Secure Control of Inverters for Mobile Microgrids (SCI2M)

Faculty of Electrical Engineering, University of Montenegro, MNE
Faculty of Electronic Engineering, University of Niš, SRB
Faculty of Electrical Engineering, University of Sarajevo, B&H

NATO OTAN
This project is supported by: The NATO Science for Peace and Security Programme

NATO SPS Programme

- The SPS Programme promotes dialogue and cooperation between NATO member states and partner countries based on scientific research, technological innovation and knowledge exchange.
- The SPS Programme offers funding, expert advice and support to tailor-made, civil security-relevant activities that respond to NATO's strategic objectives.
- The SPS Programme supports scientific cooperation through established grant mechanisms that provide funding for Multi-Year Projects and Events.
- The MYP Projects have a typical duration of 24 to 36 months.
- The MYP budget is EUR 250,000-400,000 over the entire duration of the project.

NATO OTAN

This project is supported by: The NATO Science for Peace and Security Programme

NATO SPS Programme

- Environment, Climate Change and Security
- Energy Security
- Innovation and Emerging Technologies
- Counter-terrorism
- Chemical/Biological/Radiological/Nuclear Management
- Resilience and Cyber Defense
- Critical Underwater Infrastructure
- Assessing and addressing threats posed by the Russian Federation
- Strategic Foresight
- Human and Social Aspects of Security

NATO OTAN

This project is supported by: The NATO Science for Peace and Security Programme

SCI2M project plan

- Environment, Climate Change and Security
- Energy Security
- Innovation and Emerging Technologies
- Counter-terrorism
- Chemical/Biological/Radiological/Nuclear Management
- Resilience and Cyber Defense
- Critical Underwater Infrastructure
- Assessing and addressing threats posed by the Russian Federation
- Strategic Foresight
- Human and Social Aspects of Security

NATO OTAN

This project is supported by: The NATO Science for Peace and Security Programme

SCI2M key project activities

MOBILE uG RESILIEN DESIGN

- Development of uG harmonic power flow method
- Optimization of role and functionality of UuGC
- Ensuring Secure Communication in uGs
- Proposal of secure and resilient uG architecture

ADVANCED CONTROL of UuGC in uGs

- Data-driven computational modeling and simulation
- Robust controller design
- Implementation of fault-tolerant mechanisms

uG and UuGC OPERATION TESTS

- Development of models for HIL simulations
- Testing in C-HIL environment
- Testing in P-HIL environment
- Mobile microgrid cluster testing

NATO OTAN

This project is supported by: The NATO Science for Peace and Security Programme

GRID-FORMING INVERTERS: Enabling the Next Generation of Renewable Power Systems

Prof. dr Senad Huseinbegović
Faculty of Electronic Engineering, University of Sarajevo, B&H
shuseinbegovic@etf.unsa.ba

17. savjetovanje, Neum, 12 - 15.10.2025.

Presentation overview

- Why Microgrids (uGs)?
- Classification of uGs
- Challenges in uGs
- Power Electronic Converters in uGs
- Inverters as the Heart of uGs
- Grid-following vs Grid-Forming
- Different types of Grid-Forming
- Robust Control of uGs
- Security and Resilience in uGs
- Testing and Validation
- Instead of a Conclusion

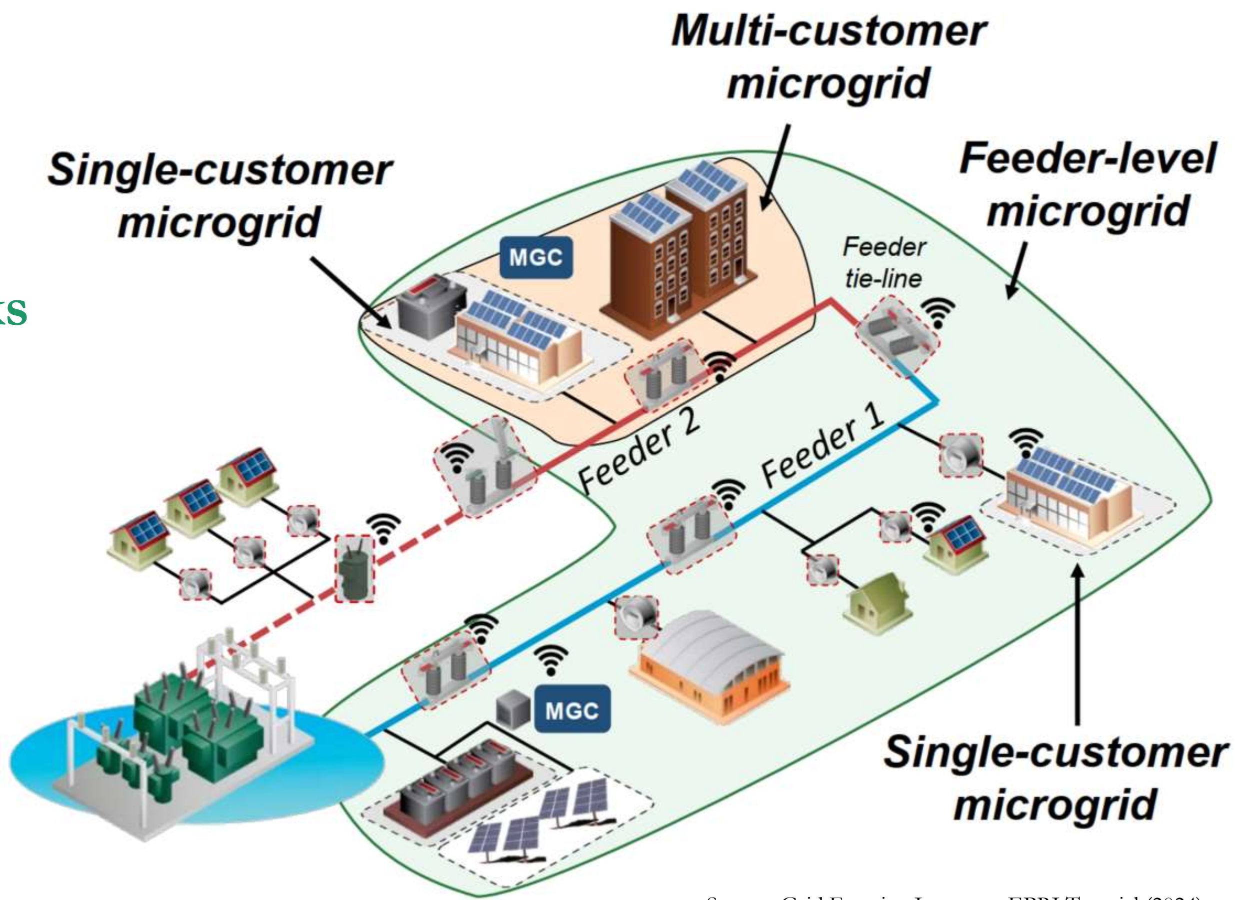
Why Microgrids?

- Global transition towards distributed and renewable energy sources

- Microgrids as building blocks of the future power system

- Key features: flexibility, scalability, resilience, local energy balance, efficiency, higher power quality
- and autonomy

- Importance in emergency, military and remote operations



Source: Grid Forming Inverters: EPRI Tutorial (2024)

Why Microgrids?

- Global tra
  distribute
  energy sou

- Microgrids
  of the futu

- Key feature
  scalability, r
  energy balar
  higher powe
- and autonom

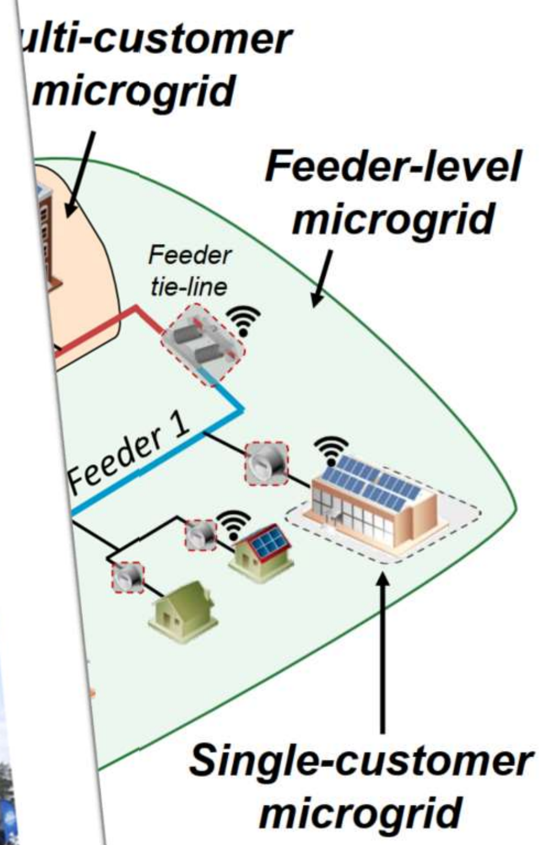
- Importance i
  military and r

NATO tests smart energy technologies at exercise in Poland

03 Jun. 2019 - 13 Jun. 2019 | Last updated: 13 Jun. 2019 15:14

English | French | Russian | Ukrainian

NATO tested new energy-saving technologies in Poland during Exercise Capable Logistician 2019 (3-13 June 2019), including to make Allied militaries more energy efficient, reduce their reliance on fossil fuels in the field, and enhance interoperability between national armed forces. Combined with linked national activities, the exercise included around 3,450 troops from 30 nations, and tested some 1,000 pieces of equipment.

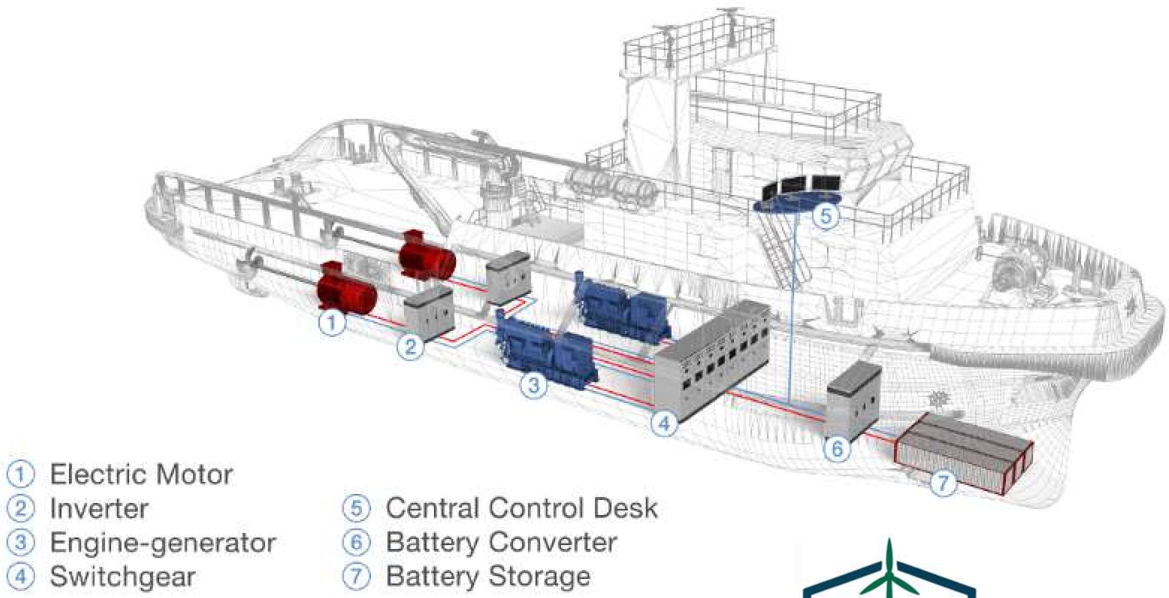


id Forming Inverters: EPRI Tutorial (2024)

SCI2M

Classification of uGs

- **Electrical architecture:** AC / DC / Hybrid
- **Grid interaction:** Grid-connected (on-grid) or Islanded (off-grid),
- **Mobility & deployment: Stationary / Mobile**
- **Scale:** Nanogrid (≤10 kW) / Microgrid (10 kW–10 MW) / Minigrid (10–50 MW)
- **Control architecture:** Centralized / Decentralized / Distributed
- **Application domain:**
  - campus/industrial,
  - healthcare,
  - military,
  - maritime/ports,
  - disaster relief,
  - communities



