Energy Transition or Disruption?

A New Paradigm for System Control

ESIG Presentation

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www.cde.gatech.edu

GT Center for Distributed Energy

Georgia Tech Center for Distributed Energy

Creating holistic solutions in electrical energy that can be rapidly adopted and scaled

WORLD ECONOMIC FORUM
TOP 3 TRANSMISSION GRID INNOVATIONS
2010-2020
"Accelerating the Energy Transition"

Platform Initiatives

Grid Asset Augmentation


7.2 kV 50 kVA Hybrid Transformer


13 kV 1 MVA Modular Transformer


Smart Wires

- 13 kV/50 kVA FUT
- 13 kV 1 MW Power Router
- 67 MVA Modular LPT
- Improving Grid Resiliency
- Smart Wires
- Meshed Grid VVC

Energy Access in Emerging Markets

- 'Exponential' Tech
- Self Organizing Nano Grid
- Pay-Go Smart Meter
- Low Cost DA for Grids
- Ad-Hoc Bottom-Up Grids
- Empower a Billion Lives


Emerging Technology: D-Light


Top 10 Emerging Markets *Source: Global Intelligence Alliance*

Next Generation Grid Power Electronics

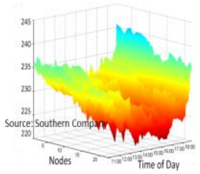
4 kV MVSI for Large PV Farms


7.2 kV 50 kVA SST

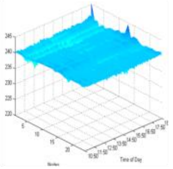
- 5 kV DC Grid Building Block
- 7.2 kV 50 kVA Grid Connected SST
- 4 kV MVSI for Large PV Farms
- Triports for PV/Storage/Grid
- MVSI with Integrated Storage
- Microgrid-Grid Interface Device

Decentralized Grid Control Techniques & Markets

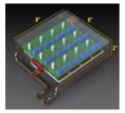
- Grid Edge Volt VAR Control
- Collaborative Control
- High PV Integration
- DER Micro grid Impact
- Self-Pricing Island Grids
- Virtual Power Plants



Feeder Voltage w/o and with GE Control


Feeder Voltage w/ Grid Edge Control

Next Generation Industrial Power Electronics


100 kVA EV Drive System


200 kVA Isolated Drives


2 MVA Industrial SIVOM

- Industrial CVR Energy Efficiency
- 100 kVA EV Drive System
- 25-500 kVA Isolated Drives
- Energy Hub – DC Fast Charging
- Programmable Load/Source
- Data Center Power Sources

Global Asset Monitoring Management & Analytics (GAMMA)

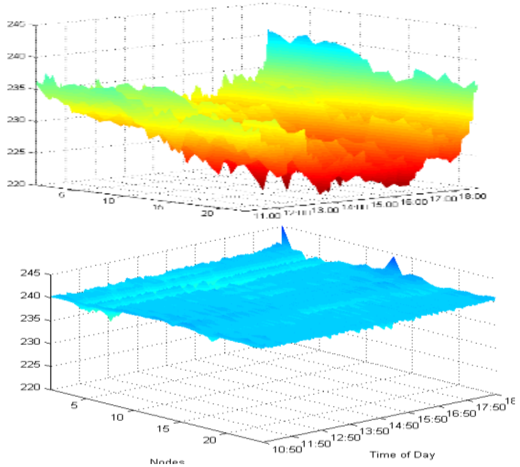
- Low-Cost Communications
- Cyber-Security
- Data Management
- AMI Data Analytics
- Global Sensor Networks
- Cloud Based GAMMA System

GAMMA Platform


Gamma kernel

Primary Drivers

Digitalization   Decentralization   Decarbonization



DECENTRALIZED CONTROL
Varentec (Sentient)

POWER FLOW CONTROL
Smart Wires

SCALABLE HYBRID SOLAR
GigaGrid

MULTIPORT ENERGY ROUTER
GridBlock

Massive Disruption at Grid-Edge…*all outside utility control*

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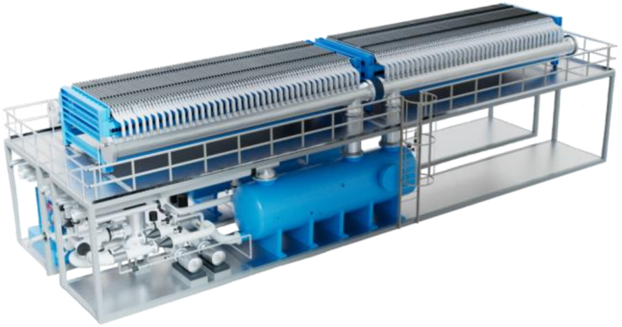
PV & Wind Farms

- PV and wind - fast global growth **120+160 GW/yr**
- Interconnection queues and curtailment


Energy Storage & Green Hydrogen

- Modular battery energy storage – **1100 GW by 2030**
- Hydro balancing, pumped hydro & green hydrogen

Load Growth - EVs, Datacenters & Electrified Industry

- 125 million EVs by 2040,buses, trucks, semis – peak load >1000 GW
- Data centers (AI) 100-1000 MW each, industrial loads (steel, etc.)


