Blackstart Distribution Grids using DERs and Dynamic Formation of Networked Microgrids

Zhaoyu Wang
Professor
Department of Electrical and Computer Engineering
Iowa State University

Blackstart and Load Restoration

- A procedure to restart a power grid after widespread outages.

Step 1
- Turn on blackstart-capable generators.

Step 2
- Energize the cranking paths for starting other non-blackstart generators.

Step 3
- Pick up critical loads.

Step 4
- Synchronize islands.

Step 5
- Pick up non-critical loads.

Transmission System	Distribution System
Blackstart resources	
• Large generators with self-starting capability, e.g., hydro, gas-fired generators, etc. • Tens or hundreds of MW in size.	• Diesel generators. • Distributed renewables with battery energy storage systems. • Hundreds of kW in size.
Establishing cranking paths	
• Cranking paths are established while isolating loads. • Meshed in nature.	• Cranking paths are established while energizing non-switchable loads. • Radial in nature.
Transient stability concerns	
• High inertia and high short circuit capabilities.	• Low inertia and low short circuit capabilities.

Challenges of Blackstarting Dist. Sys. with DERs

- Cranking paths and load pickup optimization depend on the number and locations of grid-forming resources.
- Modeling challenges of Grid-forming Inverters and their synchronization.
  - Grid-forming inverters are the root generators*.
  - While synchronizing, for every two grid-forming inverters, one must change to non-root generator to satisfy radiality constraints.
- Incorporating binary switching decisions into a three-phase unbalanced power flow.
- Dynamic radiality constraints.
  - Radiality must be satisfied in every time step. However, existing studies only ensure radiality in the final topology.
  - Must have time-varying radiality constraints adaptive to changing numbers of active lines, buses, and root generators.
- Frequency stability constraints.
- Uncertainties.
  - Renewable generations and load demands.
  - Outage duration of the transmission grid.

* Root generator is a mathematical concept in graph theory to define a radiality constraint. It doesn't change the control structure of grid-forming inverters.

Blackstart and Load Restoration Problem

- The objective is to maximize the restored loads considering priorities.

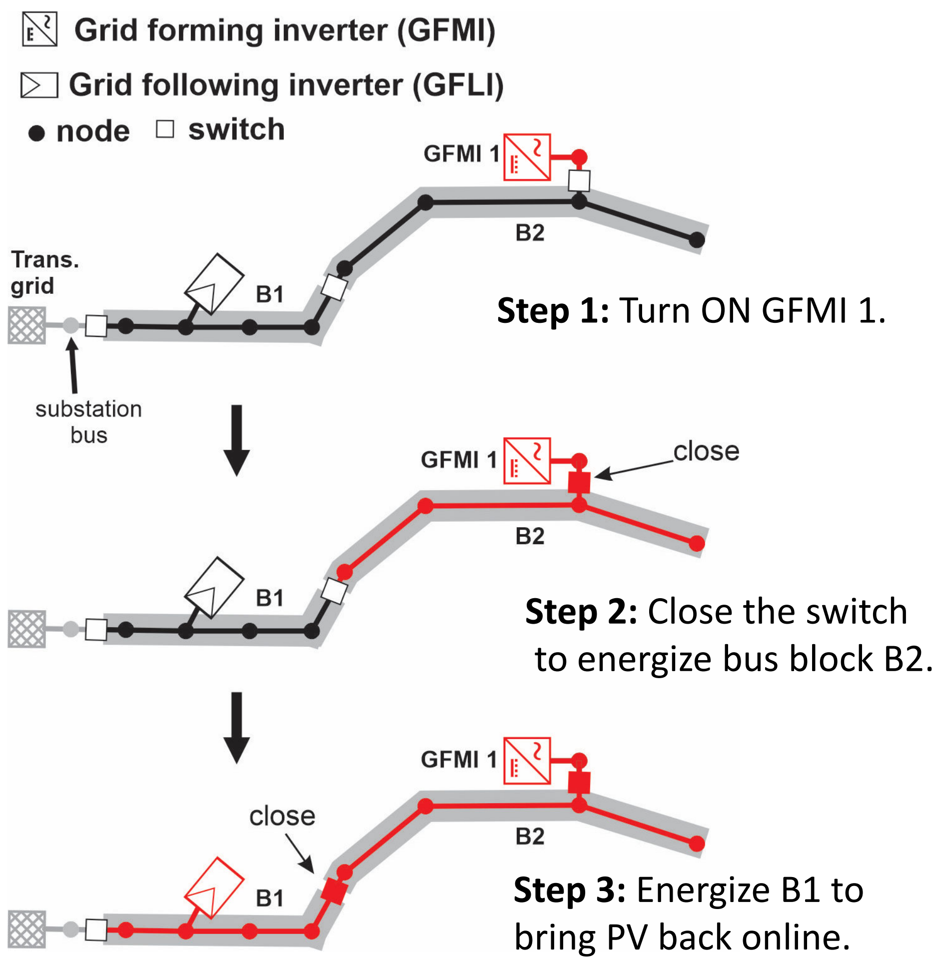
$$\max_{\boldsymbol{x}} \sum_{t \in \mathcal{T}} \left(\sum_{i \in \mathcal{B}_{CL} \cup \mathcal{B}_{NL}} P_{i,t} \right) \Delta t$$

- Subject to constraints:
  - Grid-forming inverter operation and synchronization.
  - Switching operations.
  - Dynamic radiality constraints.
  - Frequency constraints.
  - Distribution substation constraints (uncertain availabilities of transmission grid).
  - Three-phase unbalanced power flow constraints.
  - Cold load pick up
- Decision variables ($\boldsymbol{x}$):
  - Sequence of energizing cranking paths.
  - Sequence of activating grid-following resources.
  - Sequence of synchronizing decisions.
  - Sequence of load pickup.

Nomenclature:
$\mathcal{B}_{CL}$: set of buses with switchable load
$\mathcal{B}_{NL}$: set of buses with non-switchable load
$\mathcal{T}$: time horizon of problem
Δt: time step
$P_{i,t}$: power demand at time t in i^{th} bus

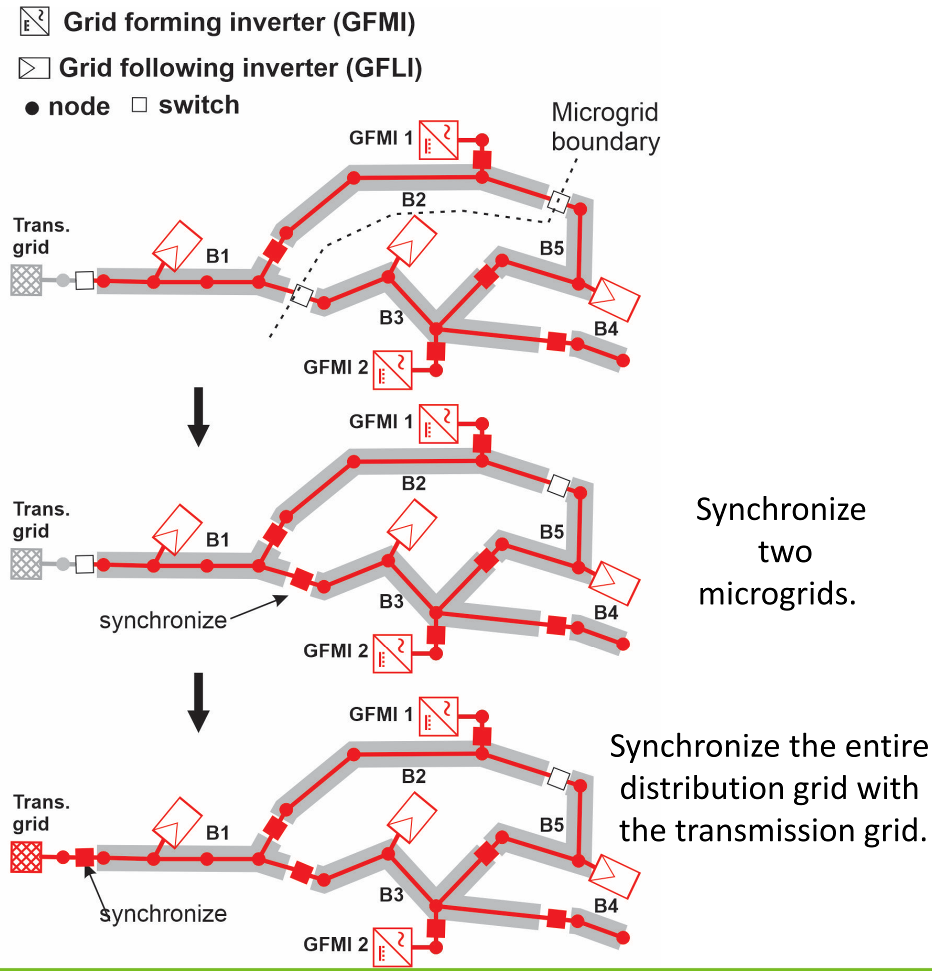
Cranking Paths Formation with One Grid-forming Inverter