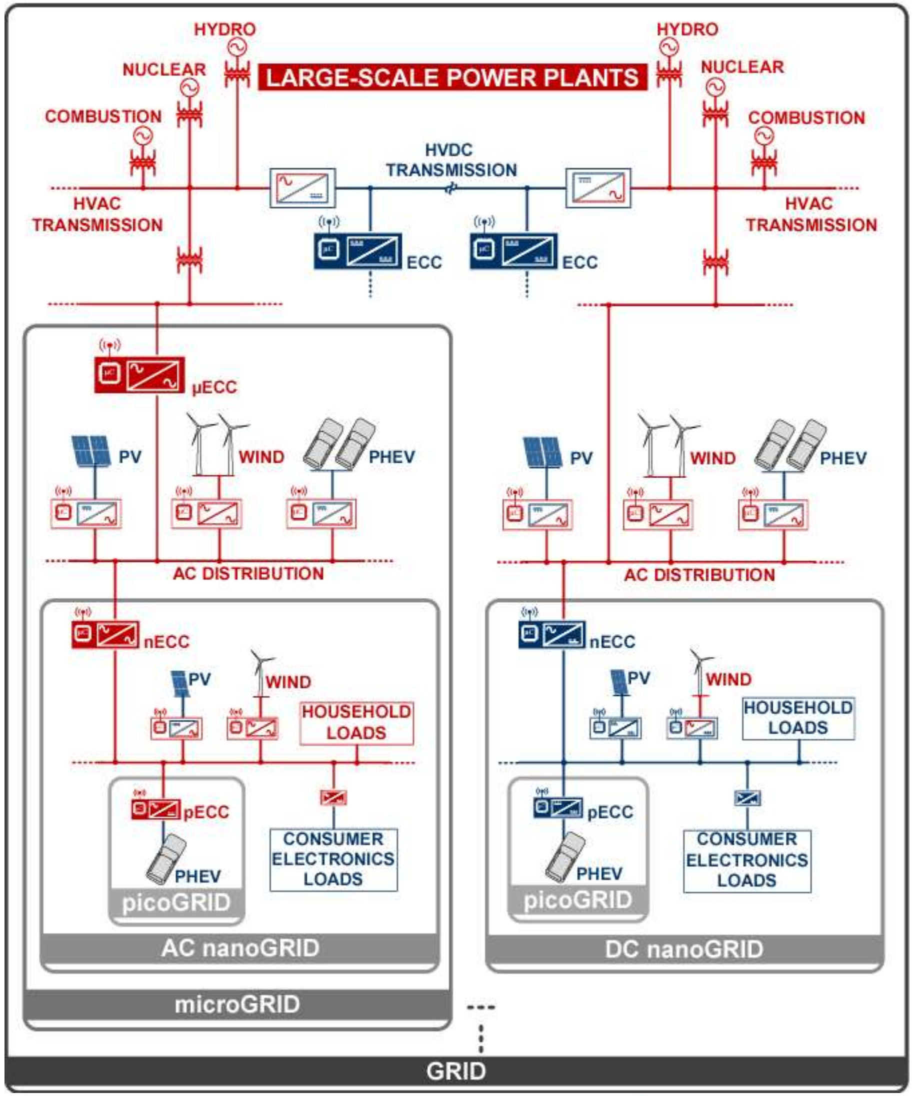
Source: TyphoonHIL - The Ship is a Microgrid (2019)

Challenges in uGs

- **Power-Quality (steady / transient):**
  Harmonic/inter-harmonic content; unbalanced waveforms; frequency variation; power oscillations; flickers; notching; fluctuation.
- **On-grid:**
  Control reactive power to support voltage; provide grid services (demand reduction, local electricity cost reduction).
- **Off-grid / Islanded:**
  Local voltage & frequency regulation (control $Q \rightarrow V$ and $P \rightarrow f$); all system imbalance must be locally supported.
- **Power flow / Power sharing:**
  Coordinated dispatch of PV, wind, storage, diesel to serve AC loads, DC loads, EVs while avoiding oscillations and imbalance.
- **Protection & mode transitions:**
  Adaptive settings for bidirectional power; islanding detection; seamless on-grid ↔ off-grid transitions under unbalanced and converter-dominated conditions.

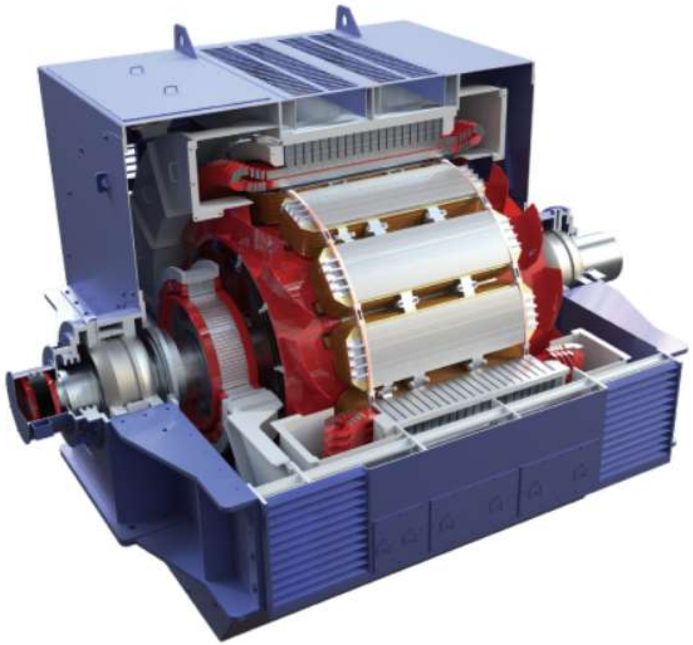
PECs in uGs

- **Inverter-based resources** (IBRs) play an important role in uGs.
- High IBRs penetration reduces synchronous inertia and fault current, lowering **system robustness.**
- uGs behave as **weak grids** with low levels of inertia and more prone to instabilities.
- IBR-dominated uGs are **faster, more complex, and difficult to control.**



Source: Boroyevich, D. et al. "Future electronic power distribution systems a contemplative view." 2010 12th International Conference on Optimization of Electrical and Electronic Equipment. IEEE, 2010.

Inverters as the Heart of uGs



VS

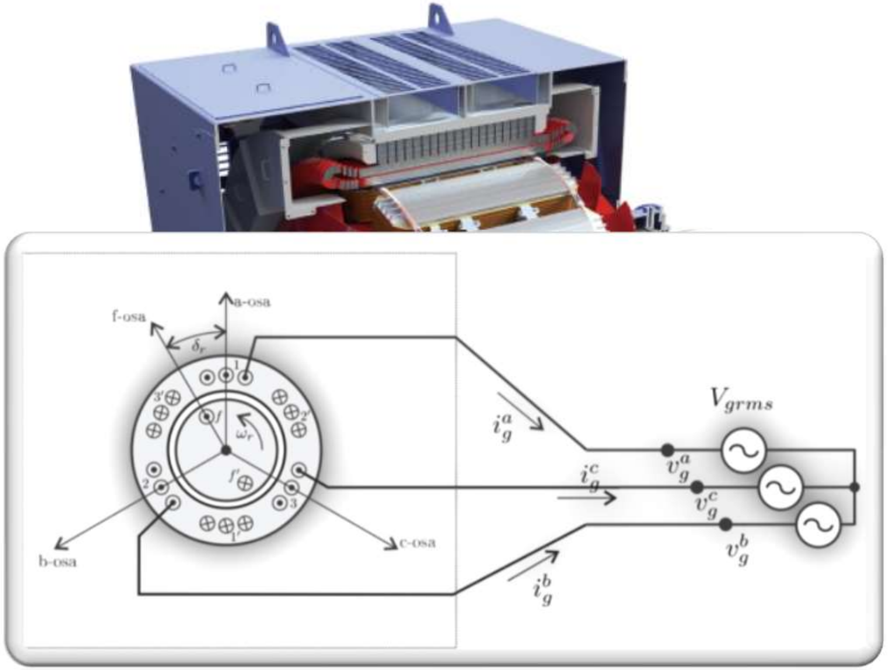
Synchronous generators:

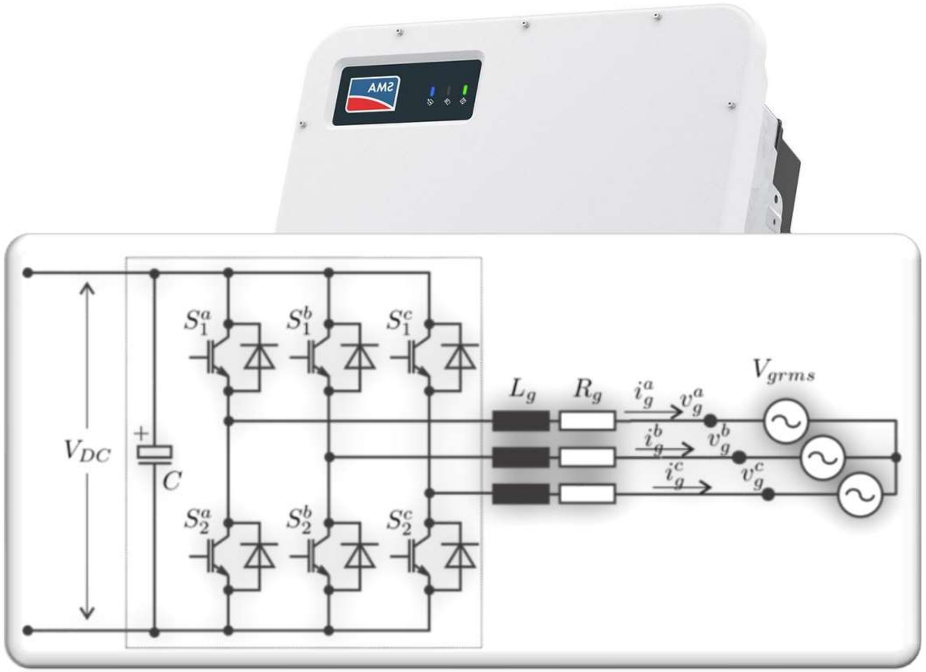
- coal/steam power plants
- combined-cycle gas turbine power plants,
- hydro power plants,
- nuclear power plants,
- diesel gensets for islanded operation
- …

Power electronic inverter:

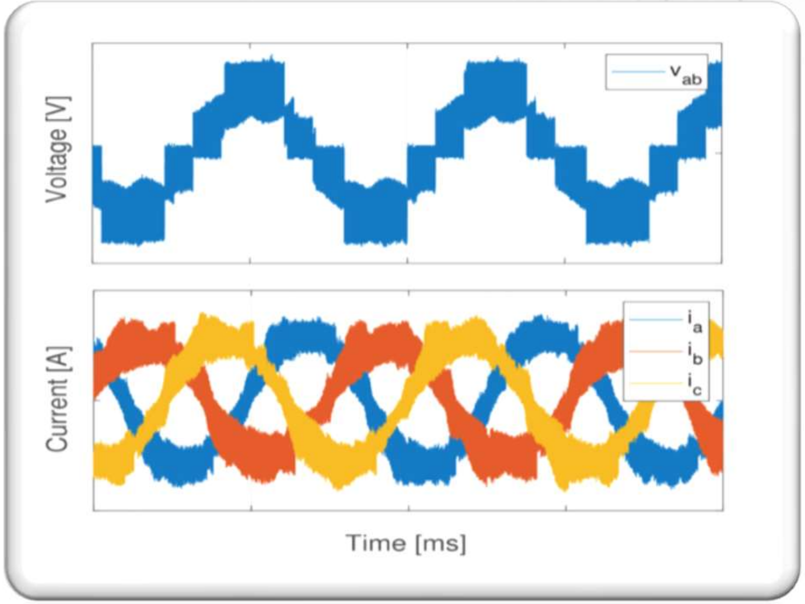
- PV plants
- Wind DFIG/PMSG
- Battery storage system
- Electromobility
- Electric drives
- Proactive loads
- …

