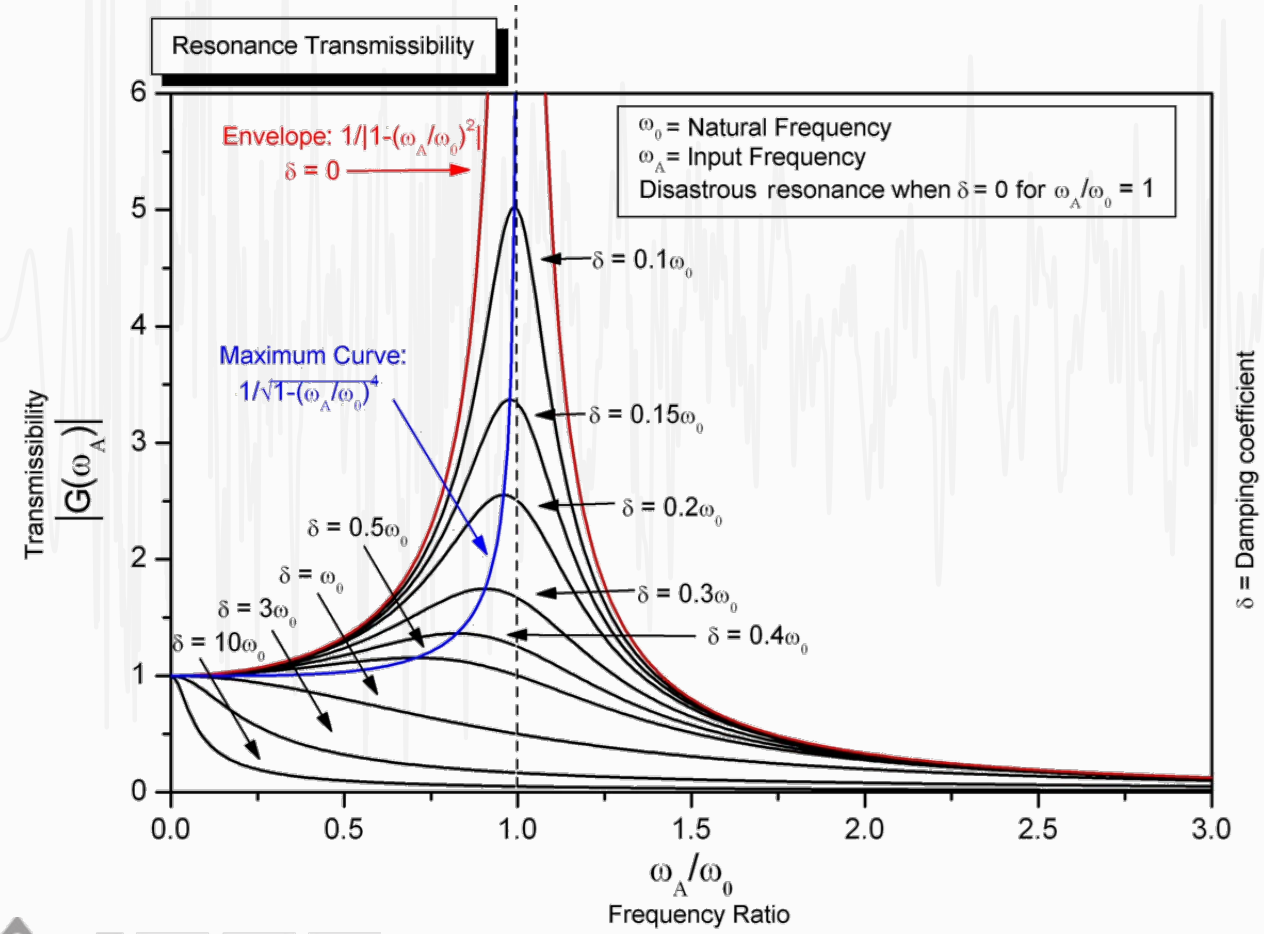
  - INL Laboratory Directed Research & Development (LDRD) Program

  - The US Department Of Energy –
    - Office of Electricity - Transformer Resilience and Advanced Components (DOE-OE-TRAC) Program
    - Office of Cybersecurity, Energy Security, and Emergency Response (DOE-CESER) Program
    - Natural Hazards Program

Bushing Seismic Resilience – Background

- Transformer-Bushing System



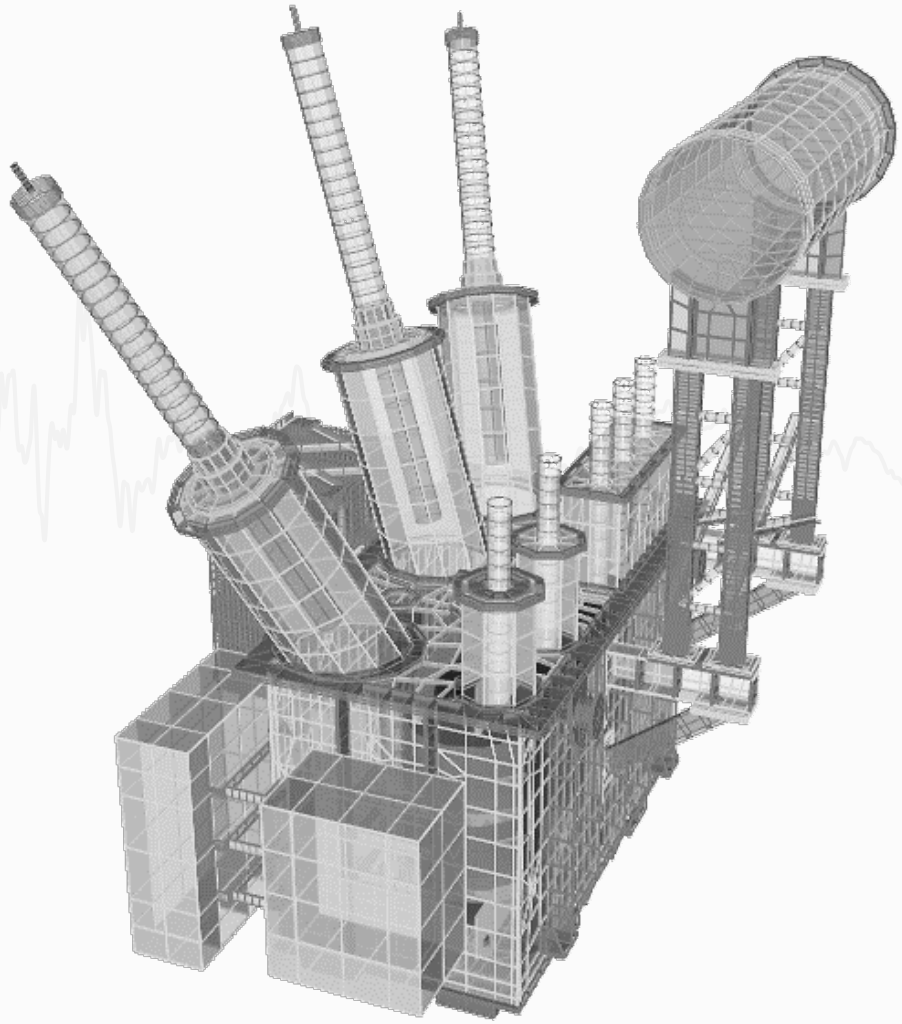
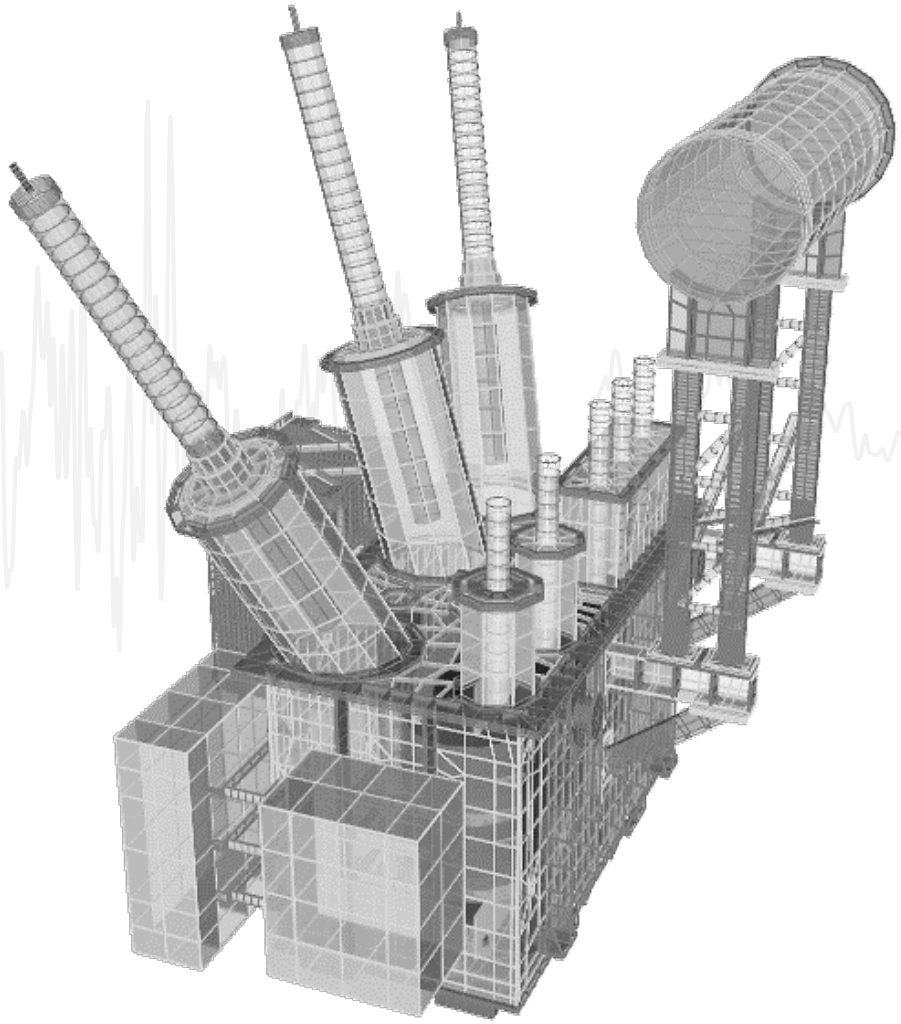
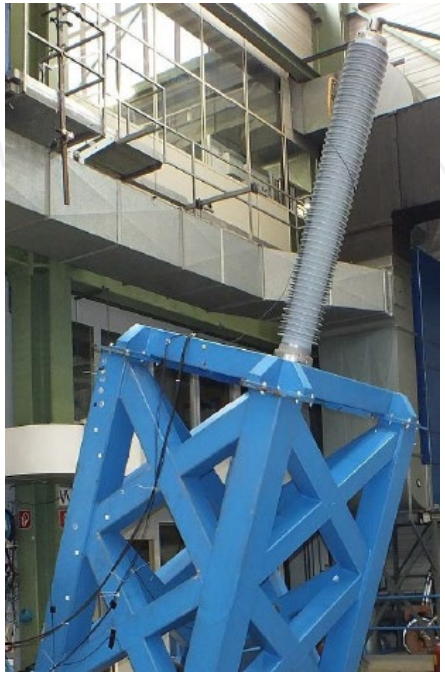


