Sandia National Laboratories

Exceptional service in the national interest

Testing and Characterization of Fault Scenarios of a Hierarchical DC Microgrid for Residential Applications

Miguel Jimenez-Aparicio, Andrew R. R. Dow, Matthew J. Reno

Sandia National Laboratories, Albuquerque, NM, USA

Daniel Bauer, Daniel Ruiz, Brian Ward

BlockEnergy (Emera Technologies), Burlington, ON, CA

CIGRE US National Committee

2023 Grid of the Future Symposium

October 10, 2023

Overview

- Motivation behind Testing and Setup
- Overview of BlockEnergy KAFB Microgrid Architecture
- Experimental Fault Test Setup
- Experimental Fault Test Results
- Future Work and Platform Development

Motivation

- Significant cost and public safety risk around faults in microgrid and distribution systems
  - Wildfire ignitions becoming more common due to high-impedance electrical faults
- DER-based systems contain less fault current, faults become 'less obvious'
  - Requires more understanding of faults on DER-based systems
- Owner-maintained residential microgrids will become more common and require better understanding around fault occurrences
  - Better protection = easier protection
- What can we do as researchers to improve this?
  - Can we **demonstrate/study** faults on a residential system?
  - Can we **develop new** fault detection methods?
- Research funded through U.S. Department on Energy Solar Energy Technologies Office
  - Adaptive Protection and Control for High Penetration PV and Grid Resilience
    - Three year program to explore fault protection and detection methods on DER-based power systems
  - Award # DE-EE0036533

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy
Sandia National Laboratories
THE UNIVERSITY OF NEW MEXICO
Emera Technologies
CLEMSON UNIVERSITY
SIEMENS

Better fault protection starts with a test platform to demonstrate controlled fault capability!

Overview of BlockEnergy KAFB Microgrid

- Kirtland Air Force Base (KAFB) DC microgrid
  - Operating since 2019 as cooperative research agreement between Sandia National Labs and Emera Technologies
  - Evaluates viability of deploying and operating DC microgrids
  - Allows for development test bed in “blue sky” and “black sky” scenarios
  - Single-bus, ten-node 250 kW DC microgrid architecture
    - Serves six residential housing units
    - Utility services to laundry and campground facilities
    - Connects to Sandia’s Distributed Energy Technology Laboratory (DETL) and Photovoltaic Systems Evaluation Laboratory (PSEL)

- **Development test bed for R&D and commercialization efforts at residential-scale!**

BlockEnergy Nanogrid Serving Residential Housing Loads

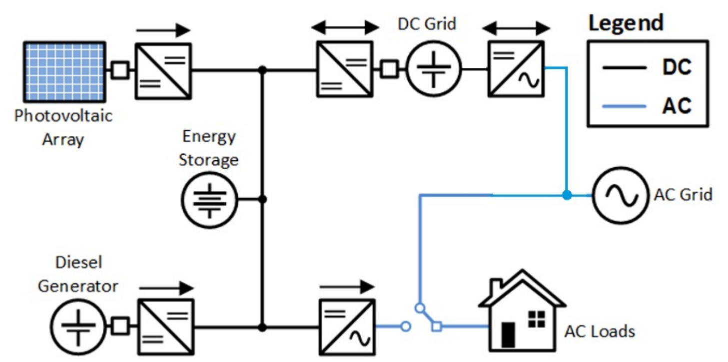
Ten-node BlockEnergy Microgrid on Kirtland Air Force Base

BlockEnergy KAFB Microgrid Architecture

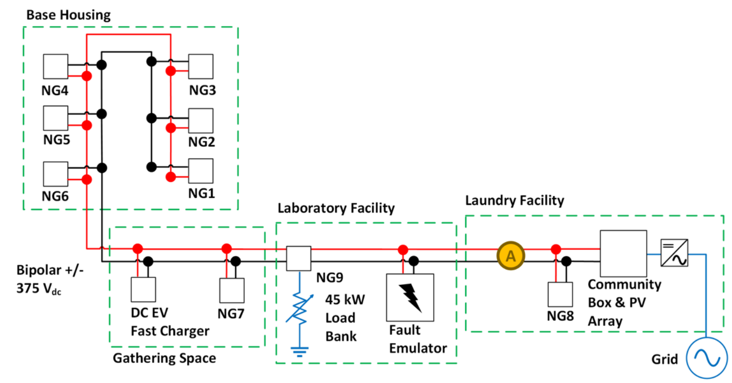
- ‘Grid-of-grid’ architecture
  - Each node supported by nanogrid system:
    - BESS, DG, PV array, and grid-forming inverter to AC loads
    - Back-up transfer switch to utility grid
    - Bidirectional DC/DC interface converter for nanogrid power share
      - Up to 10 kW import/export from each nanogrid to microgrid
    - Continues to support its load in the event of islanding

- Connected through a ±375 V_{DC} bus to form microgrid
  - Configurable radial or loop feeds for power redundancy
  - High-Z grounding scheme balanced around line voltages

- Central energy park (CEP) sets microgrid bus voltage, coordinates power sharing between NGs and utility grid
  - Main controller to networked nanogrid boxes
  - Protection device for detecting faults on DC bus
  - DC/AC inverter to utility grid for grid support
    - Up to 100 kW import/export to/from utility
    - Islanding from utility grid during outages or via control



