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Active Fault Management for Enhancing Microgrid Resilience

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FAR BEYOND

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Our Mission

Transform today's power and energy infrastructures into tomorrow's **autonomic networks** and **flexible services** towards self-configuration, self-healing, self-optimization, and self-protection against grid changes, renewable power injections, faults, disastrous events and cyber-attacks.

Strategic Directions

- **AI-Enabled Resilient Power Grids**
- **Microgrids & Networked Microgrids**
- **Grid Resiliency, Cybersecurity, and Stability**
- **Software Defined, Programmable Smart Grid**
- **Grid Forming and Renewable Energy Integration**
- **Quantum Engineered Resilient Grids**

Outline

1. Why is active fault management (AFM) important?
2. Centralized active fault management (AFM) for microgrids
3. Distributed and asynchronous active fault management (DA-AFM) for networked microgrids
4. Neural active fault management (AI-AFM) for resilient microgrids integration
5. Future work

1. **Why is active fault management (AFM) important?**
2. Centralized active fault management (AFM) for microgrids
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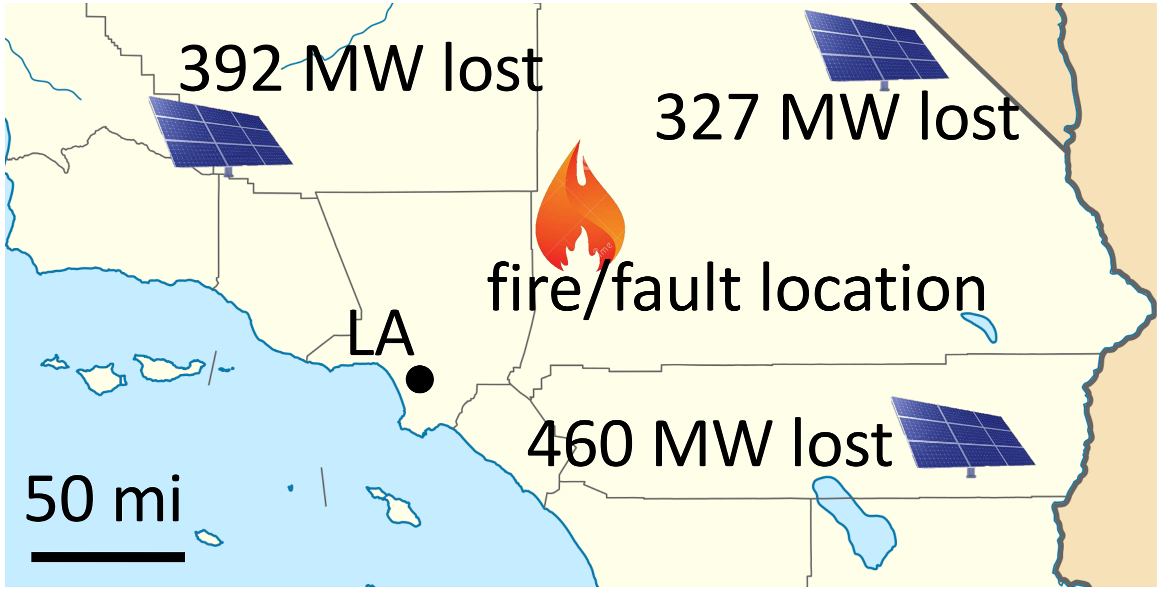
Why is AFM Important and Challenging

- **Dilemma for high penetration of microgrids**

A grid disturbance can induce a sudden loss of massive microgrids/DERs

Fault-induced solar energy interruption in California on Aug. 16, 2016



Fault event timeline

Time	Fault type	PV loss (MW)
11:45	Line to line	1,178
14:04	Line to ground	234
15:13	Line to ground	311

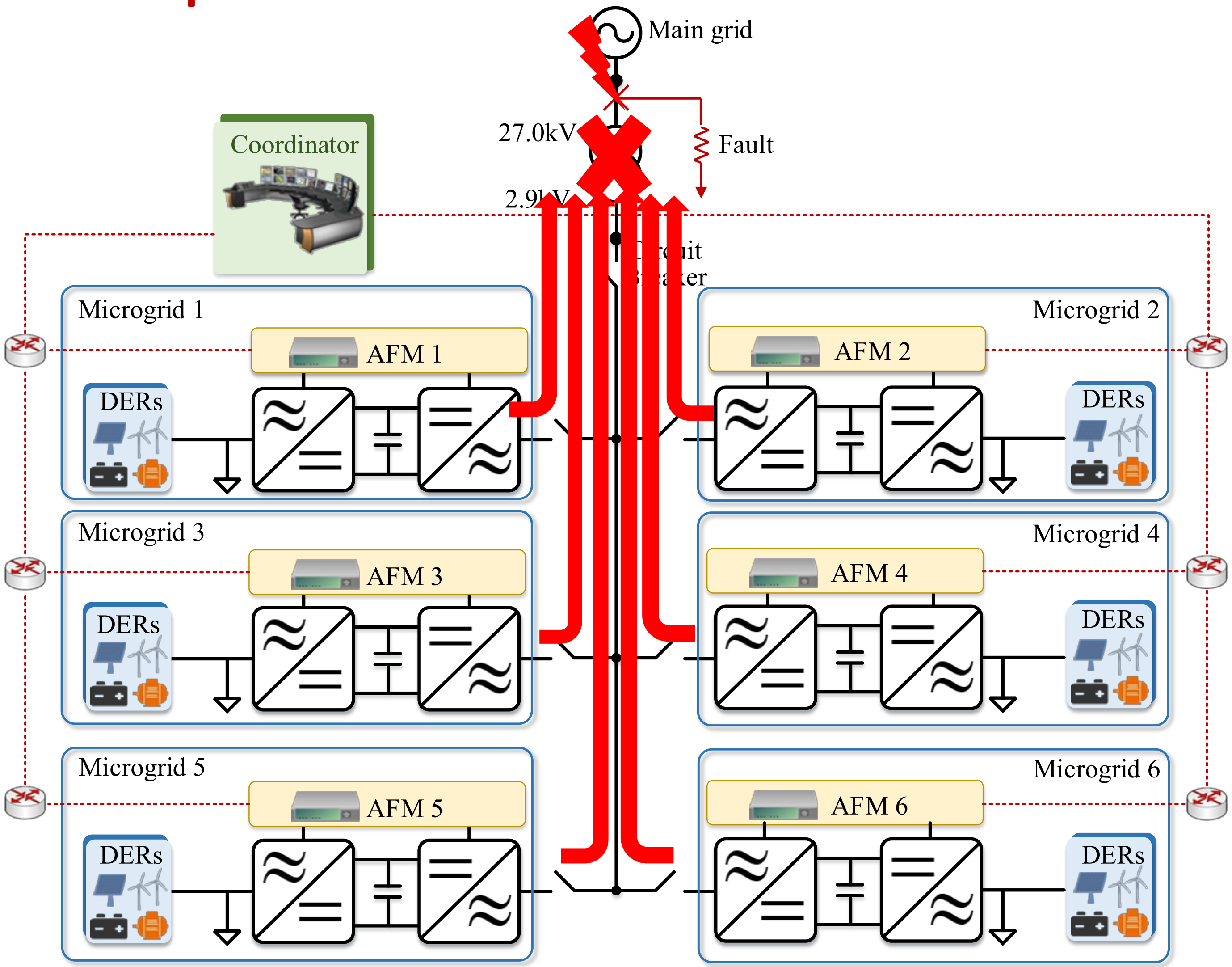
Similar events:

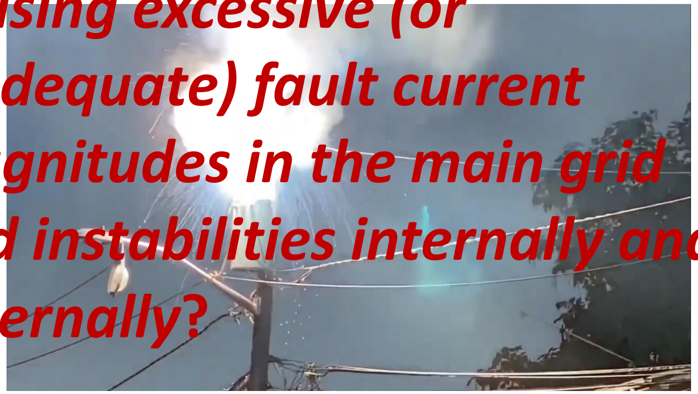
Odessa Disturbance on June 4, 2021 (loss of 2.6GW PV/sync generation);

London blackout on August 9, 2019 (1.9GW wind/gas generation loss)

❑ Dilemma for high penetration of microgrids

Coupling of microgrids/DERs with a disturbed main grid can lead to catastrophic mutual impacts



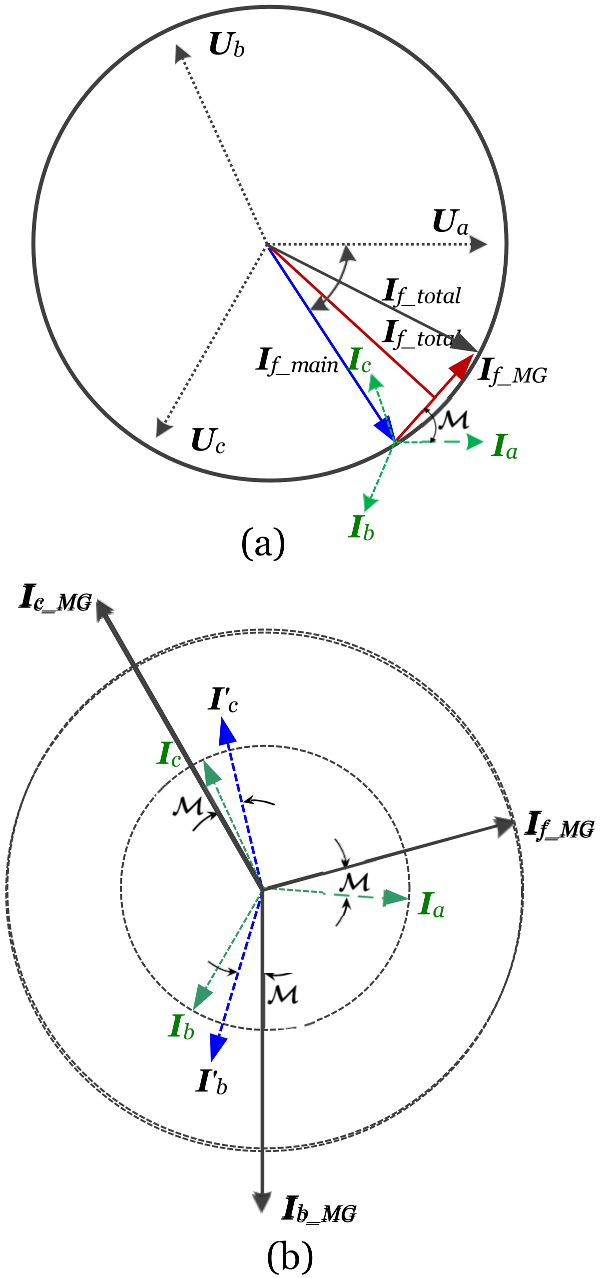


How to manage the fault responses of networked microgrids to provide critical ancillary support as required by the new IEEE Standards 1547 and 2030 without causing excessive (or inadequate) fault current magnitudes in the main grid and instabilities internally and externally?