Figure Credit: Hossain 2012 (Geotechnical Engineering III)

Bushing Seismic Resilience – Background

- Transformer-Bushing System
- Assumed Amplification
- Actual Amplification
  - Observed Failures
    - Northridge
    - Mexicali
    - Turkey
    - Wenchuan
    - Loma Prieta
    - ETC



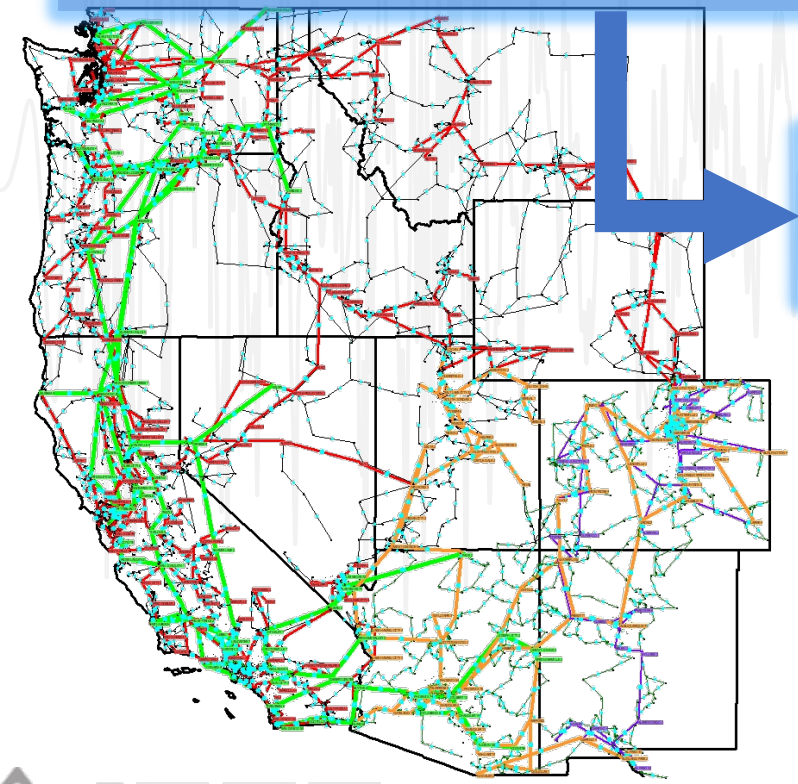


Bushing Seismic Resilience – Hazard Impact, Mitigation

- Targeting Questions:

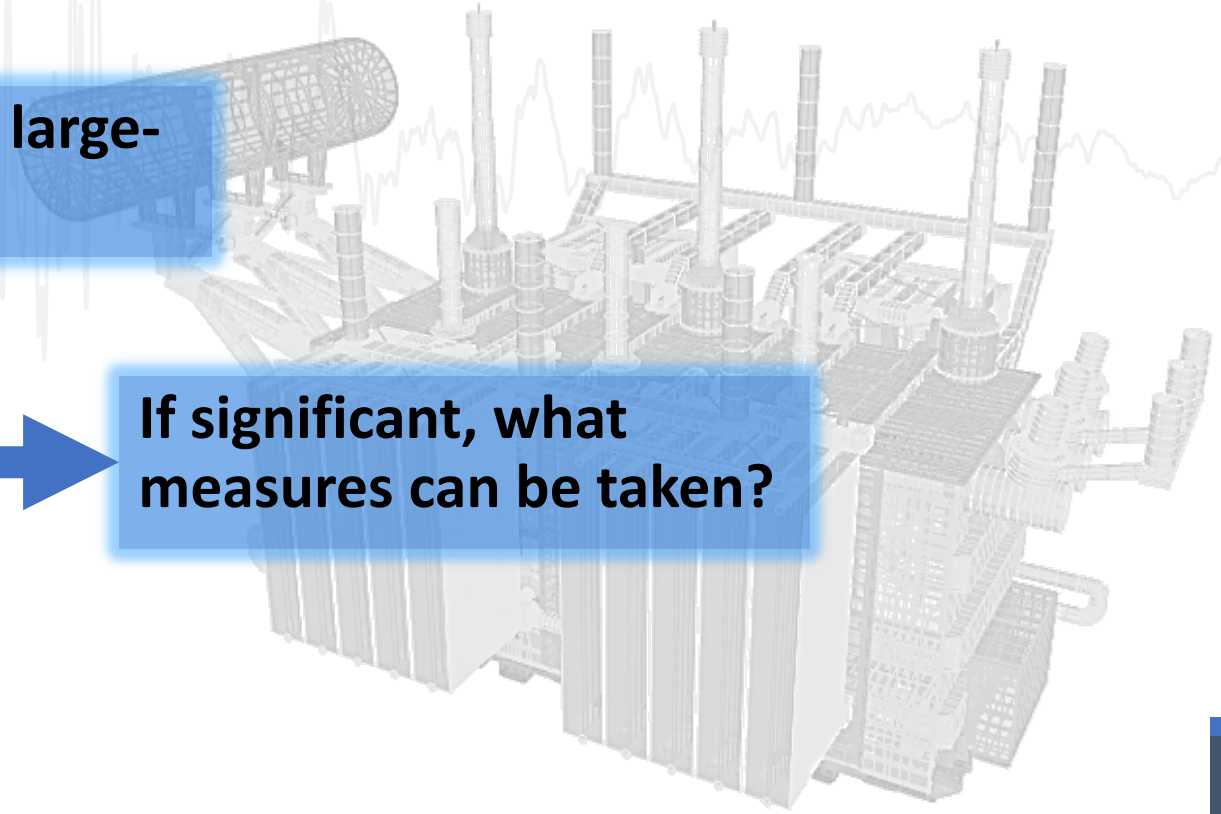
Is the state of the practice acceptable for large transformer bushings?

How do transformer and bushing design parameters affect bushing amplification?



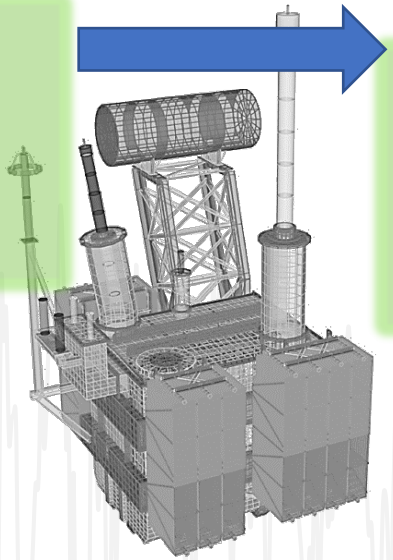
What is the large-scale risk?

If significant, what measures can be taken?



Bushing Seismic Resilience

1) Detailed FE analysis on select designs with key structural parameters of interest



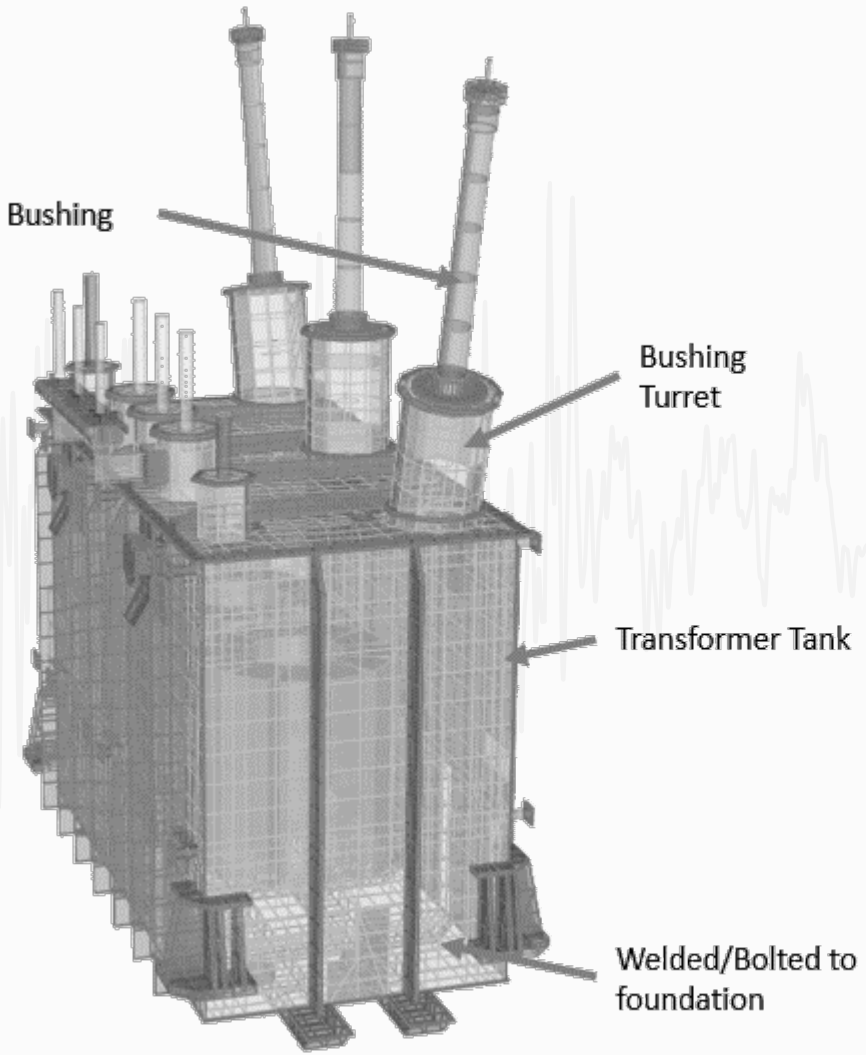
2) Iterative parametric analysis – sweep through range of critical parameters

