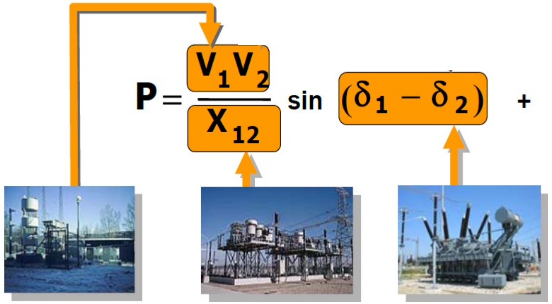
Multi-Terminal DC Grids: Perspectives and Challenges

Maryam Saeedifard

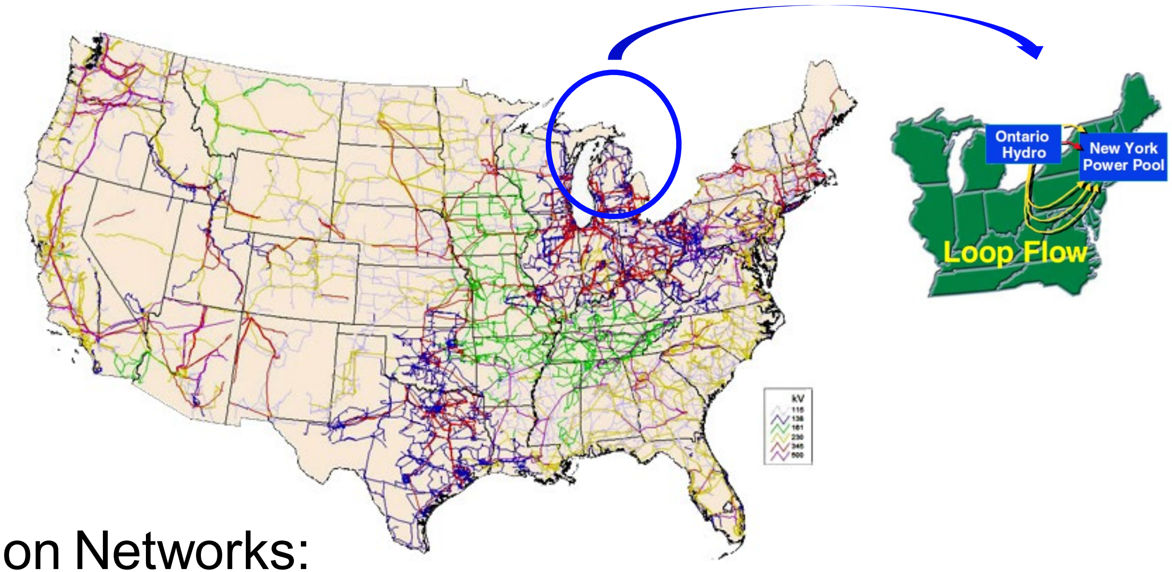
Ken Byers Professor

Georgia Institute of Technology

Introduction: Bottlenecks in Legacy AC Grid



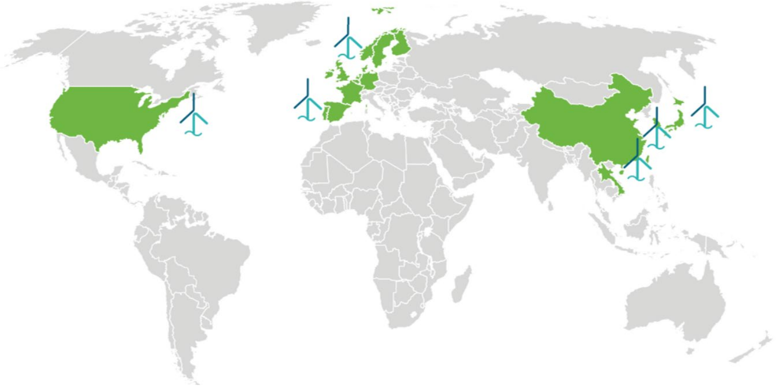
$$P = \frac{V_1 V_2}{X_{12}} \sin(\delta_1 - \delta_2) +$$



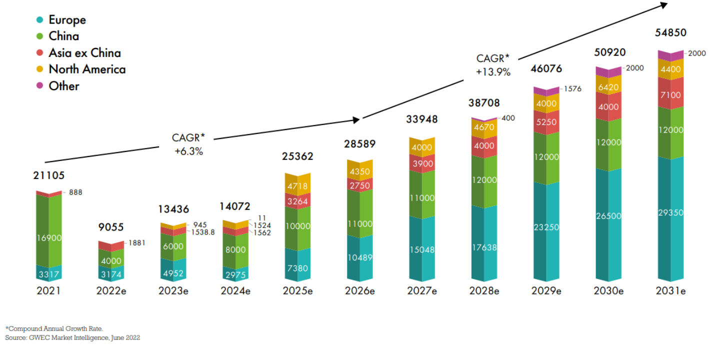
Challenges in Transmission Networks:

- Uncontrolled power flows and loop flows
- Low power transfer capability and inefficient utilization of transmission assets
- Blackout risk due to cascading effects

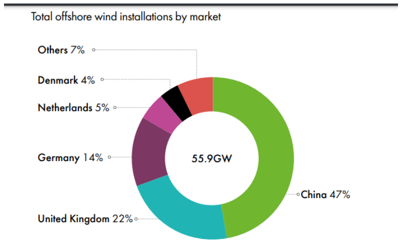
Grid Integration of Renewable Energy Resources

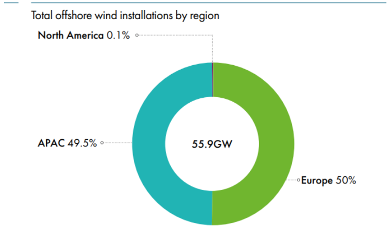


Global Wind Energy Council, “Global Offshore Wind Report 2022,” Tech. Rep., 2022.



