arpa·e
CHANGING WHAT'S POSSIBLE

varentec

Compact Dynamic Phase Angle Regulators for Transmission Power Routing

Anish Prasai

EPRI ELECTRIC POWER RESEARCH INSTITUTE | Georgia Tech | SOUTHERN COMPANY | SPX | WAUKESHA

Project: DE-AR0000229

Project Objectives

- Develop and demonstrate a compact low-cost dynamic power flow controller at 13 kV, 1 MVA.
- Establish a nationally available test-bed at NEETRAC to demonstrate and test power flow control technologies in a 13 kV AC meshed network.
- Model dynamic and steady-state impact of CD-PAR on the utility grid at both distribution and transmission levels.
- Field testing in a Southern Company network.
- Develop technology-to-market commercialization strategy.
- Analyze and explore economic/market applications.

State-of-the-Art

ABB's 400 MW HVDC station in Germany

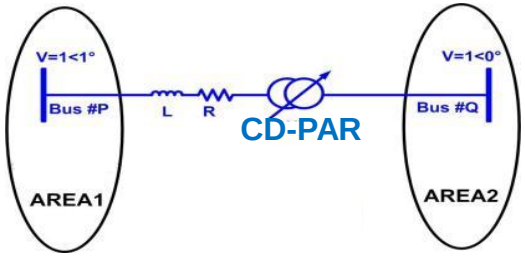
GE's 315 MW VFT near NYC

AEP's 160 MVA UPFC in Kentucky

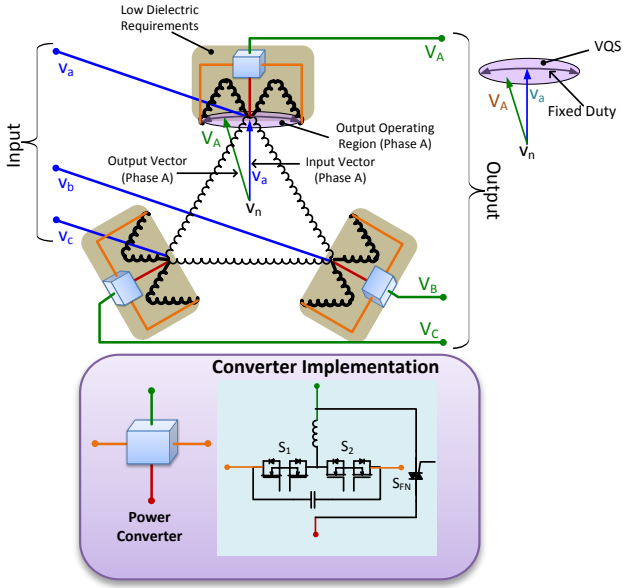
- HVDC and HVDC Light used for power delivery (merchant transmission) over long distances or undersea/underground.
- Back-to-Back, UPFC and VFT systems are custom power solutions that can control power flows on the ac system.
- Large device ratings, filters and components plus existing grid assets. DC/AC inverters need large energy storage.
- System reliability of 99.99% is higher than power converter, single point of failure can compromise system reliability.
- Complex solutions require maintenance and long time to repair, during which system is compromised.

Proposed Approach: CD-PAR

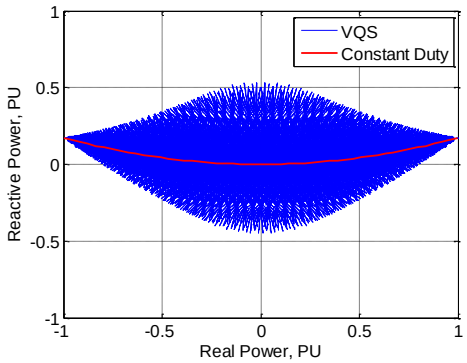
Principle: Series voltage injection for P/Q control



CD-PAR Implementation



- Integrate fractionally-rated transformer + converter.
- Converter comprised of AC switches and LC filters.
- 'Fail-normal' switch bypasses the converter under fault conditions, preserving system reliability.
- Simple duty cycle control to effect control over real power flow.
  - No grid synchronization.
  - Unit operation very stable due to direct AC/AC conversion.



