DOE Office of Electricity TRAC

Peer Review

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

PROJECT SUMMARY

Continuously Variable Series Reactor (CVSR) for Distribution System Applications

The viability and valuation of Continuously Variable Series Reactor (CVSR) in distribution system applications were investigated in this project. Special requirements that the distribution applications may have for CVSRs were analyzed, representative use cases were identified, 3-ph prototypes were developed and tested, and grid integration studies were conducted.

PRINCIPAL INVESTIGATORS

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The Numbers

DOE PROGRAM OFFICE:
OE – Transformer Resilience and Advanced Components (TRAC)

FUNDING OPPORTUNITY:
AOP

LOCATION:
Oak Ridge, TN

PROJECT TERM:
11/01/2018 to 12/31/2021

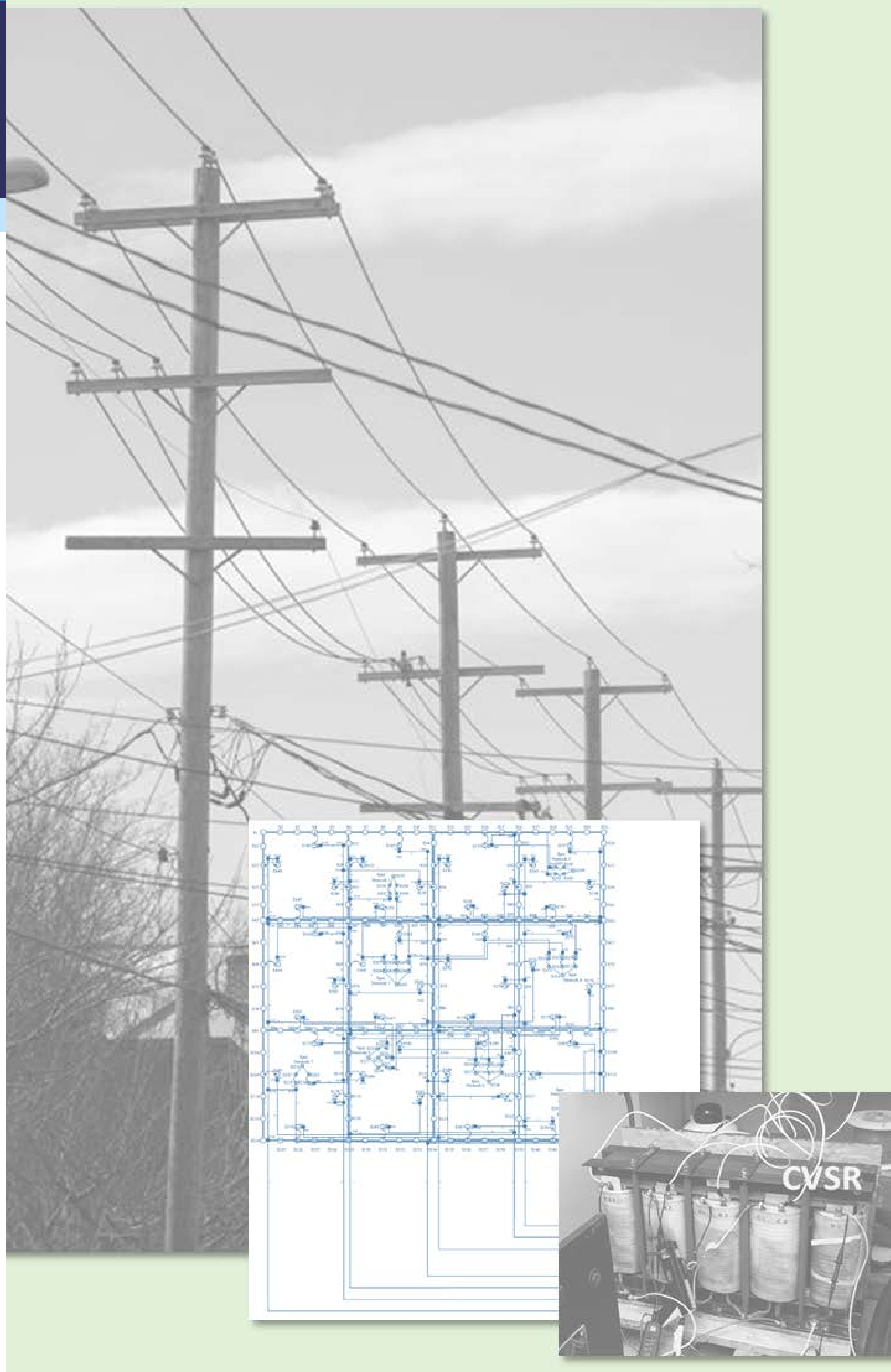
PROJECT STATUS:
Incomplete

AWARD AMOUNT (DOE CONTRIBUTION):
$625,000

AWARDEE CONTRIBUTION (COST SHARE):
$0

Primary Innovation

- Identified representative use cases of CVSR and associated specifications for distribution system applications.
- Developed and tested the first 3-ph CVSR prototype for distribution system applications.



Strategy

CVSR

- ✓ Compact 3-ph design
- ✓ MEC & FEA method for design and validation
- ✓ Lab-scale prototype for validation

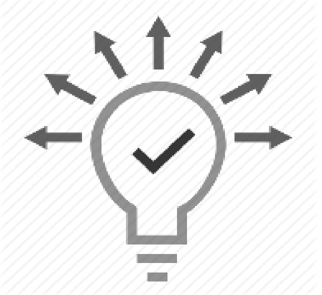
Use case

- ✓ Based on standard models
  - IEEE 342-node
  - ConEd model
- ✓ Power flow, sensitivity analysis

Valuation

- ✓ Quantitative integration study for optimal
  - Sizing
  - Placement

Impact

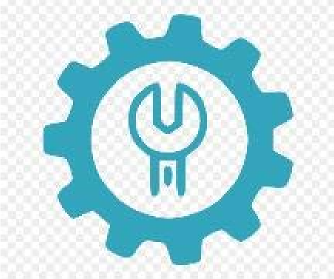


Proof of concept

A novel low-cost power flow control technology for distribution systems

In-depth valuation

Help understandthe viability, benefits, and limits of CVSR in the context of distribution system applications



Insight into design & development

Help identify potential issues in design & development and facilitate scale-up

Innovation Update

- System integration studies
  - ❑ Use case identified – transformer overloading relief
  - ❑ Optimal placement of CVSR

