U.S. DEPARTMENT OF
ENERGY
Office of Electricity

Continuously Variable Series Reactor (CVSR) for Distribution System Applications

TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

Oak Ridge, TN

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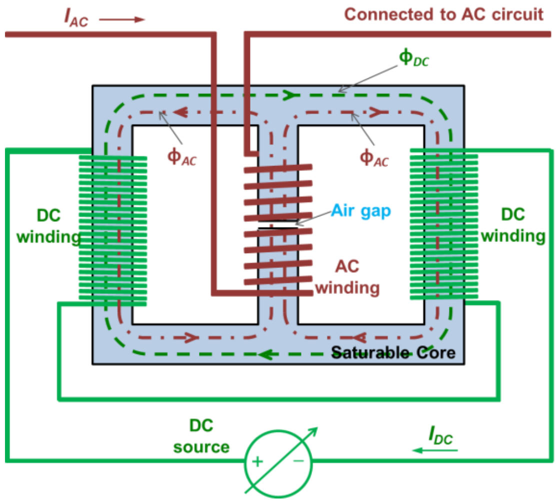
Project Overview

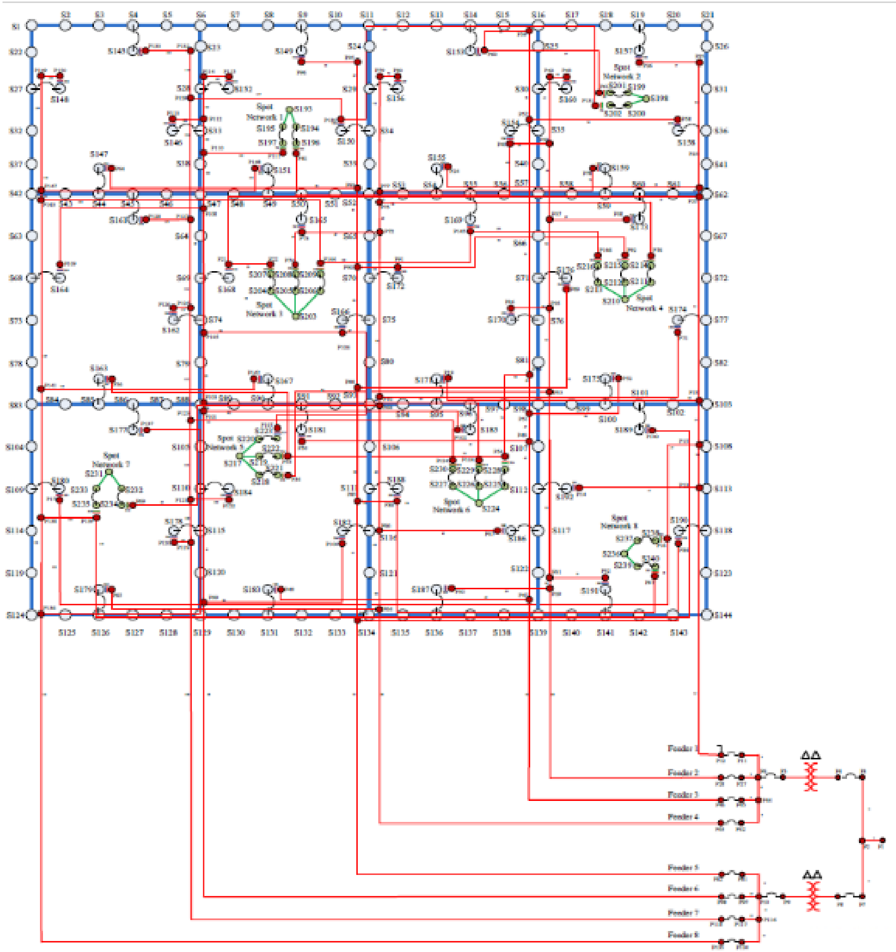
- Objective
  - ✓ CVSR concept extended to distribution grid applications
  - ✓ Preliminary studies facilitating future development and deployment
    - o Use case
    - o Valuation
    - o Prototype
- DOE award: $450k
- Duration: 18 months (01/19 – 06/20)
- Team
  - ✓ ORNL (lead)
  - ✓ UCF
  - ✓ UTK



Transmission level CVSR prototype from previous ARPA-e project

Context concerning the problem being addressed

- Distribution system for metropolitan and suburban districts



- ✓ Configuration complexity
- ✓ High load density
- ✓ Restrict reliability requirements
- ✓ Increased complexity of power flow
- ✓ Insufficient PFC capability

Need for power flow solutions

- Low cost/high reliability
- Meeting distribution system-specific requirements

State of the art approaches

- Full/partial-rating power electronics (P.E.) based solutions, e.g., Grid Energy Router*, modular control transformer

P.E. solutions

CVSR solution

Factors to consider

- Control flexibilities
- Reliability
- P.E. rating
- Cost
- Compactness

* Reference: NRECA report, “Field Demonstration: Grid Energy Router – Advanced Device for Voltage Control and Power Quality Management,” February 2016. https://www.cooperative.com/programs-services/bts/documents/reports/grid_energy_router_demo.pdf

Strategy and uniqueness of the proposed solution

CVSR

- ✓ Proved in previous projects
- ✓ Analysis tools for design & optimization
  - FEA
  - MEC
- ✓ Lab-scale prototype for validation

Use case

- ✓ Interests of utilities
- ✓ Standard models (easy for research) and real system models (reflecting real problems)
- ✓ Quantitative analysis
  - Power flow
  - Sensitivity analysis

Valuation

- ✓ Cost assessment
- ✓ Quantitative analysis for economic benefits
  - Optimization
  - Placement
- ✓ Scalability

Specific research questions being addressed

- What are the problems in distribution grid possibly to be solved by using CVSR?
- What are the use cases best proving the values of the technology in the selected system models?
- How to determine the appropriate specifications for the identified use case?
- Identify potential issues in advance through prototype development.

Significance of the results, if successful

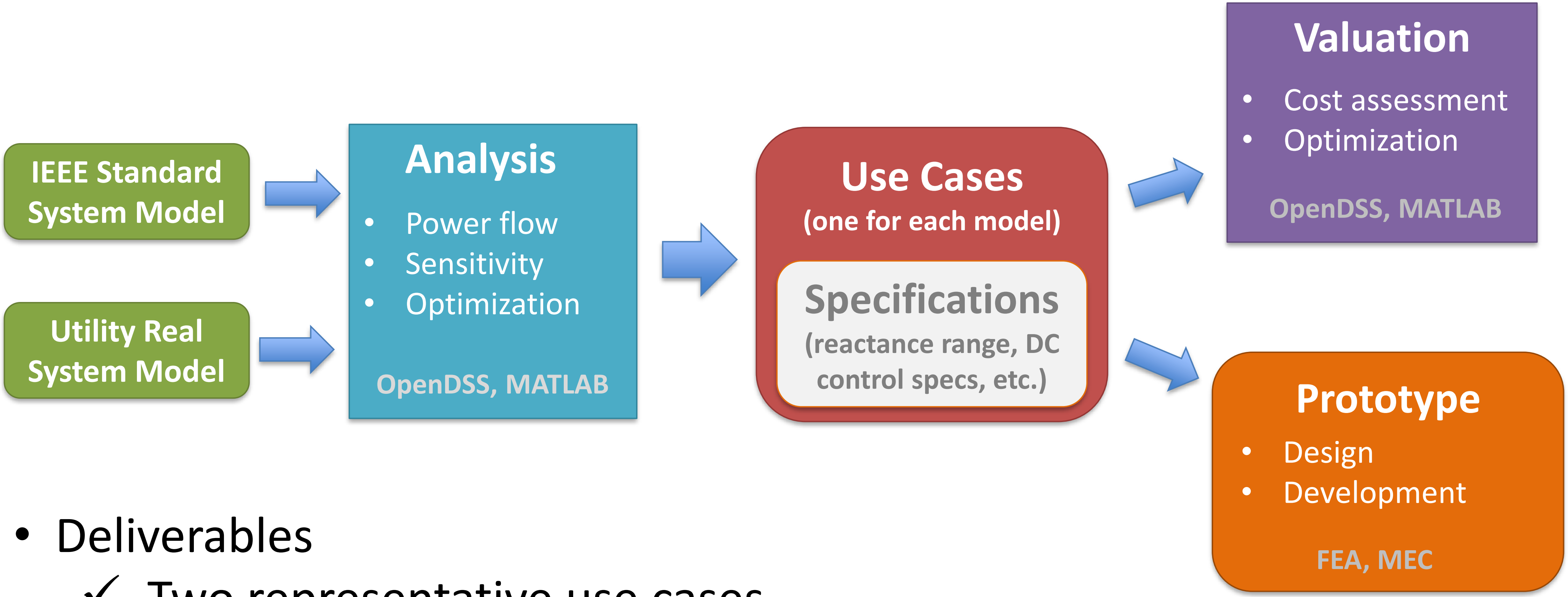
Representative Use Cases
Identify and solve problems in real systems

Valuation
Boost stakeholders’ confidence & facilitate technology adoption

Analysis Framework
Help future R&D of the technology or similar

Potential Issue Detection
Identify potential issues in advance to reduce risks

Proposed approach



- Deliverables
  - ✓ Two representative use cases
  - ✓ Valuation study results
  - ✓ One lab-scale prototype