Community Resiliency - Microgrids

- Hurricanes, wildfires & ice-storms - grid edge resiliency
- Autonomous flexible microgrids may hold the answer


Accelerating Irreversible Energy Transition Underway – Are We Prepared?

Some Questions That Keep Us Awake at Night

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In 2010 there was no utility, oil or automotive CEO who believed EVs, PV or storage would be cost competitive anytime soon! How could the energy industry miss the mark by so much? And it continues!

System Level Issues

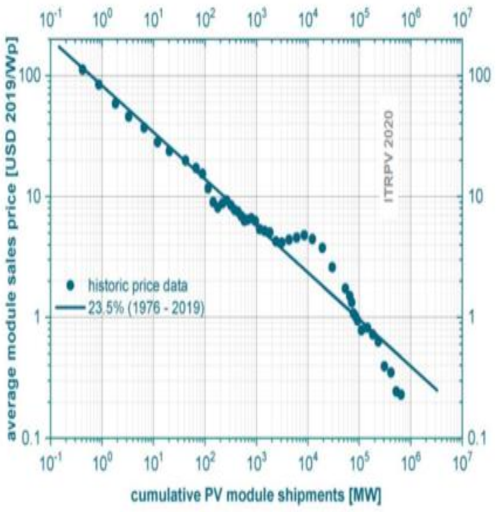
1. We have a reliable 1000 GW grid - aren't the fundamentals for a future grid with more DERs the same (100s GW of PV and wind already there) – or is it a new paradigm?
2. If the cost of solar and storage drops by 2-3X again over the next 5 years, how will existing plants compete?
3. Only three states in the US have policies that encourage energy storage – is storage not so important?
4. If gas generation is a back up for decarbonized energy, $/MWh be astronomical – will energy still be cheap?
5. Can new transmission be built at the scale needed? (NIMBY, low utilization & cheaper non-wires solutions)
6. As BTM resources are built to meet C&I customer timelines, will utilities also need generation at the edge?
7. How do we power fast-growing new loads (temporal and spatial issue) – EV charging, datacenters, electrified industry, green H2, resiliency, and can this be done with zero emissions (2050 goal)?

For most US utilities, things haven't changed much yet, but cracks are beginning to show!

But What is Causing the Disruption?

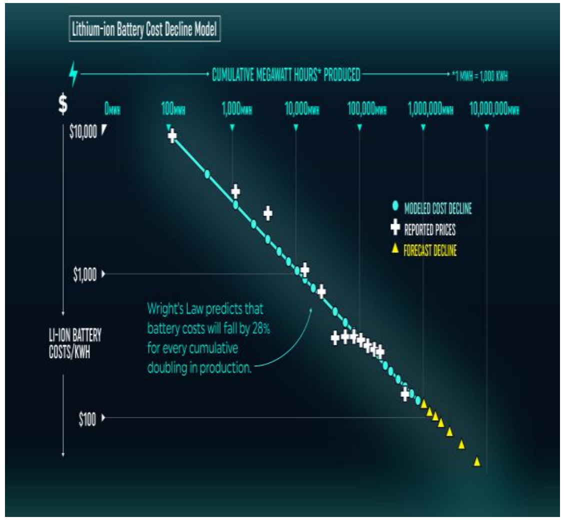
Fast-Moving Technologies - Costs Keep Declining Even As Performance Improves!

