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IEC 61850-Based Centralized Intelligent Station-Level Protection (CISP) for Power Systems with Multi-Technology DERs

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RTDS Technologies

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Content

- Background
- Methodology
- Hardware implementation
- Results
- Conclusion

Background

Grid Integration of renewables and DERs:

- Types of DER
- Locations
- Operating modes
- Types of technology

Trend towards IIDERs

- PV
- Wind
- Energy storage

Background

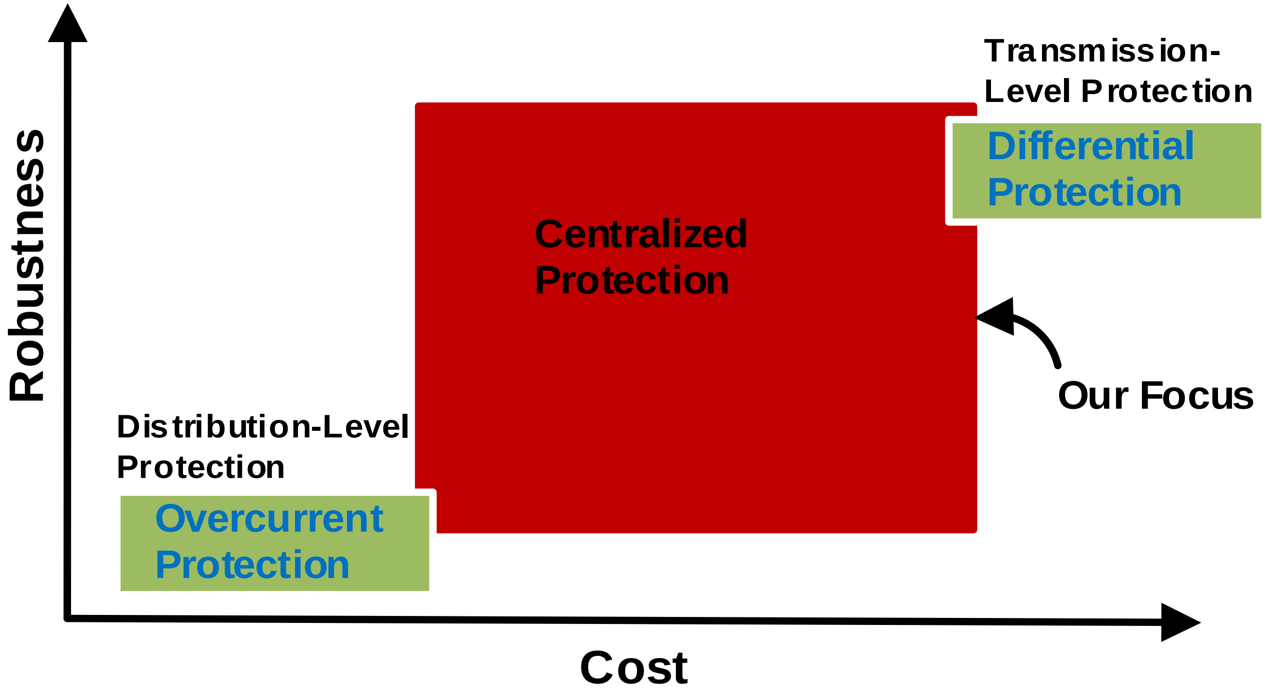
Impact of DERs on Distributions Systems

- Bidirectional distribution system
- Intermittent power flow
- Variable fault current
- Operating modes
  - Grid-connected mode
  - Islanded mode
- Dynamic electricity markets

Impact of DERs on Protection

- Loss of protection coordination
- Sympathetic tripping
- Protection blinding
- Reclosing problem
- Dynamic protection zones

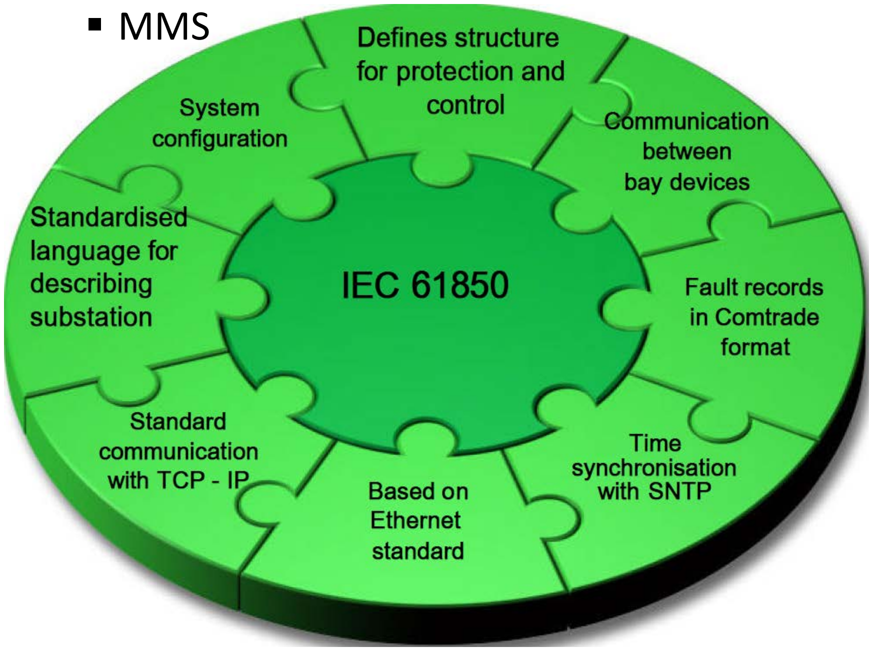
Background

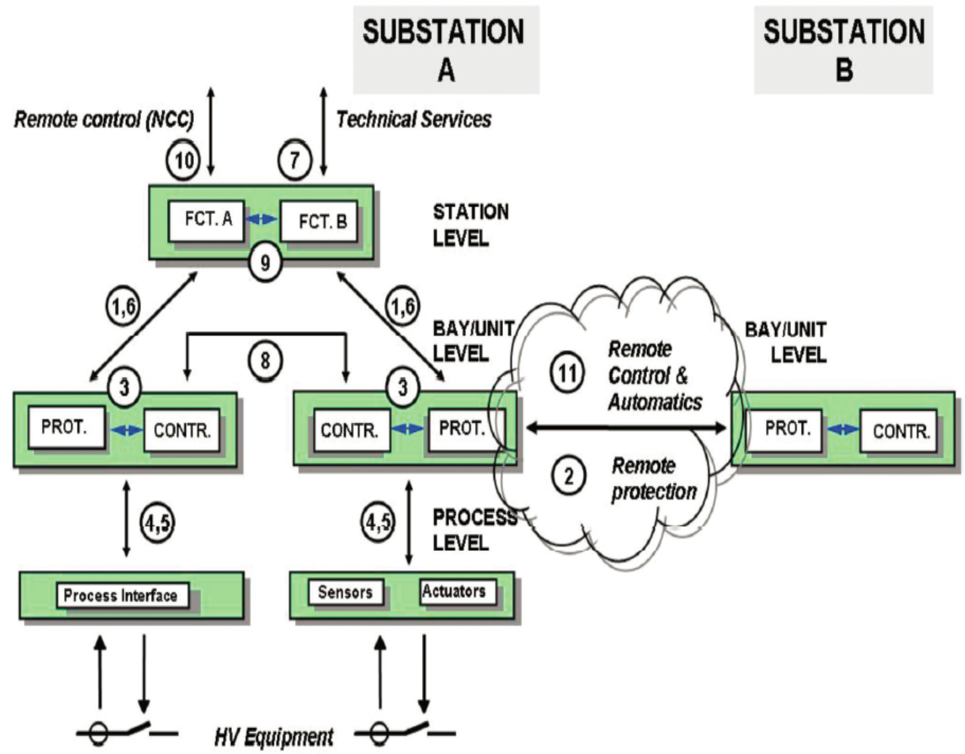

Robustness
Transmission-
Level Protection
Differential
Protection
Centralized
Protection
Our Focus
Distribution-Level
Protection
Overcurrent
Protection
Cost

Methodology

IEC 61850-Based Technology

- Object-oriented modelling approach
- IEC 61850 Services
  - Sampled Values (SVs)
  - GOOSE
  - MMS