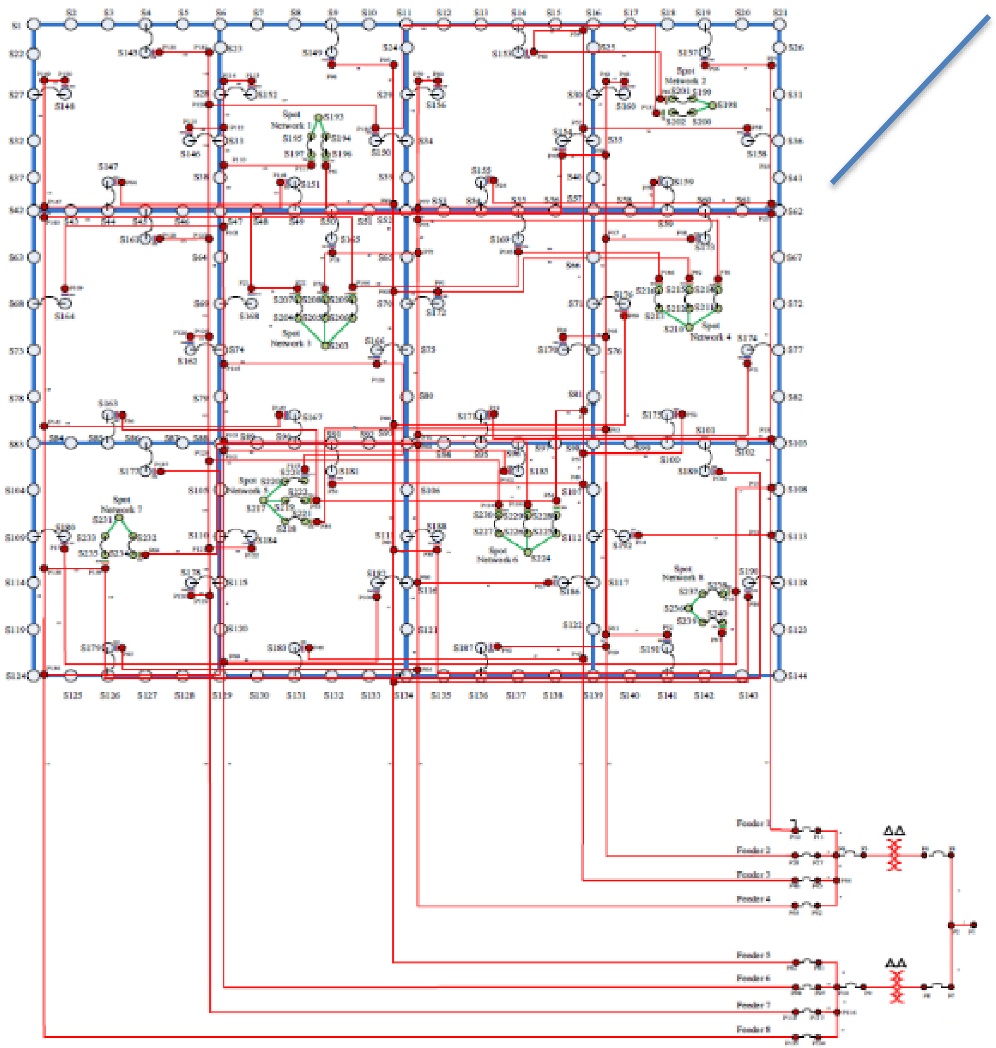
Project tasks, schedule, and funding status

Task	FY19 Q2	FY19 Q3	FY19 Q4	FY20 Q1	FY20 Q2	FY20 Q3
Task 1: Use case and device specifications						
Task 2: Modeling and design						
Task 3: Integration: optimal placement and valuation						
Task 4: Prototype development						
Task 5: Scalability study						

	Funds Remaining
ORNL	**$100k**
UTK (@ end of April)	**$70.7k**
UCF (@ end of August)	**$41k**

Progresses and results

- System models used for integration studies



IEEE 342-node LVNTS

- 2 delta-delta step down transformers with 8x13.2 kV distribution feeders.
- Grid (meshed) and spot networks on secondary
- Secondary network transformers at 1 MVA rating, spot network transformers at 1.5, 2, and 2.5 MVA ratings.

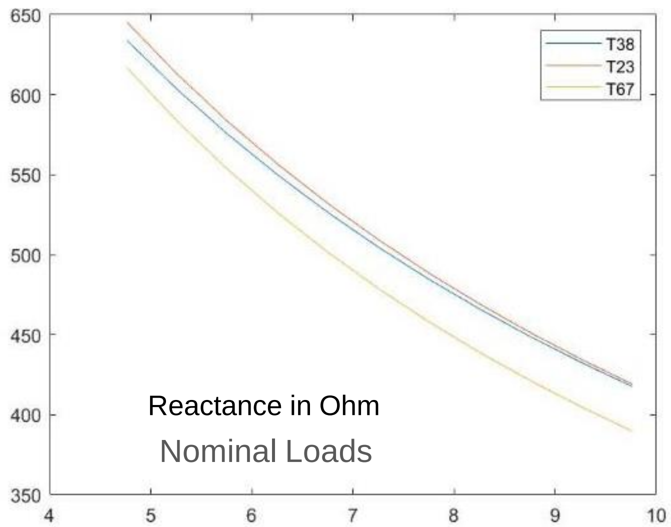
ConEd distribution system model

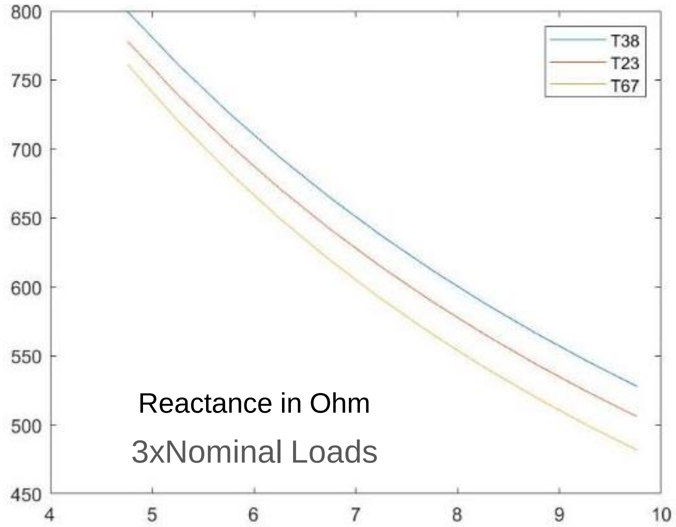
- Waiting on NDAs

Use case development - 1

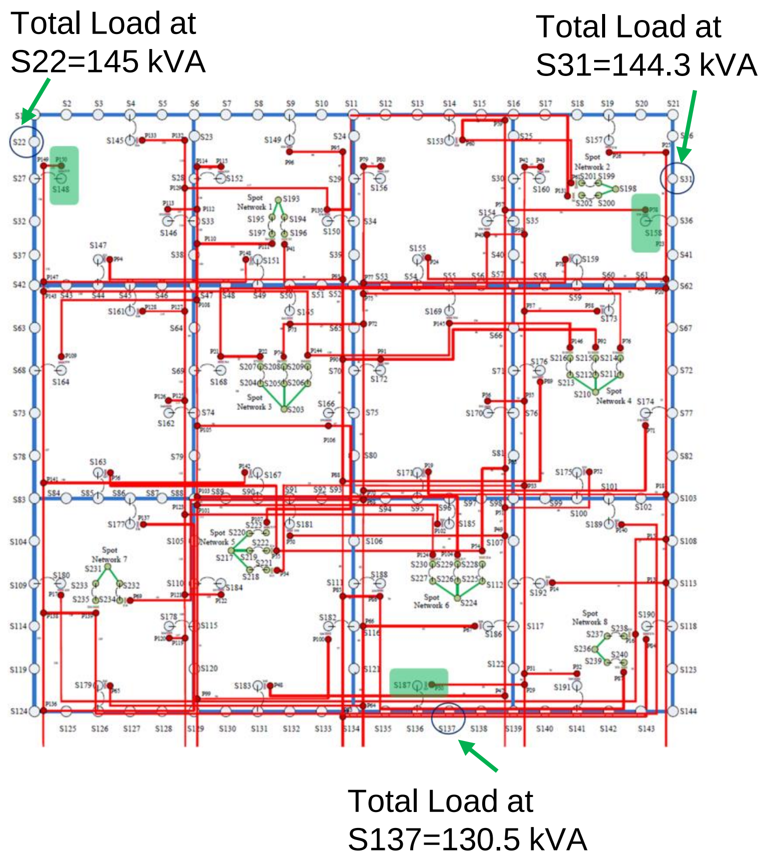
Loading sensitivity

- Nominal loads at three nodes are increased by a factor of 3.
- Results show how transformers pick up the extra load and the proportion is very close to linear.
- To find out the vulnerable transformers





