FREEDM SYSTEMS CENTER

# Microgrid Control/Coordination Co-Design (MicroC3)

Shweta Meena, PhD Student

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# Project Team



## Professors

- Dr. Srdjan Lukic, Principal Investigator
- Dr. Iqbal Husain, Demo Lead
- Dr. Aranya Chakraborty, Controls Lead
- Dr. Wenuyan Tang, Optimization Lead

## Students

- Shweta Meena, Research Assistant
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# Presentation Outline

- Project Objectives
- Approach
- Co-design Overview
- Case study
- Future Work
- References

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# Project Objectives



- Develop a toolsuite that systematically designs all aspects (plant & control) of a microgrid (MG), given a set of design objectives and performance constraints
- Tool predicts & achieves the desired MG performance & reliability metrics with significantly smaller and/or less capable & less expensive components.

| Metric | State of the Art | Proposed |
|---|---|---|
| Stability/Damping | Oversized DER stabilizes system; no guarantee of stability | Right-sized components coordinate to achieve stability; guarantee of stability |
| Reliability/Contingency planning | Achieved through redundancy/oversizing | Achieved through resource coordination and control |
| Plug & Play | Small generators/loads | Any generator/load |

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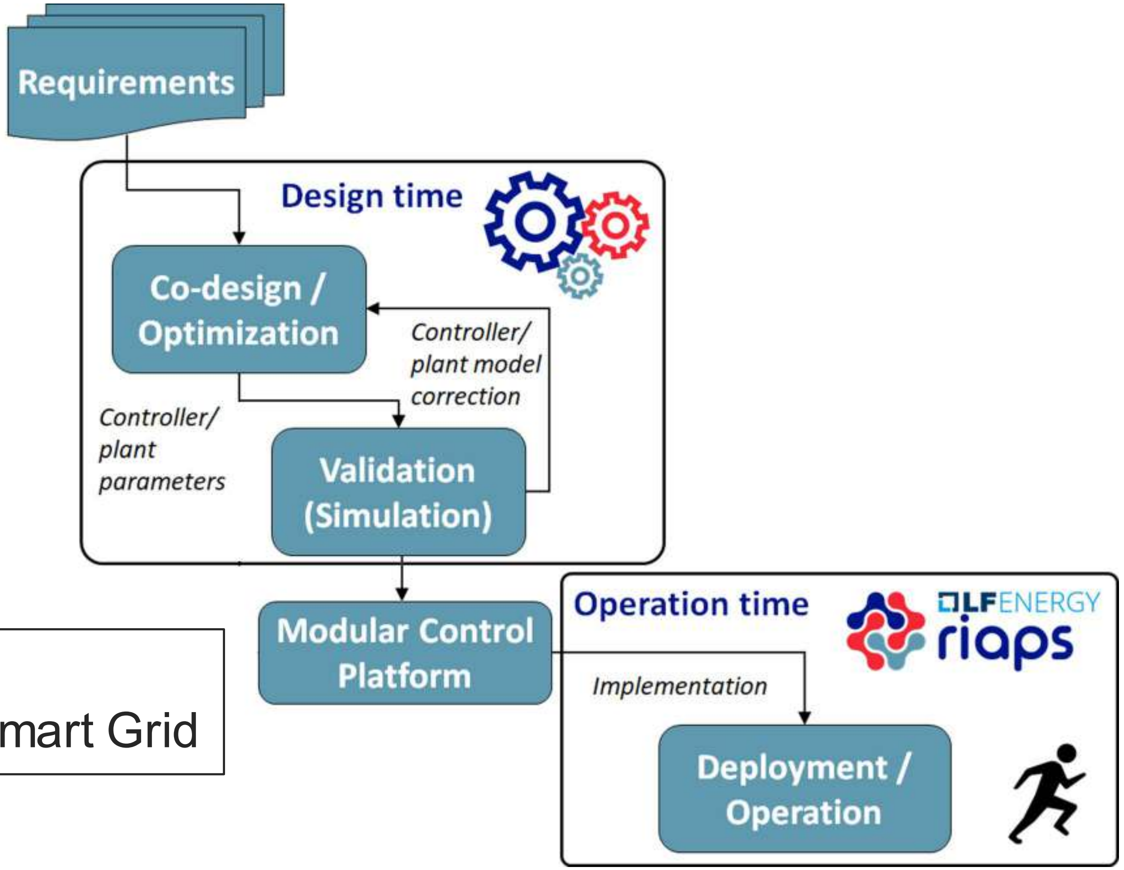
# Approach



- Design tool identifies low-cost, non-trivial MG design (plant & control)
- Validation tool verifies predicted performance and generates implementation, including code and configurations for control, communications and coordination
- Implementation is executed on MCP: ARPA-E funded open-source platform (RIAPS) extended with time sensitive networking capabilities [1]




MCP: Modular Control Platform;
RIAPS: Resilient Information Architecture Platform for the Smart Grid

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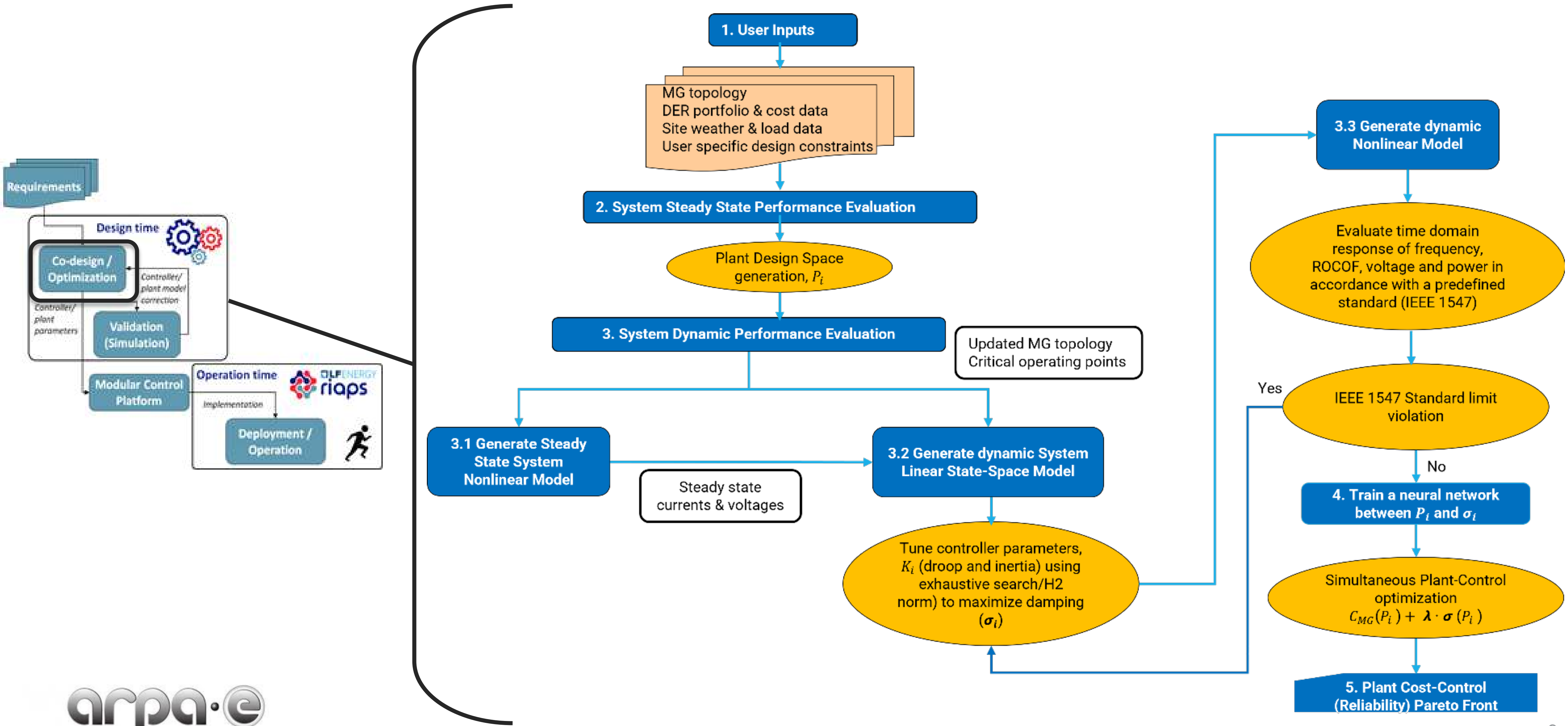
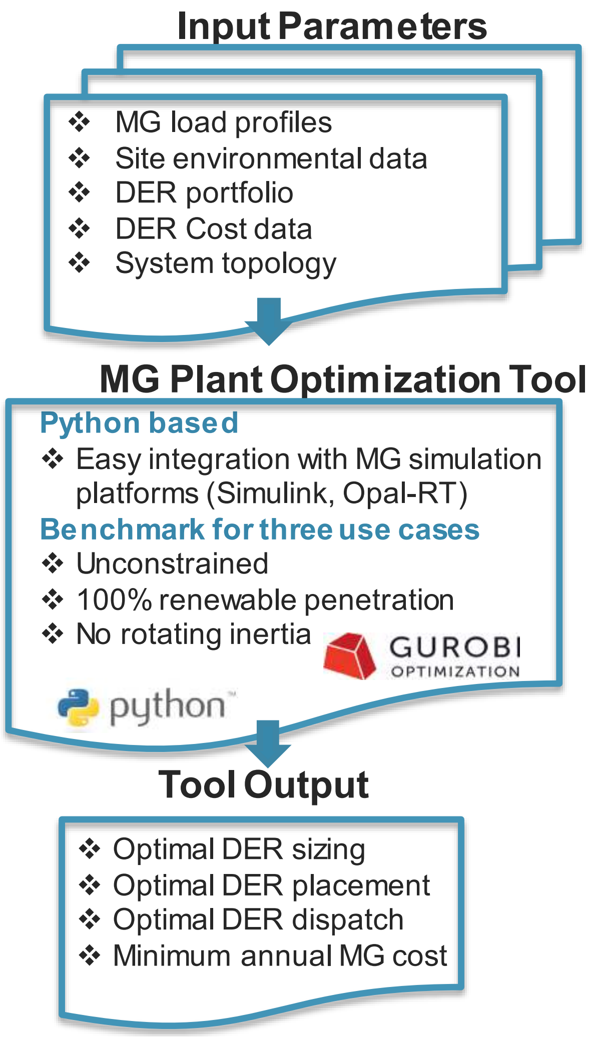
# Overview of Co-design Approach