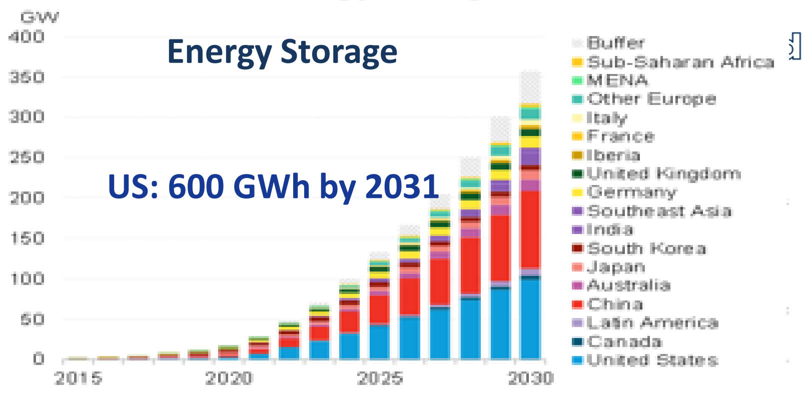
- 21st century technologies w/ steep & sustained learning rates – accelerating transition, but not fully captured by planners and utilities
- PV/Wind lower cost than coal and natural gas (incl. 4-8 hours storage)
- EVs and e-trucks lower cost to operate than ICE and Class-8 diesel trucks
- Forward leaning policies and incentives applied near break-even
- Fast and dramatic global market expansion driven by decreasing price
- Transformation is irreversible, but our actions will determine trajectory

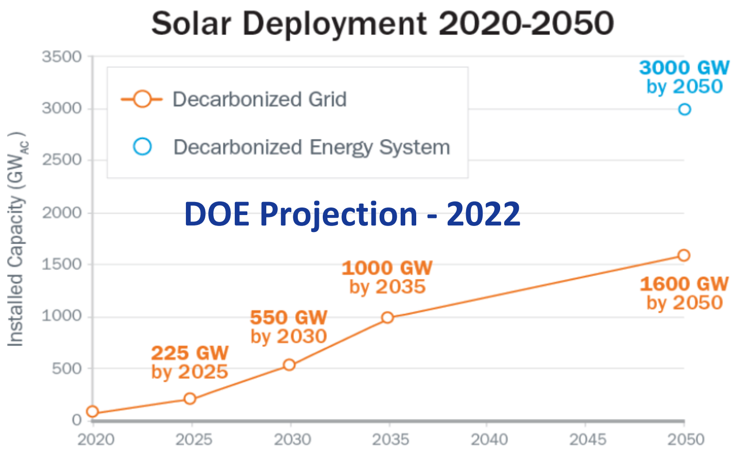


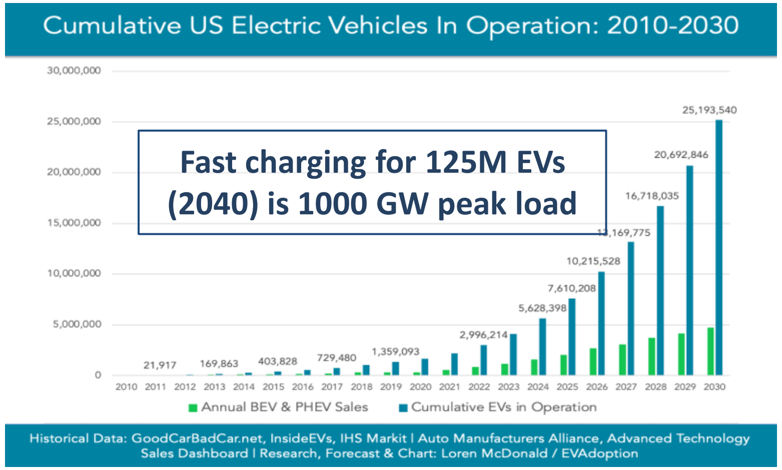
PV LCOE
$/MWHr
2000 - $850
2022 - $22
97.5% decline

Battery Cost
$/kWHr
2000 - $1500
2022 - $120
92% decline









How will these fast-moving exponential technologies disrupt the grid?

Grid Connects Fast Growing Sectors… but is growing slowly

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CAGR for Various Sectors (2040 est.)