1. Select a representative set of transformers for each voltage class (~138kV, ~162kV, ~230kV, ~345kV, ~500kV)

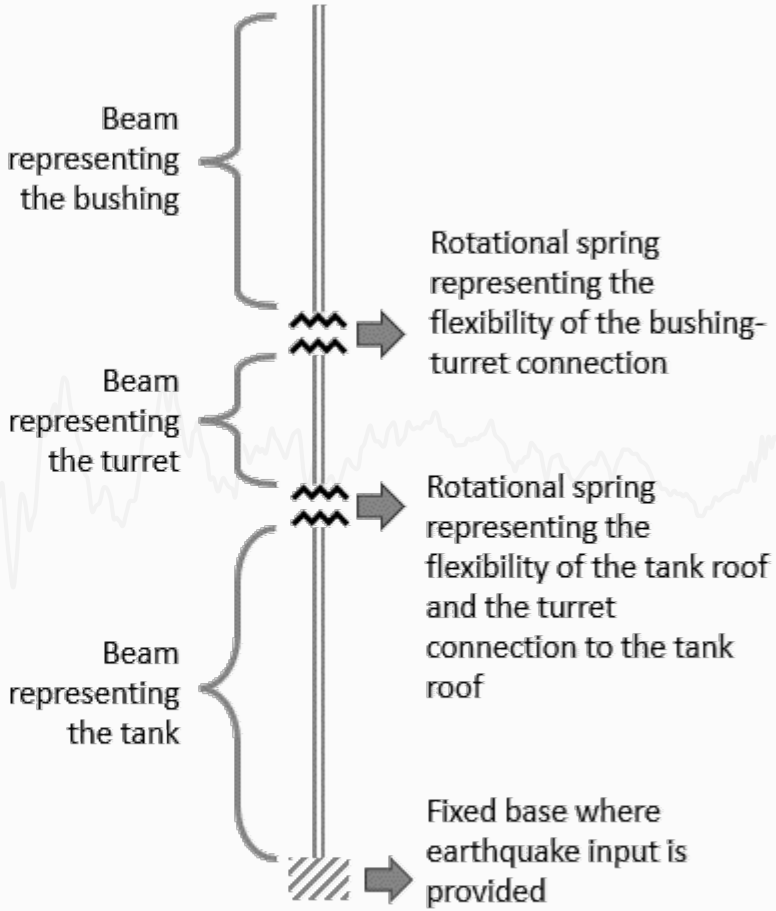
2. Perform parametric studies in MASTODON (open-source national lab developed FEA software)

Bushing Seismic Resilience

2) Parametric sweep using simplified MASTODON models



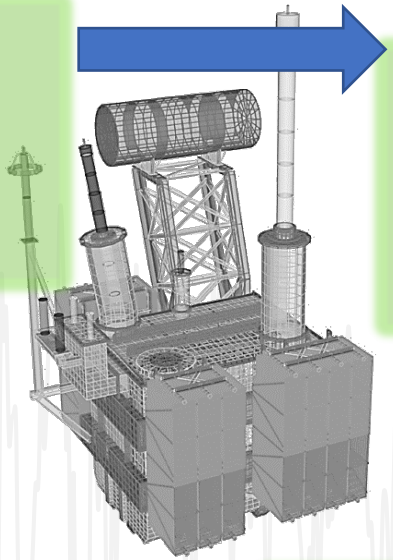
Complex transformer model



Reduced order model in MASTODON

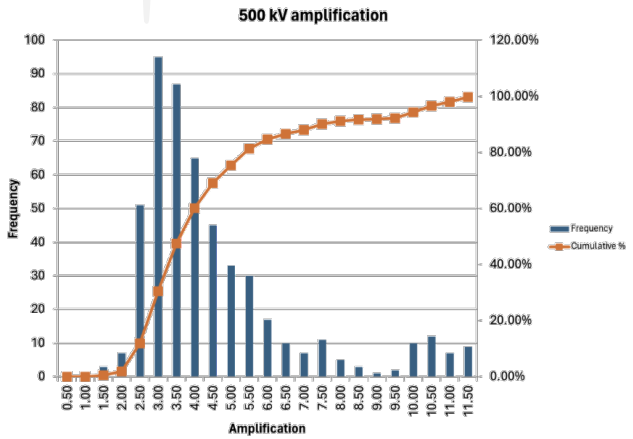
Bushing Seismic Resilience

1) Detailed FE analysis on select designs with key structural parameters of interest



2) Iterative parametric analysis – sweep through range of critical parameters

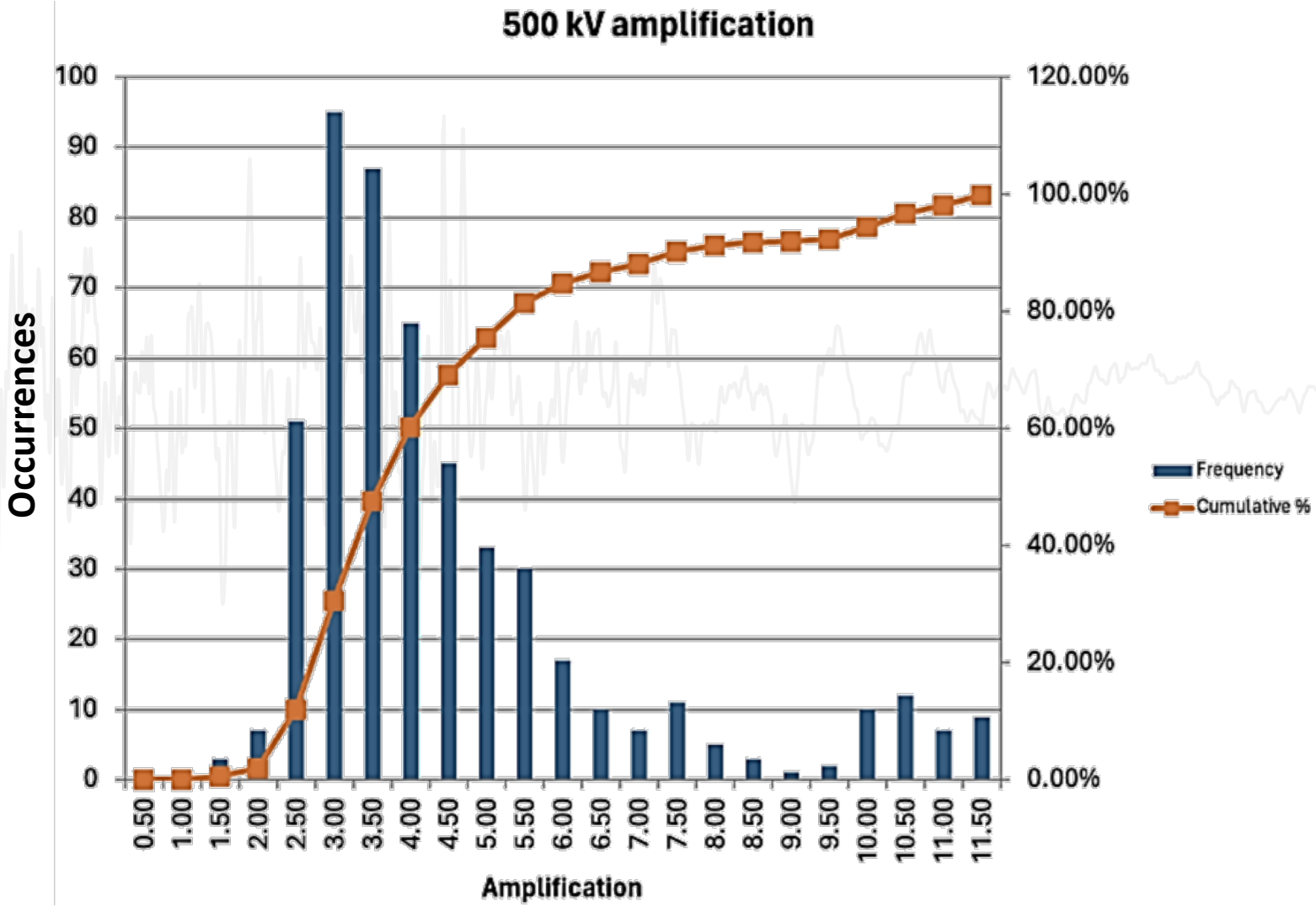
3) Amplification Probability



1. Select a representative set of transformers for each voltage class (~138kV, ~162kV, ~230kV, ~345kV, ~500kV)
2. Perform parametric studies in MASTODON (open-source national lab developed FEA software)
3. Calculate amplification distribution – each voltage class

