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Autonomous Power Control Adaptive Protection for Distributed Microgrids

9/14/2023

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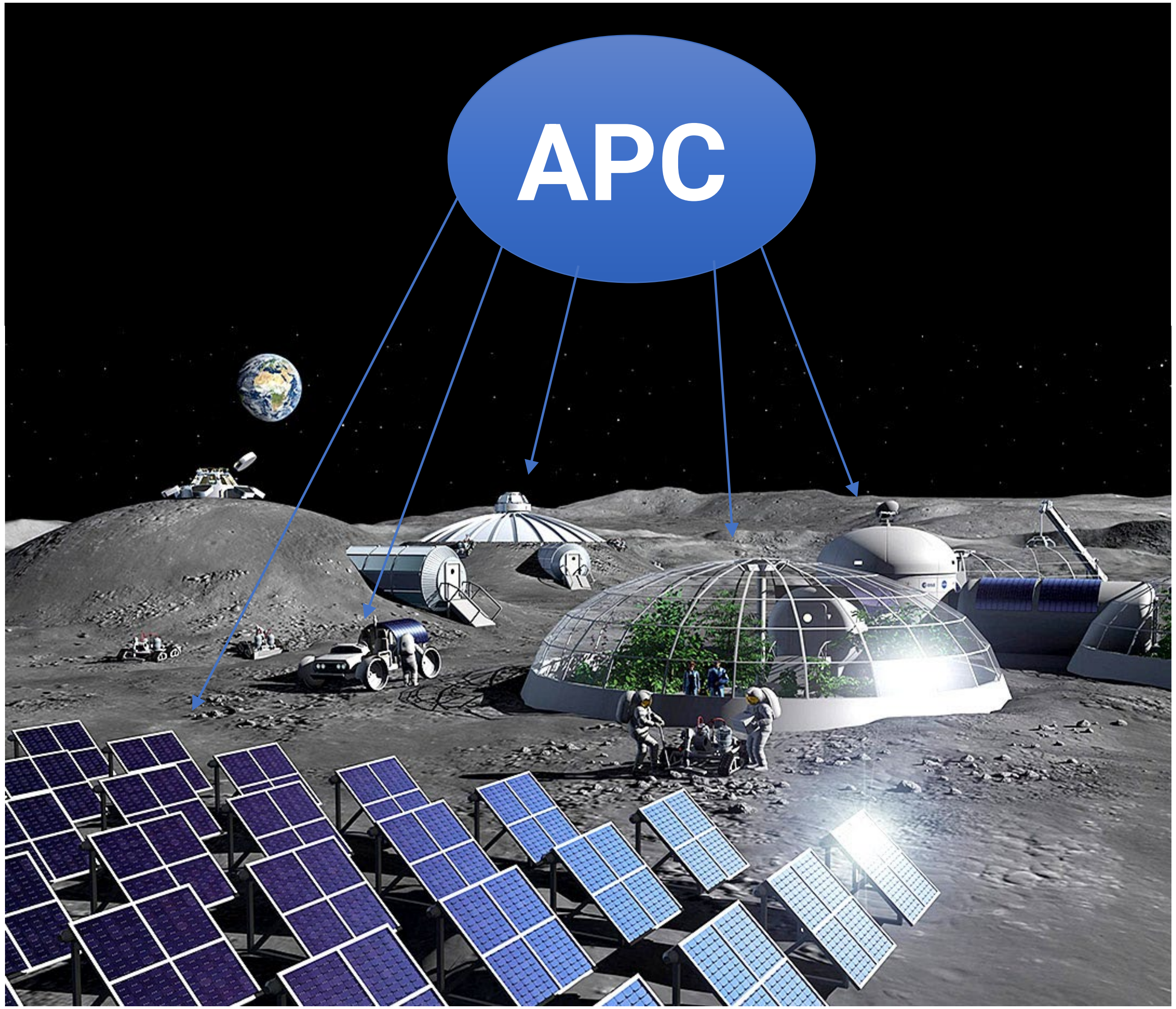
Autonomous Power Controller (APC)

What is it?

The APC is a comprehensive Energy Management System designed to minimize the need for human interaction and oversight of electric power systems in space.

- Increase *power availability* and *resilience*
  - Provide autonomous response to unexpected events
  - Prioritize mission critical loads
- Develop control strategies to achieve *autonomy*
  - Reduce the need for operator intervention
  - Quickly react to unplanned outages & failures
- Increase *interoperability*
  - System agnostic controller
  - Enable power system growth over time
  - Introduce plug-n-play components

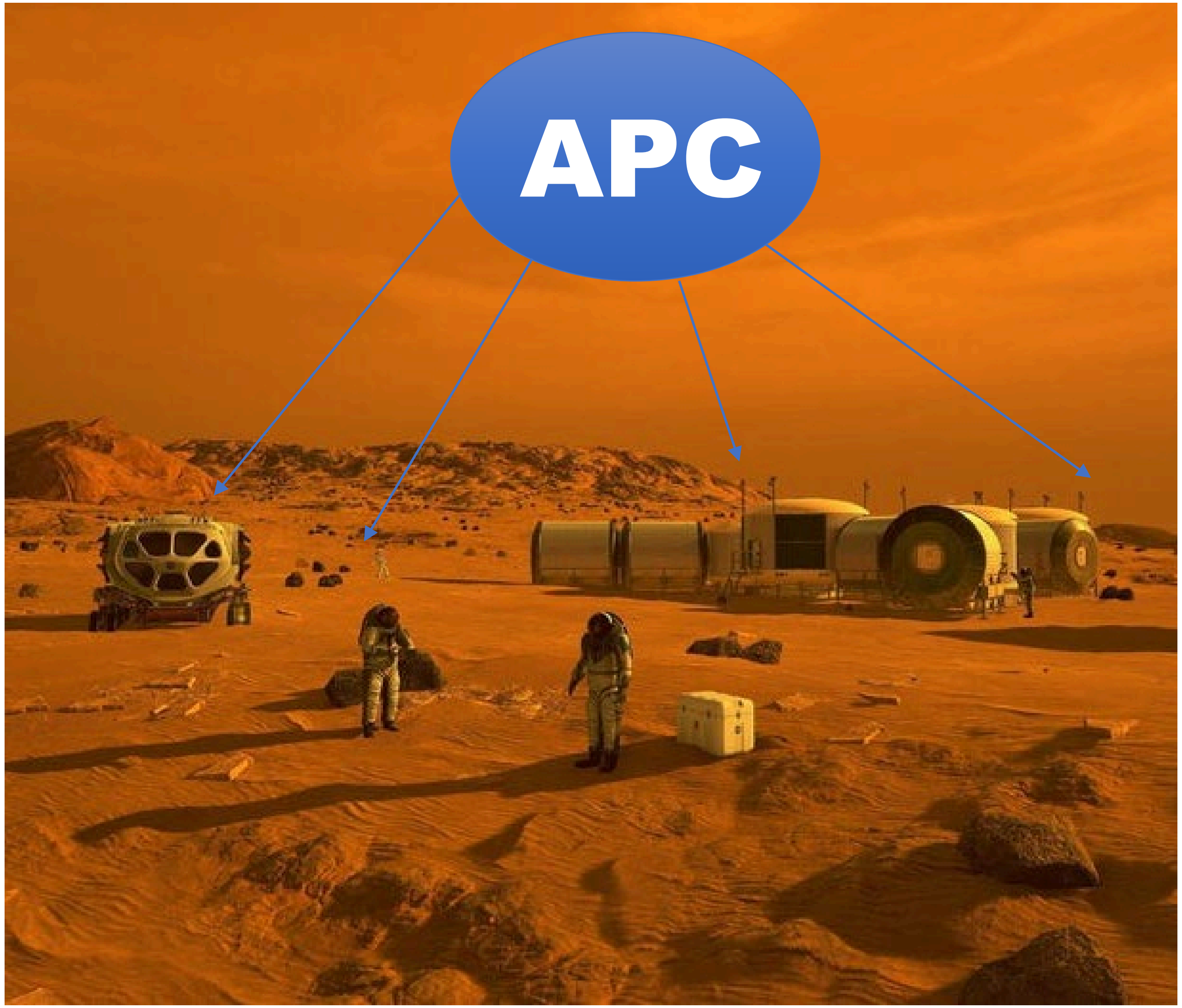


Autonomous Power Controller (APC)