# Microgrid Plant Design Optimization

- **Formulation type** Mixed Integer Linear Programming (MILP) [2, 3]
- **DER portfolio:** Photovoltaics (PV), diesel generators (DG), and battery energy storage systems (BESS)
- **Optimization period:** One year, 864 datapoints; Weekday, Weekend, and Peak day for each month on an hourly basis
- **Cost function:** Microgrid investment cost, operation cost and carbon emission cost
- **Constraints:** Power flow constraints, DER physical constraints, design constraints and reliability constraints [4]
- **Power Flow**: Lossless linearized distribution flow (LinDistFlow) [5]
- **Multiple Solutions**: PoolSolutions, Gurobi [6]




**Flowchart of the developed plant-optimization tool**

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# Plant Design Space Exploration



- **DER Portfolio:** One Diesel (3 MW), One BESS (1.75 MW, 7 MWh)
- **Maximum DER Installation at a given bus:** 1
- **DER power output at peak load:** Diesel (3 MW), BESS (0.29 MW)
- **Grid power exchange limit :** 1 MW
- **System peak load** = 4.29 MW

Solution Space

Feasible Solution (blue) | Infeasible Solution (red)

| | | BESS location | | | | | |
|---|---|---|---|---|---|---|---|
| | Bus | 2 | 3 | 4 | 5 | 6 | 7 |
| Diesel location | 2 | Infeasible | Infeasible | Infeasible | Infeasible | Feasible | Feasible |
| | 3 | Infeasible | Infeasible | Infeasible | Infeasible | Feasible | Feasible |
| | 4 | Infeasible | Infeasible | Infeasible | Infeasible | Feasible | Feasible |
| | 5 | Infeasible | Infeasible | Infeasible | Infeasible | Feasible | Feasible |
| | 6 | Feasible | Feasible | Feasible | Feasible | Infeasible | Feasible |
| | 7 | Feasible | Feasible | Feasible | Feasible | Feasible | Infeasible |

Power limit of line connecting Bus 5 and Bus 6 is violated

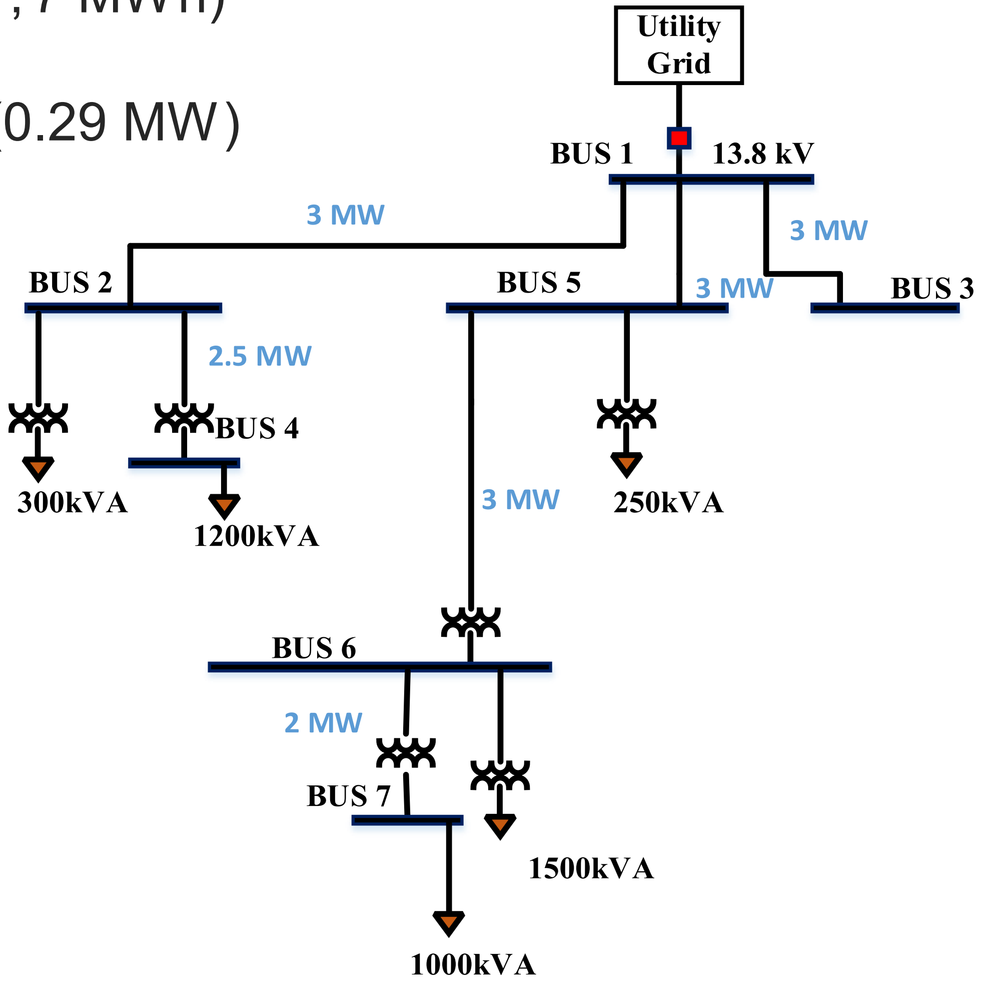
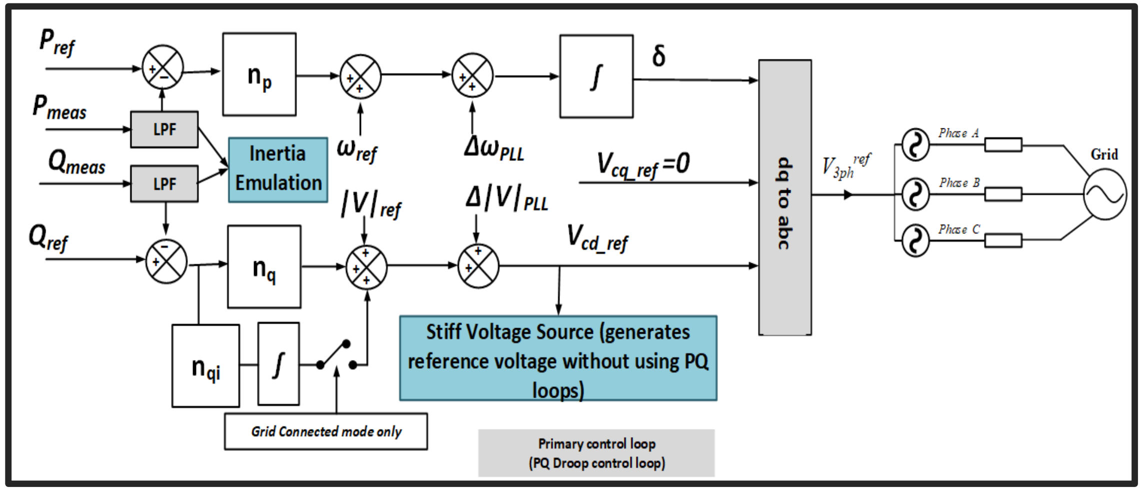