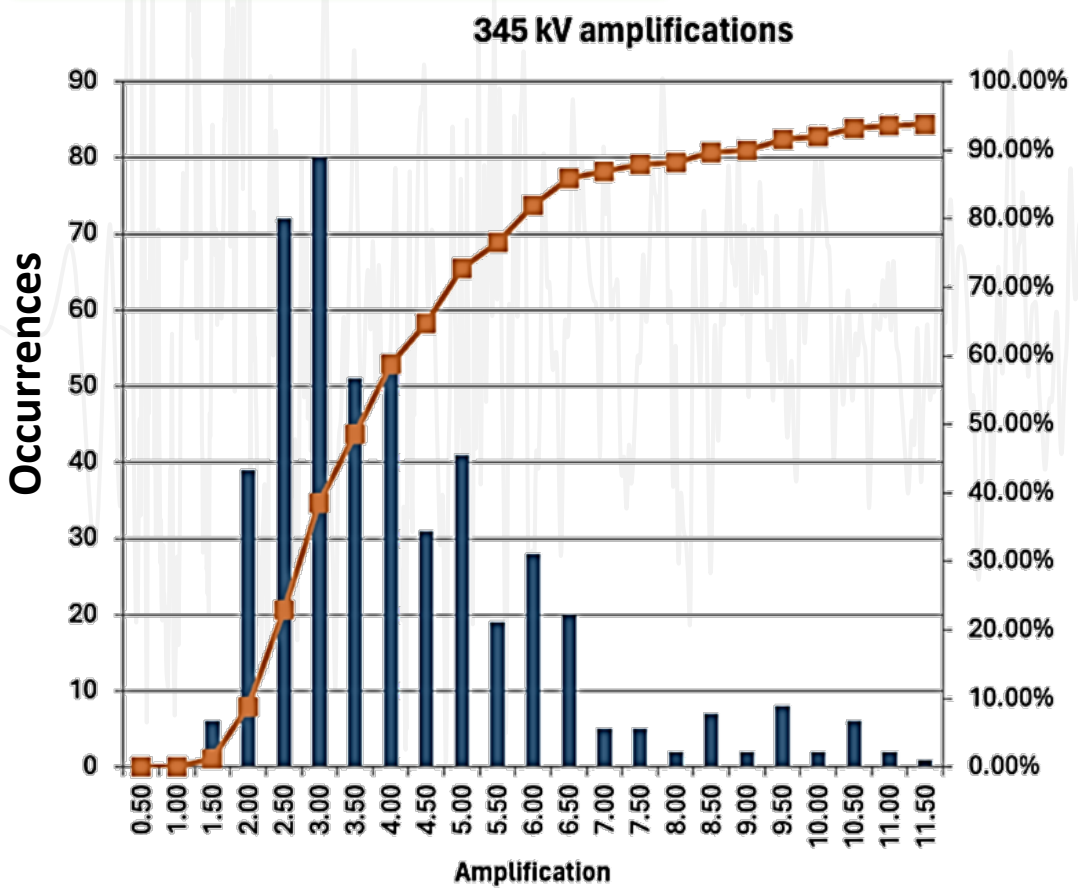
Bushing Seismic Resilience

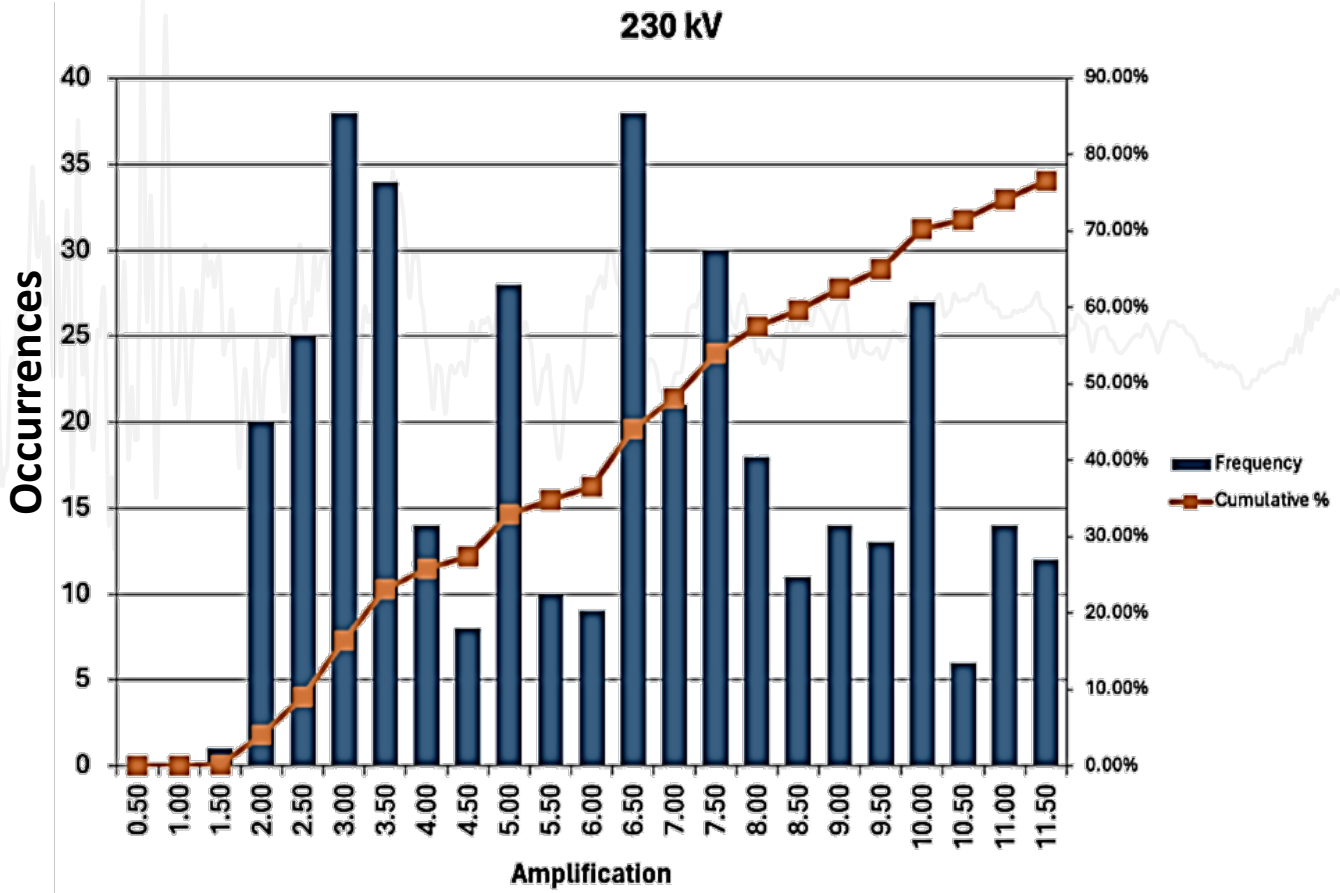
3) Amplification Probability



Bushing Seismic Resilience

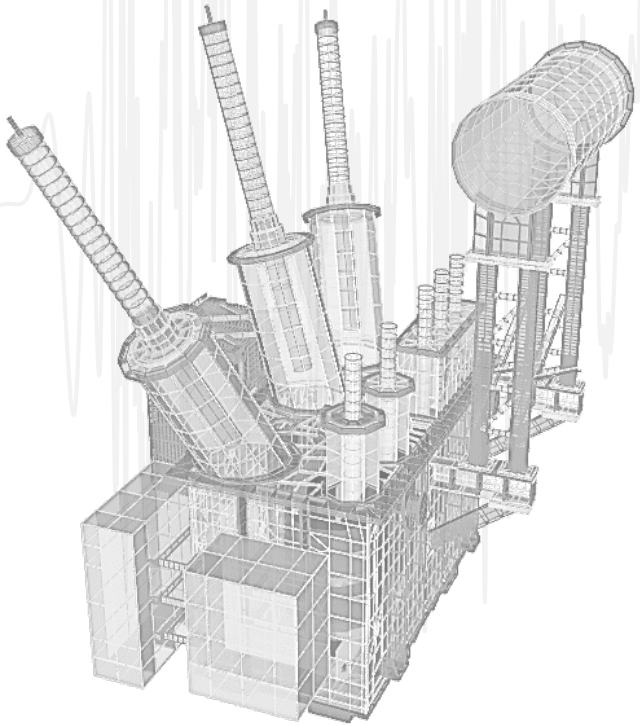
3) Amplification Probability

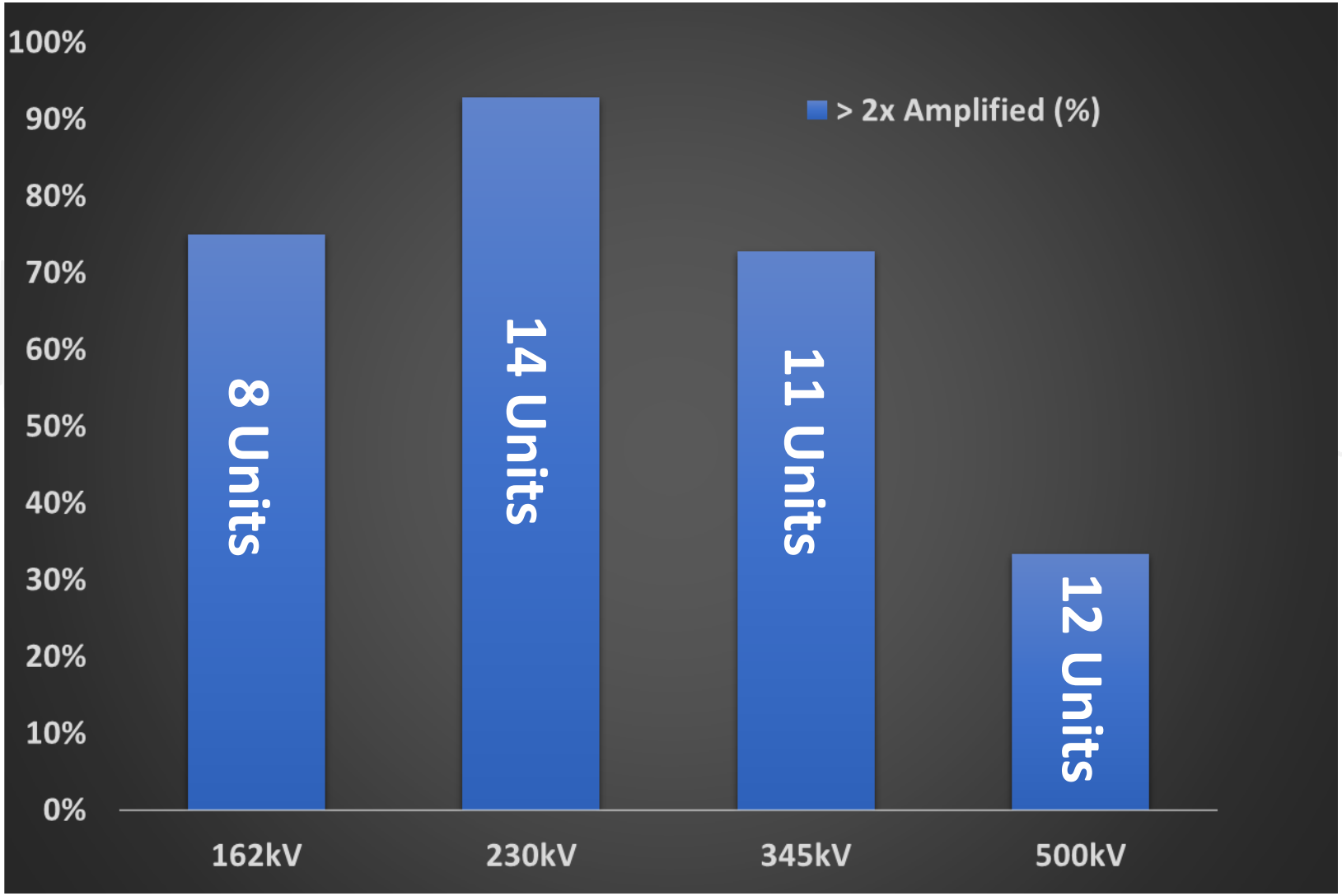




Bushing Seismic Resilience

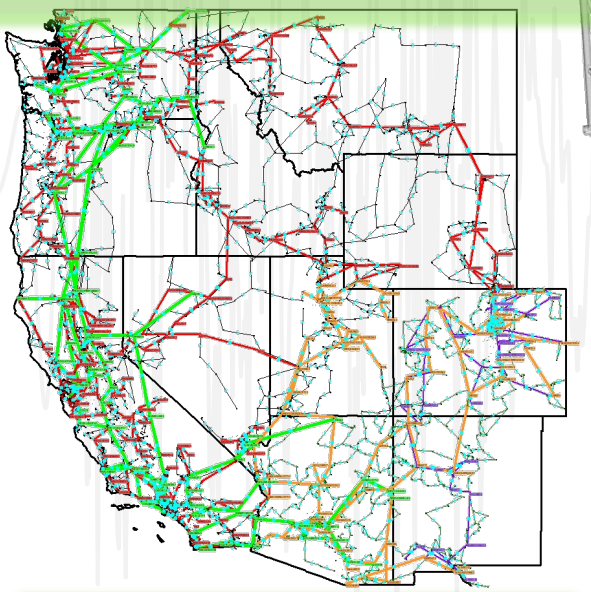
3) Amplification – Detailed Finite Element Models