- The distribution feeder comprises a chain of bus blocks separated by switches.
- A bus block refers to a cluster of buses that are interconnected by non-switchable lines.
- DERs with BESS are considered as Grid-forming inverters.
- Grid-forming inverter initiates the blackstart.
- Switch is closed to energize bus blocks one after another to enable grid-following inverters to come online.
- A series of switching actions to establish cranking paths is shown in the figure beside.



Synchronization of Two Microgrids

- Two GFMIs serve as root generators to initiate the blackstart at two locations.
- Switches are closed to expand the microgrid boundaries and cranking paths.
- Two microgrids are synchronized to interconnect the entire distribution grid. One of the GFMI is changed to non-root status to satisfy the radiality constraint.
- When the transmission grid is available, an entire distribution system is synchronized with the grid. To satisfy the radiality constraint, another GFMI is changed to non-root status.



BES-based Grid-Forming Inverter (GFMI)

- Our GFMI model is based on the control structure of a virtual synchronous generator.

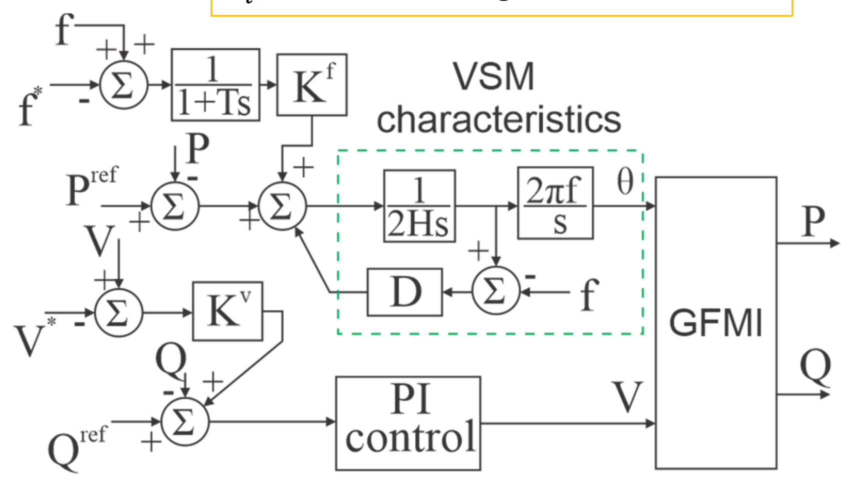
- To comply with the branch-flow model, we will use the square of voltage magnitude as the control variable of GFMI, as:

$$v_{i,n,t} = (V^*)^2 + \Delta v_{i,t}^{cc} \qquad \forall i \in \mathcal{R}, n \in \Phi$$
$$(0.95V^*)^2 \leq v_{i,n,t} \leq (1.05V^*)^2$$

- The quasi-steady state frequency of GFMI is defined as:

$$f_{i,t} = f^* \left(1 - \frac{\sum_{n\in\Phi} p_{i,n,t}^{ES}}{S_i^{rat}(D_i + K_i^f)}\right)$$
$$\lfloor f^{qss} \rfloor \leq f_{i,t} \leq \lceil f^{qss} \rceil$$

Nomenclature:
$v_{i,n,t}$: square of voltage magnitude.
V^*: Nominal voltage
$\mathcal{R}$: Set of buses containing GFMI
Φ: Set of phases
f^*: Nominal frequency
H_i: Inertia constant
D_i: Damping constant
K_i^f: Frequency droop
S_i^{rat}: Inverter rating



Dynamic Frequency Response of GFMI

- GFMI is required to comply its dynamic frequency response in terms of RoCoF and frequency-nadir for secure operation.
  - RoCoF:

$$f_{i,t}^{R} = \frac{\sum_{n\in\Phi} \Delta p_{i,n,t}^{ES}}{2S_i^{rat} H_i}$$

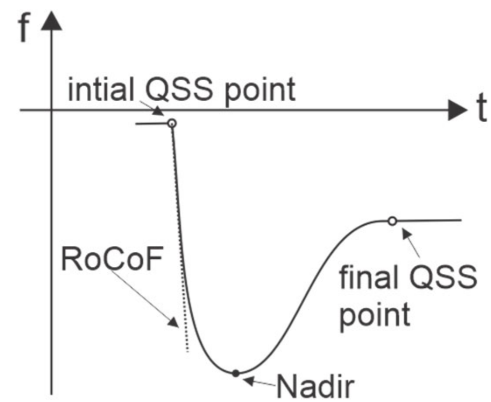
  - Frequency nadir:

$$f_{i,t}^{nad} = f_{i,t} - f^* \frac{\sum_{n\in\Phi} \Delta p_{i,n,t}^{ES}}{S_i^{rat}\left(D_i + K_i^f\right)} (1 + \gamma_i)$$

- Dynamic frequency constraints:

$$RoCoF^{min} \leq f_{i,t}^{R} \leq RoCoF^{max}$$
$$f^{min} \leq f_{i,t}^{nad} \leq f^{max}$$

Nomenclature:
$f_{i,t}^{R}$: Rate of change of frequency (ROCOF).
$p_{i,n,t}^{ES}$: Active power BES-based GFMI
γ_i : Constant exponential term
Φ: Set of phases
f^*: Nominal frequency
H_i: Inertia constant
D_i: Damping constant
K_i^f: Frequency droop
S_i^{rat}: Inverter rating



Modeling Synchronization of GFMIs

- GFMI needs to adapt its frequency set-points to allow synchronization with other GFMIs.
- It is achieved by allowing to change frequency-setpoint of GFMI while performing synchronization.

$$f_{i,t} = f^* \left(1 - \frac{\sum_{n\in\Phi} p_{i,n,t}^{ES}}{S_i^{rat}(D_i + K_i^f)}\right) + \delta_{i,t}\, \Delta f_{i,t}^*$$

- $\delta_{i,t}$ is a binary variable that is set to 1 only during the synchronizing.
- The above formulation leads to a master-slave synchronization, where a GFMI can only change its f^* when it is synchronizing.
- We implement a co-operative synchronization approach, allowing all GFMIs to decide a suitable synchronizing frequency, as:

$$f_{i,t} = f^* \left(1 - \frac{\sum_{n\in\Phi} p_{i,n,t}^{ES}}{S_i^{rat}(D_i + K_i^f)}\right) + \left(\sum_{b\in\mathcal{R}} \delta_{b,t}\right) \Delta f_{i,t}^*$$

Nomenclature:
$\Delta f_{i,t}^*$: Perturbation in nominal frequency set-point (f^*).
$\delta_{i,t}$: Binary decision variable, which is set to be 1 during synchronizing period.