Active Fault Management: Basic Concept

The concept of multi-functional AFM

- ❑ Maintain the magnitude of total fault current unchanged
- ❑ Eliminate the double line-frequency power ripples
- ❑ Ensure power flow of microgrid roughly identical before and after fault in order to maintain microgrid stability



Evolvement of AFM

Key innovation: integrate real-time optimization into power electronic controls

Computation

Centralized → Distributed; Asynchronous → Learning Based

Microgrids

Single microgrid → Networked microgrids → Dozens of microgrids → Hundreds of microgrids/DERs

Application

Microgrids → PV, wind, hydrogen, HVDC utility grids

Development

Software and SDN → HIL Testbed → IoT and edge computing

Hundreds of microgrids/DERs

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2. **Centralized active fault management (AFM) for microgrids**
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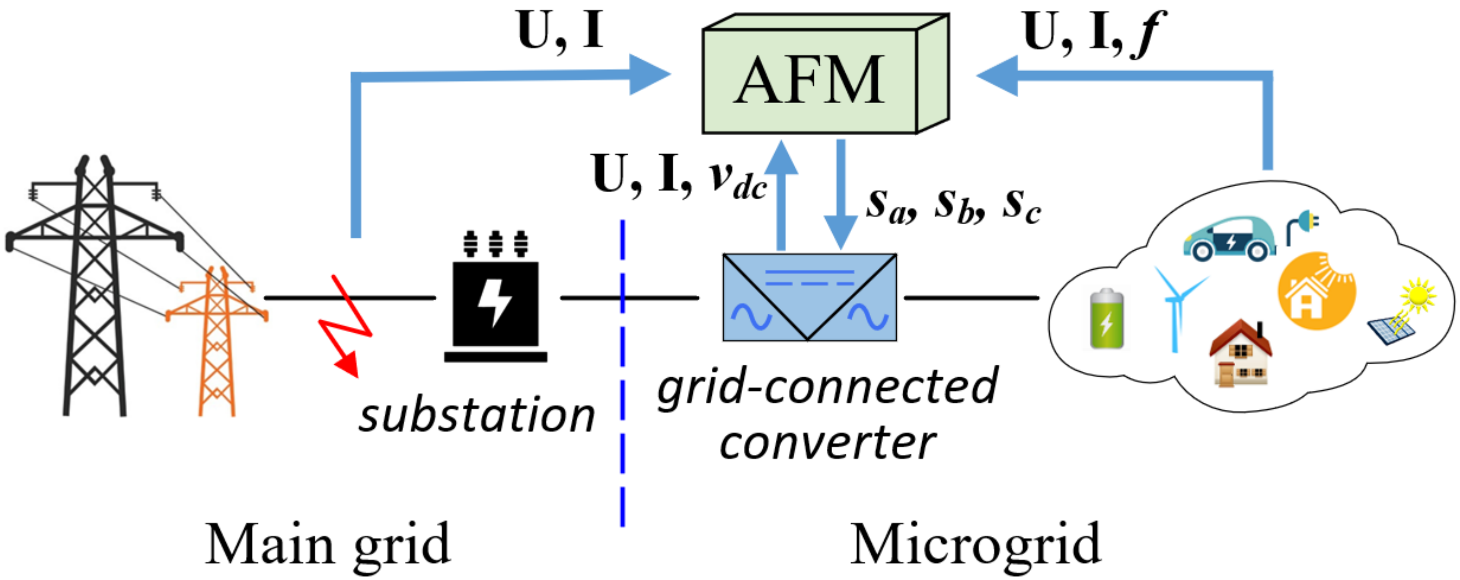
AFM: objectives

1. Reduce microgrids' fault currents contributions during fault ride-through
   (for the main grid's resilience)

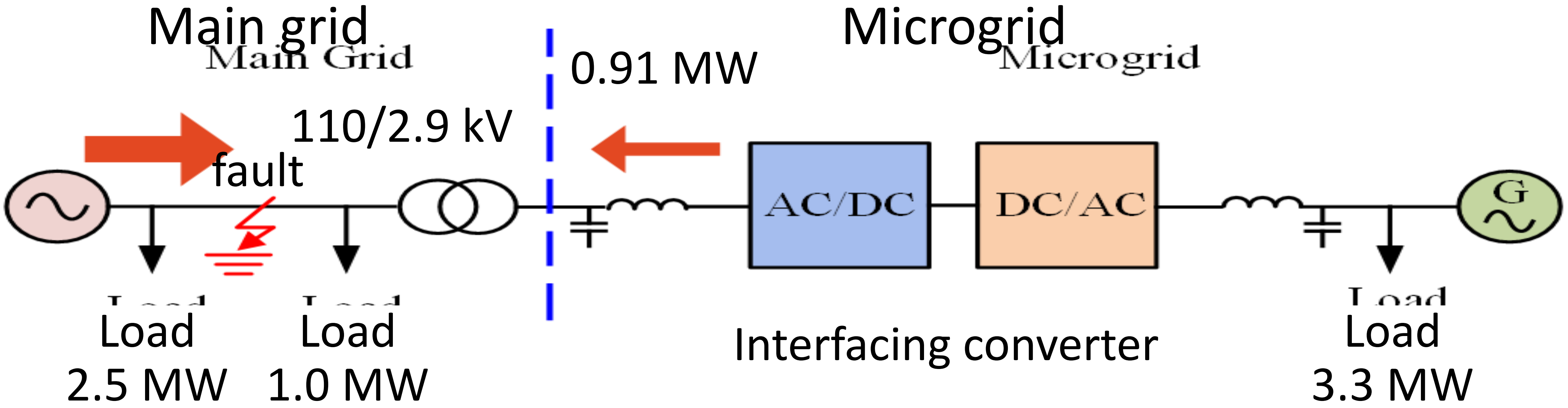
2. Reduce power ripples in microgrids' output power
   (for microgrids' resilience)

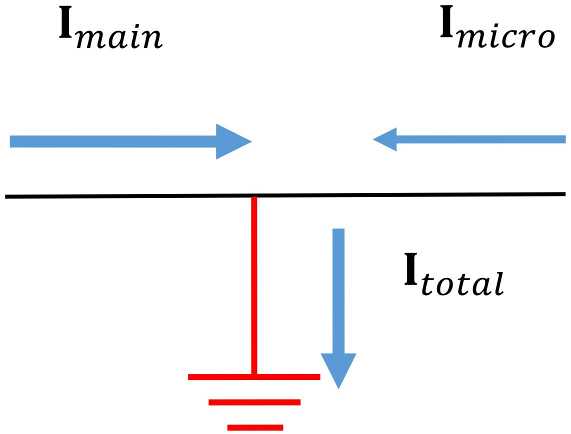
3. Ensure power balance for microgrid stability (for microgrids' resilience)



Centralized active fault management for a single microgrid

Schematic for centralized AFM





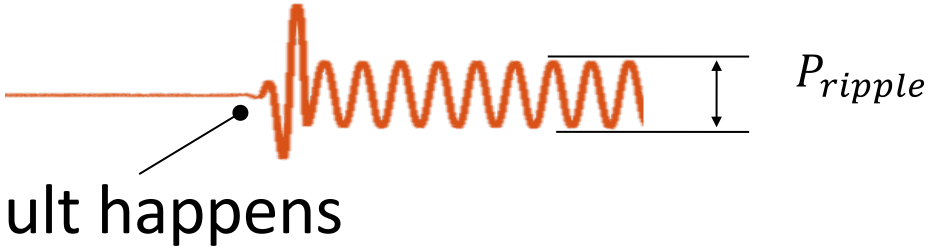
At fault location

$$F_1 = \left|\left|\mathbf{I}_{total}\right| - \left|\mathbf{I}_{main}\right|\right|$$

$$\mathbf{I}_{total} = \mathbf{I}_{main} + \mathbf{I}_{micro}$$

At microgrid's converter

$$F_2 = P_{ripple}$$



Problem formulation for AFM: objective function

minimize $mF_1 + (1-m)F_2, m \in [0,1]$

Solving algorithm:

Interior-point methods

- Objective : fault current contribution (for the grid's resilience)
- Objective : double-line-frequency ripples (for microgrids' resilience)

Problem formulation for AFM: constraints

$$\frac{1}{3}\left(U| \quad |axI_{ax} + U_{ay}I_{ay} + U_{bx}I_{bx} + U_{by}I_{by} + U_{cx}I_{cx} + U_{cy}I_{cy}\right) = P_1 \qquad (1)$$

For the grid and microgrids' resilience

$$\begin{cases} I_{ax} + I_{bx} + I_{cx} = 0 \\ I_{ay} + I_{by} + I_{cy} = 0 \end{cases} \qquad (2)$$

For elimination of zero-sequence component

$$\begin{cases} \sqrt{I_{ax}^2 + I_{ay}^2} \le I^s \\ \sqrt{I_{bx}^2 + I_{by}^2} \le I^s \\ \sqrt{I_{cx}^2 + I_{cy}^2} \le I^s \end{cases} \qquad (3)$$

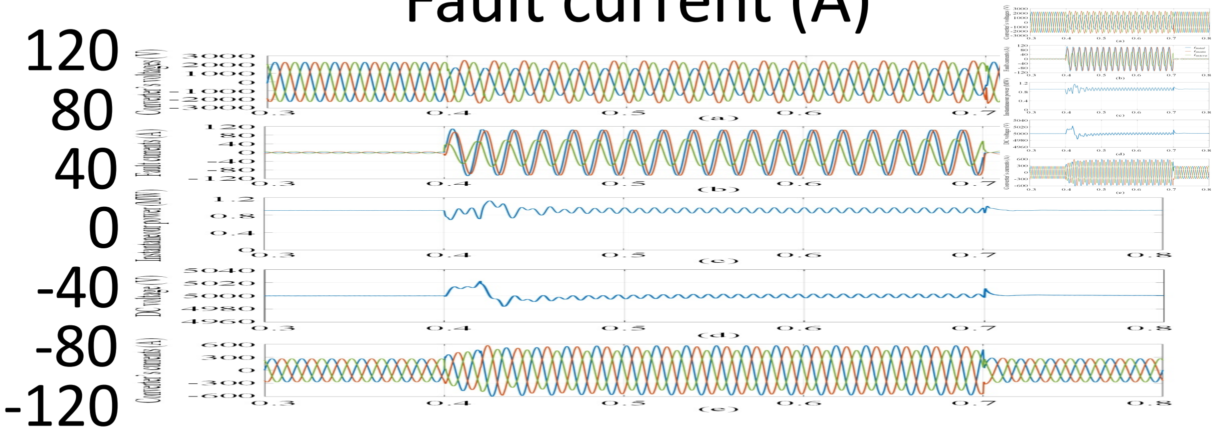
For safety ratings of the microgrid

Single-phase-to-ground fault

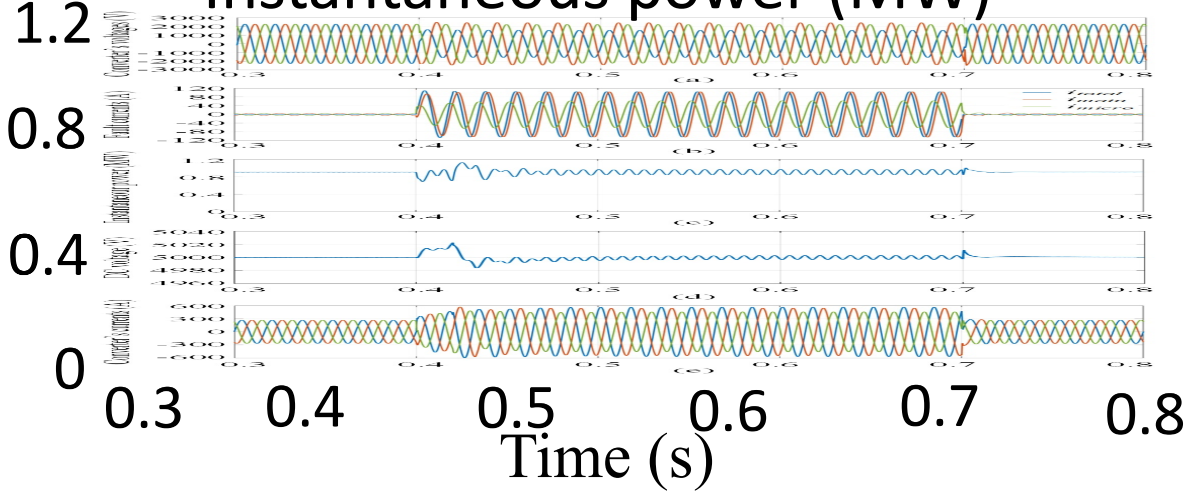
NAVAL POSTGRADUATE SCHOOL

AFM

Fault current (A)



Instantaneous power (MW)