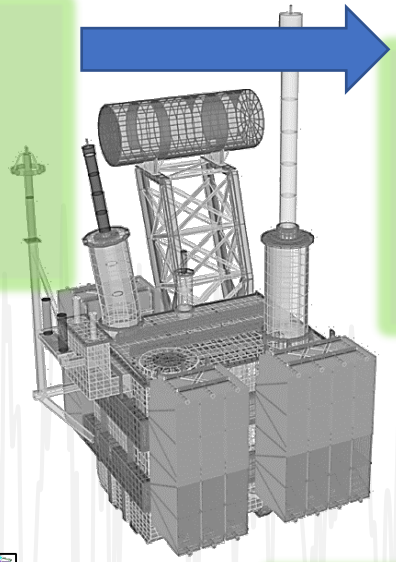




Bushing Seismic Resilience

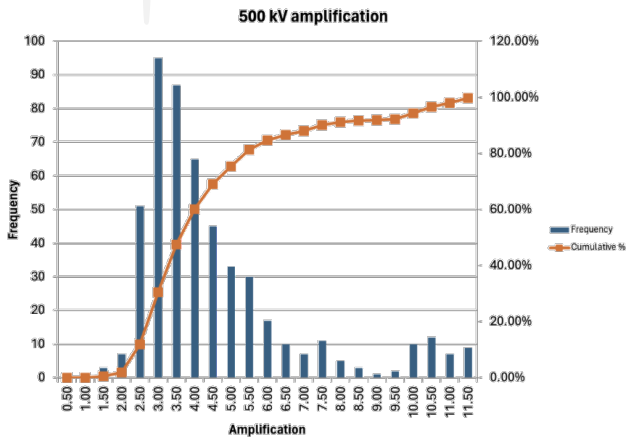
1) Detailed FE analysis on select designs with key structural parameters of interest





2) Iterative parametric analysis – sweep through range of critical parameters

3) Amplification Probability

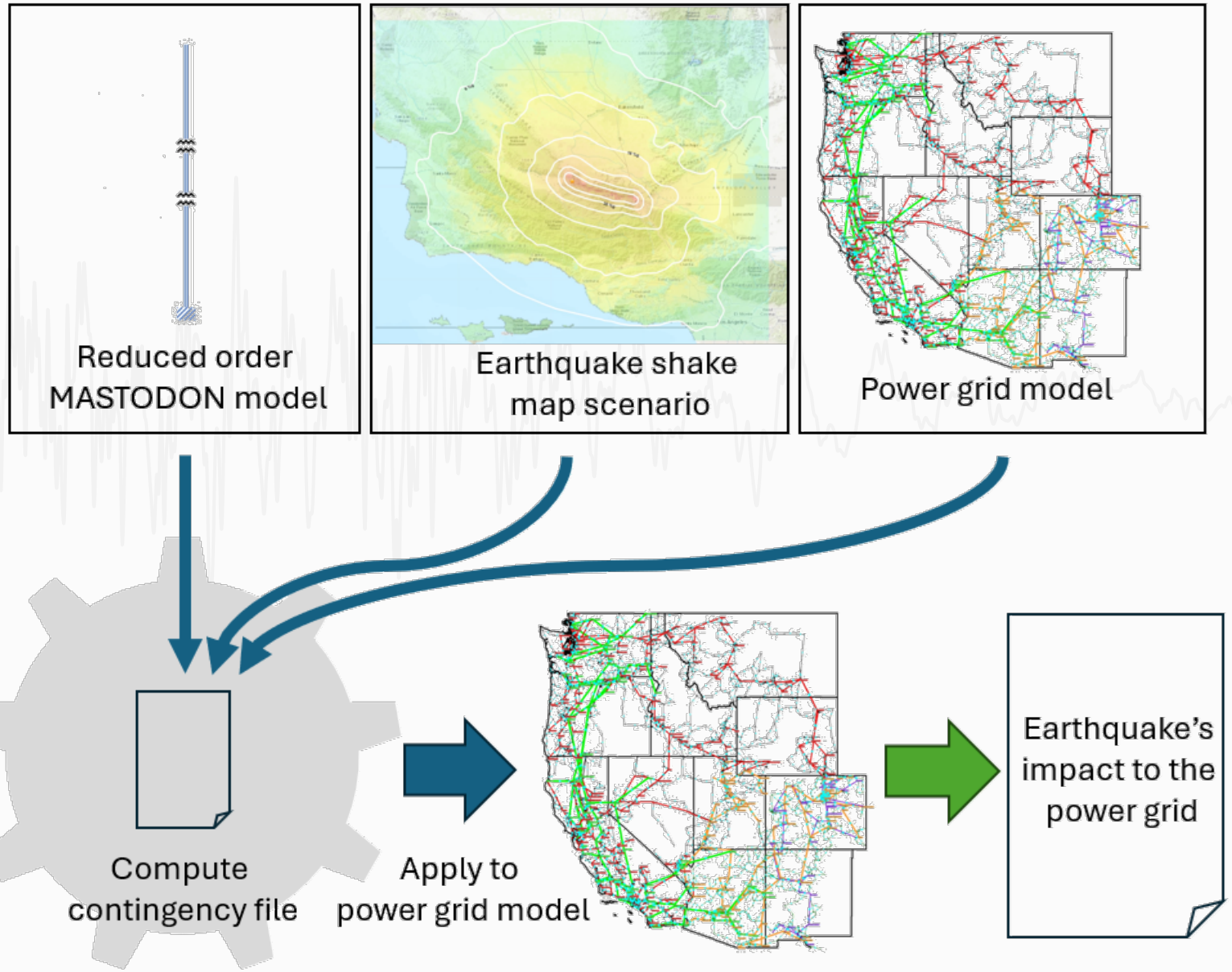


4) Impact on bulk grid

1. Select a representative set of transformers for each voltage class (~138kV, ~162kV, ~230kV, ~345kV, ~500kV)
2. Perform parametric studies in MASTODON (open-source national lab developed FEA software)
3. Calculate amplification distribution – each voltage class
4. Power grid seismic contingency analysis (determine potential impacts)