Switching Structure of the Distribution System

- Blackstart and restoration depends on switching structure that may comprise of
  - Bus blocks
  - Energizing switches
  - Synchronizing switches

Nomenclature:
y_i^B : status of i^th bus
y_{ij}^L: status of a line (i, j)
y_m^{BB} : status of bus block m

Modeling Bus Block Energization

- A bus block is segregated by multiple switches and will be energized by closing any of them.

$$y_{m,t}^{BB} \geq y_{ij,t}^{SW} \quad \forall switches\ (i,j) in\ bus\ block\ m$$

- After a bus block is energized, statuses of all buses and lines in this bus block must be changed to active.

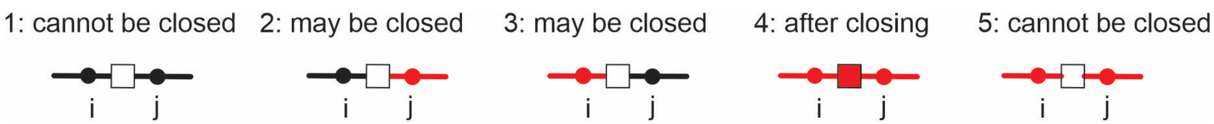
$$y_{ij,t}^{L} = y_{m,t}^{BB} \quad \forall lines\ in\ bus\ block\ m \quad and \quad y_{i,t}^{B} = y_{m,t}^{BB} \quad \forall buses\ in\ bus\ block\ m$$

- Once a bus block status is active, it should not be inactive again.

$$y_{m,t}^{BB} \geq y_{m,t-1}^{BB}$$

Modeling Energizing Switch (ESW)

- ESWs are turned ON to power the inactive bus blocks.
- Breaker, reclosers, or tie-switches.
- An energizing switch (i, j) may have five states while blackstarting.



- All five states of the switch can be defined as:

states	$y^B_{i,t-1}$	$y^B_{j,t-1}$	$y^{SW}_{ij,t-1}$	$\Delta y^{SW}_{ij,t}$
1	0	0	0	$\Delta y^{SW}_{ij,t}=0$
2	0	1	0	$\Delta y^{SW}_{ij,t} \leq 1$
3	1	0	0	$\Delta y^{SW}_{ij,t} \leq 1$
4 (after closing)	1	1	1	$\Delta y^{SW}_{ij,t}=0$
5	1	1	0	$\Delta y^{SW}_{ij,t}=0$

$$y^{SW}_{ij,t} \leq y^B_{i,t-1} + y^B_{j,t-1}$$
$$\Delta y^{SW}_{ij,t} = y^{SW}_{ij,t} - y^{SW}_{ij,t-1}$$
$$\Delta y^{SW}_{ij,t} \leq 2 - y^B_{i,t-1} - y^B_{j,t-1}$$
$$\Delta y^{SW}_{ij,t} \geq 0$$

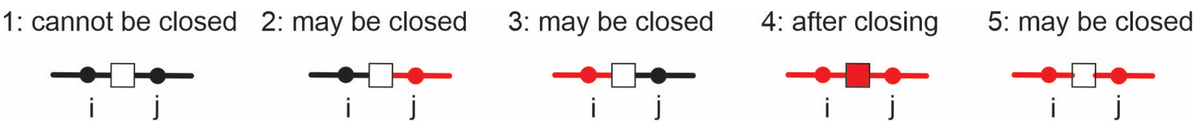
Nomenclature:
$y^B_{i,t}$: status of i^{th} bus
$y^{SW}_{ij,t}$: status of a switch (i, j)
$\Delta y^{SW}_{ij,t}$: change of switch status
$f_{i,t}$: frequency at bus i

- When a switch (i, j) is closed, $f_i = f_j$, whereas when switch is open $f_i \neq f_j$

$$-(1 - y^{SW}_{ij,t})M \leq f_{i,t} - f_{j,t} \leq (1 - y^{SW}_{ij,t})M$$

Modeling a Synchronizing Switch (SSW)

- Switch equipped with Intelligent Electronic Device that facilitate synchronization.
- SSWs can energize bus blocks or synchronize the microgrids.
- An SSW (i, j) may have five states while blackstarting.



- All five states of the switch can be defined as:

states	$y^B_{i,t-1}$	$y^B_{j,t-1}$	$y^{SW}_{ij,t-1}$	$\Delta y^{SW}_{ij,t}$
1	0	0	0	$\Delta y^{SW}_{ij,t} = 0$
2	0	1	0	$\Delta y^{SW}_{ij,t} \leq 1$
3	1	0	0	$\Delta y^{SW}_{ij,t} \leq 1$
4 (after closing)	1	1	1	$\Delta y^{SW}_{ij,t} = 0$
5 (before closing)	1	1	0	$\Delta y^{SW}_{ij,t} \leq 1$

$$y^{SW}_{ij,t} \leq y^B_{i,t-1} + y^B_{j,t-1}$$

$$\Delta y^{SW}_{ij,t} = y^{SW}_{ij,t} - y^{SW}_{ij,t-1}$$

$$\Delta y^{SW}_{ij,t} \geq 0$$

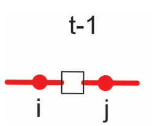
Nomenclature:
$y^B_{i,t}$: status of i^th bus
$y^{SW}_{ij,t}$: status of a switch (i, j)
$\Delta y^{SW}_{ij,t}$: change of switch status
$f_{i,t}$: frequency at bus i

- When a switch (i, j) is closed, $f_i = f_j$, whereas when switch is open $f_i \neq f_j$

$$-(1 - y^{SW}_{ij,t})M \leq f_{i,t} - f_{j,t} \leq (1 - y^{SW}_{ij,t})M$$

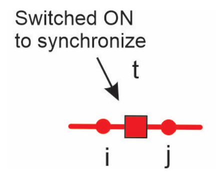
Power Flow Constraint for SSW

- While closing an SSW, ideally the power flow across it should be zero.
- This is imposed to match the voltage magnitude and angle of bus i and j across the switch (i, j).



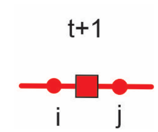
$P_{ij,t-1} = 0$

$Q_{ij,t-1} = 0$



$-\epsilon \leq P_{ij,t} \leq \epsilon$

$-\epsilon \leq Q_{ij,t} \leq \epsilon$



$-M \leq P_{ij,t+1} \leq M$

$-M \leq Q_{ij,t+1} \leq M$

Nomenclature:

$P_{ij,t}$: Active power across (i, j)

$Q_{ij,t}$: Reactive power across (i, j)

$z_{ij,t}$: binary variable defining synchronizing instant.

