Presentation Submission Information:

Include the following information on the first slide of your presentation. This is required information for submission and will not be displayed during your presentation.

- Presentation ID#: 5.2
- Presentation Title: Novel three-in-one High-Temperature-Superconducting (HTS) Direct-Current (DC) cables for grid revolution
- Author(s): Doan Nguyen (PI) and Fahmid Sadeque (co-PI)
- Organization(s): Los Alamos National Laboratory (LANL) and Pacific Northwest National Laboratory (PNNL)

Novel Three-In-One High-Temperature-Superconducting (HTS) Direct-Current (DC) Cables for Grid Revolution

Lead Institution: Los Alamos National Laboratory (LANL)
Partner Institution: Pacific Northwest National Laboratory (PNNL)

DOE OE TRAC Peer Review 2026

Project Overview

- **Project Description:** *This project will develop novel inductive DC superconducting cables that enable high-power-density transmission with reduced right-of-way (ROW), robust fault-current limiting (FCL), and self-stabilizing operation for safer, more reliable, and rapidly deployable medium-voltage/high-voltage (MV/HV) DC grids*. LANL team focuses on computational and experimental approaches to develop novel inductive DC HTS cables and evaluate their FCL performance. PNNL team focuses on validating cable performance through real-time simulations and performing cost analyses of grids incorporating the developed HTS cables.
- **Period of Performance:** 10/01/2025 to 09/30/2027
- **Award Amount:** $1,200,000
- **Prime Awardee:** Doan Nguyen (LANL)
- **Partners:** Fahmid Sadeque (PNNL)
- **Technology Area:** Advanced Conductors, Busbars, and Dielectric Materials
- **Alignment/Supports strategic pathway:**
  1. **Stabilize**: Self-stabilizing capability to improve grid performance and reliability
  2. **Optimize**: Fast-and-robust FCL capability for safer and more resilient multi-terminal MV/HV DC grids
  3. **Grow**: Tenfold higher current density enables significantly smaller rights-of-way for accelerated deployment of additional transmission capacity.

Problem Statement

- By 2050, US transmission capacity may need to triple to support the rapid growth of electrification and energy generation [1]:
  - AI datacenter energy consumption: annual growth rate of 44.7%, reaching 146.2 TWh by 2027.
- MV/HV DC technologies are cost-effective solutions [2]:
  - Superior power transfer capability with much lower losses compared to AC transmission (due to skin effect and reactive power loss).
  - Flexible, fast, and accurate power flow control capability → enhanced grid resilience and reliability.
- **However, there are some significant challenges for MVDC/HVDC technologies:**
- Right-of-way (ROW)-related problems are the top cause of delays for deployment of new projects [3].
- Handling DC faults in MV/HV DC grids is challenging (no zero-crossing points, lack of line inductance causing rapid fault current rise) → impedes adoptions of resilient multi-terminal MV/HV DC grids [2].

Therefore, we will develop *new inductive DC superconducting cables* to overcome those challenges and provide other benefits for more resilient and reliable MV/HVDC grids.

Technical Approach and Proposed Research

LANL focus on computational and experimental approaches to develop novel inductive DC HTS cables and study their FCL performance:

- Standard HTS cables: consist of several layers of Rare-Earth Barium Copper Oxide (REBCO) tapes wound around a flexible core in *alternatively opposite directions* to minimize the cable inductances.
- **Proposed inductive cables:** layers of REBCO tapes spirally wrapped around a flexible core in the *same direction* to achieve much higher cable inductance L.
- Inductance of cable can also be significantly enhanced with soft magnetic core.



Typical Conductor-on-Round-Core (CORC™) cable fabricated from REBCO HTS tapes.

PNNL focus on validating cable performance through real-time simulations and performing cost analysis for grids using developed HTS cables:

- Conduct grid-level real-time simulation to validate the efficacy of the cable design.
- Perform cost analysis and compare with grid using traditional cables.

Innovation and Benefits of the Proposed Cable Design

1. **Fast-and-robust fault current limiting (FCL) capability:**
   - Fast, highly non-linear superconducting-to-normal transition to exponentially increase the voltage drop along the cable during a fault: $V \sim (I/I_c)^n$.
   - Cable inductance L will be "invisible" in normal DC operation but will be responsive to a fault because of high dI/dt.
   - **→ slow down the increase of fault current and reduce the fault current amplitude and the heating in the cable during fault → Enhance the FCL performance and enable faster cooling time during the recovery after fault.**