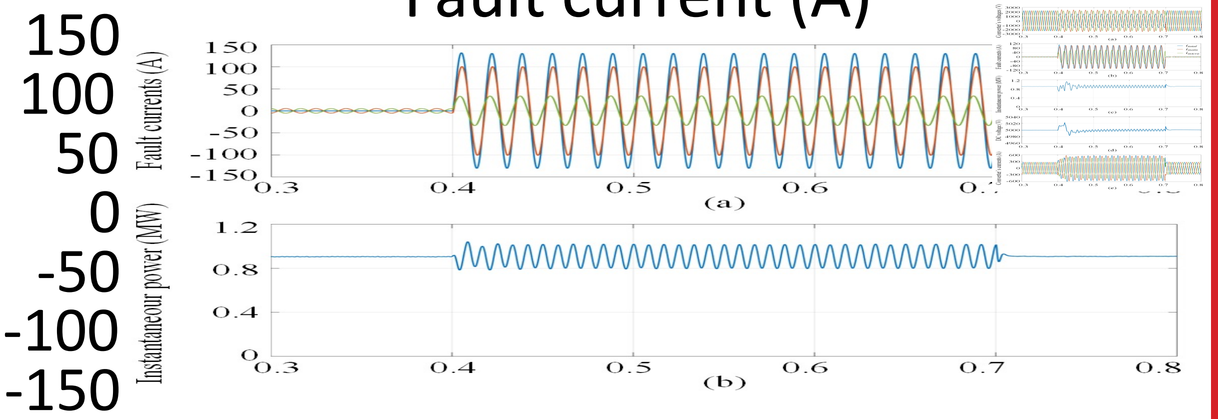


Current contribution: 0.0%

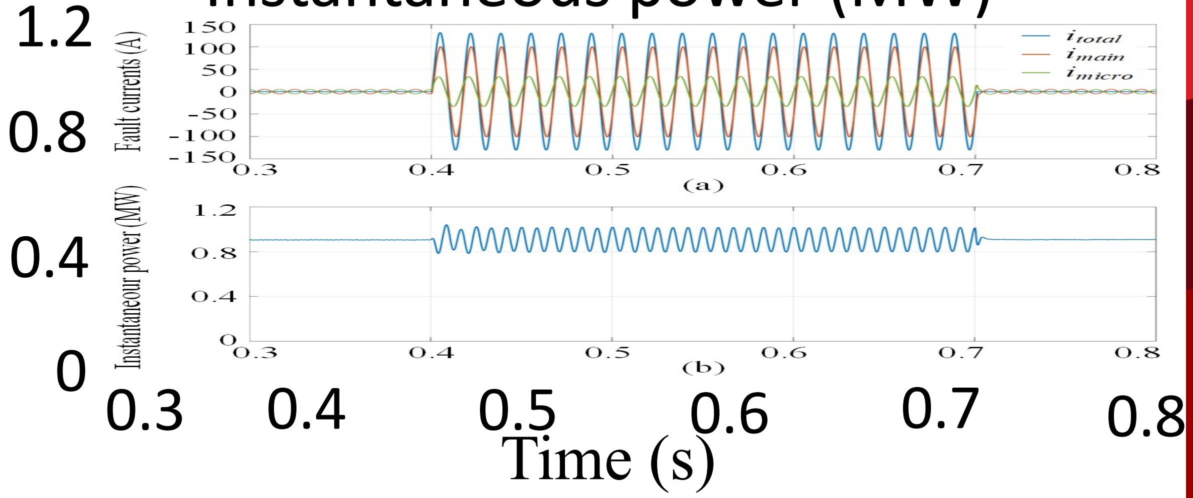
Ripples: 7.03%

A simple ride-through method

Fault current (A)



Instantaneous power (MW)



Current contribution: 25.0%

Ripples: 9.01%

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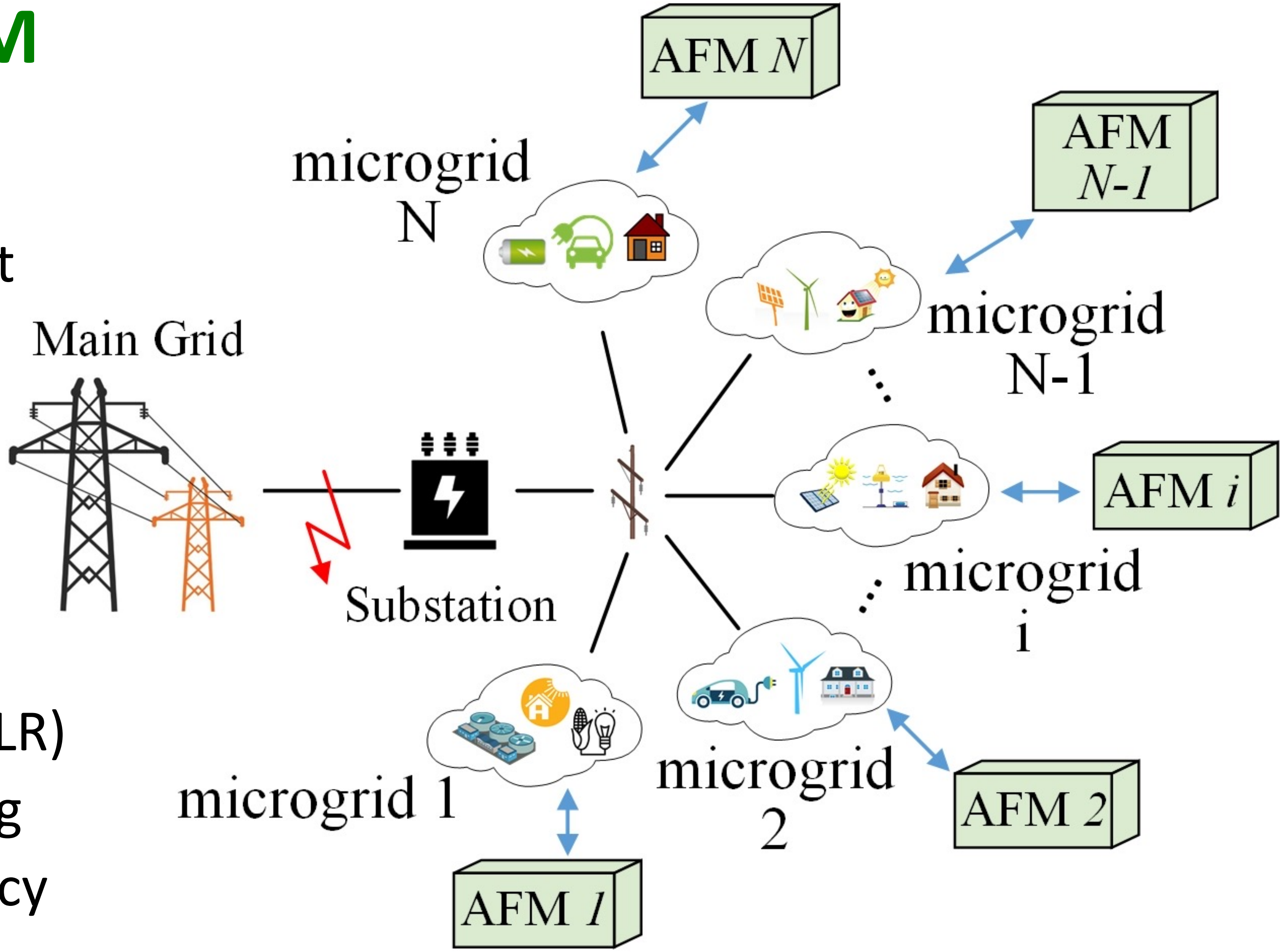
Introduction to DA-AFM

DA-AFM Advantages:

1. Distributed optimization that supports plug-and-play of microgrids or microgrid components
2. Efficient distributed and asynchronous surrogate Lagrangian relaxation (DA-SLR)
3. Software-defined networking (SDN) for enabling low-latency distributed computing



Distributed and asynchronous active fault management (DA-AFM) for networked microgrids

DA-AFM: from centralized optimization to distributed optimization

Centralized

Min.

$$\alpha F_1 + (1-\alpha) F_2, \quad \alpha \in [0,1]$$

s.t.

$$\sum_j [\mathrm{Re}(\mathbf{U}_{i,j})\mathrm{Re}(\mathbf{I}_{i,j}) + \mathrm{Im}(\mathbf{U}_{i,j})\mathrm{Im}(\mathbf{I}_{i,j})] = P_i$$

$$\sum_j \mathbf{I}_{i,j} = \mathbf{0}$$

$$[\mathrm{Re}(\mathbf{I}_{i,j})]^2 + [\mathrm{Im}(\mathbf{I}_{i,j})]^2 \le (I_i^S)^2$$

$$[\mathrm{Re}(\sum_{i=1}^{N} \mathbf{S}_i \mathbf{I}_{i,j})]^2 + [\mathrm{Im}(\sum_{i=1}^{N} \mathbf{S}_i \mathbf{I}_{i,j})]^2 \le (I^{S,M})^2$$

For each microgrid

Min.

$$\alpha F_{i',1} + (1-\alpha) F_{i',2} + \boldsymbol{\lambda}^T \boldsymbol{g} \quad \alpha \in [0,1]$$

$$\sum_j [\mathrm{Re}(\mathbf{U}_{i,j})\mathrm{Re}(\mathbf{I}_{i,j}) + \mathrm{Im}(\mathbf{U}_{i,j})\mathrm{Im}(\mathbf{I}_{i,j})] = P_i$$

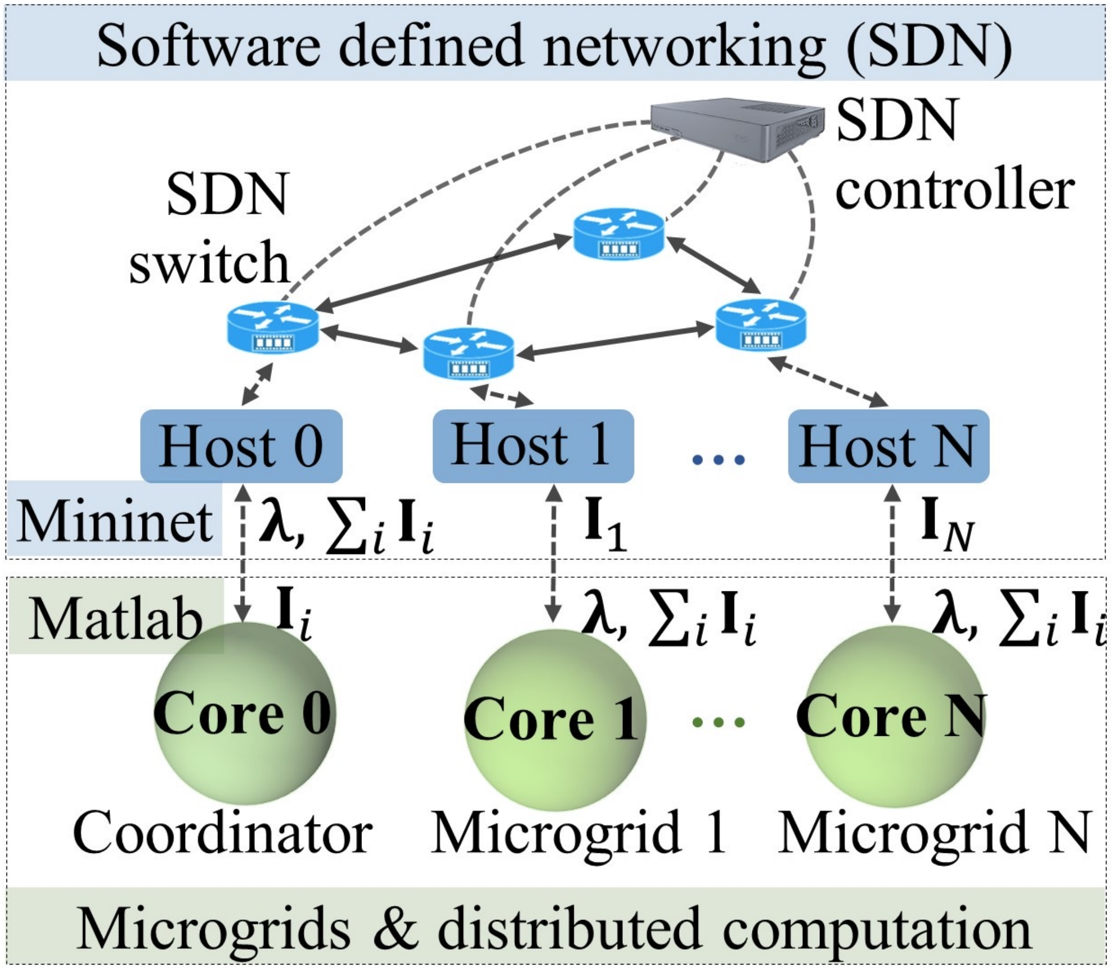
$$\sum_j \mathbf{I}_{i,j} = \mathbf{0}$$

$$[\mathrm{Re}(\mathbf{I}_{i,j})]^2 + [\mathrm{Im}(\mathbf{I}_{i,j})]^2 \le (I_i^S)^2$$