**Fig.** Feeder 1 of Banshee Microgrid

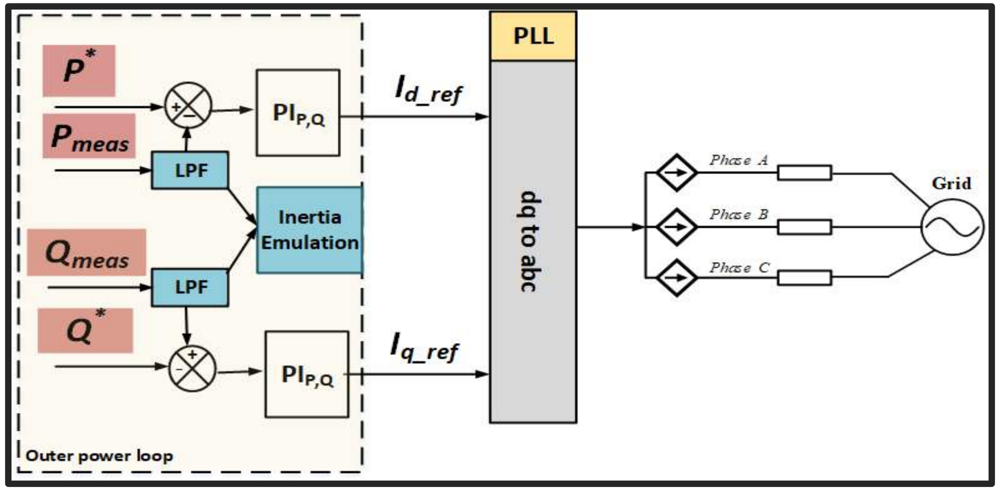
# DER Modeling



## Simplified modeling of DERs with droop and LPF control loops



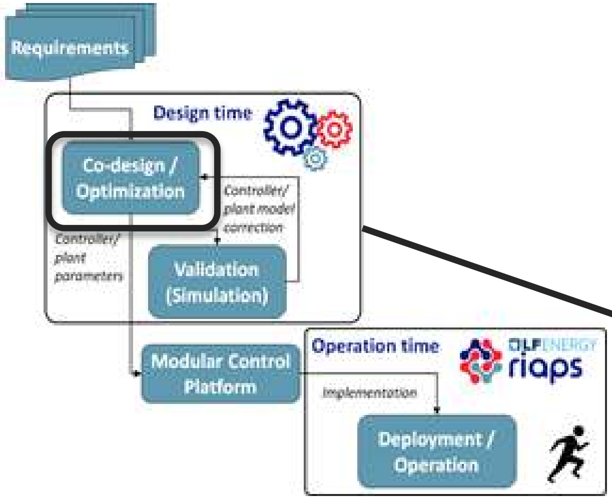

BESS (GFM)

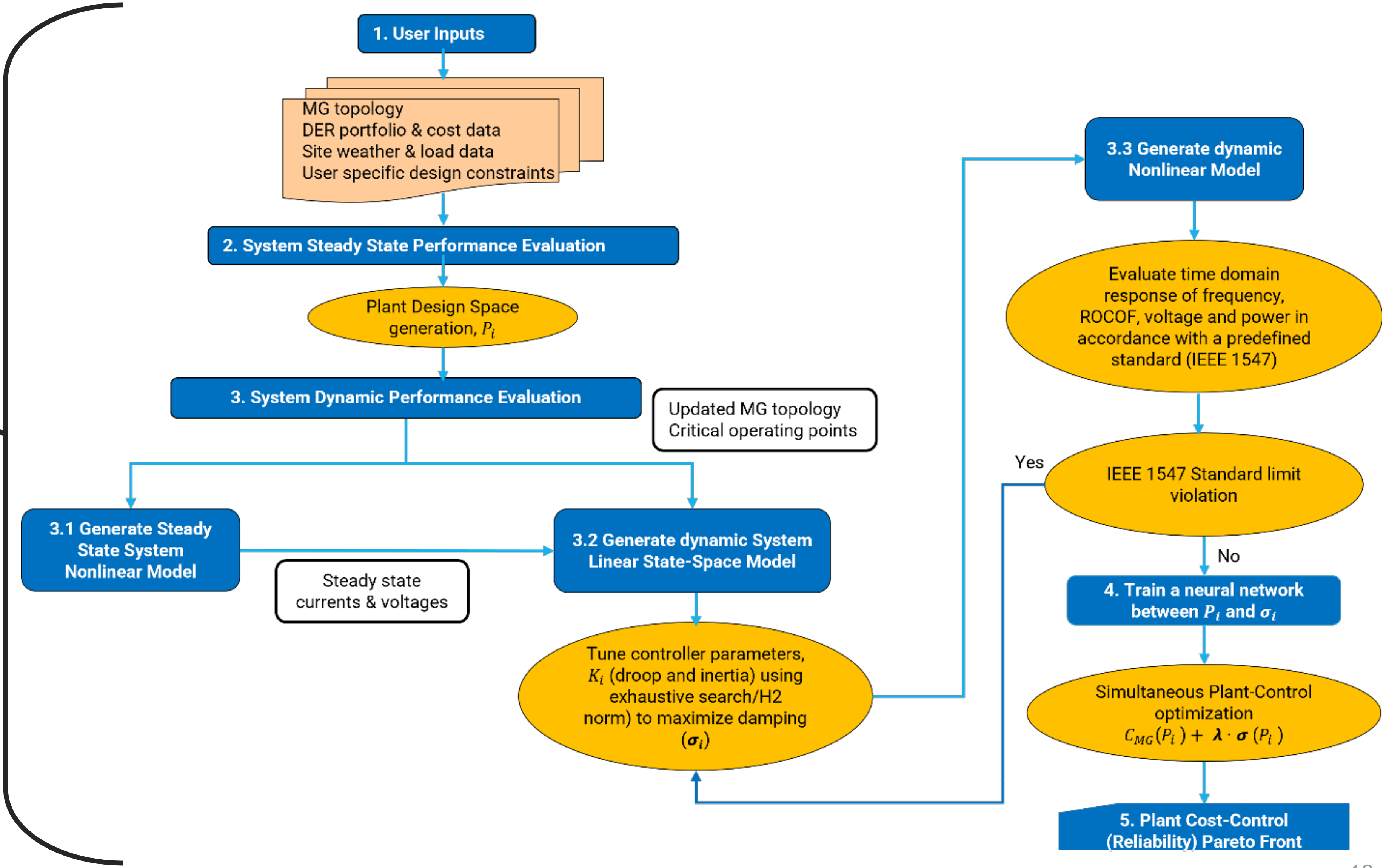



PV (GFL)

# Overview of Co-design Approach





# Nonlinear Model



- **Inputs:** System Topology, Load location, Generation Mix and DER setpoints
- **Nonlinear model outputs:**
  - Steady state operating point parameters (frequency, currents and voltages in the dq reference frame)
  - Time domain waveform using differential algebraic equations [6]
- **Model currently handles:** GFM and GFL with droop and LPF control loops and RL loads

# Nonlinear Model



Develop a nonlinear dynamic model of the microgrid having multiple **grid forming** inverters and loads