Power Flow on the Primary Side of Transformers



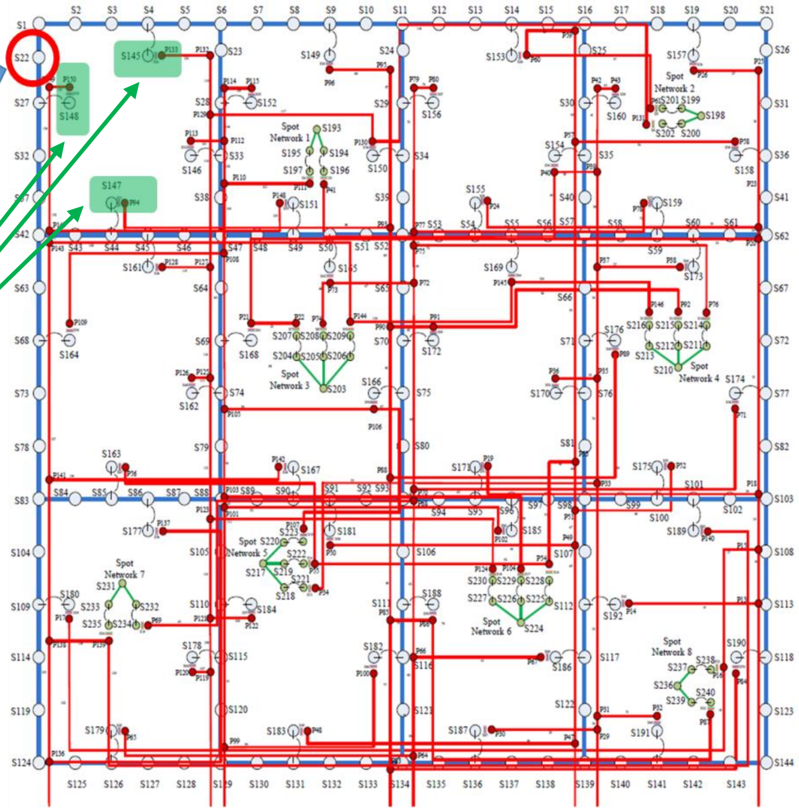
All transformers are secondary network transformers, and they are rated at 1MVA

Use case development - 2

- Transformer loading relief when load @S22 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

Use case development - 3

- Determine optimal reactance value(s) of CVSR

Case 1: Use one CVSR unit

Case 1: Only T-23 has CVSR device						
S22	T-23		T-24		T-31	
	kVA	ohm	kVA	ohm	kVA	ohm
Coefficient = 8	1132	4.76	945.3	4.76	728.3	4.76
	1076	5.26	960.6	4.76	740.2	4.76
	1024	5.76	974.3	4.76	750.9	4.76
	977.4	6.26	986.9	4.76	760.7	4.76
	934.2	6.76	998	4.76	769.5	4.76
	894.5	7.26	1008	4.76	777.5	4.76

Case 2: Use two CVSR units

Case 2: T-23 and T-24 have CVSR device						
S22	T-23		T-24		T-31	
	kVA	ohm	kVA	ohm	kVA	ohm
Coefficient = 8	1132	4.76	945.3	4.76	728.3	4.76
	1088	5.26	914.3	5.26	743.2	4.76
	1046	5.76	884.8	5.76	757.1	4.76
	1008	6.26	856.6	6.26	769.8	4.76
	971.1	6.76	829.5	6.76	781.5	4.76
	936.9	7.26	803.88	7.26	792.3	4.76
	904.9	7.76	779.4	7.76	802.3	4.76
	874.6	8.26	756.1	8.26	811.6	4.76

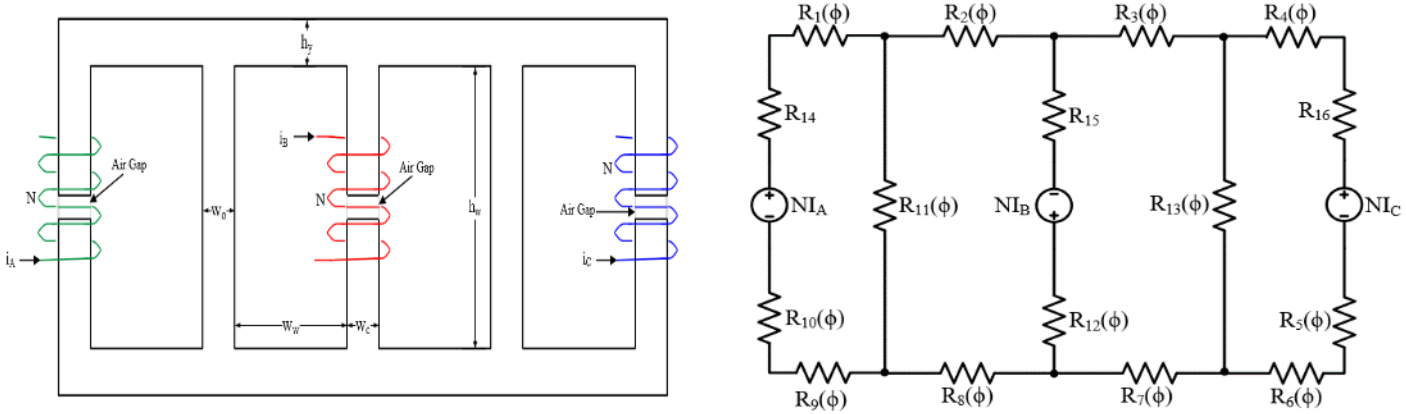
Use case development - 4

- Linear optimization analysis and comparison with OpenDSS

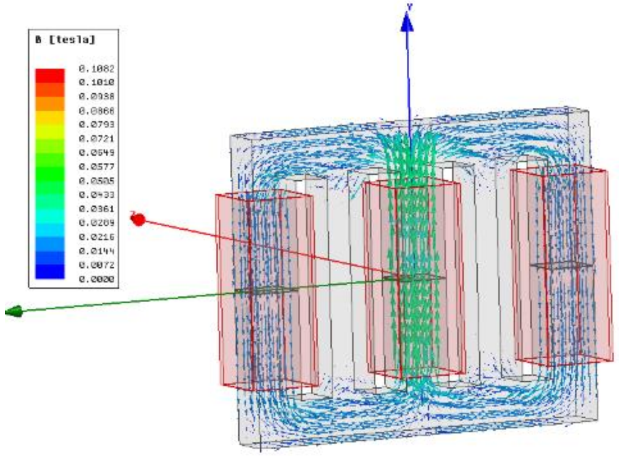
Case 1: Only T-23 has CVSR device						
S22	T-23		T-24		T-31	
Coefficient = 8	kVA	ohm	kVA	ohm	kVA	ohm
Optimization Result from MATLAB (Linprog)	1000	6.096	980.48	4.76	755.76	4.76
OpenDSS (Benchmark)	992.31	6.096	982.82	4.76	757.55	4.76
Relative Error in Percent	0.774%	--	0.238%	--	0.236%	--

CVSR device modeling - 1

- Modeling of CVSR by using analytical and numerical methods
- For designing the lab-scale prototype



Magnetic Equivalent Circuit (MEC) method



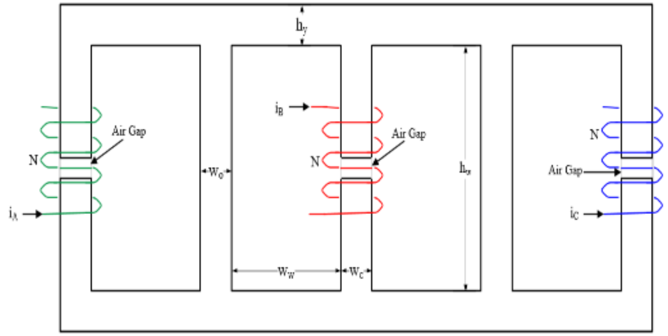
Finite Element Analysis (FEA) method

One example for analysis:

- 13.8kV, 500kVA transformers
- Phase current ~30A

CVSR device modeling - 2

- Configuration design and reactance regulation of 3-phase device

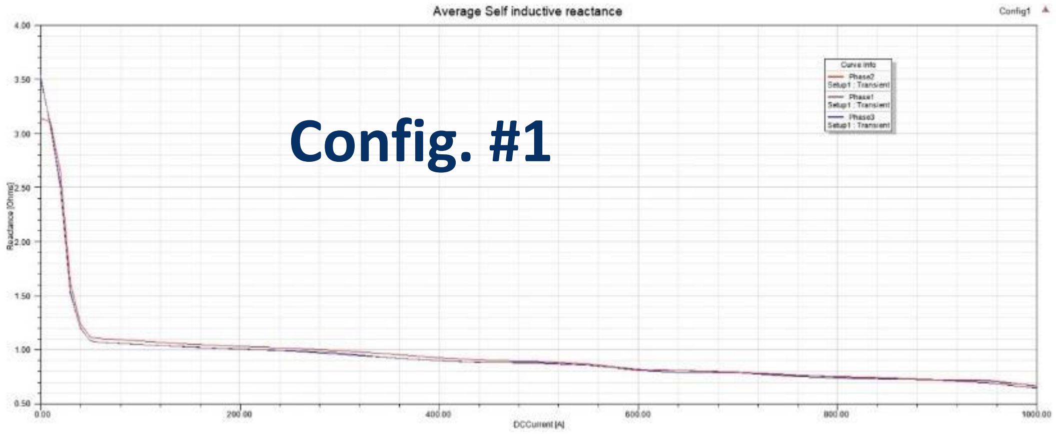


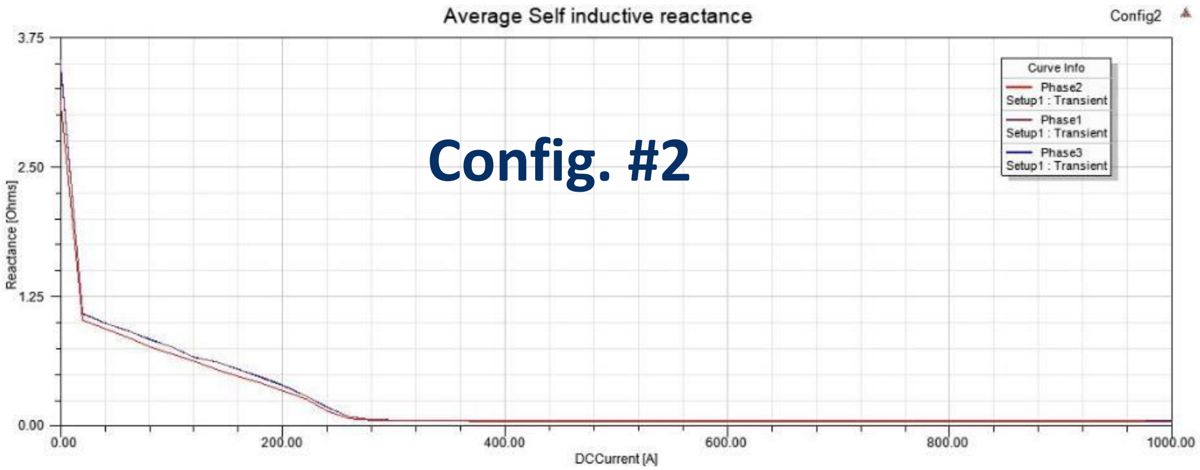
* G = Gap
Nac = 42
Ndc = 39

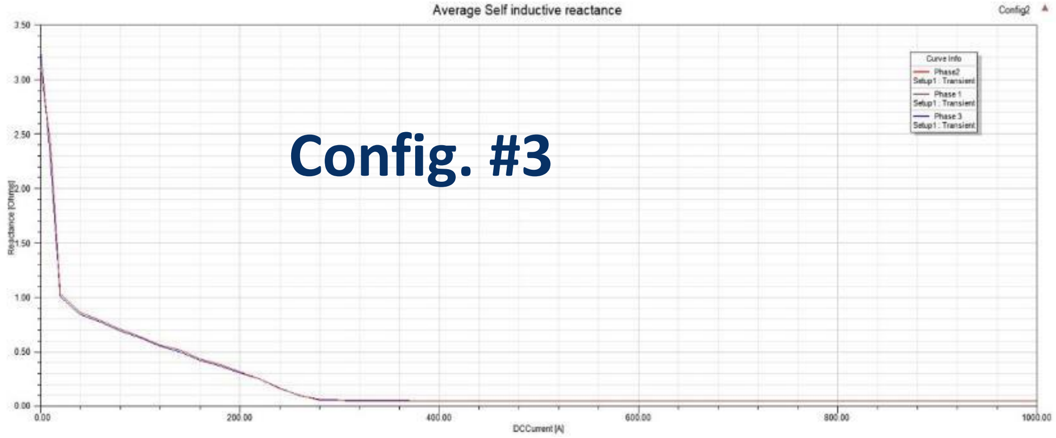
		1 (G)	2	3 (G)	4	5 (G)
Config. #1	DC MMF	0	$N_{dc}I_{dc}$	0	$N_{dc}I_{dc}$	0
	AC MMF	$N_{ac}I_a$	0	$N_{ac}I_b$	0	$N_{ac}I_c$
Config. #2	DC MMF	$N_{dc}I_{dc}$	$-1.5N_{dc}I_{dc}$	$N_{dc}I_{dc}$	$-1.5N_{dc}I_{dc}$	$N_{dc}I_{dc}$
	AC MMF	$N_{ac}I_a$	0	$N_{ac}I_b$	0	$N_{ac}I_c$
Config. #3	DC MMF	$-1.5N_{dc}I_{dc}$	$N_{dc}I_{dc}$	$N_{dc}I_{dc}$	$N_{dc}I_{dc}$	$-1.5N_{dc}I_{dc}$
	AC MMF	0	$N_{ac}I_a$	$N_{ac}I_b$	$N_{ac}I_c$	0

CVSR device modeling - 3

- Configuration design and reactance regulation of 3-phase device



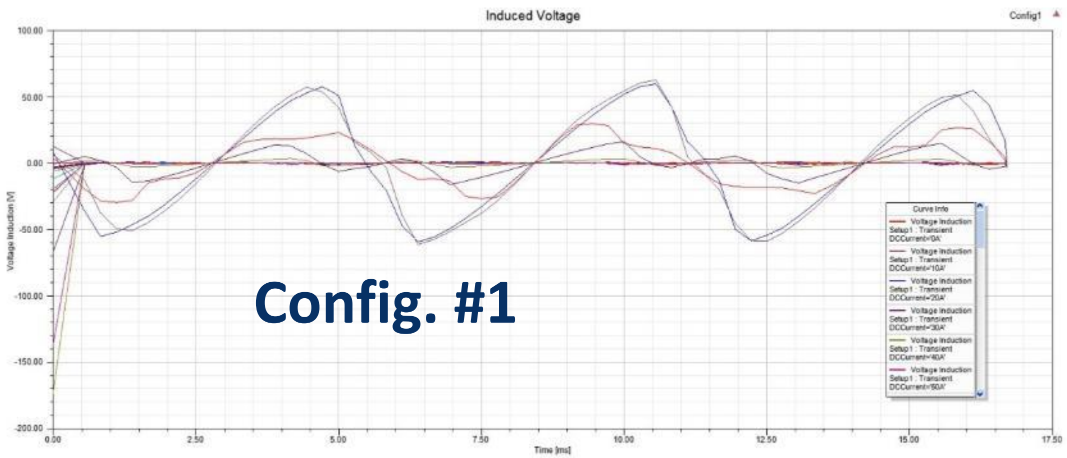


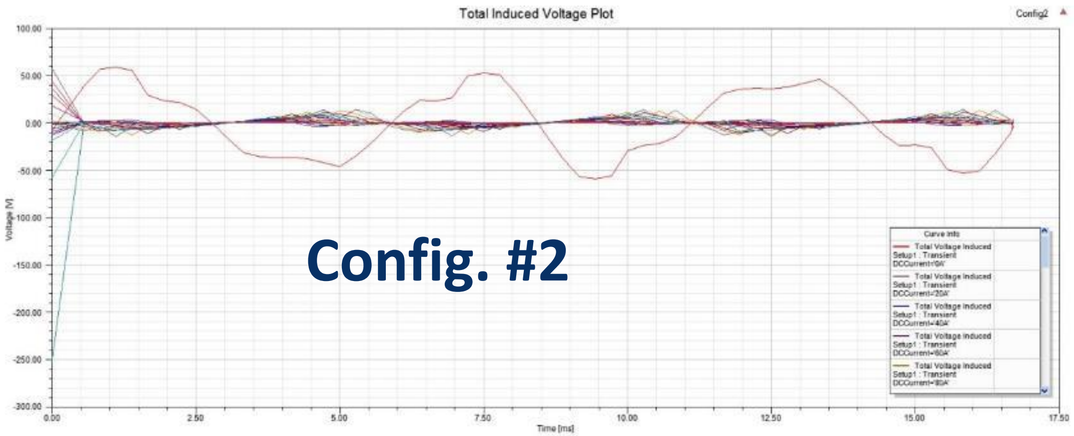


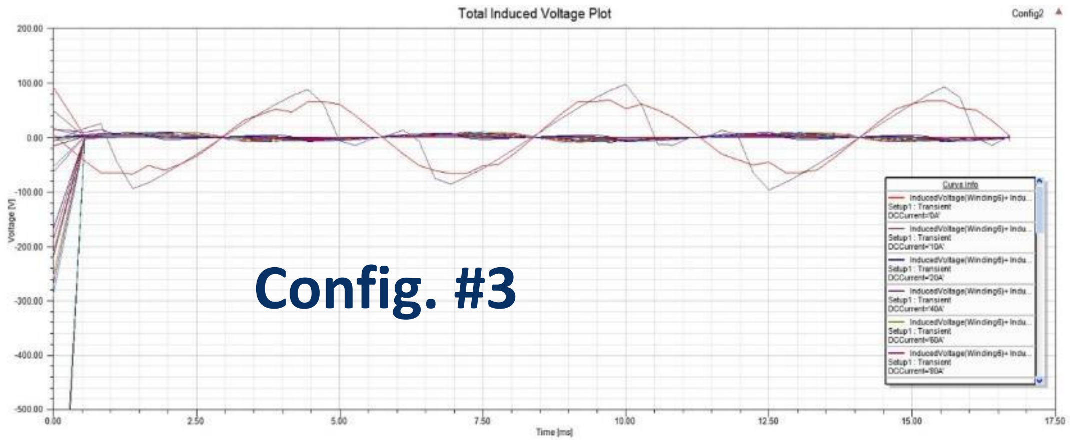
Reactance regulation range (reactance vs. DC)

CVSR device modeling - 4

- Configuration design and reactance regulation of 3-phase device







- ✓ **#2 and #3 are better than #1 in terms of reactance range.**
- ✓ **#3 has larger induced voltage on DC winding compared to the other two (200V pk-pk vs. 120V pk-pk)**

Anticipated challenges and risk mitigation strategies

Model Sharing

ConEd's membership to CURENT simplifing NDA process

Model Compatibility

Conditioning, format conversion may be necessary

Timing & Cost

Recycle the DC controller (DCC) from previous projects to save time and cost

Next steps

- Conduct use case development for ConEd system once the model is available
- Conduct cost assessment and valuation by optimization analysis
- Determine the optimal design of core and winding configurations for the CVSR prototype
- Improve MEC model by considering saturation, for validation
- Preparing technical reports and publications.