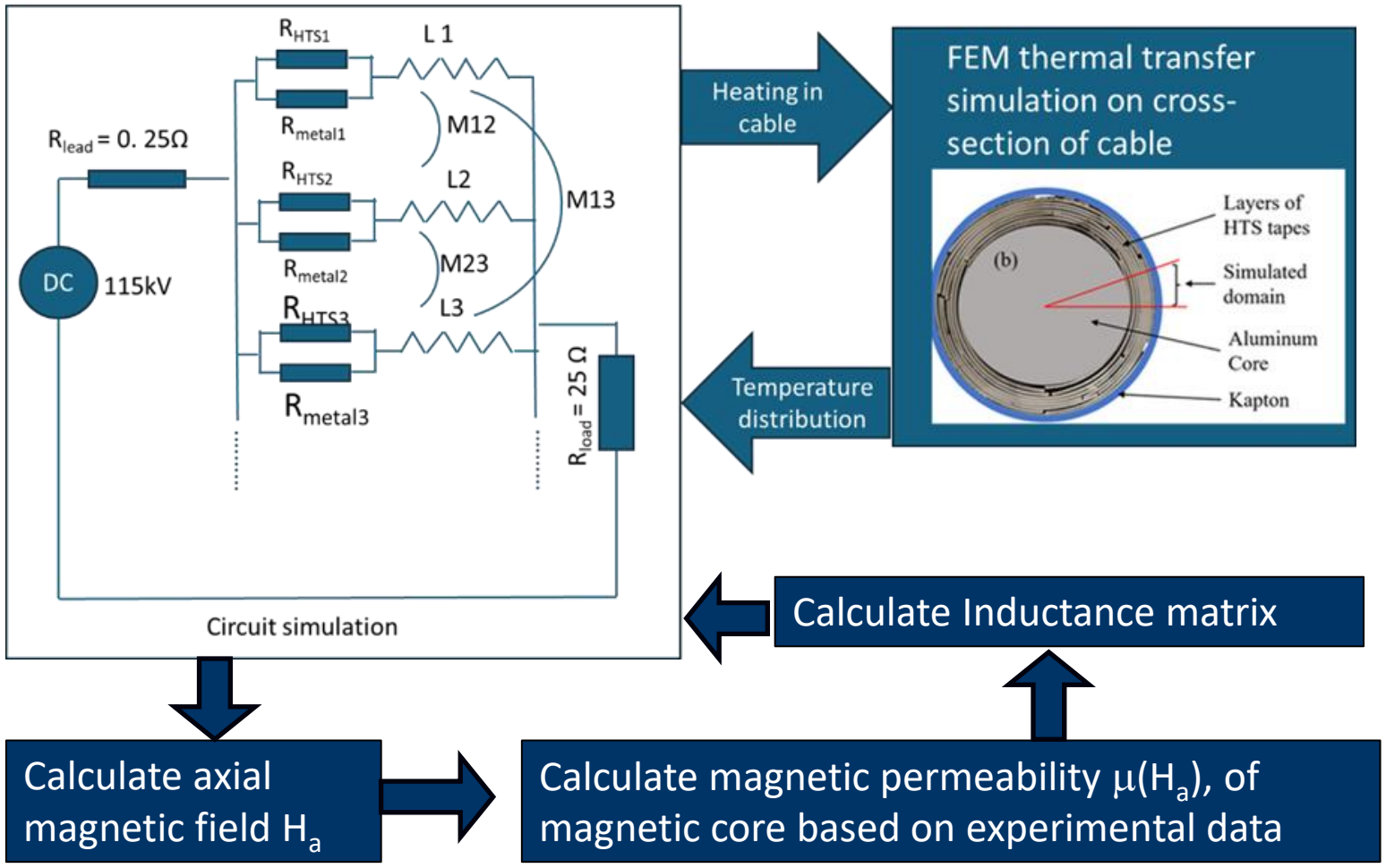
2. **Much smaller ROW for faster deployment**:
   - HTS cables can carry 10 times more current than conventional cables → considerably lower operation voltages but still provide higher power transmission capability.
   - Lowering operation voltage allows narrower ROW, simplified siting and permitting requirements, as well as lower cost for substations and electronic/electrical equipment.

3. **Inductive cables can suppress the instability:**
   - Cable inductance and stored magnetic energy would effectively suppress the grid ripples.
   - The cable inductance and stored magnetic energy can be controlled by cable core diameter, winding pitch, and winding direction.

New Fault Current Limiting Simulation Model

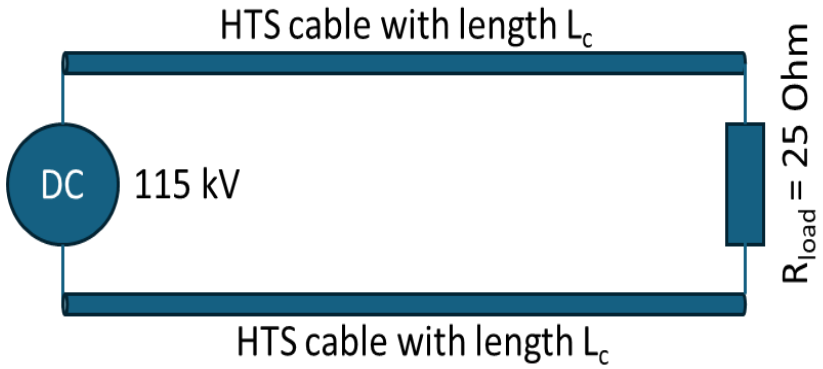
Coupled circuit simulation and heat transfer Finite Element Analysis (FEA) :

1. Circuit simulation, each YBCO layers has:
   - Resistance of HTS layer: RHTS ~ (I/Ic)n,
   - Resistance of metal layers Rmetal~ ρ(T)
   - Inductance matrix including self inductances Li and mutual inductance Mij. Those inductive components are calculated from winding radii, pitches and direction**, and magnetic permeability of the core μ(Ha).**
2. FEA to model the heat transfer on 2D cross-section of cable:
   - Only need to perform on a section of cross-section.
   - Temperature dependences of thermal properties of materials must be considered.



Flow diagram of the new FCL simulations.

Understanding FCL Performance of HTS Grids by Simulations



Simplified diagram of a grid with HTS cables.