## Inverter dynamics

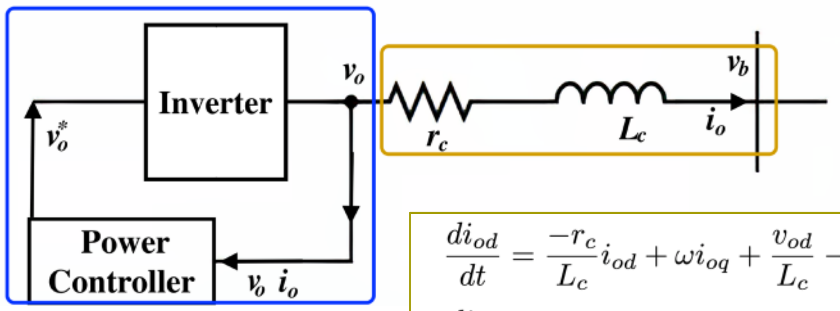



**Figure 1:** Inverter model

$$\frac{di_{od}}{dt} = \frac{-r_c}{L_c} i_{od} + \omega i_{oq} + \frac{v_{od}}{L_c} - \frac{v_{bd}}{L_c}$$

$$\frac{di_{oq}}{dt} = \frac{-r_c}{L_c} i_{oq} - \omega i_{od} + \frac{v_{oq}}{L_c} - \frac{v_{bq}}{L_c}$$

$$p = (v_{od} i_{od} + v_{oq} i_{oq}) \rightarrow P = p \cdot \frac{w_c}{s + w_c}$$

$$q = (v_{od} i_{oq} - v_{oq} i_{od}) \rightarrow Q = q \cdot \frac{w_c}{s + w_c}$$

$$\omega = \omega_n - mP, \dot{\delta} = w - w_{com}$$

$$v_{od} = v_{od}^* - nQ, v_{oq}^* = 0$$

## State variable model for inverter

$$x_{inv} := [\delta, P, Q, i_{od}, i_{oq}]^T \in \mathbb{R}^5$$

$$y_{inv} := [V_{od}, V_{oq}, V_{bd}, V_{bq}]^T \in \mathbb{R}^4$$

$$\alpha_{inv} := [m, n, w_c, r_c, L_c]^T \in \mathbb{R}^5$$

## Line current and load dynamics

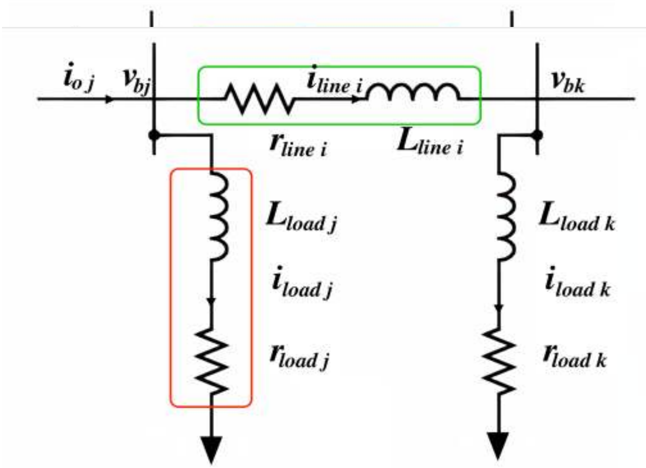



**Figure 2:** General network model with line and load internal dynamics

$$\frac{di_{lineDi}}{dt} = \frac{-r_{linei}}{L_{linei}} i_{lineDi} + \omega i_{lineQi} + \frac{v_{bDj}}{L_{linei}} - \frac{v_{bDk}}{L_{linei}}$$

$$\frac{di_{lineQi}}{dt} = \frac{-r_{linei}}{L_{linei}} i_{lineQi} - \omega i_{lineDi} + \frac{v_{bQj}}{L_{linei}} - \frac{v_{bQk}}{L_{linei}}$$

$$\frac{di_{loadDj}}{dt} = \frac{-r_{loadj}}{L_{loadj}} i_{loadDj} + \omega i_{loadQj} + \frac{v_{bDj}}{L_{loadj}}$$

$$\frac{di_{loadQj}}{dt} = \frac{-r_{loadj}}{L_{loadj}} i_{loadQj} - \omega i_{loadDj} + \frac{v_{bQj}}{L_{loadj}}$$

## Power balance expression

$$v_{bDj} = r_N(i_{oDj} - i_{loadDj} + i_{lineDi})$$

$$v_{bQj} = r_N(i_{oQj} - i_{loadQj} + i_{lineQi})$$

## State variable model for network

$$x_{net} := [i_{lineDi}, i_{lineQi}, i_{loadDj}, i_{loadQj}]^T \in \mathbb{R}^{2(n-1)}$$

$$y_{net} := [V_{bDj}, V_{bQj}, V_{bDk}, V_{bQk}]^T \in \mathbb{R}^n$$

$$\alpha_{net} := [r_{linei}, L_{linei}, r_{loadj}, L_{loadj}]^T \in \mathbb{R}^{4(n-1)}$$

# Small Signal Model



- Takes the operating point information from the non-linear model to find the steady state operating point
- Linearize the DAEs around the operating point and eliminate the algebraic part to get the small-signal model
- Model Currently Used for Inverter Parameter Tuning using exhaustive search (alternative H2 norm optimization )

**Algorithm 1:** Eigenvalue Analysis

**1** Find the eigenvalues ($\lambda$) of the parameterized small-signal model A($\rho$) matrix
**2** Find the real part of the eigenvalue closest to the imaginary axis ($\lambda^* = -min(|\mathbf{Re}(\lambda)|)$
**3** Run an exhaustive search for

$$\max_{\rho} |\lambda^*| \quad \forall \quad \rho \in [\rho_{min}, \rho_{max}]$$

**Algorithm 1:** $H_2$ norm optimization

**1** Assign $\rho^k \leftarrow \rho_o$ and choose $0 < \beta < 1$.
**2** Apply a perturbation $\Delta\rho_i$ to the $i$th element of $\rho^k$.
**3** Find the perturbation in $G(s)$ due to $\Delta\rho_i$
$\Delta G^i_{\Delta\rho_i} = G^i_{\rho^k+\Delta\rho_i} - G^i_{\rho^k} = C^i_p(sI - A^i_p)^{-1}B^i_p$
**4** The total perturbation of all parameters is
$\Delta G_{\Delta\rho} = \sum_{i=1}^{2s}(\Delta G^i_{\Delta\rho_i})$
**5** Find the final perturbed transfer function
$G_{\rho^k+\Delta\rho} = G_{\rho^k} + \Delta G_{\Delta\rho} = \bar{C}_p(sI - \bar{A}_p)^{-1}\bar{B}_p$
**6** Solve the Lyapunov equation to get $P$
$P\bar{A}_p + \bar{A}_p{}^T P + \bar{C}_p{}^T \bar{C}_p = 0$
**7** With $\bar{B}_p = [B_1 \quad B_2]$, find descent direction
$[\partial J/\partial\rho] = 2B_2^T P B_1$.
**8** Compute $\rho^{k+1} = \rho^k - \beta[\partial J/\partial\rho]$.
**9** Assign $\rho^k \leftarrow \rho^{k+1}$ and goto Step 2.

# Small Signal Model



Develop nonlinear dynamic model of the microgrid

$$\begin{cases} \dot{x} = f(x, y, u; \alpha_c) \\ 0 = g(x, y, u; \alpha_c) \end{cases}$$

where,

$$x := [x_{inv}, x_{net}]$$
$$y := [y_{inv}, y_{net}]$$
$$u := [i_{inj}]$$
$$\alpha_c := [\alpha_{inv}, \alpha_{net}]$$

$$x_{inv} := [\delta, P, Q, i_{od}, i_{oq}]^T \in \mathbb{R}^5$$
$$y_{inv} := [V_{od}, V_{oq}, V_{bd}, V_{bq}]^T \in \mathbb{R}^4$$
$$\alpha_{inv} := [m, n, w_c, r_c, L_c]^T \in \mathbb{R}^5$$
$$x_{net} := [i_{lineDi}, i_{lineQi}, i_{loadDj}, i_{loadQj}]^T \in \mathbb{R}^{2(n-1)}$$
$$y_{net} := [V_{bDj}, V_{bQj}, V_{bDk}, V_{bQk}]^T \in \mathbb{R}^n$$
$$\alpha_{net} := [r_{linei}, L_{linei}, r_{loadj}, L_{loadj}]^T \in \mathbb{R}^{4(n-1)}$$

Find the steady state operating points

$$\begin{cases} 0 = f(x^*, y^*, 0; \alpha_c) \\ 0 = g(x^*, y^*, 0; \alpha_c) \end{cases}$$

Linearize the DAEs around the operating point and eliminate the algebraic part to get the small-signal model

$$\Delta\dot{x} = \frac{\partial f}{\partial x}\Delta x + \frac{\partial f}{\partial y}\Delta y + \frac{\partial f}{\partial u}\Delta u$$
$$0 = \frac{\partial g}{\partial x}\Delta x + \frac{\partial g}{\partial y}\Delta y + \frac{\partial g}{\partial u}\Delta u$$

$$\Delta\dot{x} = [\frac{\partial f}{\partial x} - \frac{\partial f}{\partial y}(\frac{\partial g}{\partial y})^{-1}\frac{\partial g}{\partial x}]\Delta x + [\frac{\partial f}{\partial u} - \frac{\partial f}{\partial y}(\frac{\partial g}{\partial y})^{-1}\frac{\partial g}{\partial u}]\Delta u$$

$$\Delta\dot{x} = A(\rho)\Delta x + B(\rho)\Delta u$$

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# Case Study



A single feeder of Banshee Network that requires seamless islanding and has critical loads that are ROCOF sensitive.

| Description | Constraint/Metric |
|---|---|
| Component/System Limits | Power Flow |
| | DER Power and Capacity |
| | ROCOF Constraint |
| | Voltage Limits |
| | Frequency Limits |
| Resiliency | Seamless Islanding |
| Stability | Damping, ROCOF |

Small-signal and time-domain evaluations are unique to MicroC3.