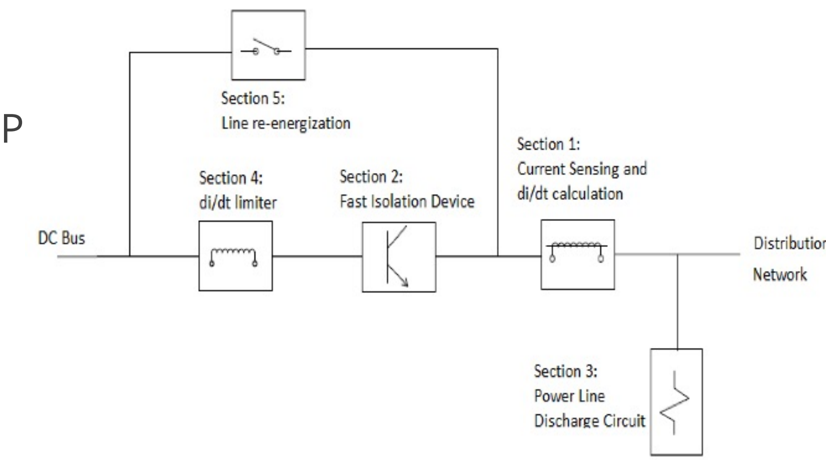
BlockEnergy Nanogrid One-Line for Residential Service Application



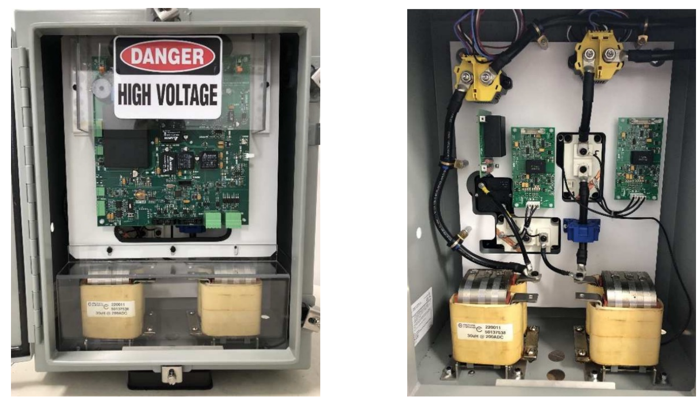
BlockEnergy Microgrid One-Line in a Radial Feed Configuration

Microgrid Fault Protection Scheme

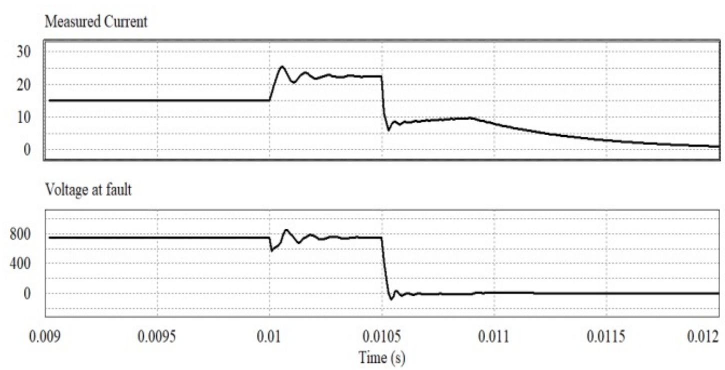
- Custom protection device enabled on microgrid bus at CEP
  1. Senses high di/dt change onto DC bus
  2. Series power device isolates CEP output from DC bus
  3. Remove any stored energy on the bus through discharge resistance
  4. Series inductive element limits di/dt
  5. Line re-energizer gracefully re-introduces bus voltage once fault has been cleared
- Fault detect and disable within <u>2 milliseconds</u>
- Device serves as EUT as well as safety net for normal use



Fault Protection Device Block Diagram



Fault Protection Device Hardware Assembly

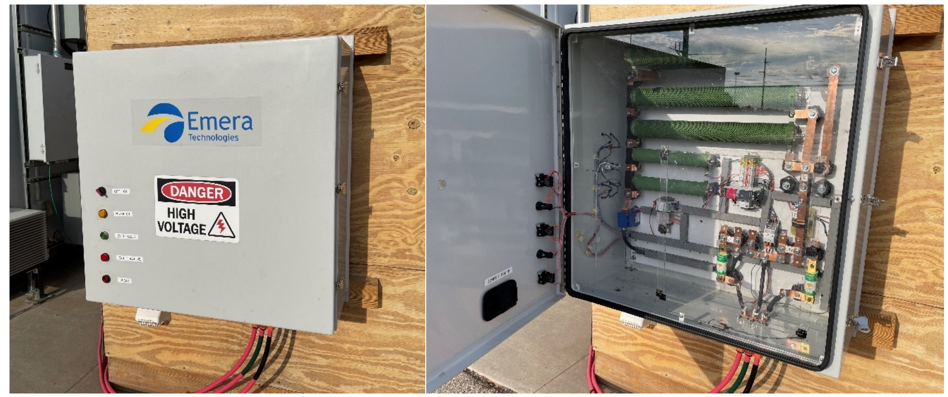


Time response of detection and disable for simulated fault event

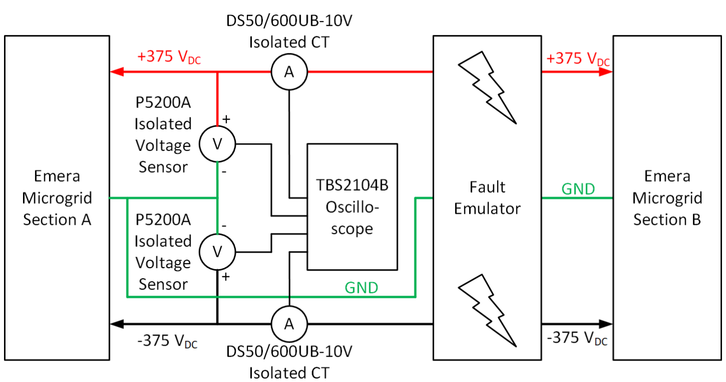
L. Zubieta, Y. Zhang and D. Bauer, "Protection Scheme for a Residential DC Microgrid," *2021 IEEE Fourth International Conference on DC Microgrids (ICDCM)*, Arlington, VA, USA, 2021

Experimental Fault Test Setup

- Fault emulator hardware introduces fault impedance onto microgrid bus
  - Manually actuated via contactors
- Connected in multiple locations on microgrid bus
- Microgrid bus monitored for fault effects
  - Current, voltage sensors to study transients during fault
  - GPS synchronization used to time-align data across location (1 PPS, +/-30 nanoseconds)