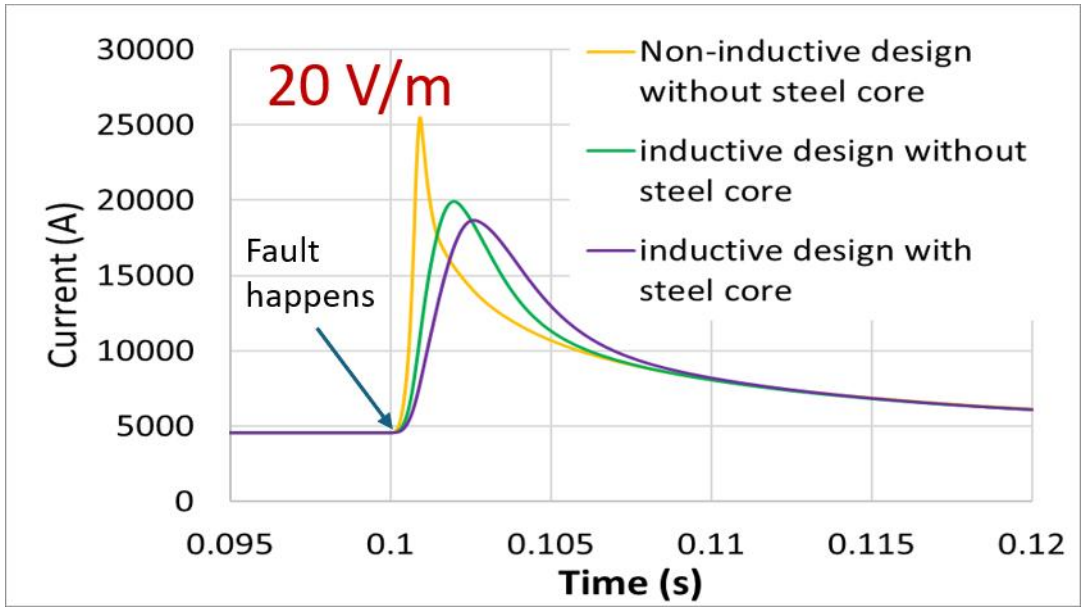
- 115 kV – 4600A (or 550 MW) grid with HTS cables.
- 6-layer HTS cable with 24 HTS tapes, cable OD =13 mm, cable critical current, I_c = 5300 A.
- The current is ~ 4600 A or ~ 35 A /mm^2 (x7 of copper).
- Varying transmission distance L_c to understand FCL at different voltage drop (V/m) levels on HTS cables.
- **Three cable designs: Non-inductive, inductive with and without magnetic core.**

Simulation case study	Voltage drop along cable during fault (fault voltage)	Potential applications
Case 1: 115 kV - L_c = 100 km	0.575 V/m or equivalent 500 kV / 450 km	Inter-subgrid connections, HTS cable along highway for EV charging stations
Case 2: 115 kV - L_c = 10 km	5.75 V/m or equivalent to 15kV/1.3 km	Local transmissions: Substations/dedicated power plan to data center;
Case 3. 115 kV - L_c = 2.875 km	20V/m or equivalent to 2kV/50m or 800V/20m	Extreme cases: Electric airplane, short distance inside data center

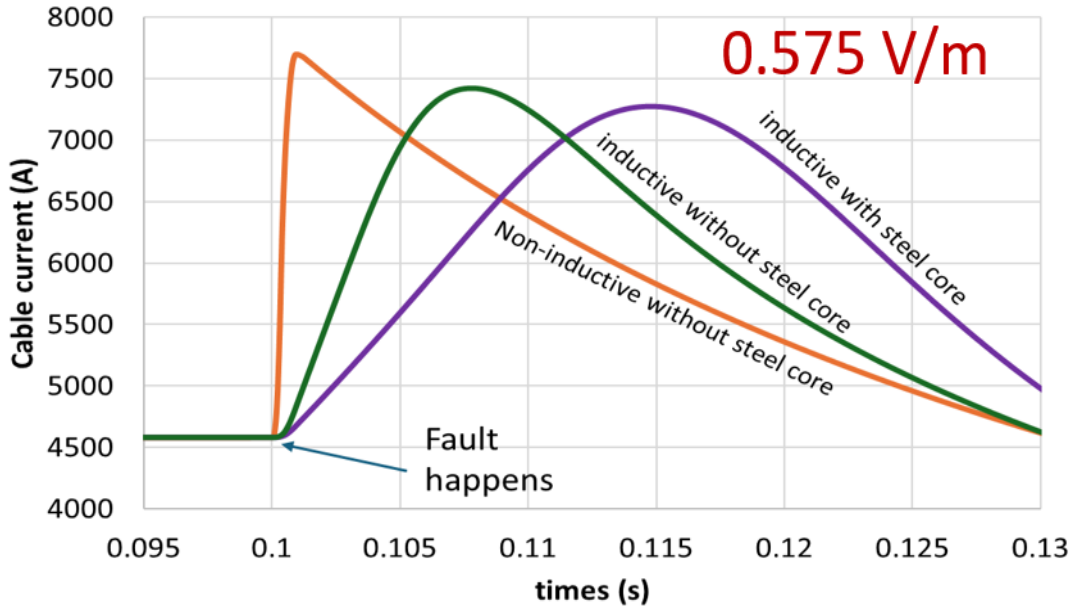
Table summary: Description of simulation case studies.

Fault Current Behavior in Different Cable Designs and Fault Voltages

Fault currents in HTS cables with different designs when fault voltage = 20 V/m.



Fault currents in HTS cables with different designs when fault voltage = 0.575 V/m.



- Higher fault voltage result in higher fault current.
- At 20V/m fault voltage, fault current may reach 25 kA or about nearly 5 times of cable $I_{c.}$
- Higher cable inductance suppress the peak of fault current better but broadens the fault-current waveform.

Fault Current Behavior in Different Cable Designs and Fault Voltages (Cont.)

Table summary: Peak fault currents in kA for different cable designs.

Fault voltage (V/m)	Non-inductive w/o core	Inductive w/o core	Inductive w/ core
0.575 V/m	7.7	7.4	7.3
5.75 V/m	13.6	11.8	11.1
20 V/m	25.9	19.9	17

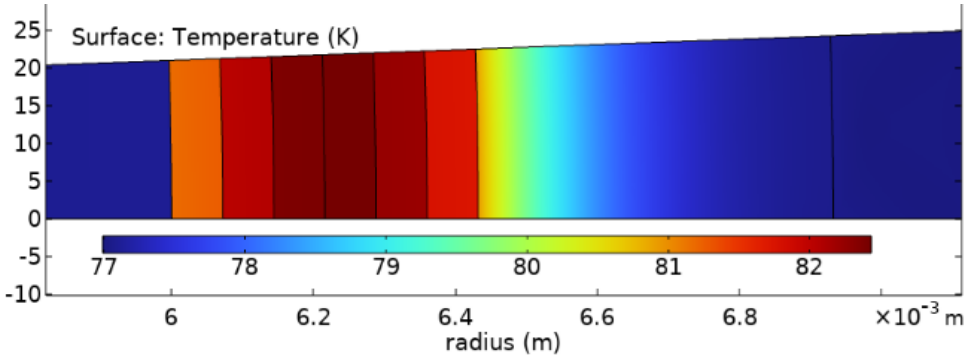
x10 x35 x2 x3

For normal conductor, the fault current is nearly propositional to the fault voltage. **However, in our case, the superconducting-to-normal transition and cable inductance help to significantly reduce peak fault current:**

- Fault voltage increase ~10 times, fault current only increase by only < 2 times.
- Fault voltage increase ~35 times, fault current only increase by only < 3 times.