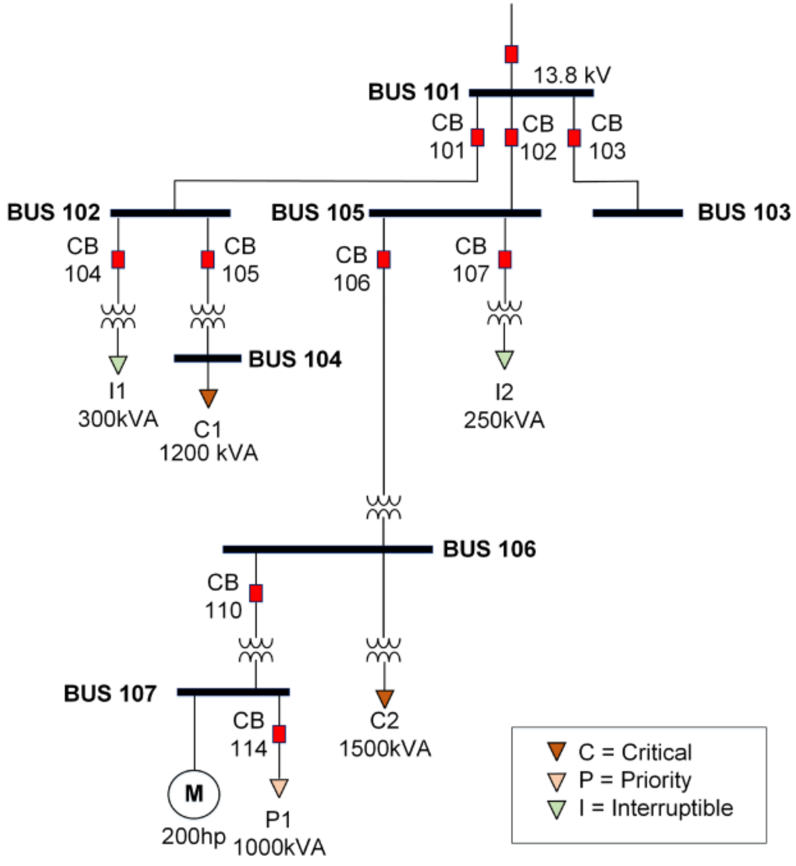


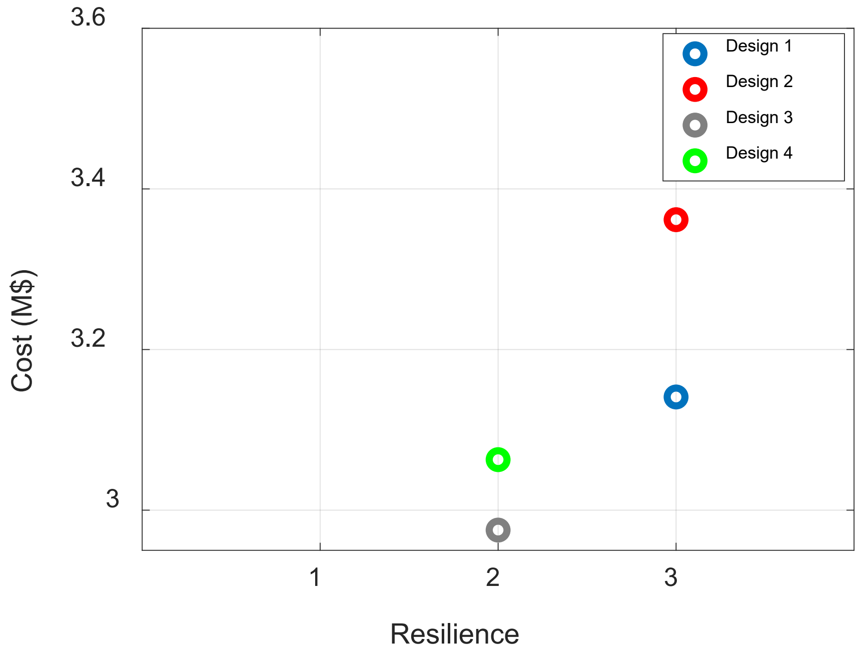

**Fig.** Feeder 1 of Banshee Microgrid [7]

# Plant Design Evaluation



**Plant Optimization formulation like DER-CAM**

- Seamless islanding with no load shedding
  - Design 1: Generation exceeds load
  - Design 2: IBR (BESS) generation exceeds load
- Seamless islanding with no critical load shedding
  - Design 3: Generation exceeds critical load
  - Design 4: IBR (BESS) generation exceeds critical load