CD-PAR Control Range

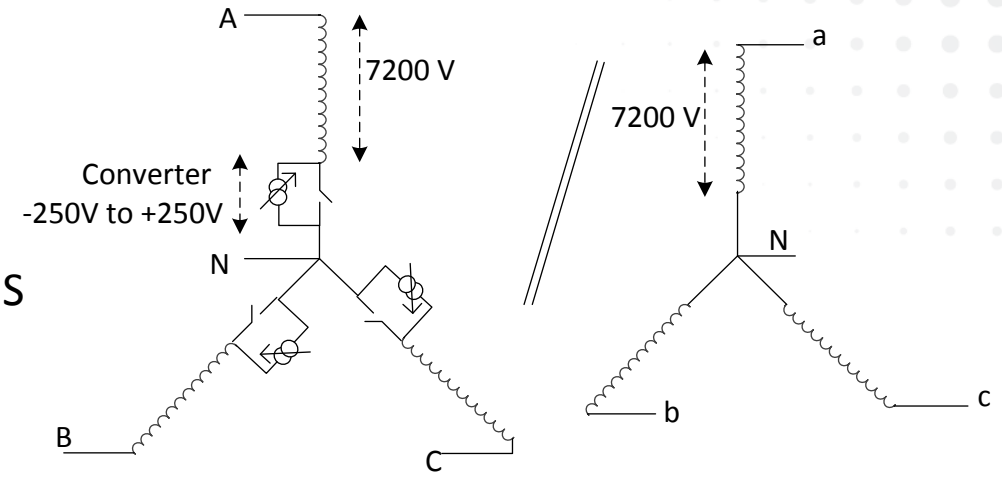
Target Metrics

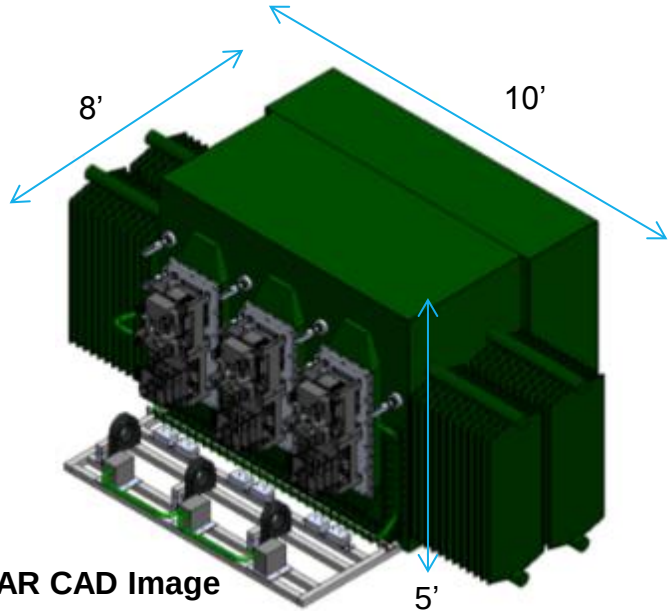
- Move the technology from TRL3 to TRL7.
- Nominal Operational Metrics:
  - 12 kV / 1 MVA three-phase operation.
  - < 1% losses of the rated power flow controlled.
  - -20 to 50 °C ambient.
  - Harmonics compliance with IEEE 519.
- Fault metrics:
  - 110 kV BIL.
  - 15 kA of fault current handling capability for 30 cycles.
  - Target price point of $20-30/kVA of power controlled for the final product in volume.

13 kV 1 MVA CD-PAR Schematic

- Standard transformer with LV taps integrated with Ac-AC converter to achieve CD-PAR
  - 3-ph, 13 kV/13 kV ,1 MVA
  - GCD-PAR control range +/- 250V.
- Integrated cooling: The transformer TMS serves to cool the electronics as well.