Fault Impedance Emulator Attached to Microgrid Bus



Fault Measurement Setup on Microgrid

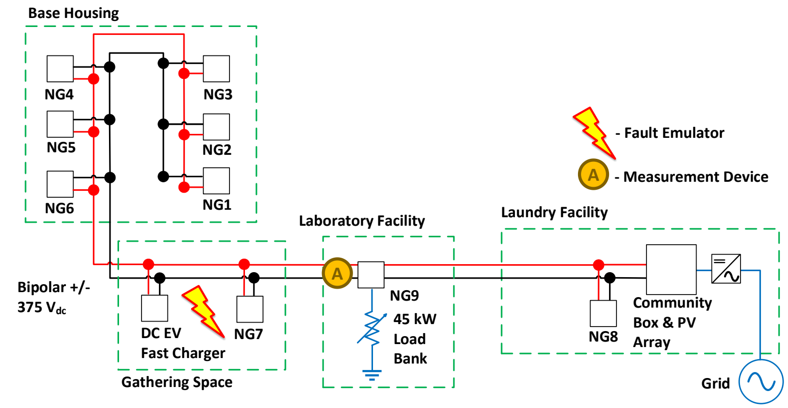
Experimental Fault Test Configurable Parameters

Fault Impedance	1 Ω, 4.7 Ω, 500 Ω, 1000 Ω
Fault Location	DETL, CEP, KAFB housing
Fault Connection	+375V to GND, -375V to GND, +375V to -375V
Bus Topology	Radial Feed or Loop Configuration
AC Grid Interface	Islanded or Grid Connected

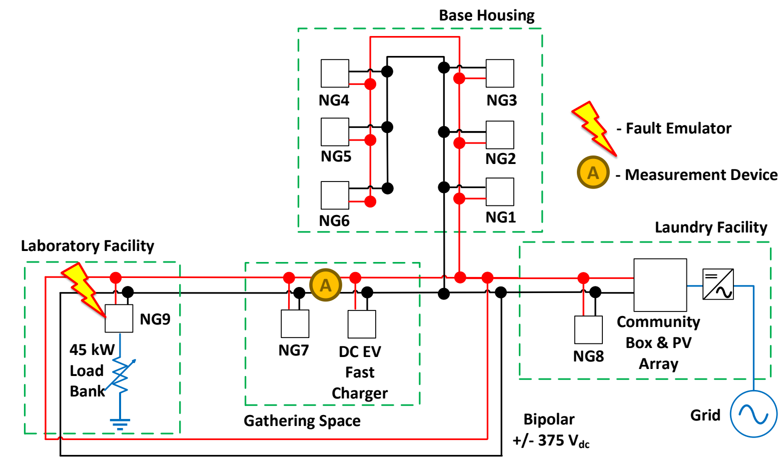
Experimental Fault Test Setup

- Three fault scenarios explored further:

1. 4.7 Ω, +375 V_{DC} to -375V_{DC} fault at KAFB housing in radial feed
    - Low-impedance **line fault**
2. 1 Ω, +375 V_{DC} to GND fault at DETL facility in loop feed
    - Low-impedance **ground fault**
3. 500 Ω, -375 V_{DC} to GND fault at DETL facility in loop feed
    - High-impedance **ground fault**



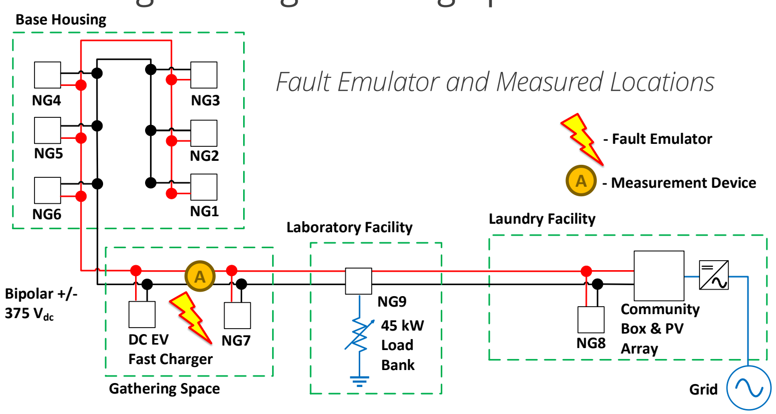
BlockEnergy Microgrid One-Line in a Radial Feed Configuration



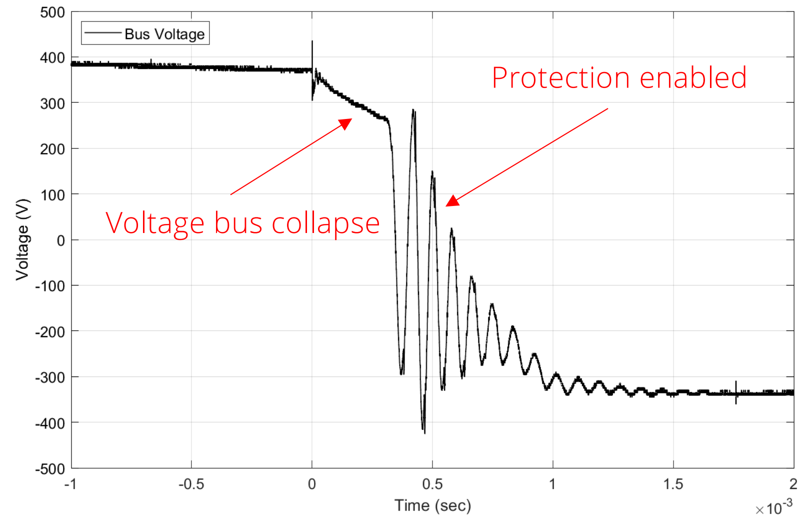
BlockEnergy Microgrid One-Line in a Loop Configuration