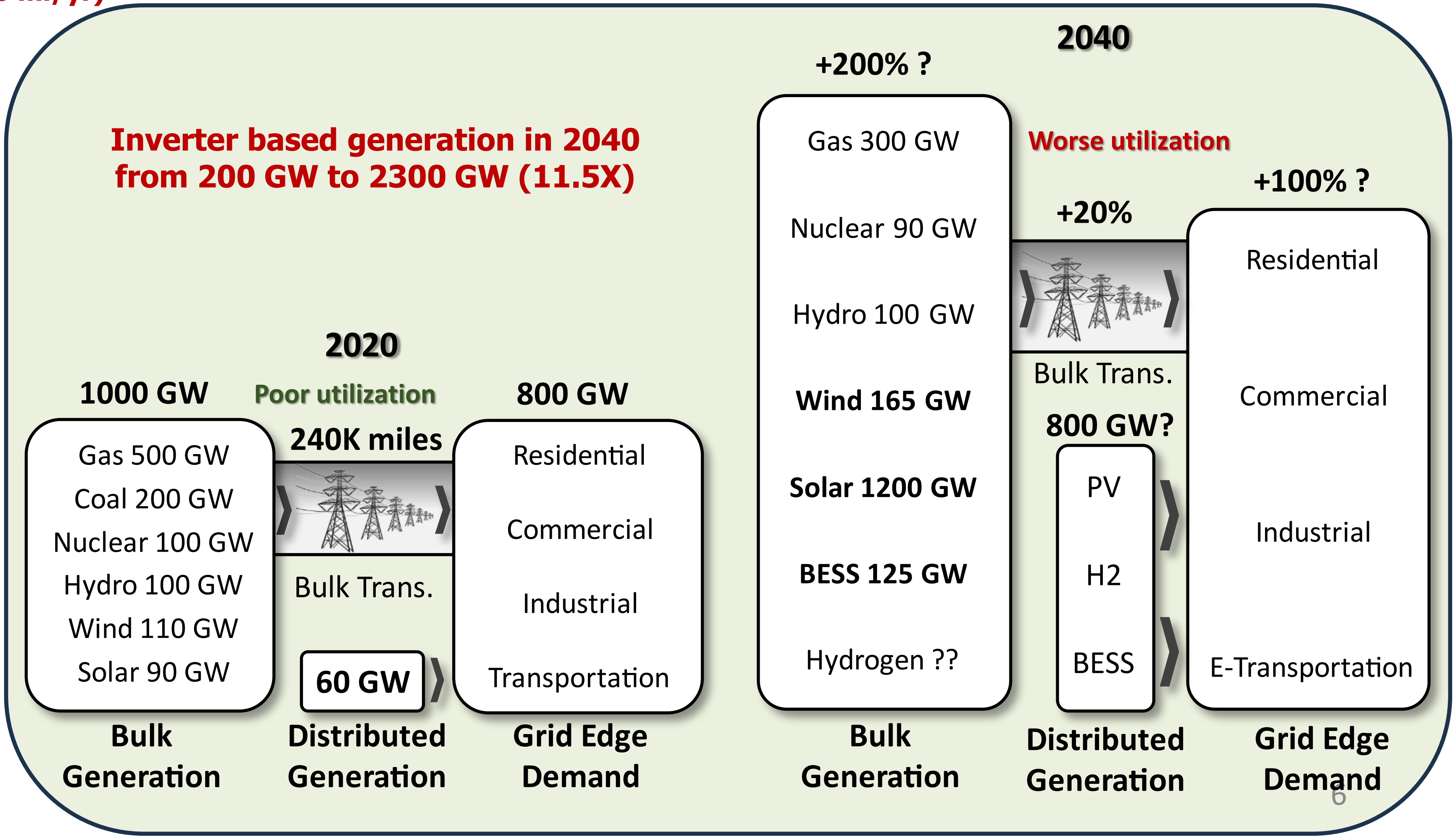
PV/Solar	34% (500 GW pk)
Energy Storage	30% (125 GW pk)
Electric Vehicles	60% (1000 GW pk)
Transmission Grid	**0.25% (1000 mi/yr)**

Fast speed of commerce meets slow pace of regulation!

The BIL, IRA and Chips Acts - >$1.3T to deploy proven solutions – but will those meet 21st century grid needs?

Inability of grid to serve new loads is forcing growth of distributed BTM resources

We do not have technology, policy, or economic solutions!