Inverters as the Heart of uGs



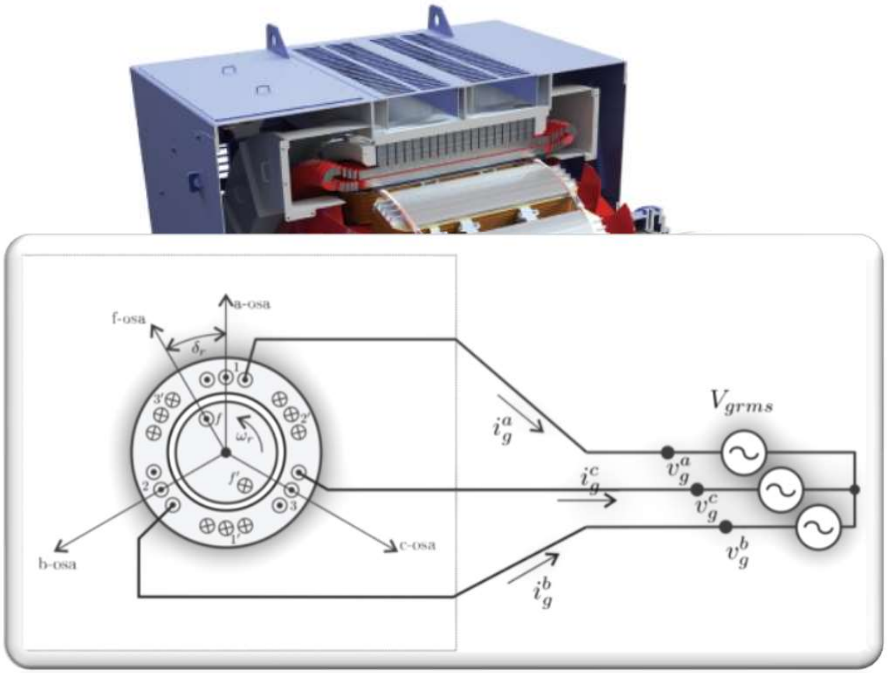


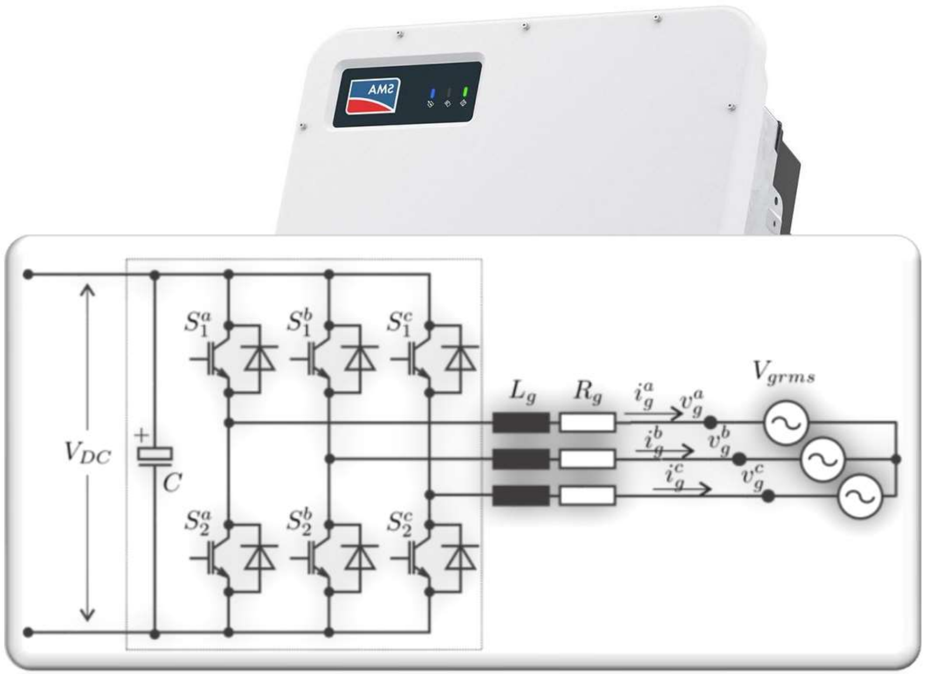
Synchronous generators naturally generate a sinusoidal output voltage waveform.



Power-electronic inverters synthesize the sinusoidal AC waveform via high-frequency switching (PWM).

Inverters as the Heart of uGs

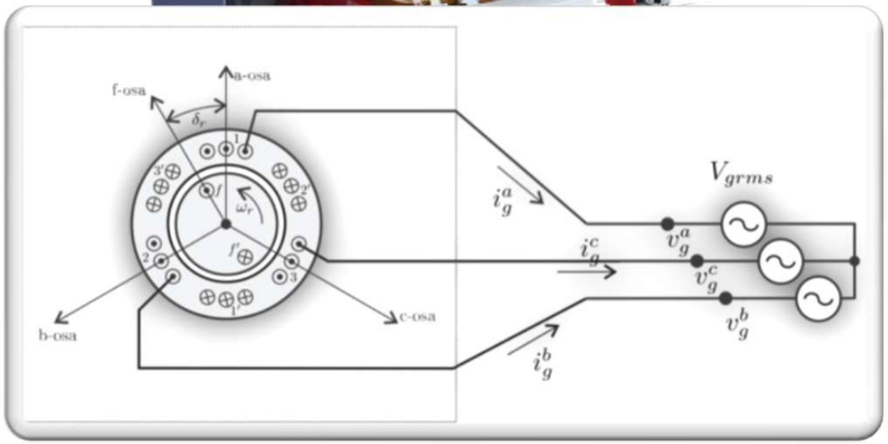


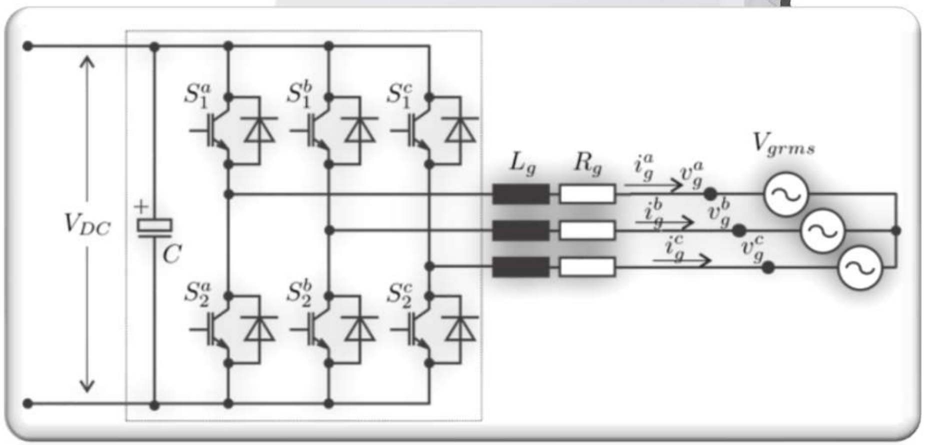


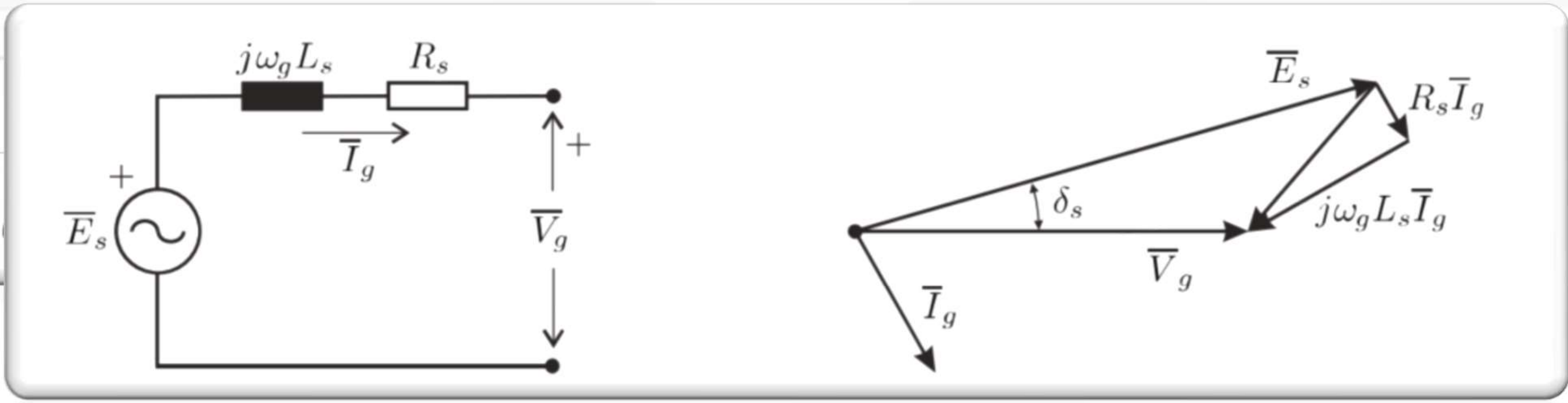
$$j\,\omega_g\,L_s\,\overline{I}_g = -R_s\,\overline{I}_g + \overline{E}_s - \overline{V}_g$$

$$j\,\omega_g\,L_g\,\overline{I}_g = -R_g\,\overline{I}_g + \overline{V}_o - \overline{V}_g$$