3-ph 13 kV 1 MVA CD-PAR schematic





CD-PAR CAD Image

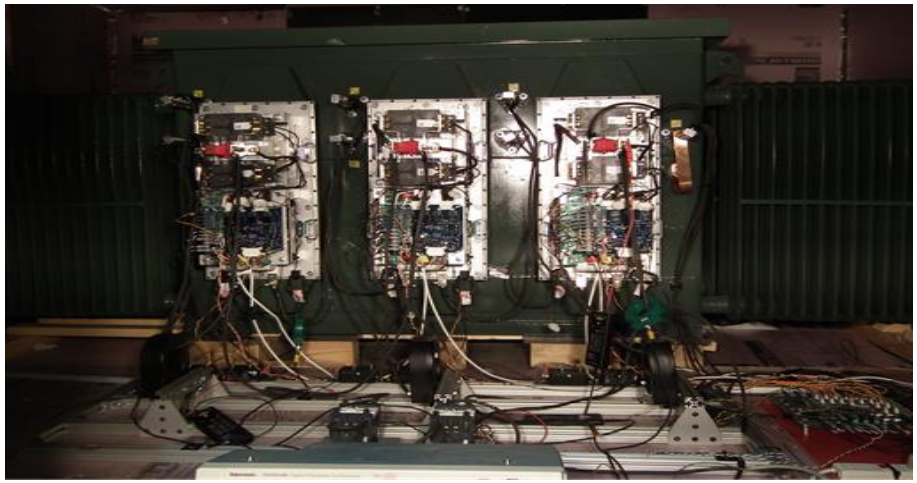


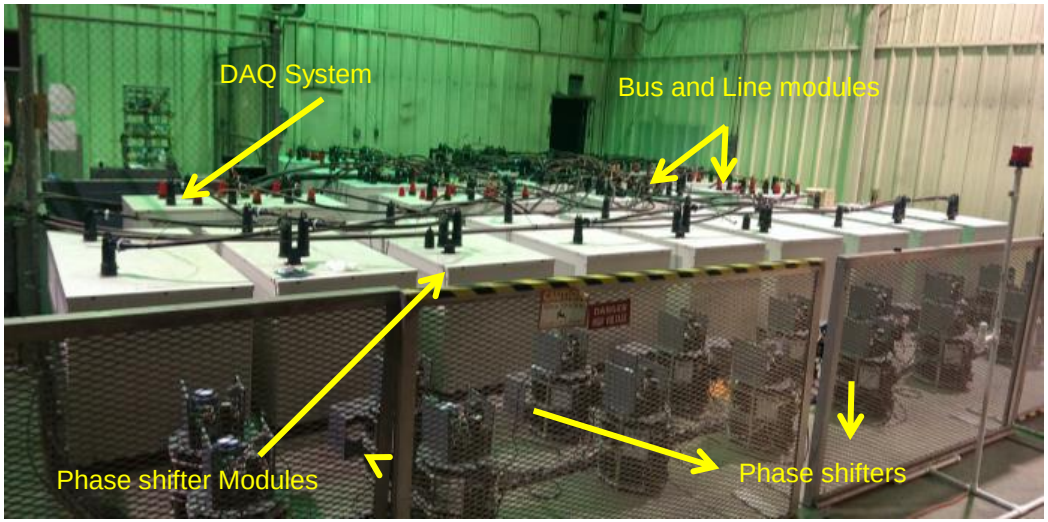
Image of CD-PAR Prototype

5-Bus Test Bed at NEETRAC

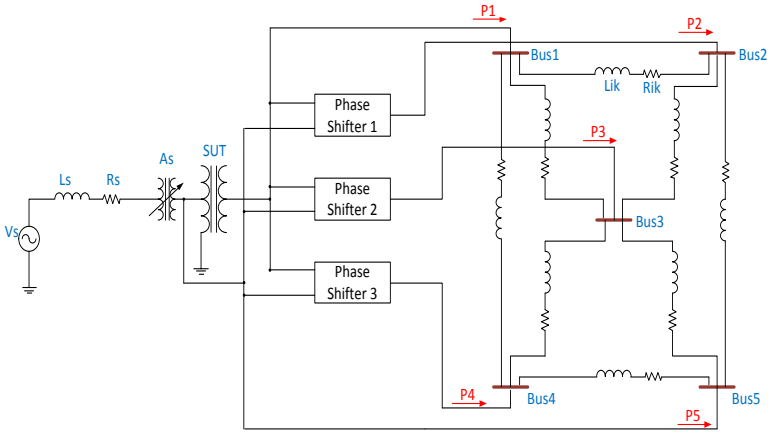
1st & 2nd Year Accomplishments

- A 5-Bus test-bed at NEETRAC was built to demonstrate and test power flow control technologies in a 12 kV AC meshed network.
- Test bed is fully functional and tested at 7.2 kV, 50A.