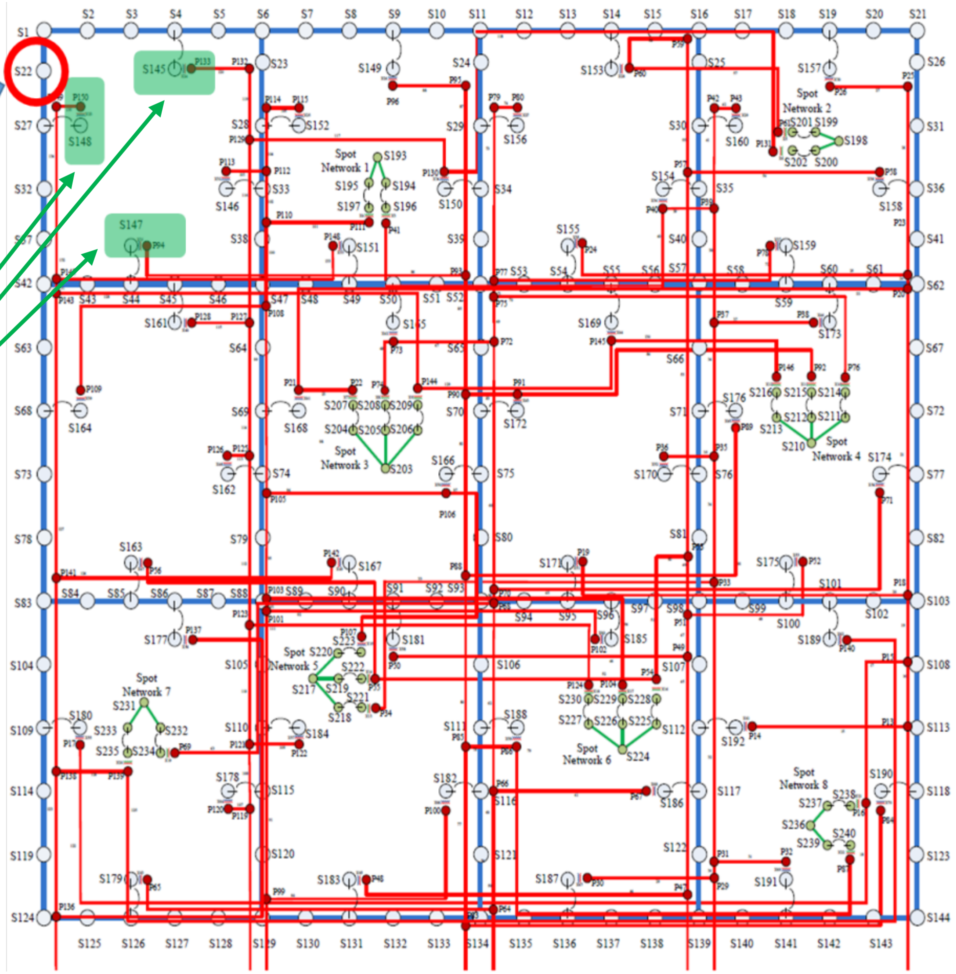
- Prototype design, development, and testing
  - ❑ 3-ph CVSR device design and simulation validation
  - ❑ Prototype testing

Transformer Loading - IEEE 342-node Model

- CVSR is used to relieve transformer overloading when the load at S22 is significantly increased.

Total load @ S22 (145kVA) multiplied by 8

3 transformers nearby considered

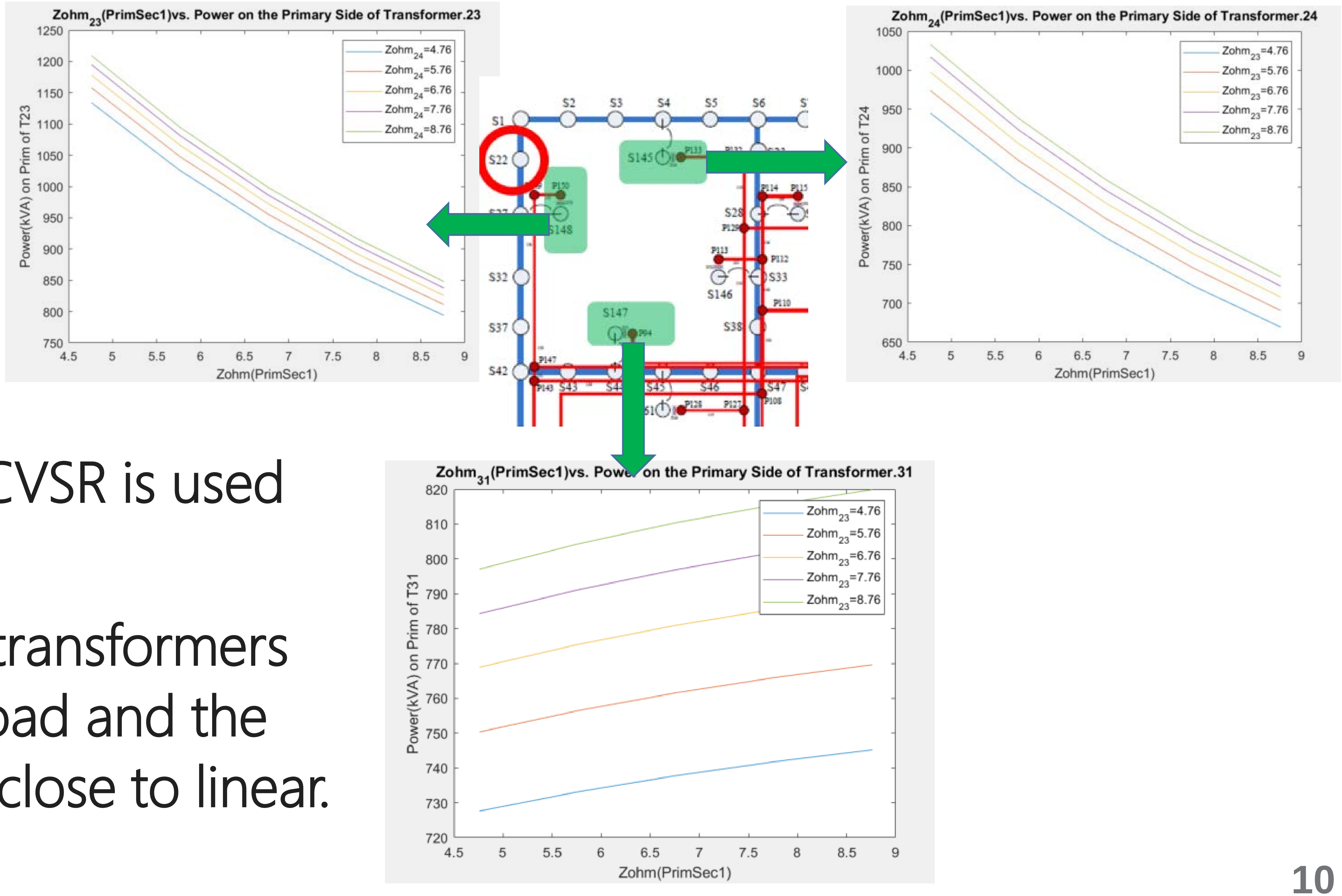


- ✓ Use CVSR to keep transformers T23, T24, and T31 from overloading.
- ✓ Simulation results are obtained through OpenDSS-MATLAB

Transformer sensitivity matrix

$$TS=\begin{bmatrix} \frac{dP_1}{dXhl_1} & \frac{dP_1}{dXhl_2} \\ \frac{dP_2}{dXhl_1} & \frac{dP_2}{dXhl_2} \end{bmatrix}$$