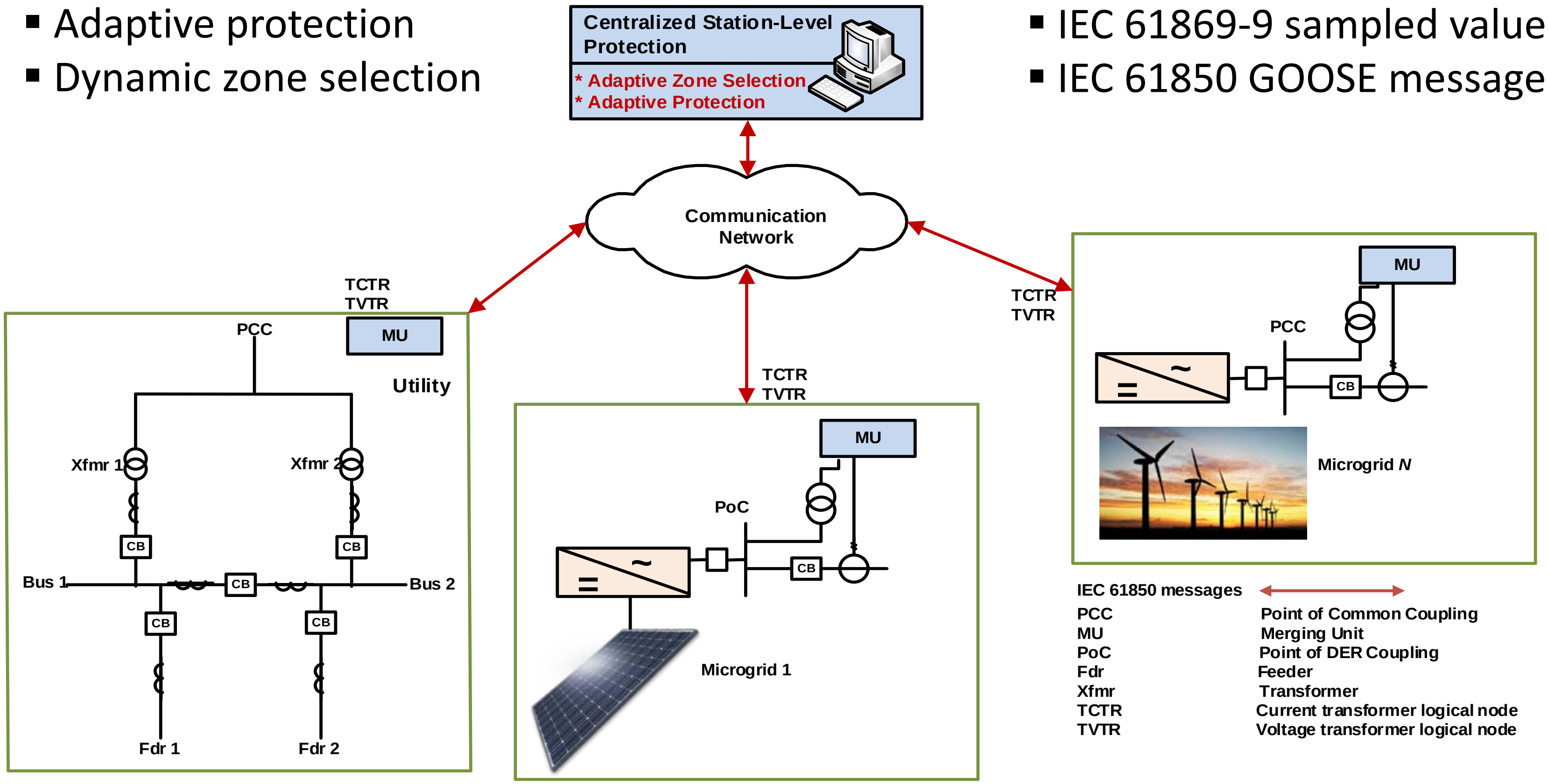
Logical levels and interfaces in IEC 61850 Standard

IEC 61850, “Communication networks and systems in substations,” International Electrotechnical Commission (IEC), 2003.

Methodology

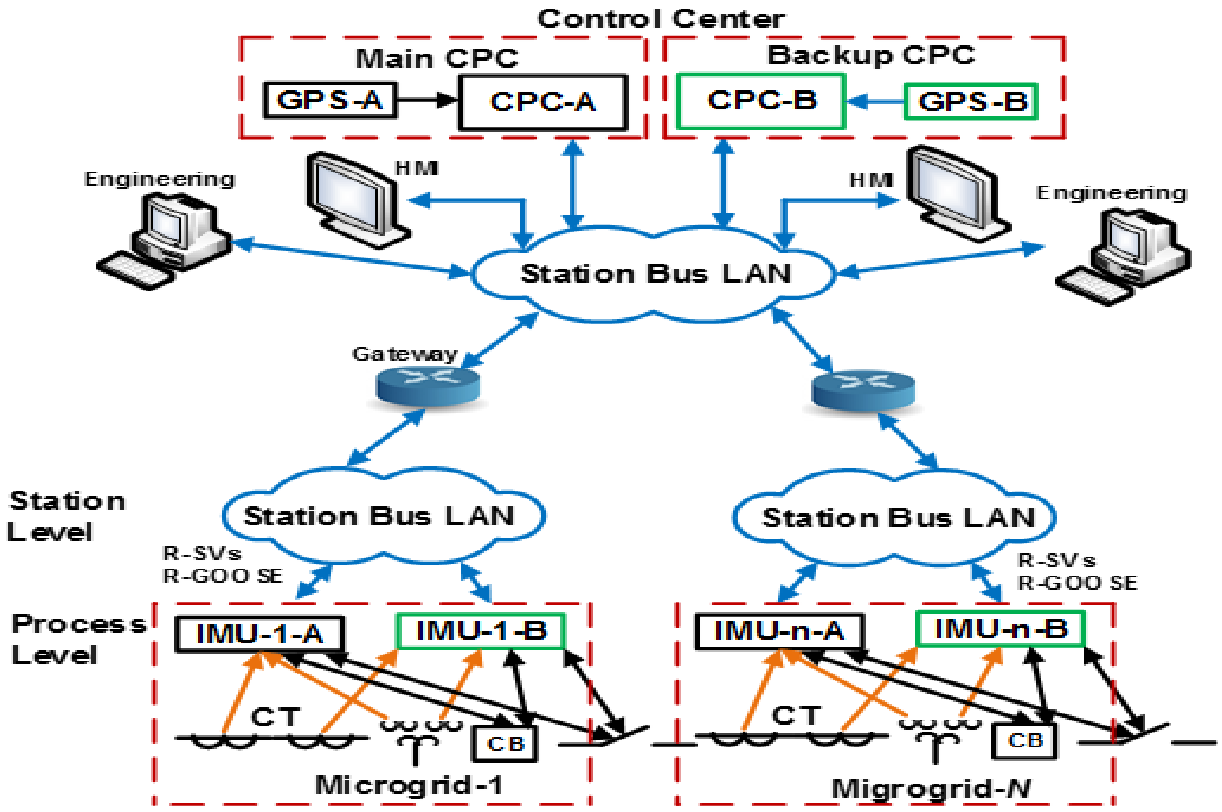
- Centralized station-level protection
  - Adaptive protection
  - Dynamic zone selection

- Explores digital power automation
  - IEC 61869-9 sampled values
  - IEC 61850 GOOSE messages



Centralized protection architecture for networked microgrids

Methodology



Proposed architecture for centralized protection of networked microgrids

Methodology

Centralized Intelligent Station-Level Protection (CISP):

- Sensor module
  - CTs/VTs or NCITs
  - IEC 61850/61869-9 Merging Units (MUs)

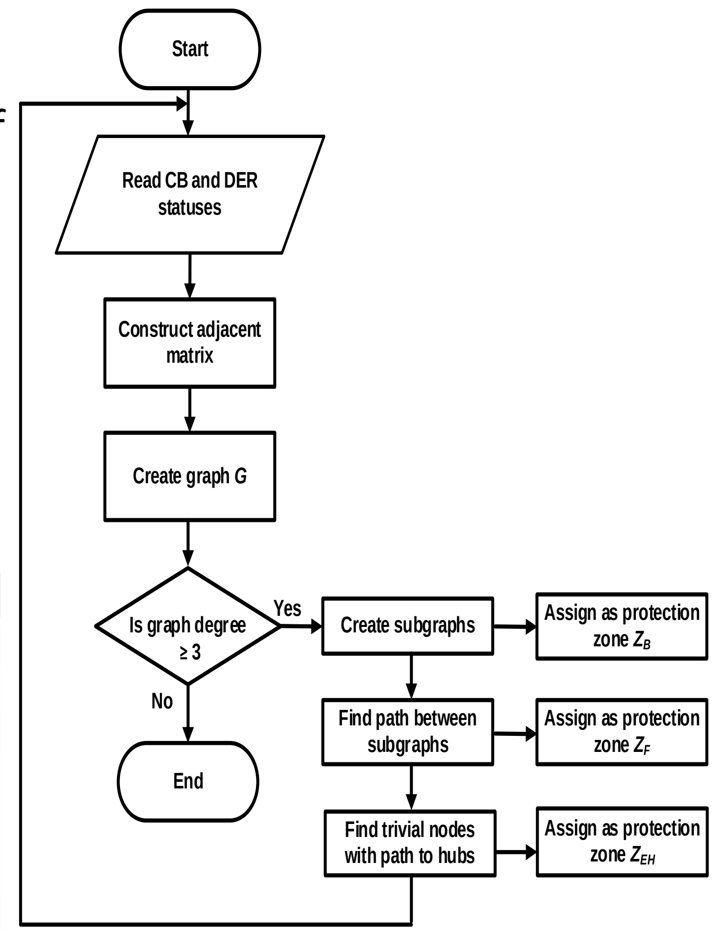
- Zone selection module
  - Graph theory-based topology processor
  - Zone selection

- Protection module
  - Supervised Current Differential (SCD)
  - Incremental Transient Energy (ITE) Directional Algorithm
  - Directional-Rate of Change of Current (D-ROCOC)

- Actuation module
  - Fault Interrupting Devices (FIDs)
  - Breaker failure algorithm

Methodology: Zone Selection

- Graph $G\{V, E\}$ using an a $n \times n$ adjacency matrix A. Vertices $V = \{v_0, v_1, \dots, v_n\}$ is a non-empty finite set of elements
- Edges $E = \{(v_0, v_1), \dots, (v_i, v_j), \dots, (v_m, v_n)\}$ is a finite set of unordered elements. An edge e_{ij} is a pair of vertices (v_i, v_j), and v_i and v_j are referred to as adjacent or neighboring vertices.