- At synchronizing time-step, the following condition holds.

$$z_{ij,t} = \Delta y_{ij,t}^{SW} \left(y_{i,t-1}^{B} + y_{j,t-1}^{B} - y_{ij,t}^{SW} \right) \quad \rightarrow 1$$

- The above three states of power flow across SSW is defined with respect to $z_{ij,t}$.

$$-(1 - z_{ij,t})M - \epsilon \leq P_{ij,t} \leq \epsilon + (1 - z_{ij,t})M$$
$$-(1 - z_{ij,t})M - \epsilon \leq Q_{ij,t} \leq \epsilon + (1 - z_{ij,t})M$$

Dynamic Radiality Constraints

- Generally, radiality constraint states: $\sum lines = \sum buses \ - \sum root\ buses$
- In black start problem, the number of active lines, buses, and root buses are dynamic.

$$\sum_{(i,j)\in\mathcal{L}} y_{ij,t}^{L} = \sum_{b\in\mathcal{B}} y_{b,t}^{B} + \sum_{b\in\mathcal{B}_{ss}} y_{b,t}^{SS} - R_t$$

$$where,$$

$$R_t = \sum_{b\in\mathcal{R}} y_{\mathrm{b},t}^{ES} + \sum_{b\in\mathcal{B}_{ss}} y_{b,t}^{SS}$$

$$y_{\mathrm{b},t}^{ES} \le y_{\mathrm{b},t-1}^{ES} \quad \forall b \in \mathcal{R}$$

- Considering R_t as an optimization variable allows synchronization of islands.
- GFMI are assigned to be root generator ($y_{\mathrm{b},t=0}^{ES}$ = 1) when the black start is initiated.
- When a GFMI generator is switched to non-root status, the synchronizing binary variable ($\delta_{b,t}$) is activated, as:

$$y_{\mathrm{b},\tau}^{ES} = 1 - \sum_{t\in[t_0,\tau]} \delta_{b,t} \ \forall b \in \mathcal{R}$$

Nomenclature:

y_{ij}^{L}: status of line (i, j)

$\mathcal{L}$: set of lines

y_{i}^{B}: status of i[th] bus

$\mathcal{B}$: set of buses

$y_{b,t}^{SS}$: status of substation bus

$\mathcal{B}_{ss}$: set of substation buses

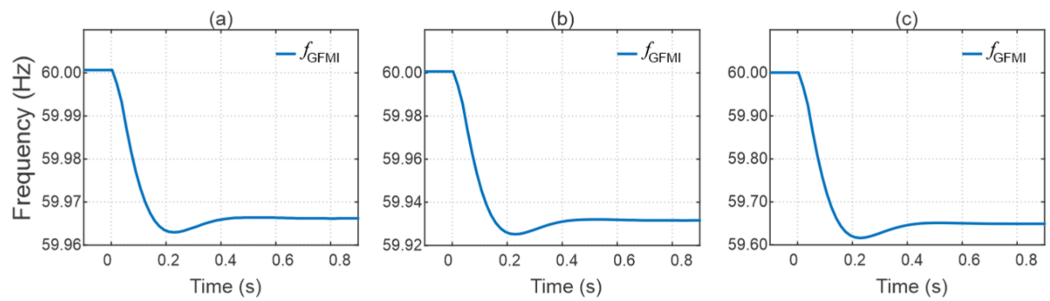
R_t: number of root buses, i.e., grid-forming inverters

$y_{i,t}^{ES}$: status of GFMI as a root generator

$\mathcal{R}$: set of buses with GFMI.

Verification of Dynamic Frequency Response from a GFMI

- RMS model of IEEE 123 feeder with VSG-based GFMI was developed in DigSILENT PowerFactory.
- The dynamic frequency responses of GFMI are recorded for 1, 2, and 10 MW load pickups.
- Measure the estimation accuracy for
  - Quasi-steady state frequency
  - RoCoF
  - Frequency nadir
- The estimation accuracy are above 90%.
- Note that, the dynamic frequency responses are estimated without requiring to run dynamic models.



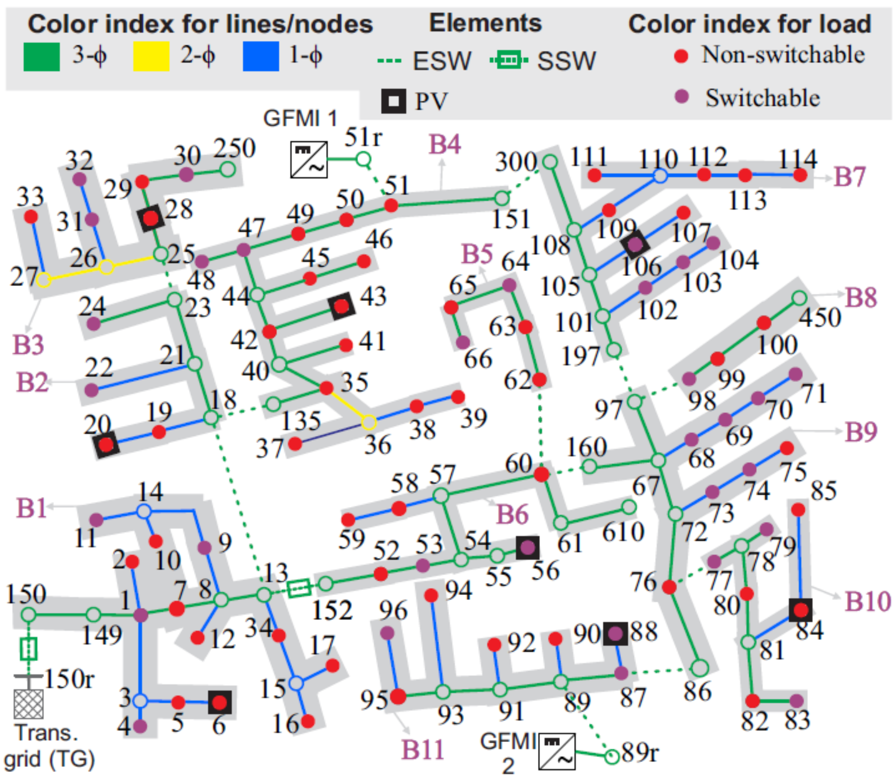
VALIDATION OF ESTIMATED FREQUENCY RESPONSES

Pick-up load (MW)	1	2	10
Measured $\dot{f}$ (Hz/s)	-0.3529	-0.7058	-3.6106
Estimated $\dot{f}$ (Hz/s)	-0.3780	-0.7500	-3.7500
Accuracy of $\dot{f}$ (%)	92.89	93.74	96.14
Measured f^{nad} (Hz)	59.9629	59.9251	59.6161
Estimated f^{nad} (Hz)	59.9635	59.9272	59.6357
Accuracy of f^{nad} (%)	98.38	97.20	94.89
Measured f^{qss} (Hz)	59.9662	59.9316	59.6490
Estimated f^{qss} (Hz)	59.9666	59.9333	59.6666
Accuracy of f^{qss} (%)	98.82	97.51	94.99

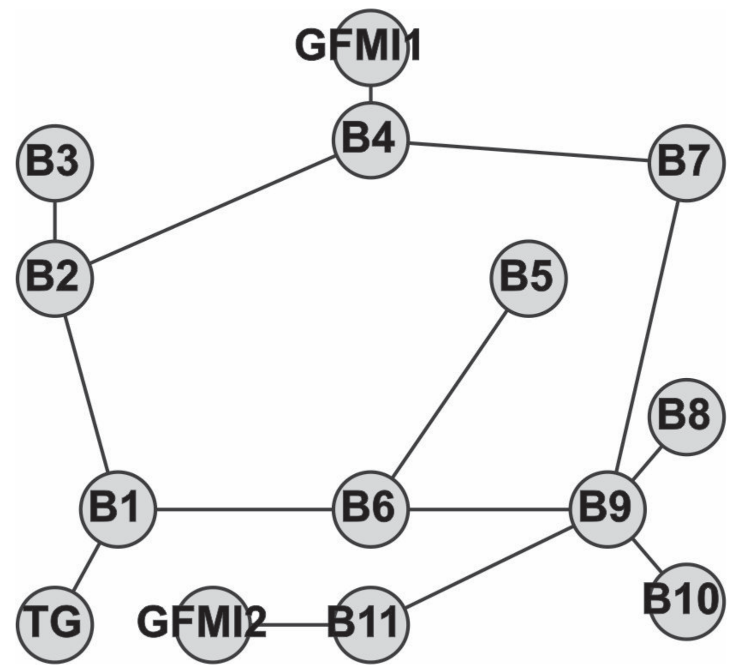
VSG-BASED GFMI PARAMETERS

Parameters	values in pu
(H, D, K^f, γ)	(4,1, 89, 0.093)