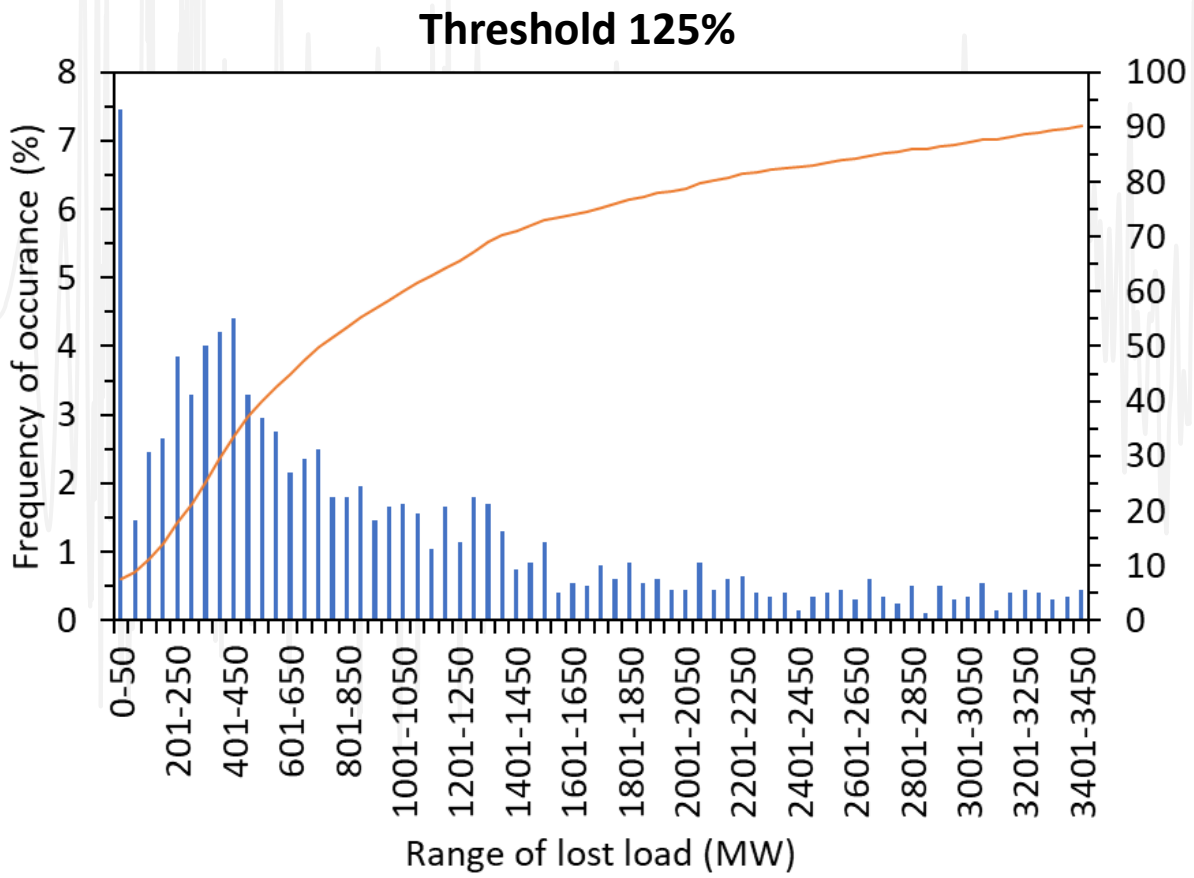
Bushing Seismic Resilience

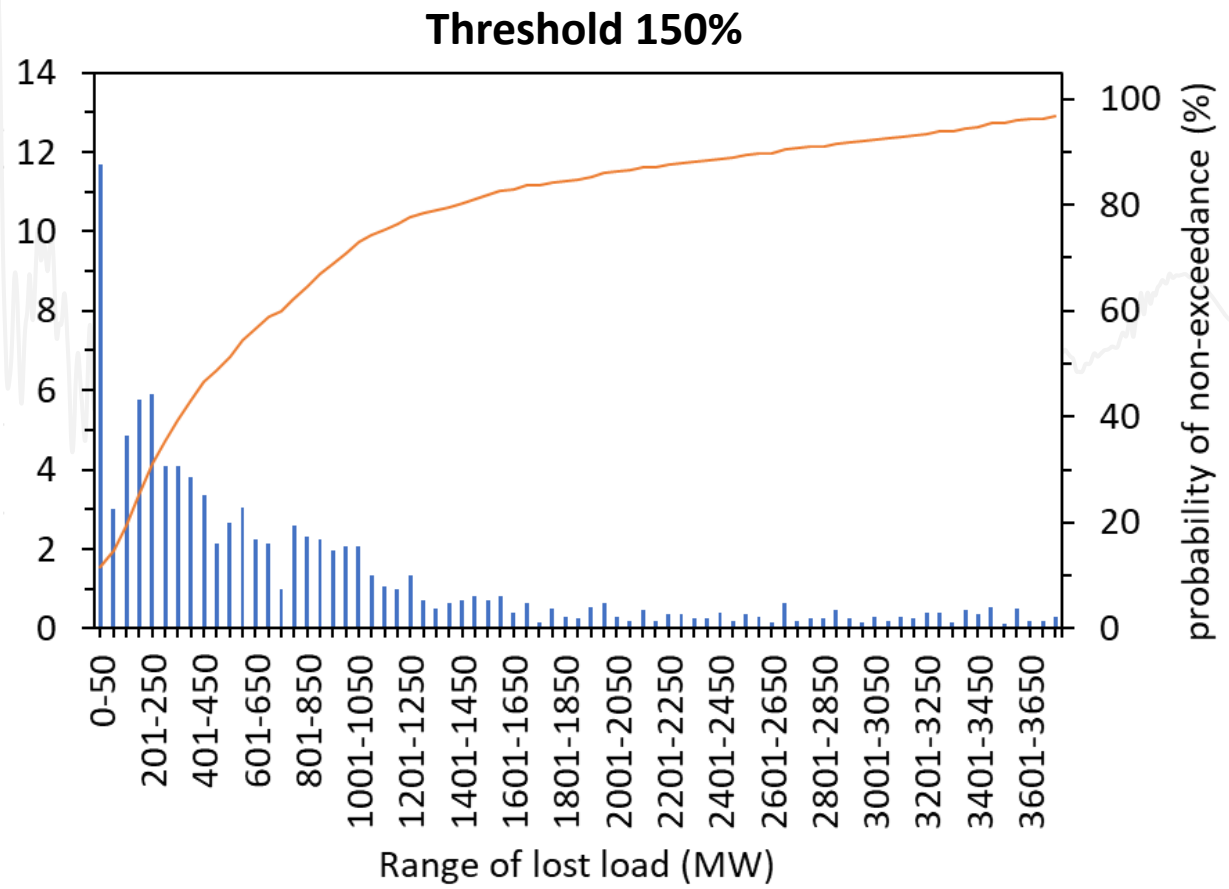
4) Impact on bulk grid



Bushing Seismic Resilience

4) Impact on bulk grid – Scenario 1 – San Andreas

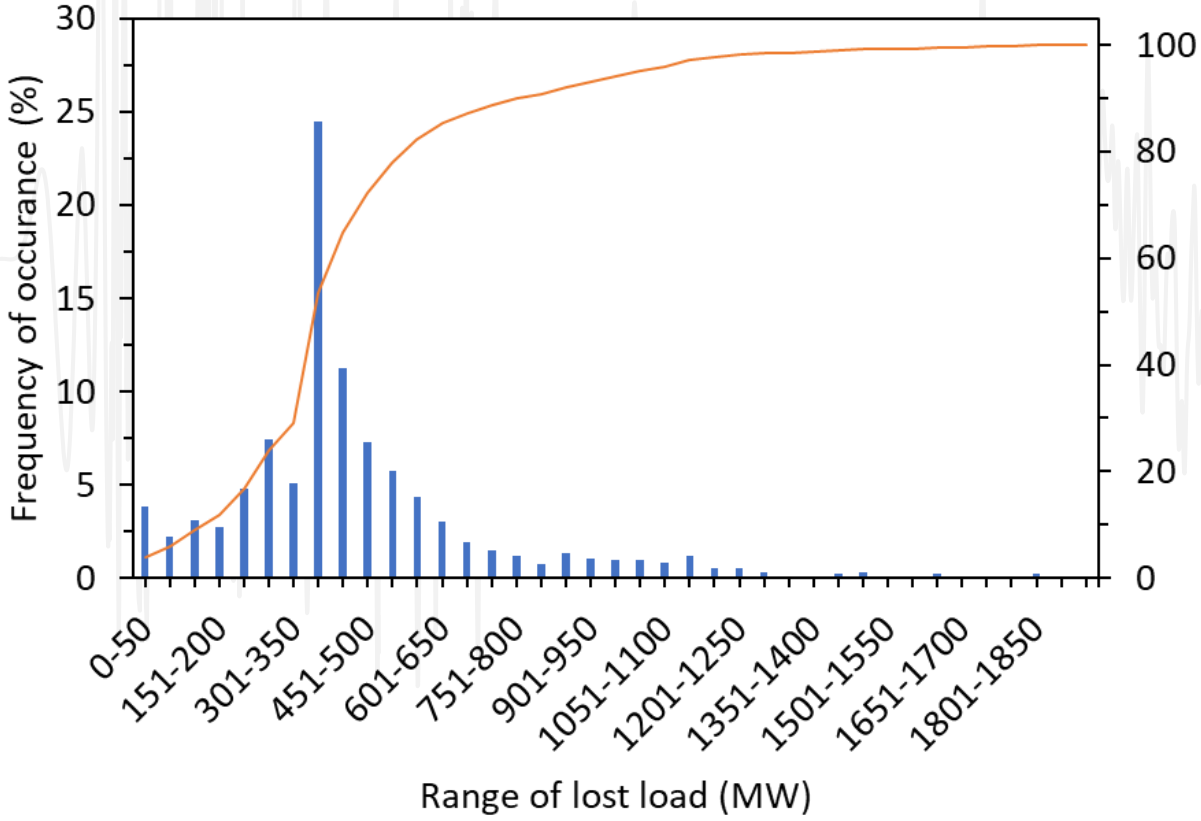




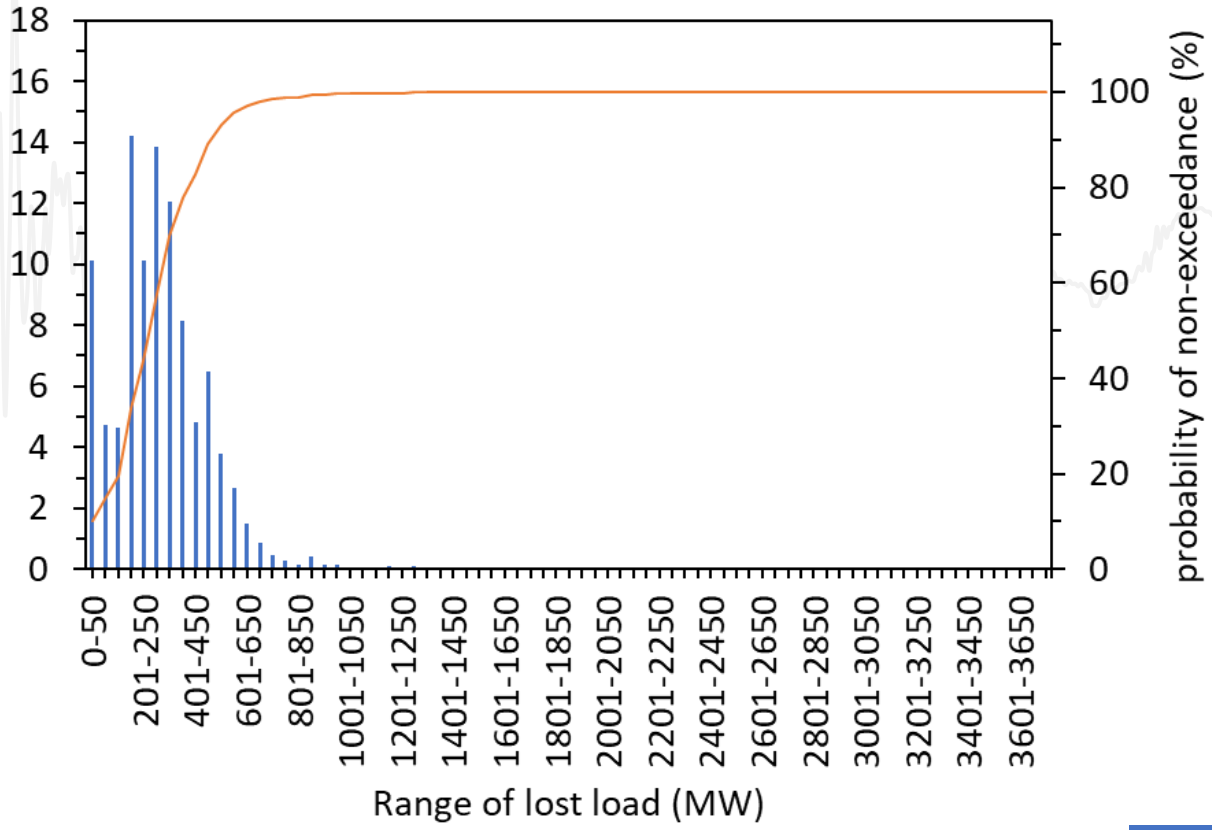
Bushing Seismic Resilience

4) Impact on bulk grid – Scenario 2 – Middle Fault Zone Seattle

Threshold 125%



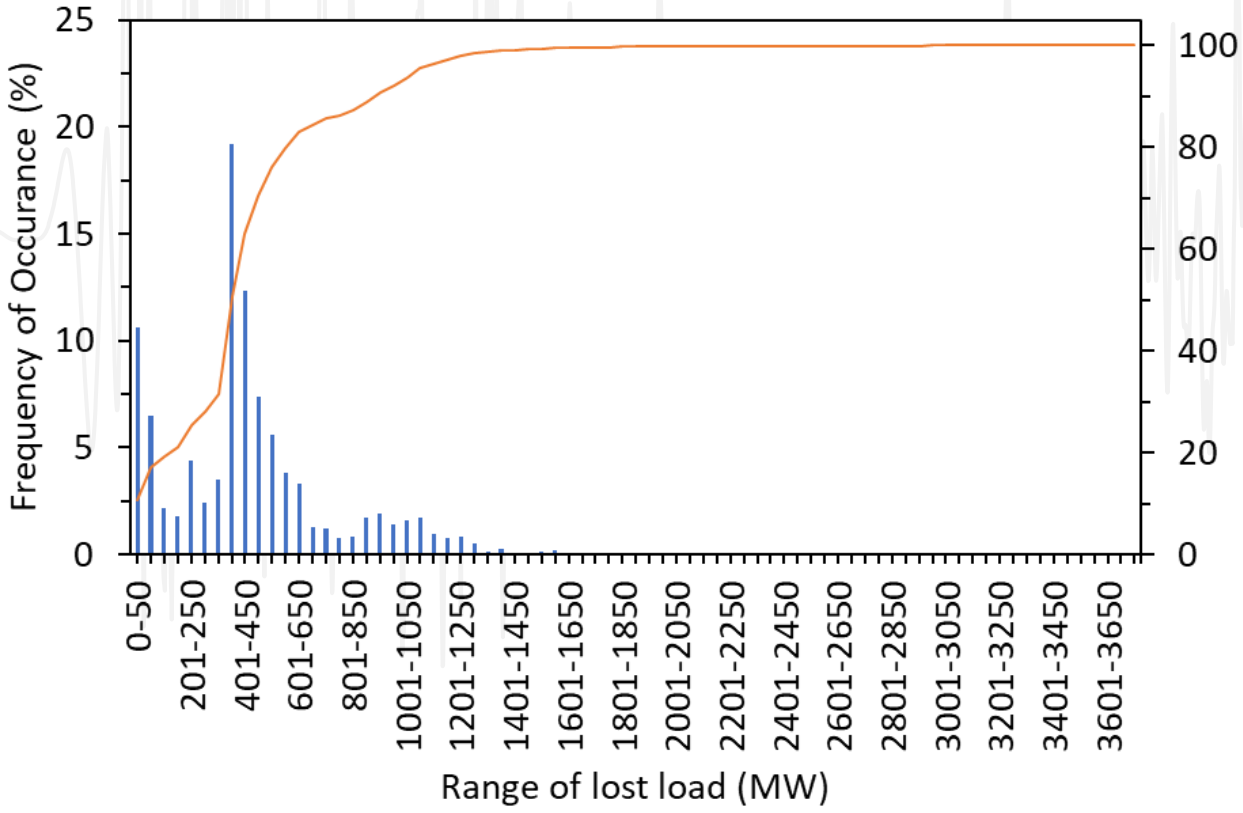
Threshold 150%



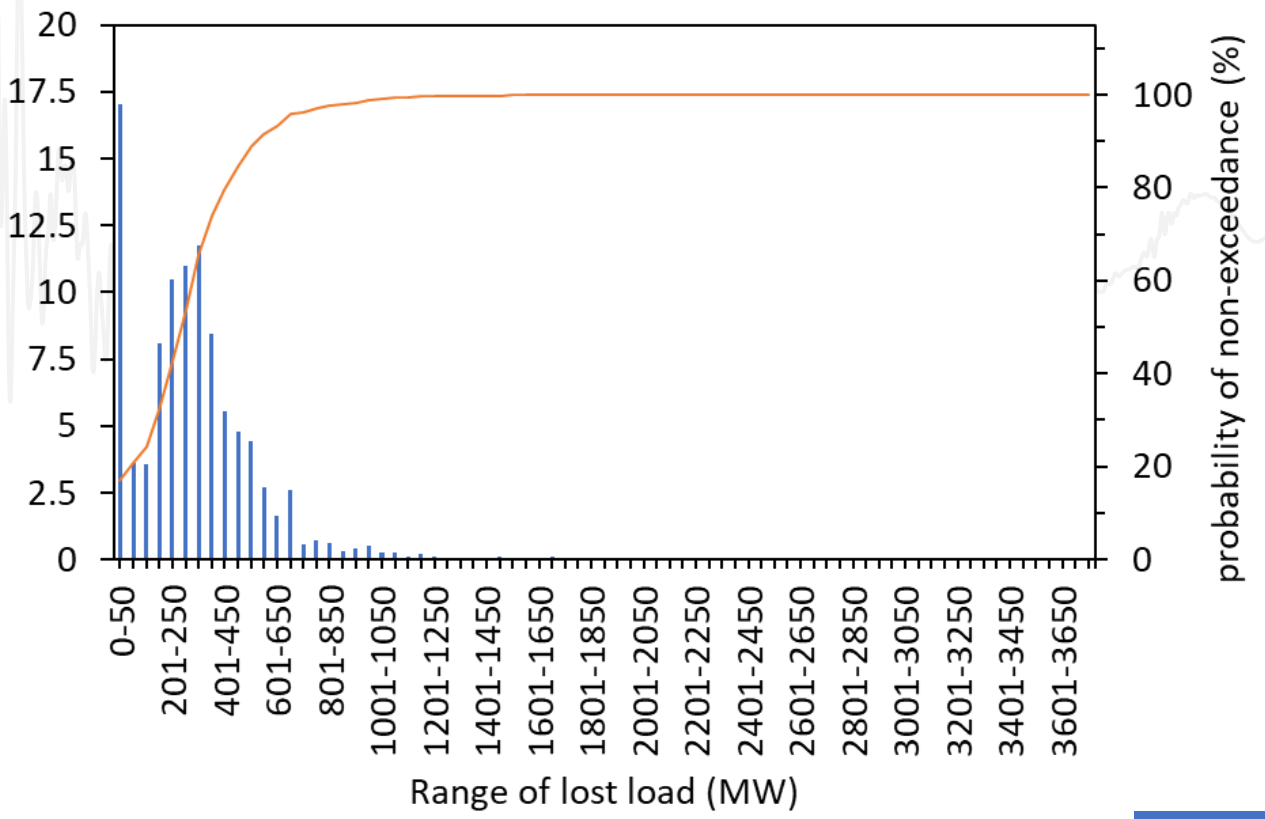
Bushing Seismic Resilience

4) Impact on bulk grid – Scenario 3 – North Fault Zone Seattle

Threshold 125%