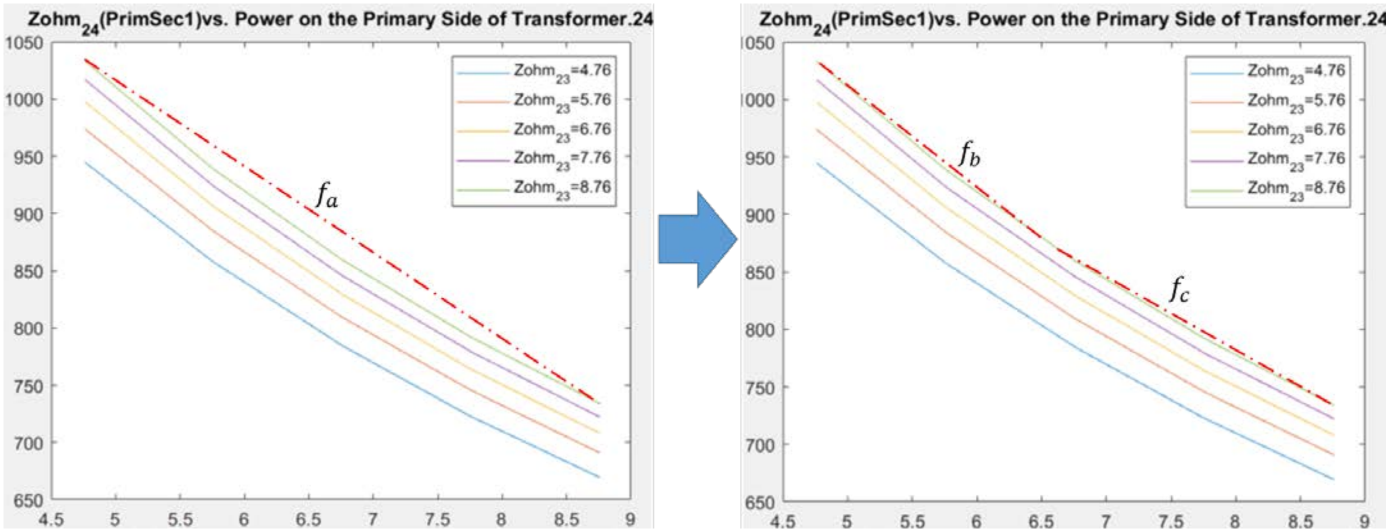
CVSR on Single Transformer



- Assume only one CVSR is used at a time.
- Results show how transformers pick up the extra load and the proportion is very close to linear.

CVSR on Two Transformers

- Install CVSR on T23 and T24 to relieve overloading.
- Use piecewise linearization of loading curve to improve the results.

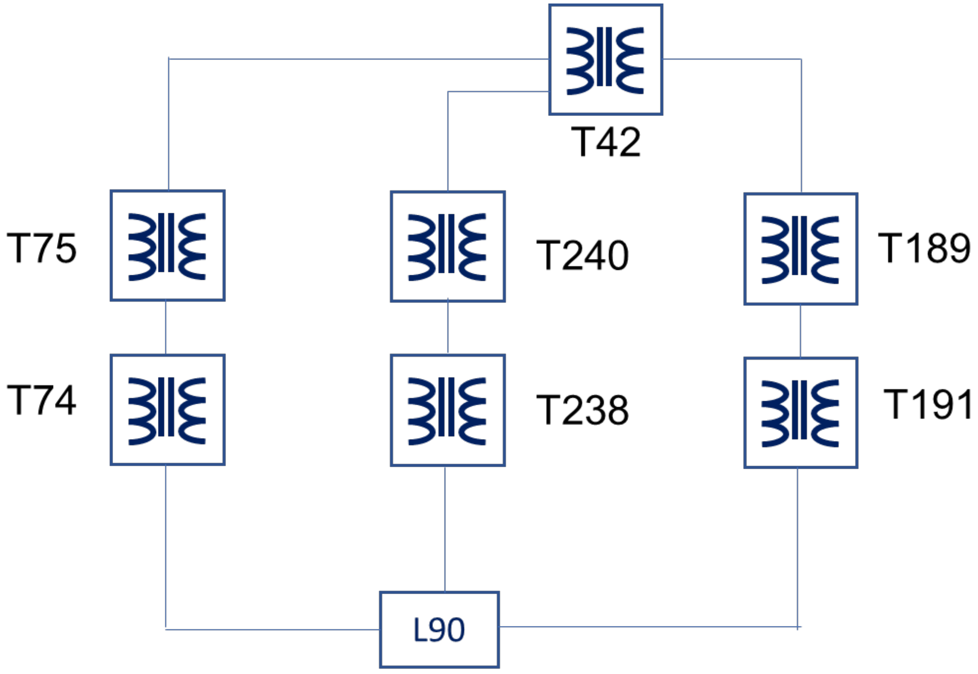


Results by using equal 5-segment

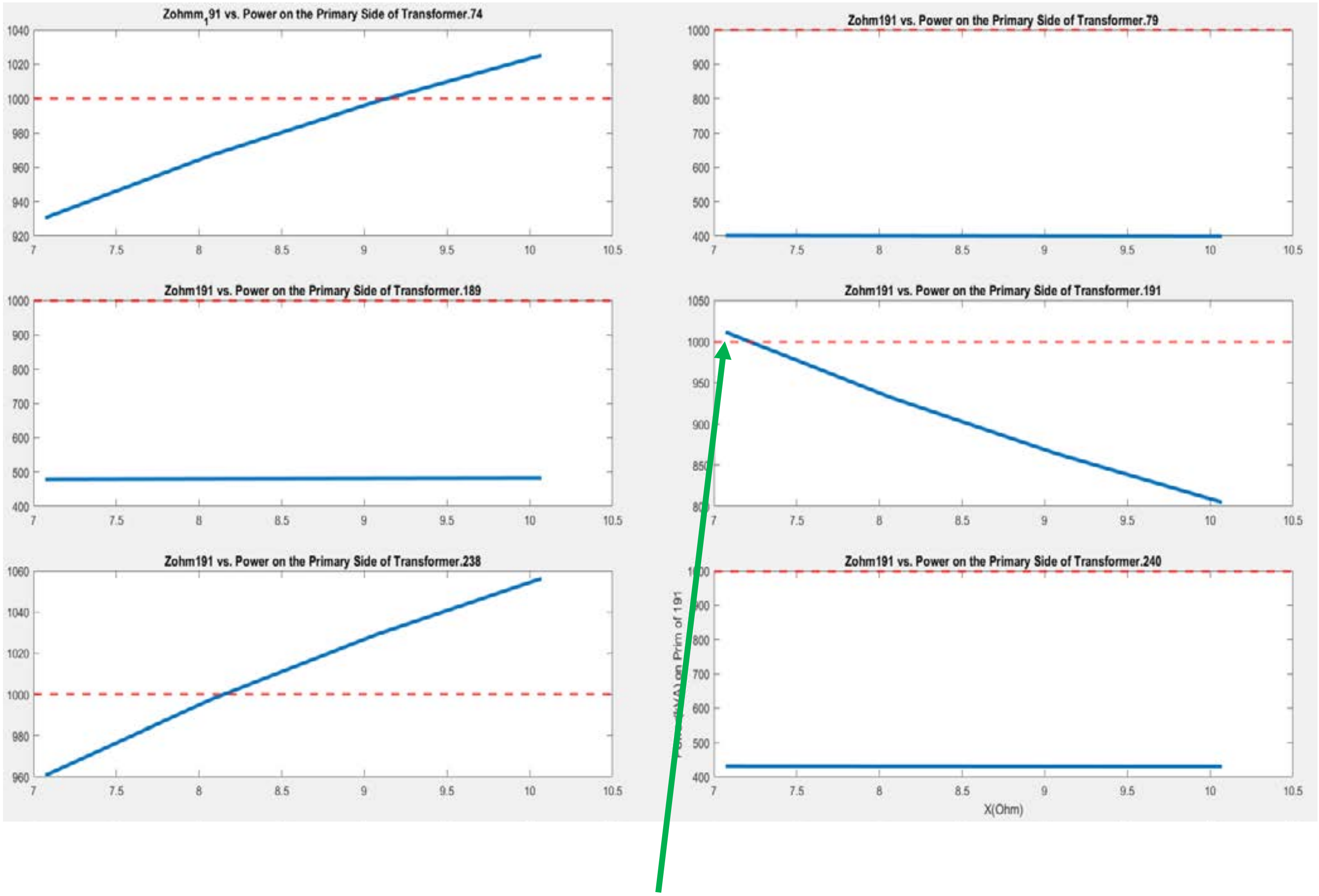
Xhl23 (ohm)	Xhl24 (ohm)	P23 by OpenDSS	P23 by Sensitivities	P24 by OpenDSS	P24 by Sensitivities	Transformer Limits
4.76	4.76	1133.96 kVA	1133.96 kVA	944.72 kVA	944.72 kVA	No Limit
4.76+1.275	4.76+0	999.85	1000	980.91	980.74	1000
4.76+1.994	4.76+0.522	947.59	950	947.65	950	950
4.76+2.879	4.76+1.363	892.90	900	891.95	900	900