Experimental Fault Test #1

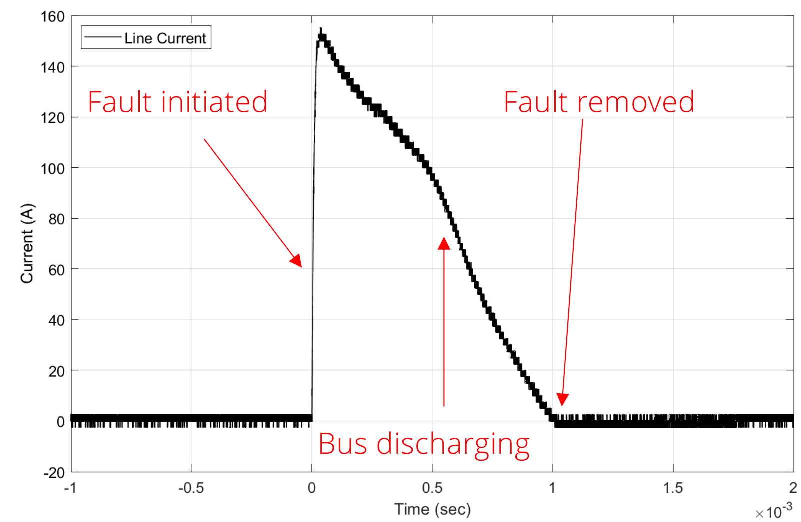
- 4.7 Ω, +375 V_{DC} to -375V_{DC} bus fault
- Radial feed w/ fault location at KAFB Gathering Space
- Monitoring across three locations:
  1. **KAFB Gathering Space**
  2. DETL Test Facility
  3. CEP / Community Box
- Peak transients on current into fault high (150 A_{pk})
  - Very high di/dt detected by protection device
- Fault current removed within 1 millisecond
  - Bus being discharged through protection device



Fault Emulator and Measured Locations



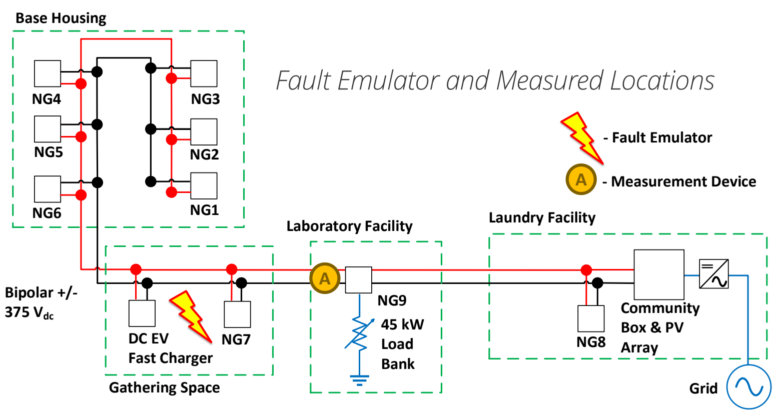
Voltage-Time Domain Response During Fault Event



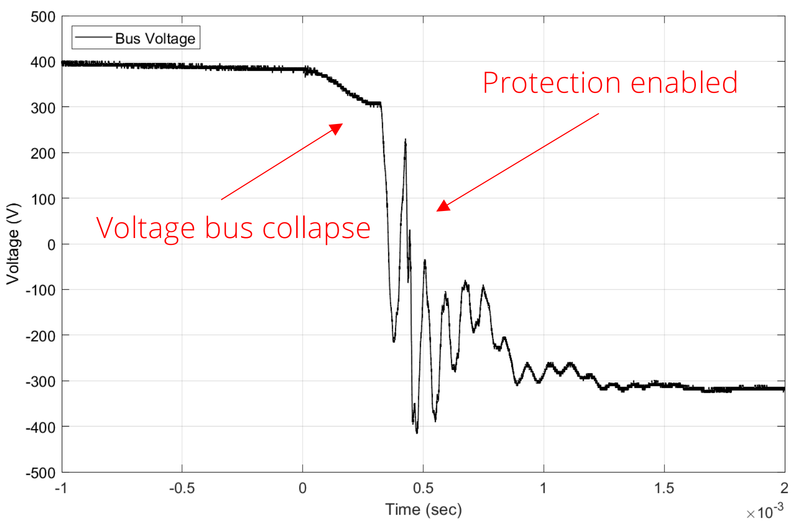
Current-Time Domain Response During Fault Event

Experimental Fault Test #1

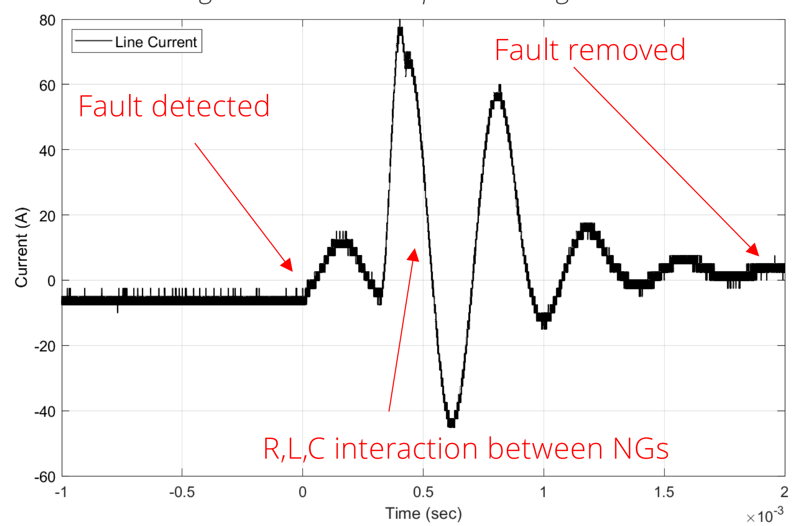
- 4.7 Ω, +375 V_{DC} to -375V_{DC} bus fault
- Radial feed w/ fault location at KAFB Gathering Space
- Monitoring across three locations:
  1. KAFB Gathering Space
  2. **DETL Test Facility**
  3. CEP / Community Box
- High current and voltage ringing due to mid-bus interaction between fault and nanogrids