~~$$[\mathrm{Re}(\sum_{i=1}^{N} \mathbf{S}_i \mathbf{I}_{i,j})]^2 + [\mathrm{Im}(\sum_{i=1}^{N} \mathbf{S}_i \mathbf{I}_{i,j})]^2 \le (I^{S,M})^2$$~~

DA-AFM: One optimization problem → N optimization subproblems

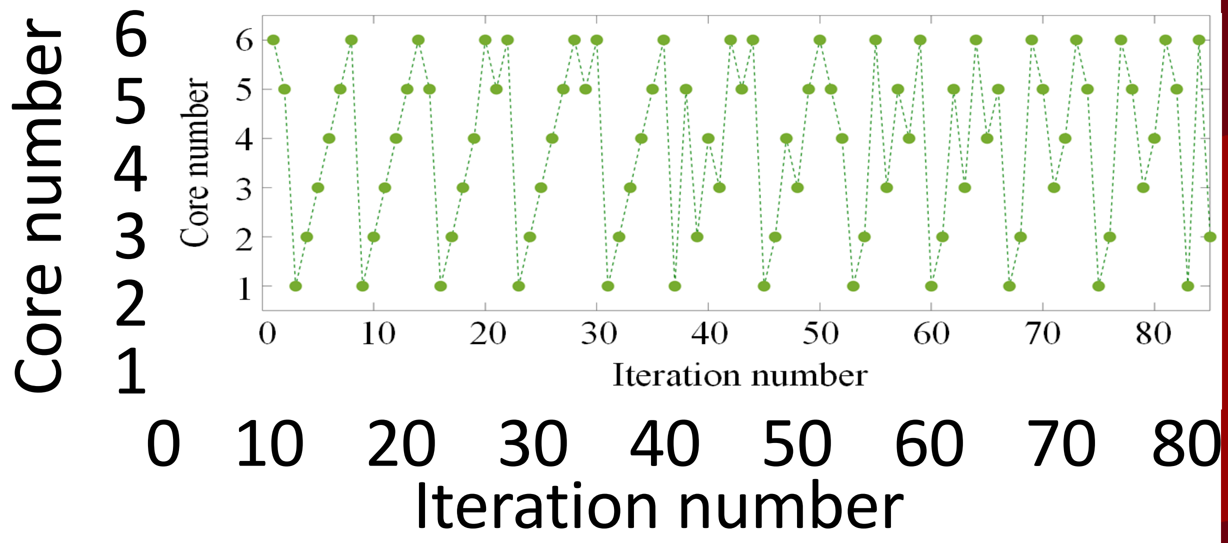
DA-AFM: Implementation



Implementation of DA-AFM with one CPU of multiple cores

- Each subproblem is assigned to a different core
- Each core computes asynchronously
- Calculation sequence is decided by each core's speed.

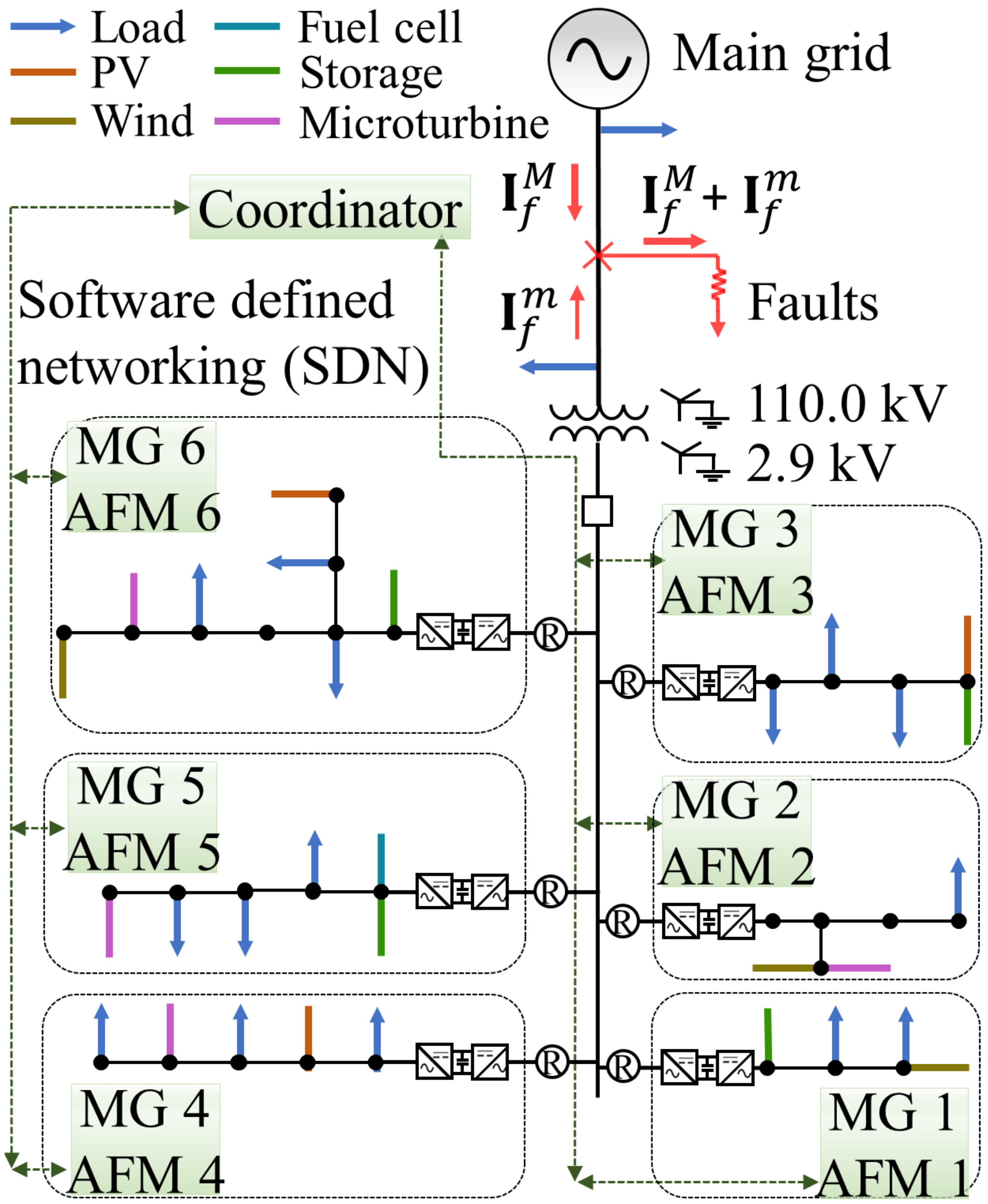
Calculation sequence with six microgrids for one calculation of DA-AFM



DA-AFM: system and case study

Microgrid #	1	2	3	4	5	6
Power delivered (kW)	213	278	221	302	381	407

1. Single-phase-to-ground (SPG) fault
2. Double-phase-to-ground (DPG) fault
3. Phase-to-phase fault
4. Three phase fault
5. Plug-and-play of DA-AFM
6. Scalability of DA-AFM
7. Real-time performance of DA-AFM
8. DA-AFM performance under miscellaneous situations



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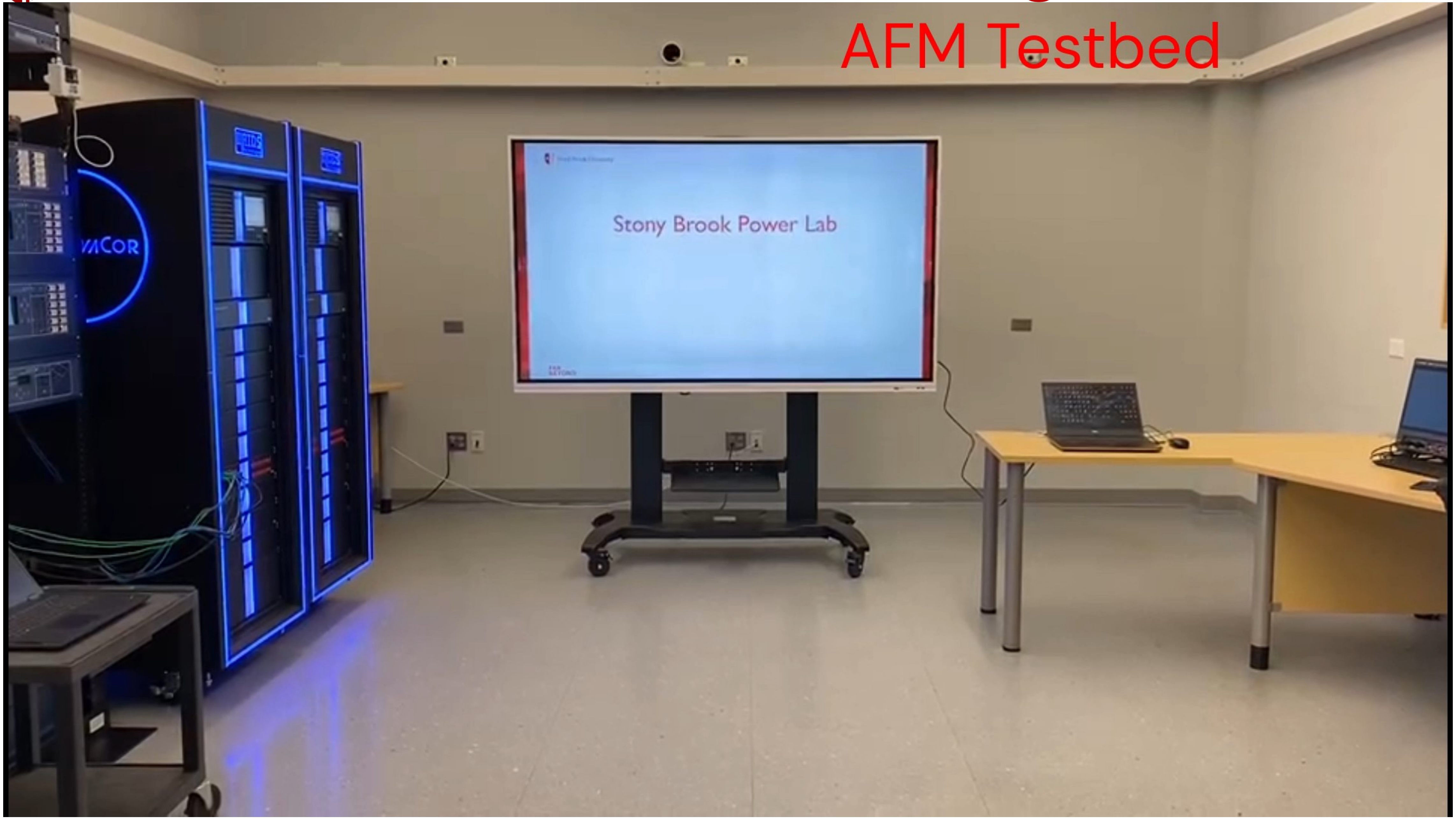
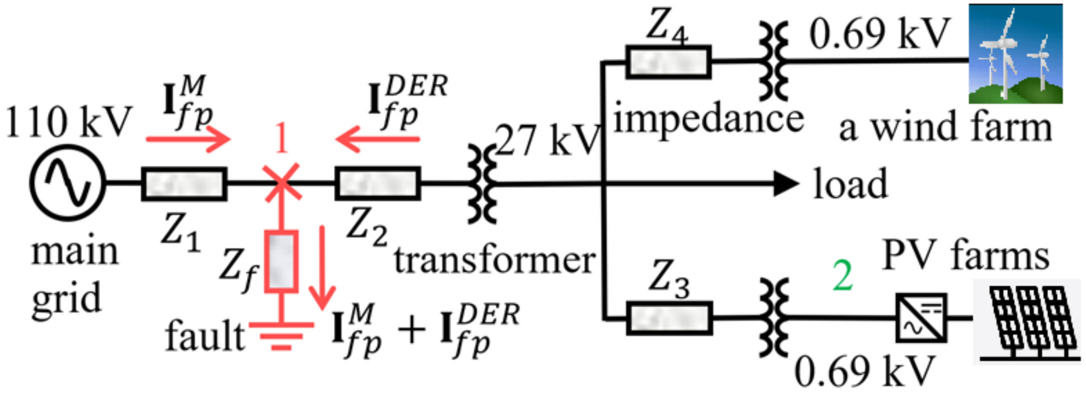
AFM for Networked Microgrids