Threshold 150%



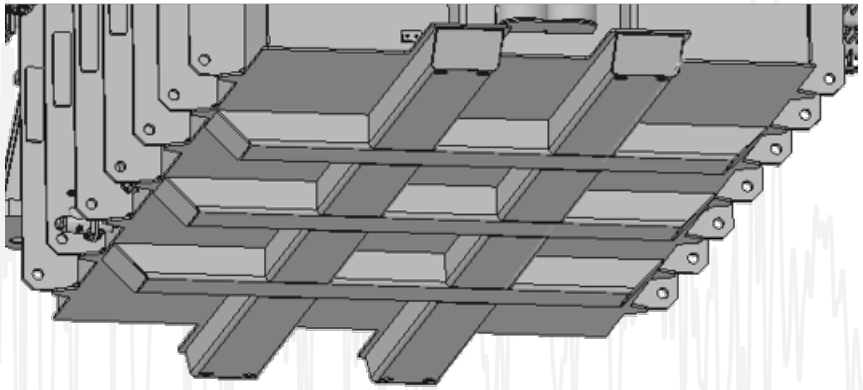
Summary

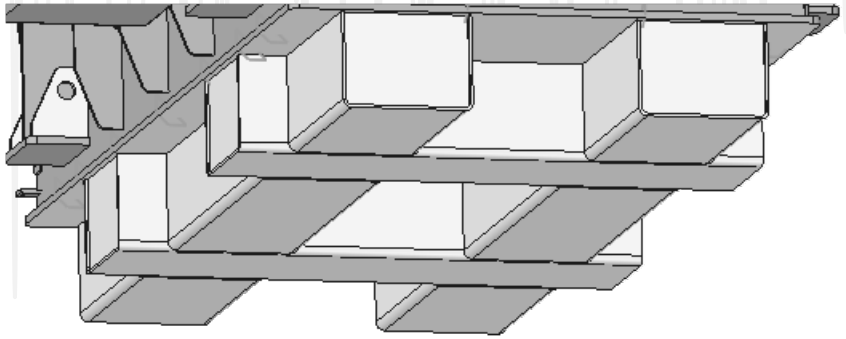
- Transformer Bushing Seismic Resilience – Grid Impact
  - Many Transformer Designs May Cause Excessive Bushing Amplification
  - Significant Load Loss Due to Transformer Bushings Very Likely

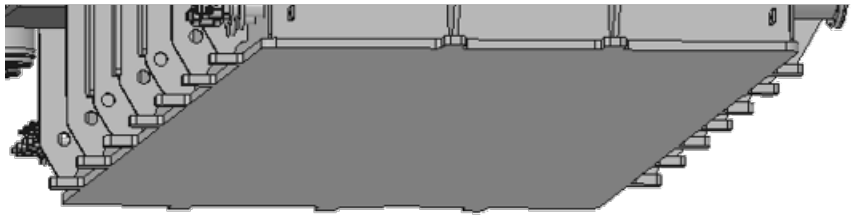
***Following a Seismic Event Matching Scenarios Selected From USGS Database**
***According to Simulations**

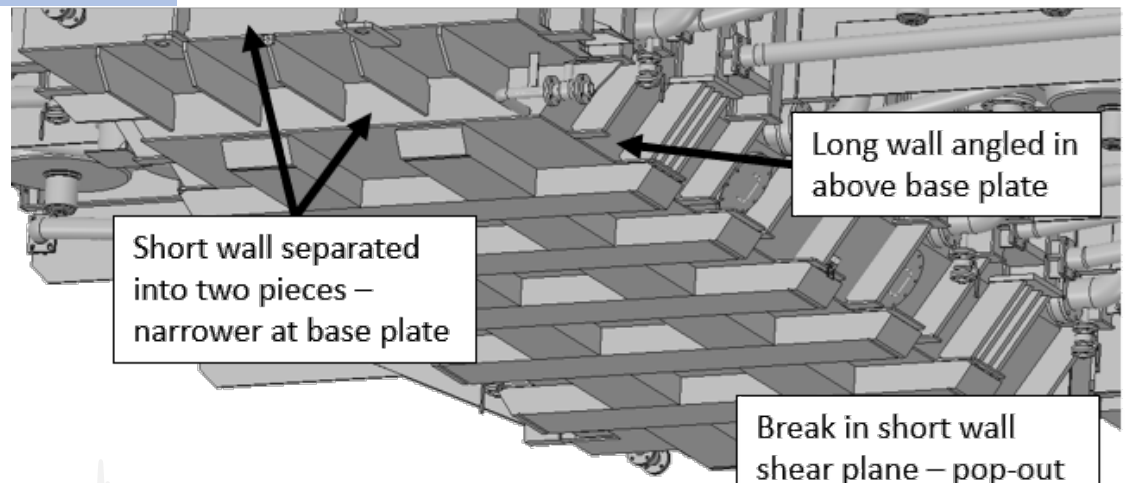
Next Steps

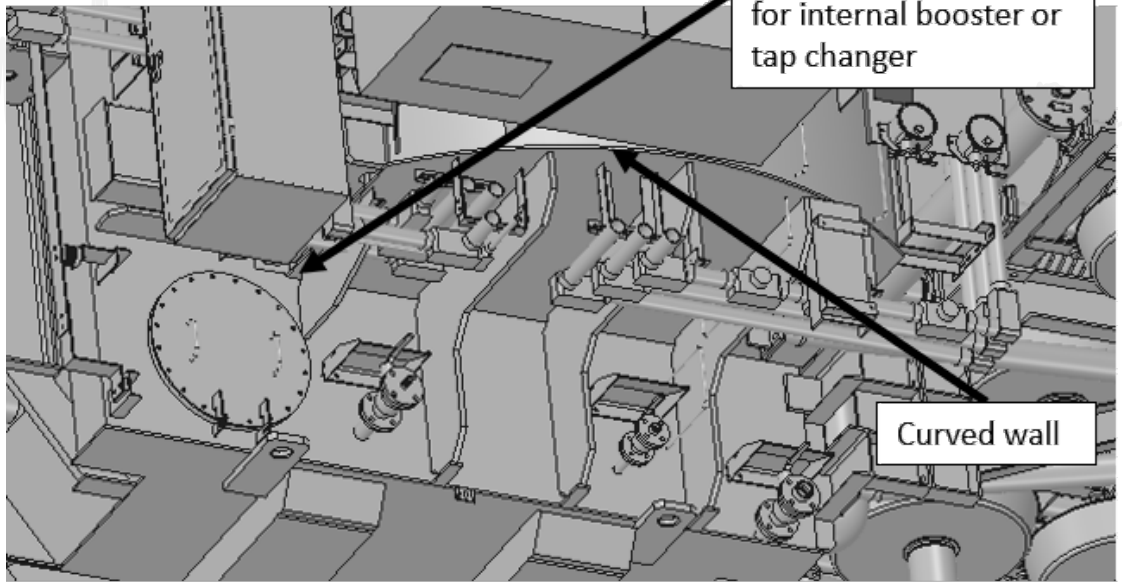
- Transformer Design Recommendations
  - Load Path Discontinuity (Stiffness)