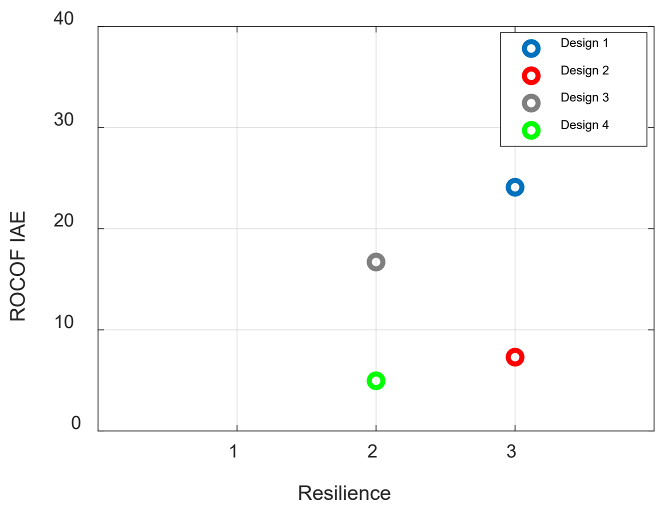


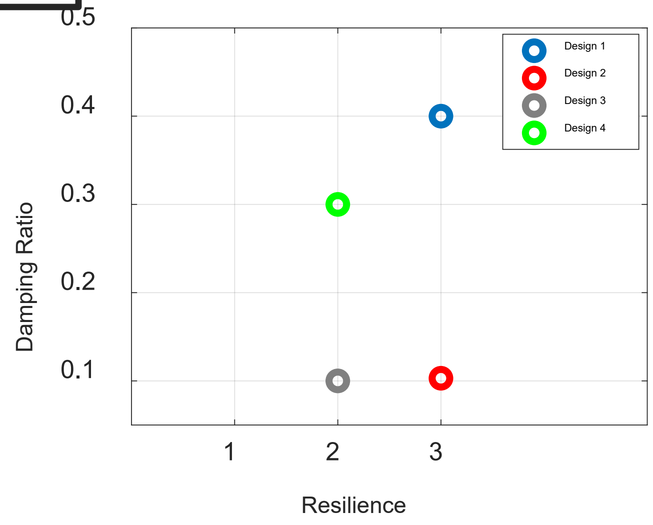

1: Blackout
3: Seamless Islanding
2: Seamless with load shedding

# Dynamic Evaluation Without Controller Tuning

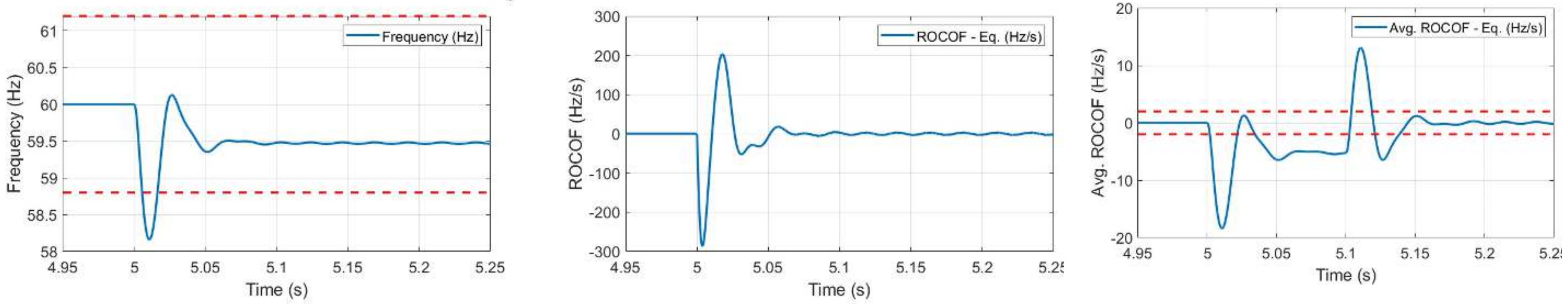
- Design1:
  GFM1: Droop: $1e^{-5}$, LPF= 20 Hz
  GFM2: Droop: $1e^{-6}$, LPF= 10 Hz

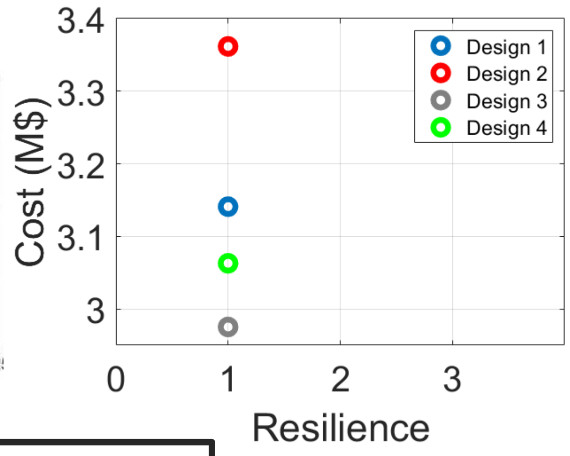
IAE – Integral Absolute Error




Design 1 - GFM1




✖ : Old Design
○ : New Design

1: Blackout 3: Seamless Islanding
2: Seamless with load shedding

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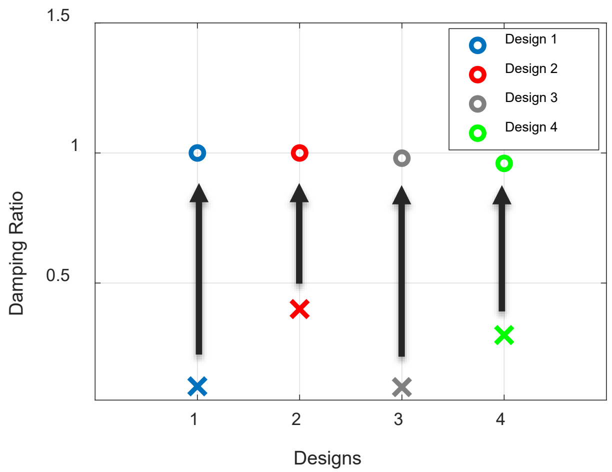
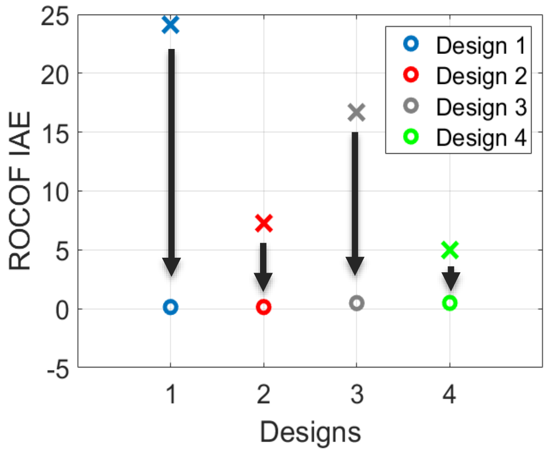
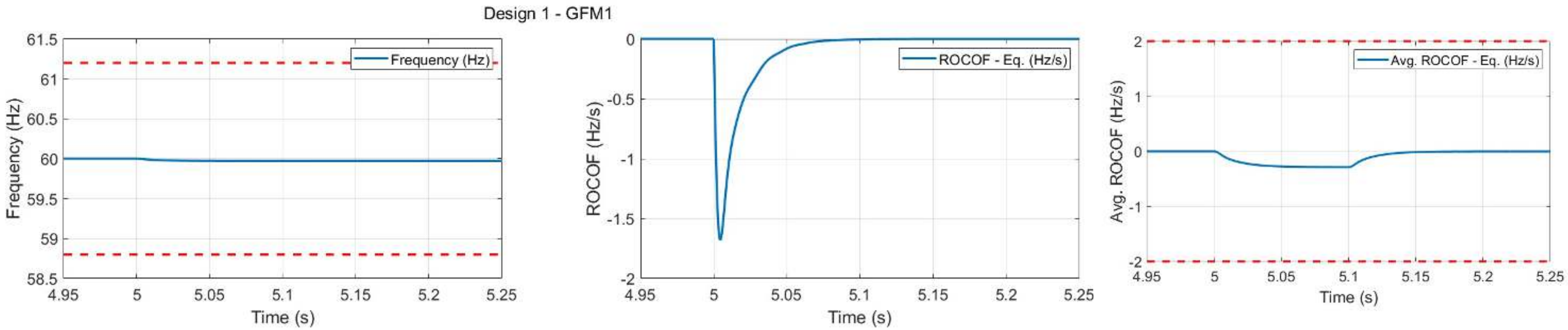
# Dynamic Evaluation With Controller Tuning

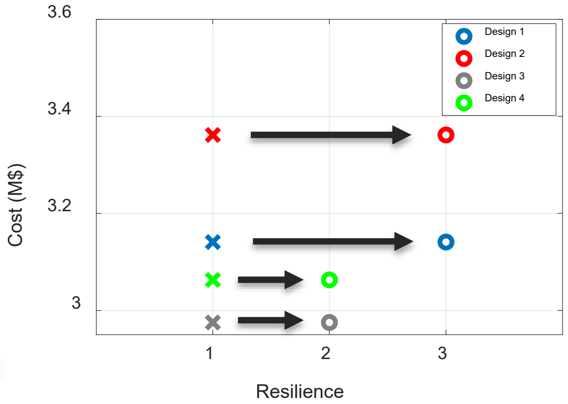
- Design1:
  GFM1: Droop: $1e^{-7}$, LPF= 10 Hz
  GFM2: Droop: $1e^{-7}$, LPF= 10 Hz