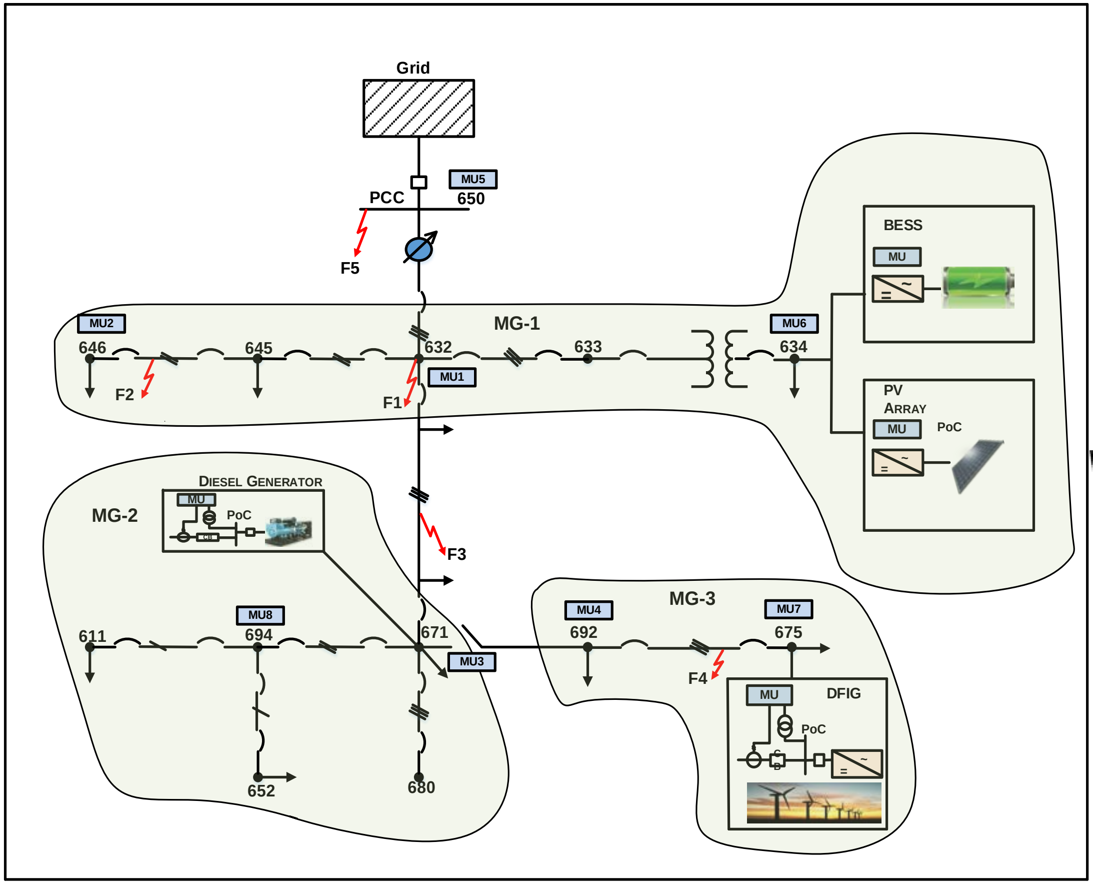


Zone selection flowchart

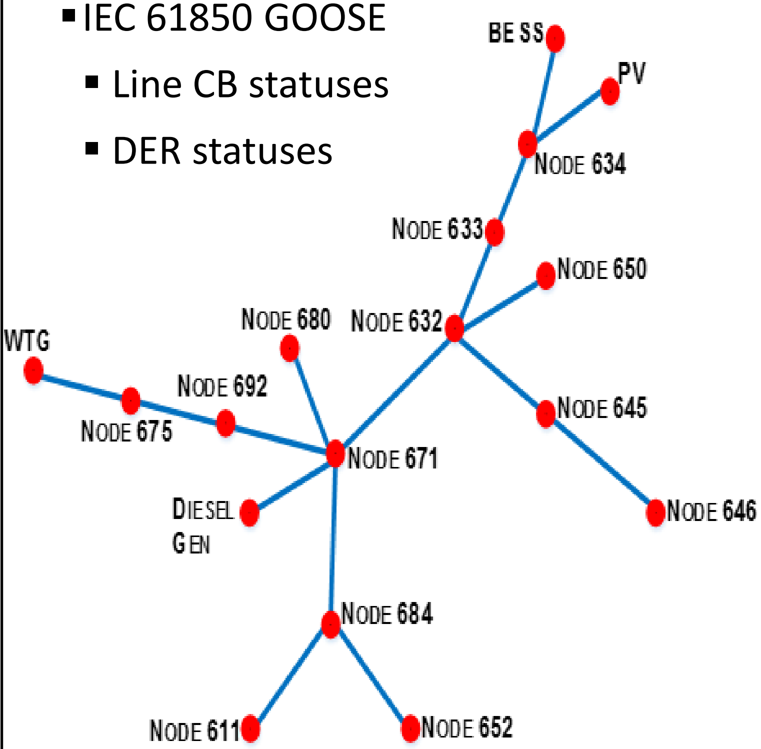
- Table I: Graph-zone descriptions used.

Graph Component	Description
Network graph	Networked microgrids (MGs)
Subnetworks	Individual MGs
Vertices	Busbars, nodes
Edges	Circuit Breakers (CBs), switches, disconnectors, CTs, CB-CT branches, fuses, power transformers
Subgraphs (Z_B)	Vertices with degree d(v) > d_{thr}.
Shortest path (Z_F)	Path between subgraphs
MG Diameter (Z_{EH})	Path between end vertices in the MGs and hubs

Methodology: Zone Selection



- Real-time
- Adaptive
- IEC 61850 GOOSE
  - Line CB statuses
  - DER statuses



Methodology: Protection Algorithms

ITE-Based Directional Algorithm

The voltage (v^{fault}) and current (i^{fault}) during the fault are:

$$v^{fault}(t) = v^{pre}(t) + \Delta v(t) \quad (1)$$

$$i^{fault}(t) = i^{pre}(t) + \Delta i(t) \quad (2)$$

where v^{pre} and i^{pre} are the prefault voltage and current quantities, Δv is the superimposed (incremental) voltage, and Δi is the superimposed current.

The differential (interphase) incremental transient energy is:

$$e_{inc,AB}(t) = \int_0^T \Delta v_{AB}(t) \cdot \Delta i_{AB}\, dt \quad (3)$$

$$e_{inc,CA}(t) = \int_0^T \Delta v_{CA}(t) \cdot \Delta i_{CA}\, dt \quad (4)$$

where $e_{inc,AB}$, Δv_{AB}, and Δi_{AB} are the differential incremental energy transient, incremental voltage, incremental currents between phases A and B.

$$\Delta i_{AB} = \left(i_A^{fault} - i_B^{fault}\right) - \left(i_A^{pre} - i_B^{pre}\right) \quad (5)$$

$$\Delta v_{AB} = \left(v_A^{fault} - v_B^{fault}\right) - \left(v_A^{pre} - v_B^{pre}\right) \quad (6)$$

Similar derivation applies for the differential quantities for phase CA.