Temperature rise after 50-ms fault for different cable designs and fault voltages

Simulation model was used to calculate temperature rise in cable cross-section during a fault.



Temperature rise in an inductive cable with steel core, after 50 ms fault at fault voltage = 0.575 V/m, T_{max} = 82.4K

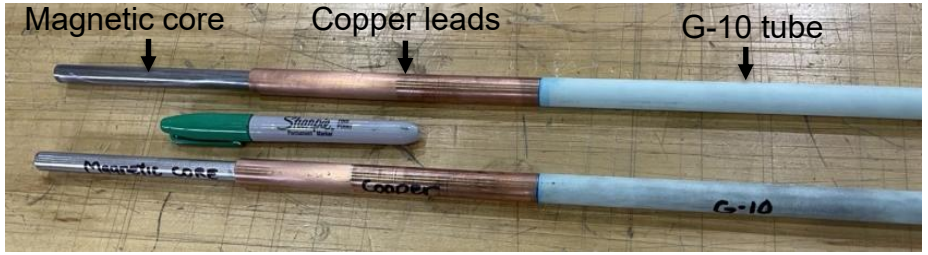
Table summary: Maximum temperature rise after 50-ms fault for different designs and fault voltages

Fault voltage (V/m)	Non-inductive w/o core	Inductive w/o core	Inductive w/ core
0.575 V/m	81.7 K	81.8 K	82.4 K
5.75 V/m	111.5 K	112.1 K	113.7 K
20 V/m	213 K	214 K	215 K

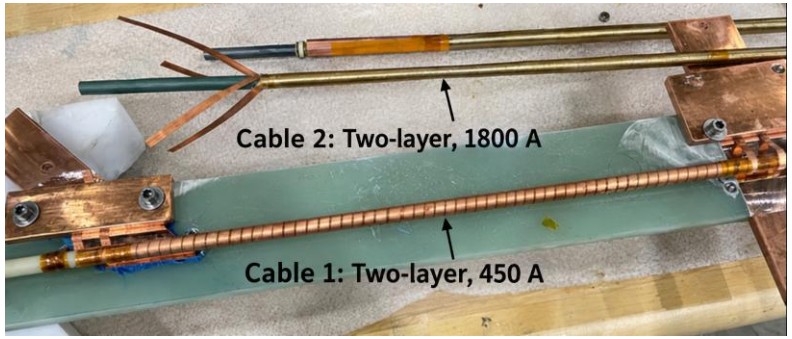
- **Even at extreme case of 20V/m fault, the temperature rise reaches about 215K, below the room temperature and should not damage HTS tapes.**
- **Cable inductance reduces fault-current amplitude but not fault heating. A magnetic core alone cannot provide enough inductance to suppress heating.**

Progress in Experimental Work

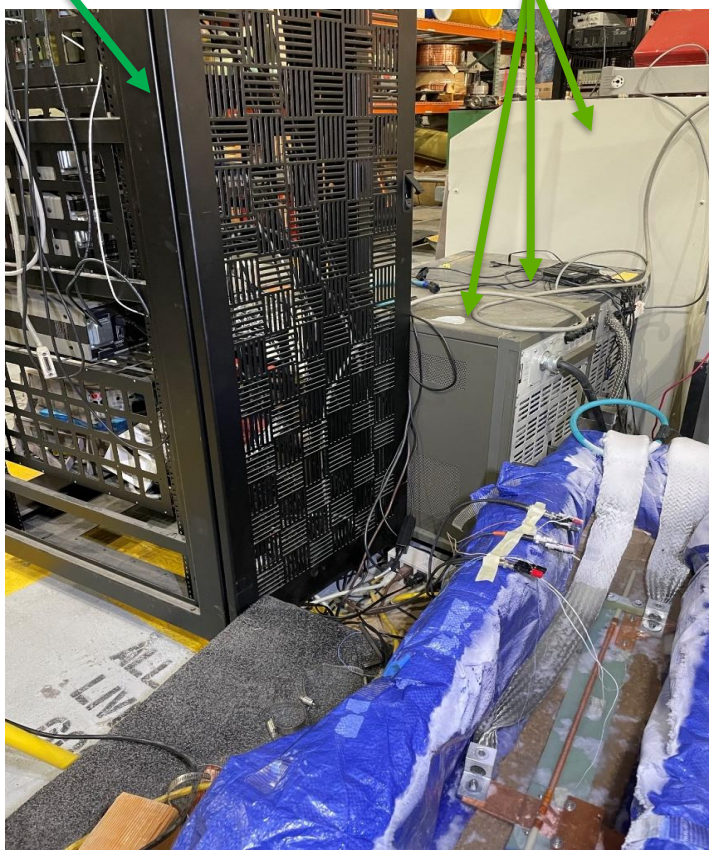
- Measure the magnetic property of the ferromagnetic cores at 77 K to implement those properties in the simulation codes.
- Build protype noninductive and inductive cables for testing.
- Build experimental facility to measure critical current and FCL performance of HTS cables (on going).
- Perform measurements of critical currents and FCL performance of HTS cable with inductive/non-inductive designs in combination with and without magnetic core (on going).



Cable former with copper leads and G10 tube.