Inverters as the Heart of uGs

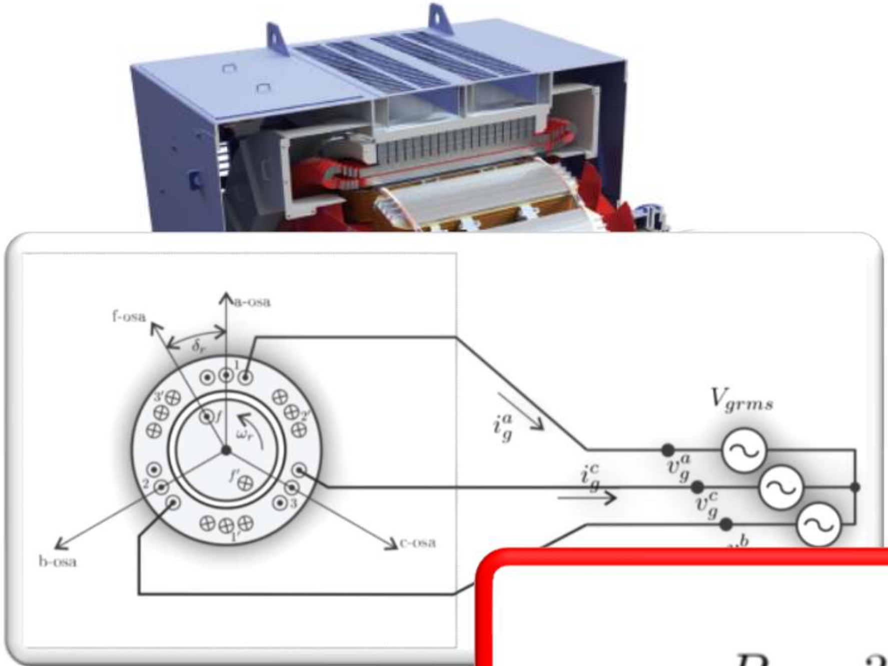


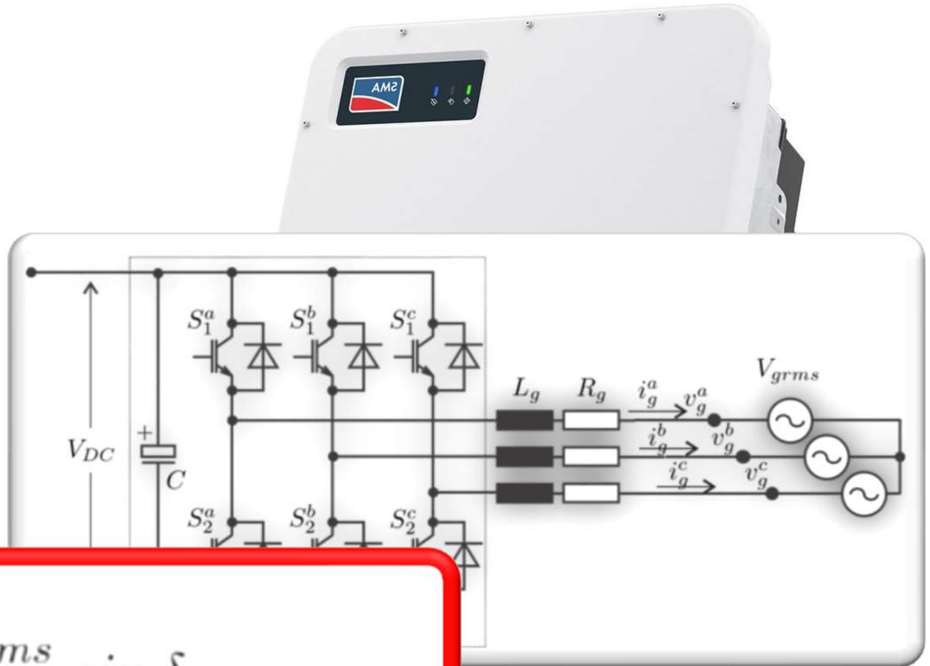


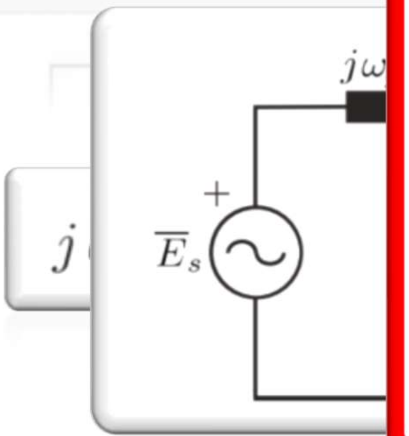


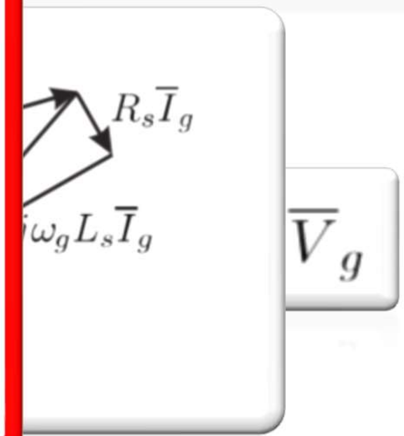
SCI2M

Inverters as the Heart of uGs





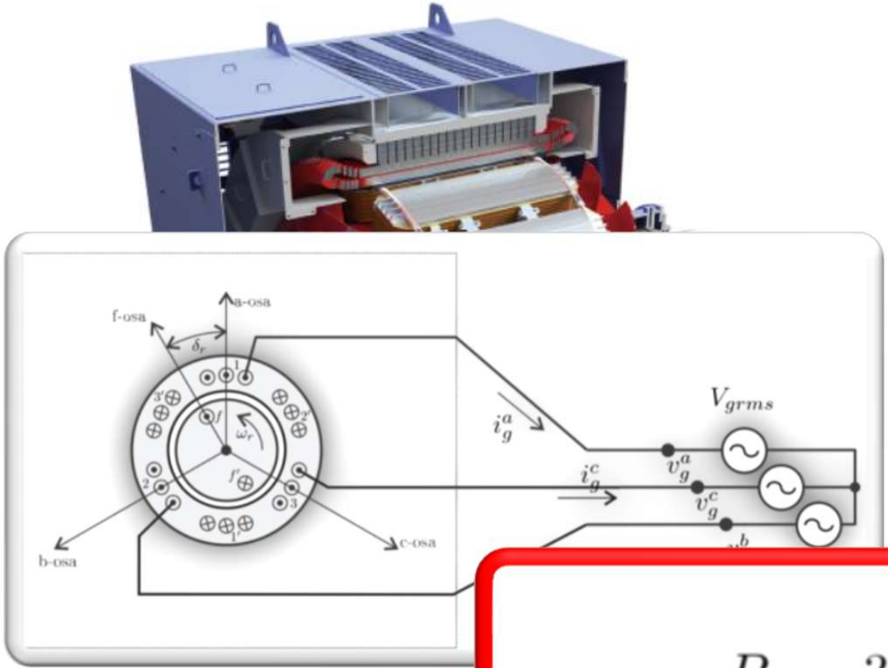


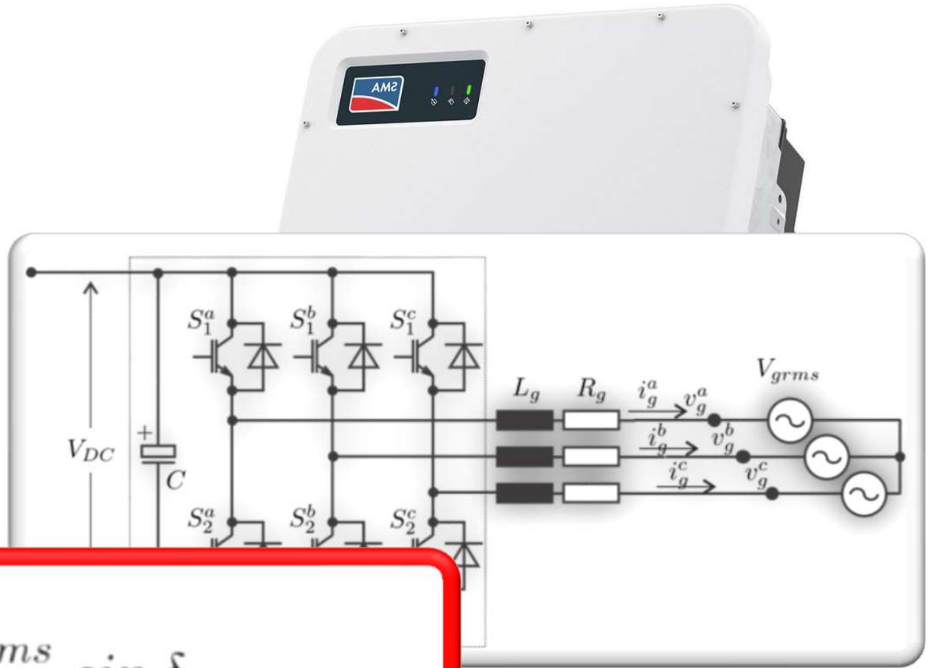


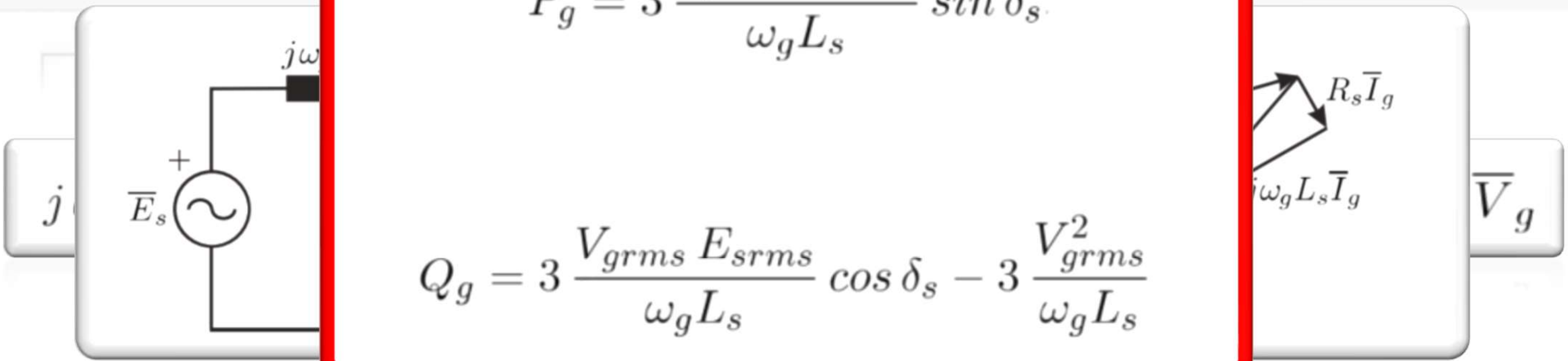
$$P_g = 3\,\frac{V_{grms} E_{srms}}{\omega_g L_s}\, sin\,\delta_s$$

$$Q_g = 3\,\frac{V_{grms} E_{srms}}{\omega_g L_s}\, cos\,\delta_s - 3\,\frac{V_{grms}^2}{\omega_g L_s}$$

Inverters as the Heart of uGs







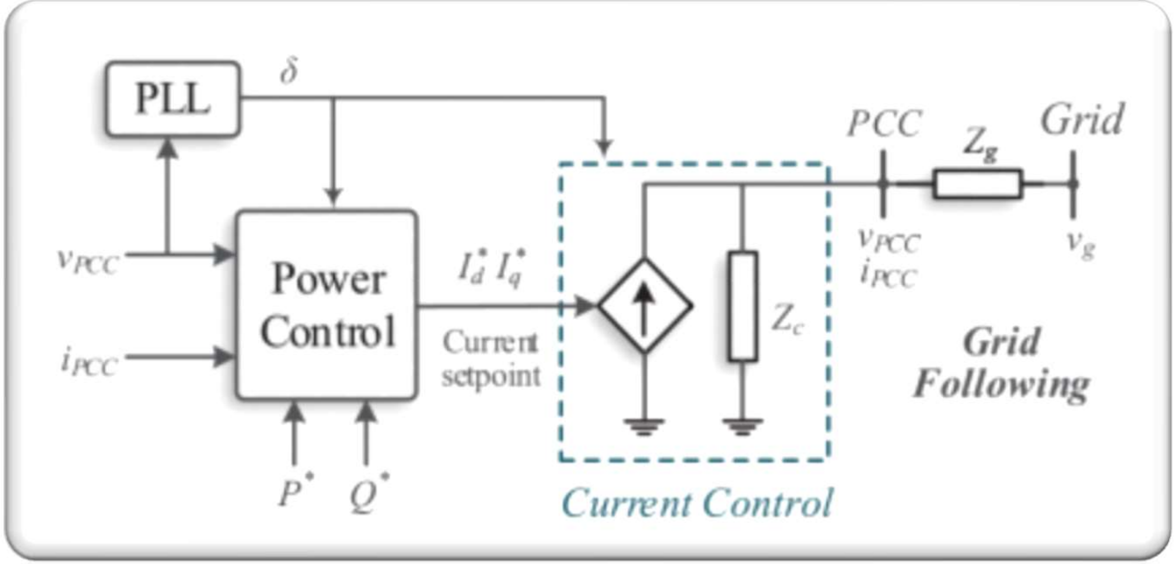
$$P_g = 3\,\frac{V_{grms}\,E_{srms}}{\omega_g L_s}\,\sin\delta_s$$

$$Q_g = 3\,\frac{V_{grms}\,E_{srms}}{\omega_g L_s}\,\cos\delta_s - 3\,\frac{V_{grms}^2}{\omega_g L_s}$$

Synchronverter

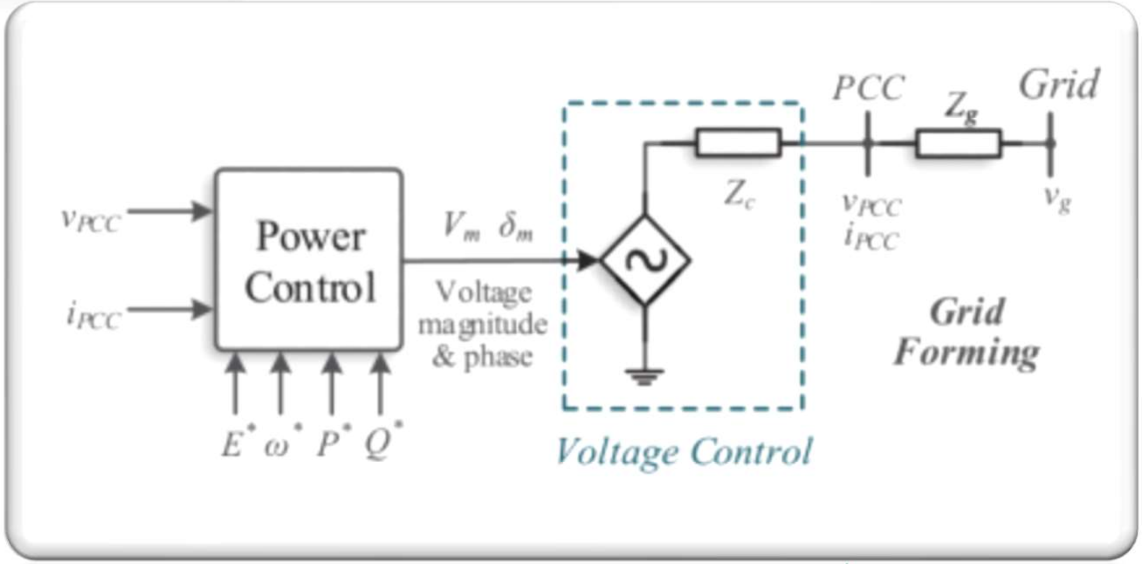
inverter that mimics a synchronous generator

Grid-Following vs Grid-Forming



- Current source (injects commanded P & Q with external V/f reference)
- No black-start
- Fast & efficient control for PV/BESS
- Provides VAR/harmonic support.
- Needs a strong grid or GFM reference
- Fault current limited