IAE – Integral Absolute Error



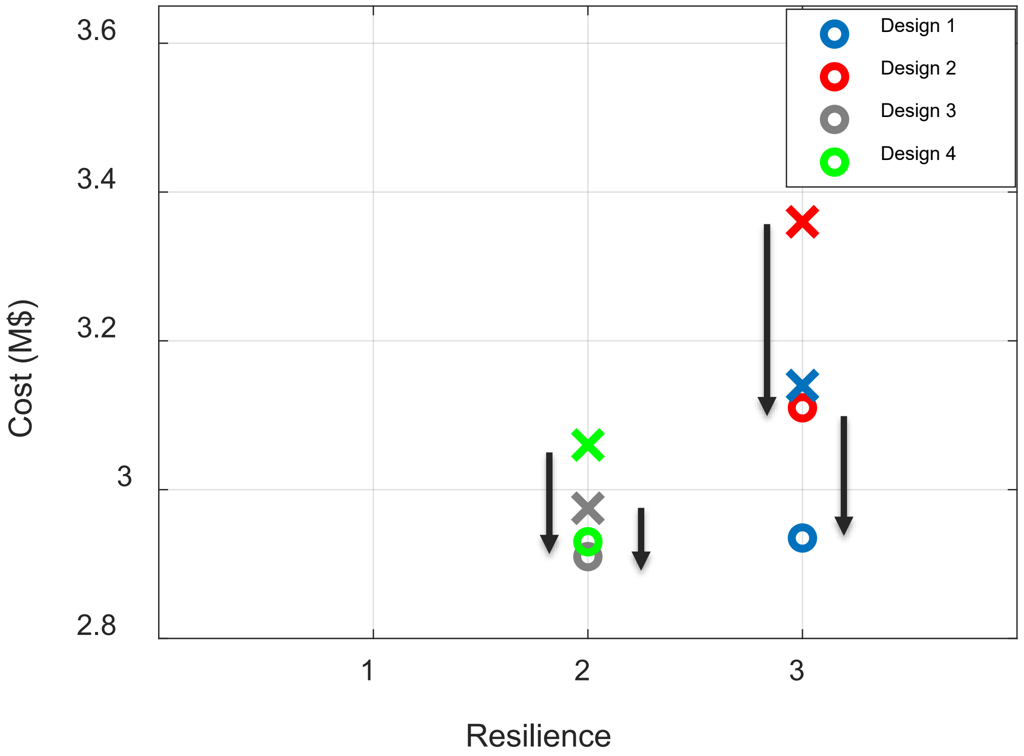

✖ : Old Design
○ : New Design

1: Blackout
2: Seamless with load shedding
3: Seamless Islanding

# Plant Design Improvement based on dynamic Evaluation



- Successfully scaled down the size of the DERs while still meeting the resiliency metrics




: Old Design
: New Design

1: Blackout
3: Seamless Islanding
2: Seamless with load shedding

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# Future Work



- Use detailed models for GFM and GFL
- Replace exhaustive search for controller tuning with $H_2$ norm
- Automate the plant design improvement step
- Modify plant optimization to include other DERs like wind turbine, flywheels, etc.

# References

[1] H. Tu, Y. Du, H. Yu, A. Dubey, S. Lukic and G. Karsai, "Resilient Information Architecture Platform for the Smart Grid: A Novel Open-Source Platform for Microgrid Control," in IEEE Transactions on Industrial Electronics, vol. 67, no. 11, pp. 9393-9404, Nov. 2020.

[2] S. Mashayekh, M. Stadler, G. Cardoso, and M. Heleno, “A mixed integer linear programming approach for optimal der portfolio, sizing, and placement in multi-energy microgrids,” Applied Energy, vol. 187, pp. 154–168, 2017

[3] B. Yan, P. B. Luh, G. Warner, and P. Zhang, “Operation and design optimization of microgrids with renewables,” IEEE Transactions on Automation Science and Engineering, vol. 14, no. 2, pp. 573–585, 2017.

[4] M. Baran and F. Wu, “Optimal sizing of capacitors placed on a radial distribution system,” IEEE Transactions on Power Delivery, vol. 4, no. 1, pp. 735–743, 1989.

[5] Gurobi Optimization, LLC, “Gurobi Optimizer Reference Manual,” 2023. [Online]. Available: https: //www.gurobi.com

[6] The MathWorks Inc., “vpasolve (R2012b),” Natick, Massachusetts, United States, 2012. [Online]. Available: https://www.mathworks.com

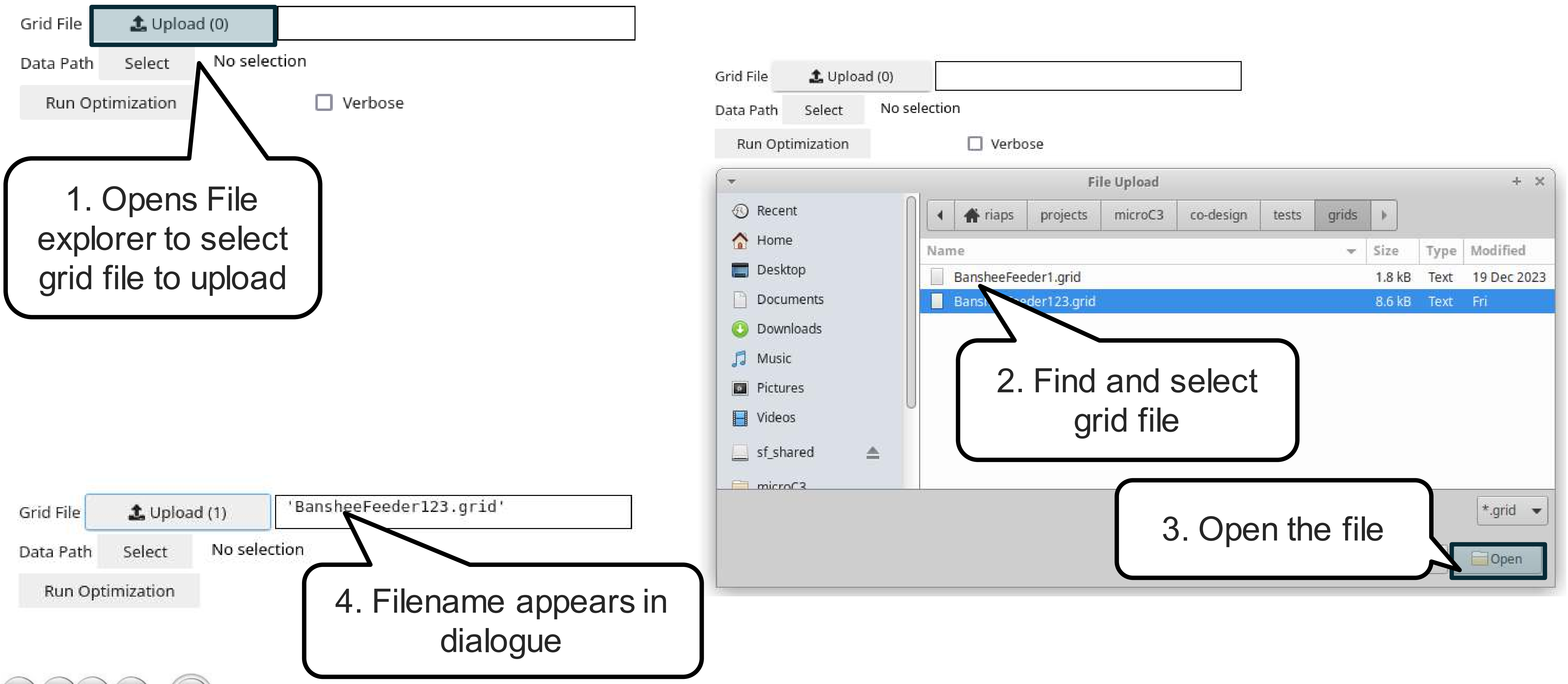
[7] R. Salcedo, et al.,“Banshee distribution network benchmark and prototyping platform for hardware-in-the-loop integration of microgrid and device controllers,” The Journal of Engineering, vol. 2019, no. 8, pp. 5365–5373, 2019. [Online]. Available: https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/joe.2018.5174