Case Studies with IEEE 123-Bus System



Graph representation of IEEE 123 system



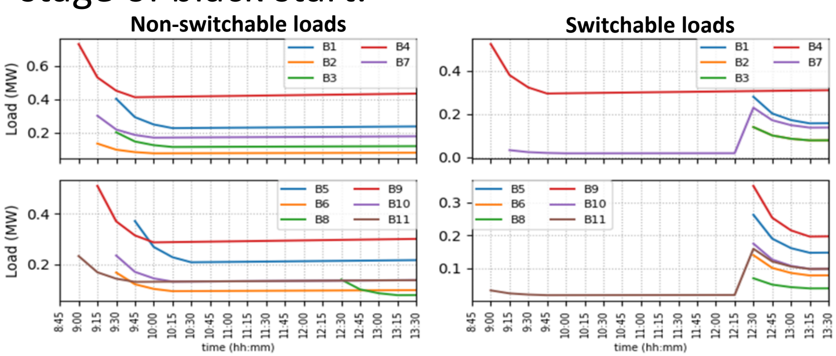
System Information:

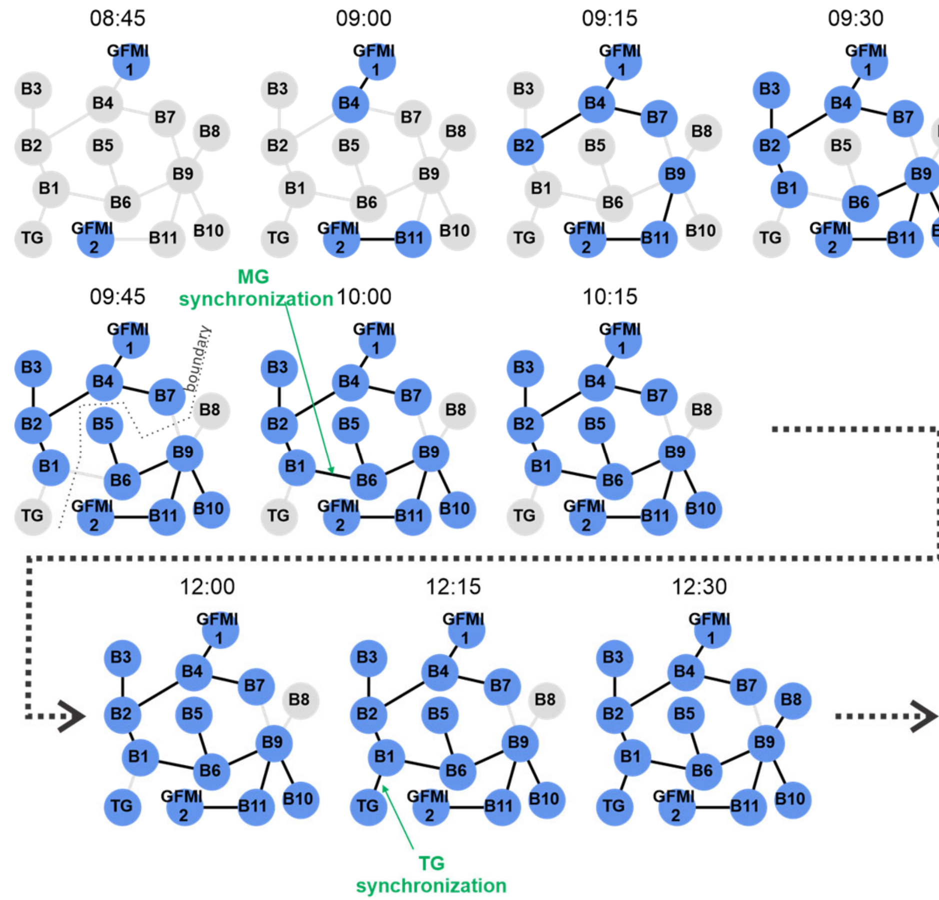
- Peak demand = 3.49 MW; 60% of loads are non-switchable; 11 bus blocks and 11 switchable lines.
- Black start resources: Two BES inverters
- Non-black start resources: 965 kW of distributed PVs

Simulation Results with TG recovering at 12:00

TG recovers at 12:00 which is 180 min after blackstart

- Blackstart initiated at 8:45.
- Cranking paths from two grid-forming inverters extend at each time step.
- Note that there are two islands until 9:45.
- Islands merge at 10:00, where GFMI2 changes to non-root generator to support synchronization.
- At 12:15, the entire distribution system is synchronized with the transmission grid, while GFMI1 changes to non-root generator.
- Note that the system is radial at each intermediate stage of black start.