Fault Emulator and Measured Locations



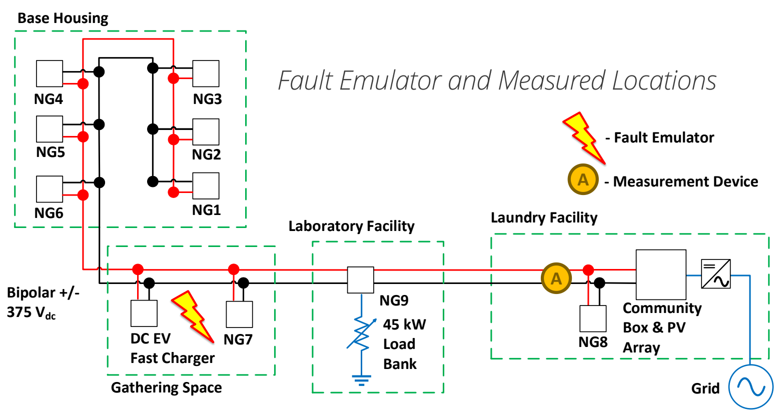
Voltage-Time Domain Response During Fault Event



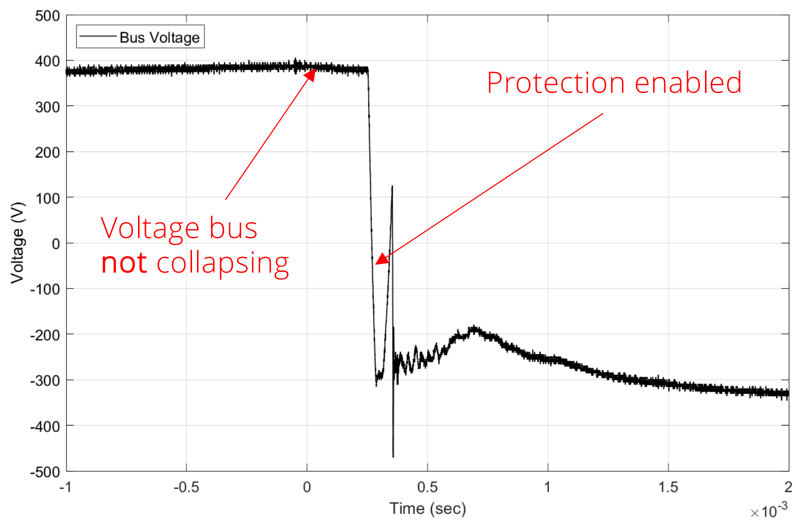
Current-Time Domain Response During Fault Event

Experimental Fault Test #1

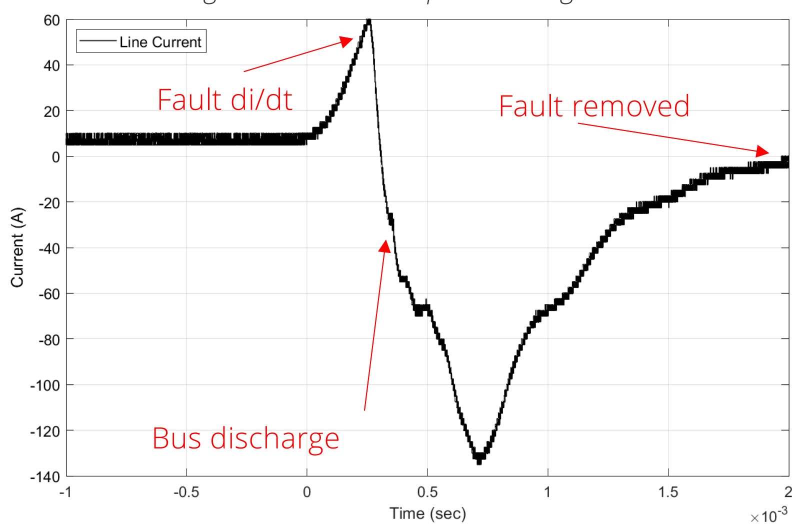
- 4.7 Ω, +375 V_{DC} to -375V_{DC} bus fault
- Radial feed w/ fault location at KAFB Gathering Space
- Monitoring across three locations:
  1. KAFB Gathering Space
  2. DETL Test Facility
  3. **CEP / Community Box**
- Further from fault and closer to the protection device shows completely different result!
- Fault current sunk into protection device