Grid Under Stress

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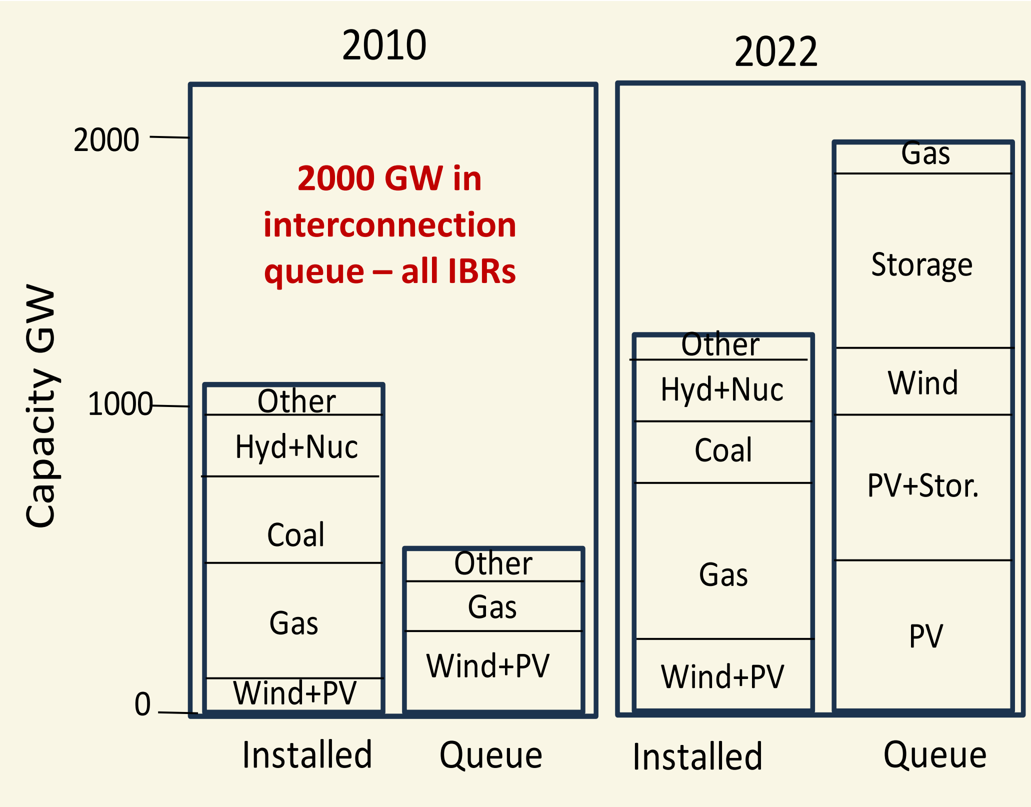
- EPRI & major utilities have decarbonization goals of 50% by 2030 & 100% by 2050 – existing $2T infrastructure constrains actions
- Poor utilization (40%) of meshed transmission due to lack of control & (N+1) redundancy, gets worse w/ low-capacity-factor renewables
- Centralized grid is being transformed to distributed system
- Future grid will need dynamic balancing, inertial support, grid forming, damping and stabilization – all with a dispersed IBR base!
- Regulated utility industry cannot accept high-risk solutions



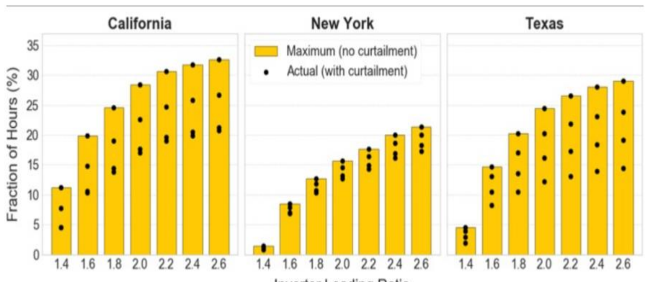
Why did the interconnection queue go from 500 GW to 2000 GW in 10 years?

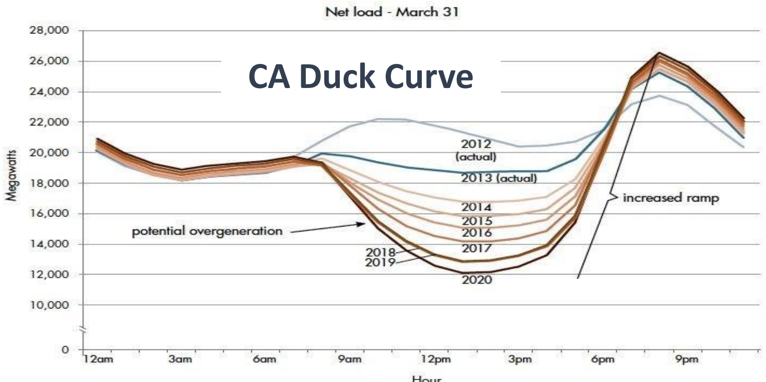
PV Curtailment

Pure PV is the enemy of the grid!

2021 $1T infra bill - $2.5B for Transmission v/s $360B needed

$36B+/13 yrs – Plant Vogtle





Inverters and the Grid*…we have 50 years experience!!*

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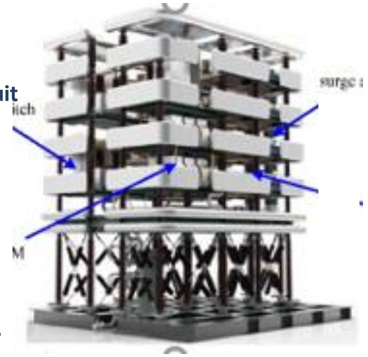
Centralized – Bulk Power

- Typically, centralized and customized – expensive and long lead time
- VSC provides grid support and black start, grid interactions challenging