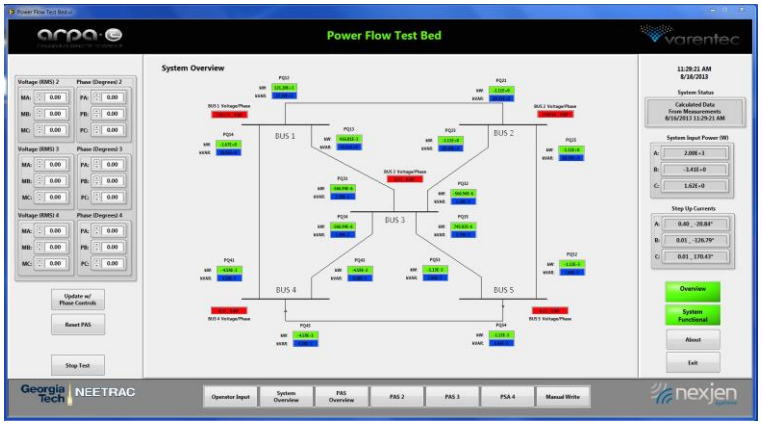
Picture of 5-bus test bed



5-bus test bed to test power router technologies



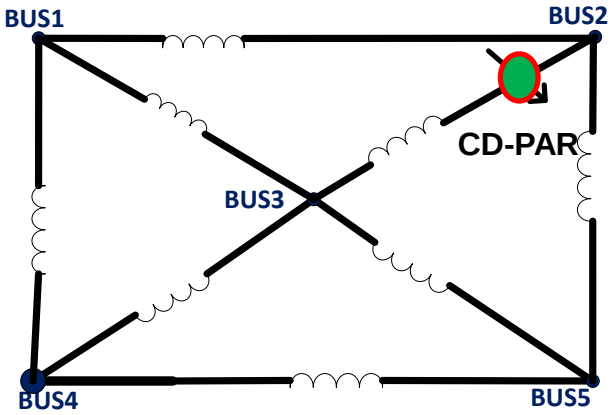
Control Interface



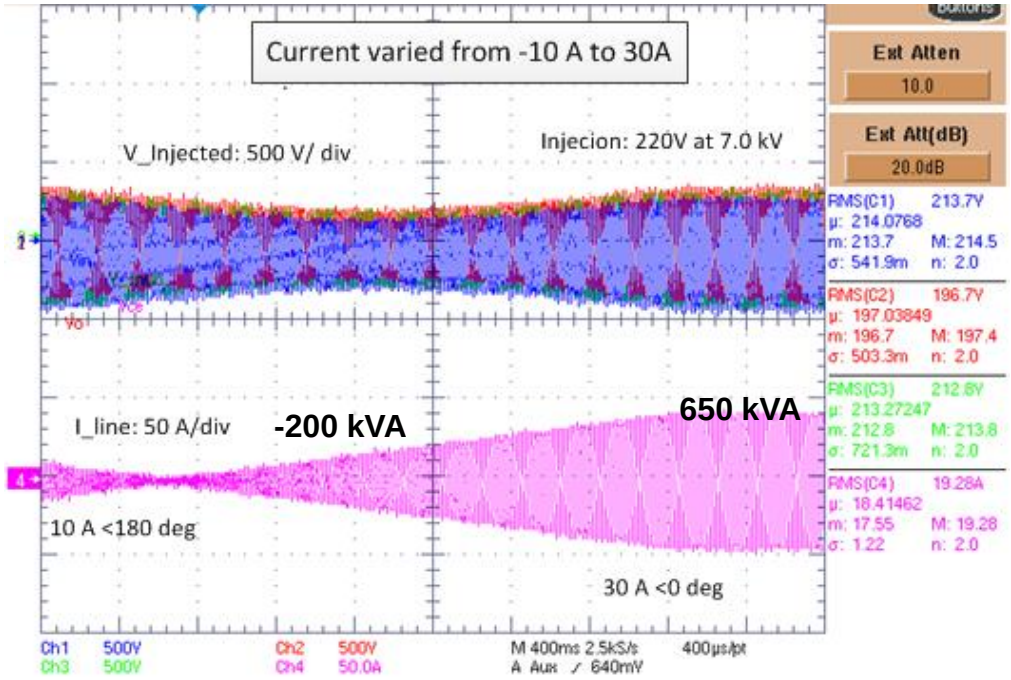
13 kV, 1 MVA CD-PAR Test Results

- The CD-PAR was connected in Line 2-3 in the 5-bus test bed and tested at 7.2 kV, 850 kVA..
- With CD-PAR the power in line 2-3 was changed from -200 kVA to 650 kVA demonstrating a power flow range of 850 kVA.