Methodology: Protection Algorithms

Adaptive Supervised Current Differential (SCD)

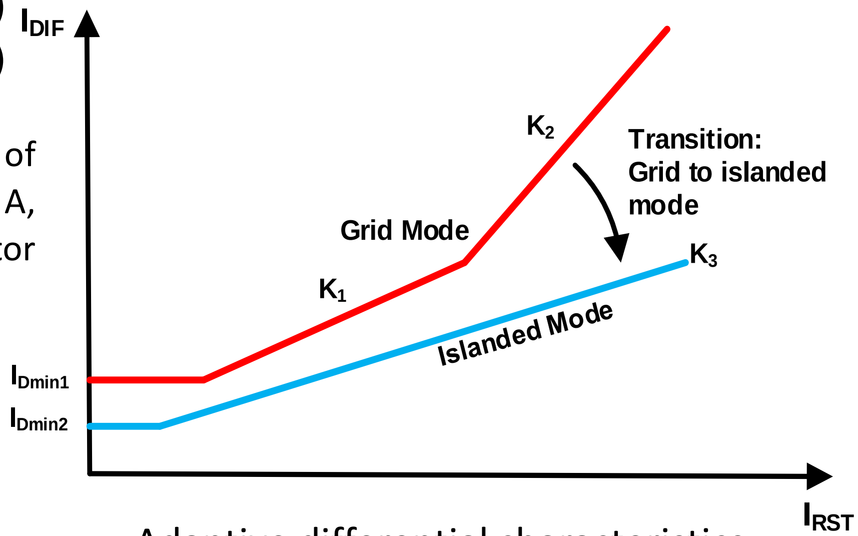
$$I_{DIF,Ph} = \left|\sum_{k=1}^{N} i_{k,Ph}(t)\right| \quad (7)$$

$$I_{RST,Ph} = k_{res} \times max\left|i_{k,Ph}(t)\right| \quad (8)$$

where i_k is the current at the kth terminal, N is the number of terminals connected to the protected zone, Ph denotes phases A, B, and C, and k_{res} is the restraining current multiplying factor (typically 0.5 or unity).

The dual slope percentage differential characteristic is:

$$I_{DIF,Ph} \geq \begin{cases} I_{Dmin,Ph} + K_1 I_{RST,Ph} & when\ I_{RST} < I_{R2,Ph} \\ I_{Dmin,Ph} + (K_1 - K_2) I_{R2,Ph} + K_2 I_{RST,Ph} & when\ I_{RST} \geq I_{R2,Ph} \end{cases} \quad (9)$$



Adaptive differential characteristics

Directional-Rate of Change of Current

The ROCOC at the jth path is given as: $\left|\frac{di^j}{dt}\right| = \frac{i_n^j - i_{n-1}^j}{\Delta T_s}$ (10)

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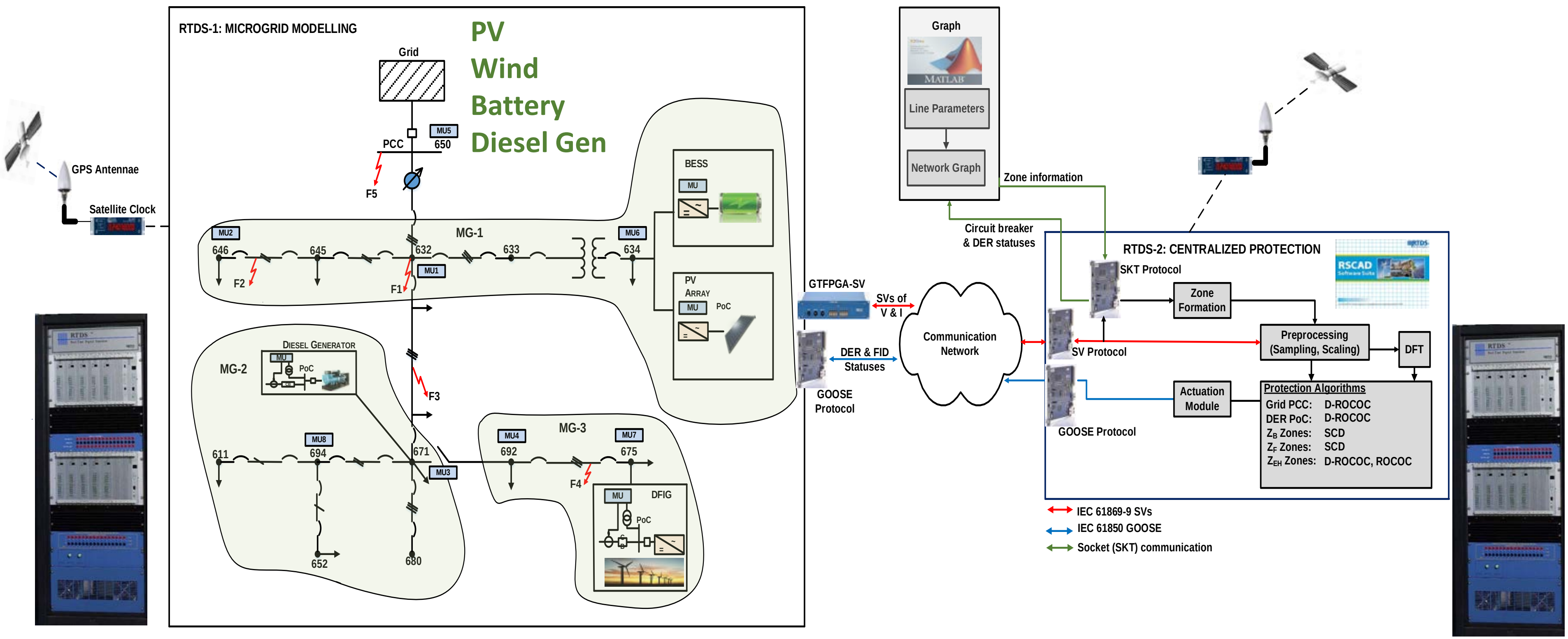
Hardware Implementation

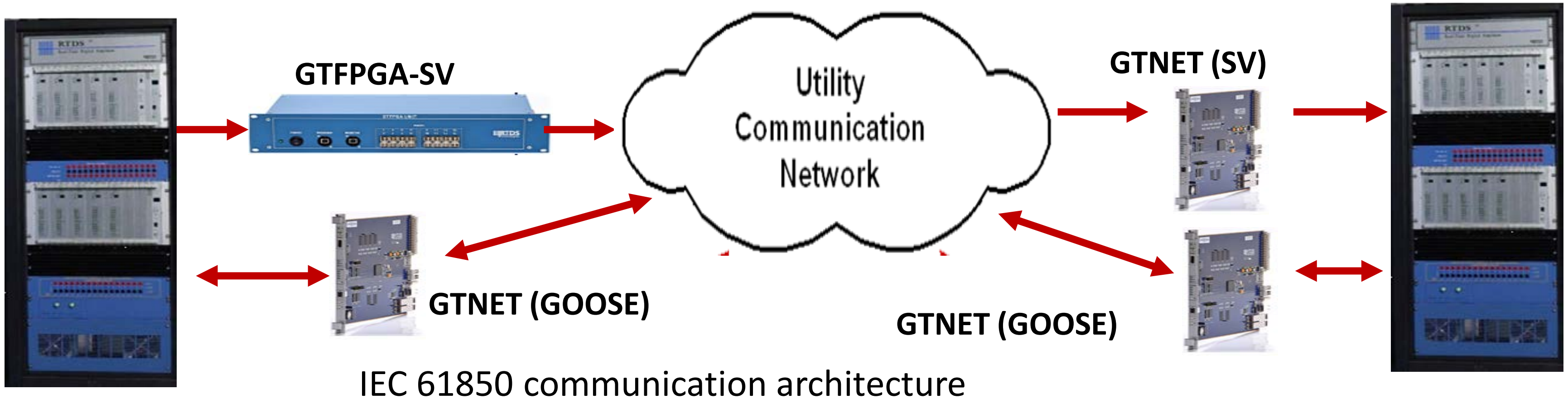
Power System Model

Centralized Protection



Hardware implementation architecture

Hardware Implementation



IEC 61850 communication architecture

- RTDS Rack-to-RTDS Rack: GTFPGA-SV publishing
  - Multiple streams of sampled values of currents and voltages
  - Sampling rate of 96 s/c
- RTDS Rack-to-RTDS Rack: GTNET-SV subscription
- RTDS Rack-to-RTDS Rack: GTNET-GOOSE subscription
- RTDS-to-MATLAB: GTNET SKT Protocol