300 MW VSC
Voltage Source Converter

Distributed – Bulk Power

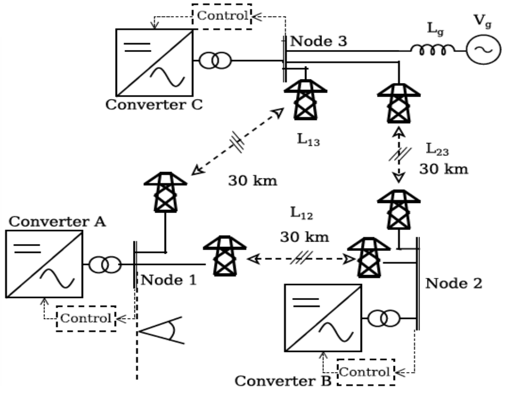
- Distributed modular solutions – lower cost and fast deployment
- Strong growth of distributed generation and microgrids at grid edge

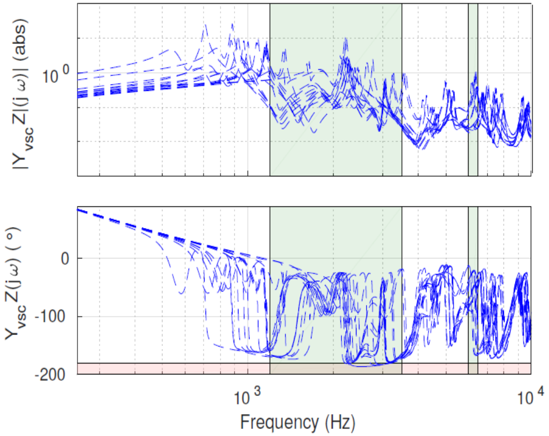
Distributed – Grid Edge & Resiliency

- Energy storage, rooftop solar, EV charging, microgrids – all grid resources
- Value stacking – resiliency, both sides of the meter, regulatory challenges

Fundamental Issues for High Inverter Penetration Systems

- Stability, grid-forming, interactions, cyberattacks, tech obsolescence
- Interoperability, lagging standards, plug-n-play, autonomous control
- Proprietary controls, changing topology, modeling, black-start, ROCOF





More Questions That Keep Us Awake at Night

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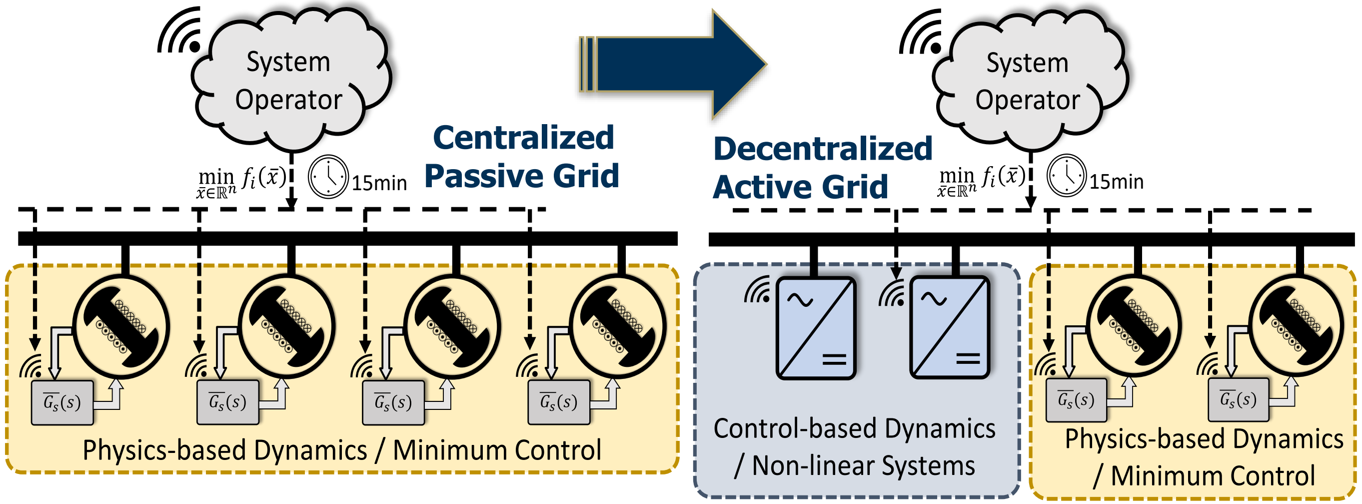
Dynamic Grid & IBR Management Issues

9. Can we guarantee stability and reliability for a grid that is dominated by IBRs?
10. Aren’t there standards that guarantee that there are no issues with grid integration of IBRs, particularly at scale?
11. As millions of geo-dispersed IBRs from varied manufacturers & technology generations are deployed, will they work together, and with existing grid elements?
12. How do we analyze, model & simulate grids with millions of IBRs running non-linear proprietary controls, with poor system knowledge, and comms/cyber challenges?
13. What type-testing of IBRs is needed before grid operators can allow installation – what happens if a few lines of code are changed, or OTA software update is done?