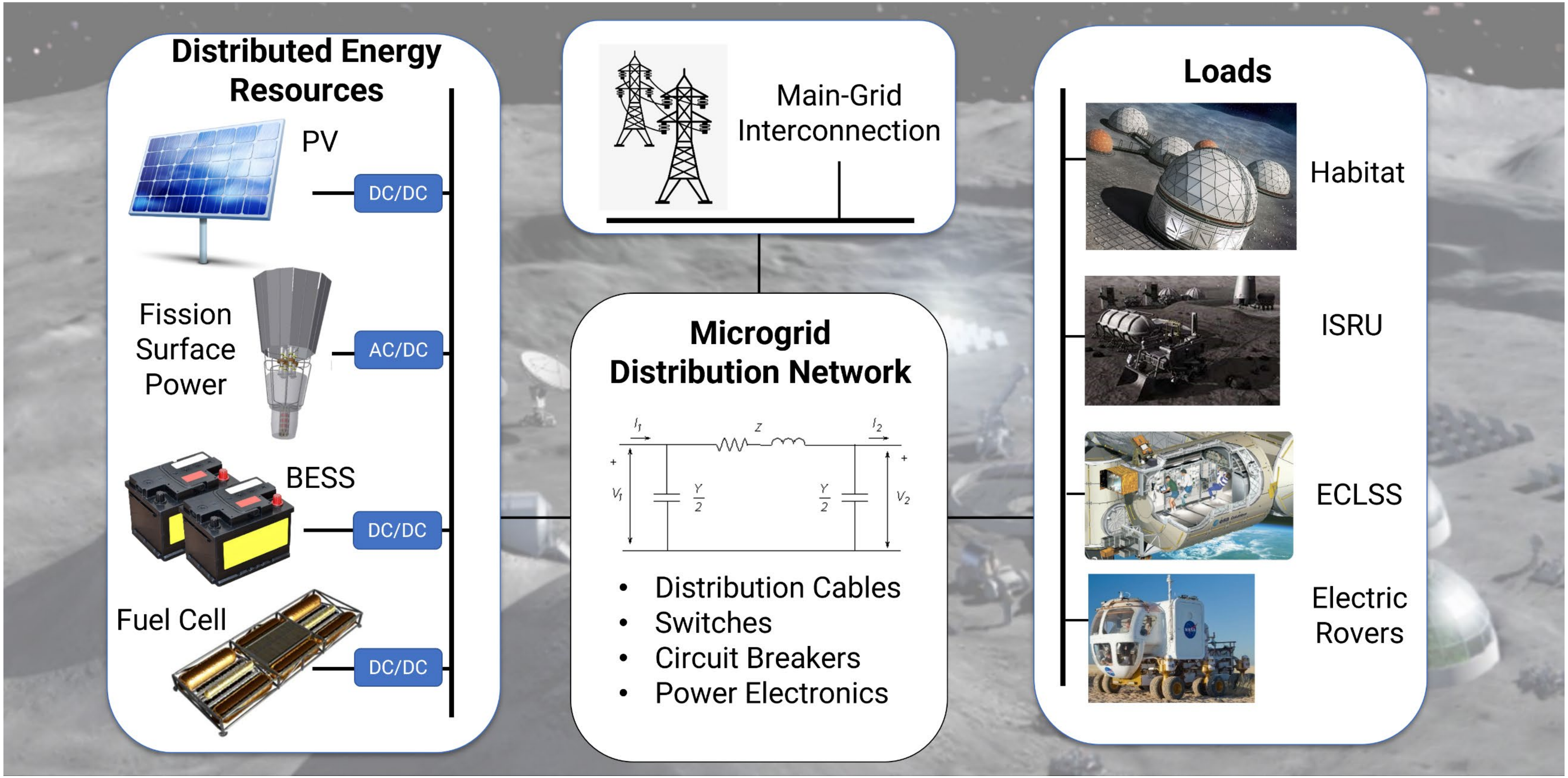
Towards the future:

The goal of the APC project is to deliver a fully autonomous power system control platform that will enable a sustained presence in deep space.

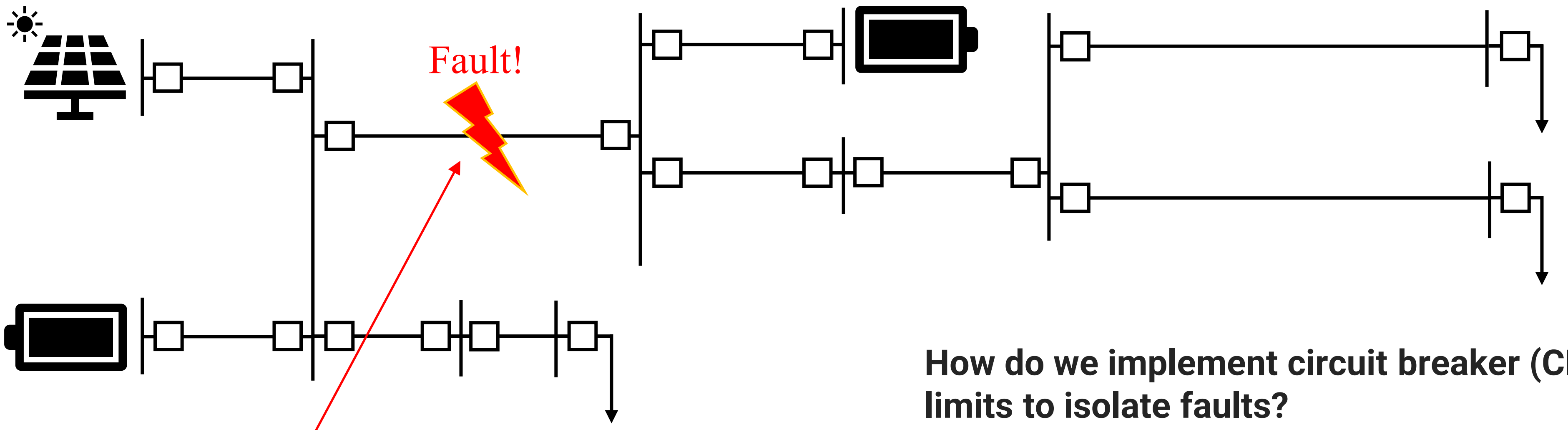
- Communication delays (~44 minutes round trip) force the need for improved autonomy and control within the electric power system.
- Autonomous controls software will enable astronauts (or robotics) to seamlessly assemble and expand a power system.
    - Plug-n-play technology
    - Integration of dissimilar and distributed sources
    - Adaptive and interoperable controls
- Development, testing, and demonstration on the lunar surface will provide the necessary proving ground to provide reliable and secure power on Mars.



Lunar Surface Power Architecture

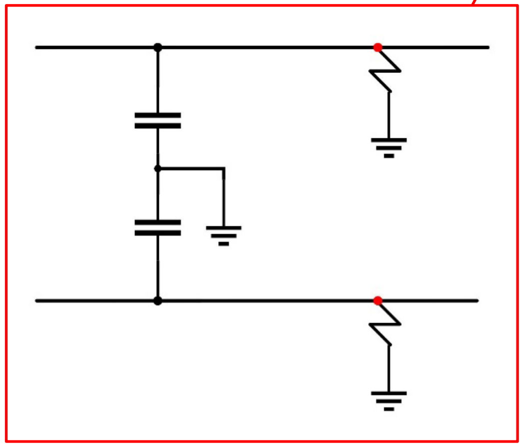


APC Adaptive Protection Objectives

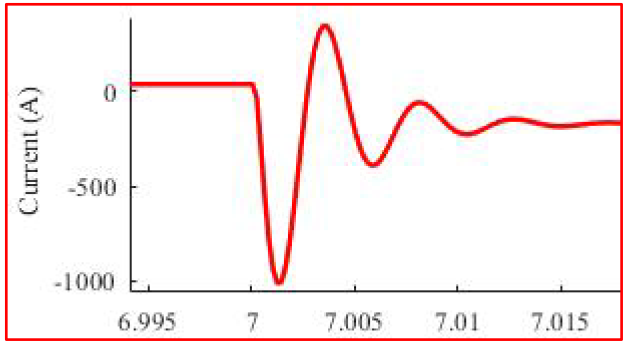


How do we implement circuit breaker (CB) trip times & current limits to isolate faults?

- Accurately model faults and protection response to test APC
- Isolate faults with bidirectional power flow
- Prevent cascading failures due to improper protection setting
- Update trip times as new components are added or load levels change