Broader Impact

- Facilitating research on similar technologies to be used in distribution systems
- Pave the road to development of device for real system applications
- Boost utilities' confidence of CVSR applications in distribution network

Contact Information

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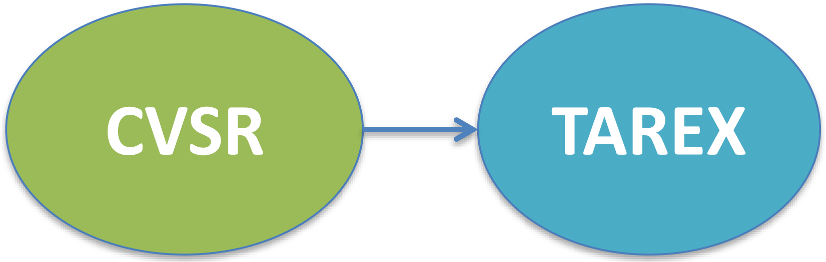
- UCF: Prof. Aleksandar Dimitrovski, ADimitrovski@ucf.edu
- UTK: Prof. Kevin Tomsovic, tomsovic@tennessee.edu

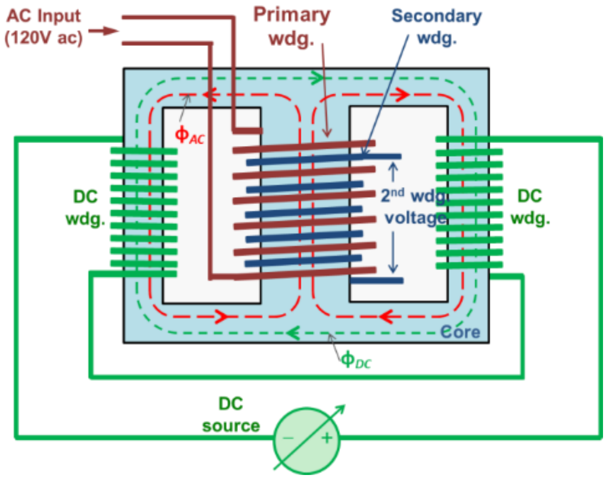
Updates on TAREX Project

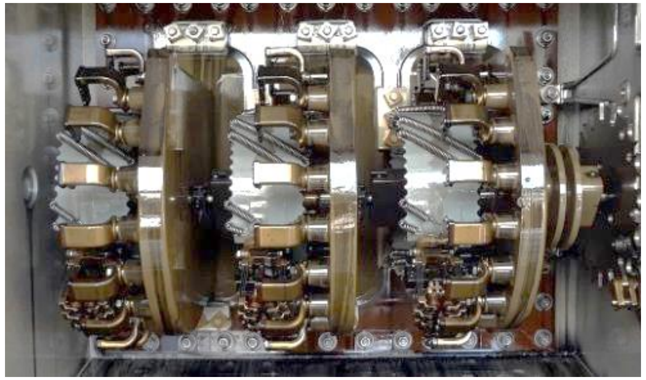
Concept

Tapless Regulating Power Transformer (TAREX)

- **CVSR concept extended to transformer**
- **Magnetically regulated transformer voltage**
- **To replace mechanical tap changer**







Project Status

- Close to completion
- Final report being prepared, one invention disclosure being filed

Overview

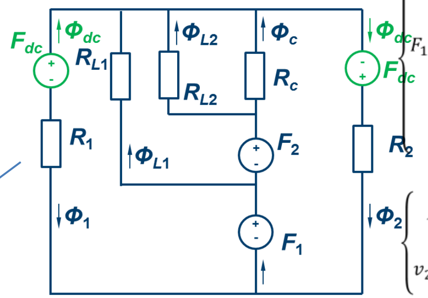
Objective

- To understand physics of TAREX and prove the concept

Accomplishments

- **Modeling** – multiple analysis models successfully developed and TAREXs' mechanism well understood
- **Demonstration** – for the first time, demonstrated the magnetically regulated voltage of a transformer
- **Validation** – validated the developed analysis models on a bench-top prototype
- **Deliverables** – a comprehensive and validated approach to the analysis of TAREX for future projects

Analytical model

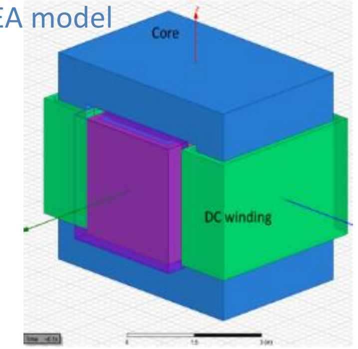


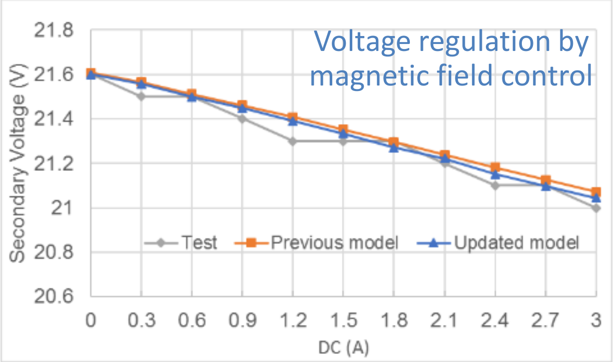
$$\begin{cases} F_{dc} + H_1 l_1 - \Phi_{L1} R_{L1} + H_c l_c = 0 \\ -F_1 + \Phi_{L1} R_{L1} - \Phi_{L2} R_{L2} = 0 \\ F_2 + \Phi_{L2} R_{L2} = 0 \\ F_1 - F_2 + F_{dc} + H_2 l_2 - H_c l_c = 0 \\ F_1 = N_1 i_1(t) \\ F_2 = N_2 i_2(t) \\ F_{dc} = N_{dc} I_{dc} \end{cases}$$

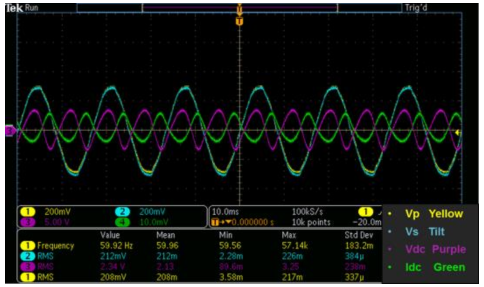
B–H curve for interpolation

$$\begin{cases} v_1 = r_1 i_1 + L_{l1} \frac{di_1}{dt} + N_1 \frac{d\Phi_c}{dt} \\ v_2 = -r_2 i_2 - L_{l2} \frac{di_2}{dt} + N_2 \frac{d\Phi_c}{dt} \end{cases}$$

FEA model



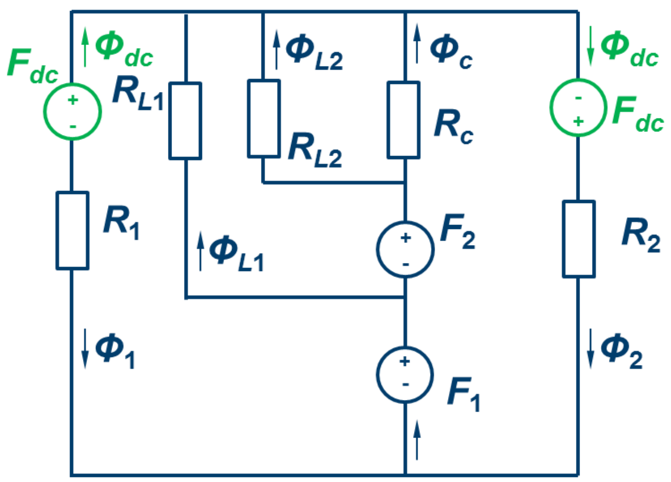




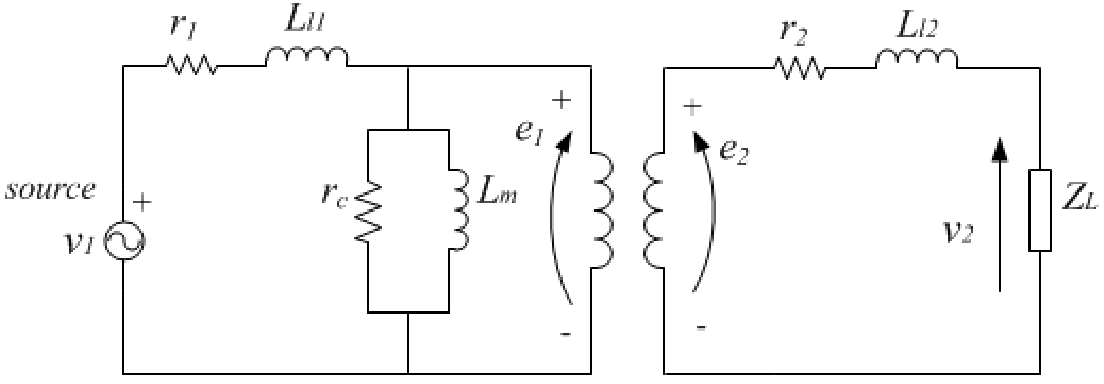
Bench-top prototype and testing

Results - 1

- An analytical model developed and validated for modeling voltage regulation under dc biased magnetization
  - ✓ Considering dynamics in all three windings (primary, secondary, and dc)
  - ✓ Improved material characteristics based on testing results