The Changing Grid – *this is a new paradigm!*



Today's Grid Works Well – Should IBRs Behave Like SGs?

Challenges with IBRs Emulating SGs:

- ❑ 10 pu inverters w/ large X at 100 MW level not viable
- ❑ SG has series damping – IBRs do not (mainly shunt)
- ❑ SGs are 'identical' in code/controls, not possible with IBRs (multiple vendors, IP, lagging standards, fast-moving tech)

Legacy Passive Grid	IBR Rich Active Grid
Fixed electromechanical plant, slow controls, no local intelligence, <u>well understood response and stability</u>	Fast Non-linear Time Varying control in each IBR, local intelligent agent with fast response, <u>not predictable</u>
Analysis possible with large number of SGs in system, even w/ large transients – linear system	Challenging to analyze system where local intelligent agent response dominates system dynamics
SG and system models well known, extensive knowledge	Non-linear IBRs are complex to model and may involve proprietary IP

Today: Frequency as a universal 'DC' parameter provides a signal for slow physics-limited SG controls, including effects of inertia & damper winding.

Future Grid: *IBR-rich active grids react fast to local frequency measurements – which are instantaneously different across the network*

The current centralized paradigm will be challenged to address the scaling issues identified here

Challenge: Scaling the centralized grid to an IBR-rich grid

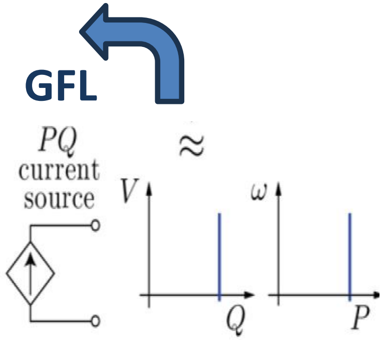
Use Case: Ensure that millions of inverters operating autonomously with poor system visibility & knowledge, and <u>without low latency communications can maintain cybersecure real-time-must-run capability under all conditions</u>

Use Case: Ensure that fast evolving multi-IBR multi-vendor grids at scale are well behaved & stable for normal, transient (small/large), & fault events

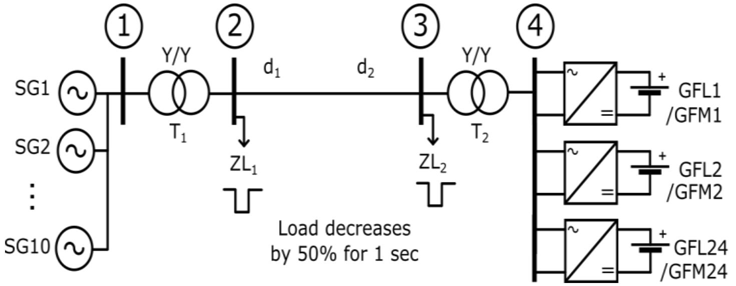
GFL and GFM IBR Technologies

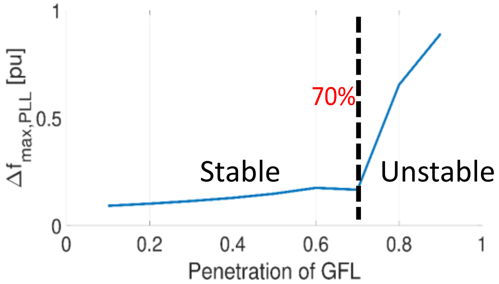
Grid-Following (GFL) IBRs

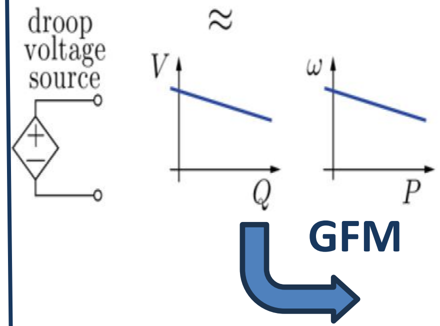
- ❑ GFL IBRs are widely deployed ⟹ **GFL acts as a current source,** injects the available or desired power into grid
- ❑ Vast majority of deployed IBRs are GFL