AFM for enhanced system resilience

DA-AFM cost-effectively increases hosting capacity of renewables

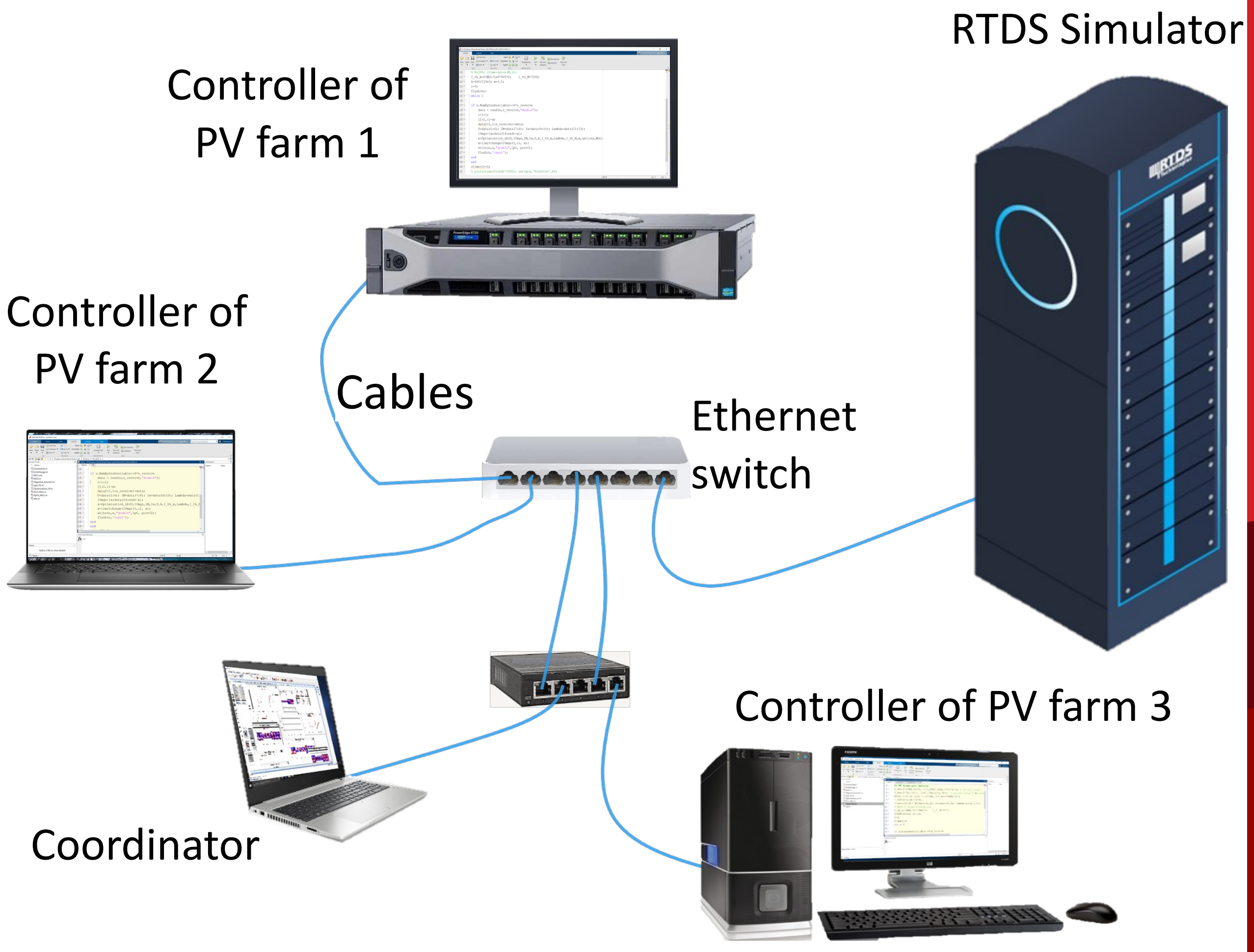


Studied system

1. Faults happen at the 110 kV
2. One wind farm and three PV farms are simulated

RTDS setup

1. RTDS sends voltage and currents to controller
2. Controller runs DA-AFM algorithm
3. Controller sends commands to RTDS



Hardware setup for real-time DA-AFM test

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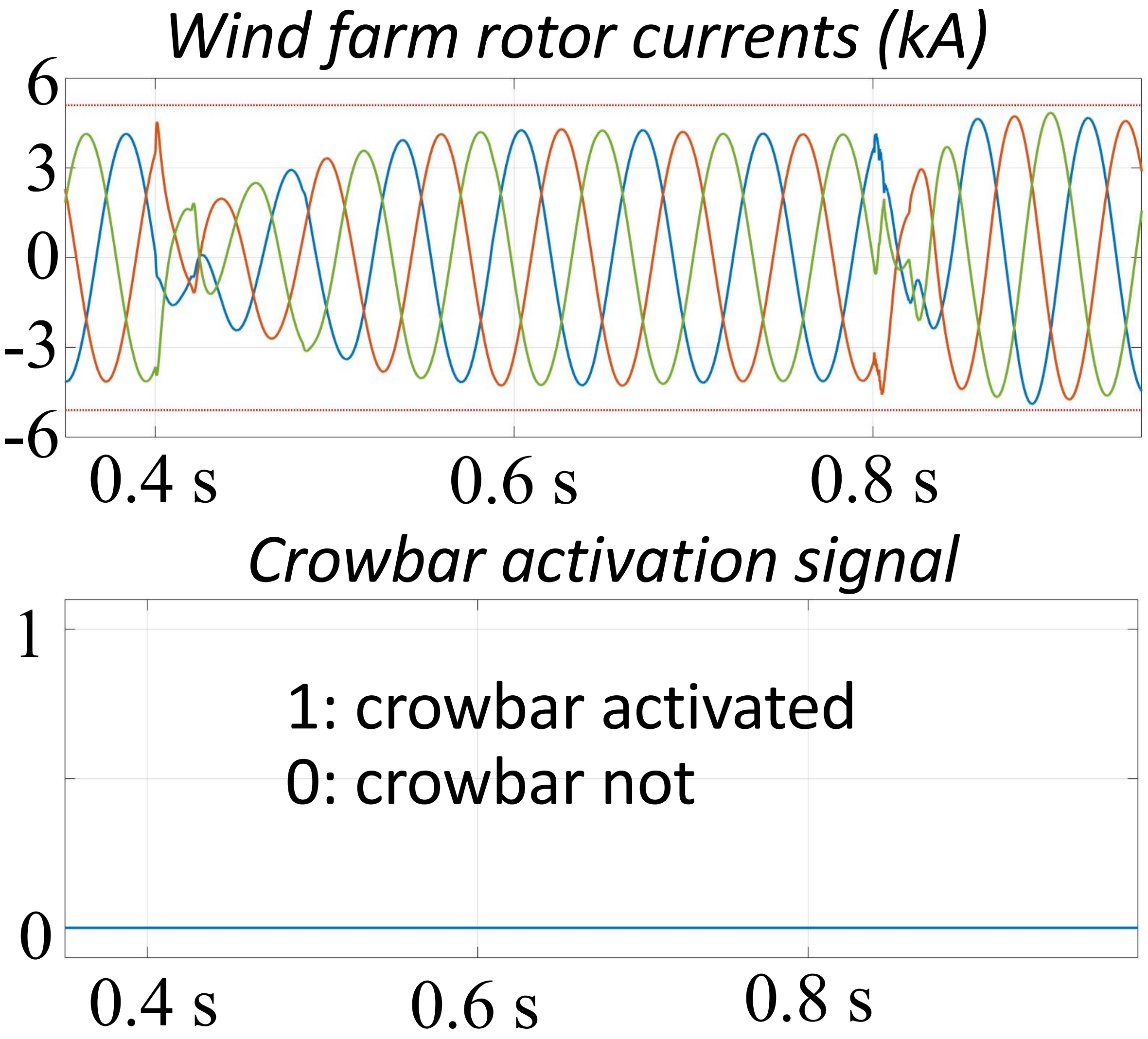
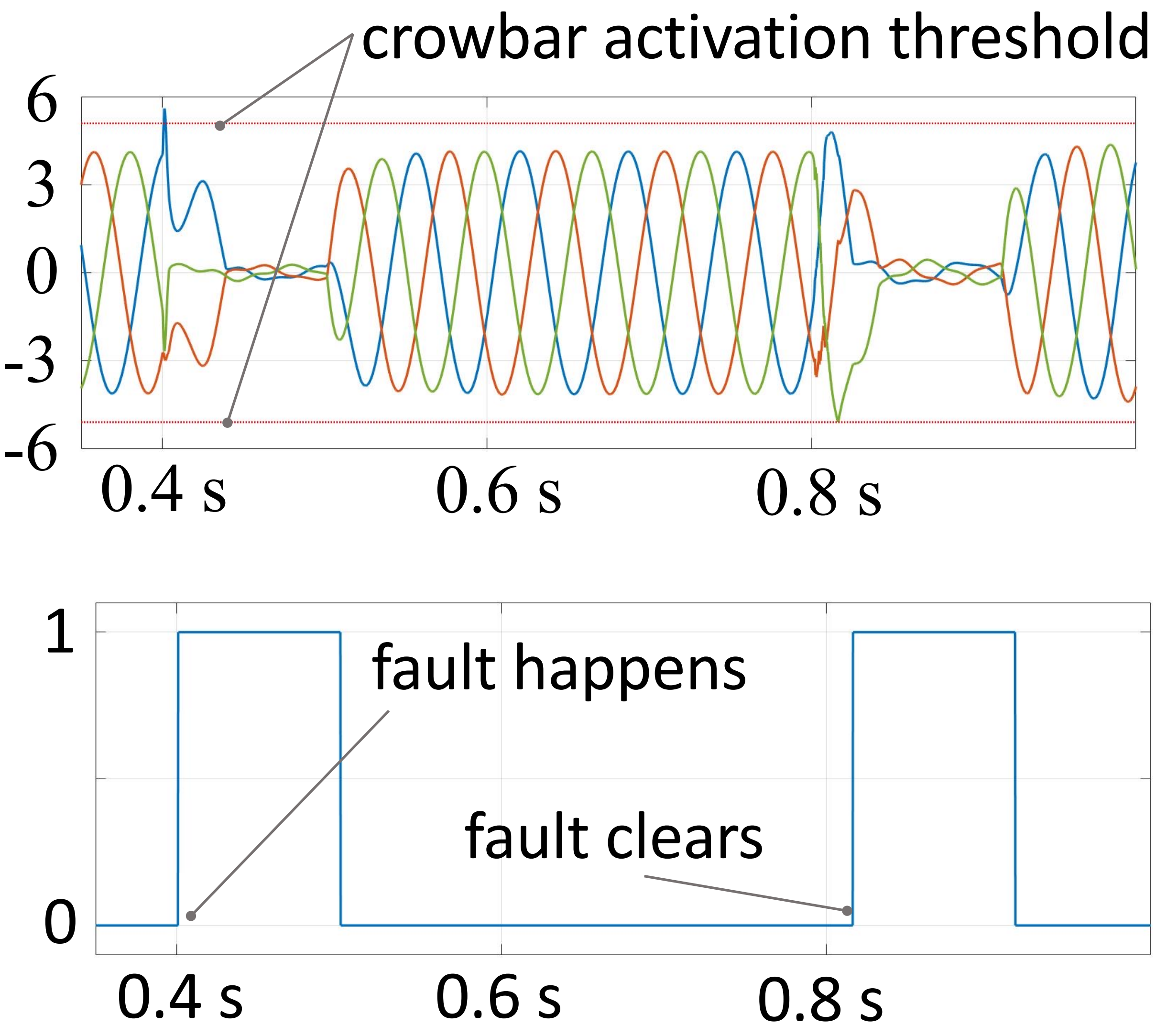
With AFM