Fault Emulator and Measured Locations



Voltage-Time Domain Response During Fault Event

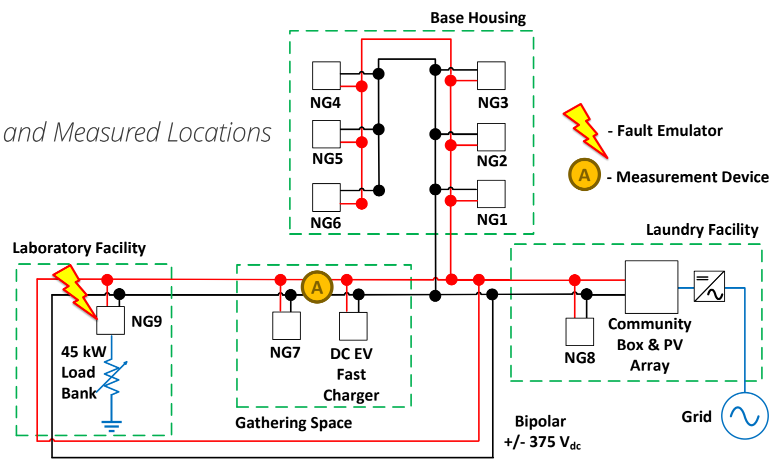


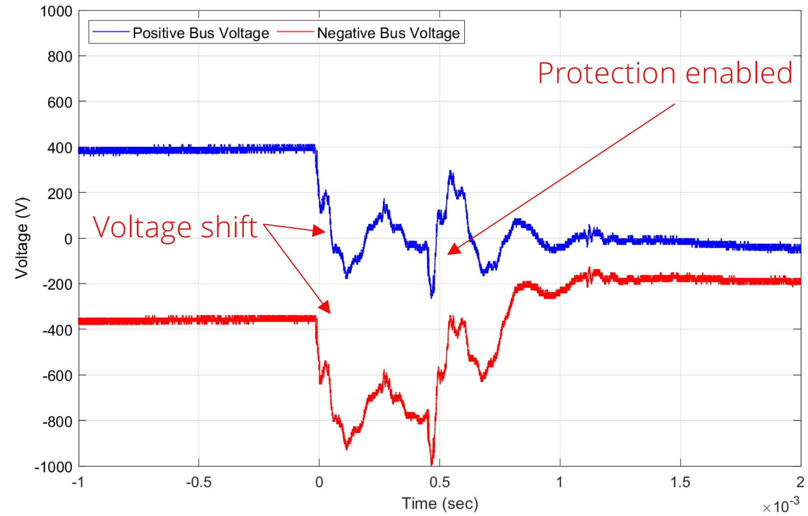
Current-Time Domain Response During Fault Event

Experimental Fault Test #2

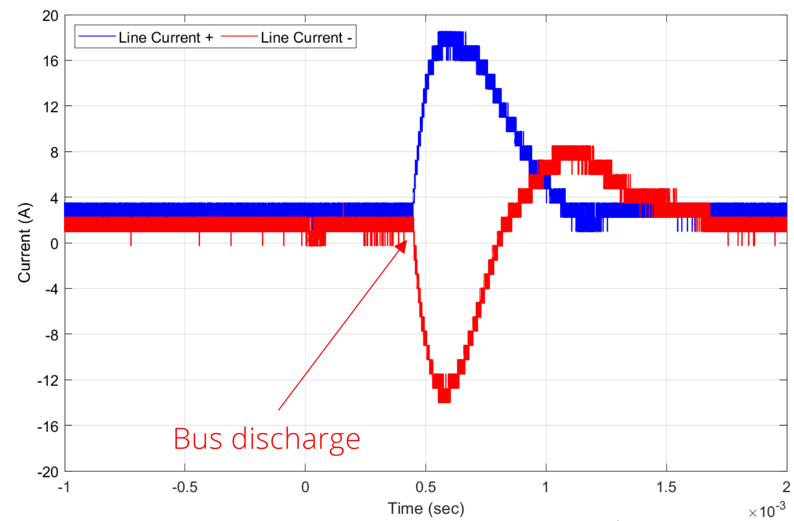
- 1 Ω, +375 V_{DC} to GND fault
- Loop feed w/ fault location at DETL test facility
- Monitoring across two locations:
  1. **KAFB Gathering Space**
  2. CEP / Community Box
- Ground faults 'shift' rather than collapse bus
  - High-Z grounding scheme
- Protection device triggered causing bus to discharge

Fault Emulator and Measured Locations





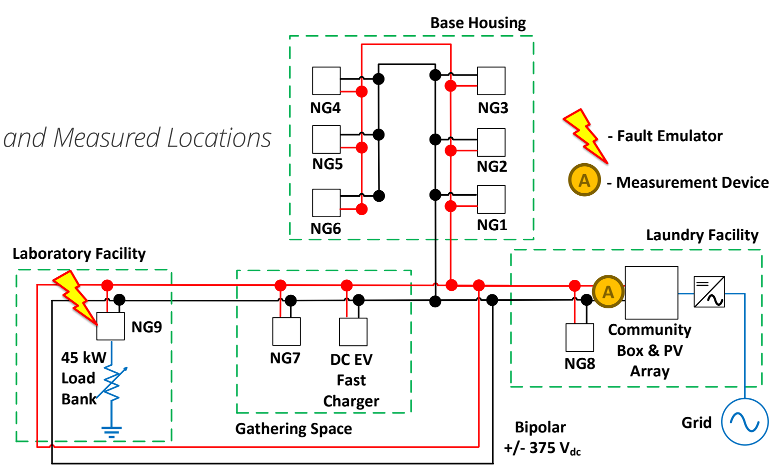
Voltage-Time Domain Response During Fault Event



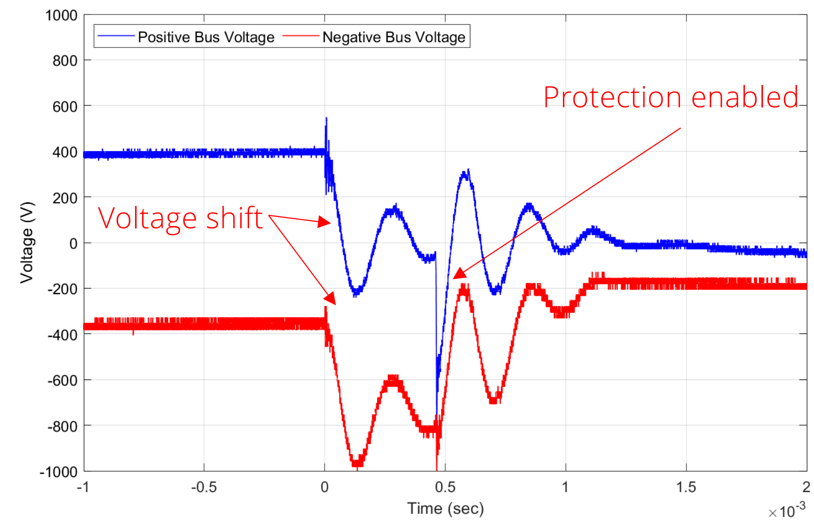
Current-Time Domain Response During Fault Event