Schematic of CD-PAR Installed in 5-bus test bed



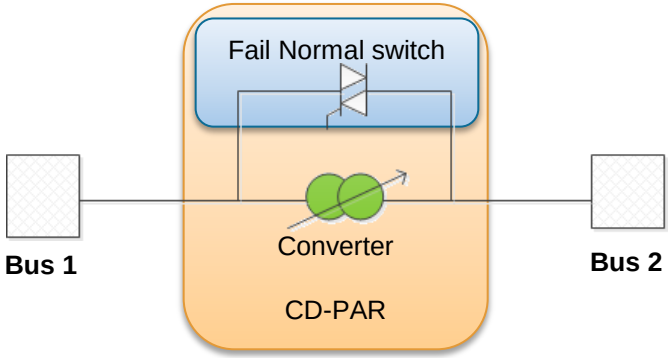
Power Flow in Line 2-3 varied from -200 kVA to 650 kVA



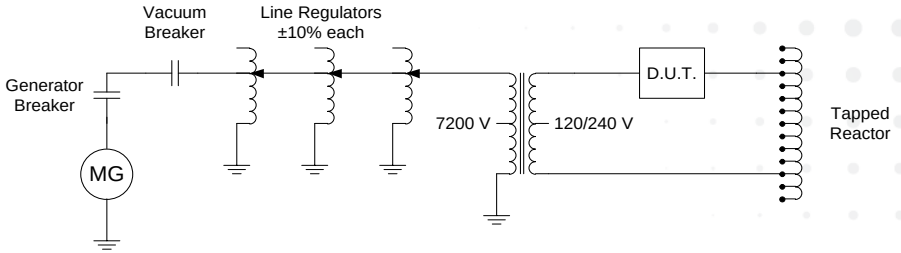
3-phase CD-PAR operation verified at 13 kV 1 MVA.

Fail Normal Switch

- Since CD-PAR is a series connected device, the fail-normal switch is critical for
  - Protecting the converter from the system disturbances like line faults.
  - Isolating the network from the disturbances in the converter.
- The fail-normal prototype was tested to handle 15 kA for 30 cycles.

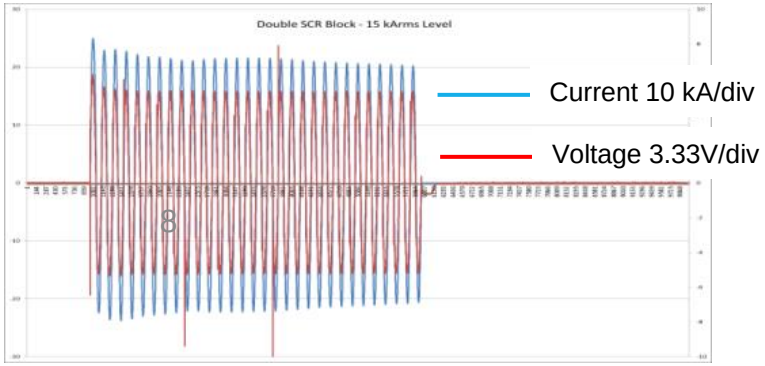


Schematic of the fail-normal switch test setup.



Picture of test setup.

Test results



TMS Design Validation

- A thermal chamber was built to verify the thermal design.
- The initial design is verified with inductor heaters simulating converter load.
- The thermal design is verified to maintain device temperature < 120 degC at full load and 40 degC ambient temperature.