Forecasted Offshore Wind Growth Outlook to 2031

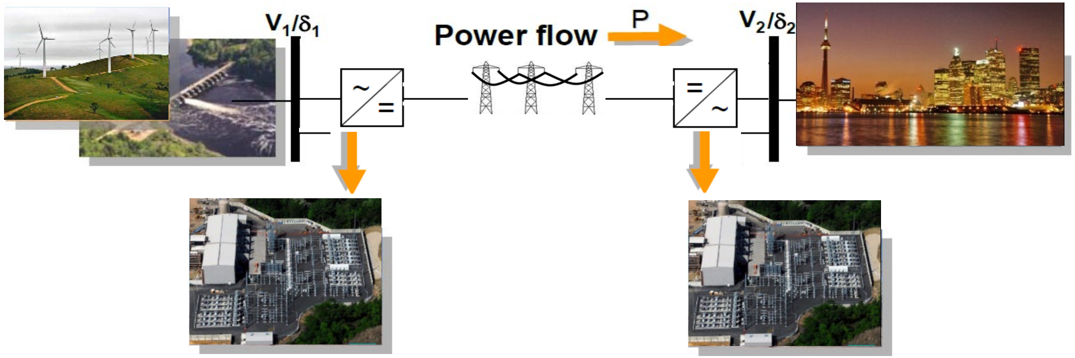


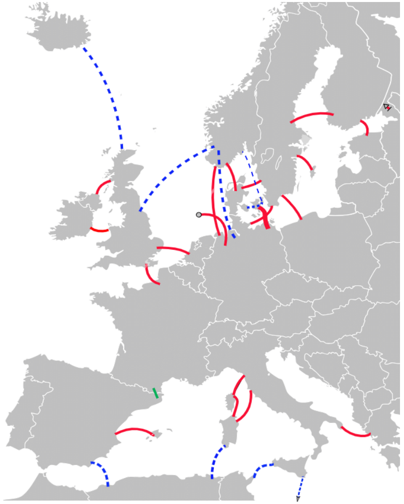


DOE Offshore Wind Energy Pathway: 30 GW by 2030 and 110 GW by 2050

IEEE

Point-to-Point HVDC Transmission





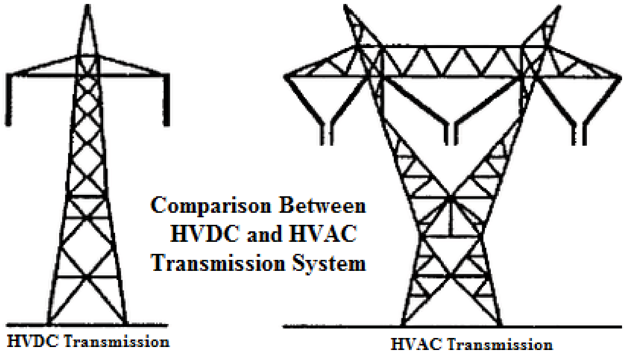
Examples of HVDC links in Europe

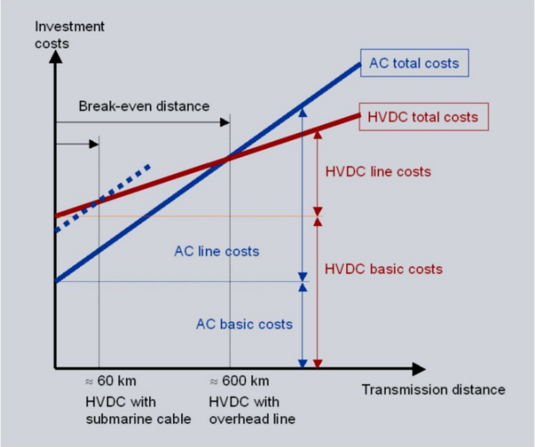
$$P = V_{dc} I_{dc}$$

HVDC: High Voltage Direct Current Transmission System

WHY HVDC?

- Long-distance bulk power transmission
- Improved reliability, flexibility, stability, and functionality

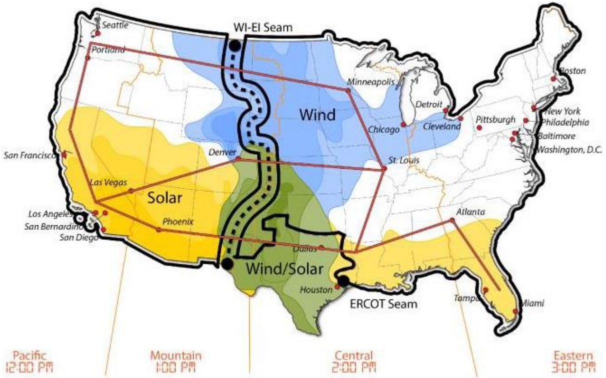




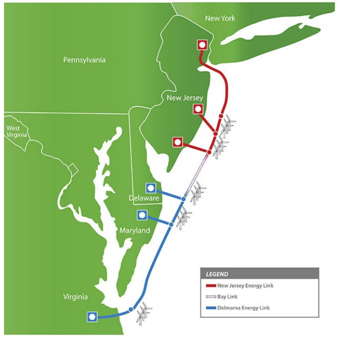
Multi-Terminal DC (MTDC) Grids

Euro “SuperGrid”

Zhangbei HVDC grid



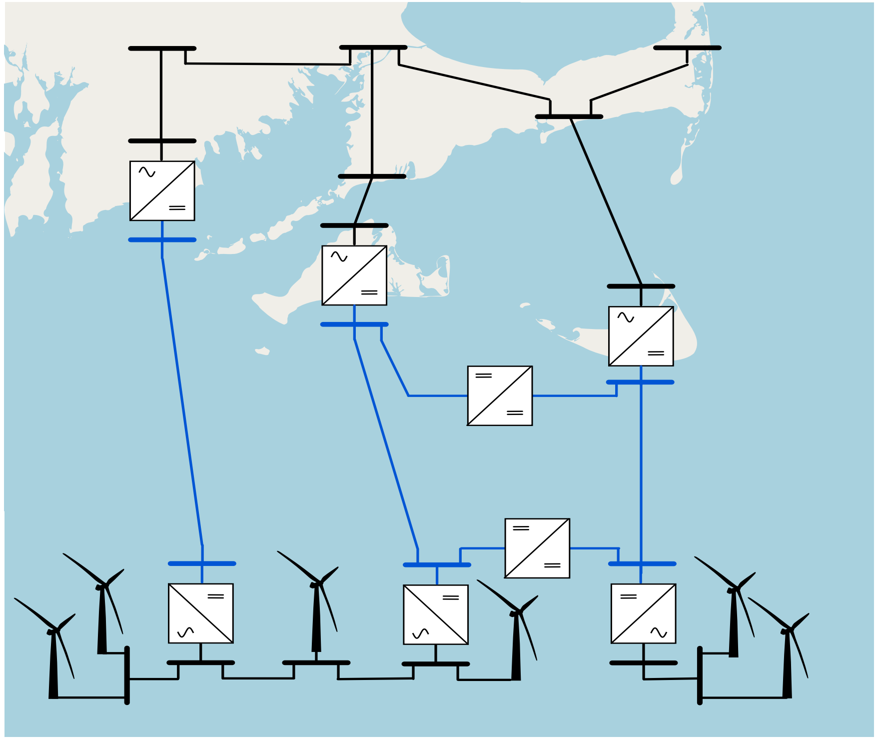
US Eastern and Western Interconnects

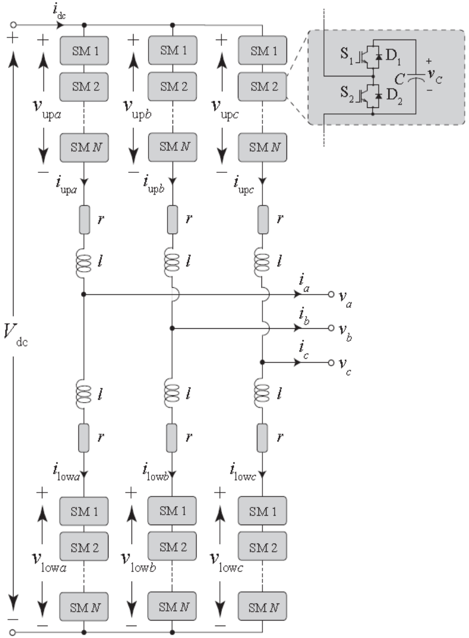


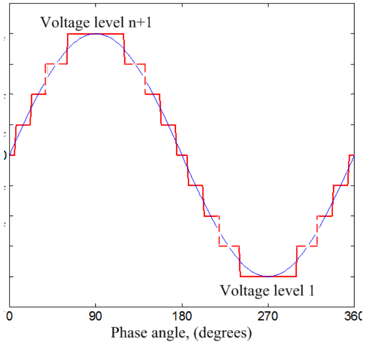
Atlantic Wind Project

[1] DESERTEC, “The Desertec Concept for Energy, Water and Climate Security,” DE-SERTEC Foundations, Tech. Rep., 2009.
[2] Y. Li, “China Upgrades Capacity to the Zhoushan Islands,” T&DWorld, Mar. 2017.
[3] Connection, Atlantic Wind, "The Atlantic Wind Connection: A Bold Plan That Makes Sense. Brochure,“ 2012.