Experimental Fault Test #2

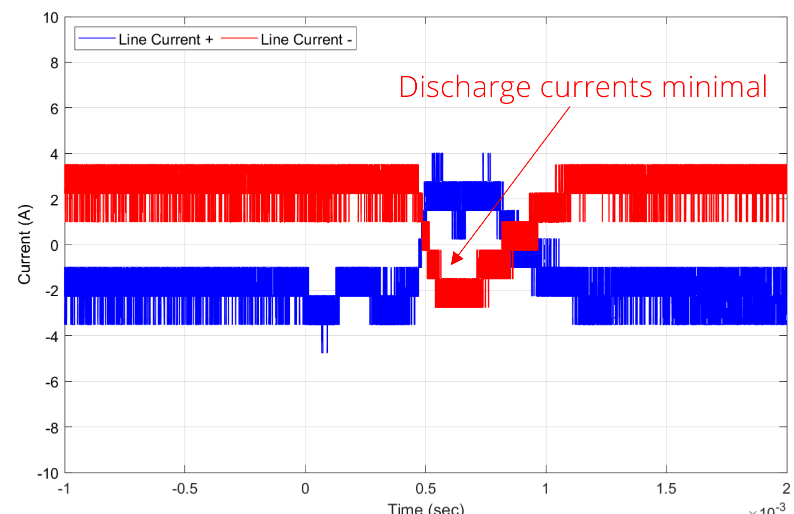
- 1 Ω, +375 V_{DC} to GND fault
- Loop feed w/ fault location at DETL test facility
- Monitoring across two locations:
  1. KAFB housing
  2. **CEP / Community Box**
- Fault and bus discharge currents are much less pronounced due to faulting to high-Z ground as compared to microgrid bus



Fault Emulator and Measured Locations



Voltage-Time Domain Response During Fault Event

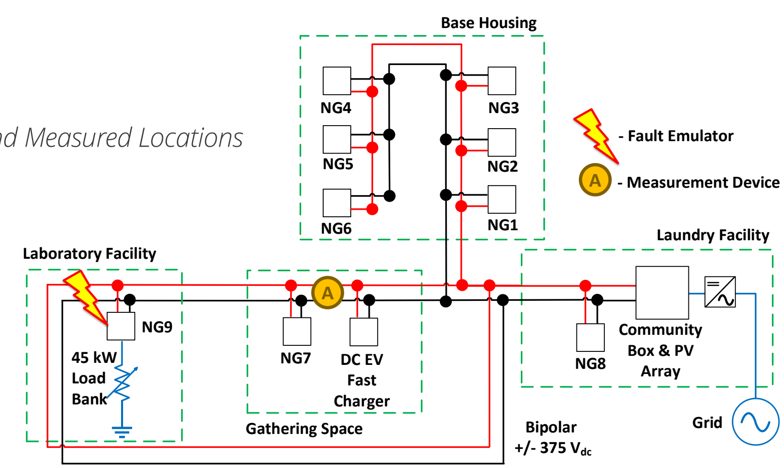


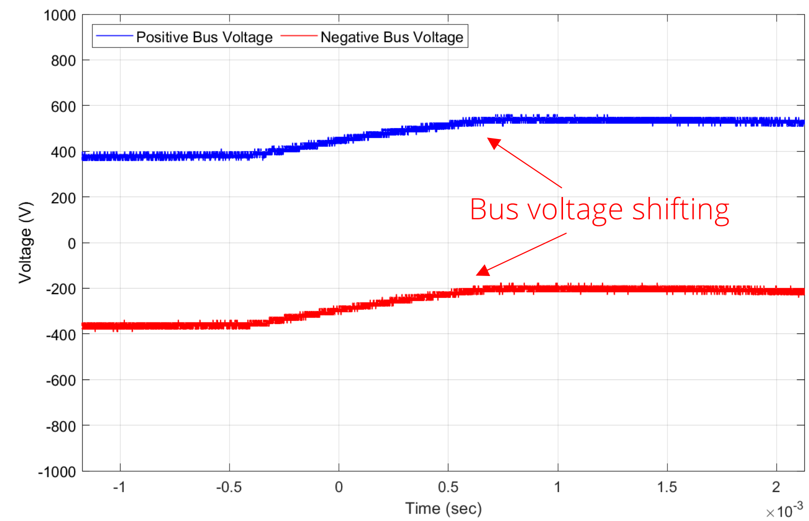
Current-Time Domain Response During Fault Event

Experimental Fault Test #3

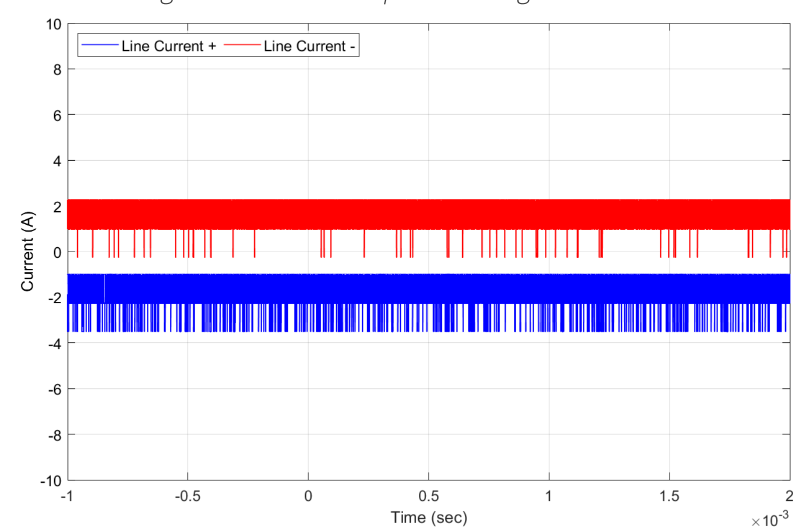
- 500 Ω, -375 V_{DC} to GND fault
- Loop feed w/ fault location at DETL test facility
- Monitoring across two locations:
  1. **KAFB Gathering Space**
  2. CEP / Community Box
- Subtle shift in bus voltage at higher impedance
  - Bipolar rails are up ~175 V from nominal