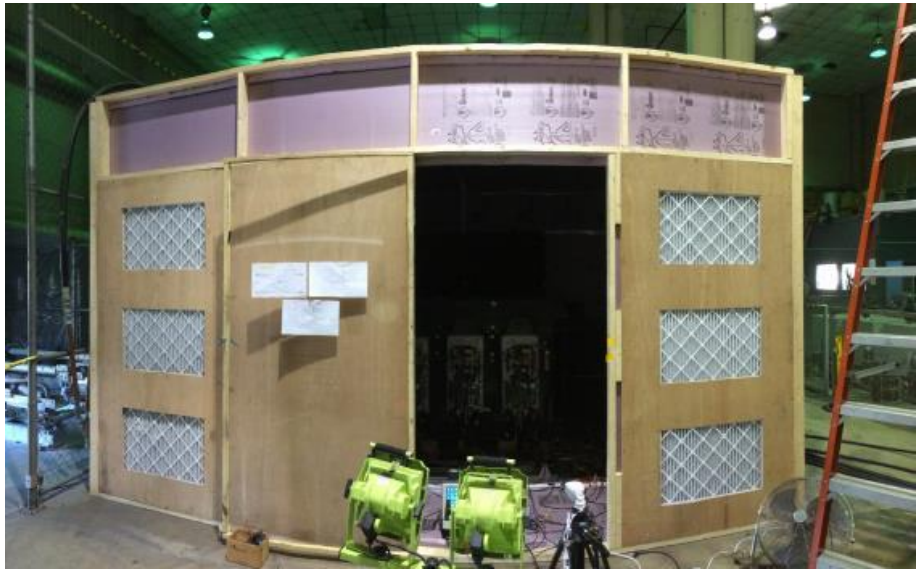
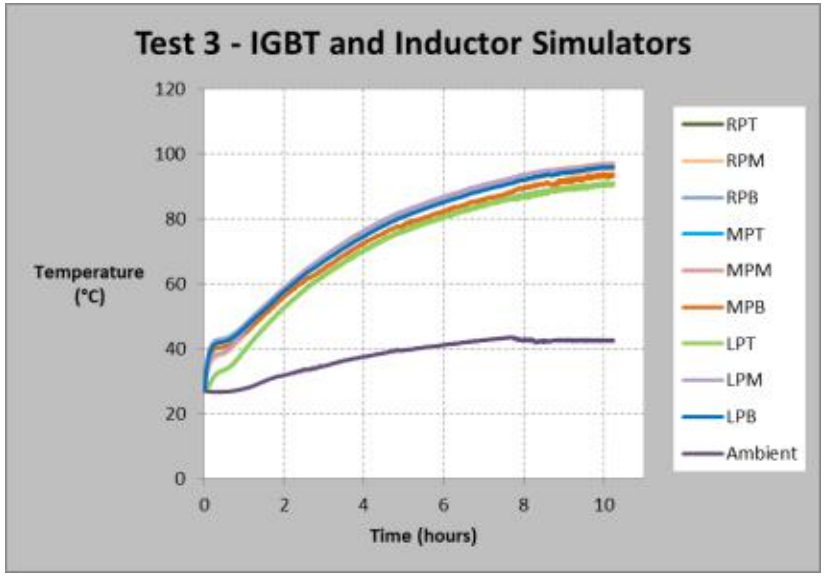