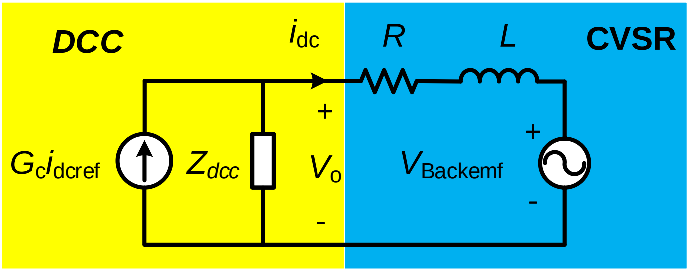


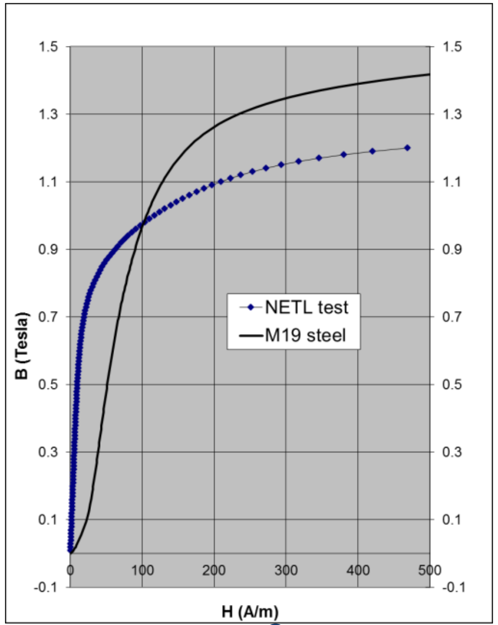
MEC model



Circuit model

DCC model



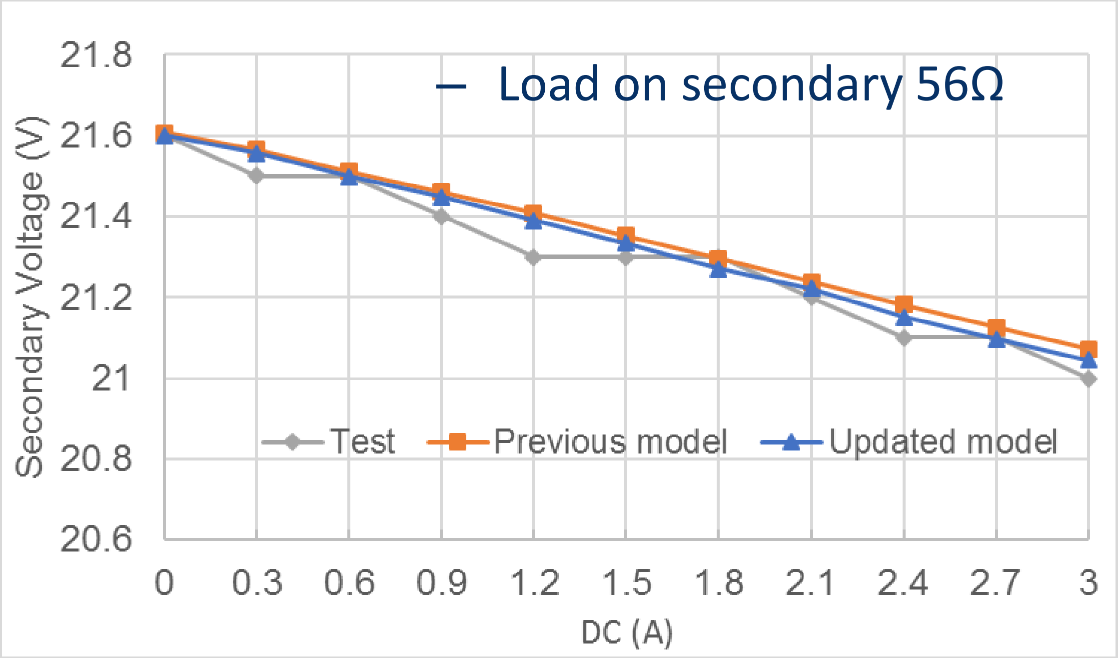


B-H curve from test

Results - 2

- 115V/115V, 500VA prototype developed for validation

Voltage regulation

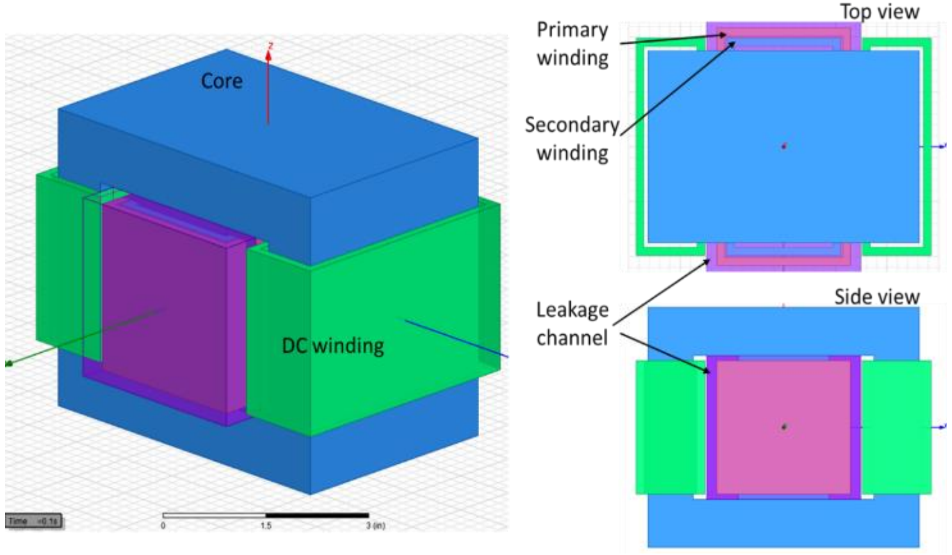


Prototype testing setup

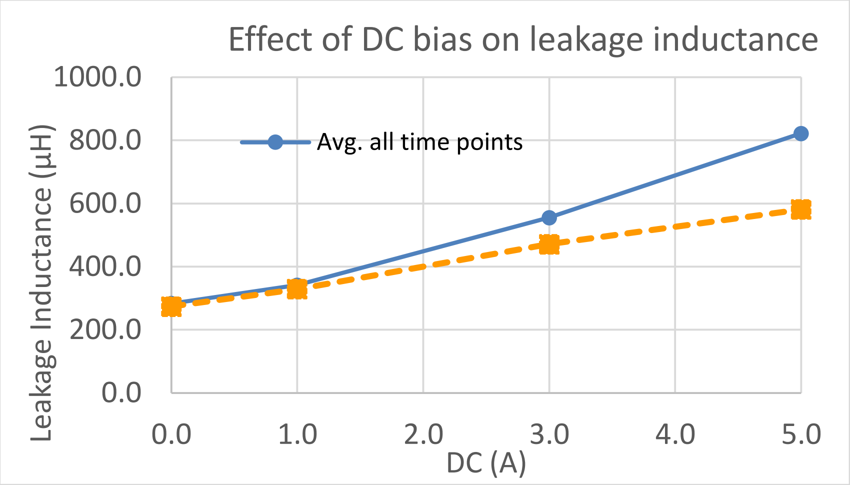
Results - 3

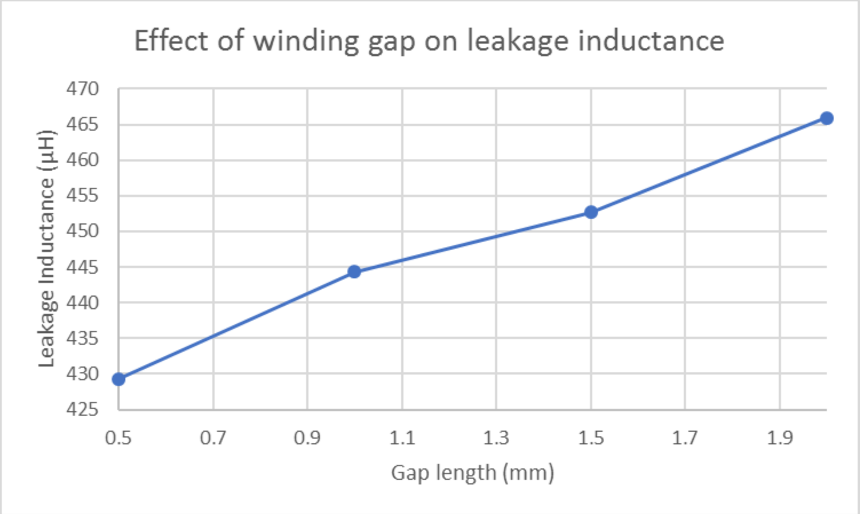
- Leakage inductance modeled and analyzed

$$W = \frac{1}{2} L_l I^2 = \frac{1}{2\mu_0} \int_{leakage\ channel} B^2 dV$$



FEA method to calculate leakage





Conclusion

- DC-biased magnetization can be used to regulate winding voltage of transformers
- The voltage regulation is the consequence of a number of electromagnetically coupled processes, including magnetic induction, saturation, change of leakage inductance, etc.
- Leakage inductance is affected by DC bias in the core and geometry of the windings
- Only small range of voltage regulation is realized on the prototype. To reach larger range of regulation, the transformer should be carefully designed