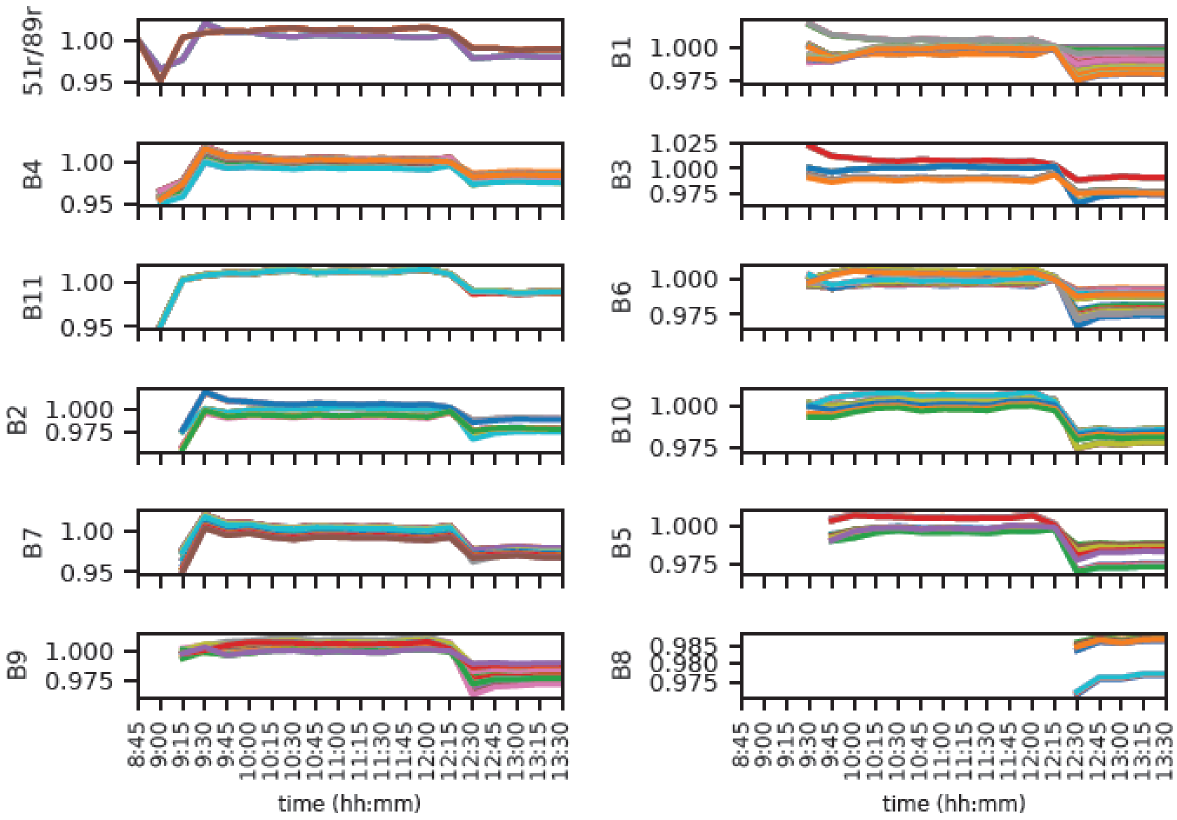




Time evolution of cranking paths

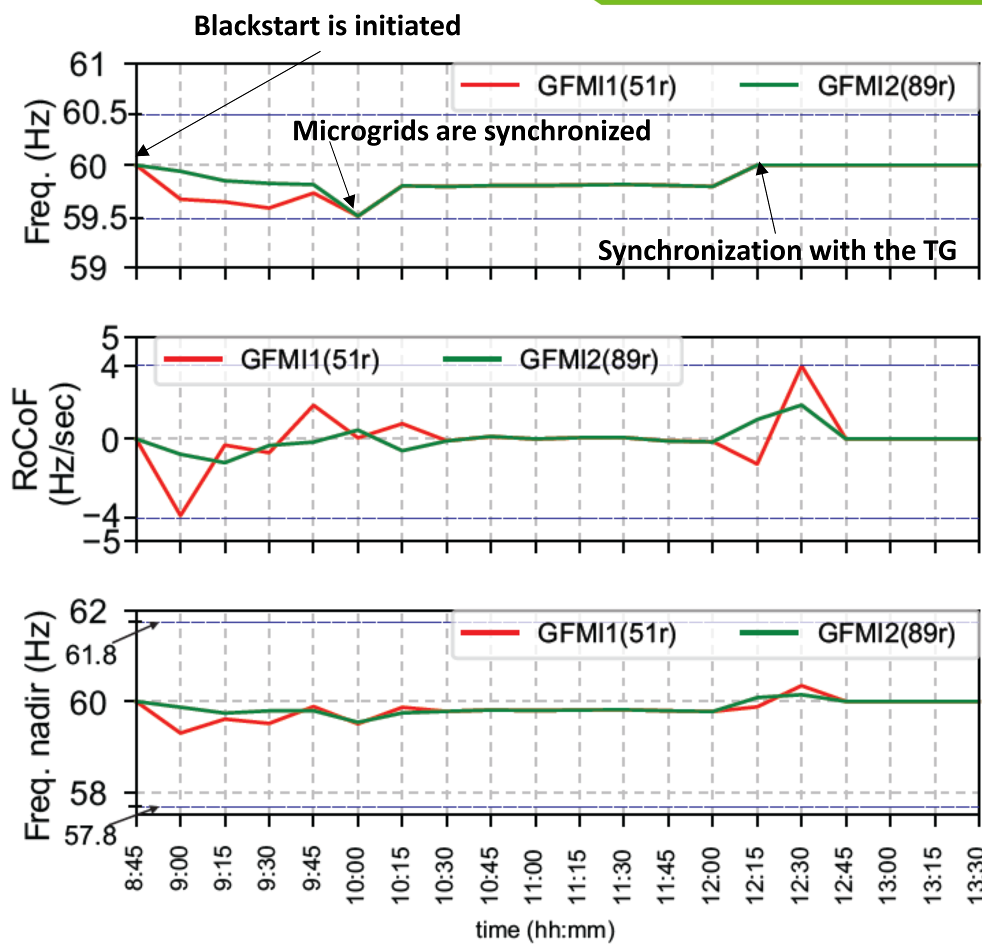
Results: Node Voltages on Bus Blocks

- When black start is initiated at 8:45, only root bus 51r and 89r is active.
- Bus blocks B4 and B11 are energized at 9:00.
- B2, B7, and B9 are energized at 9:15.
- The last bus block B8 is energized at 12:30.
- Node voltages at the active bus blocks are all within 0.95 to 1.05 pu.

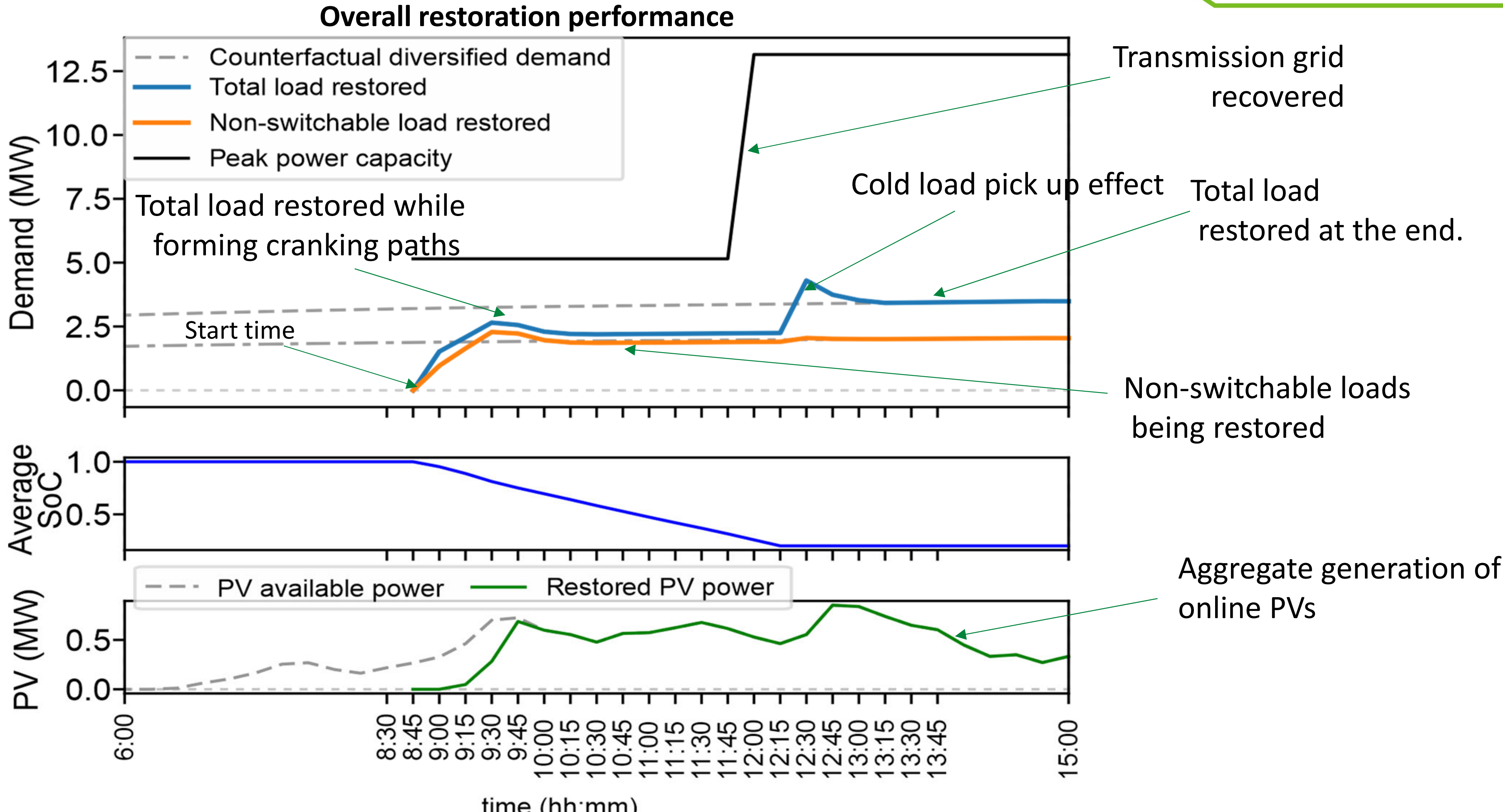


Results: Frequency

- Frequency of GFMIs are at 60 Hz when they are started.
- Their frequency dropped while restoring loads.
- Two GFMIs is synchronized at 10:00.
- Both GFMIs are synchronized and reconnected with TG at 12:15.
- RoCoF and frequency nadir are within the secure limits in the entire process.
- Security limits are:
    - RoCoF: (-4 to 4 Hz/sec)
    - Frequency nadir: (57.8 to 61.8 Hz)