Key Components of MTDC Grids

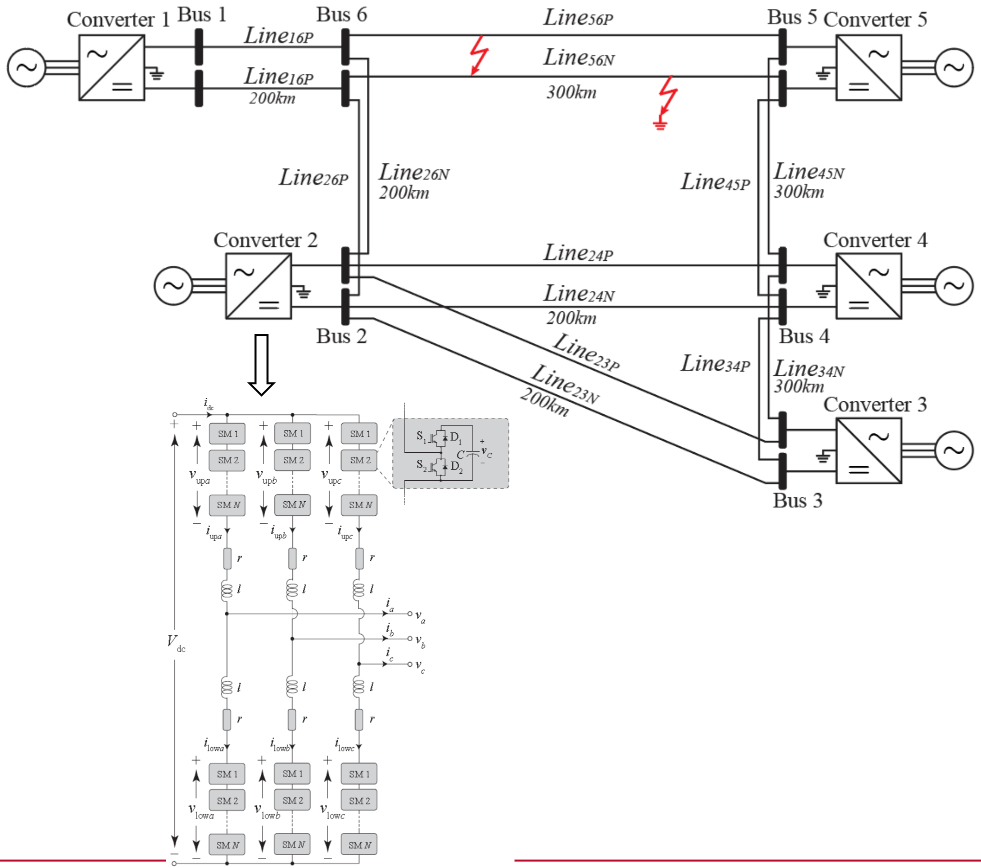


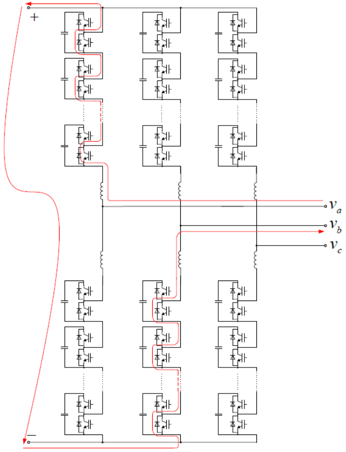


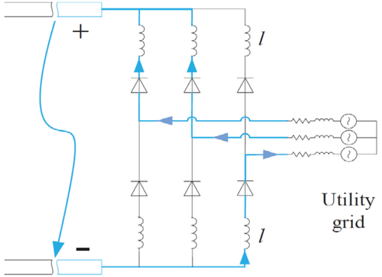


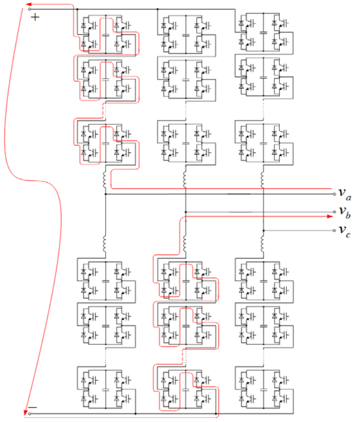
Converter Technology: The Modular Multilevel Converter (MMC)