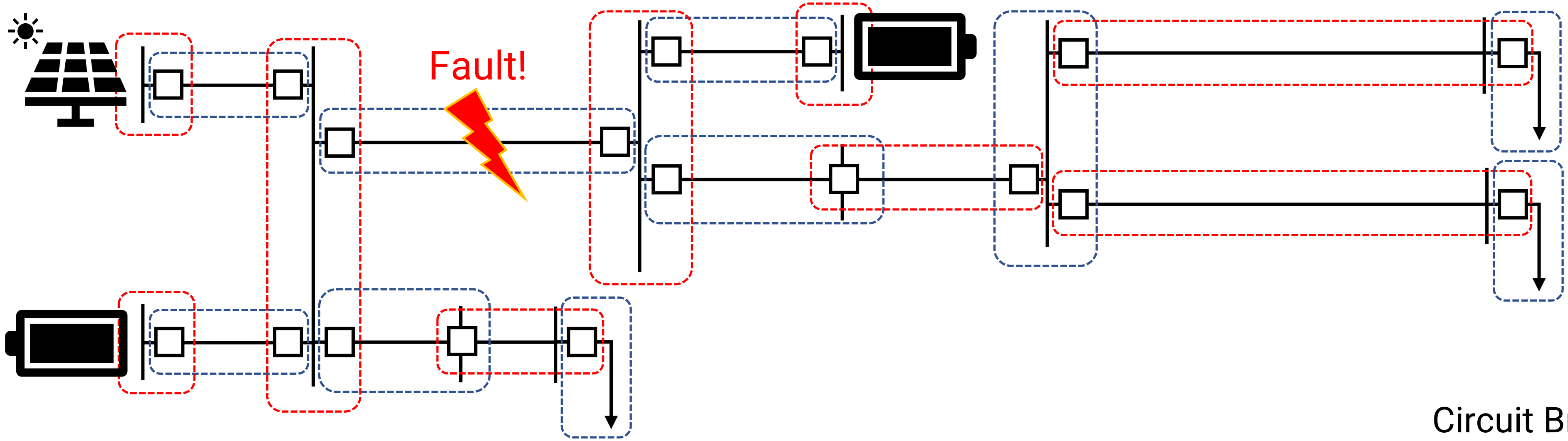


Schematic of a Line-to-Ground Fault



Simulated Fault Current

Lunar Surface Power Architecture



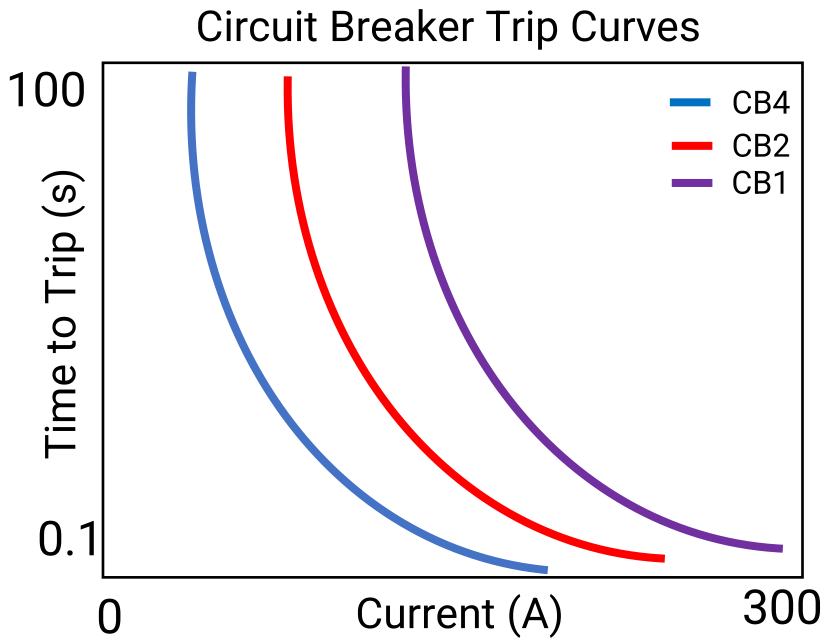
What is “zonal protection”

- The ability to isolate a fault within a specified zone from the rest of the power system
- It maximizes the functioning parts of a power system

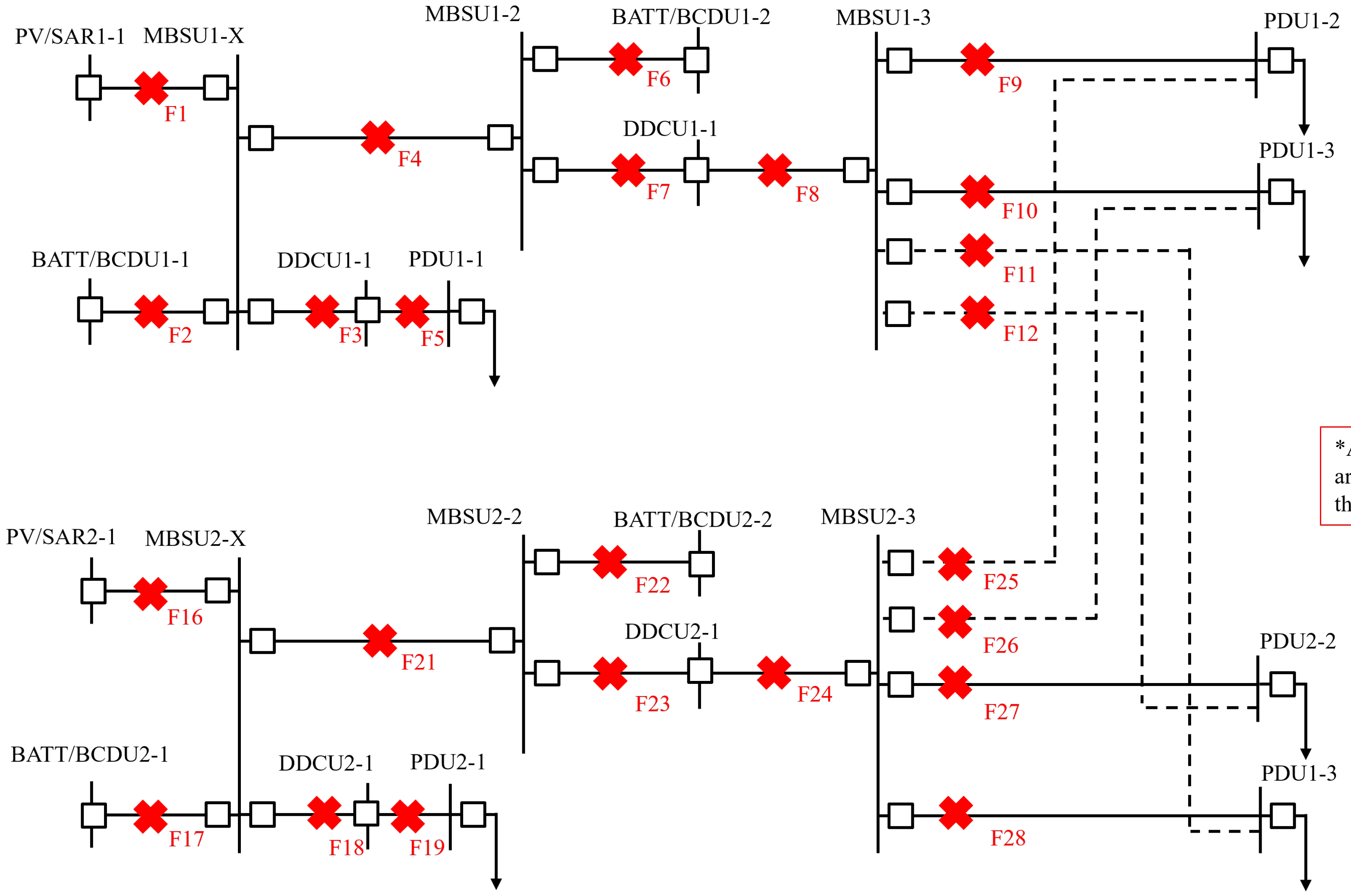
How are zones defined?

- Zones are overlapped
- Circuit breakers and isolating transformers are in the overlap regions
- For a fault anywhere in a zone, all the CBs in that zone open to isolate the fault

CB trip settings (based on current threshold and time to trip) need to be set properly



Simulated Fault Capability



*All fault impedances are configurable via the APC

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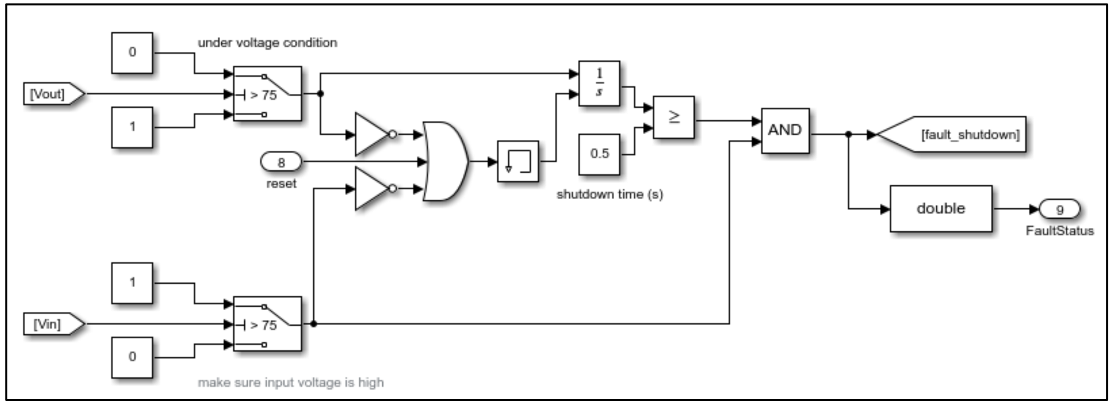
Coordinated Protection Implementation

- Device-Level Fault Detection
- Automatic Circuit Breaker Trip-Time Setting
- Automatic Current Threshold Setting