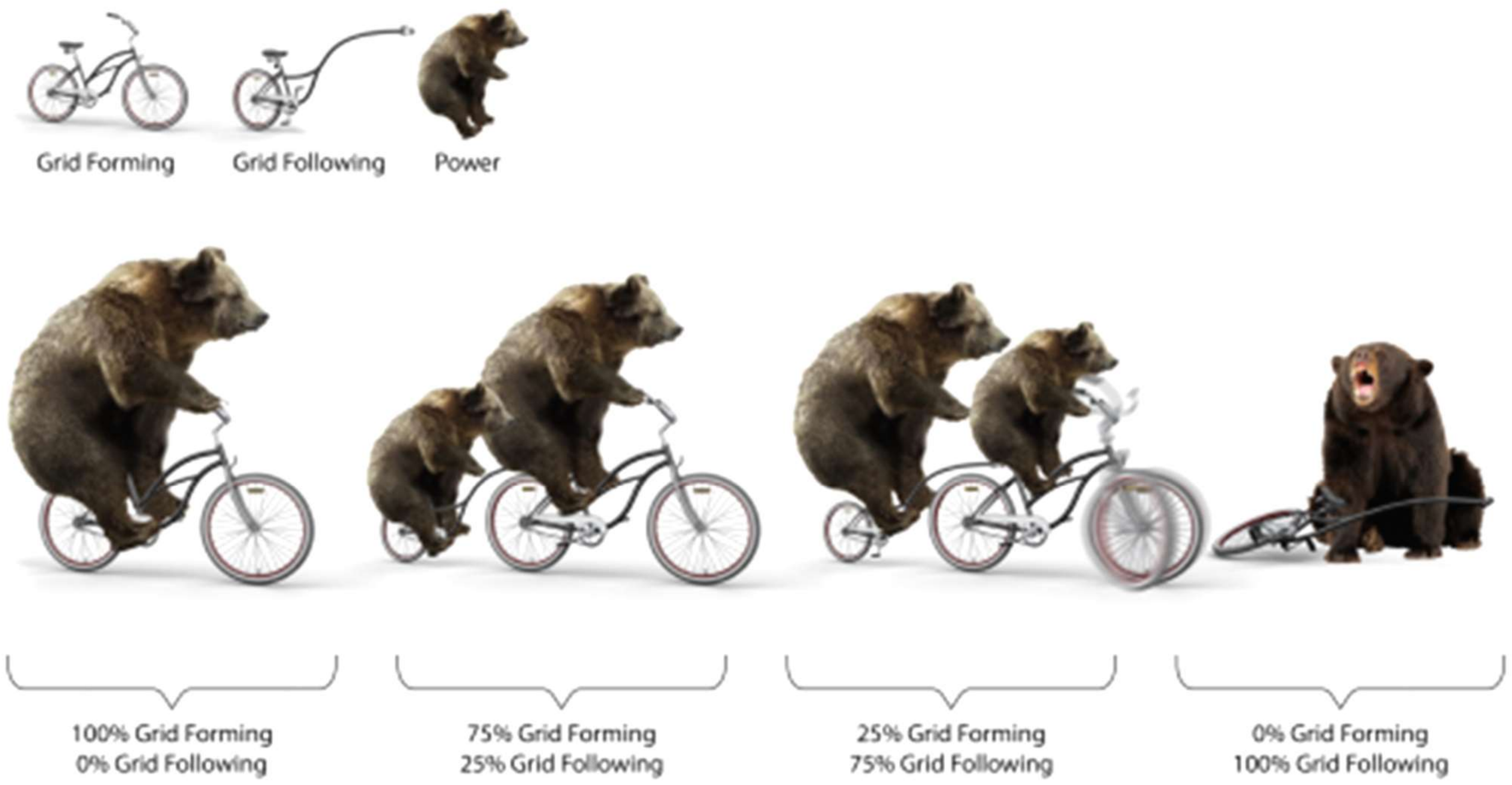
- Voltage source (sets V & f)
- Supports black-start and islanded operation
- Droop-based sharing with P–f and Q–V regulation
- Add virtual inertia/damping
- Stabilizes weak grids
- Fault current limited



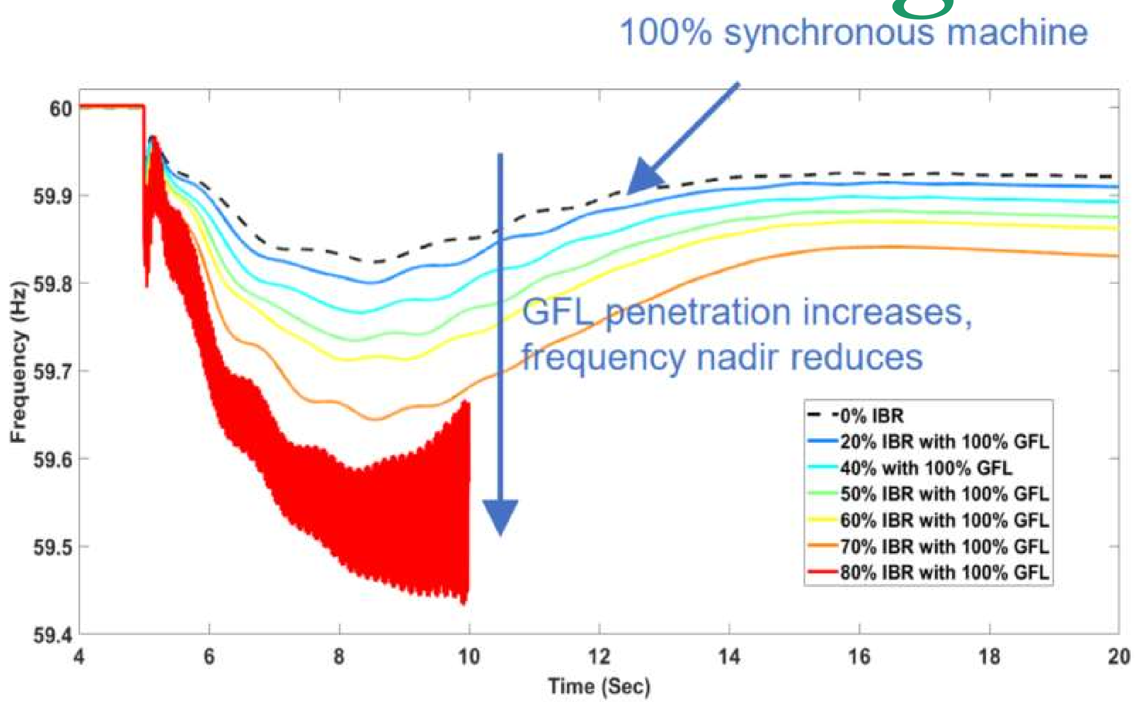
SCI2M

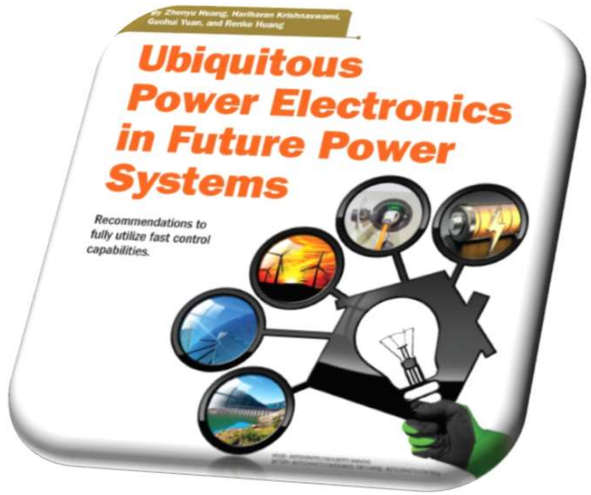
Grid-Following vs Grid-Forming

Source: R.W. Kenyon, et al., “Stability and control of power systems with high penetrations of inverter-based resources,” Solar Energy, 2020

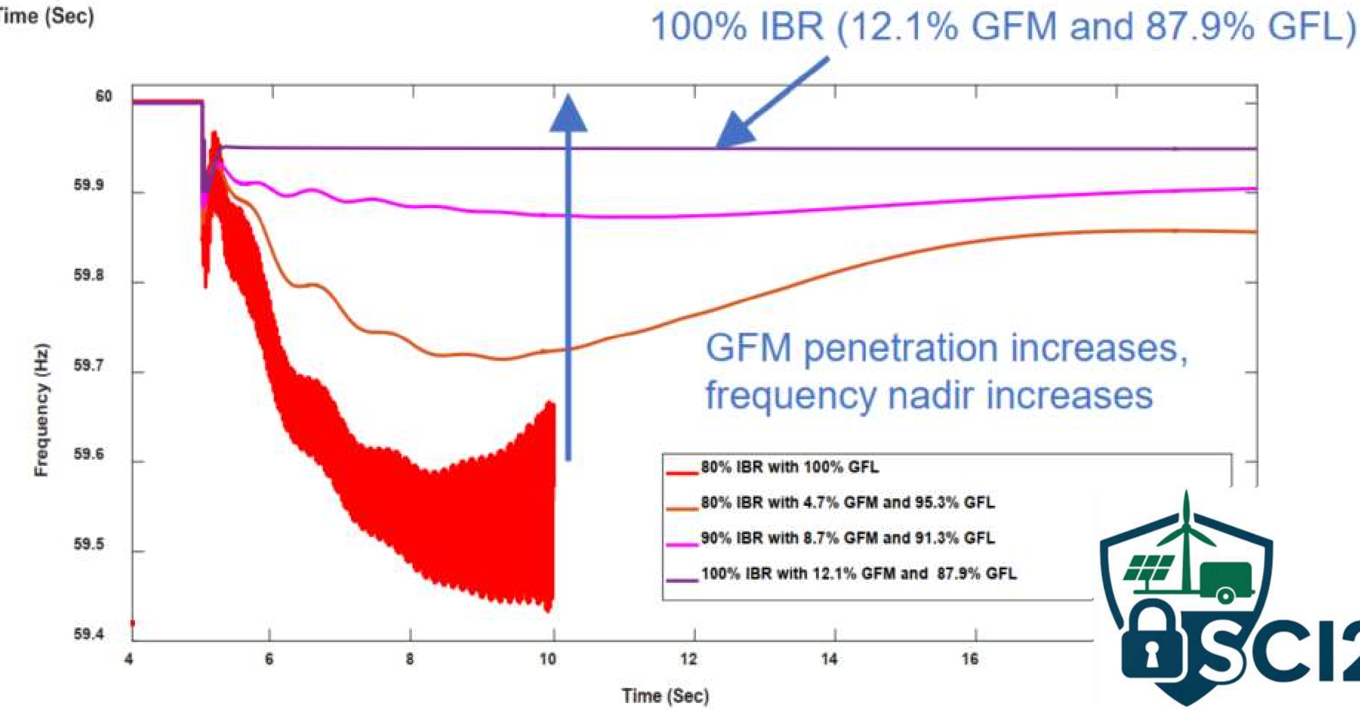


Grid-Following vs Grid-Forming

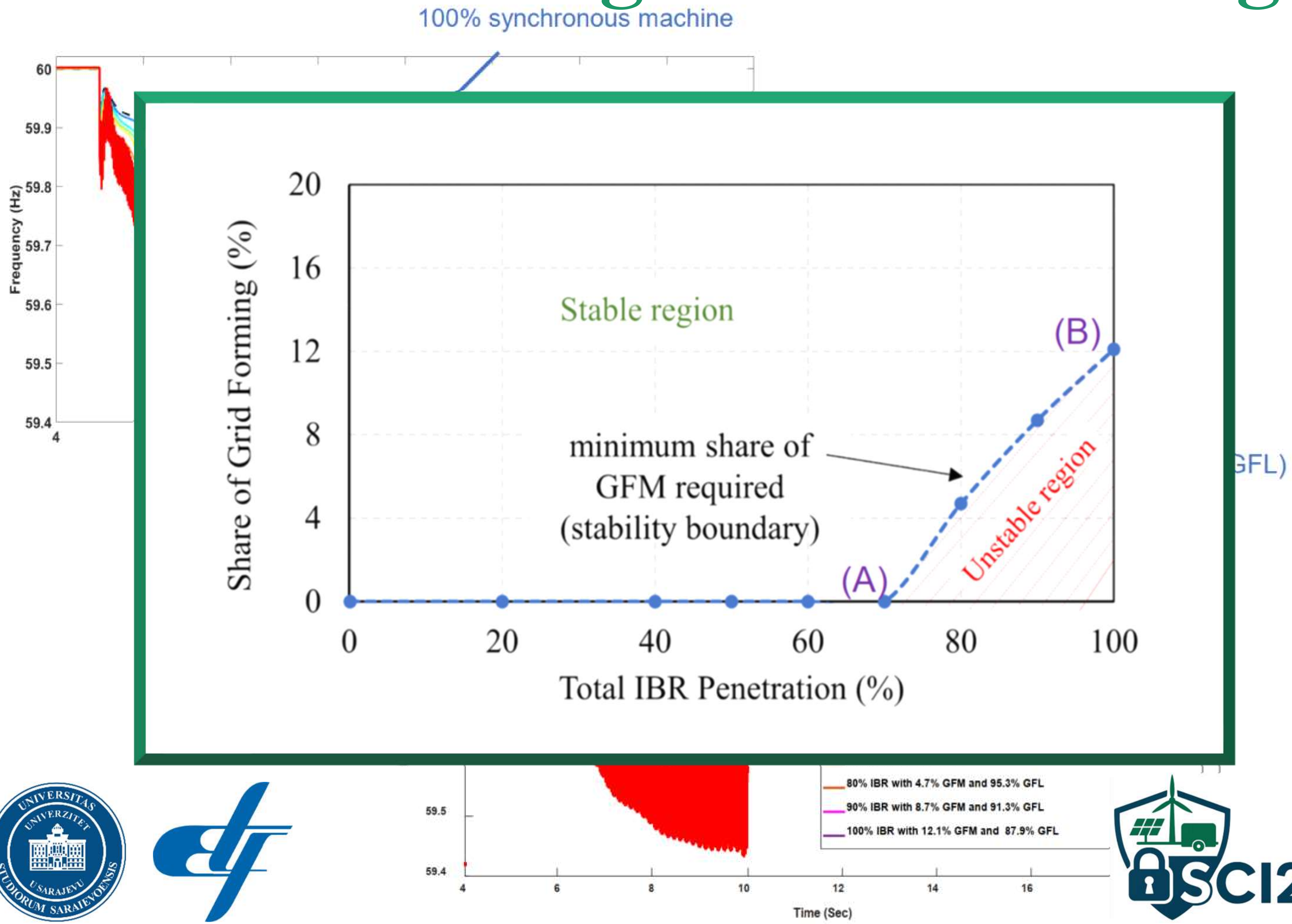




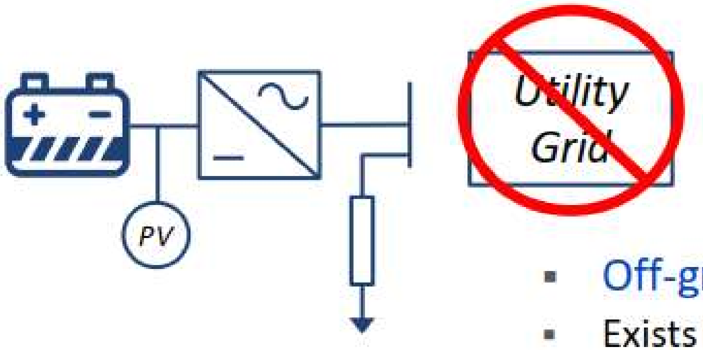
Dynamic simulation of the modified IEEE 8500-Node Test Feeder with 550 IBRs in GridLAB-D after tripping the two generation units.