Results: Zone Selection

0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0
0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1
0	1	0	0	0	0	0	1	0	0	1	1	0	1	0	0	0
0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0
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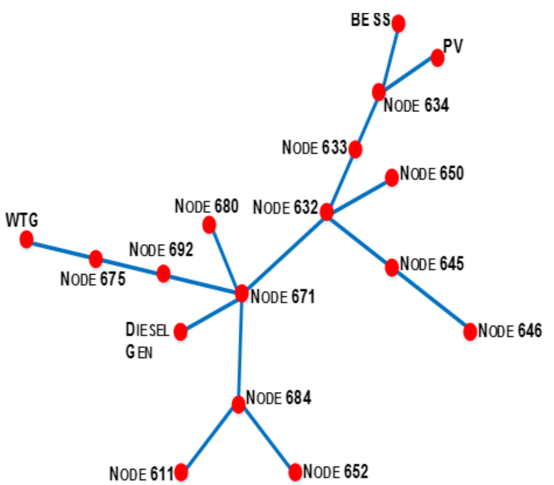
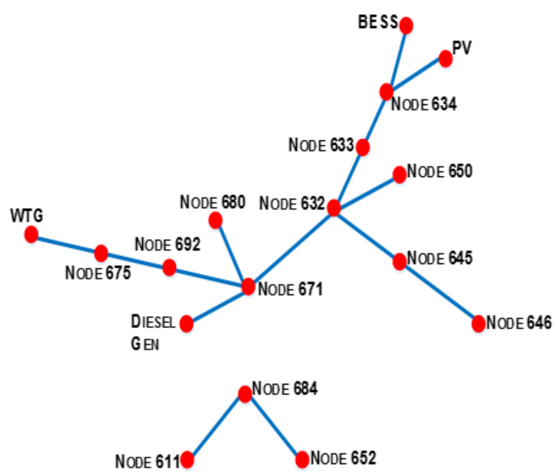
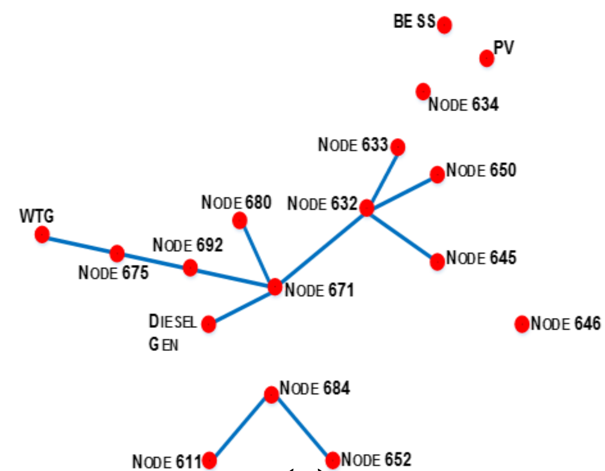
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



(a)



(b)



(c)

Adjacency matrix and graph for IEEE 13-node feeder (a) steady-state,
(b) Node-671-684 CBs open, (c) open CBs at Line 645-646, line 633-, PV, and BESS

Results: Zone Selection

TABLE III: Protection zones for some scenarios

Case study	Scenario	Number of Prot. zones	Protection zones
Case study-1	Steady-state (All CBs closed)	6	Z_B: {632,671,645,633}, {671,680,684,692}, {684,611,671,652} Z_F: {632-671}, {684-671} Z_{EH}: {646-632}
Case study-2	Node-671 CB open	5	Z_B:{632,671,645,633}, {671,680,684,692}, {684,611,671,652} Z_F: {684-671} Z_{EH}: {646-632}
Case study-3	Node-633, 645, 646, PV, BESS CBs open	4	Z_B:{632,671,645,633},{671, 680,684,692}, {684,611,671,652} Z_F: {684-671}

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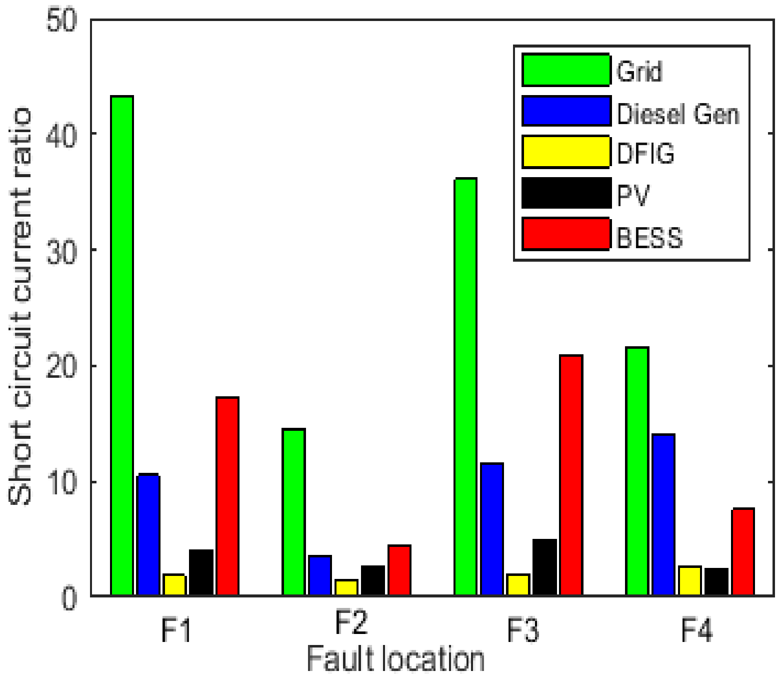
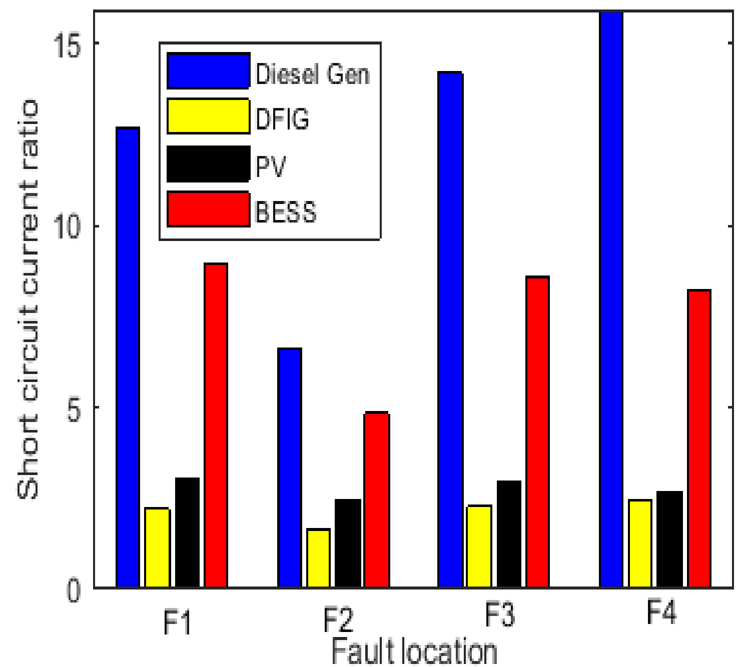
Results: Faults Currents from Sources



(a)



(b)

Fault current contributions (a) Grid-connected mode, (b) Islanded mode

$$I_{fault,m} = \left(Op_{bit,G} \times I_{k,G} \times I_{Grid}\right) + \sum_{i=1}^{j}\left(Op_{bit,i} \times I_{k,i} \times I_{DER,i}\right) \qquad (11)$$

where $Op_{bit,G}$ – operating mode of the grid

$Op_{bit,i}$ – operational DER(s) in the interconnected microgrids

$I_{k,G}$ and $I_{k,i}$ are the estimated average fault current multiplying factors from the grid and the *i*th DER in the microgrid, respectively.