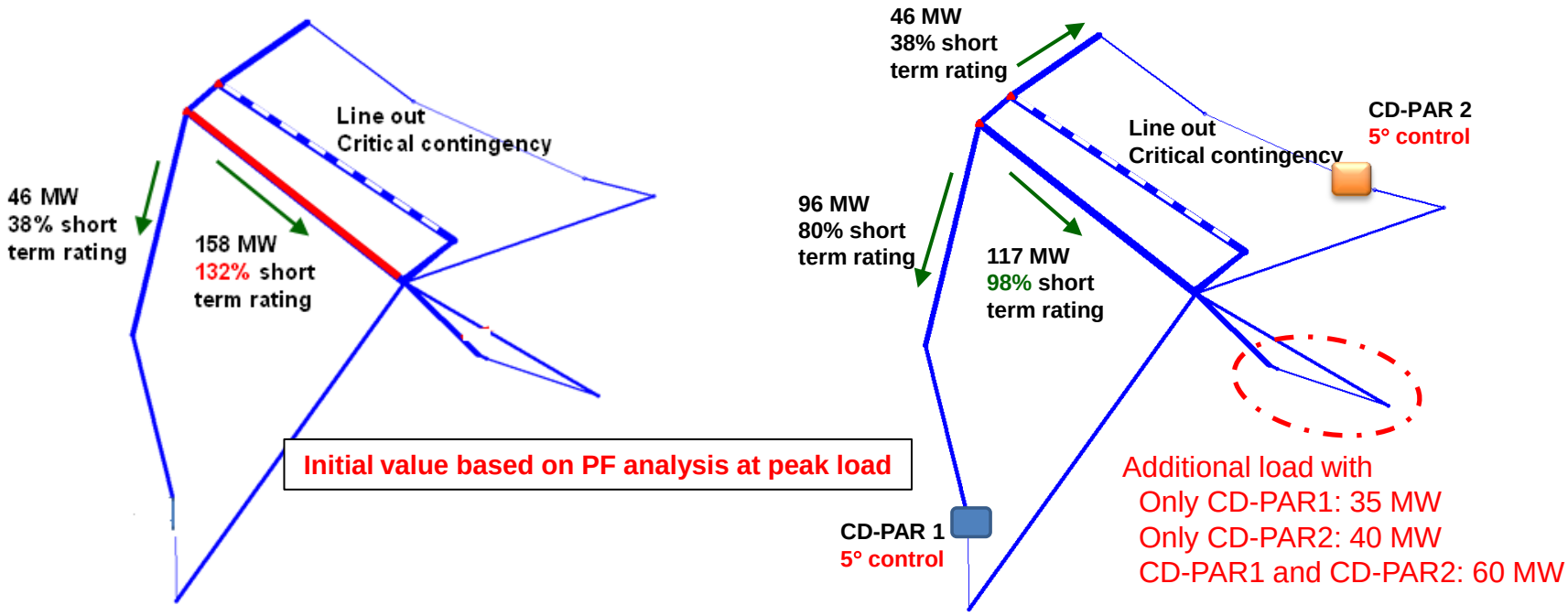
Image of Thermal Chamber with CD-PAR



Temperatures measured at various test points on the CD-PAR

Impact of CD-PAR

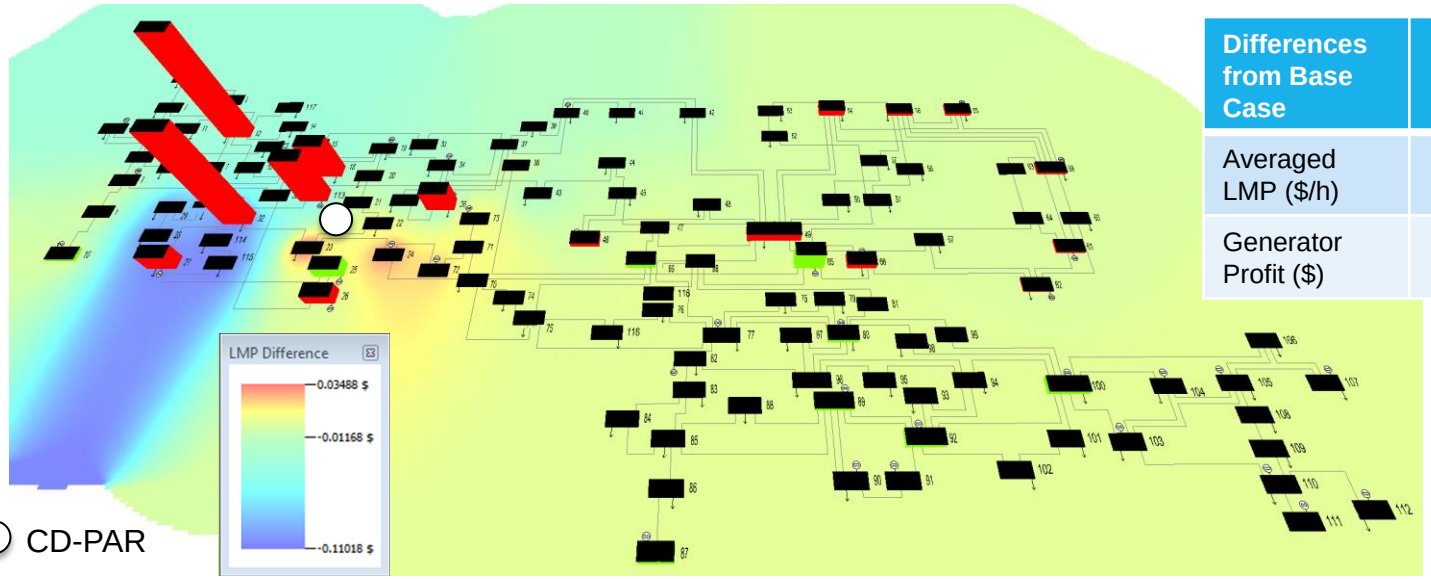
- Previously the impact of CD-PARs on transmission networks was analyzed.
- This year the work is extended to sub transmission networks (33kV, 69 kV).
- Study conducted on an actual 60 kV network that feeds a medium size city in CA.
- The study had shown that CD-PAR can increase loadability: serve increasing load with existing network assets.



Case study: Impact of CD-PAR on loadability in sub transmission network.