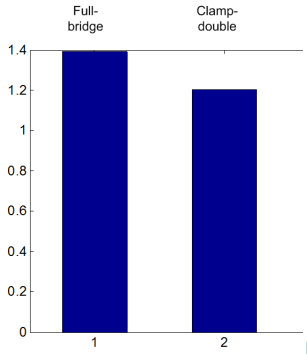
DC-Side Fault Protection Issue



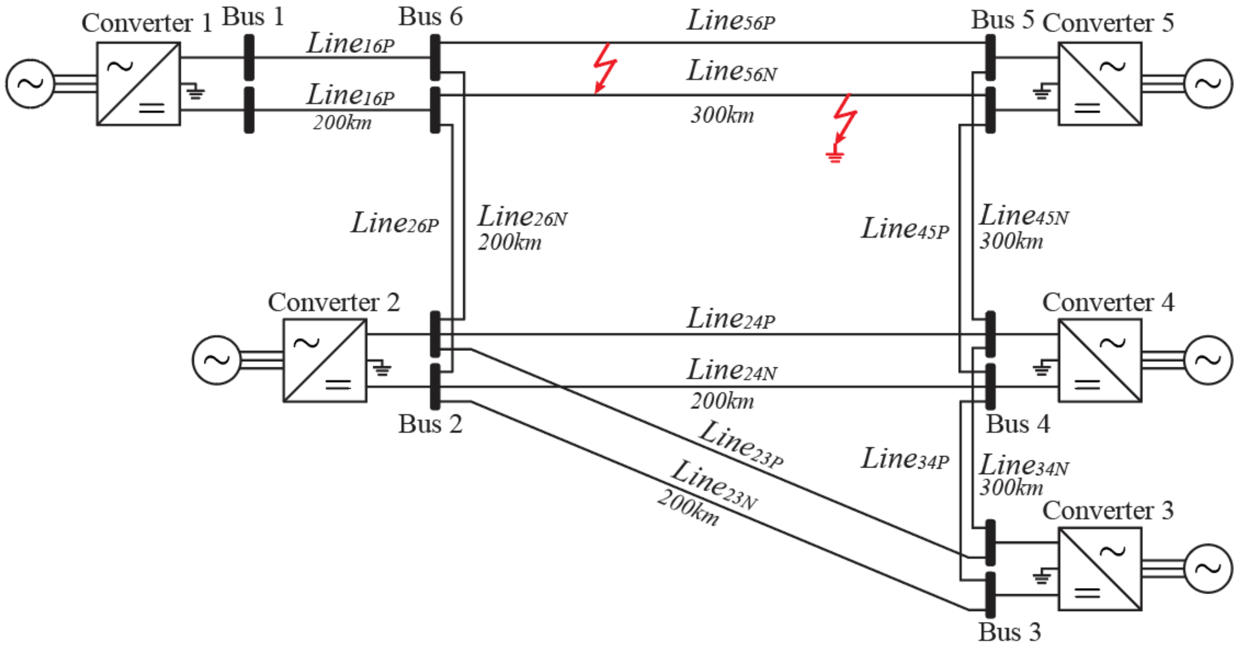




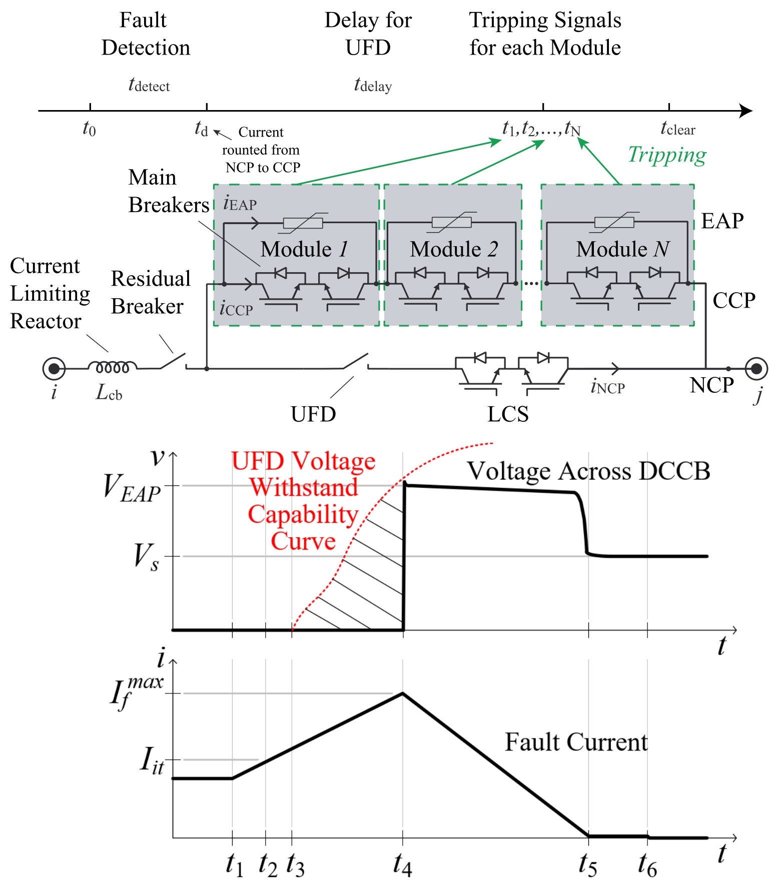




DC-Side Protection Based on DC Circuit Breakers



Tripping of Hybrid DC Breaker



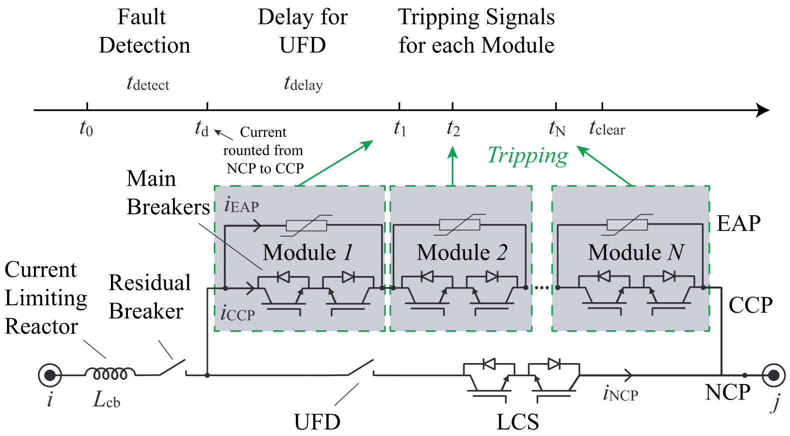
Challenge: **Cost, Footprint, Speed**

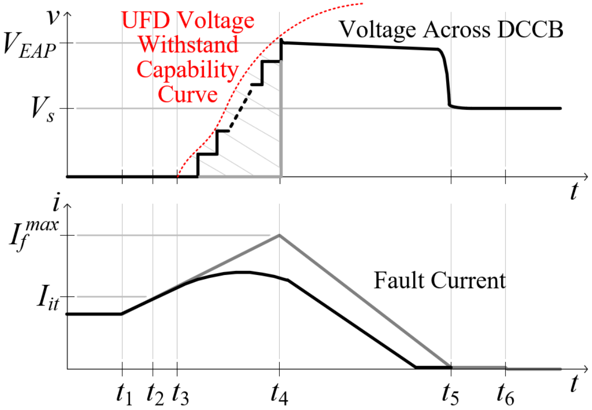
- High electrical stress
- Long interruption time
- All metal-oxide varistors (MOVs) inserted simultaneously
- Under-utilized FMS curve

Sequential Tripping of Hybrid DC Breaker

The solution combines three key features:

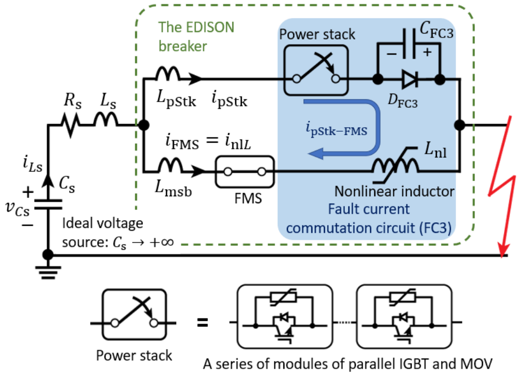
- Sequentially tripped MOVs rather than simultaneously tripped MOVs
- Optimized tripping sequence with minimal number of switching events
- Closed-loop structure to ensure equal energy absorption under all conditions



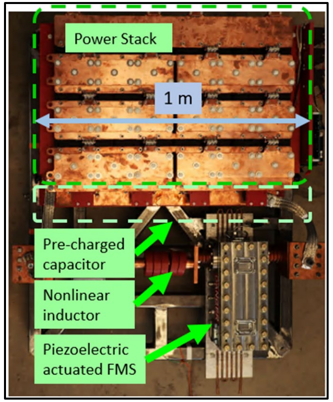


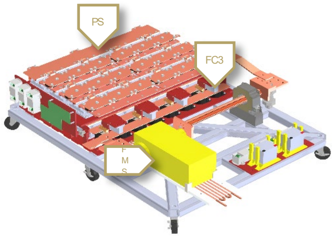
The Hybrid DC Circuit Breaker

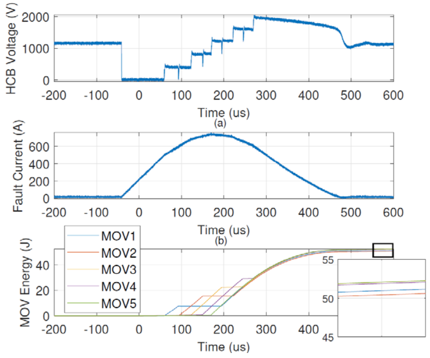
EDISON - Efficient DC Interrupter with Surge Protection



	Mechanical	Solid-State	Hybrid with Conventional Tripping	**Hybrid with Proposed Tripping**
ON-state power loss	< 0.01 %	> 0.3 %	< 0.01 %	**< 0.01 %**
Interruption time	10-100 ms	< 100 μs	< 3 ms	**< 2 ms***
DC voltage limit	3 kV	Scalable	Scalable	**Scalable**
Rel. power density	High	Low	Medium	**High**