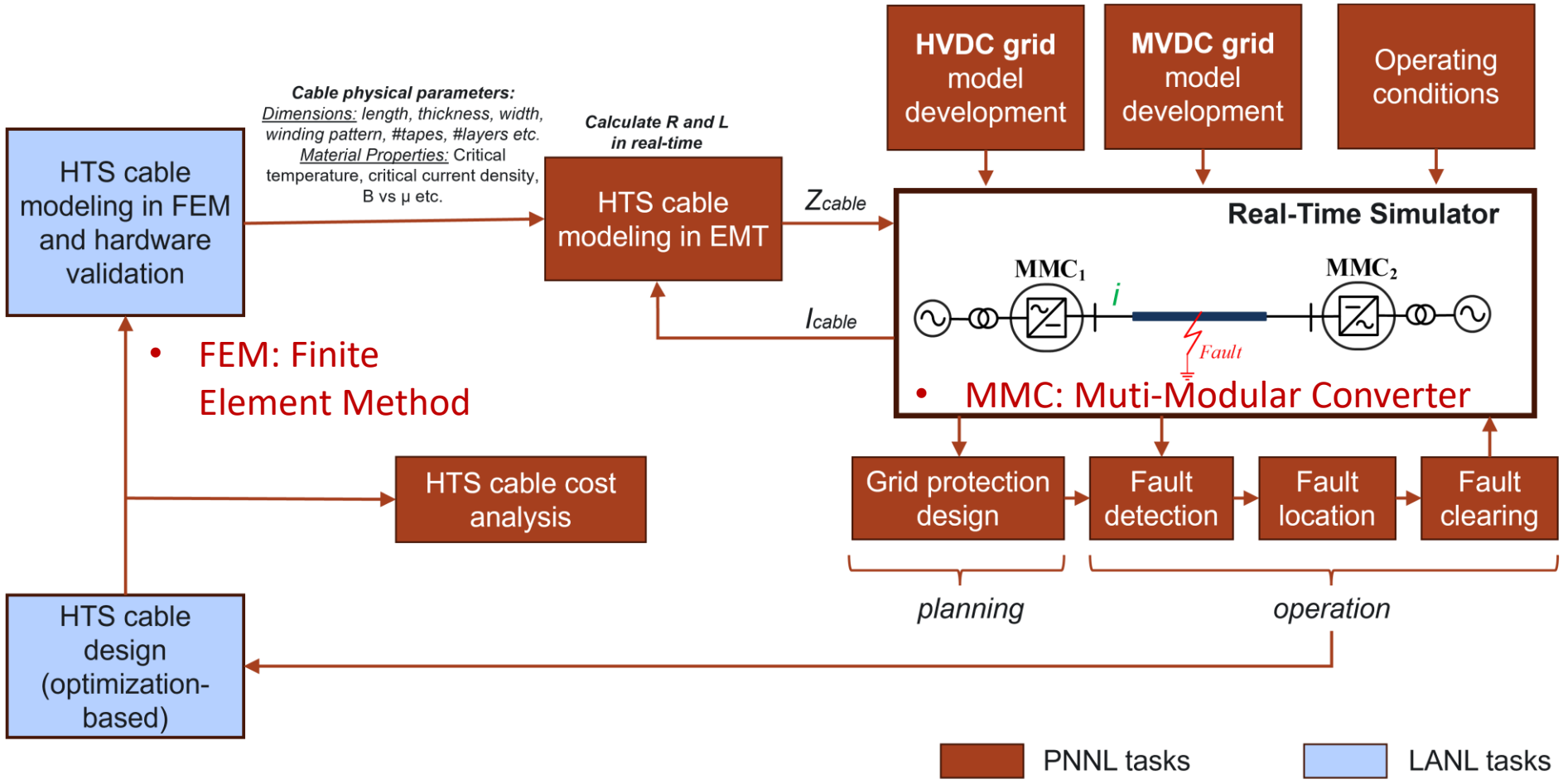


Protype 2-layer inductive cables for testing.



Experimental facility with high-power power suppliers, liquid Nitrogen bath.

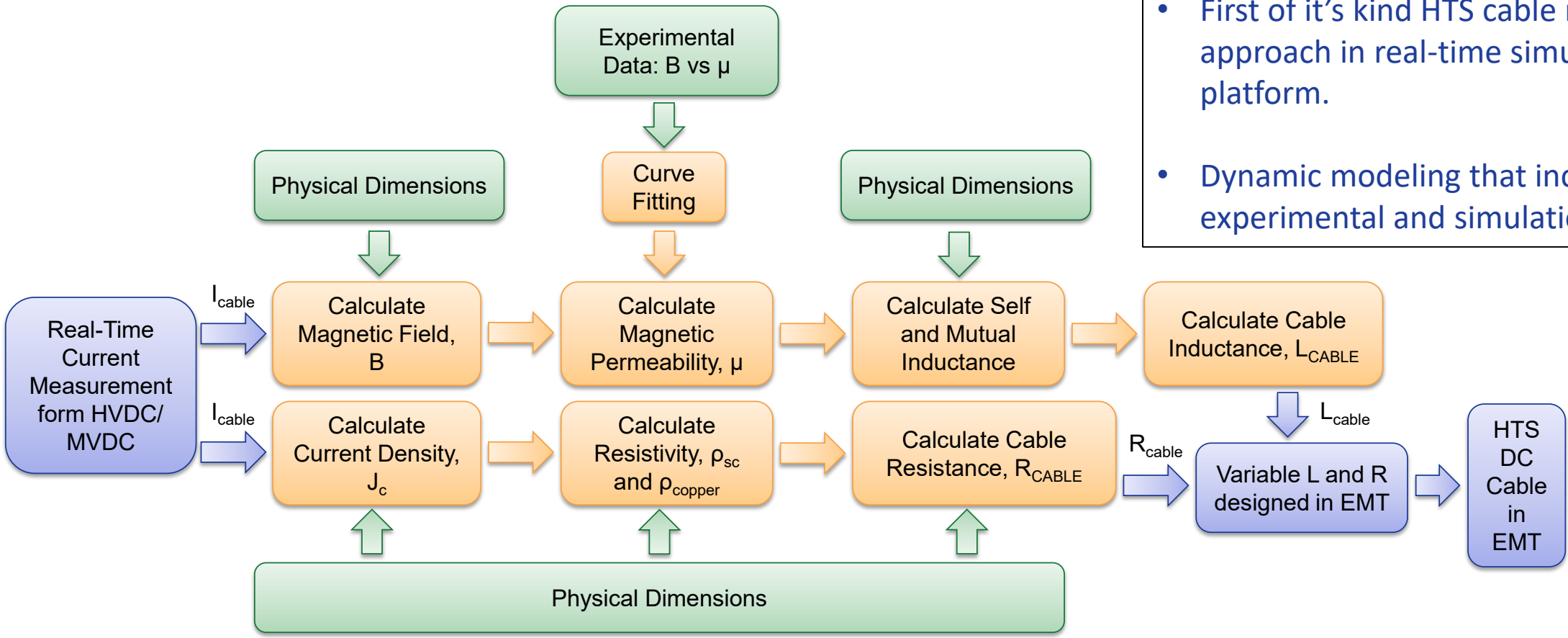
From Cable Design to System-Level Electromagnetic Transient (EMT) Simulation