# Thank You!

# Questions?

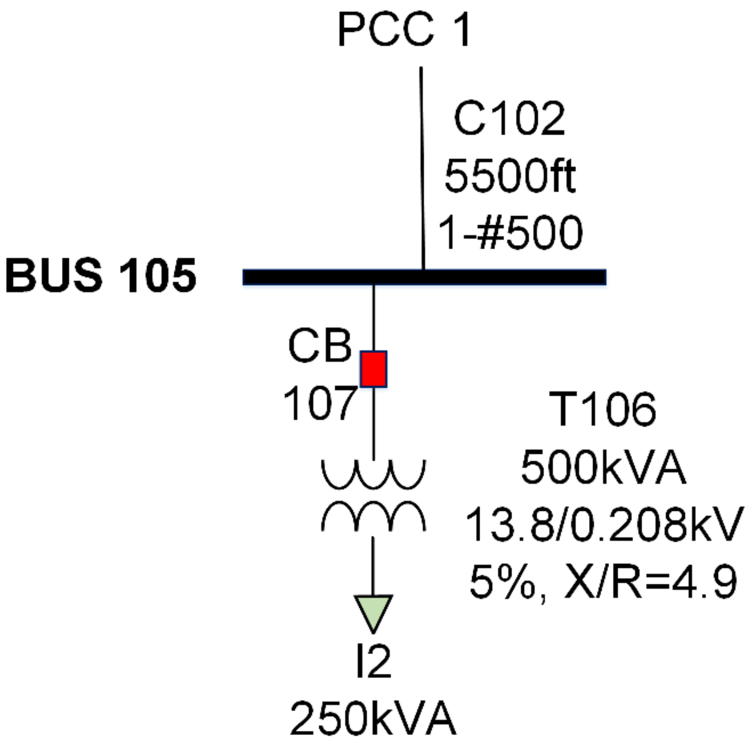
# Backup

# Toolchain Overview – Load grid model



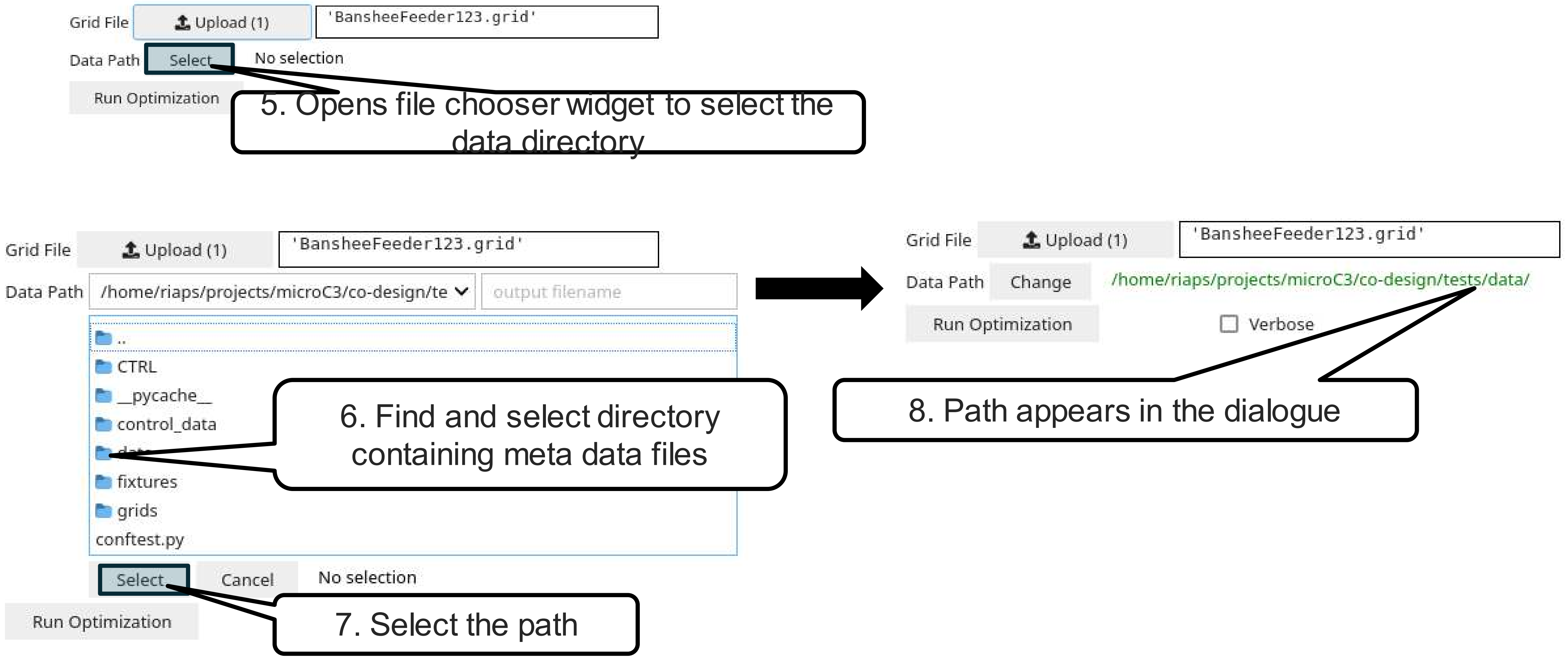
# Example .grid model and its corresponding one-line diagram






```
LineType 500kcml R 0.1206 X 0.1878

PCC PCC1 {
    export limit 5.0 kW
    import limit 100.0 MW
    impedance R 0.05
    impedance X 0.05
}

Line C102 {
    connect PCC1 to BUS105
    length 5500 ft
    nominal ampacity 512 A
    type 500kcml
}

Bus BUS105 { voltage 13.8 kV }

Switch CB107 { term1 [BUS105] term2 [T106.primary_term] closed }

Transformer T106 {
    rating 500 kVA
    impedance 5.0%
    XR_ratio 4.9
    primary_voltage 13.8 kV
    secondary_voltage 0.208 kV
    primary_term [CB107.term2]
    secondary_term [I2]
}

Load I2 { is_critical true }
```

# Toolchain Overview – Set data path

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# Toolchain Overview

Grid File | Upload (1) | 'BansheeFeeder123.grid'

Data Path | Change | /home/riaps/projects/microC3/co-design/tests/data/

Run Optimization ☐ Verbose

9. Runs the Codesign optimization toolchain

Grid File | Upload (1) | 'BansheeFeeder123.grid'

Data Path | Change | /home/riaps/projects/microC3/co-design/tests/data/

Run Optimization ☐ Verbose

```
Running optimization
PCC indices in bus variables:  [0]
PCC variable indices:  [0]
shape of electricalLoad: (7, 864)
Plant Optimization complete
Number of solutions found: 1
DG_alloc: [0. 0. 1. 0. 0. 0. 0.]
Batt_alloc: [0. 0. 0. 0. 0. 0. 1.]
PV_alloc: [0. 0. 0. 0. 0. 0. 0.]
objective: 5655343.30554272
Adding path /home/riaps/projects/microC3/co-design/src/coop/interfaces/mfunctions
Getting operating points for design 0
Run Matlab function
best_parameterization:
          BUS103     BUS107
mp  5.000000e-07   0.000004
wc  5.000000e+01  50.000000
Time taken for 0: 0 days 00:00:02.076982
Total time taken:  0 days 00:00:02.077110
Design 0. Cost: $5655343.31. Stability: -25.17.
```

Design ID

Estimated cost of the design

Design Stability metric

| | DGs | Batteries | PVs |
|---|---|---|---|
| **BUS101** | 0 | 0 | 0 |
| **BUS102** | 0 | 0 | 0 |
| **BUS103** | 1 | 0 | 0 |
| **BUS104** | 0 | 0 | 0 |
| **BUS105** | 0 | 0 | 0 |
| **BUS106** | 0 | 0 | 0 |
| **BUS107** | 0 | 1 | 0 |

Allocation of DERs to Buses in the solution

# Example metadata file

The metadata file contains:

- data for reading bus load and solar data files.
- Financial context parameters
- A list of bus names, where installing DERs is permissible.
- designation of a slack bus.
- Plant optimization constraints:
- Control optimization parameters

```yaml
data:
  points_per_day: 24
  typical_days_per_year: 36
  num_points: 864
  load:
    path: "profilesAllNodesHourly.csv"
    units: "kW"
    headers: [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]
    header_names: [
      "BUS101", "BUS102", "BUS103", "BUS104", "BUS105", "BUS106", "BUS107",
      "BUS201", "BUS202", "BUS203", "BUS204", "BUS205", "BUS206", "BUS207",
      "BUS301", "BUS302", "BUS303", "BUS304", "BUS305", "BUS306", "BUS307"
      ]
    date_collected: "2023-12-01"
  weather:
    path: "weatherOneHour.csv"
    units: ["degC", "W/m2"]
    date_collected: "2023-12-01"
  financial:
    nominal_interest_rate: 0.041
    expected_inflation_rate: 0.01
    project_lifetime_years: 15
    CURTAILMENT_PENALTY_PER_KWH: 0.18
   ...
```

```yaml
bus_names:
  - "BUS101"
  - "BUS102"
  - "BUS103"
  - "BUS104"
  - "BUS105"
  - "BUS106"
  - "BUS107"
slack_bus: "BUS101"
constraints:
  MAX_BUS_VOLTAGE_PU: 1.05
  MIN_BUS_VOLTAGE_PU: 0.90
  BATT_INI_SOC: 0.8
  CURTAIL_MAX: 0
  MAX_DGS: 6
  MAX_PVS: 0
  MAX_BATTERIES: 6
  ALLOWED_DER_MODELS: ["PV_1000_kW", "BATTERY_7000_kWh"]

control:
  NOMINAL_OPERATING_FREQUENCY: 60.0
  BUS_RESISTANCE_OHMS: 100000
  GRID_IMPEDANCE_RX_OHMS:
    - 0.000882
    - 0.001046942034994
  LOAD_OPERATING_VOLTAGE_V: 480
```

CHANGING WHAT'S POSSIBLE