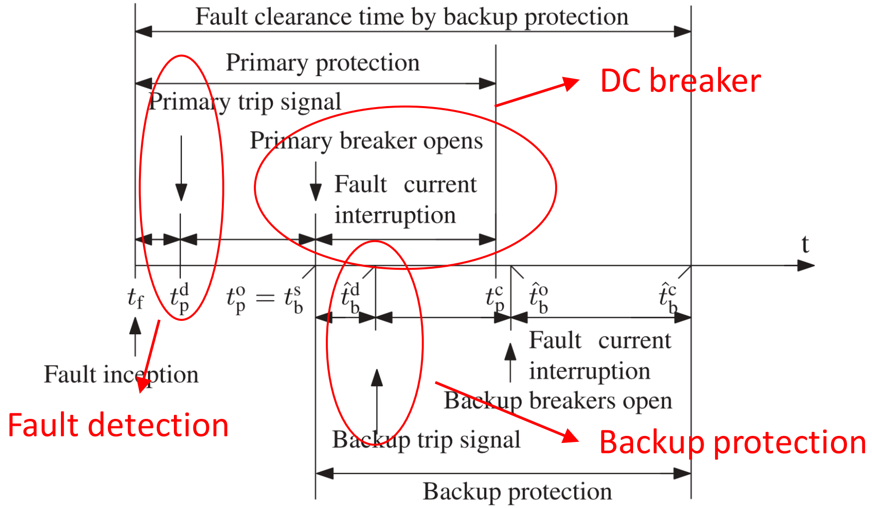


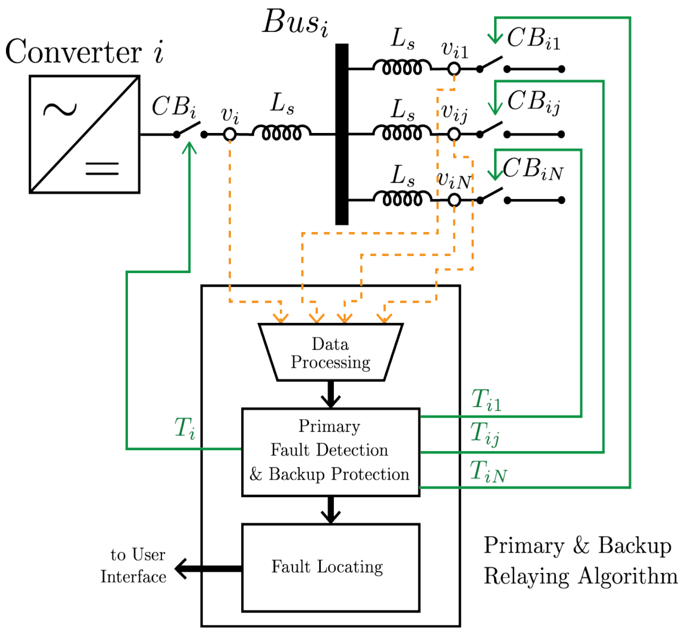




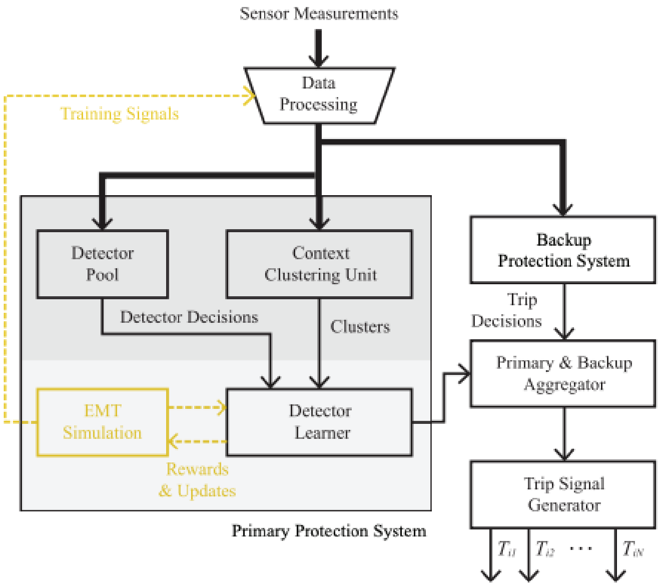
* Calculation is based on an 8-kA fault current in 450 μs

The Layout of the Protection System

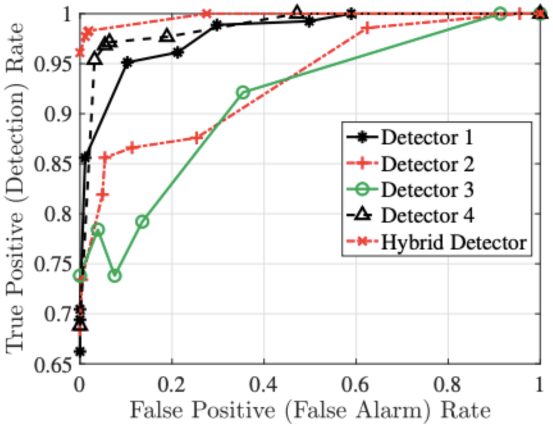




Primary Protection: Architecture



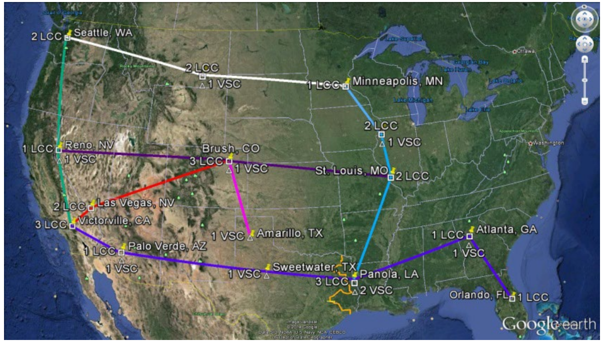
Architecture of the proposed hybrid primary protection unit

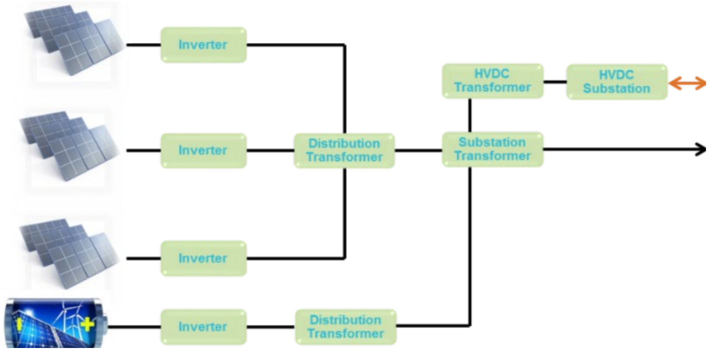


Receiver Operating Characteristics (ROC) Curves

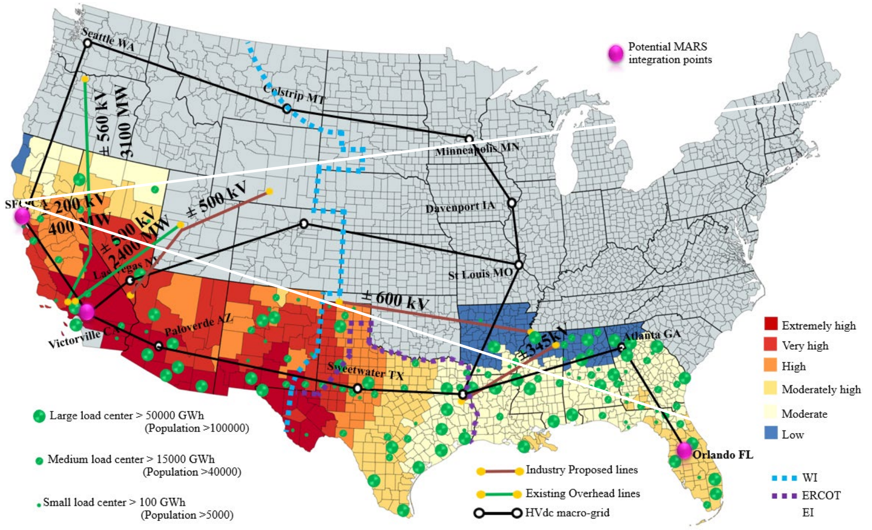
Discrete Development of HVDC, PV and ESS

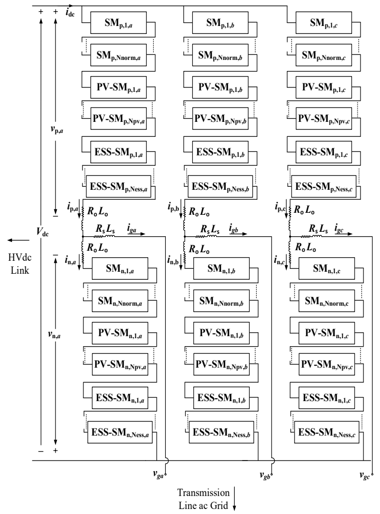
- **Discrete development of HVDC, solar, and ESS**
  - Increased costs
  - Reduced reliability
  - Reduced efficiency
  - Competing controls
  - Transient stability problems