Transformer Loading – ConEd System Model

- Transformer loading when load L90 is increased by 1.62 times
  - ❑ T191 installed with a CVSR
  - ❑ Loading on each transformer is monitored when CVSR reactance varys.



A small portion of ConEd system model with meshed configuration



Initially, only T191 overloaded

CVSR Optimal Placement

- T191, T74, and T238 installed with CVSR. Optimization analysis to determine the values of the CVSRs. (Loading limit 1MVA)

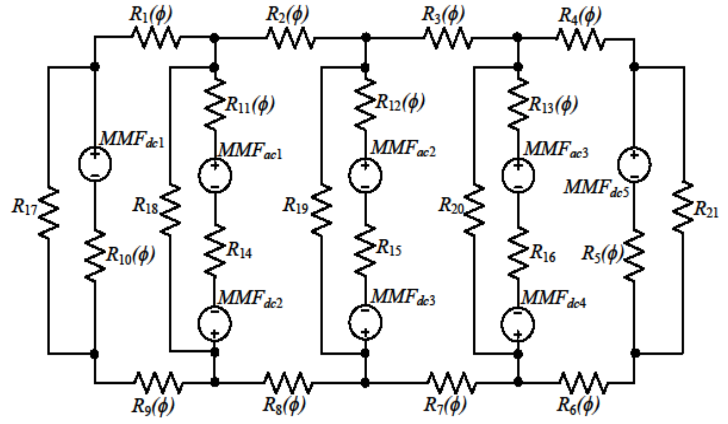
	Transformers | Loading	Initial (kVA)	1.62x Load Increment (kVA)	CVSR Reactance in Ohms	MATLAB Optimization (kVA)	OpenDSS (Benchmark) (kVA)
Piecewise 2-segment	T.191	648.3	1011.7	0.73 Ohm	966	962.7
	T.74	572	930.58	0 Ohm	964	969.3
	T.238	597.9	960.7	0.29 Ohm	964	964.4
Piecewise 4-segment	T.191	648.3	1011.7	0.69 Ohm	966	964.6
	T.74	572	930.58	0 Ohm	964	966.9
	T.238	597.9	960.7	0.27 Ohm	965	965.2

CVSR Prototype Development

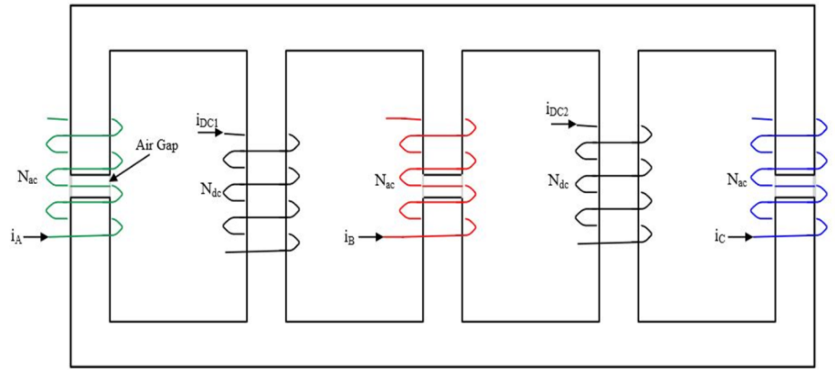
- CVSR prototype design was developed and validated by using analytical (MEC) and numerical (FEA) methods