- Study the integration of HTS cable in power grid.
- Hi-Fidelity simulation platform with large-scale power system integration capability.

Figure: PNNL scope and coordination between LANL-PNNL.

HTS DC Cable Modeling in EMT Domain



- First of it's kind HTS cable modeling approach in real-time simulation platform.
- Dynamic modeling that incorporates experimental and simulation data.

Figure: Flowchart showing the HTS DC cable modeling approach in EMT.

EMT Simulation for Fault Current Limiting in Grid

Demonstrated the advantages of HTS cable under fault in a realistic grid scenario.

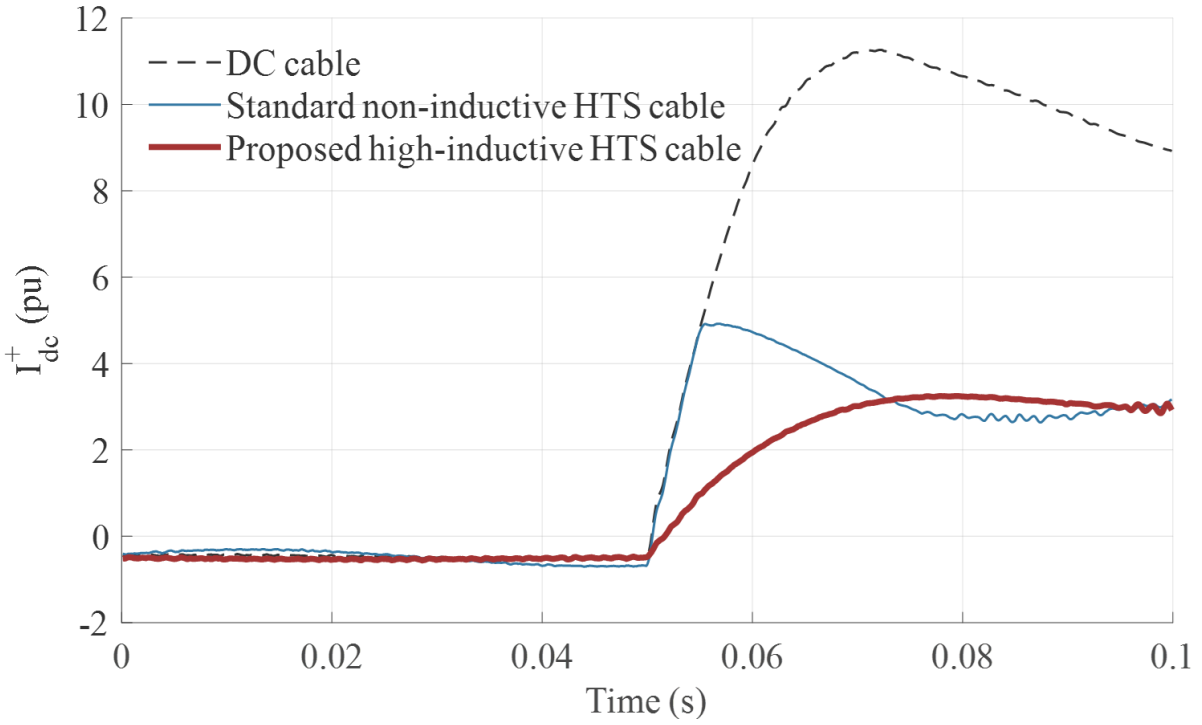


Figure: Simulation result shows that the proposed HTS cable can achieve lower fault current peak and slower fault current increase rate.

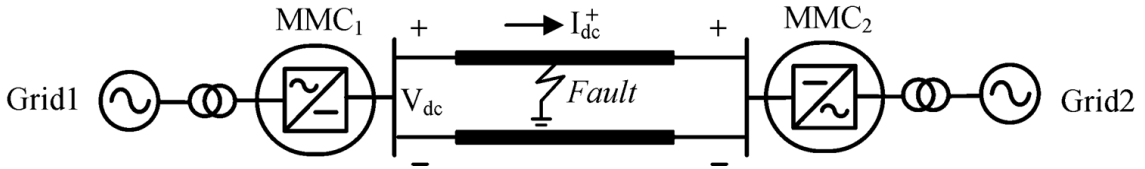


Figure: HVDC testbed for simulation study

Table summary: HVDC system parameters

Parameters	Value
V_{dc}	580 kV
L_{12}	1.45 mH/km
R_{dc_line}	0.015 Ω/km
R_{fault}	0.1 Ω
Line Length	200 km

Advantage of the proposed high-inductive HTS cable:

- Lower fault current peak.
  - Reduced breaker size.
  - Lower protection cost.
- Reduced fault-current rise rate: Expand time-duration for protection action.

HVDC System Development for HTS Cable Study in Large Power Grid

- 525kV HVDC test system connected to the 240-bus miniWECC AC system: Mimics the PDCI (Path 65) between California and Northwest.
- Capability Development: Large power system integration through e-PHASORSIM – HYPERSIM co-simulation: A real-world case study.