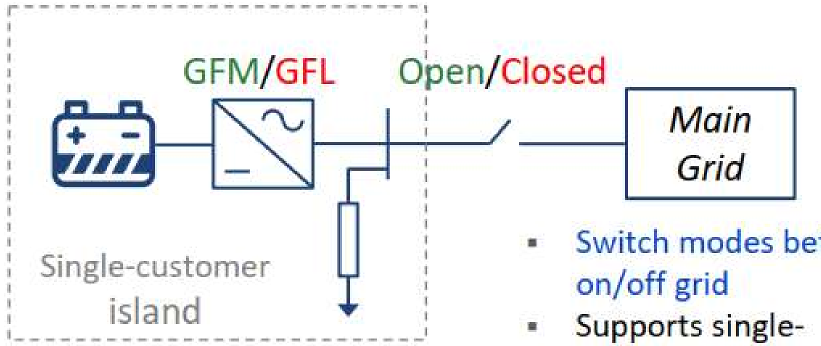
Grid-Following vs Grid-Forming



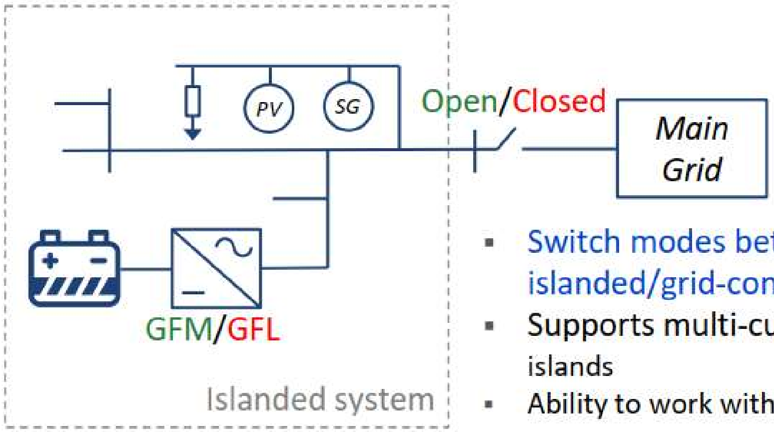
Different Types of Grid-Forming



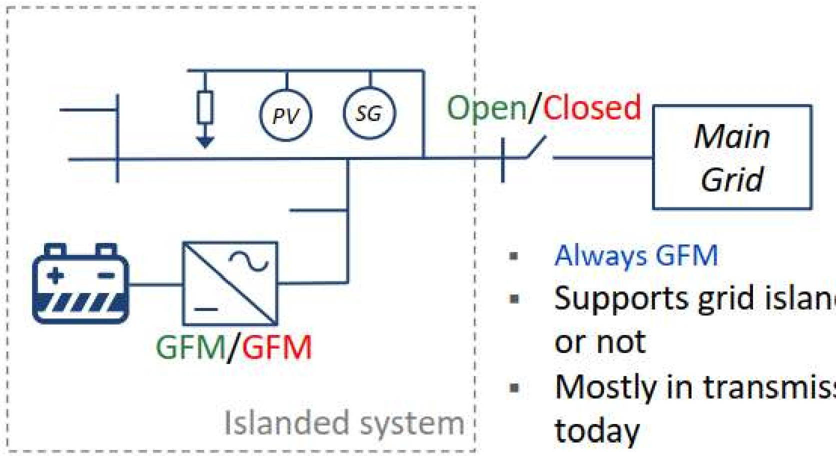
- Off-grid only
- Exists for decades



- Switch modes between on/off grid
- Supports single-customer islands



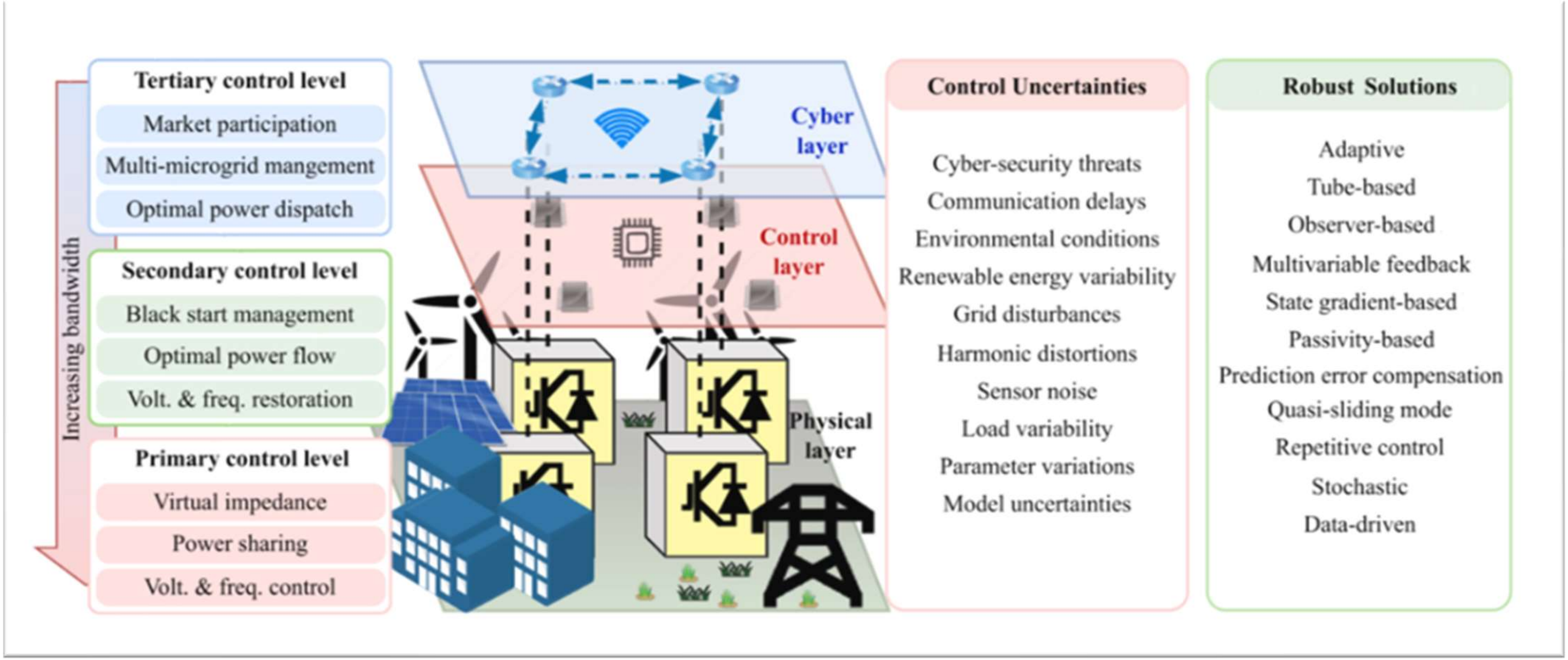
- Switch modes between islanded/grid-connected
- Supports multi-customer islands
- Ability to work with other resources



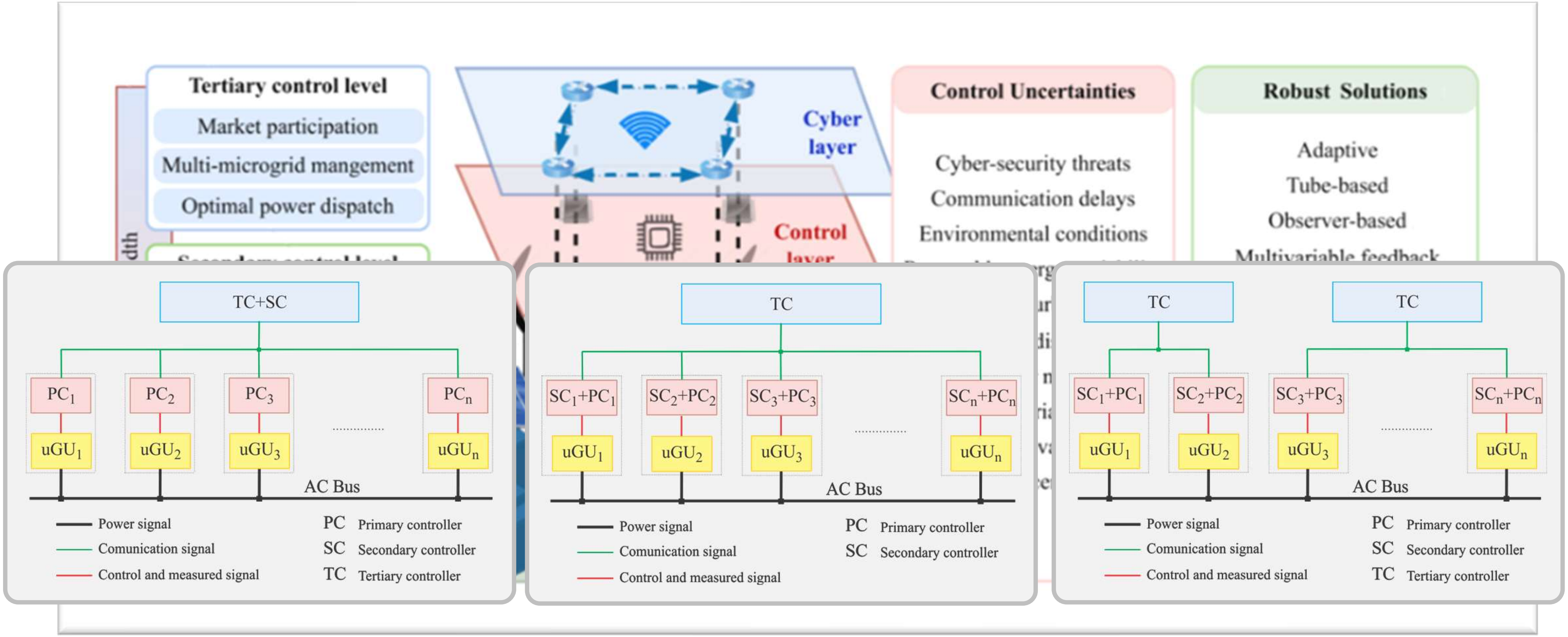
- Always GFM
- Supports grid islanded or not
- Mostly in transmission today

A grid-forming inverter, as virtual synchronous generator, emulates synchronous-machine dynamics while synthesizing the AC voltage waveform.