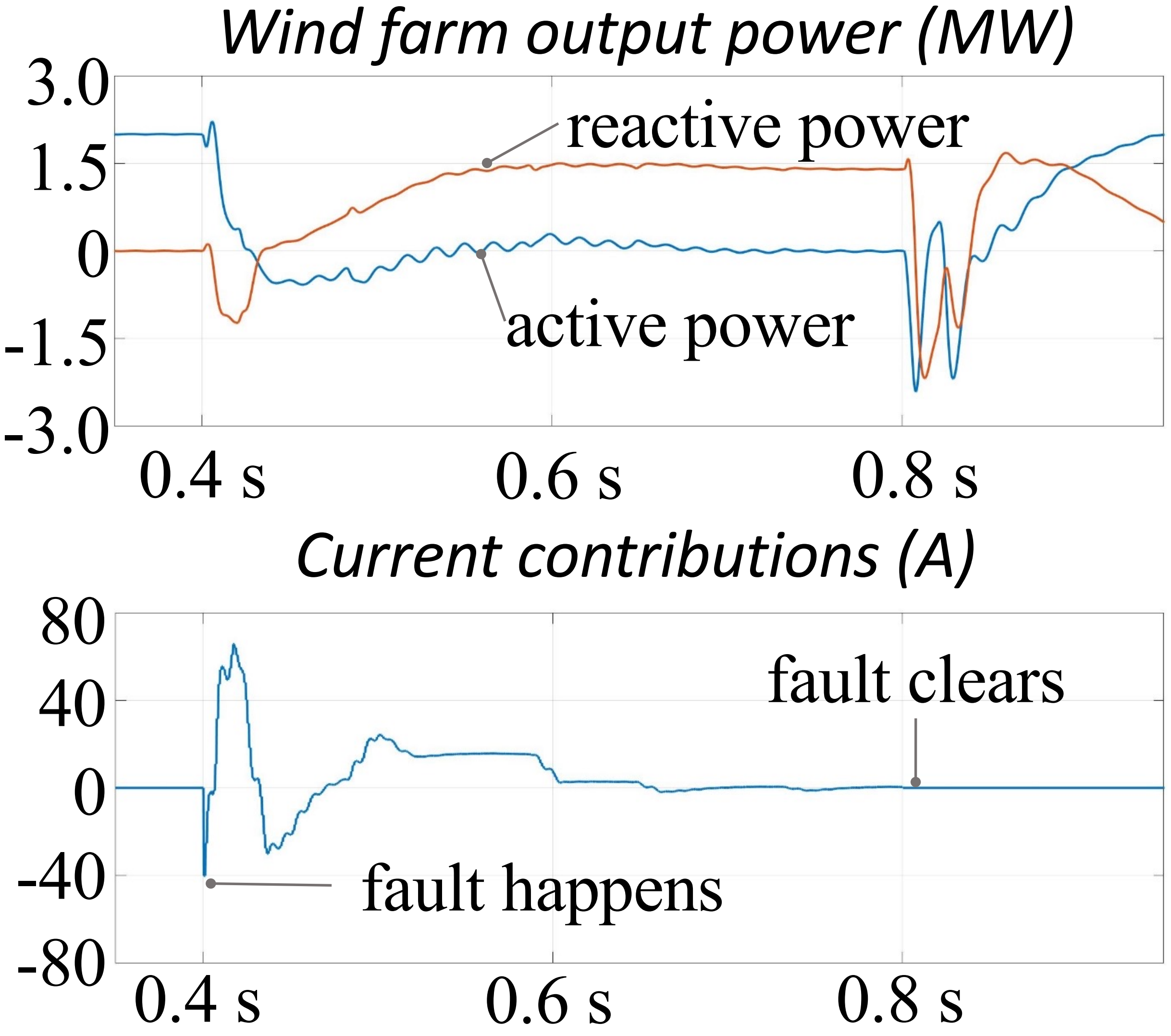


Simple ride-through method

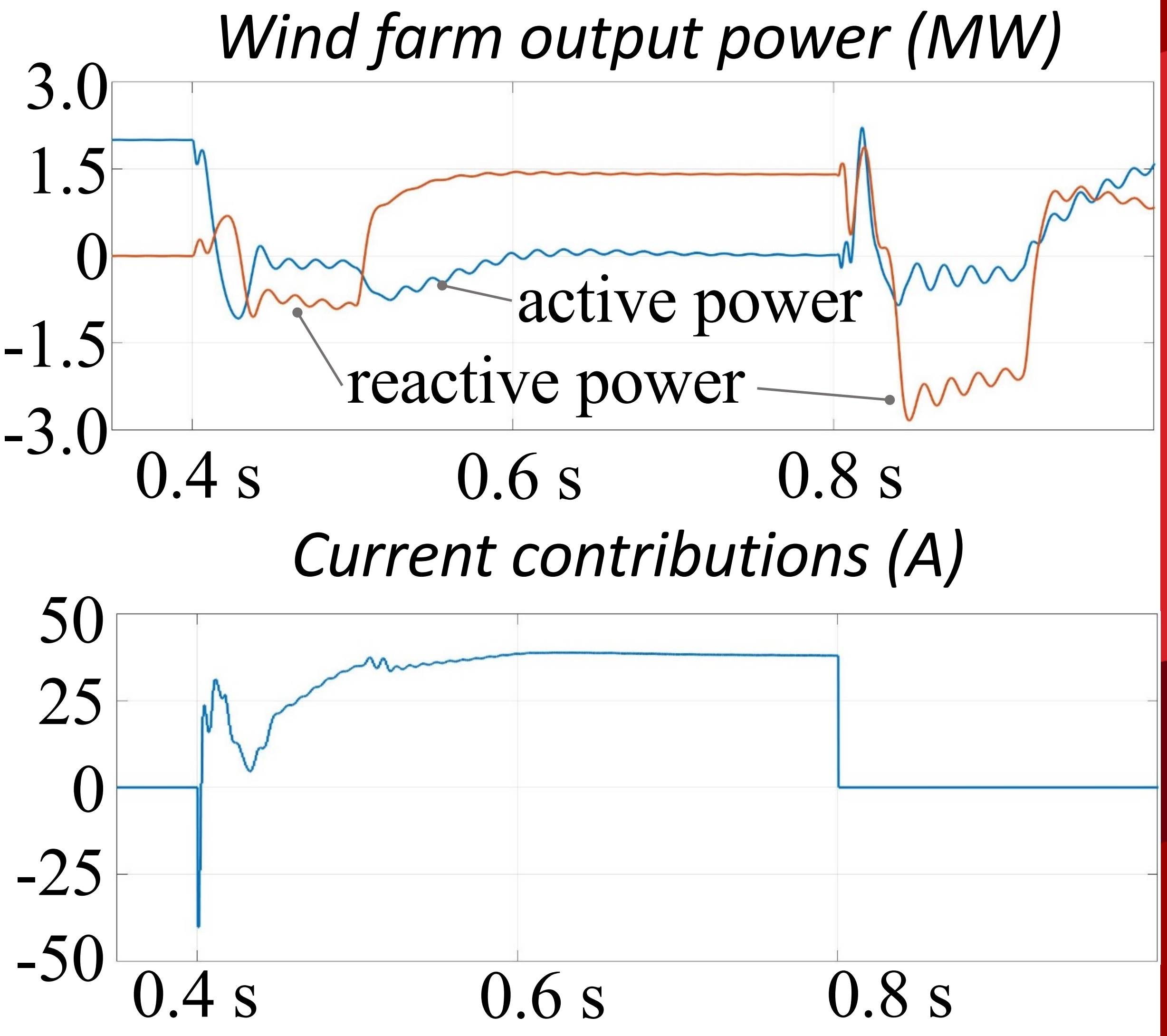


The crowbar is not activated in wind farm because of AFM's voltage smooth function

With AFM

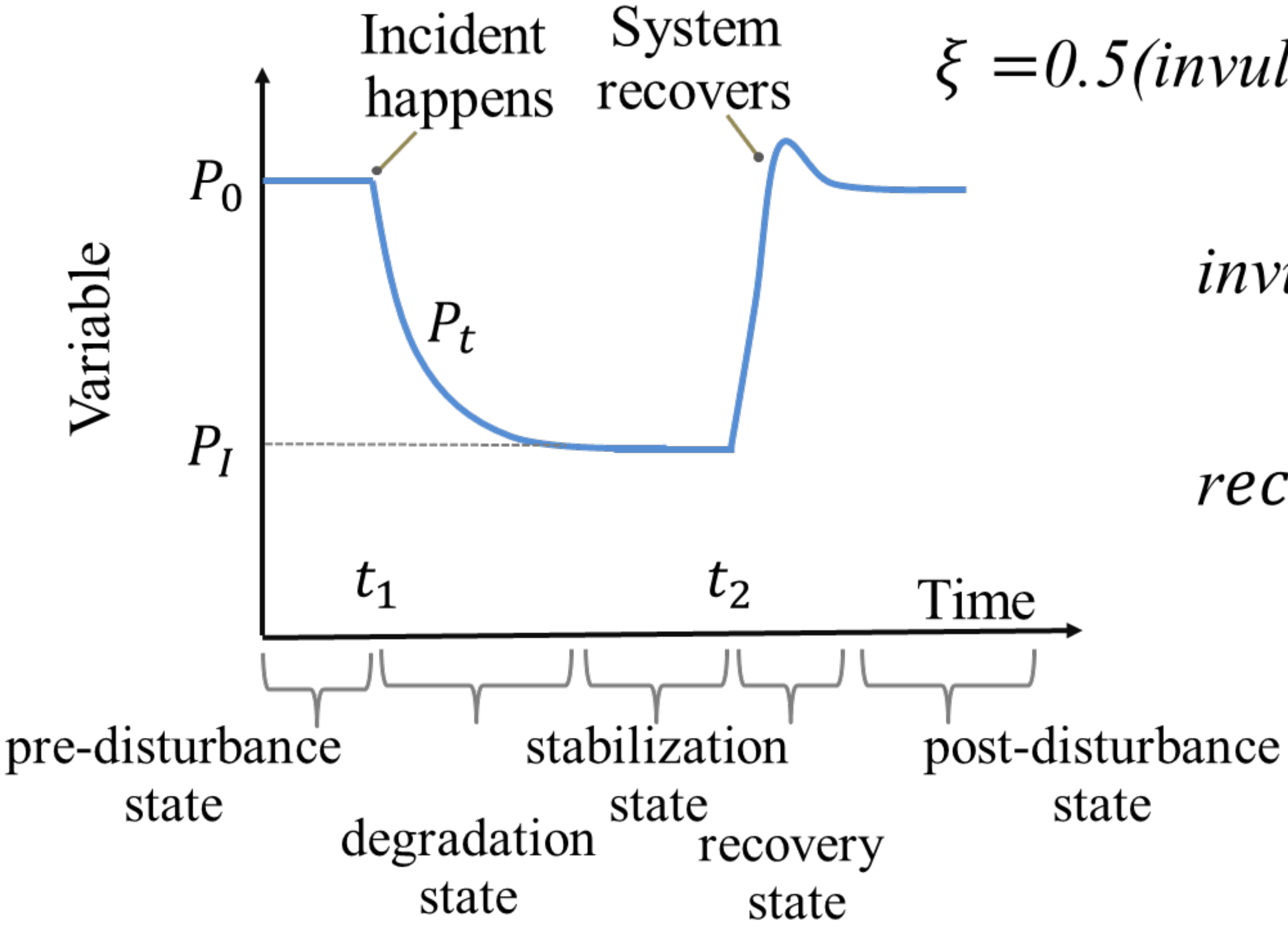


Simple ride-through method



PV and wind farms contribute to increasing total fault currents by 38 A without AFM