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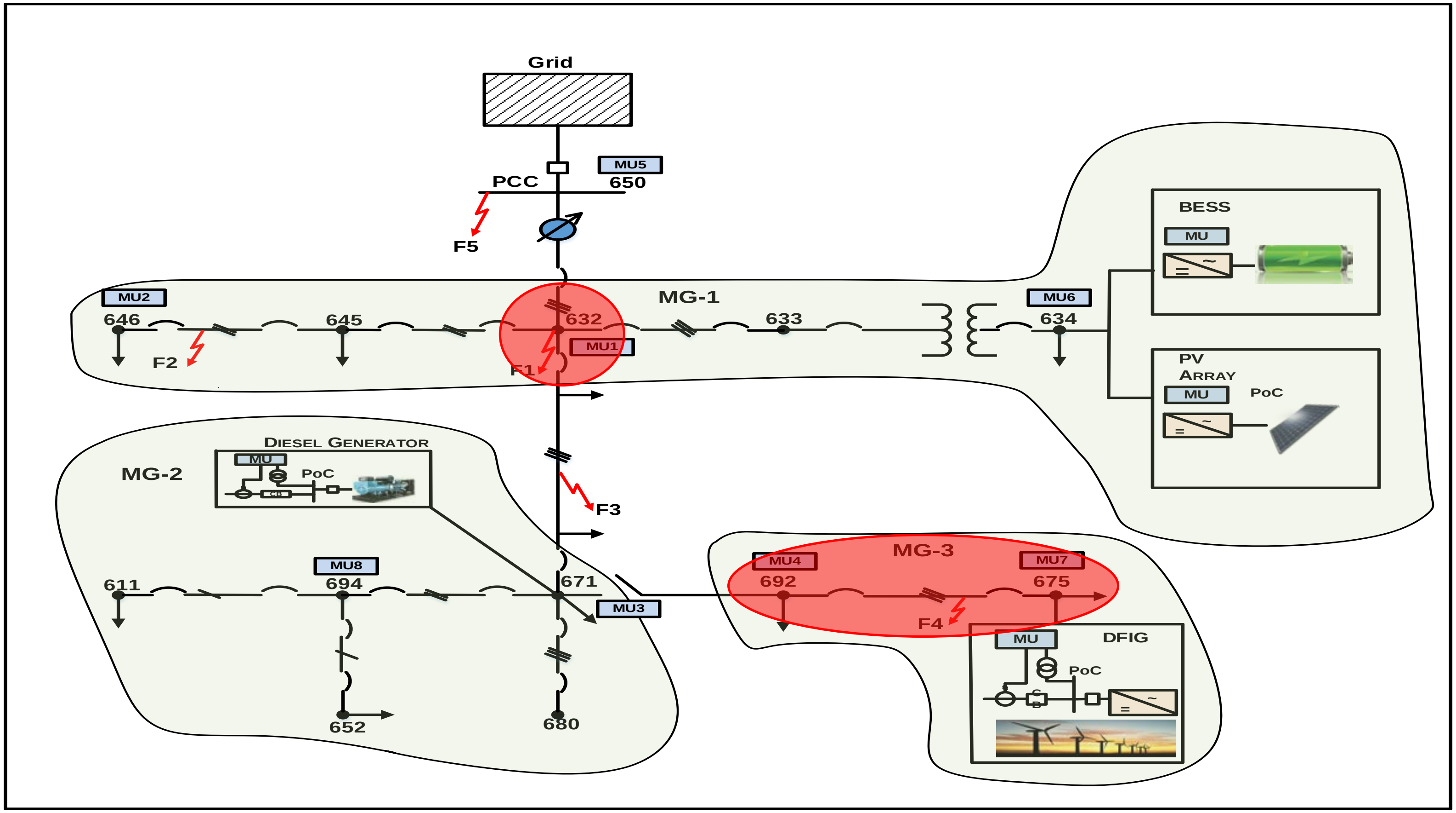
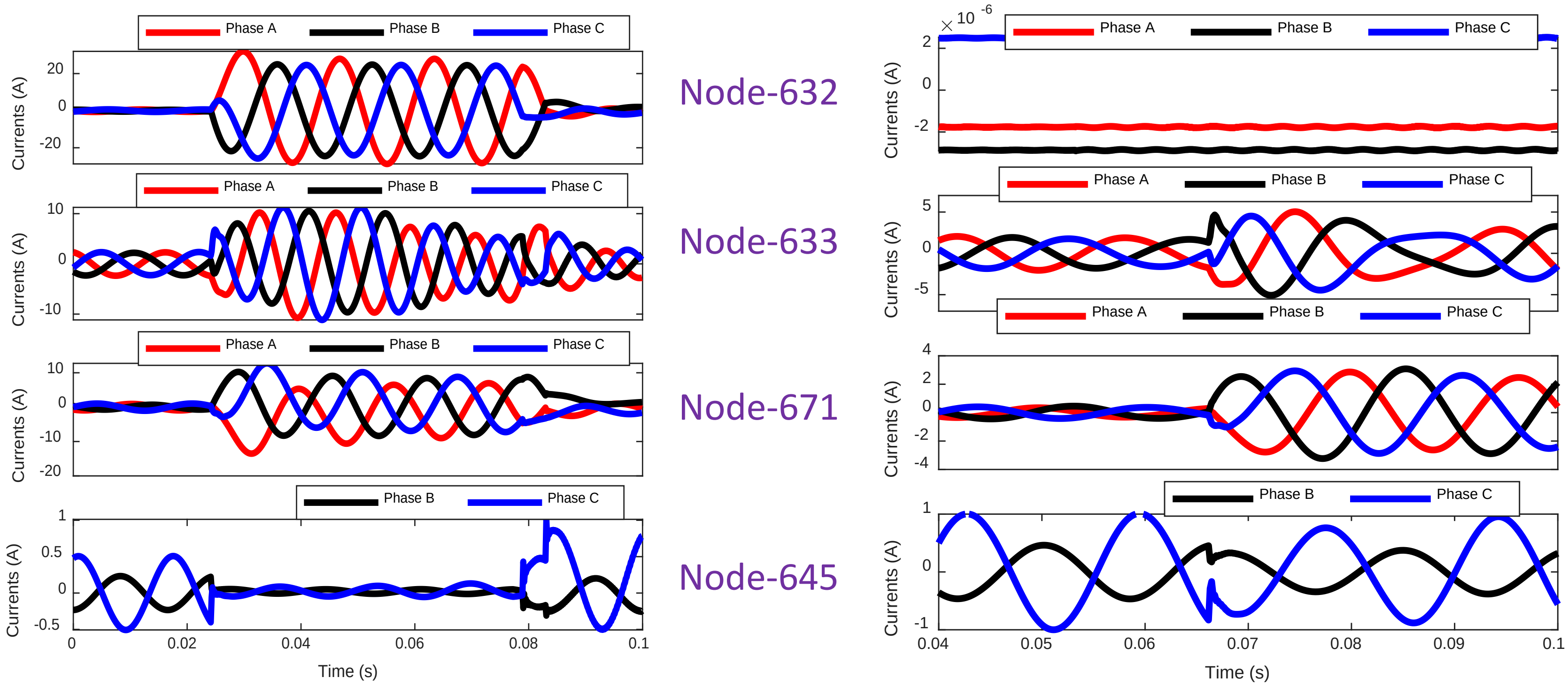
Results:


Grid
MU5
650
PCC
F5
MU2
646
F2
645
632
MU1
F1
MG-1
633
MU6
634
BESS
MU
PV
ARRAY
MU
PoC
MG-2
DIESEL GENERATOR
MU
PoC
F3
MU8
611
694
671
MU3
652
680
MG-3
MU4
692
MU7
675
F4
MU
DFIG
PoC

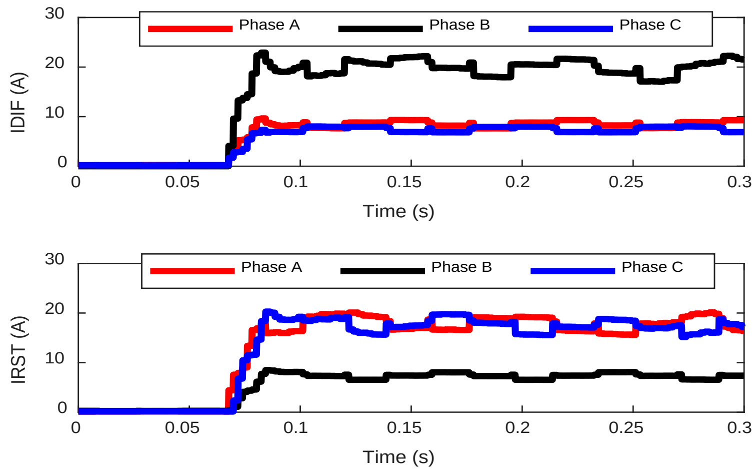
Results: Fault at Node-632 (F1)



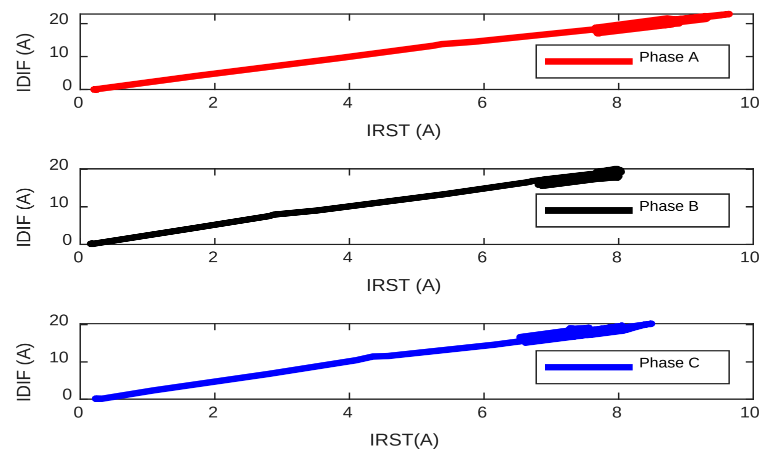
(a) (b)

Fault currents at F1 (Node-632) for (a) Grid-connected mode, (b) Islanded mode

Results: Fault at Node-632 (F1)

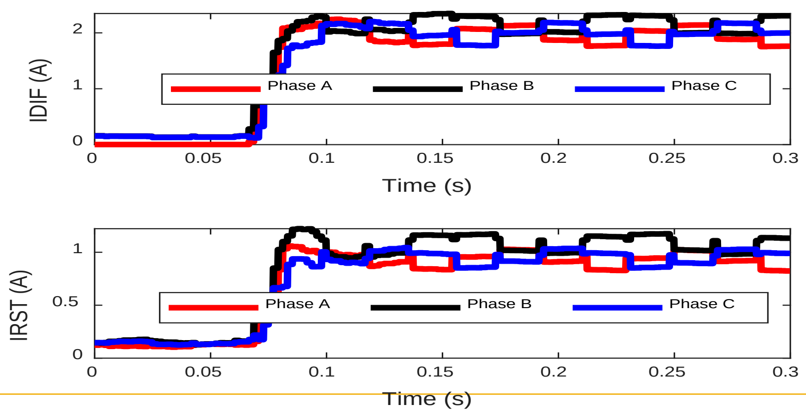


(a)