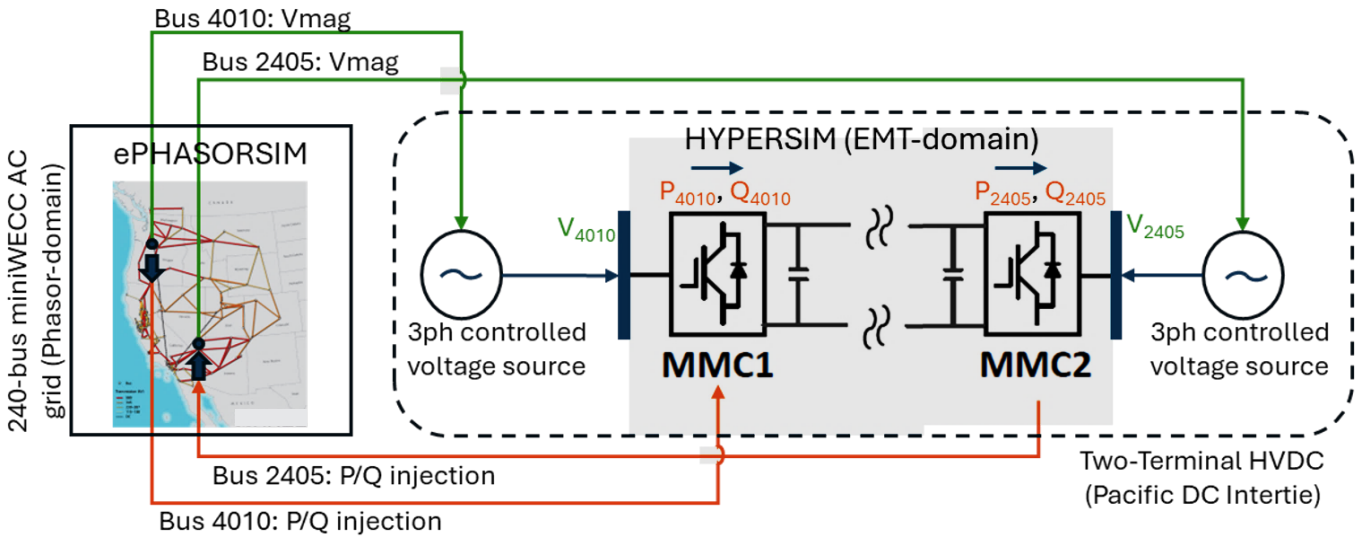


Figure: HVDC system and 240-bus miniWECC co-simulation

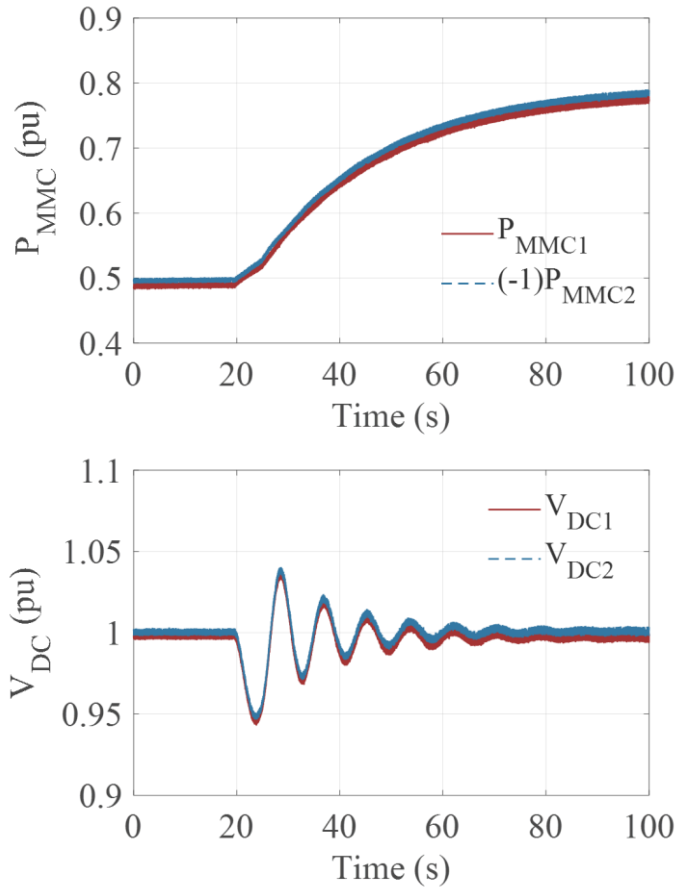


Figure: Stable active power and DC voltage following a scheduling change.

Preliminary results confirm the effective maintenance of stability in the real-time HVDC testbed developed using the proposed inductive HTS cable.

MVDC – MV Distribution System Testbed Development for Study of HTS Cable

- 35kV MVDC test system connected to the 24-bus distribution system.
- Stability, fault study, economic assessment in MV distribution system with HTS cable.