Next Steps

- Transformer Design Recommendations
  - Tank-Foundation Stiffness (**230kV**) – Bypassing (resolving) the Load Path Discontinuity
    - ➢ Reduce Bushing Demands

Case Number	Amplification Change (%Diff)
1	13%
2	-50%
3	-41%
4	-10%
5	-47%
6	-32%
7	-41%
8	-42%
9	21%
Mean	**-25%**
Max	**-50%**

Note: Results are preliminary & specific to these designs. Other designs and kV classes may respond differently

Next Steps

- Transformer Design Recommendations
  - Tank-Foundation Stiffness (**230kV**) – Bypassing (resolving) the Load Path Discontinuity
    - ➢ Reduce Bushing Demands
  - Increasing the Anchorage Stiffness (LP Already Continuous)

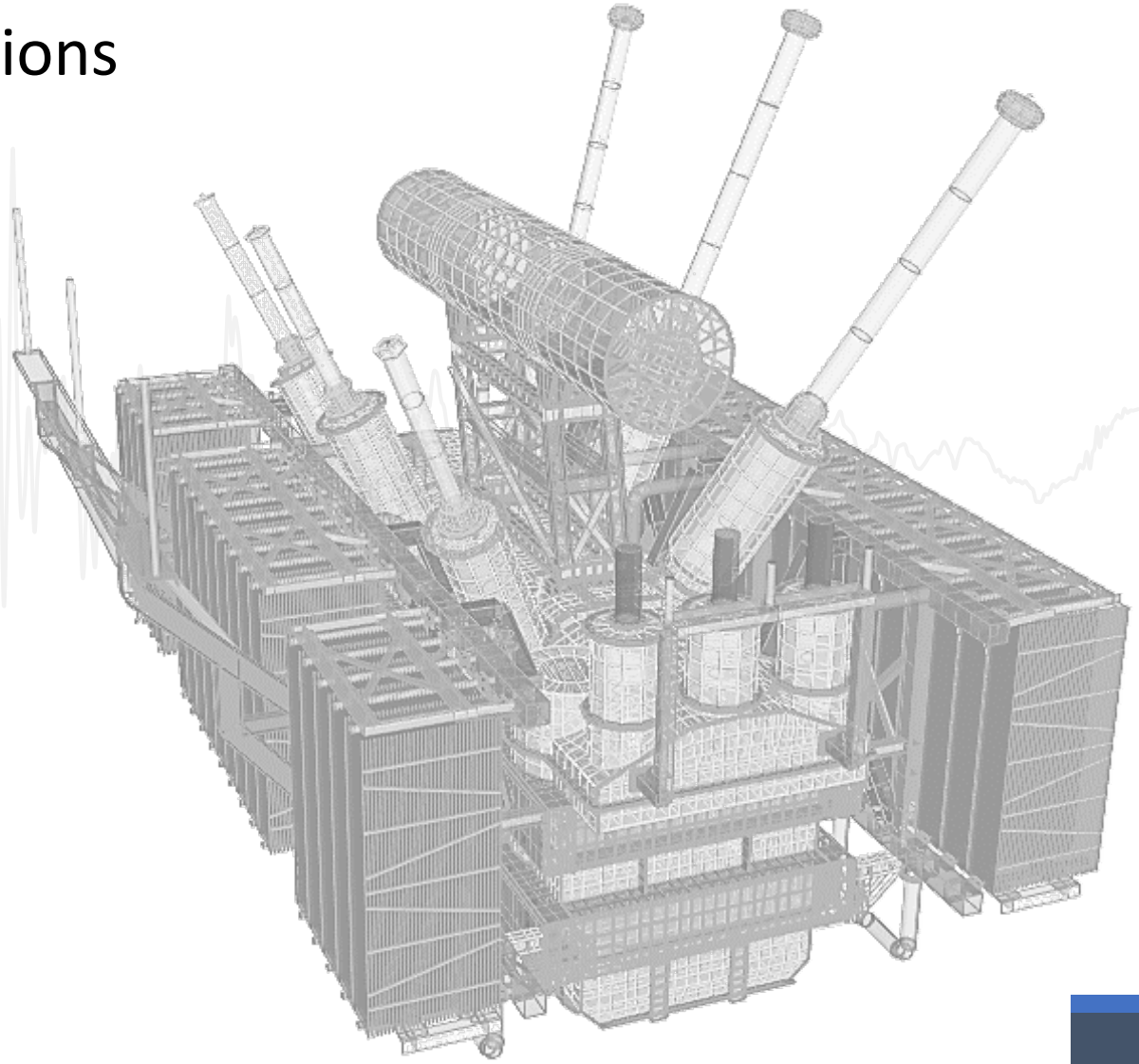
Case Number	Modification	Amplification Change (%Diff)
10	Increase Anchor Weld Length (Flat Base)	-21%
11	Max Anchor Weld Length (All-Around)	-51%

Case Number	Amplification Change (%Diff)
1	13%
2	-50%
3	-41%
4	-10%
5	-47%
6	-32%
7	-41%
8	-42%
9	21%
Mean	**-25%**
Max	**-50%**

Note: Results are preliminary & specific to these designs. Other designs and kV classes may respond differently

Next Steps

- Transformer Design Recommendations
  - Tank-Foundation Stiffness
  - Anchorage Detail/Stiffness
  - Cover design?



Next Steps

- Transformer Design Recommendations
- Physical Experimentation
  - In Situ
    - Snap-Back Testing
  - Shake Table
    - UCSD
    - 230kV Transformer
    - 3-Phase (~500kip)
  - Bushing Protection

Summary

- Transformer Bushing Seismic Resilience – Grid Impact
  - Many Transformer Designs May Cause Excessive Bushing Amplification
  - Significant Load Loss Due to Transformer Bushings Very Likely

***Following a Seismic Event Matching Scenarios Selected From USGS Database**
***According to Simulations**

- Next Steps / Solutions
  - Some Transformer Design Details Could Minimize
  - Physical Experimentation
    - Validation of Numerical Results
    - Test Mitigation Measures
  - Develop Bushing Protection

Questions?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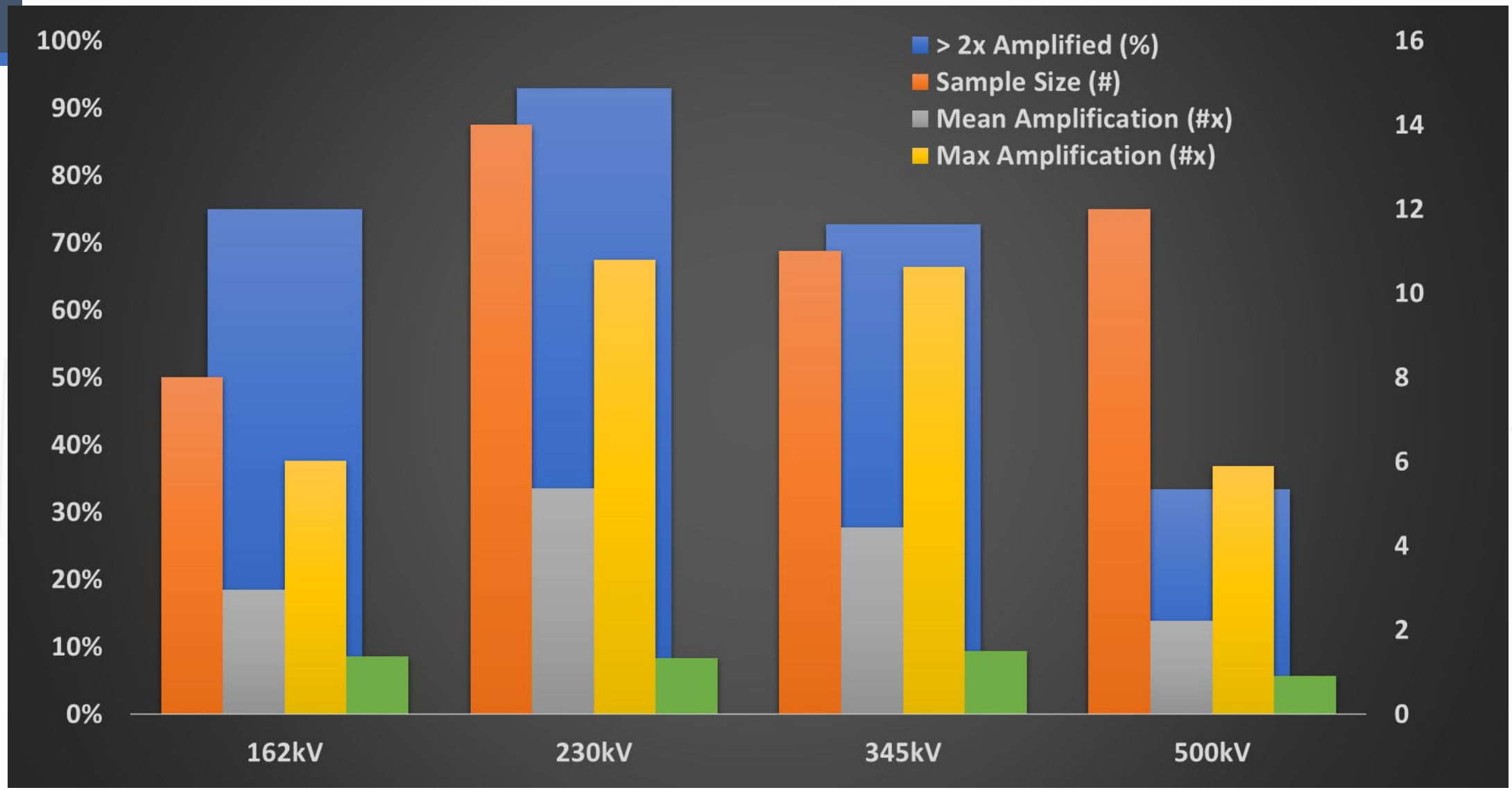
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
16
14
12
10
8
6
4
2
0
> 2x Amplified (%)
Sample Size (#)
Mean Amplification (#x)
Max Amplification (#x)
162kV
230kV
345kV
500kV