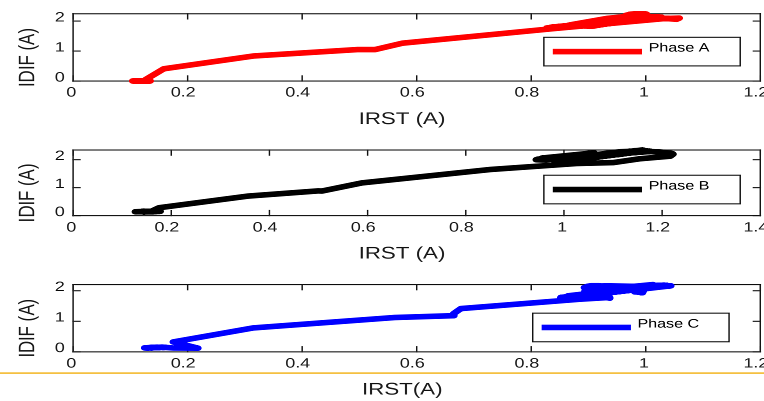


(b)

Fault at F1 in the grid-connected mode (a) I_{DIF} and I_{RST} and (b) $\frac{I_{DIF}}{I_{RST}}$.



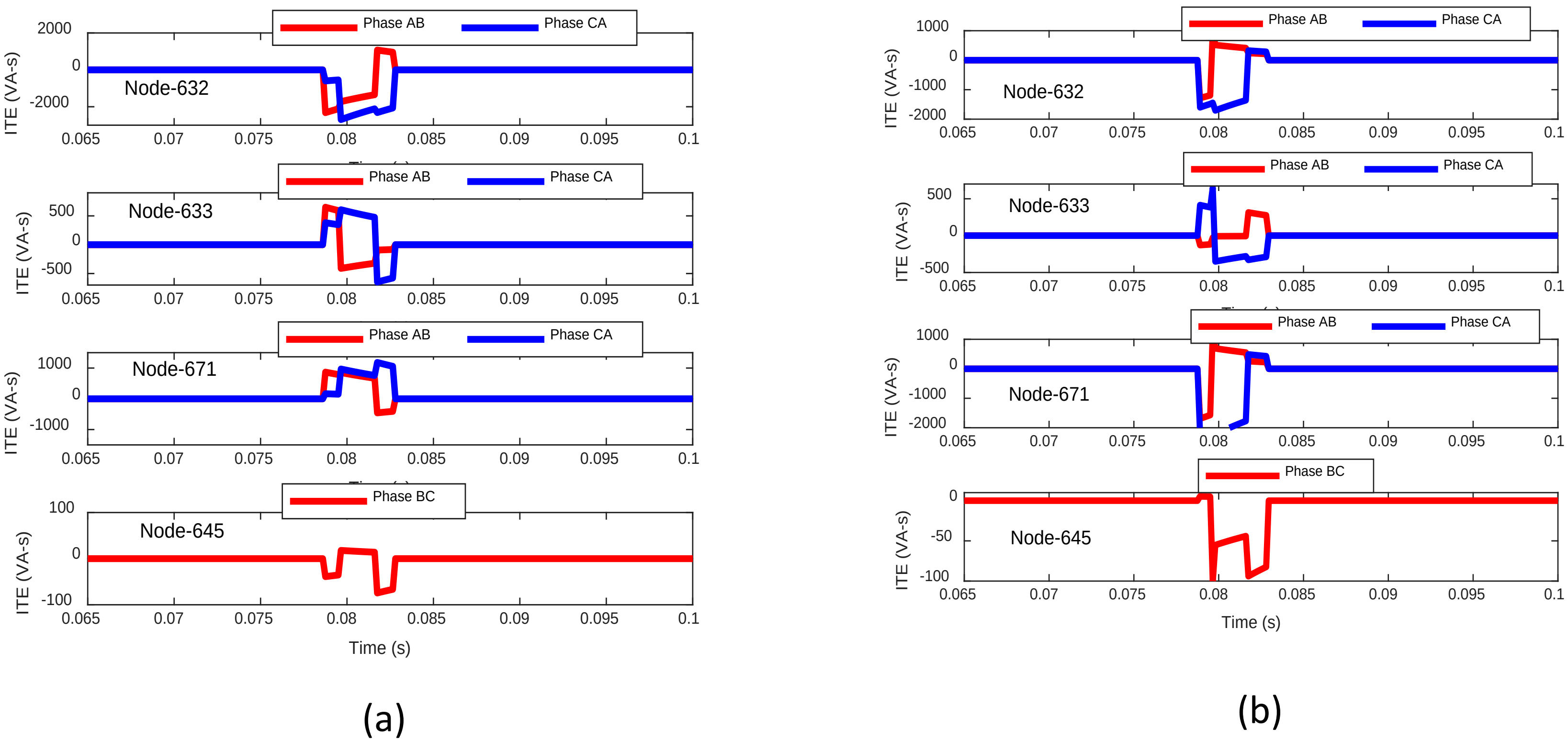
(a)



(b)

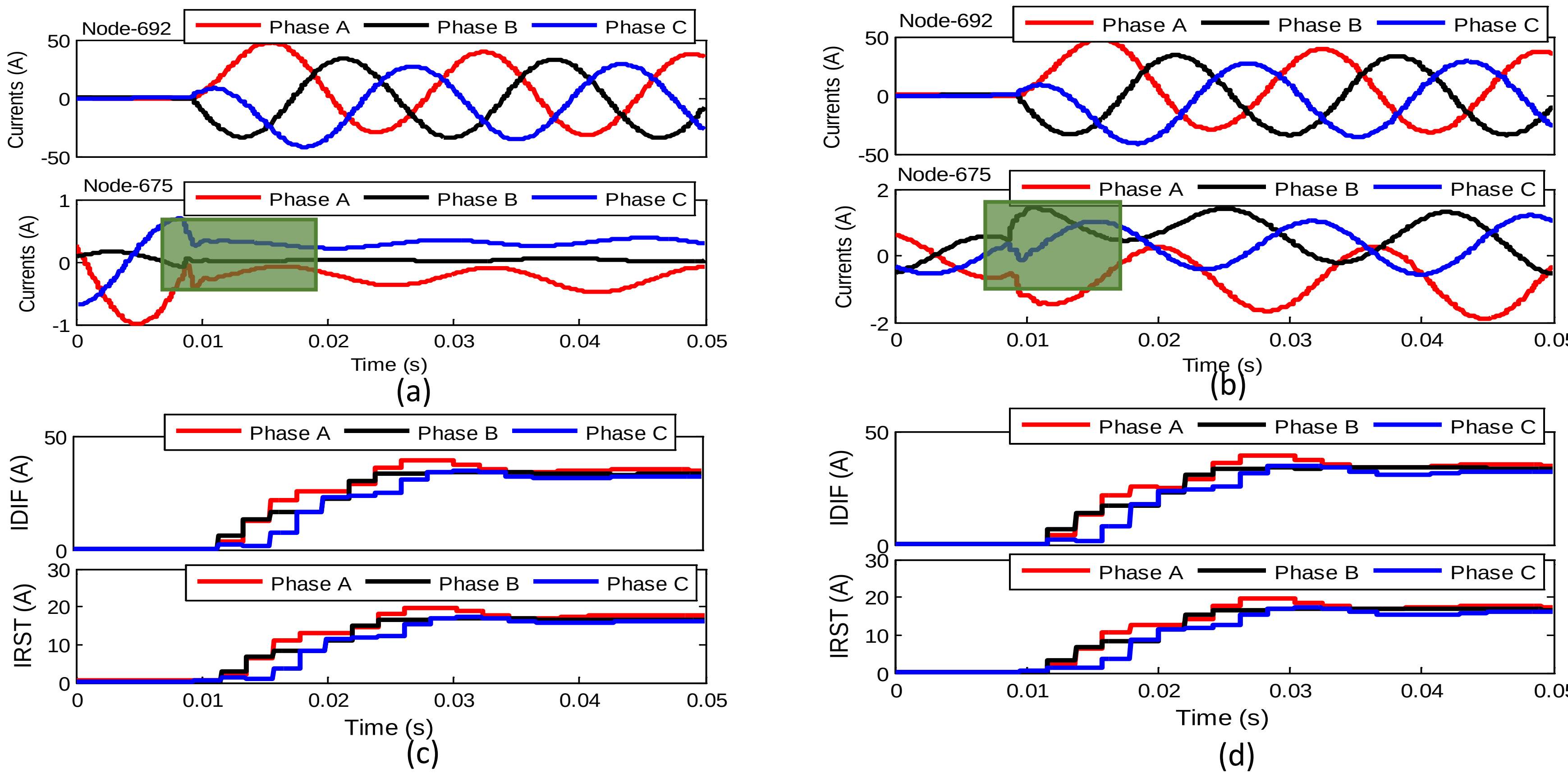
Fault at F1 in the islanded mode (a) I_{DIF} and I_{RST} and (b) $\frac{I_{DIF}}{I_{RST}}$.