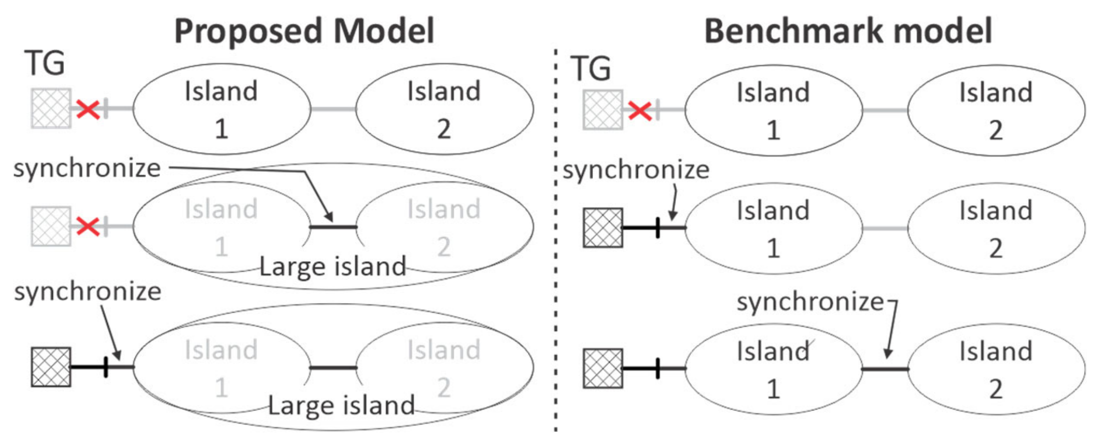


Overall Performance



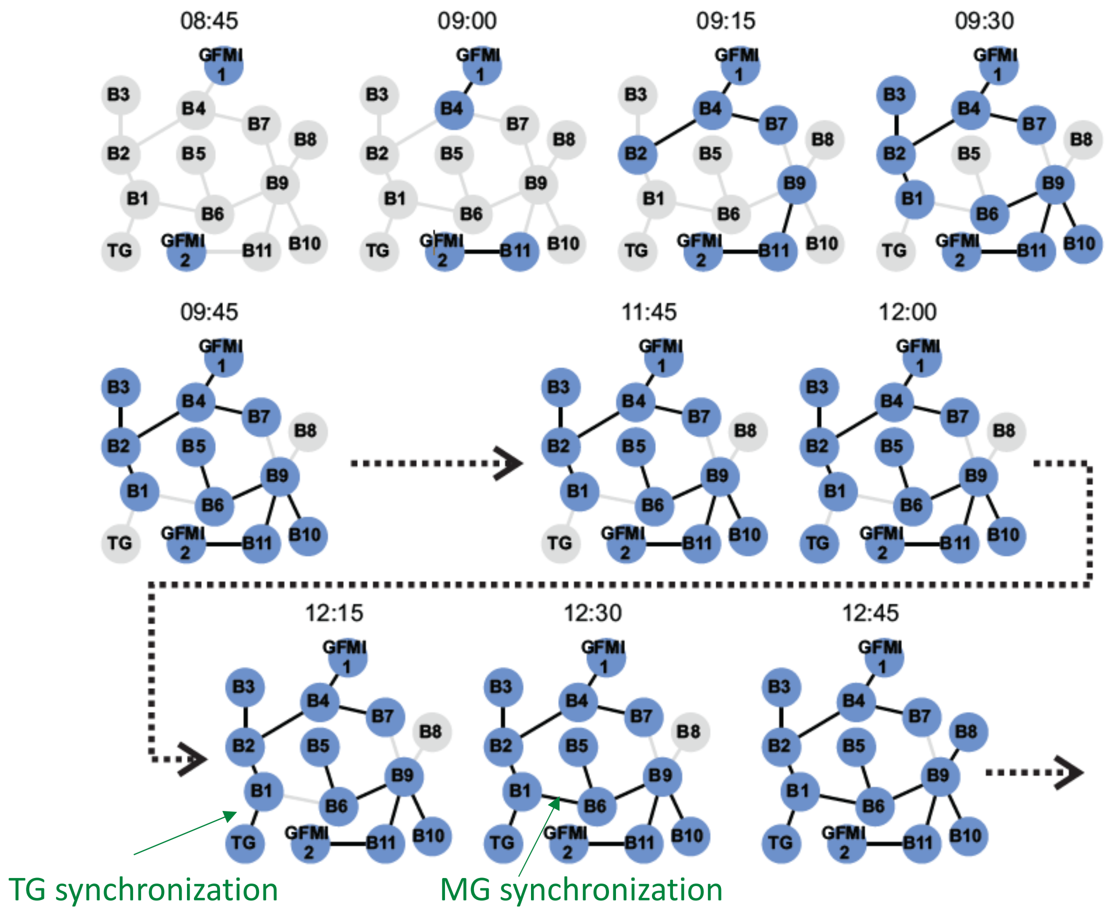
Benchmark Model for Blackstart and Load Restoration

- Proposed Model:
    - Both energizing and synchronizing switching are optimized.
- Benchmark Model:
    - Only Energizing switches are optimized.
    - Synchronizing of microgrid islands is conducted after TG comes online, where the islands are connected one after another.