- Multiple winding configurations were analyzed to identify the optimal design

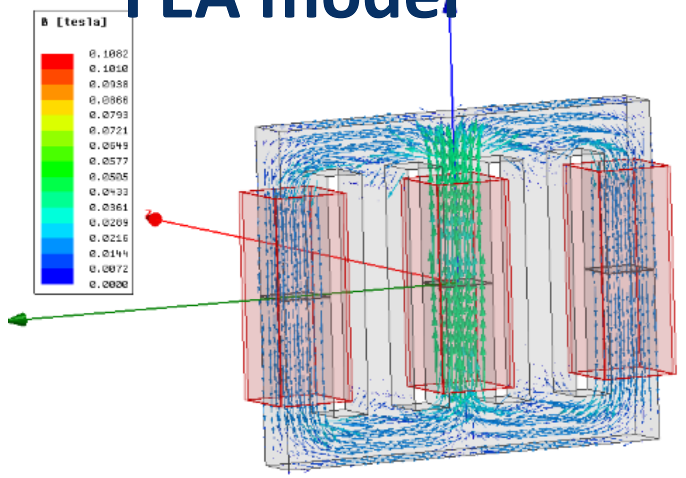
MEC model



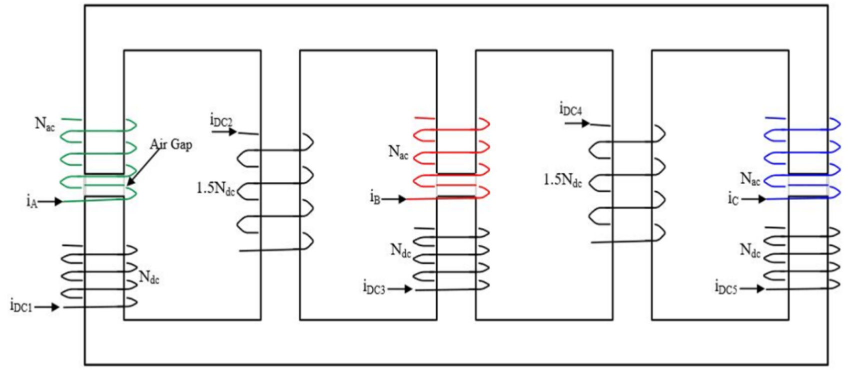
Config. #1



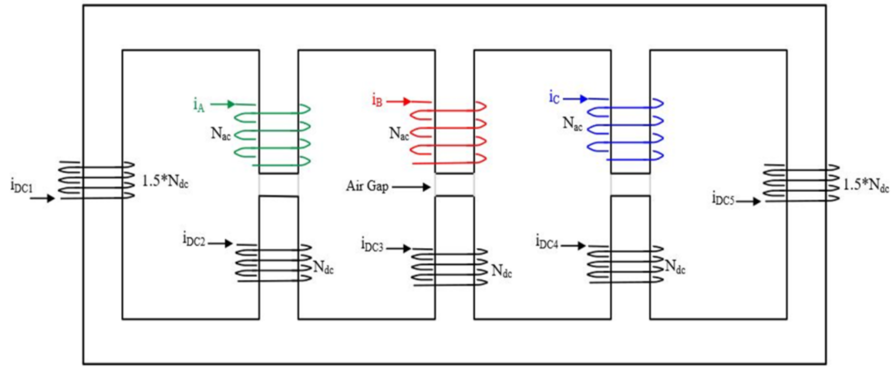
FEA model



Config. #2

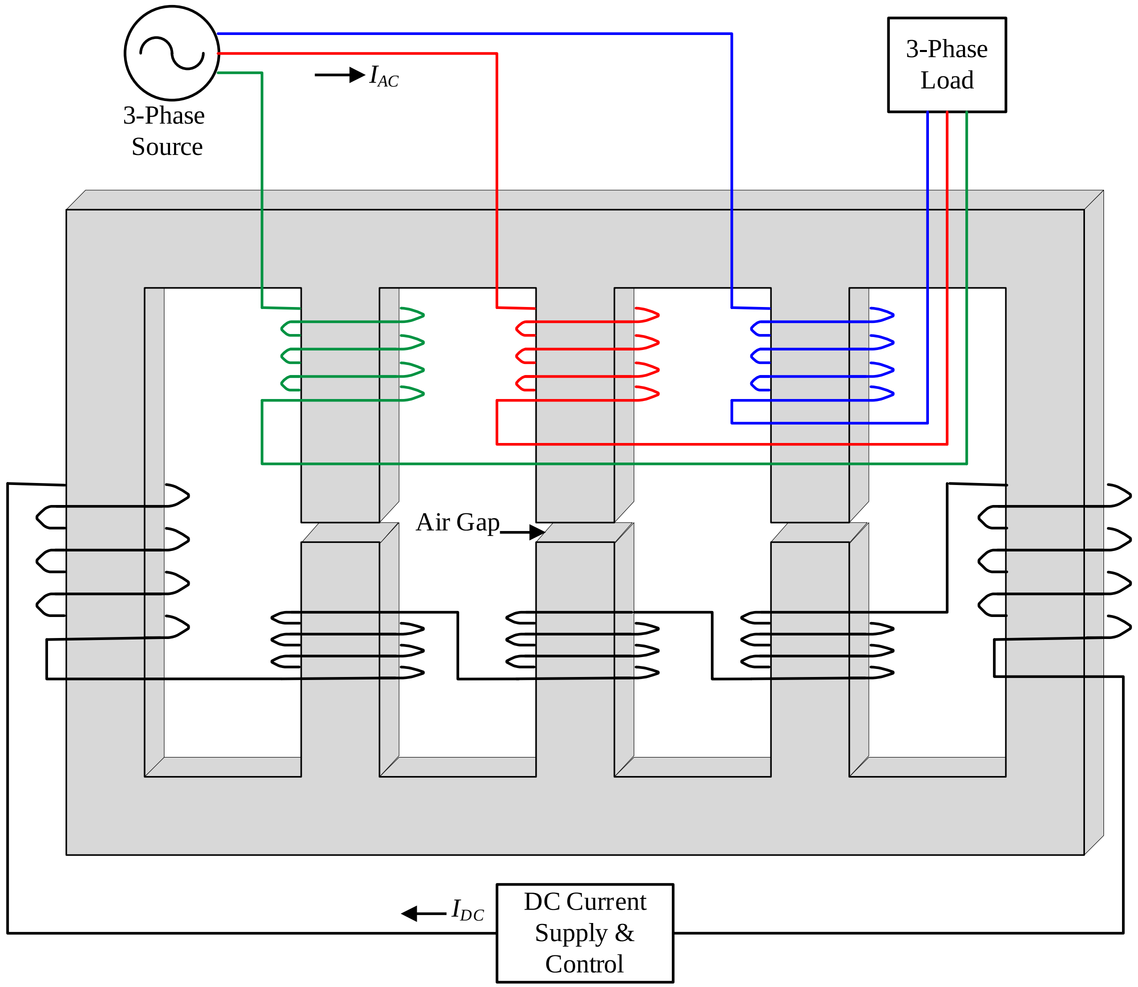


Config. #3

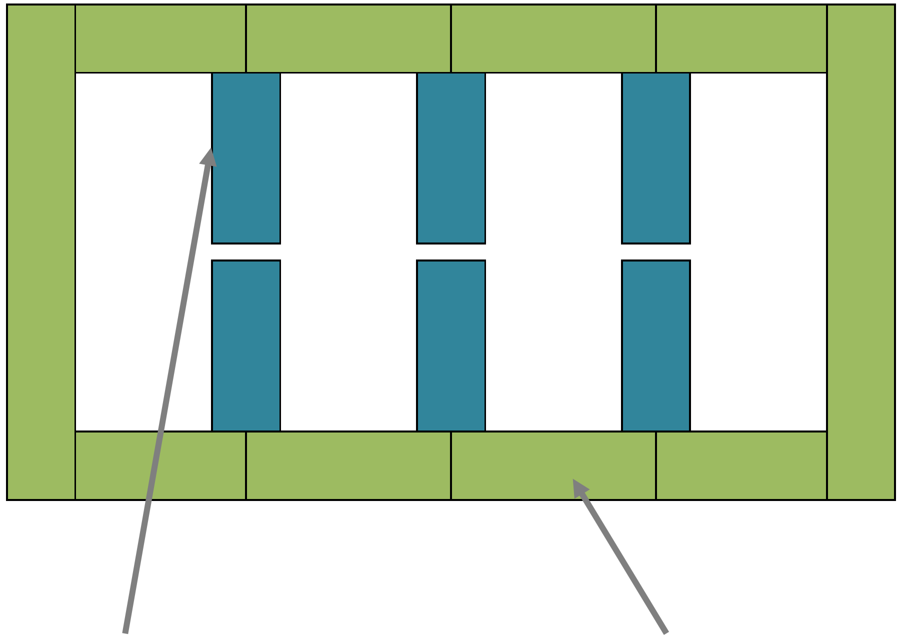


Design of Prototype #1

- Config. #3 was selected as the winding arrangement for the CVSR prototype.