Integrated Development of HVDC, PV and ESS

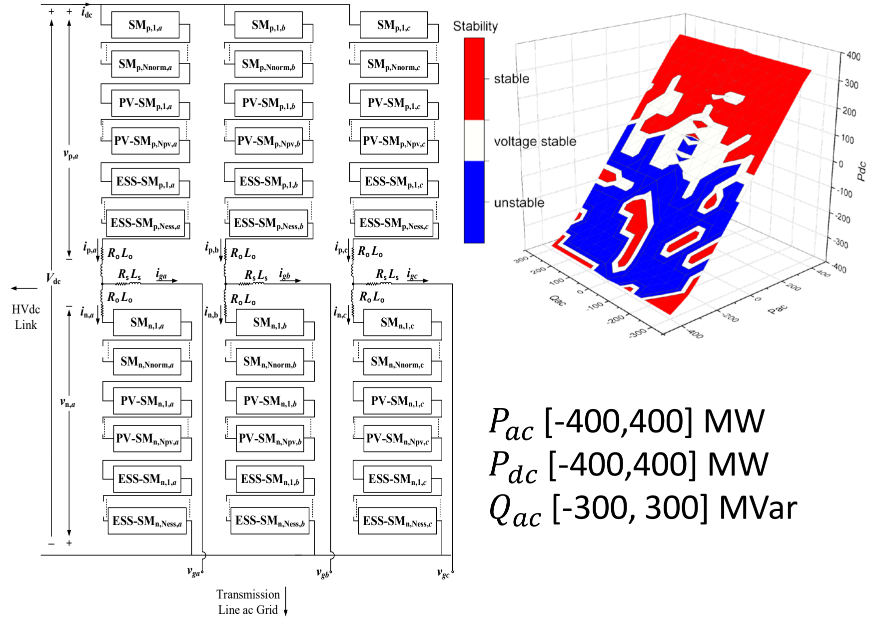




Develop integrated power electronics (MARS)to interface utility-scale solar power, energy storage, dc, and ac systems with advanced grid services.

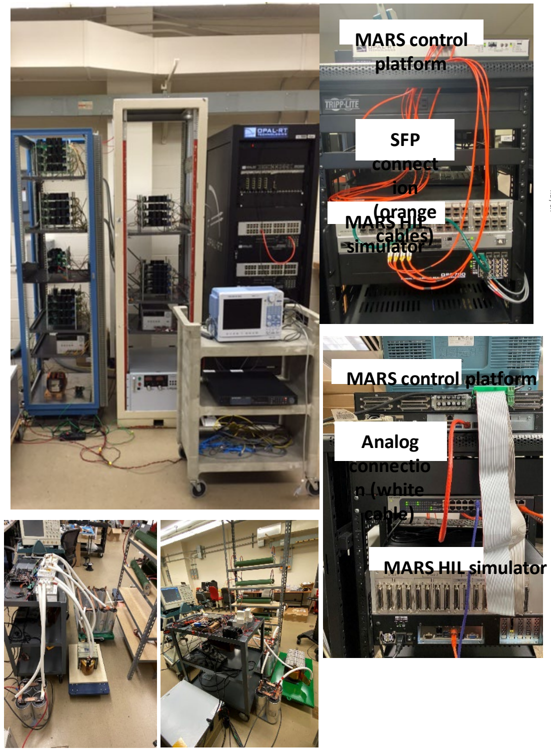
- Reduced costs and losses than the discrete development.
- Provide primary and secondary frequency response improvement, congestion relief, and disturbance control rejection.