Resilience models



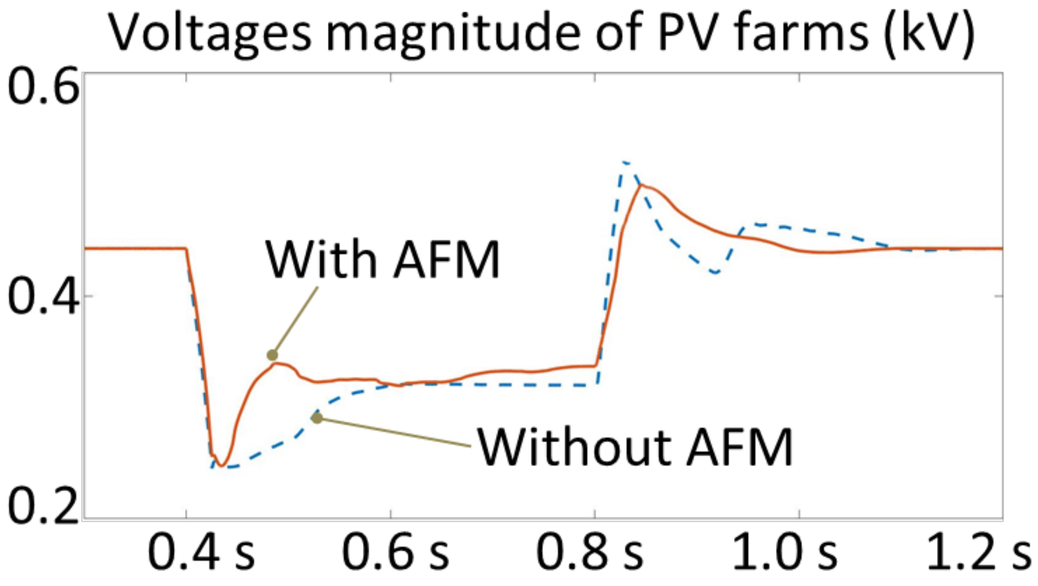
$$\xi = 0.5(invulnerability + recovery)$$

$$invulnerability = \frac{P_0}{P_I}$$

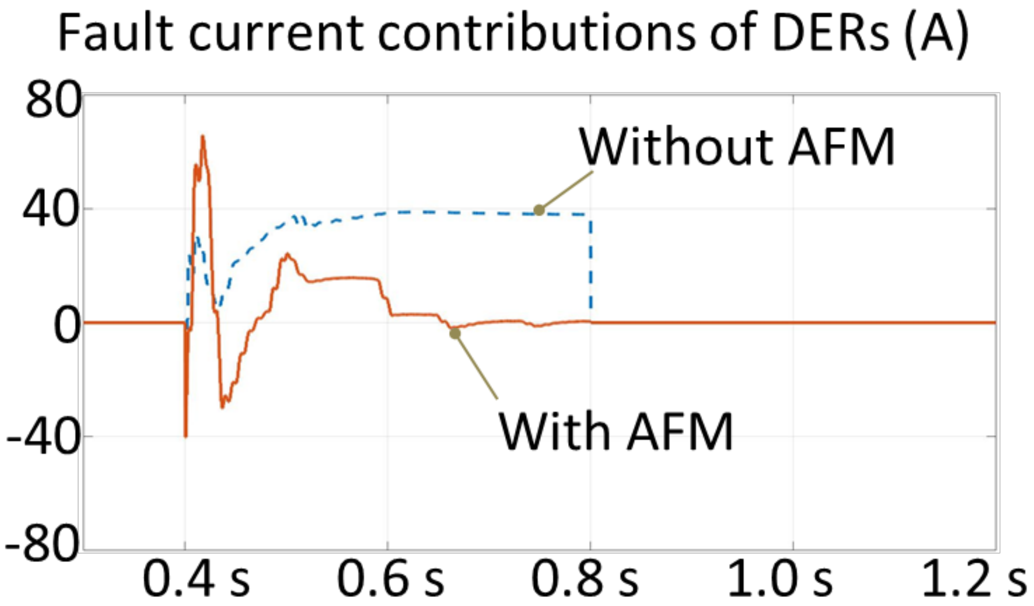
$$recovery = \frac{\int_{t_1}^{t_2} P_t \, dt}{P_0(t_2 - t_1)}$$

Assessing Resilience Microgrid Academy, Bill Anderson, PE, CEM, LEED AP, Director, Utilities Engineering & Management, NAVFAC EXWC PW6, 17 November 2020

Resilience curves



Metric	With AFM	Without AFM
Invulnerability	75.1%	72.4%
Recovery	73.6%	69.1%
Resilience	74.4%	70.8%



Metric	With AFM	Without AFM
Invulnerability	100%	5.0%
Recovery	76.5%	15.3%
Resilience	88.3%	10.2%

Based on worst contributions 40 A

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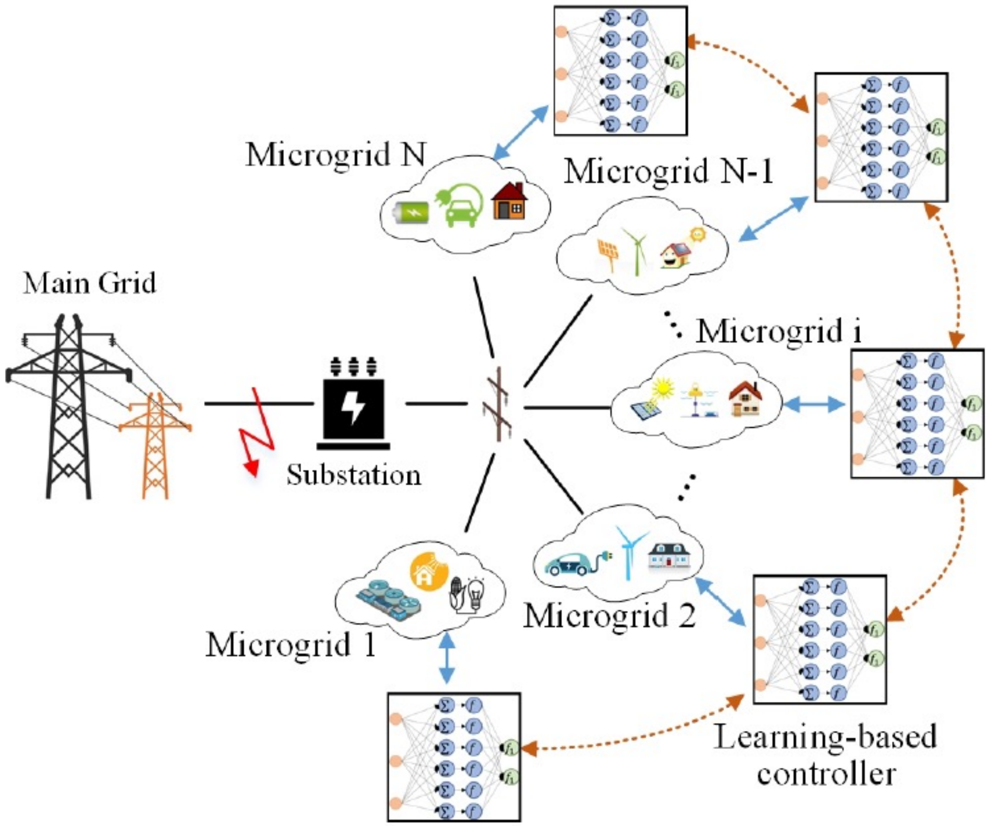
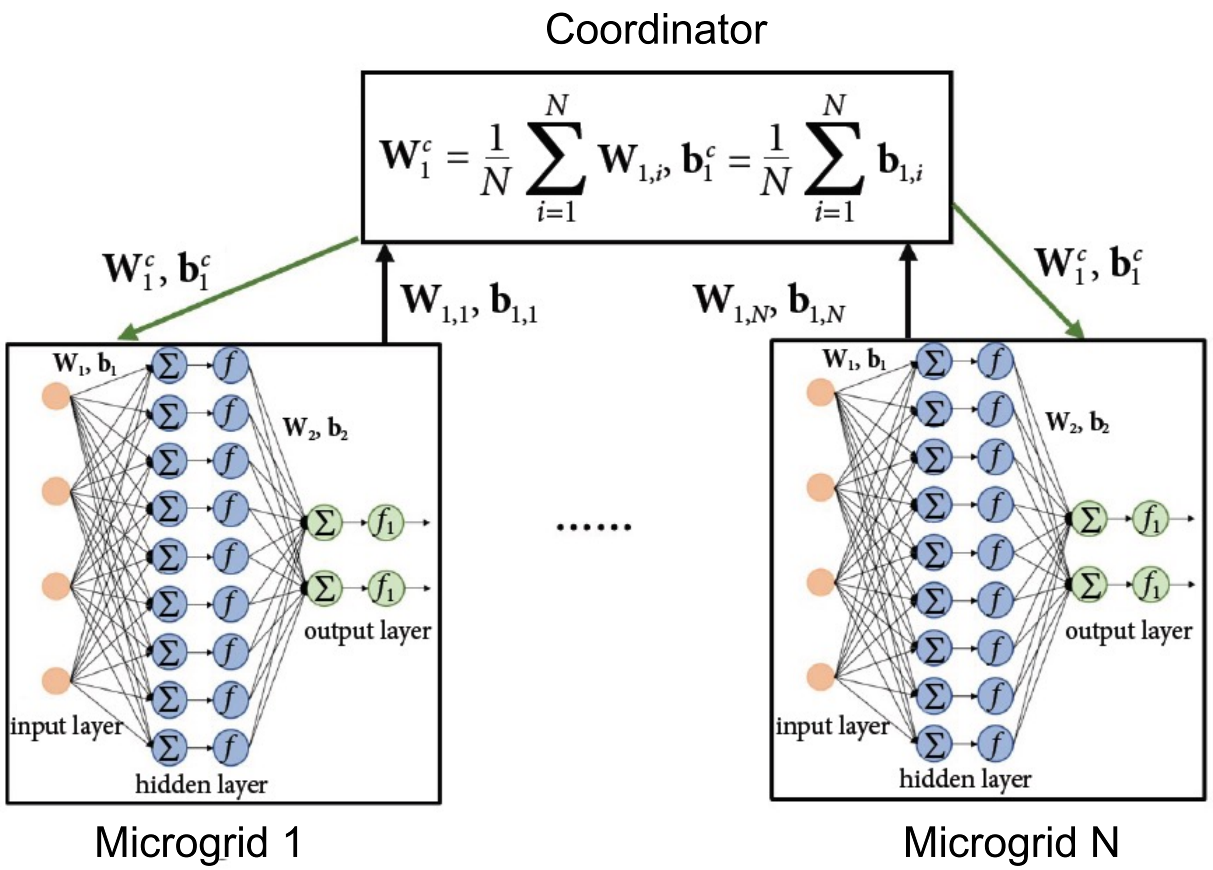
Safety-assured, real-time neural AFM for resilient microgrids integration

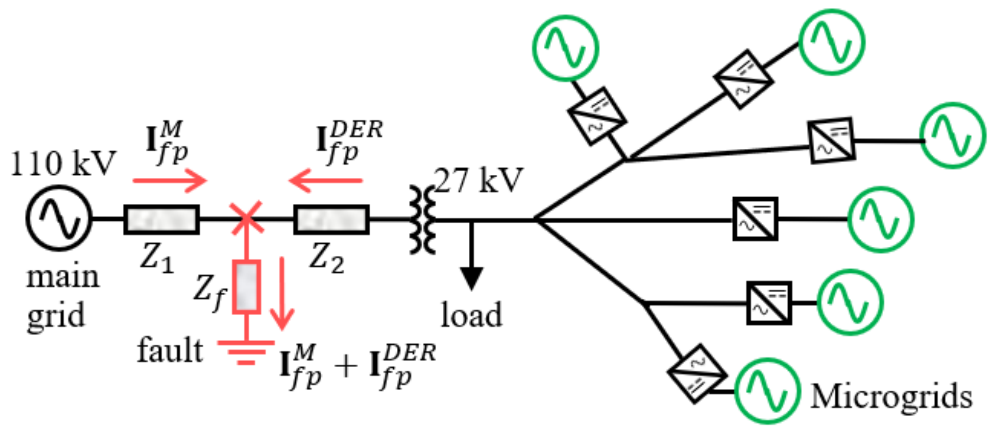
Replace optimization-based AFM with a learning-based framework



Schematic of learning-based AFM for microgrids integration.