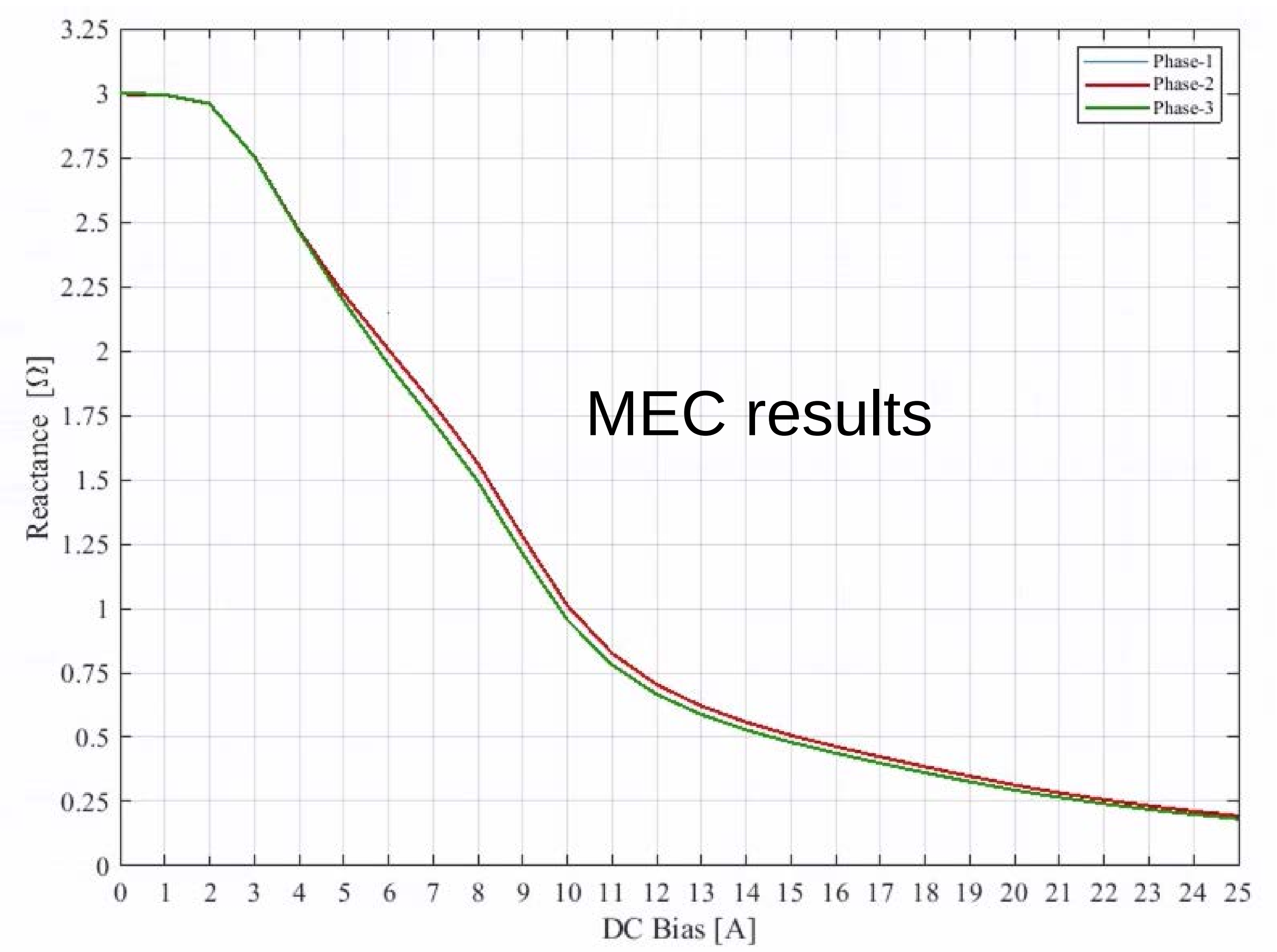


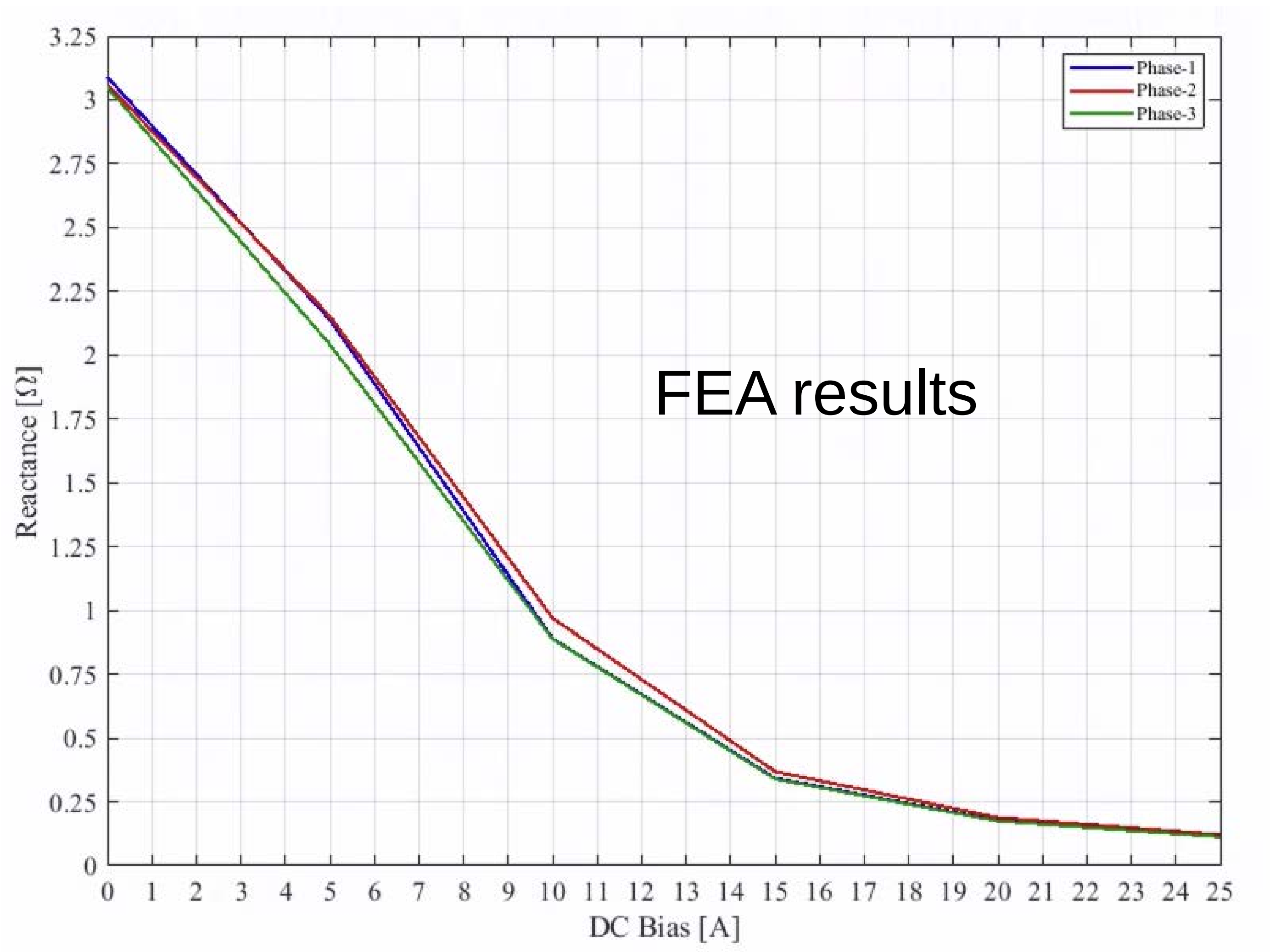
Heterogeneous core for ease of saturation and smoother reactance modulation