Economic Impact of CD-PAR Per MW

- Identify the winners and losers for market participants as LMPs are impacted by the CD-PAR.
- Figure shows the difference between yearly values with CD-PAR (white dot) and the base case.
- The color gradient represents how the average energy cost has changed.
- The area where generators were exercising excessive market power sees a decrease in energy cost.
- The 3rd dimension represents the generator profits (red: decrease and green: increase in profits).
- The generators mostly effected are the generators that were taking advantage of the fact that less expensive generation was not able to be imported into the area due to congestion.



Differences from Base Case	Min	Max	Total
Averaged LMP ($/h)	-.11 (Bus 32)	.03 (Bus 23)	-
Generator Profit ($)	-77,062 (Bus 12)	12,974 (Bus 65)	-224,707

Case study: Impact of CD-PAR on LMPs in 118 bus system

Final Year Goals

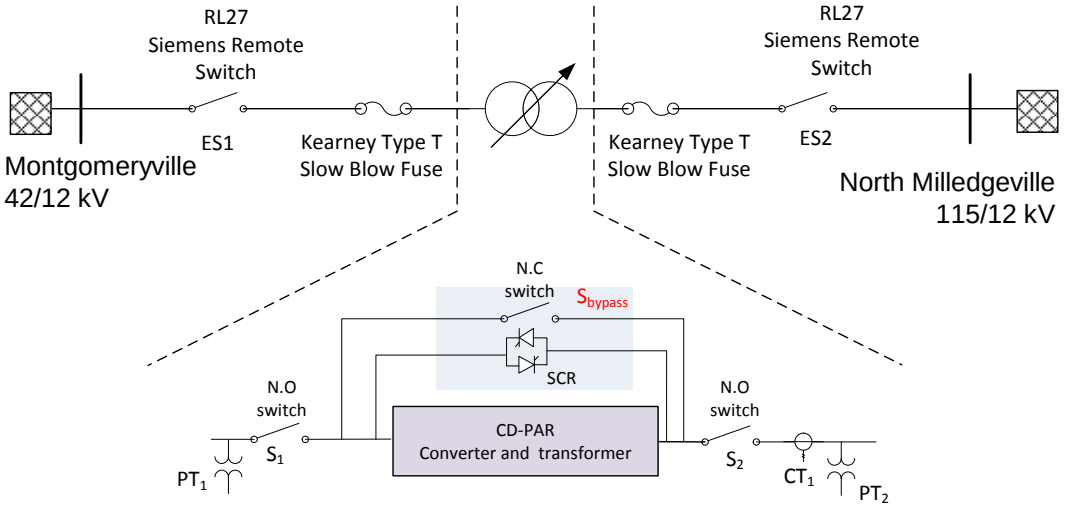
- Test multiple CD-PAR operation on the 5-bus test bed developed at NEETRAC campus.
- Demonstrate CD-PAR field operation on the Southern company 13 kV grid.
- Design and develop simulation platforms that will be used in analyzing the impact of CD-PAR on electricity markets.
- Deliver the final technology-to-market commercialization plan.

Field Test Plan

- The CD-PAR operation will be demonstrated on the 13 kV grid.
- The test site was identified on the Sothern company network.
- 1 MVA, bidirectional dynamic power-flow-control will be demonstrated.

Test site on the Southern company grid.

Schematic of the 13 kV feeder setup with CD-PAR



Technology-to-Market

- Working with Southern to develop a detailed use case for power routers to interconnect two distribution feeders.
- Working with muni customer with a 13 kV meshed grid. They are working with us to develop a full business case for power routing on their network.
- Interacting with 3-4 additional utilities to explore their interest in power routing technologies.
- Still need to talk with ISOs to explore the impact that power routing can have on their systems, and to build a business case at modest penetration levels of power routing technology

Conclusions

- The first of three CD-PAR units has been tested successfully against the product specifications with the other two units to be tested shortly.
- Five-bus test bed for testing power flow controllers is operational.
- The first unit will undergo additional testing in the test bed to validate its operation before being deployed to the field.
- Commissioning and testing plan being worked out with Southern Co to capture key operational data during field testing this year. The data will be used to improve the design.
- Field testing will also provide validation of the technology to the utility customers and investors, and drive adoption.
- The physical and economic impact of CD-PARs in transmission and sub transmission networks has been studied and results look very interesting. Detailed discussions are scheduled in the next session.