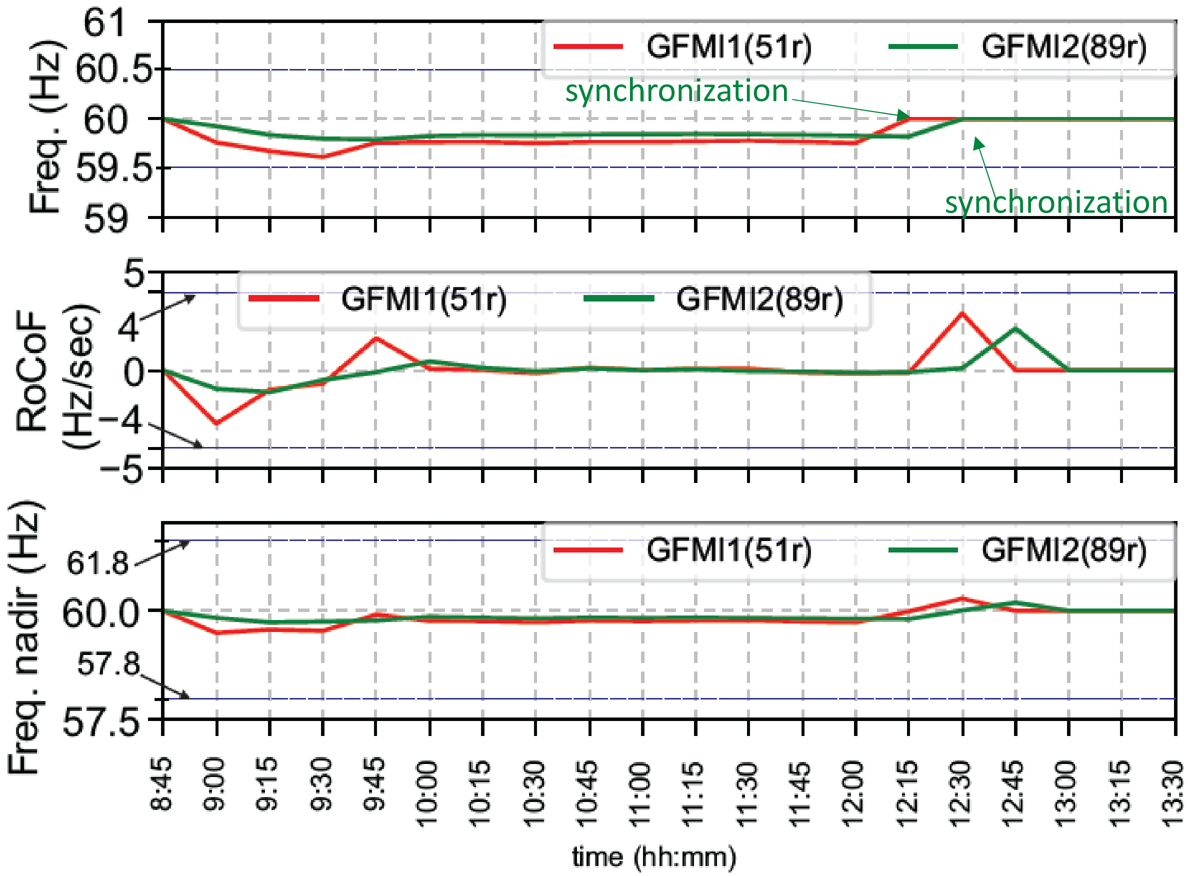
Cranking Paths with Benchmark Model

- Cranking paths with benchmark model slightly different than the proposed model.
- The difference is due to delayed synchronization.
- This also led to delayed energization of bus block B8.



System Frequency Results with Benchmark Model

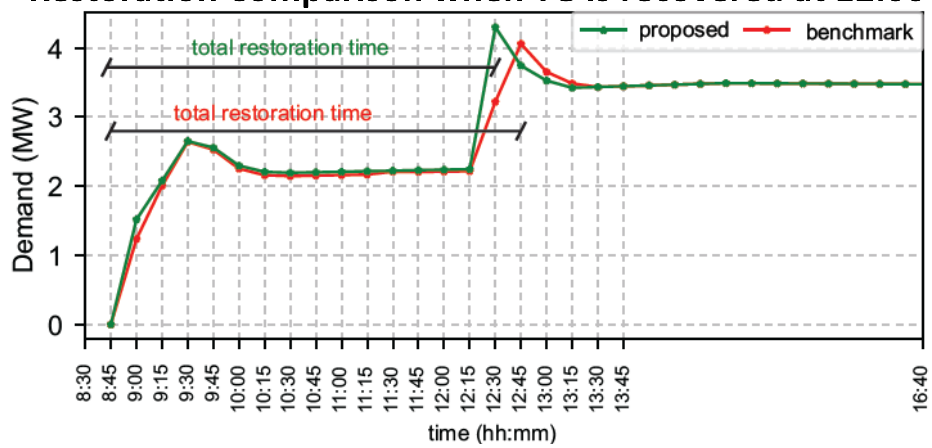
- GFMI1 is synchronized with TG at 12:15.
- GFMI2 is synchronized with TG at 12:30.
- RoCoF and frequency nadir are under secure limits.



Restoration metrics: Proposed vs Benchmark

- Two metrics are considered:
    1. Customer hours restored
    2. Restoration time
- For the case, where TG is recovered at 12:00, the proposed method has 1.46% better customer hours restoration metrics.
- And the proposed method is faster by 15 mins in restoration.
- The improvement on the metrics for longer outage durations improved marginally for 2-GFMI case.

Restoration Comparison when TG is recovered at 12:00



PROPOSED VS. BENCHMARK METHODS: 2-GFMIS CASE

TG restored at	Customer hours restored (MWh)		% improved	DS restoration time (min)		improved (mins)
	proposed	benchmark		proposed	benchmark	
10:00	26.99	26.93	0.22	105	105	0
11:00	26.25	25.95	1.16	165	180	15
12:00	23.67	23.33	1.46	225	240	15
13:00	21.11	20.74	1.78	285	300	15
14:00	18.05	17.61	2.5	345	360	15

Restoration metrics:
Proposed vs Benchmark (4-GFMIs case)

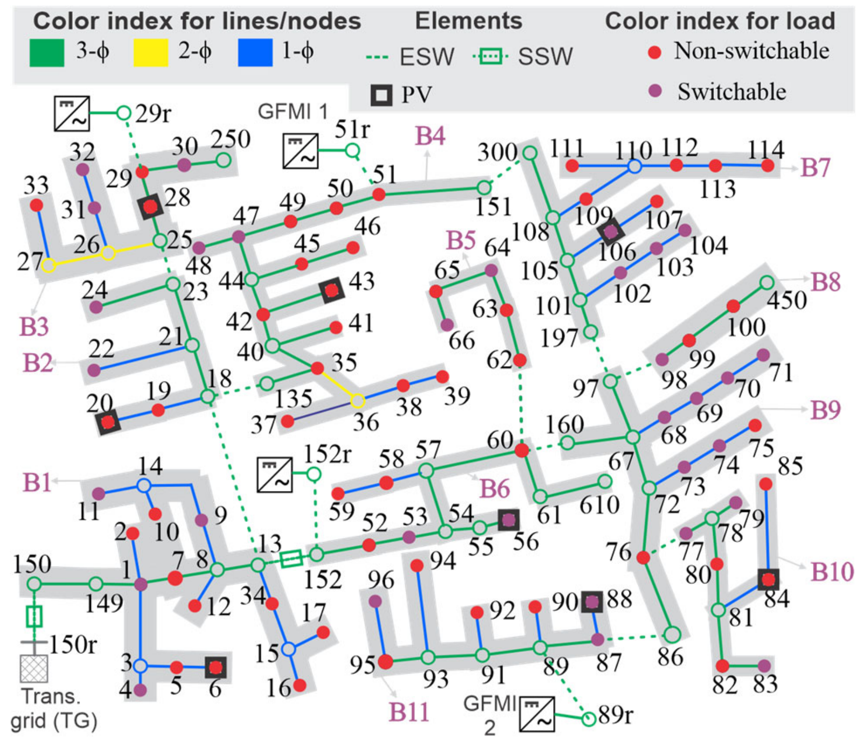
Note: For a fair comparison, the power and energy capacity for both case studies are equal.

Case studies →	**2-GFMIs**	**4-GFMIs**
Location: capacity (MVA/MWh)	51r: 2.45/4.6 89r: 2.65/3.42	51r: 1.25/2.5, 89r: 1.5/2.35, 29r: 0.95/1.17, 152r: 1.3/2.0

PROPOSED VS. BENCHMARK METHODS: 4-GFMIS CASE

TG restored at	Customer hours restored (MWh)		% improved	DS restoration time (min)		improved (mins)
	proposed	benchmark		proposed	benchmark	
10:00	27.86	26.57	4.86	105	135	30
11:00	26.59	25.28	5.18	165	195	30
12:00	23.96	22.64	5.83	225	270	45
13:00	21.35	19.54	9.26	285	330	45
14:00	18.29	16.41	11.46	345	390	45

- 11.46% improvement in customer hours restored and 45-minute improvement in restoration time.



Conclusion

- A comprehensive bottom-up framework for blackstart and load restoration is studied.
- The framework integrated (a) Blackstart capable GFMIs, (b) Sequential expansion of microgrid boundaries to establish cranking paths to energize GFLIs, and (c) Synchronization of islands to TG.
- The framework integrated quasi-steady state and dynamic frequency constraints to ensure frequency security.
- Timely synchronization of microgrid islands during the process adds up total capacity, allowing more loads to be picked up.
- The benefits of optimizing synchronizing decisions become larger with more grid-forming inverters and delayed transmission grid recovery.

Thank you!
Q&A

wzy@iastate.edu
https://wzy.ece.iastate.edu