Energy Balancing Control Challenge

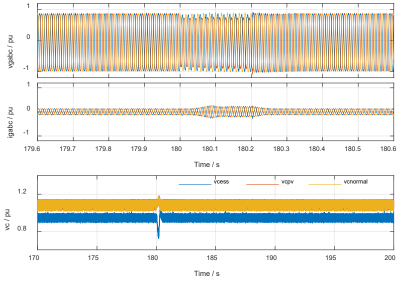


P_{ac} [-400,400] MW
P_{dc} [-400,400] MW
Q_{ac} [-300, 300] MVar

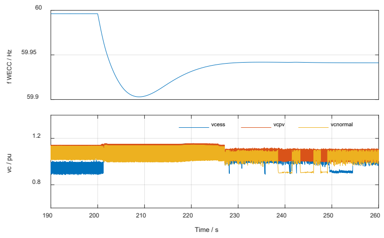
Hardware in the Loop Setup



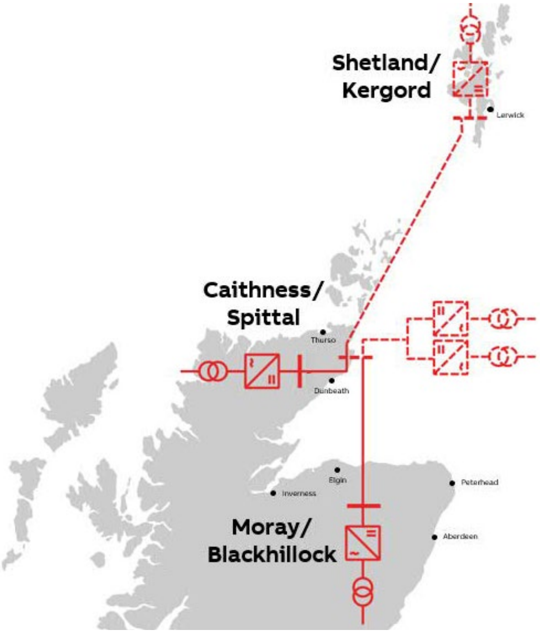
Line-line fault

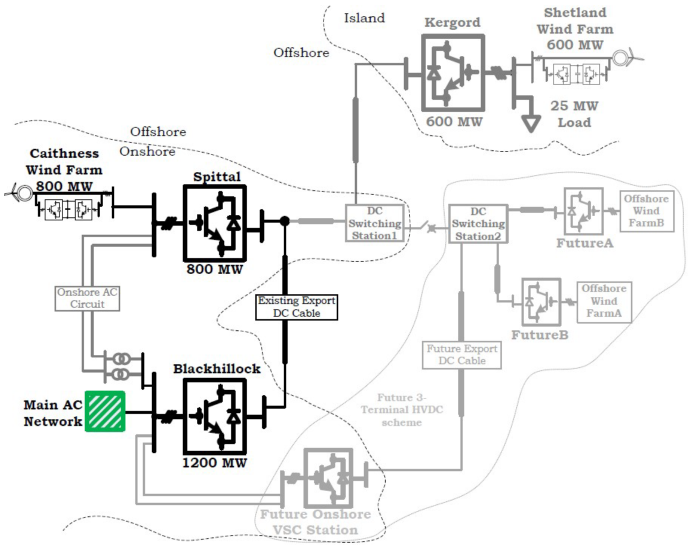


Loss of generation based on Haynes3 generator in WECC grid



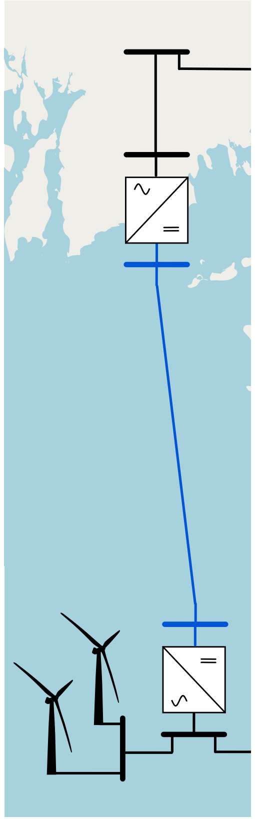
Multi-Vendor Interoperability

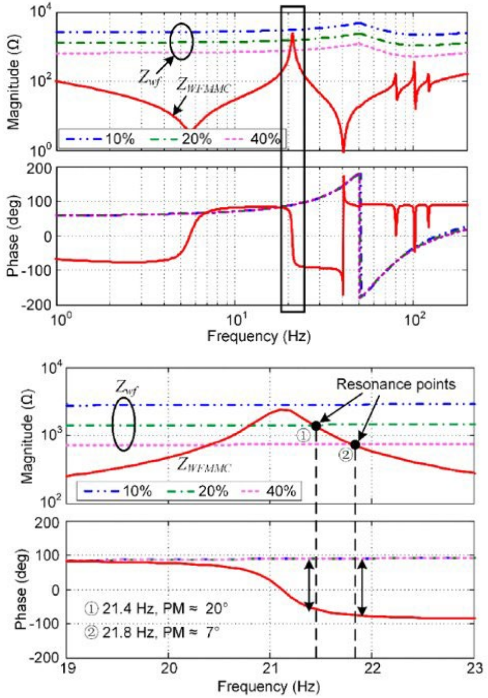


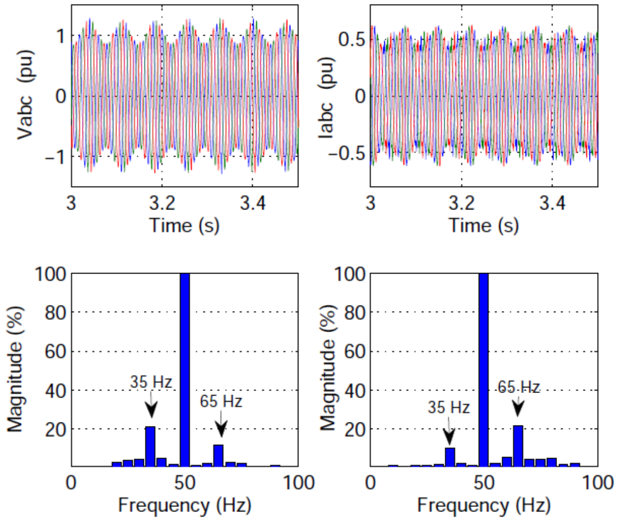


O. D. ADEUYI et. al., “Multi-terminal Extension of Embedded Point-to-Point VSC-HVDC Schemes,” Cigre B4-120, Paris, 2020.

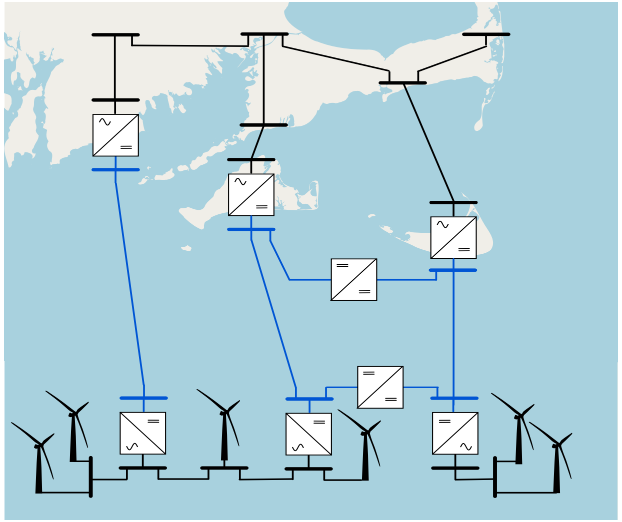
Resonances in HVDC-Connected Wind Farms







Multi-vendor Interoperability



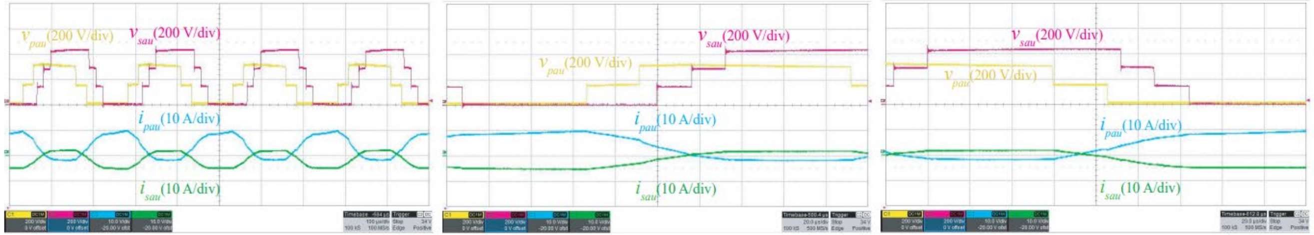
Challenges:

- Multi-vendor control
- Multi-vendor circuit breakers
- Multi-vendor hybrid AC/DC
- Grid forming/Grid-following operation

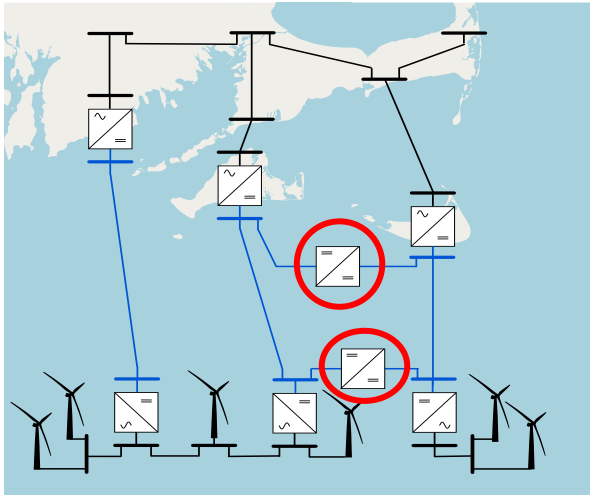
This is what we model

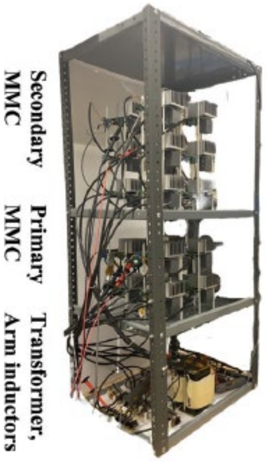
This is what we are faced with in reality!

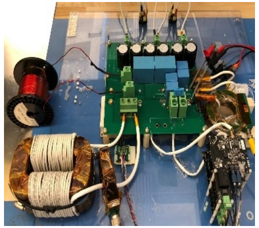
The Need for Efficient and Scalable Medium and High-Voltage DC-DC Converters



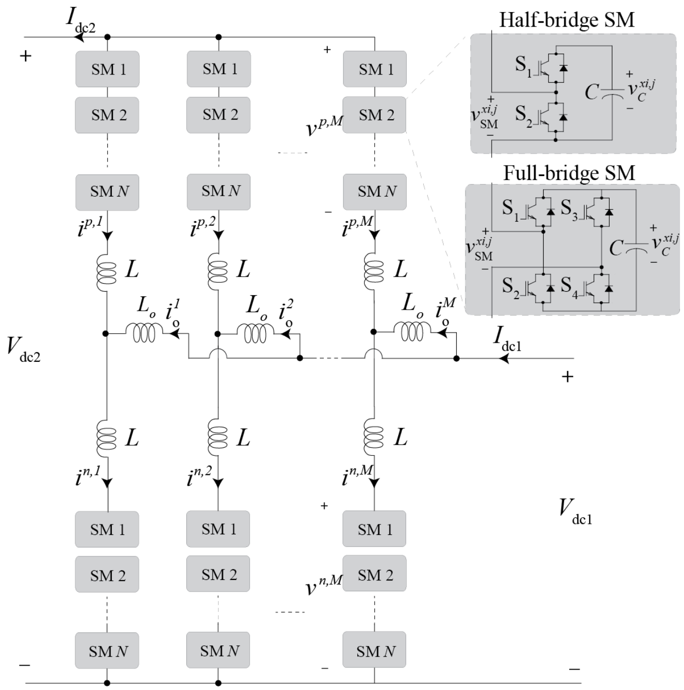
(a) (b) (c)