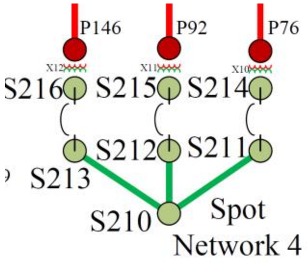
Backup

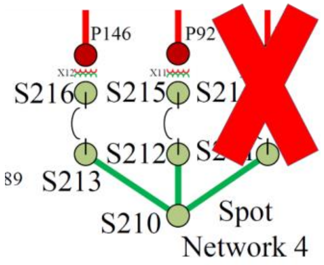
Backup slides

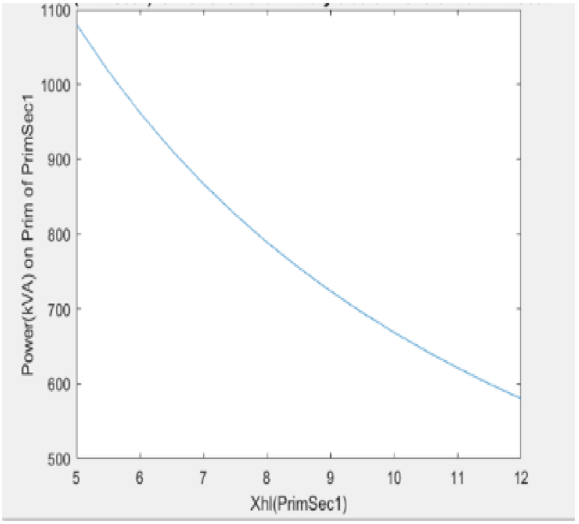
- Transformer overloading studies:

Transformer outages

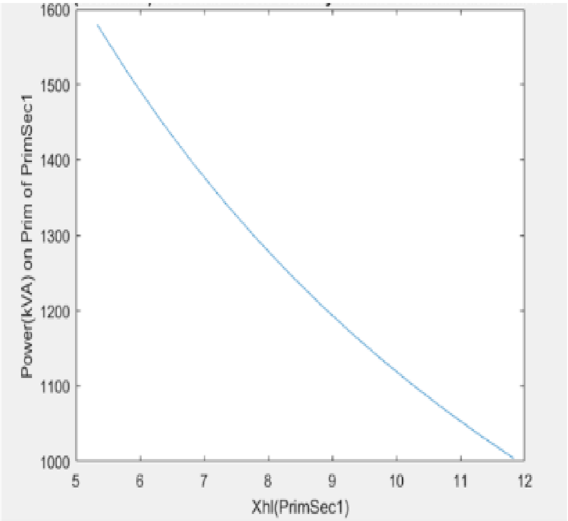
- Remove spot network Transformer-10
- Transformer-11 supplies the extra power, and its reactance affects the power flow.







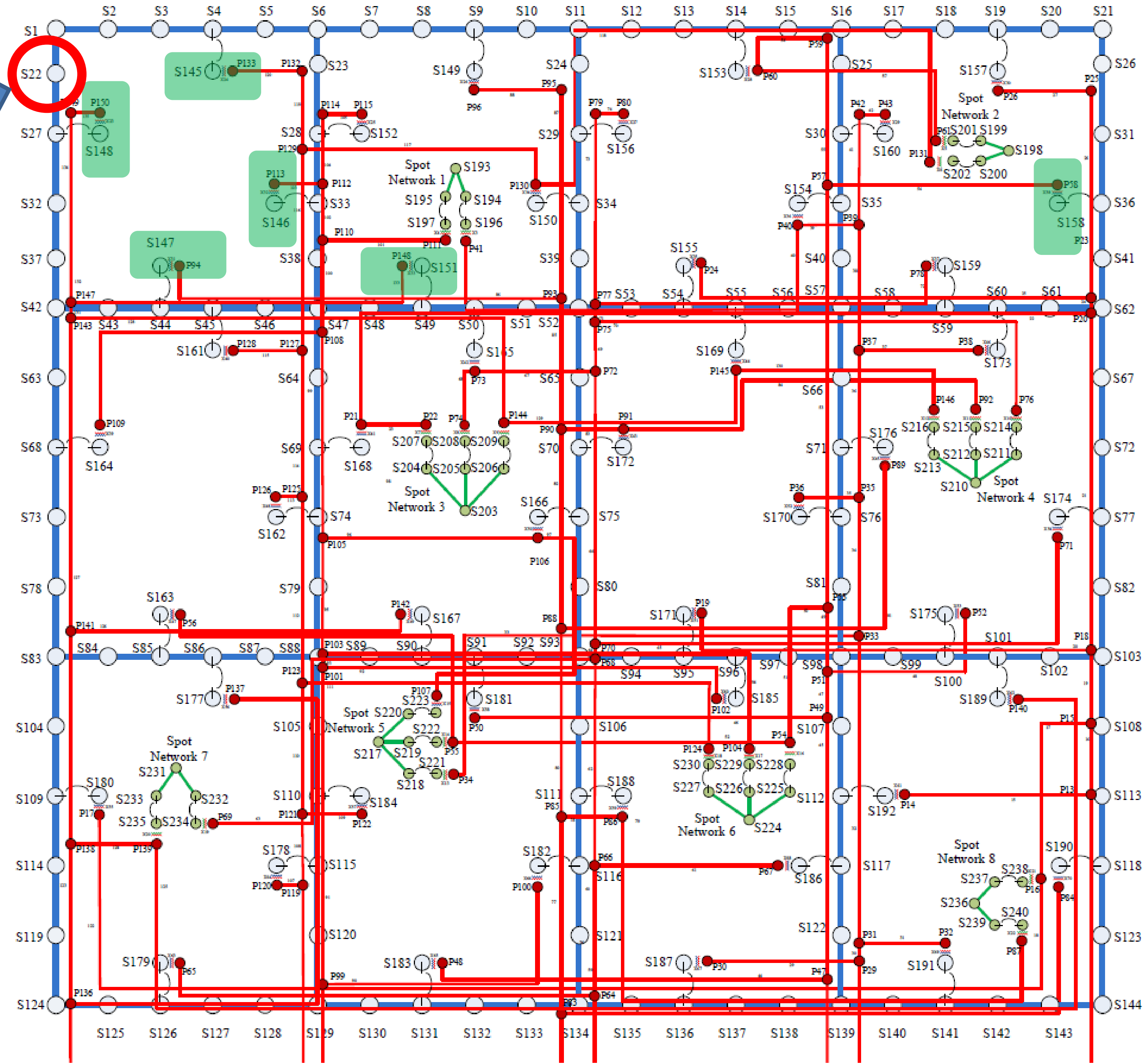
T11 - Base



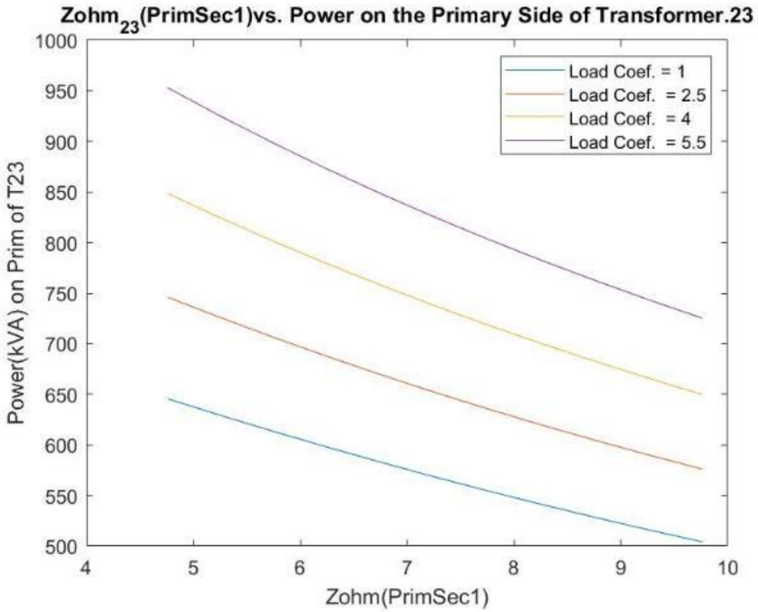
T11 (T10 is removed)

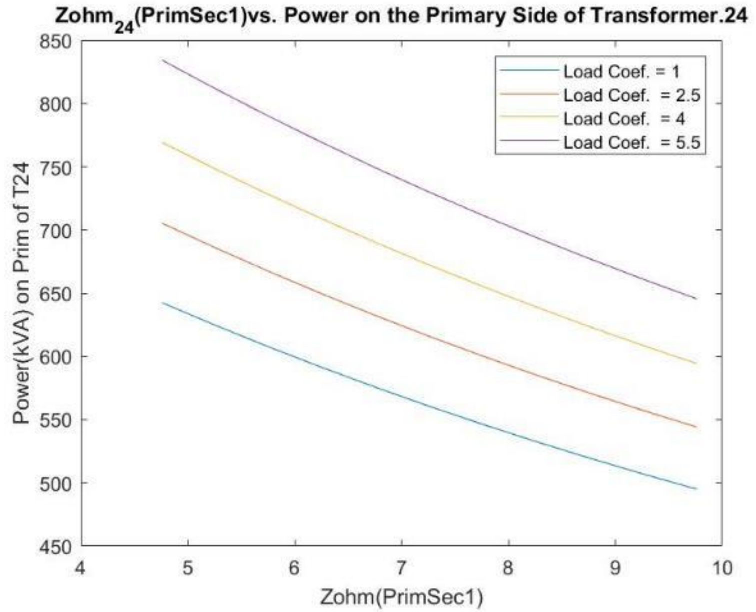
Total Load at
S22=145 kVA
Increment rate
is: **<u>1:1.5:6</u>**