Model Validation

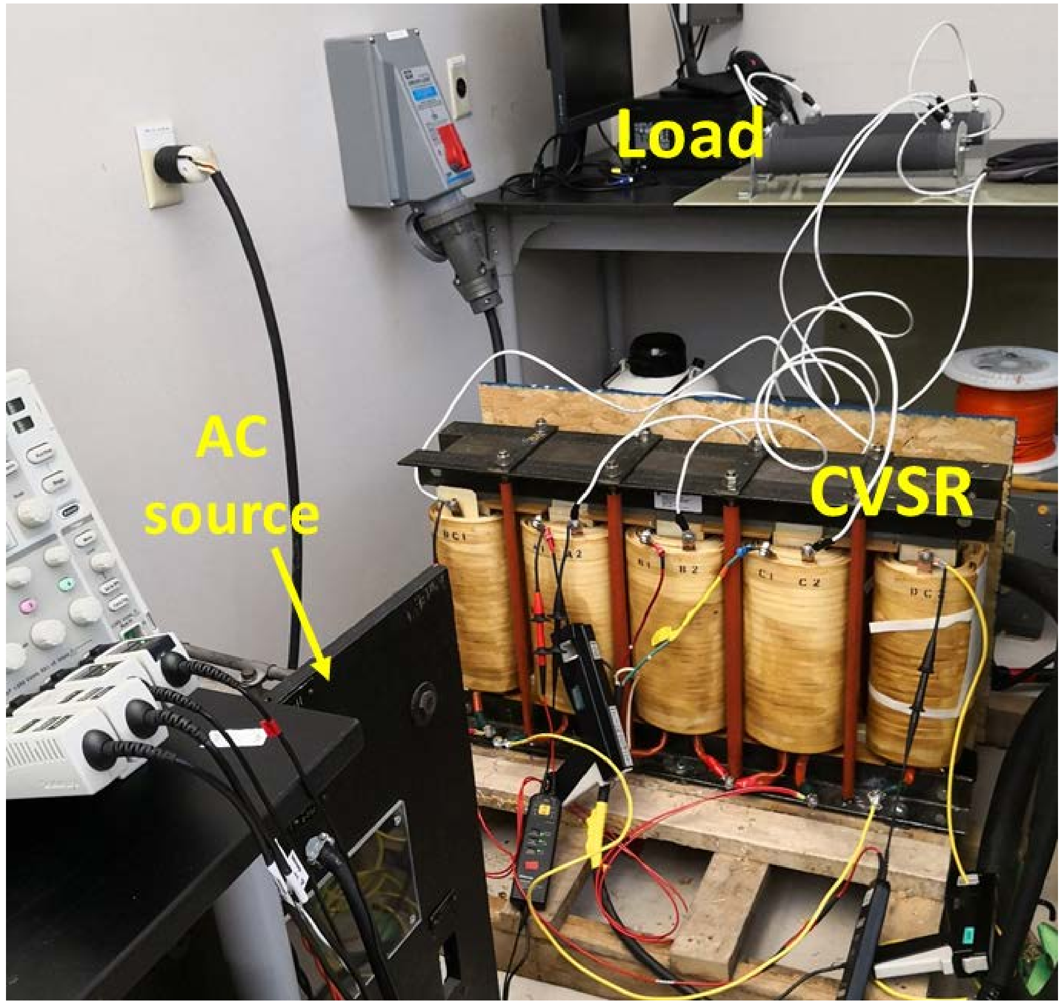
- Comparison between MEC and FEA results