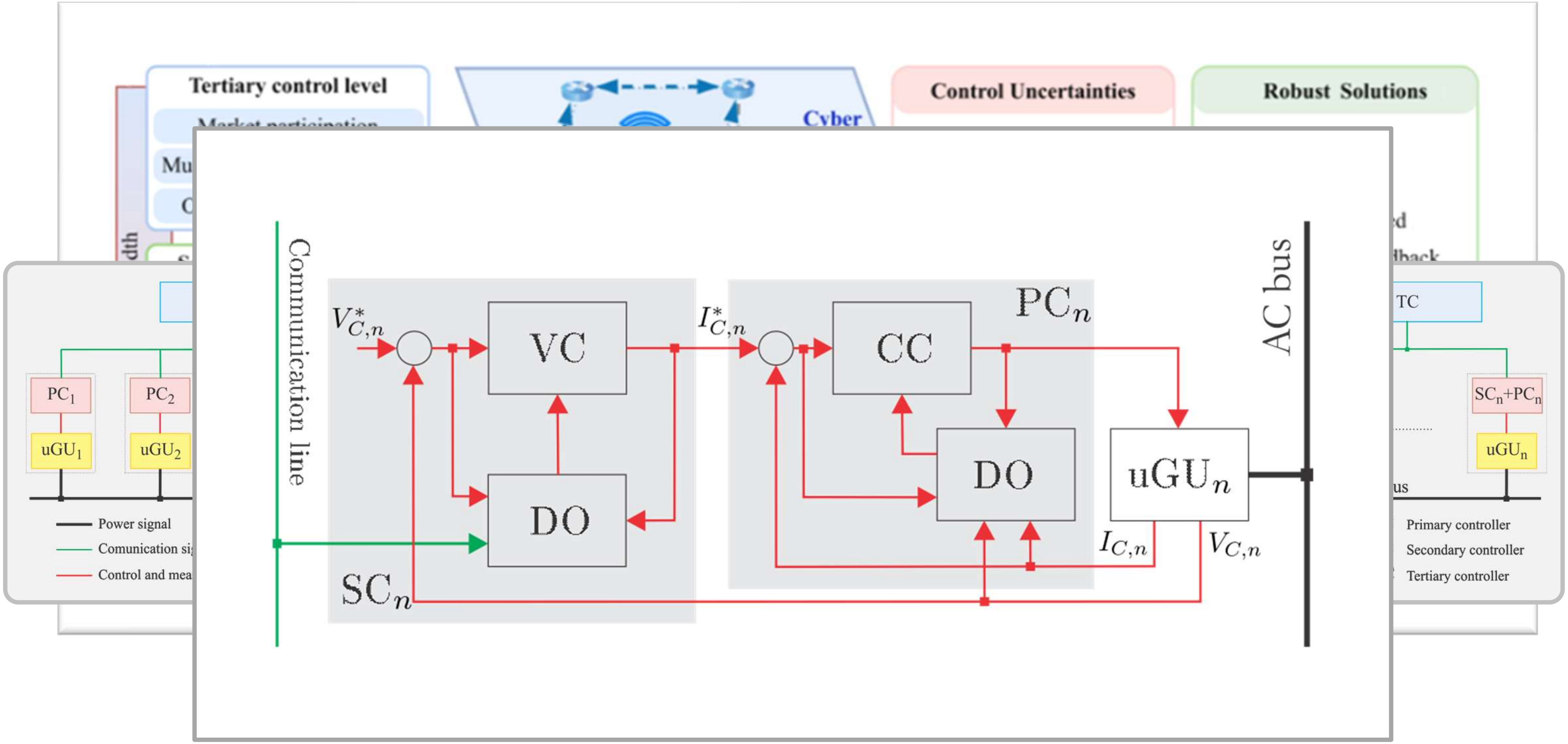
Robust Control of uGs



Robust Control of uGs



Robust Control of uGs



Security and Resilience in uGs

Concept:

Real-time digital replica of the physical microgrid synchronized with live data.

Core functions:

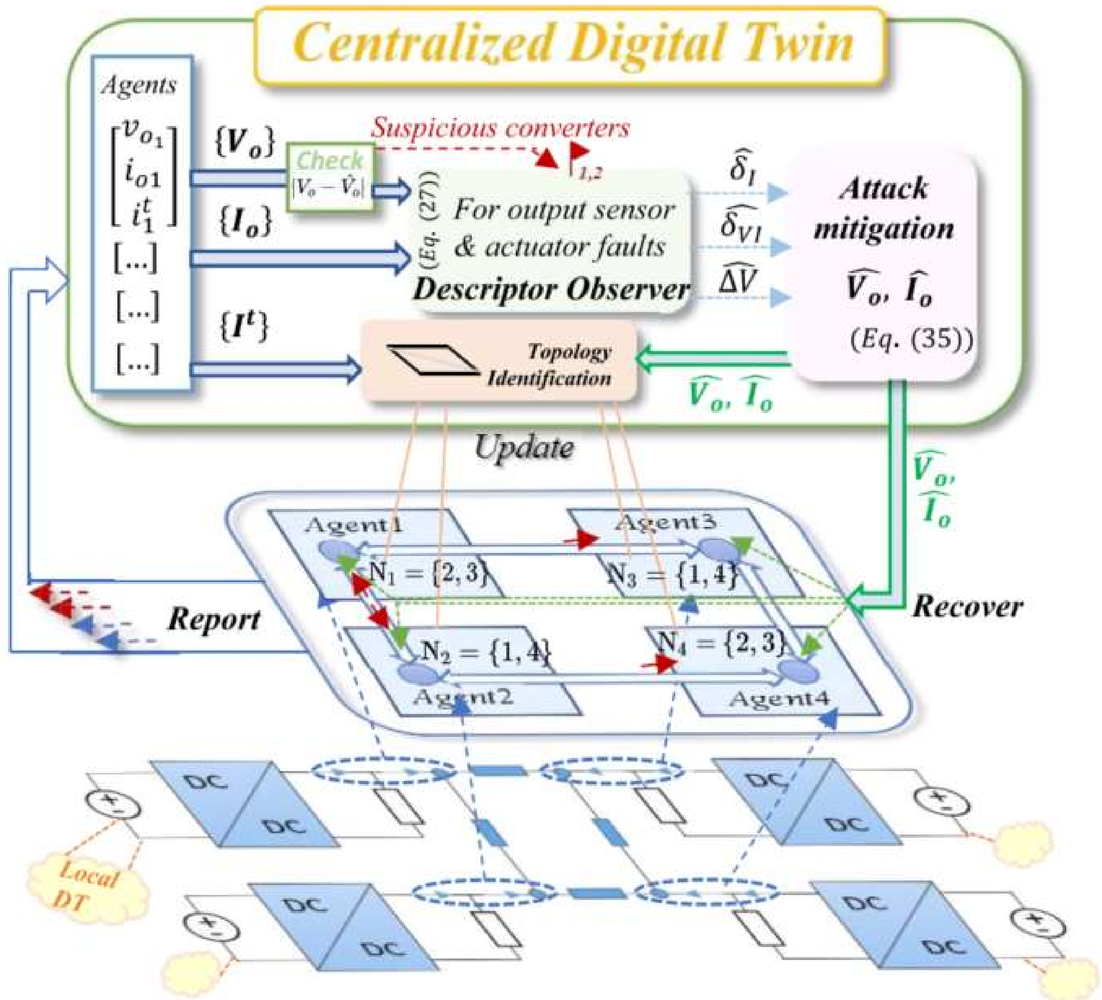
- fast prediction
- what-if analysis,
- diagnosis,
- control validation,…

Security & reliability:

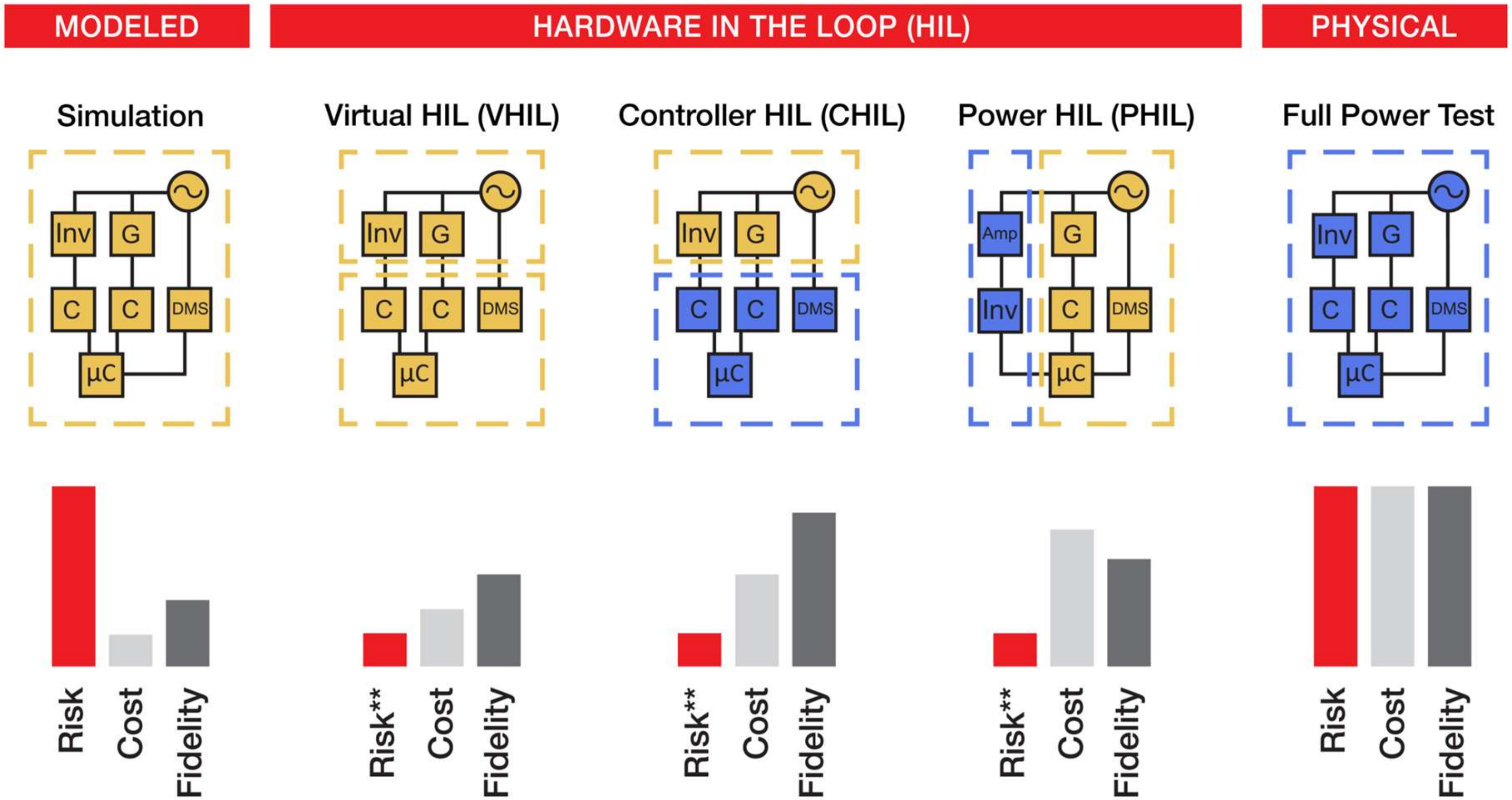
- anomaly & fault detection,
- cyber-attack detection
- health monitoring, . . .

Outcome:

- safer operation,
- faster tuning,
- resilient on-grid ↔ islanded transitions,…



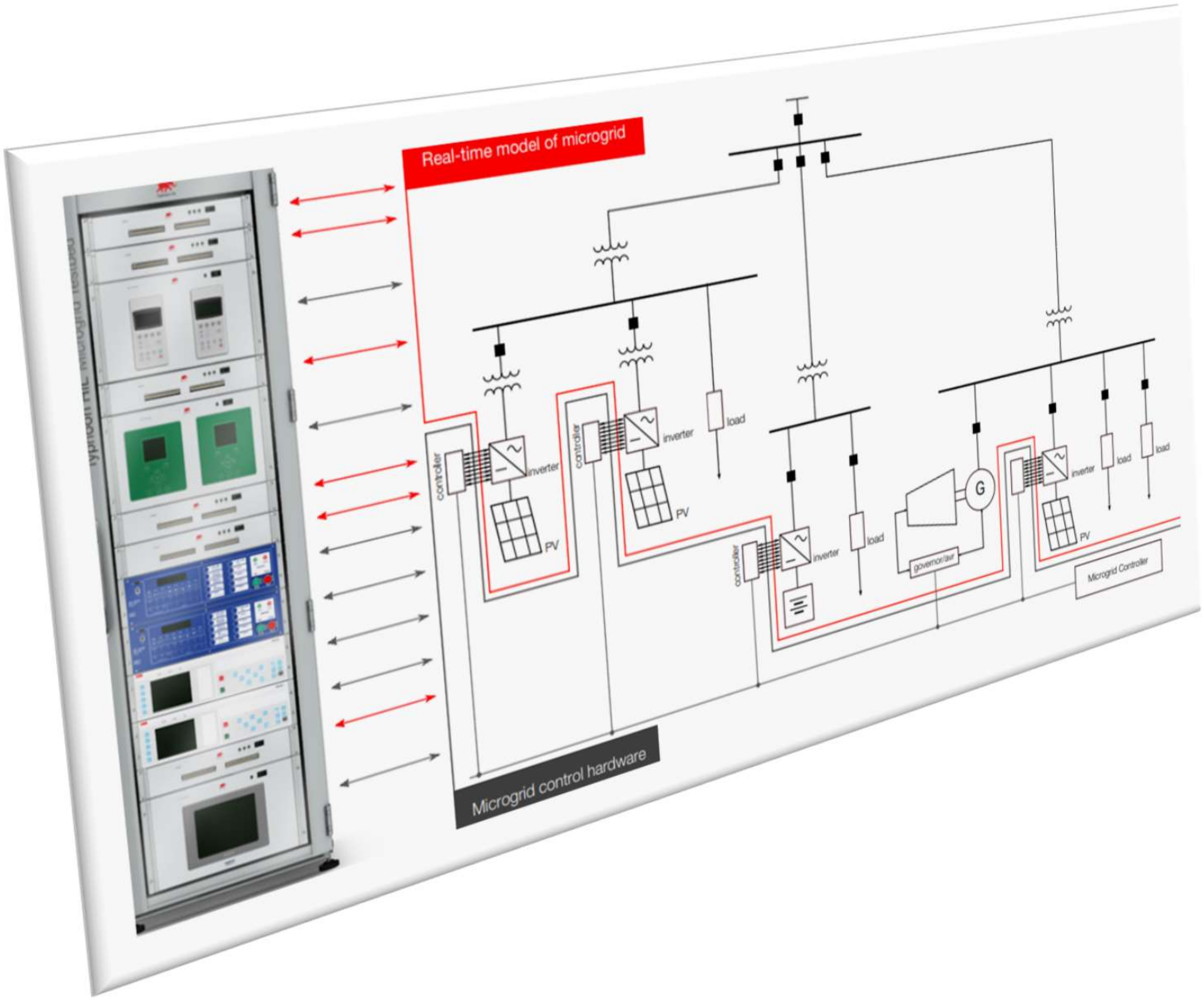
Testing & Validation



* for component OEMs

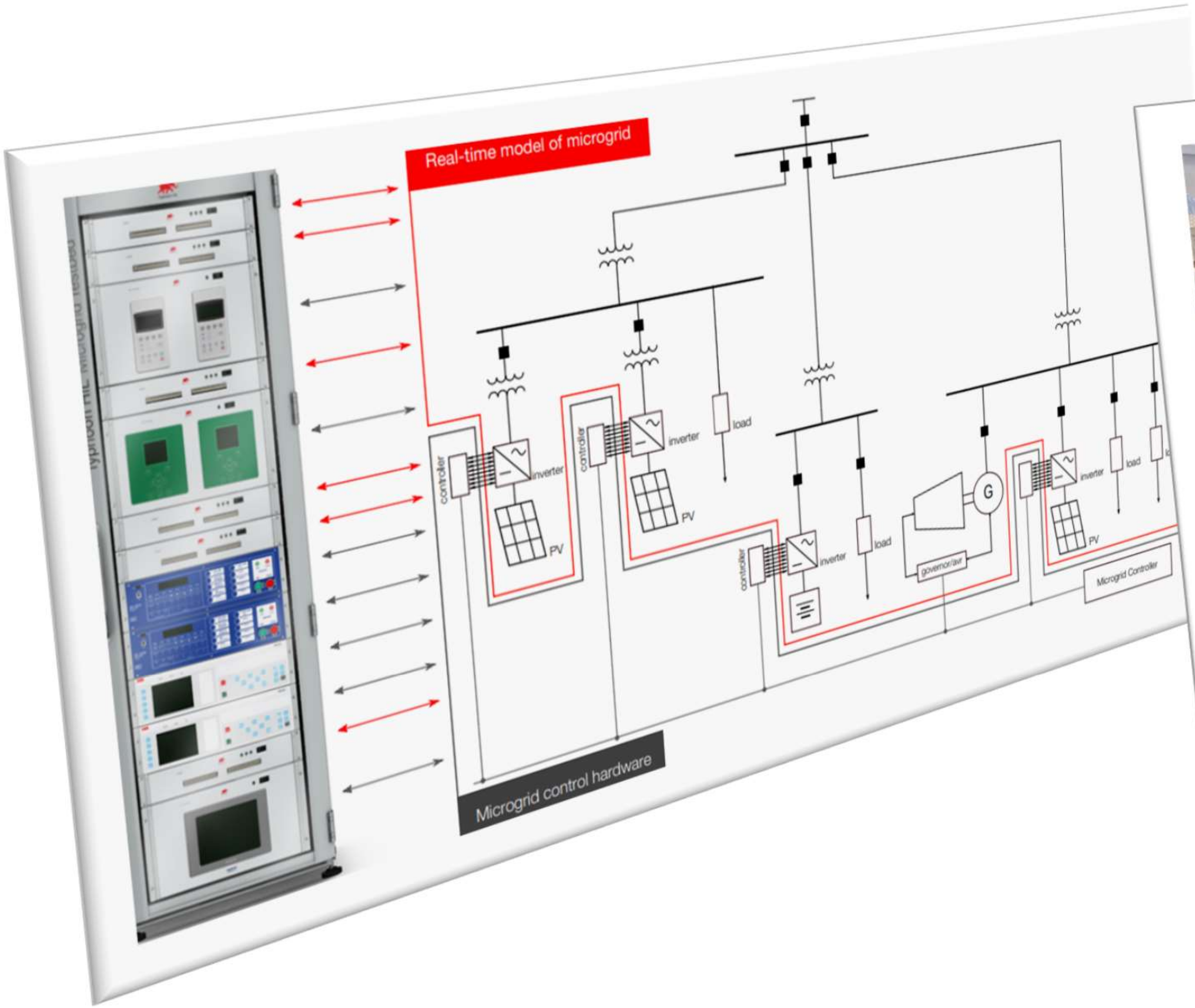
** "Risk" estimation made assuming all stages of HIL testing are performed (VHIL, CHIL, and PHIL for component OEMs); using only one type of HIL testing may result in higher risk.

Testing & Validation



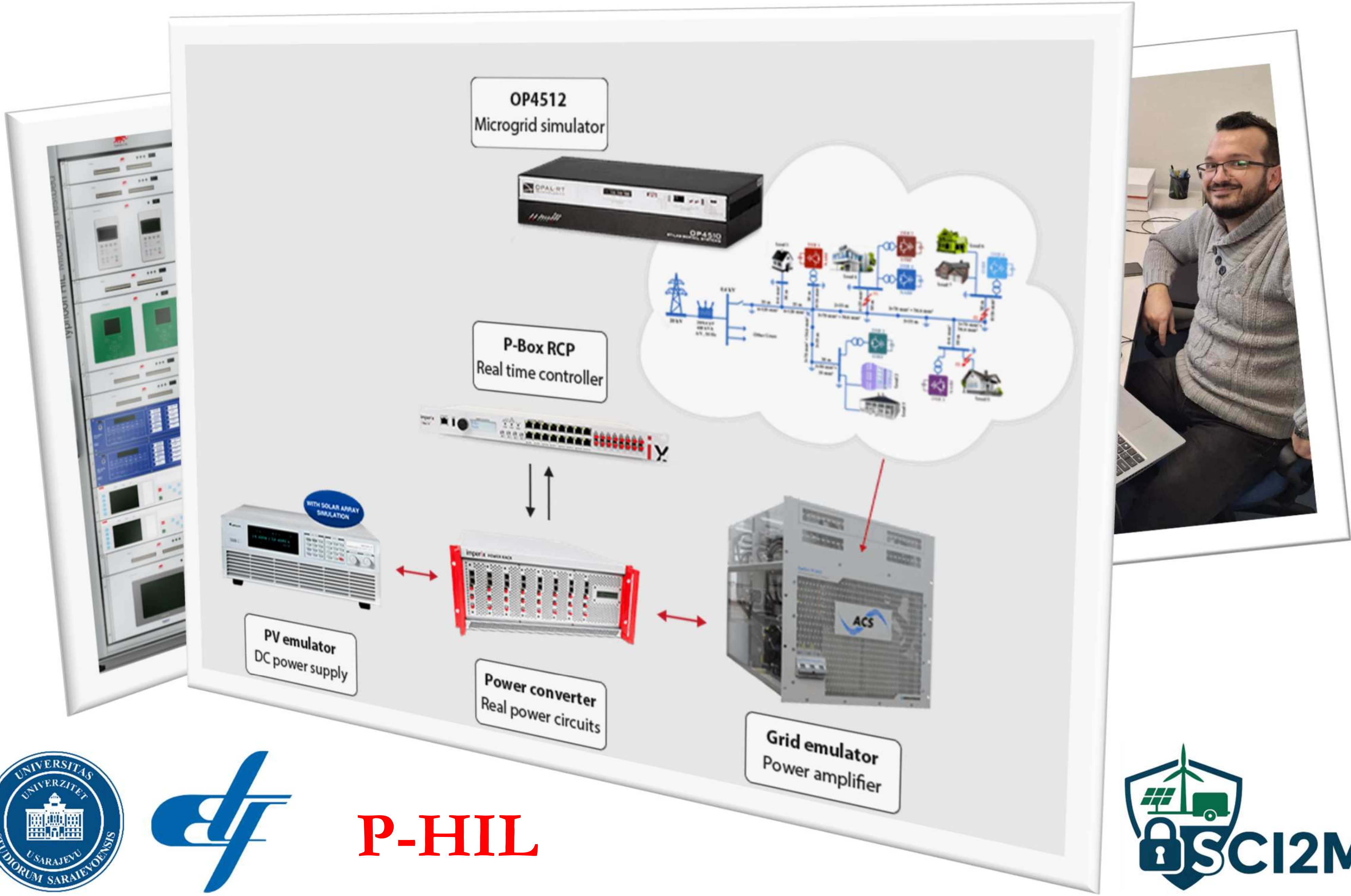
V-HIL

Testing & Validation



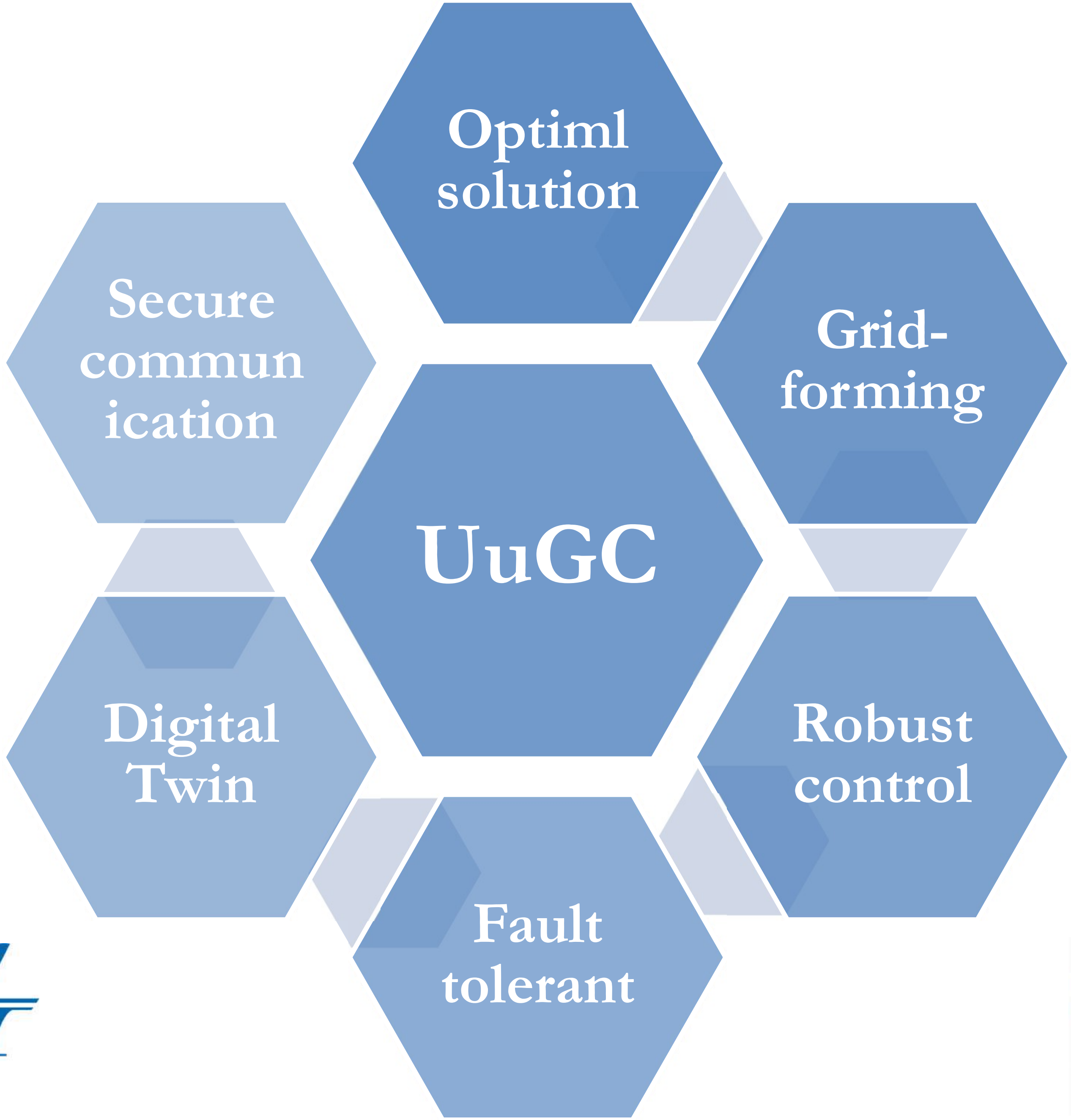
C-HIL

Testing & Validation



P-HIL

Instead of a Conclusion



Control is the new inertia – design it to be secure, resilient, and intelligent.

Questions & Discussion