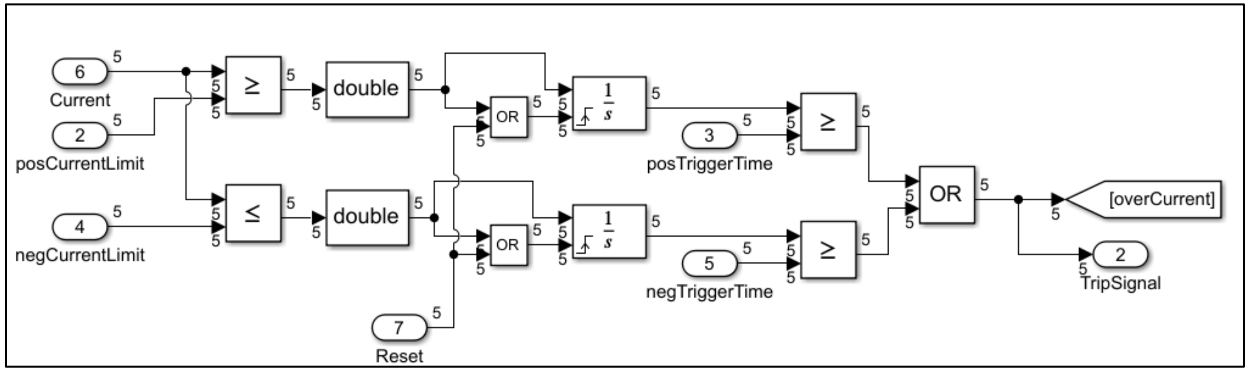
Component-Level Fault Detection

Component Types

- Power Distribution Units (PDUs) are unidirectional and therefore only have a single current limit (no trip time)
- Power electronics such as DC/DC converter units, battery charge/discharge units, solar array regulators (DDCUs, BCDUs, SARs) are current limiting and have isolating transformers. They will shut off their output after a predetermined under-voltage x time setting
- Distribution switchgear have circuit breakers (CBs) at each switch that can be programmed to update their parameters
  - Positive Current Limit
  - Negative Current Limit
  - Positive Trip Time
  - Negative Trip Time



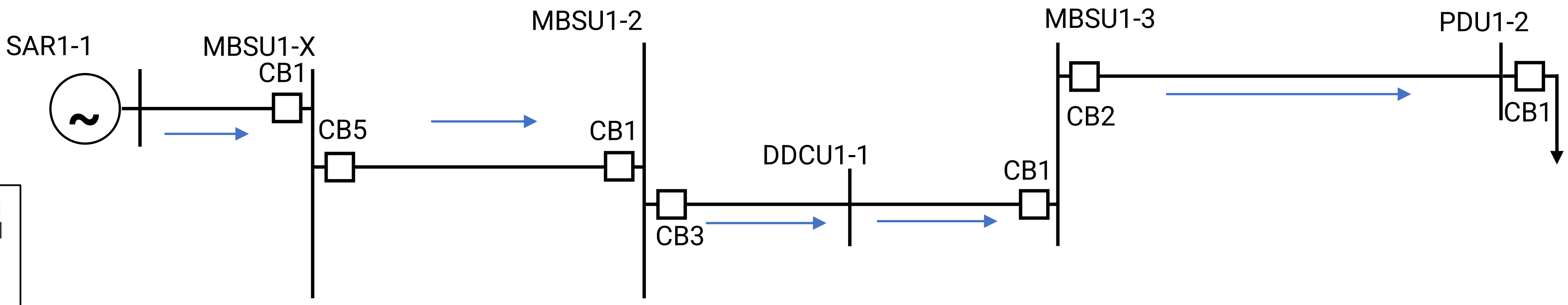
DDCU Fault Shutdown and Reset Logic



CB Fault Detection and Reset Logic

Automatic Protection Setting Algorithm

Part 1: Path finding algorithm to set trip times



Available trip times: [tmin, t1, t2, t3, t4, ... tmax]
[100, 150, 200, 250, 300, ..., 500]

t4 Slow → t1 Fast

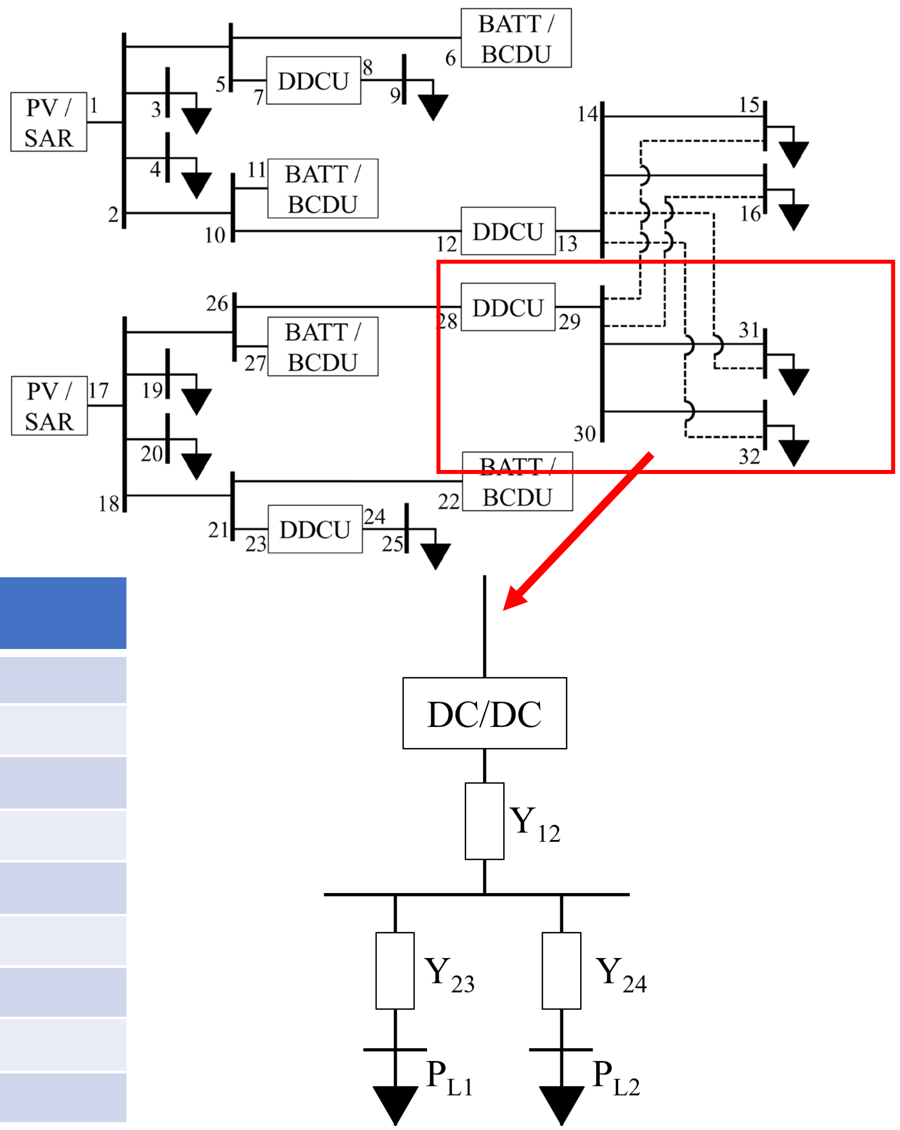
Circuit Breaker	Pos. Trip Time (ms)	Pos. Current Limit (A)	Neg. Trip Time (ms)	Neg. Current Limit (A)	Voltage Limit (V)	Trigger Time (ms)
SAR1-1	-	-	-	-	*75*	*500*
MBSU1-X CB1			250		-	-
MBSU1-X CB5	200				-	-
MBSU1-2 CB1			150		-	-
MBSU1-2 CB3	100				-	-
DDCU1-1	-	-	-	-	*75*	*500*
MBSU1-3 CB1			150		-	-
MBSU1-3 CB2	100				-	-
PDU1-1 RBI1	-	*40*	-	-	-	-

- Use graphing algorithm (from Reconfiguration function) to find the paths from all sources to each location of a possible fault.
- Order CB trip times from shortest time to longest starting at the furthest CB from the source
- Loop through all paths and select the greatest current value if multiple trip times are set.