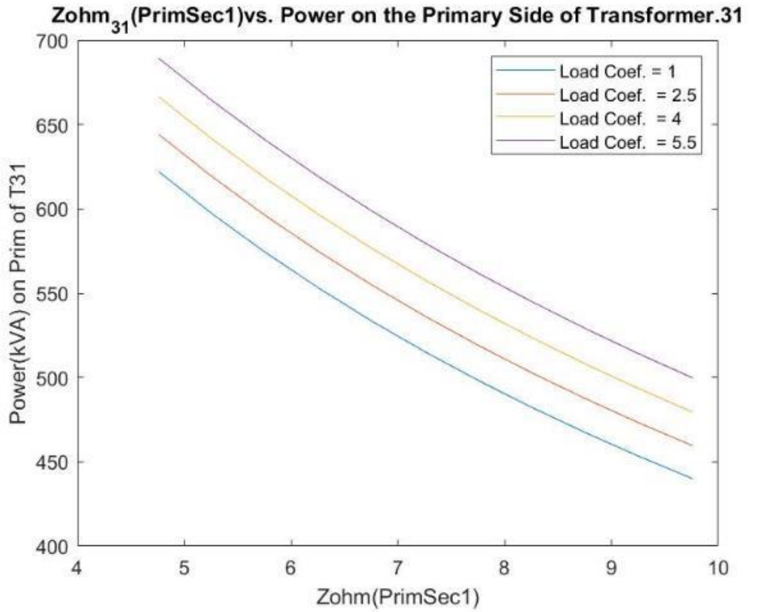
All Transformers are Secondary Network Transformers, rated at 1mVA

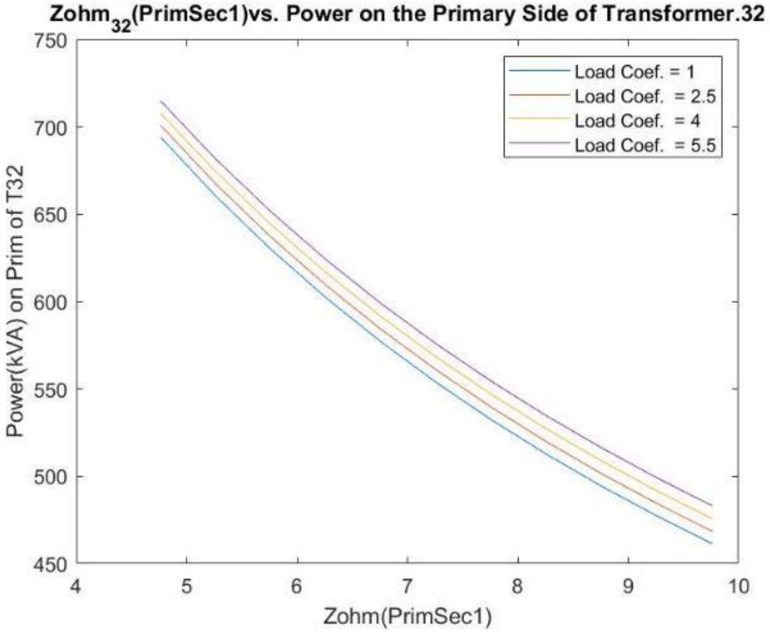


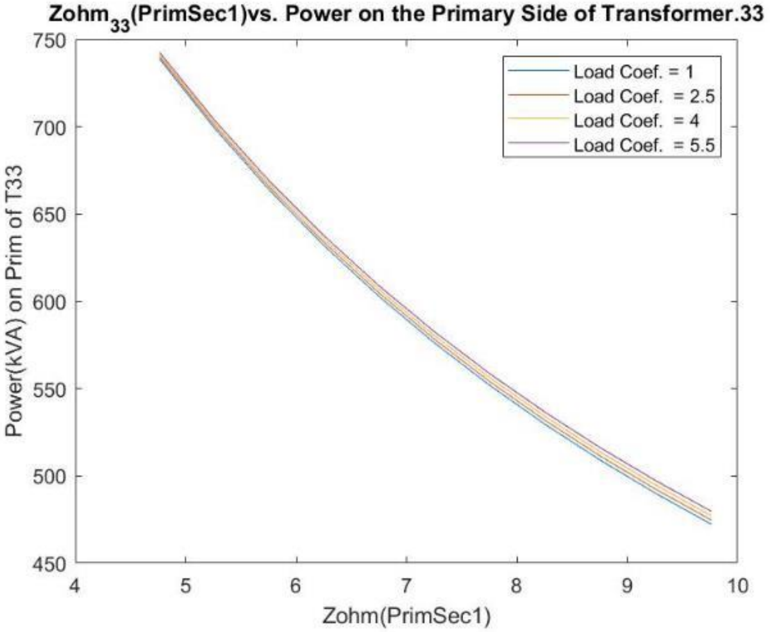
Some Simulation Results

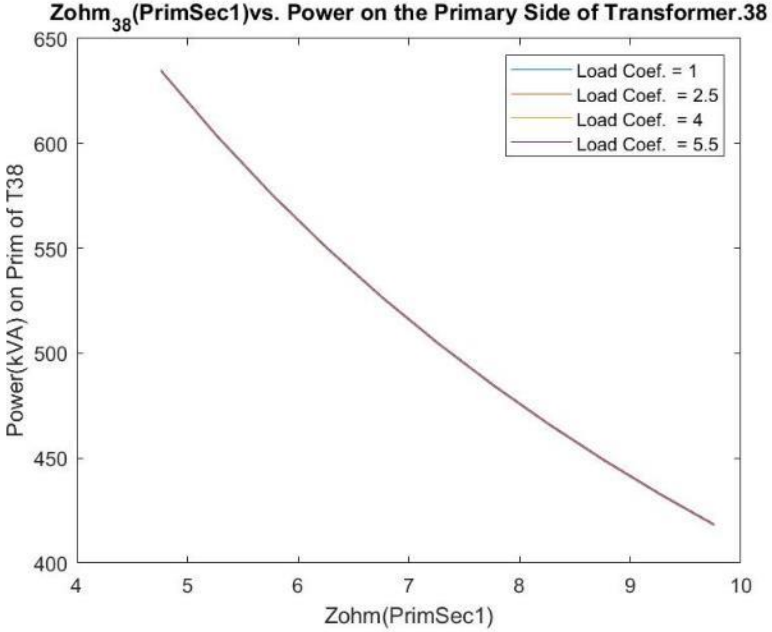












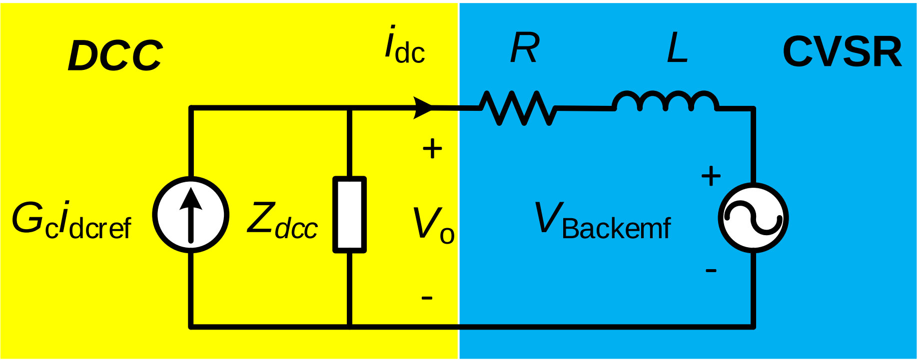
Backup slides

- CVSR parameters for the 3-ph FEA model

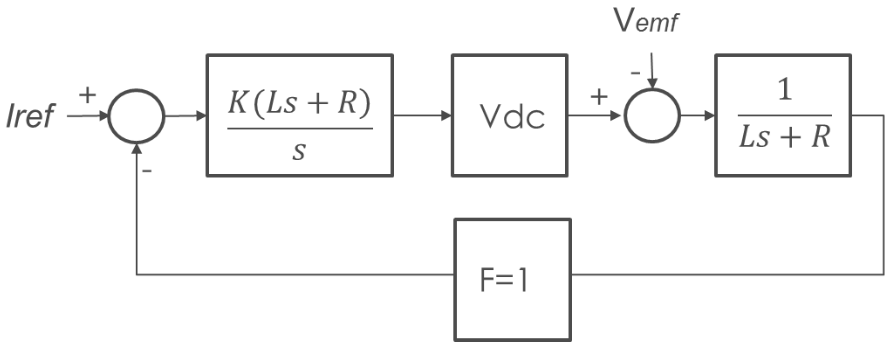
Parameters	Symbol	Value
Core height	h_c (in)	20.72
Window height	h_w (in)	14.72
Window width	w_w (in)	2.2
Air Gap	g (in)	0.06
Leg width	$w_c = w_o$ (in)	3
Core depth	d_c (in)	3
Relative Permeability of core (Silicon Steel M36)	μ_r	26673

Backup slides - TAREX

- DCC model integration



time-domain $$R i_{dc}(t) + L \frac{d[i_{dc}(t)]}{dt} + V_{emf} = 0$$



s-domain $$i_{dc}(s) = G_1(s) \cdot I_{ref} + G_2(s) \cdot V_{emf}(s)$$