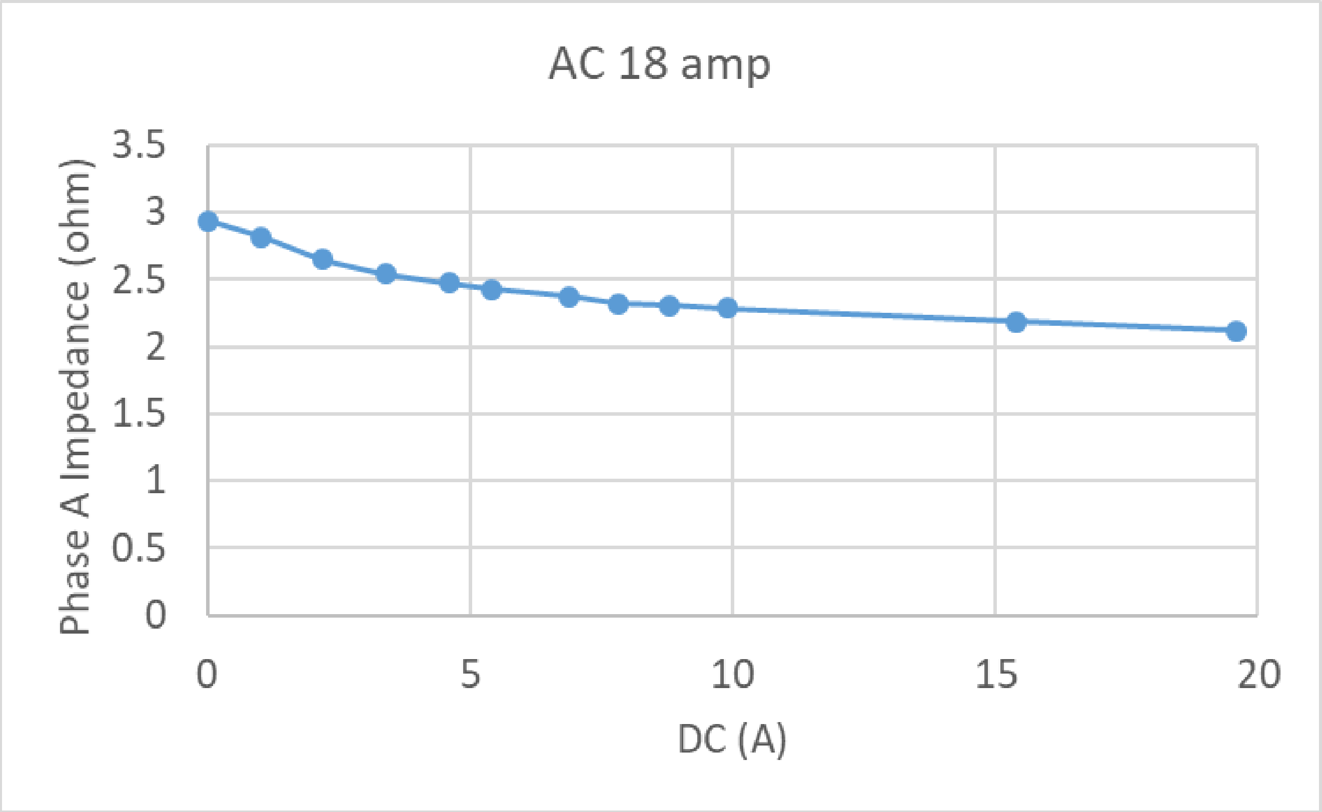
Testing of Prototype #1

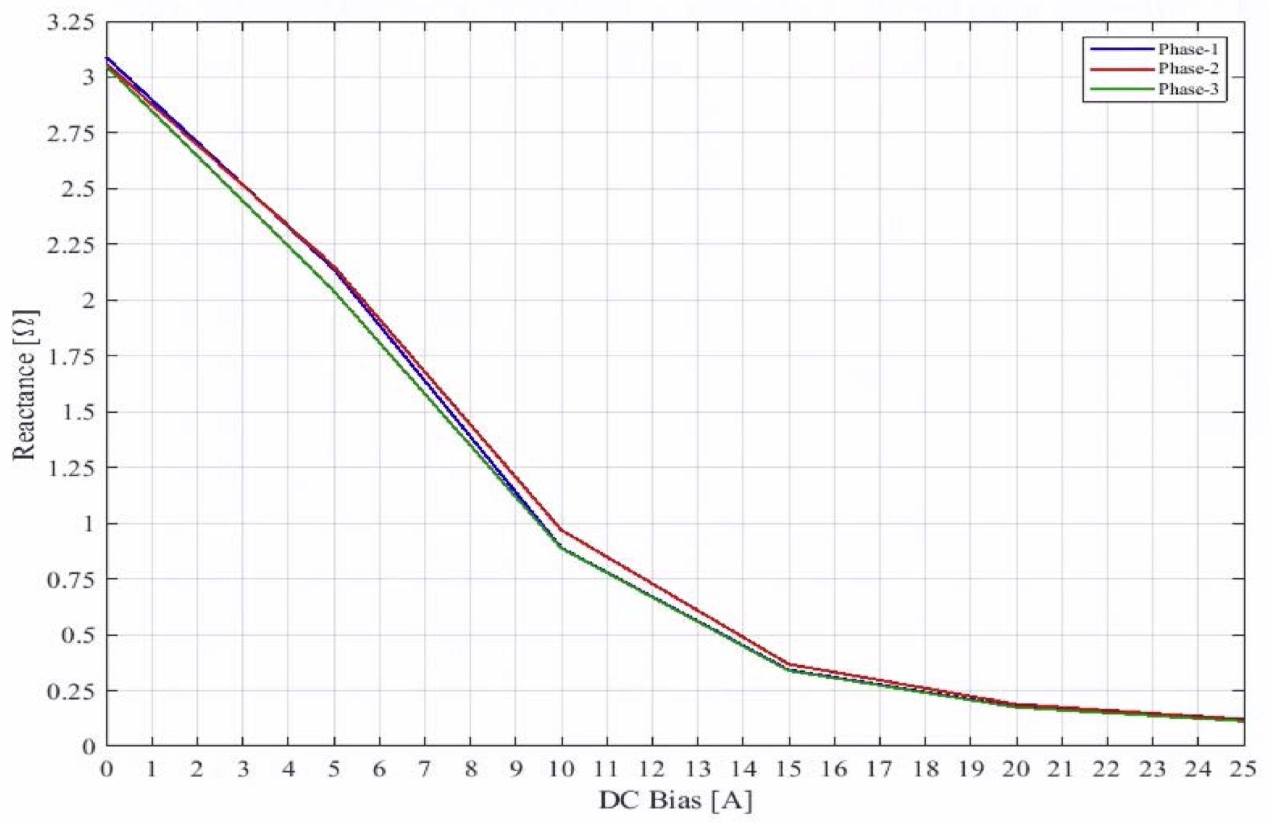
- Test to determine the reactance regulation curve of the prototype



Testing of Prototype #1

- Testing results not matching simulation results.

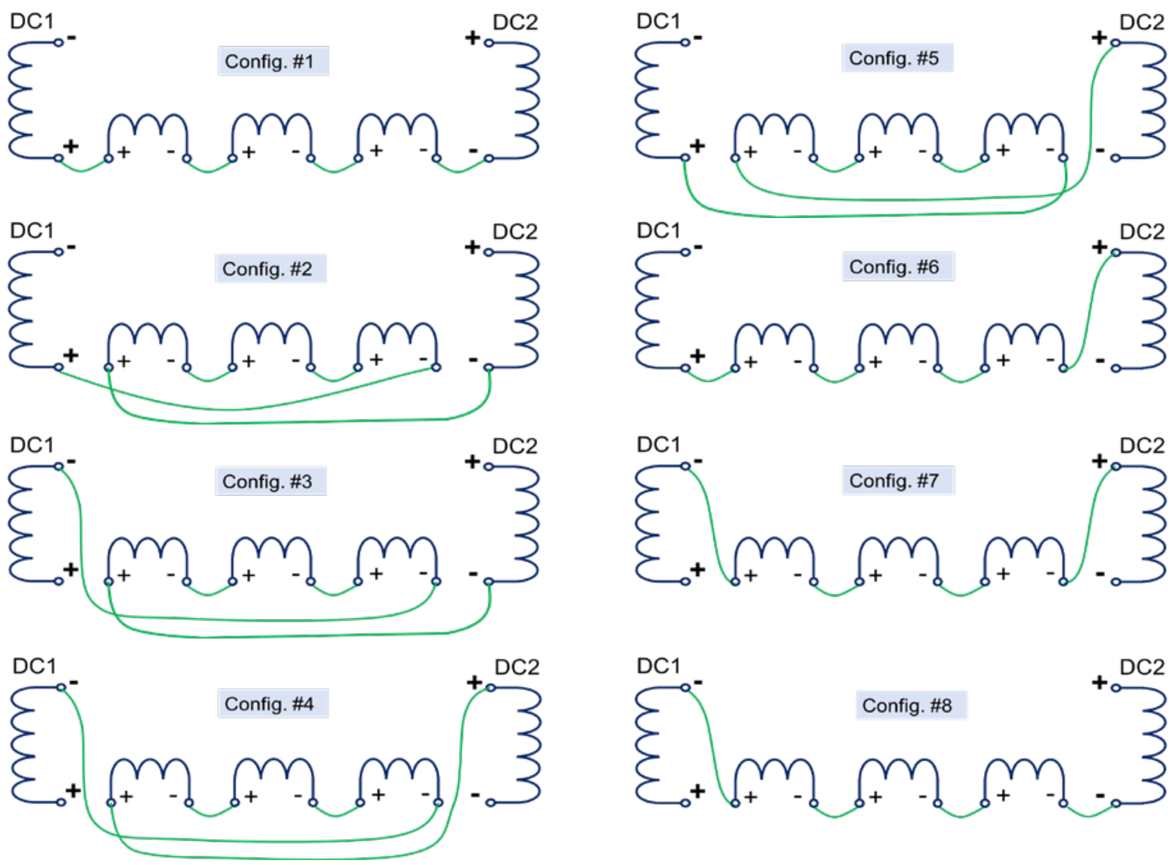




Diagnosis

- Ruled out some factors that may affect the results
  - ❑ DC winding configurations
  - ❑ 3-phase source and load balance

- DC amp-turns required to regulate inductance was underestimated due to the inductance calculation in simulation (incremental inductance by default, which is lower than the apparent inductance obtained in testing).



Checked all 8 possible connections of DC windings

Improved Design in Prototype #2

- Increased ampacity and turns of DC winding to provide enough DC amp-turns for inductance regulation
- Multiple taps were added on each of the windings for more flexibilities of winding design
- Manufacture of Prototype #2 is in process.

THANK YOU

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