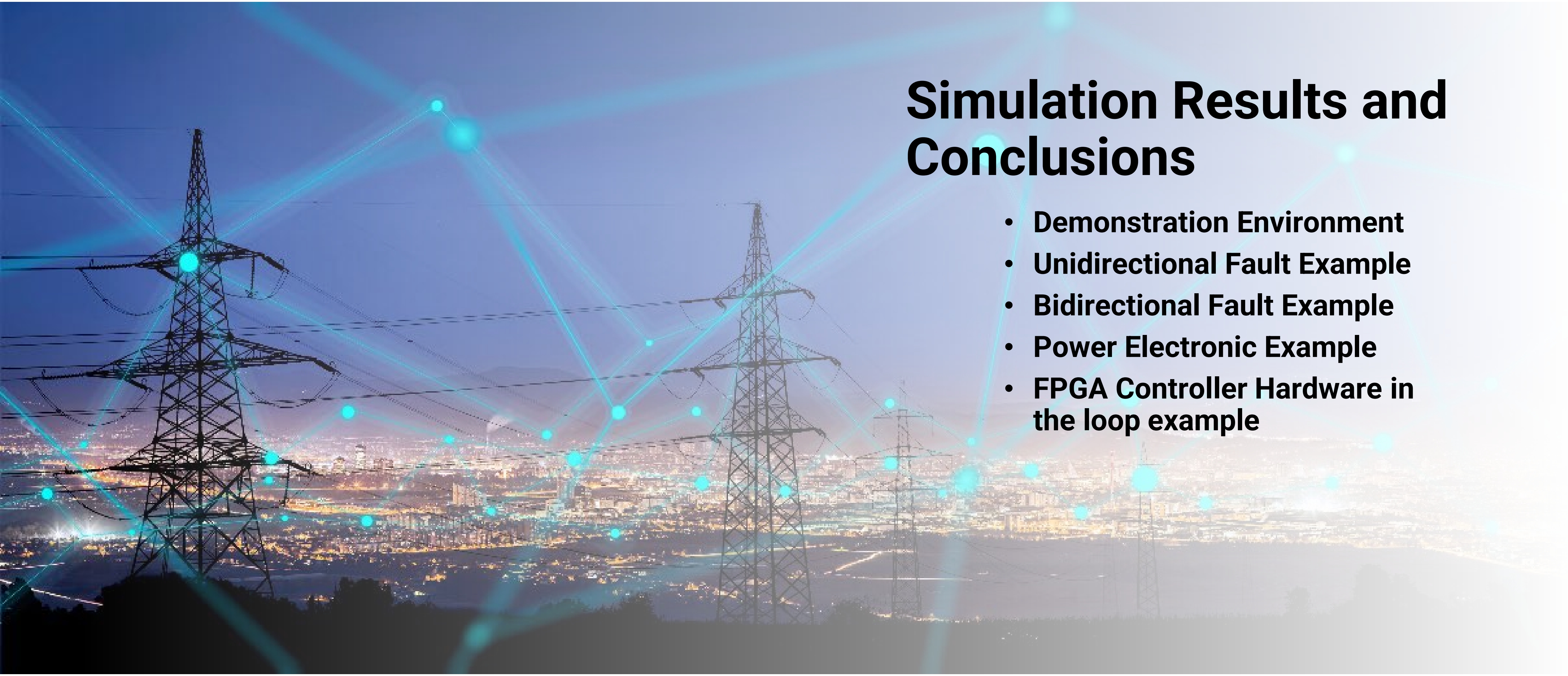
Automatic Protection Setting Algorithm

Part 2: Power flow used to determine maximum normal conditions to set current limits

- Want CBs stay closed during normal operations (with noise and disturbances) but trip in the event of a fault
- Use Newton-Raphson load flow to determine the maximal nominal power that can be supported in the system.
- Apply the max currents to the CBs in the power system with tunable scale factor



Circuit Breaker	Pos. Trip Time (ms)	Pos. Current Limit (A)	Neg. Trip Time (ms)	Neg. Current Limit (A)	Voltage Limit (V)	Trigger Time (ms)
SAR1-1	-	-	-	-	*75*	*500*
MBSU1-X CB1			250	109.5	-	-
MBSU1-X CB5	200	109.5			-	-
MBSU1-2 CB1			150	109.5	-	-
MBSU1-2 CB3	100	109.5			-	-
DDCU1-1	-	-	-	-	*75*	*500*
MBSU1-3 CB1			150	109.5	-	-
MBSU1-3 CB2	100	109.5			-	-
PDU1-1 RBI1	-	*40*	-	-	-	-

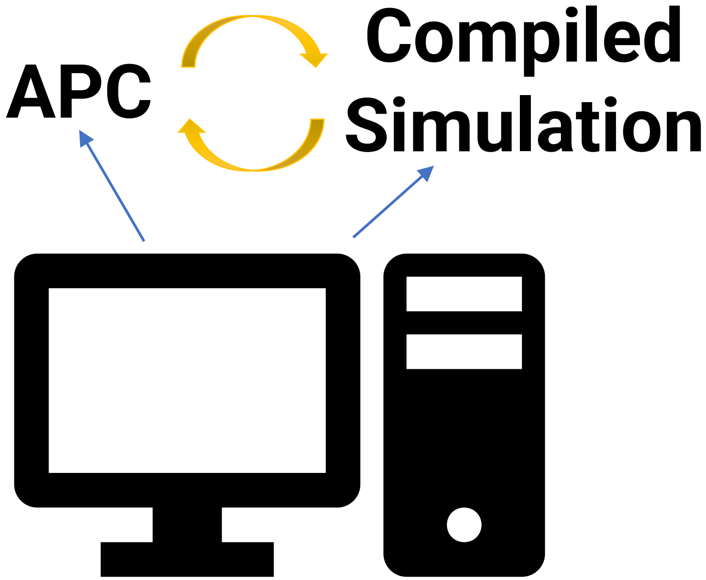


Simulation Results and Conclusions

- Demonstration Environment
- Unidirectional Fault Example
- Bidirectional Fault Example
- Power Electronic Example
- FPGA Controller Hardware in the loop example

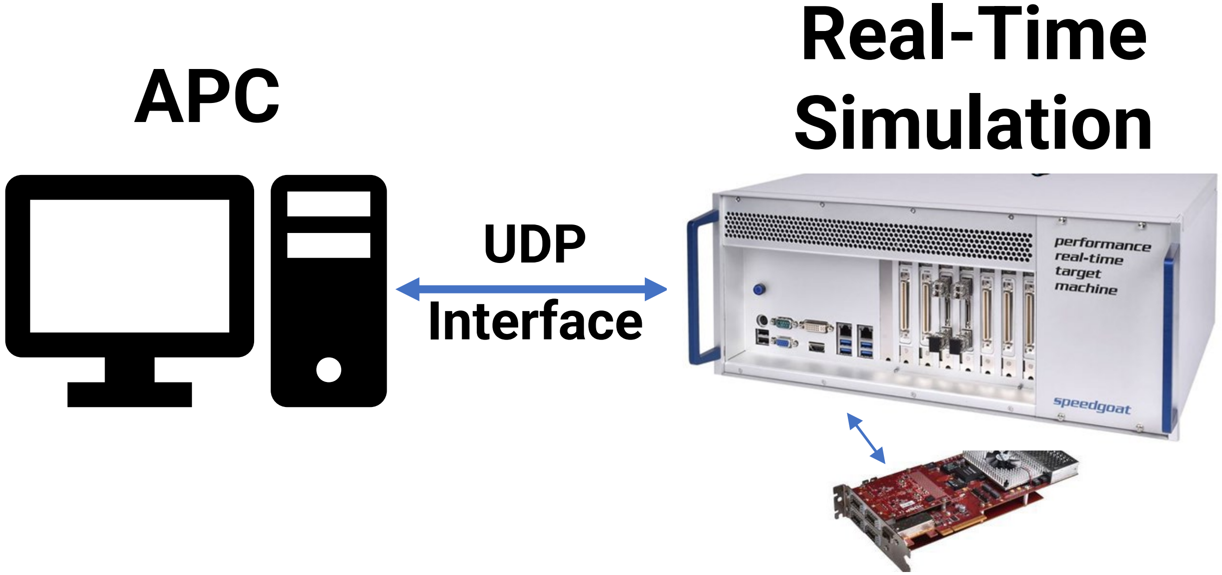
Demonstration Environment

Previous Set-up



- APC runs as compiled C++ code on Linux machine
- Simulation running as compiled C executable
- Does NOT run in real-time
- No HIL interfaces

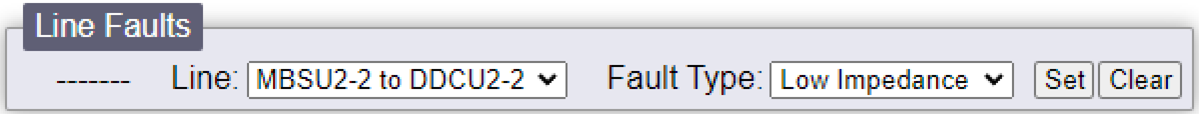
Current Set-up



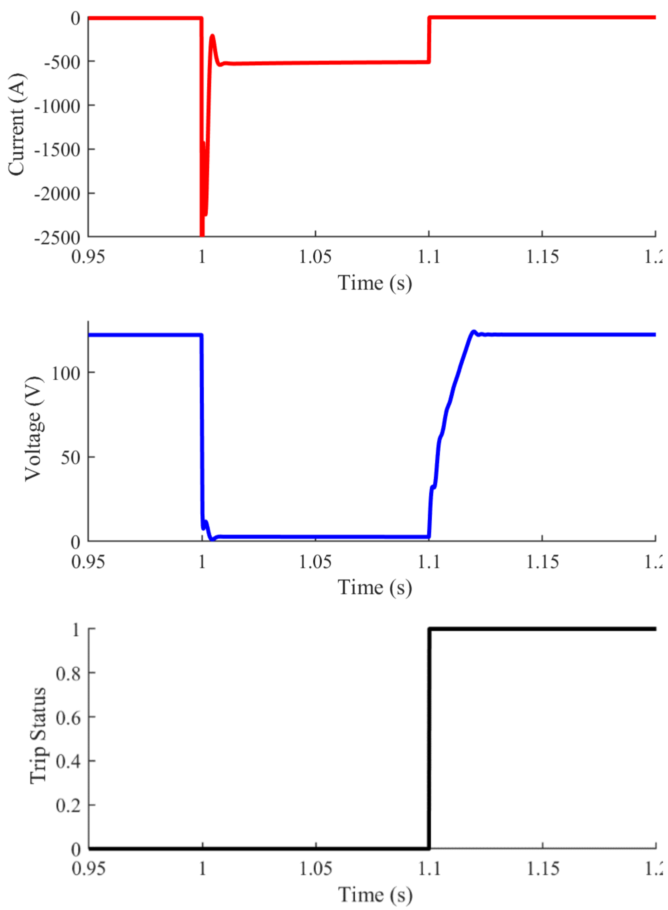
- APC runs as compiled C++ code on Linux machine
- Simulation running in real-time on Speedgoat
- Connected through ethernet UDP interface
- Has HIL interfaces (FPGA, Analog I/O, switchgear, etc.)