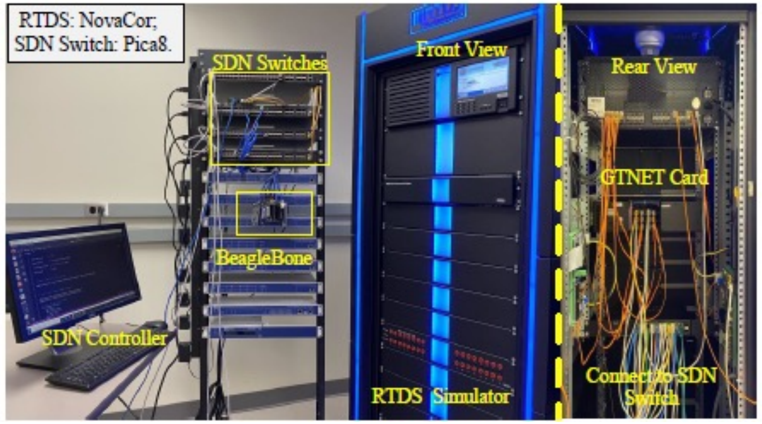
Federated learning architecture

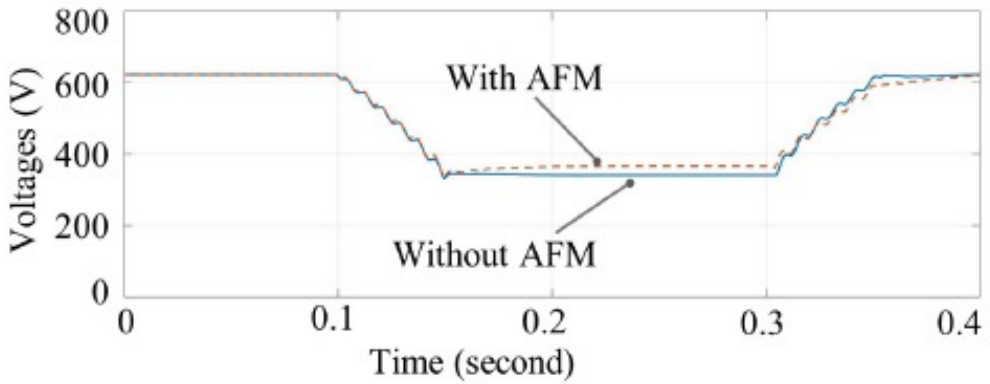


Response time in 6-microgrid system:

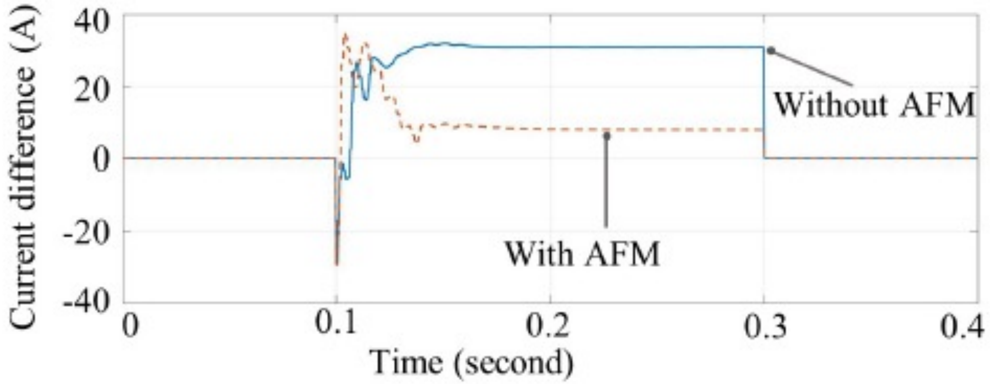
AI-AFM: 3ms;
DA-AFM: 54ms;
Without AFM: <=3ms

Same performance has been achieved on a 36-microgrid system





(a)



(b)

Resilience metrics for microgrid voltages

Metric	With AFM	Without AFM
Invulnerability	58.9%	54.9%
Recovery	63.9%	61.2%
Resilience	61.4%	58.1%

Resilience metrics for current contributions

Metric	With AFM	Without AFM
Invulnerability	85.5%	43.0%
Recovery	81.0%	46.0%
Resilience	83.3%	44.5%

Resilience curves for (a) voltages at microgrids' point of connection and (b) fault current contributions

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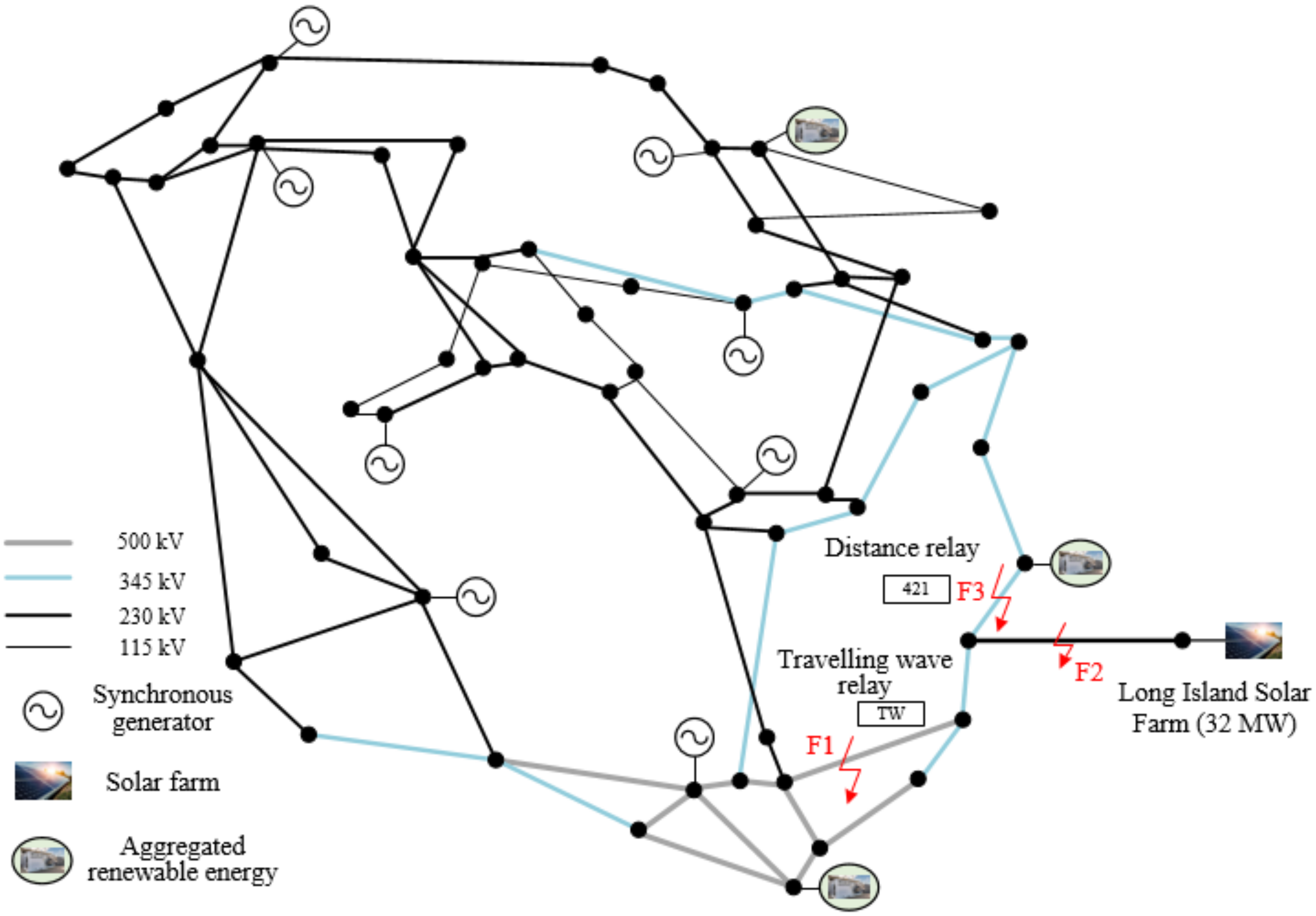
AFM Is Safe

AFM does not impede grid control and protection relay operations



NPCC System

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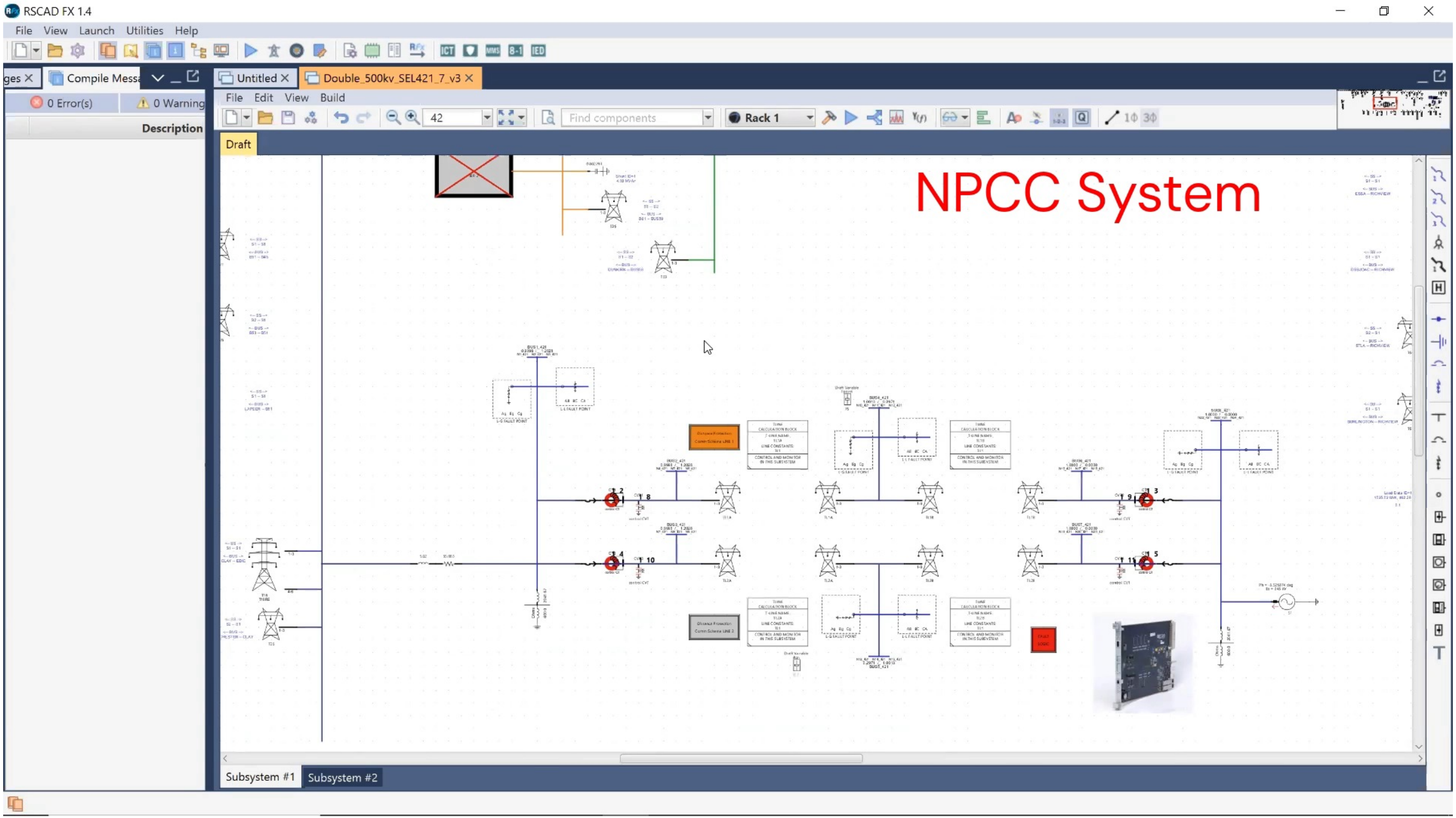
AFM is Safe: Verified



Future Work

- Sequenced AFM
- Scalable deployment of AFM
- Cybersecure AFM

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