Results: Fault at Node-632 (F1)



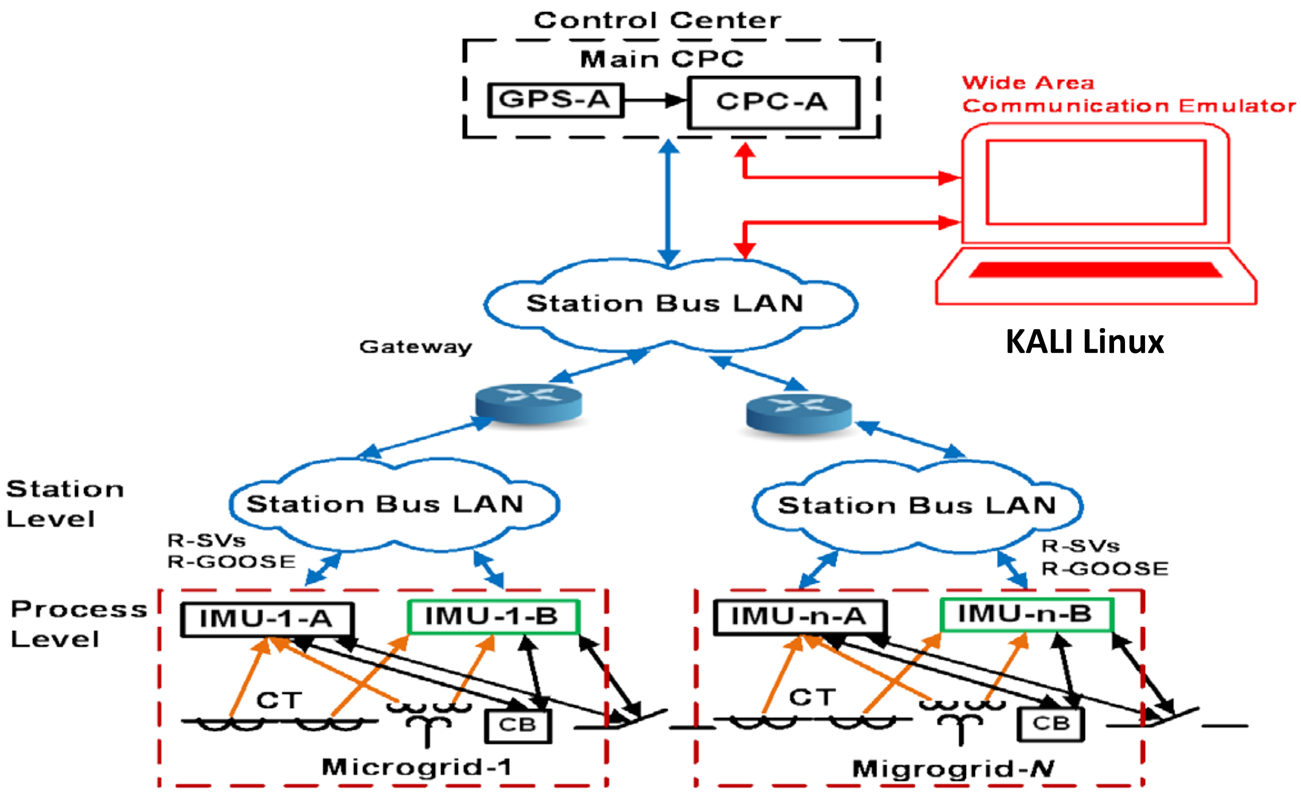
Directional ITE algorithm at Node-632 terminals for (a) internal fault at F1 and (b) external fault.

Results: Fault at Node-692-675 (F4)



Weak infeed scenario at F4 (a) without DER-3, (b) with DER-3, (c) I_{DIF} and I_{RST} without DER-3, (d) I_{DIF} and I_{RST} with DER-3.

Communication Network Emulator

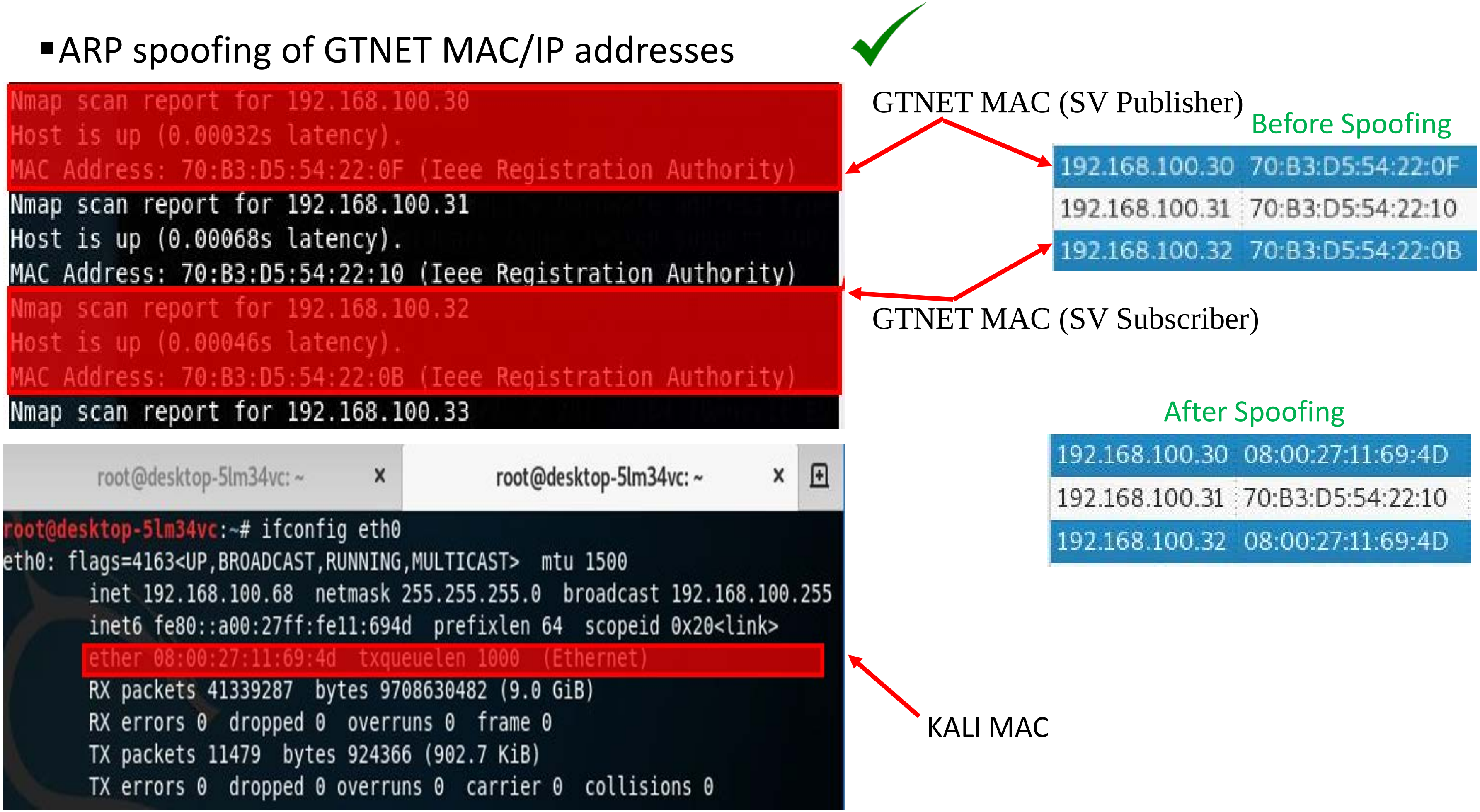


Emulate Communication QoS

- Delay
- Jitter
- Packet losses
- Corruption

Communication Network Emulation

- ARP spoofing of GTNET MAC/IP addresses



Communication Network Emulator

- ARP spoofing of GTNET MAC/IP addresses ✓
- Communication QoS for SKT communication ✓
- Communication QoS for MMS ✓
- Communication QoS for IEC 61850 SVs and GOOSE messages ✗

Conclusion

- **Deliverables**
  - IEC 61850-based lab-scale proof-of-concept microgrid protection testbed
  - Development of a centralized protection approach
  - Formulation of protection algorithms suitable for microgrids

- **Future work**
  - Impact of communication issues on centralized protection
  - Cyber security of electric power infrastructure
  - Deployment of the protection algorithms on an embedded system

Questions?

Comments