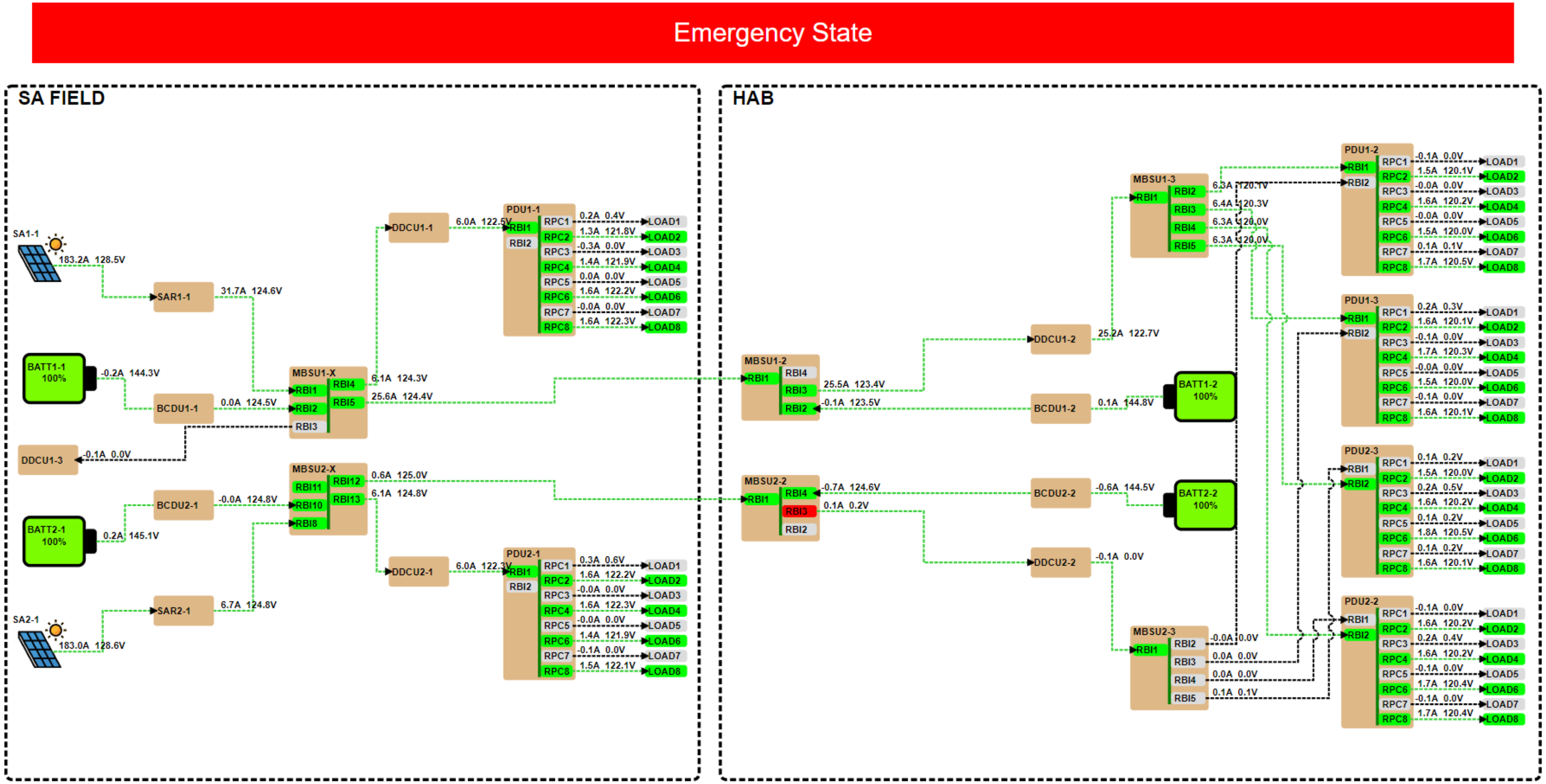
Fault 1: Unidirectional Protection

Fault: Low impedance fault between MBSU2-2 and DDCU2-2
Response: MBSU2-2 RBI3 circuit breaker trip upstream of fault



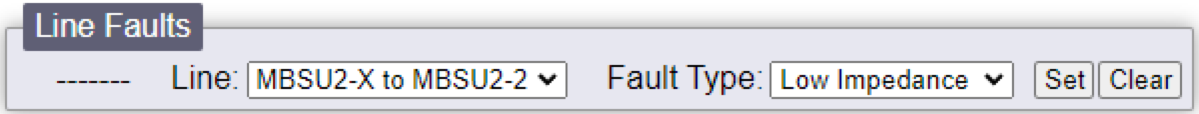
MBSU1-2 RBI3 Data



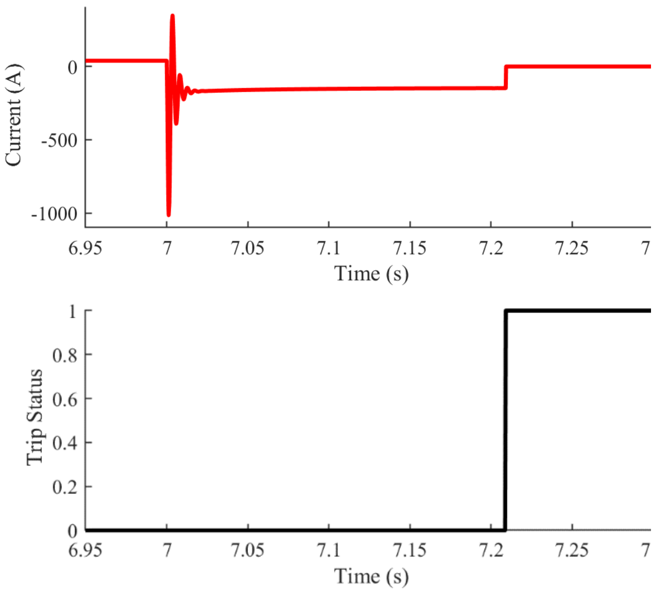


Fault 2: Bidirectional Protection

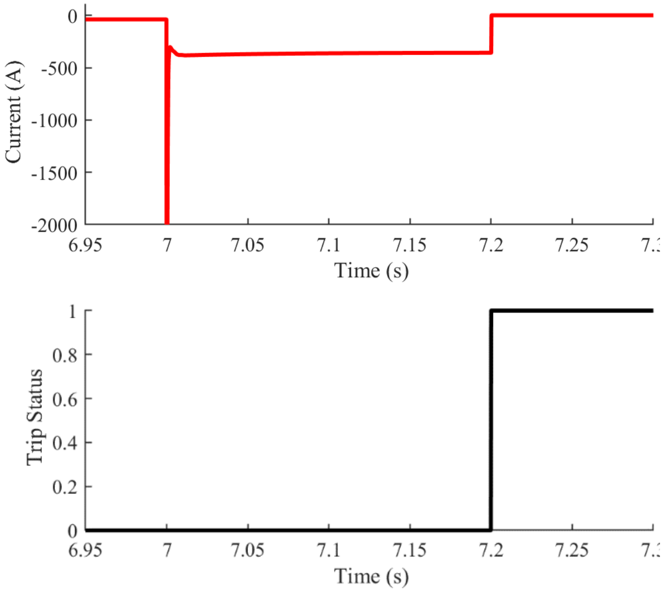
Fault: Low impedance fault between MBSU2-X and MBSU2-2
Response: MBSU2-X RBI12 and MBSU2-2 RBI1 circuit breaker trip