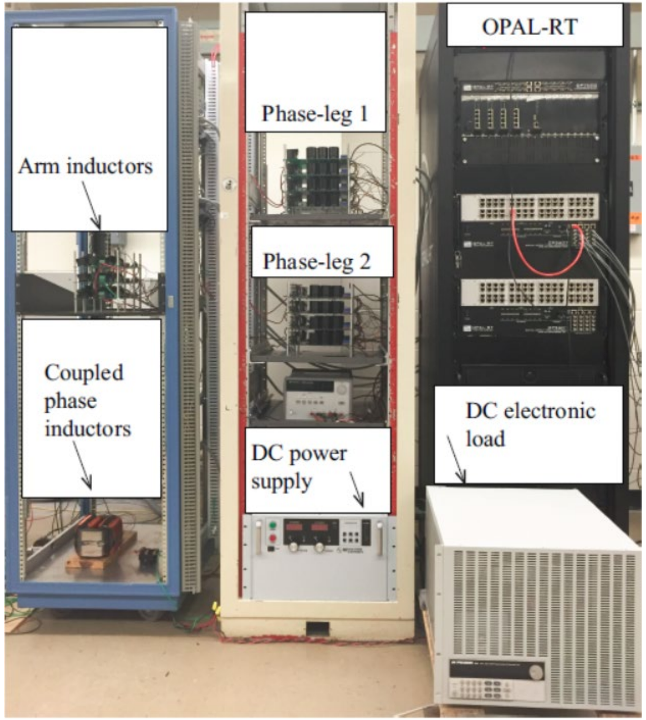


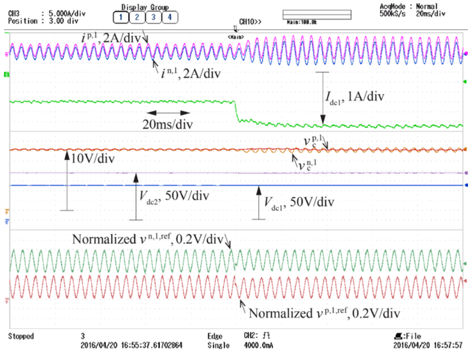


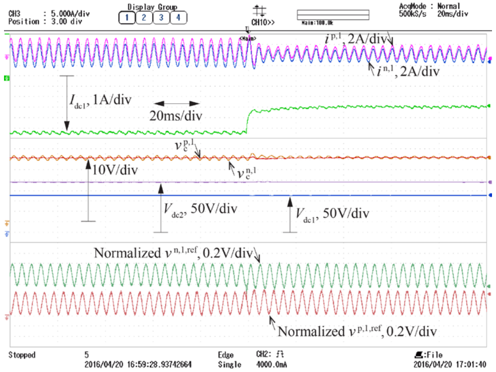


Non-Isolated DC-DC MMC



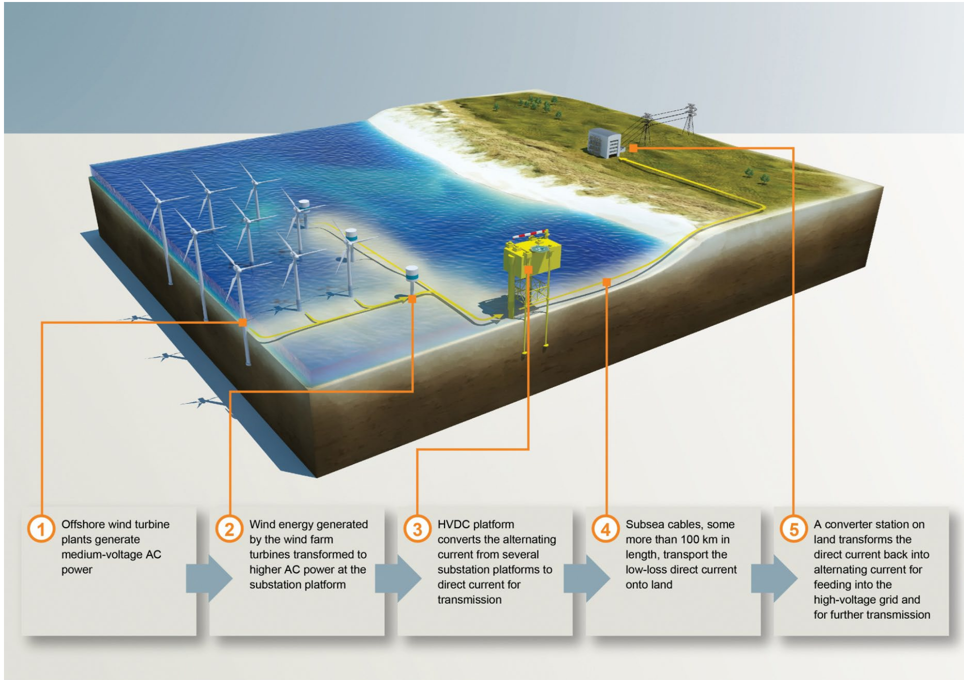






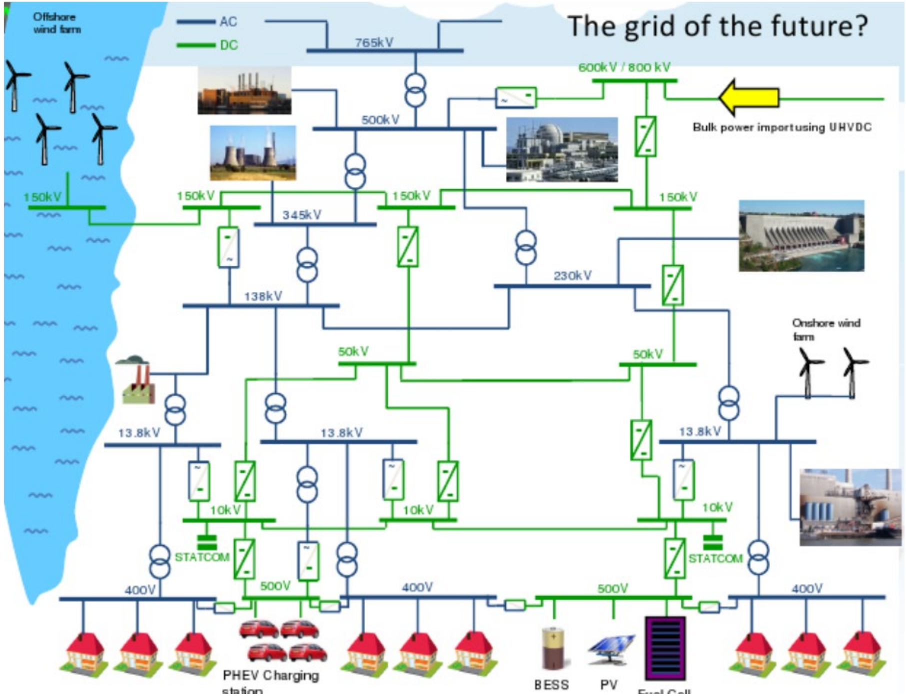
Challenges for Offshore HVDC Stations

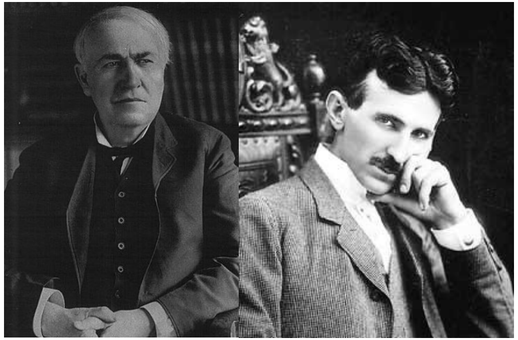
- Larger than a football field
- Construction and installation of such large structures can also be resource and cost-prohibitive
- Lifespan and reliability of power converters need to be pushed to over 30+ years



Concluding Remarks

- DC grids are key next-generation grids meshed inside the legacy grids.
- Win-win situation for both AC and DC





Thank you!