Fault Emulator and Measured Locations





Voltage-Time Domain Response During Fault Event

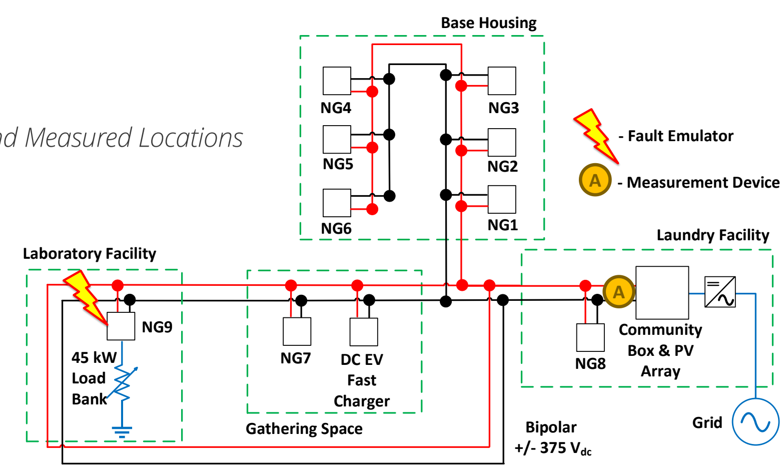


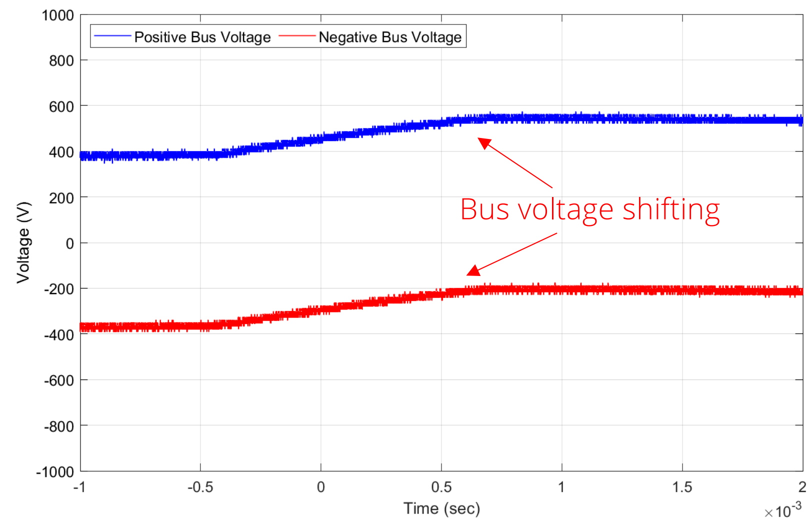
Current-Time Domain Response During Fault Event

Experimental Fault Test #3

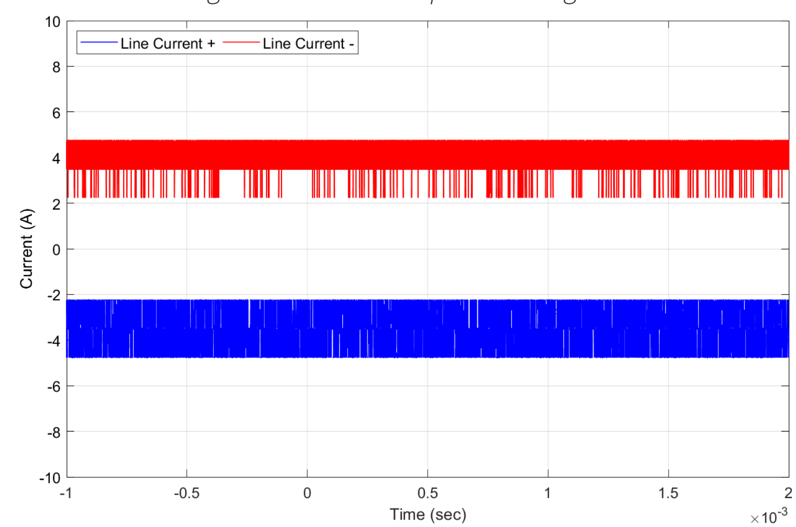
- 500 Ω, -375 V_{DC} to GND fault
- Loop feed w/ fault location at DETL test facility
- Monitoring across two locations:
  1. KAFB housing
  2. **CEP / Community Box**
- Protection device not enabled on high impedance faults
- Fault currents in the noise

Fault Emulator and Measured Locations





Voltage-Time Domain Response During Fault Event

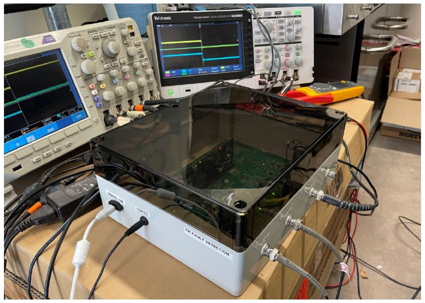


Current-Time Domain Response During Fault Event

Future Work and Test Platform Development

Test	Fault Test Config	Key Takeaways
1	4.7 Ω, +375 V_{DC} to -375V_{DC}	High fault di/dt easy to detect with current protection.
2	1 Ω, +375 V_{DC} to GND	Major bus voltage disturbance, but subtle current variation due to high-impedance grounding scheme. A little trickier.
3	500 Ω, +375 V_{DC} to GND	No noticeable current effects, but shift in voltage busses. How can we more accurately detect this? This will be a challenge.

- Continued testing based on future fault studies
  - More fault impedances, topology configurations, test conditions
  - Understand the behavior of high-impedance faults not currently detected by high di/dt capture
- Deploy new fault detection technologies onto microgrid
  - Fast fault detection using high-frequency sampling, data-driven location techniques
- Utilizing a residential-service platform for R&D
  - Bridges the gap between laboratory experiments and real-world solutions



Questions/comments? Thank you!

- Contact:
  - Miguel Jimenez-Aparicio, mjimene@sandia.gov
  - Andrew R. R. Dow, ardow@sandia.gov