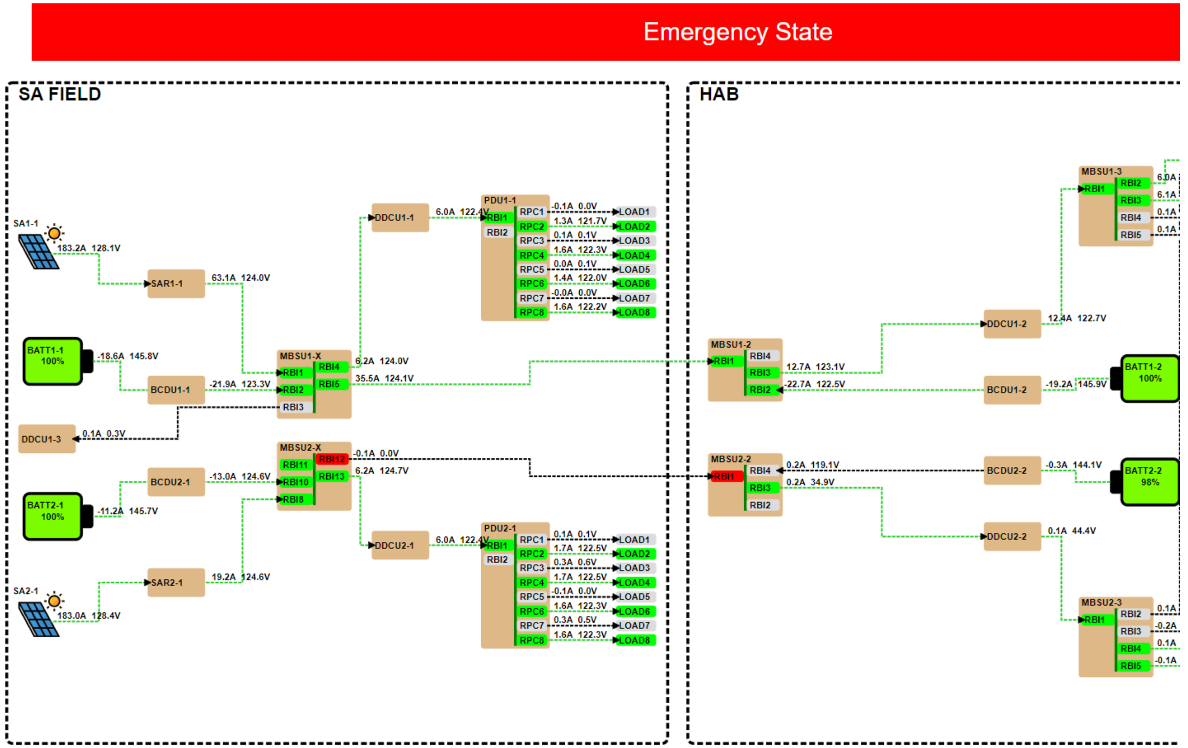


MBSU1-X RBI5 Data



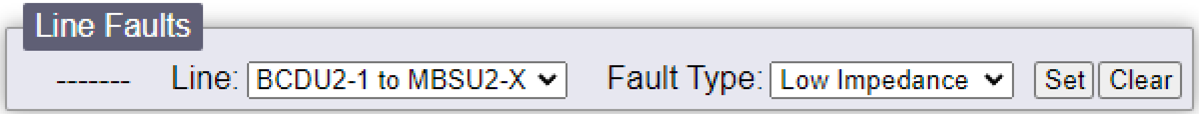
MBSU1-2 RBI1 Data



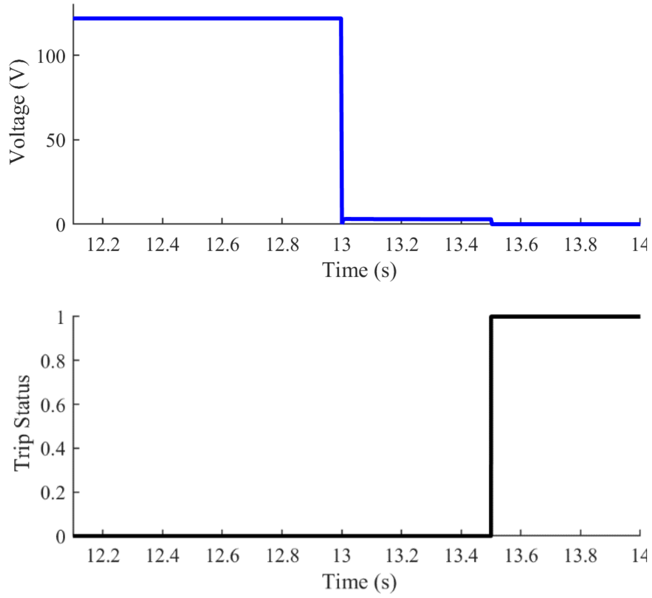


Fault 3: Power Electronics Protection

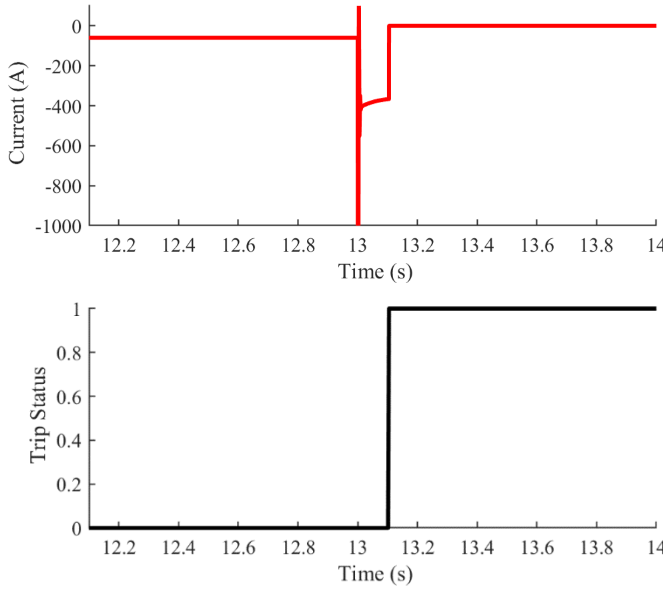
Fault: Low impedance fault between BCDU2-1 and MBSU2-X
Response: MBSU2-X RBI10 circuit breaker trip, BCDU2-1 disable output