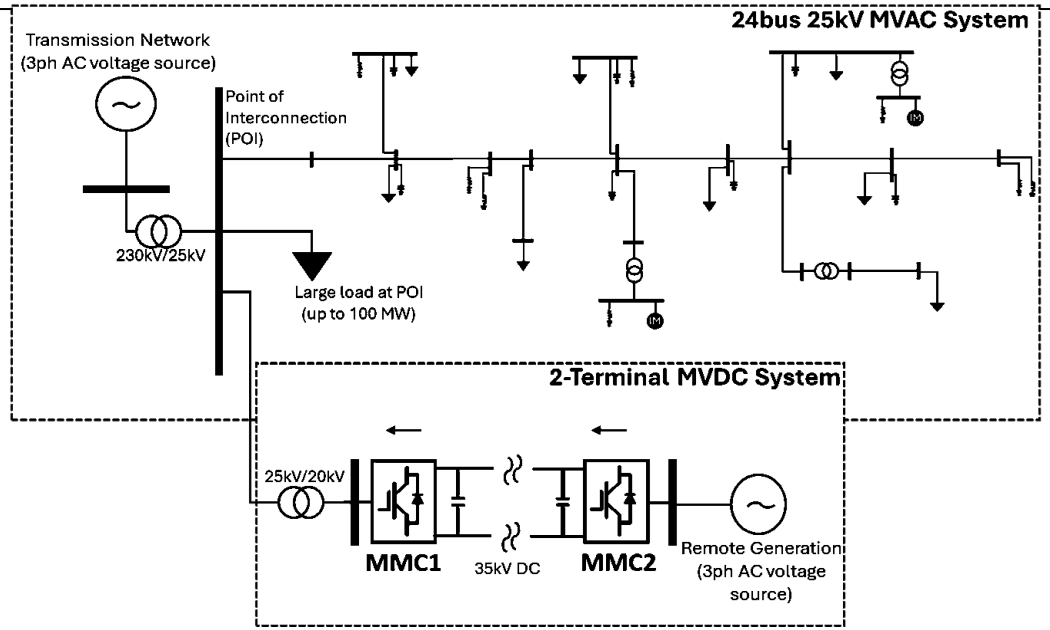


Figure: MVDC system and 24-bus distribution AC system.

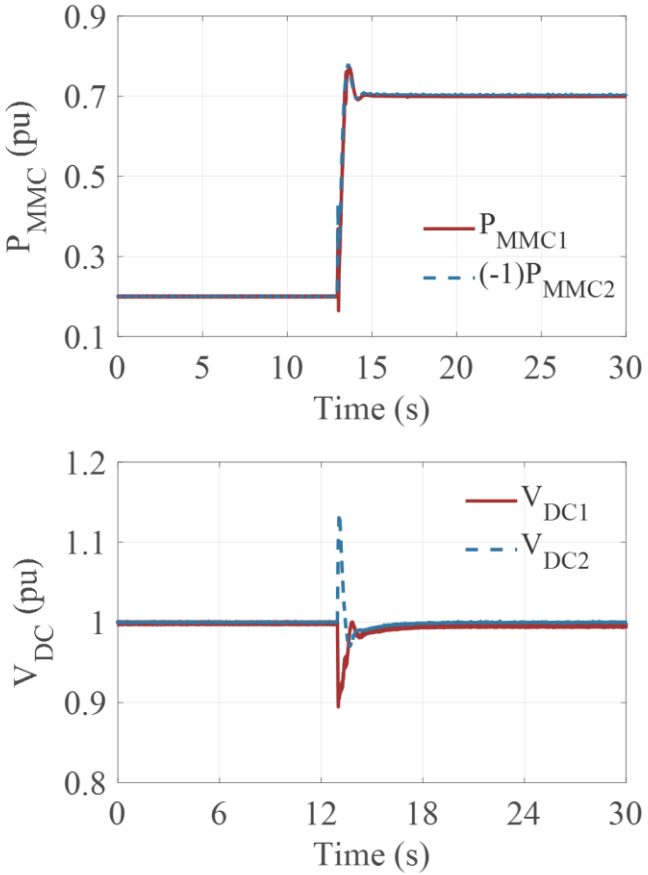


Figure: Stable active power and DC voltage following a scheduling change.

Preliminary results confirm the effective maintenance of stability in the real-time MVDC testbed developed using the proposed inductive HTS cable.

Conclusion remarks and impact (LANL)

- Developed a new FCL simulation model which couples circuit simulation and FEA thermal transfer.
- Validated model against experimental FCL data of an 8-layer non-inductive cables.
- Measured and implemented the magnetic field dependence of magnetic properties of core materials in the simulation code.
- Perform FCL simulation for 550 MW grid using 6-layer HTS cables carrying 4600 A or ~ 35 A /mm^2 (x7 of copper).
- **Simulations indicated that the superconducting-to-normal transition and cable inductance in proposed inductive HTS cables significantly reduce the peak value (an order better than normal conductor cable) and the ramp rate of the fault current, enabling safer and cheaper management of short circuit faults in MV/HV DC grids.**
- The temperature rise in HTS cable strongly depends on the fault voltage but only reach about 215 K for a 50 ms fault with fault voltage reaching extreme condition of 20V/m.
- Delivered two oral presentations at the Applied Superconductivity Conferences (Pittsburg, September 6-11, 2026).

Conclusion remarks and impact (Continue)

PNNL research:

- The proposed HTS DC cable has been modeled in a real-time EMT simulator, allowing system-level analysis of DC networks and AC-DC systems with HTS DC cables.

- Simulation results validate the expected benefits of the proposed cable: Reduces the dc fault current rise rate, enabling the use of slower, lower-rated, and more cost-effective dc circuit breakers, or potentially eliminating the need for series inductors.

- The developed co-simulation-based AC-DC test system enables system-level validation of the HTS cable and assessment of its interactions with larger AC grids.

Future Direction and Plan

LANL:

- Design and build 6 layers inductive cables using G10 tube formers, (targeting near 2 KA). Test cables with and without ferromagnetic cores and demonstrate robust FCL performance with no Ic degradation after 10 faults.
- Use experimental data to validate and refine the simulation model.
- **Apply the model to design 10 kA cables with robust FCL performance and stability for MV/HV DC grid**.
- Provide input for PNNL to perform techno-economic assessment for MV/HV DC grids using 10 kA cables.
- Work with LANL's Feynman Center to pursue potential patent protection.

PNNL:

- Test the HTS cable model under normal and fault conditions.
- Analyze results and provide feedback to improve LANL's HTS cable design.
- Integrate fault detection, location, and clearing into the HTS-based DC network.
- Assess current and future HTS cable costs and cost-to-benefit ratio for industry.

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE).

References

[1] https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf

[2] Radwan M, Azad SP. Protection of Multi-Terminal HVDC Grids: A Comprehensive Review. Energies. 2022

[3] G.K. Pall, et. al., “Causes of Delay in Power Transmission Projects: An Empirical Study,” Energies 13 (1), 17, December 2019