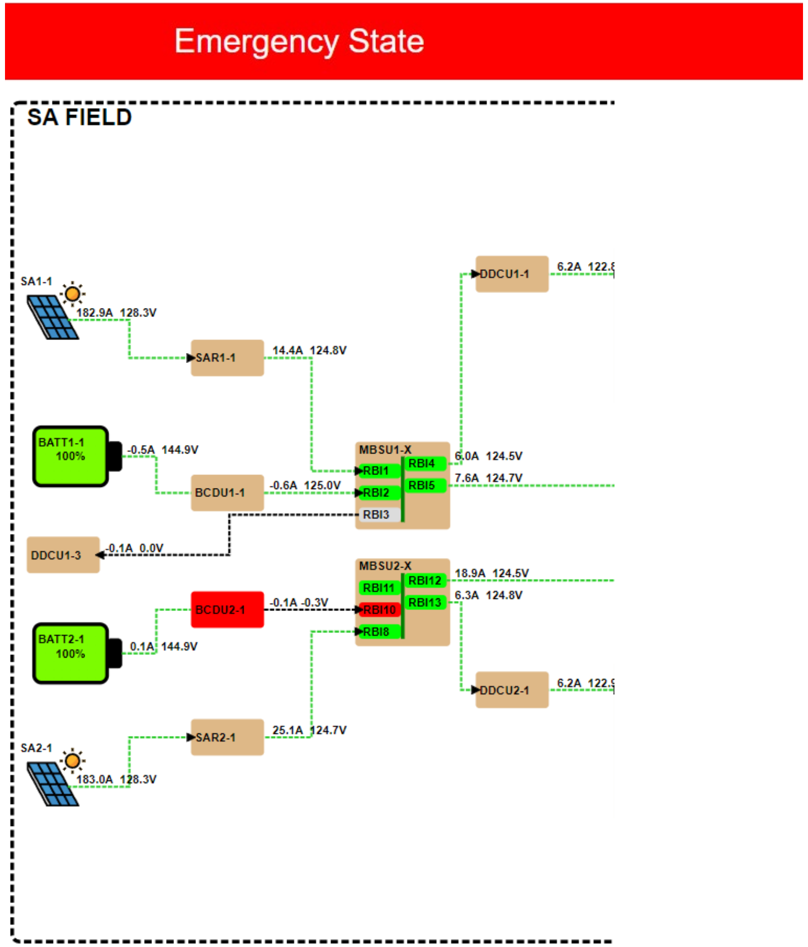


BCDU1-1 Data



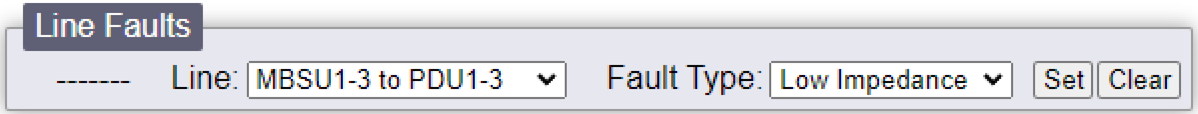
MBSU1-X RBI2 Data

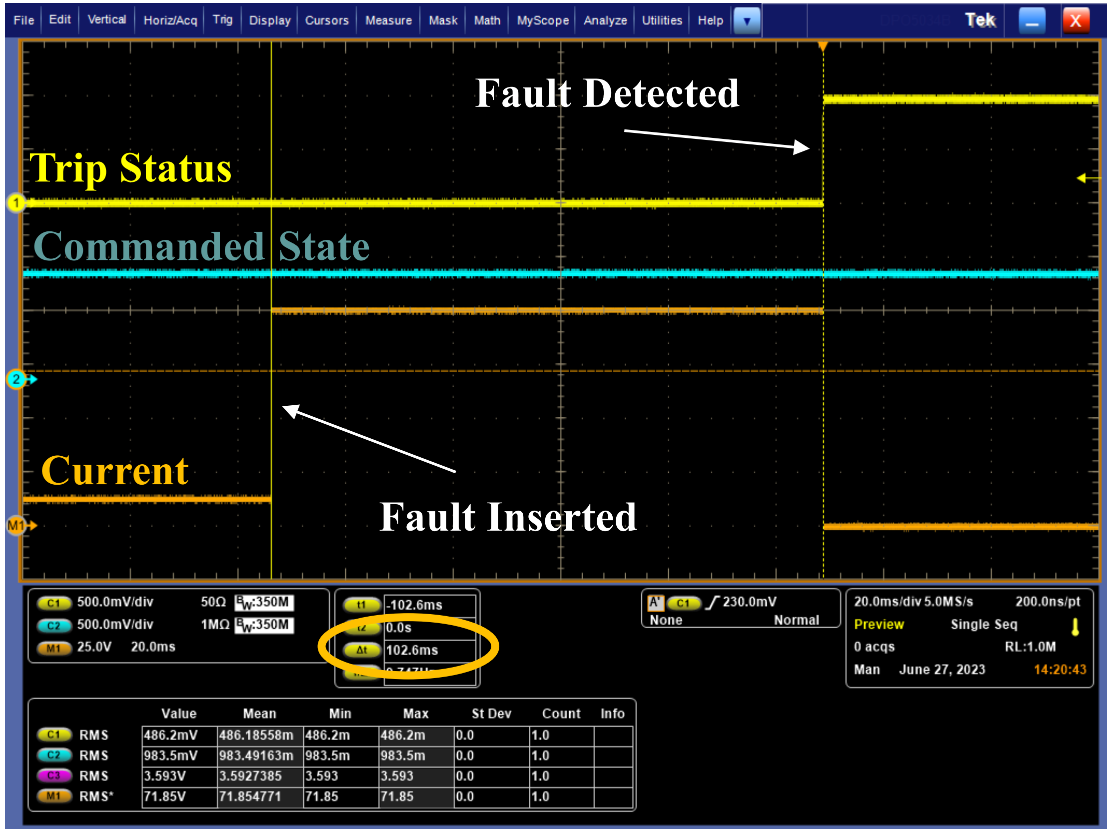




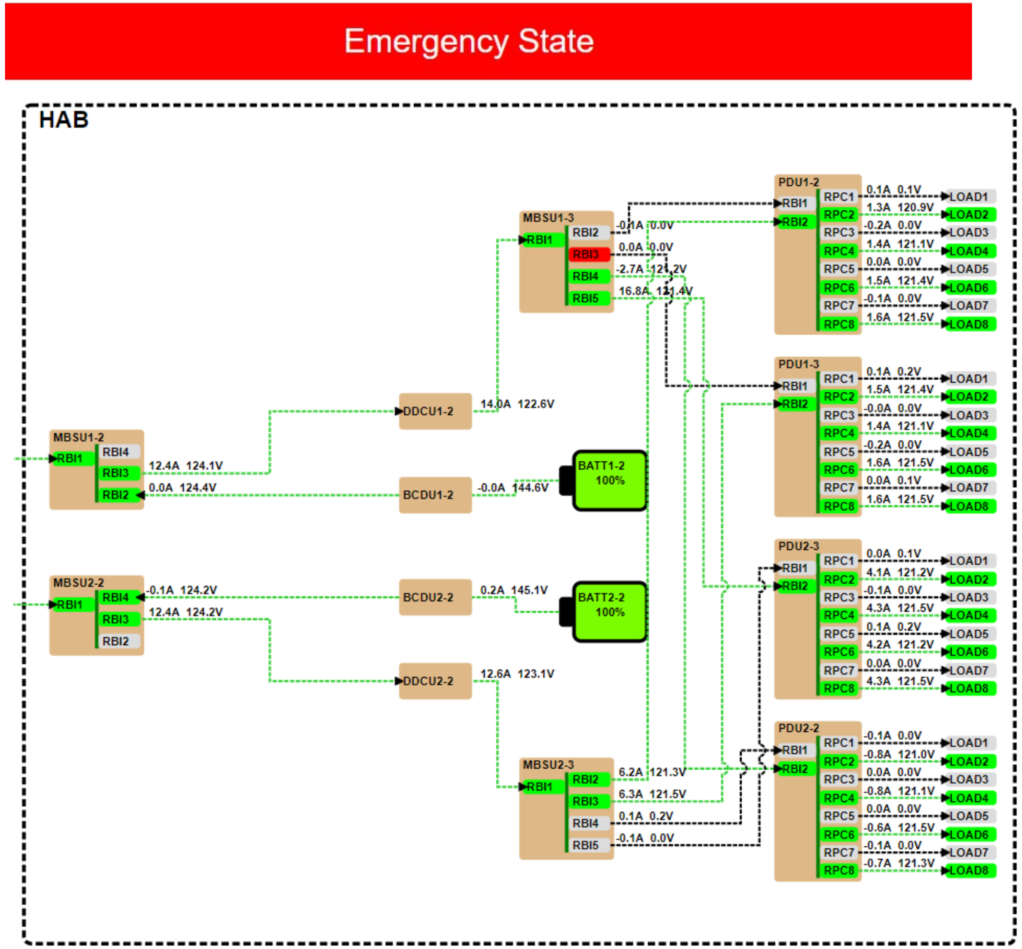
Fault 4: FPGA C.H.I.L

Fault: Low impedance fault between MBSU1-3 and PDU1-3
Response: FPGA module detects overcurrent, trips CB MBSU1-3 RBI3



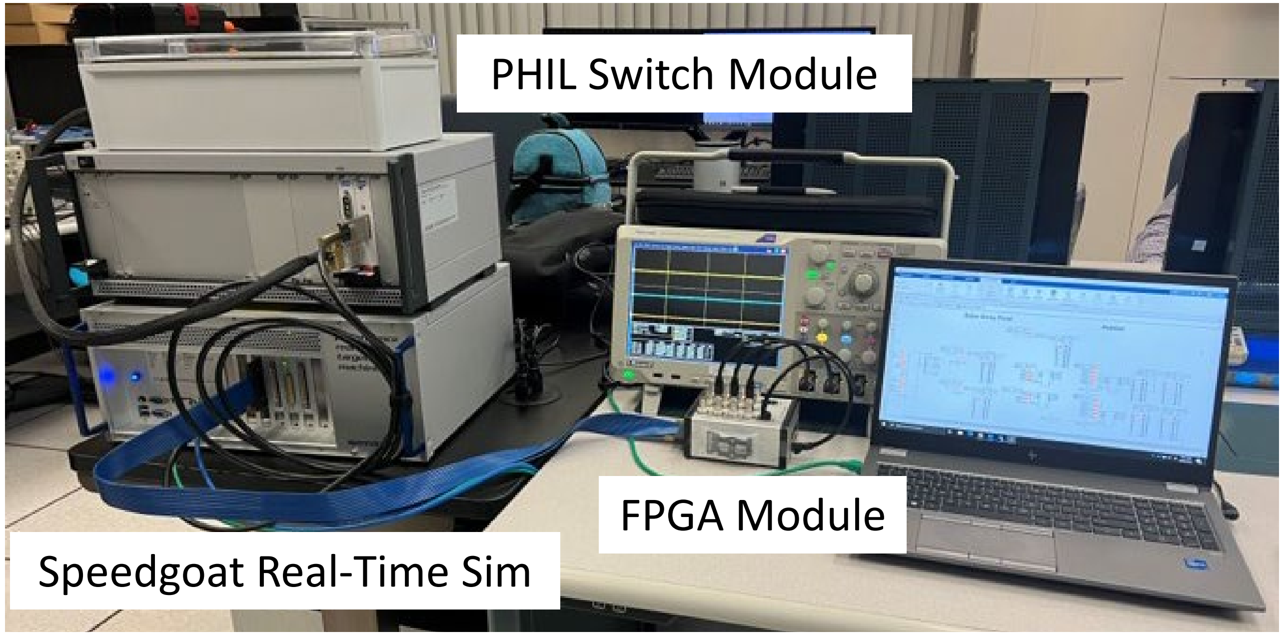


Oscilloscope Data from FPGA module



Conclusions and Future Work

- Demonstrate the automatic protection algorithm for changing configurations using device discovery (September 2023)
- Update the Tactical Microgrid Standard (TMS) to support device control parameters (e.g., trip time & current limit)
- Develop a method to update circuit breaker Trip Curve on an FPGA on the fly
- Continue HIL testing with Speedgoat switch modules



Thank you!

Questions?

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