Test System



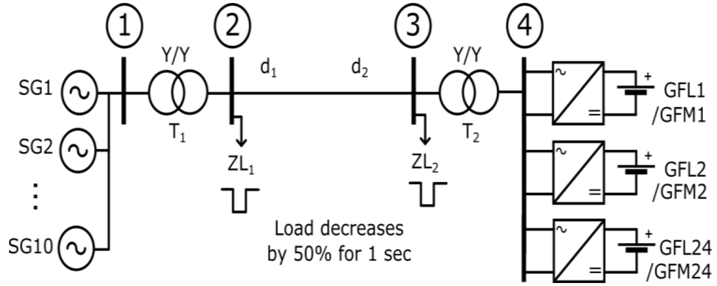


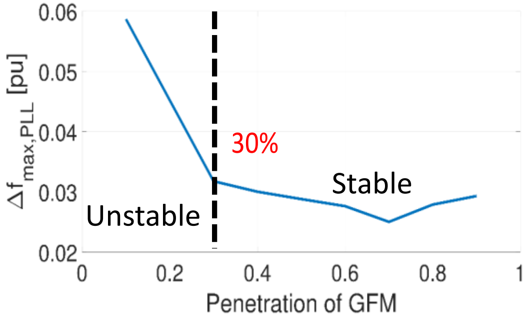


Grid-Forming (GFM) IBRs

- ❑ **GFM IBRs act as voltage source behind a real impedance** (like a synchronous generator) and typically regulate voltage & frequency at its terminals

Test System





High GFL IBR Penetration Challenges

- ❑ Many systems (e.g., Hawaii, South Australia, Tasmania, Texas & Ireland), often see instantaneous IBR penetration (wind, PV, and storage) of more than **50-90% relative to system demand**
- ❑ More SGs slow down system dynamics allowing grid-following (GFL) IBRs to accurately track grid voltage and inject the appropriate current/power
- ❑ Challenges increase dramatically when IBRs serve **>65% of system load**

- ❑ Many studies have shown that replacing some **GFL IBRs (10%-30%) with GFM controls,** stabilized the studied scenarios, even with 93% IBR penetration and very high-power transfers
- ❑ Percentage of **GFM IBRs** needed depends on system characteristics, research suggests **10–30% of total IBRs is adequate**

Early results suggest that massive & growing deployment of GFL IBRs can lead to instability. The hypothesis is that GFM converters can improve system stability and performance – is that true at scale?

IBR Control…*revisiting fundamentals for GFM IBRs*

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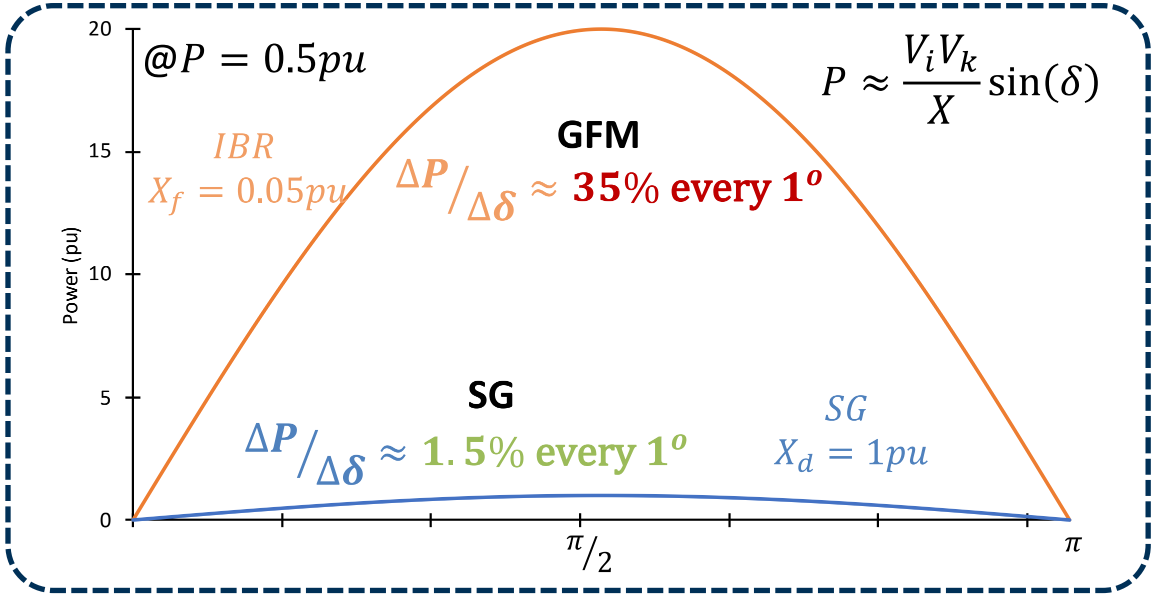
Frequency, Phase, and Power Transfer

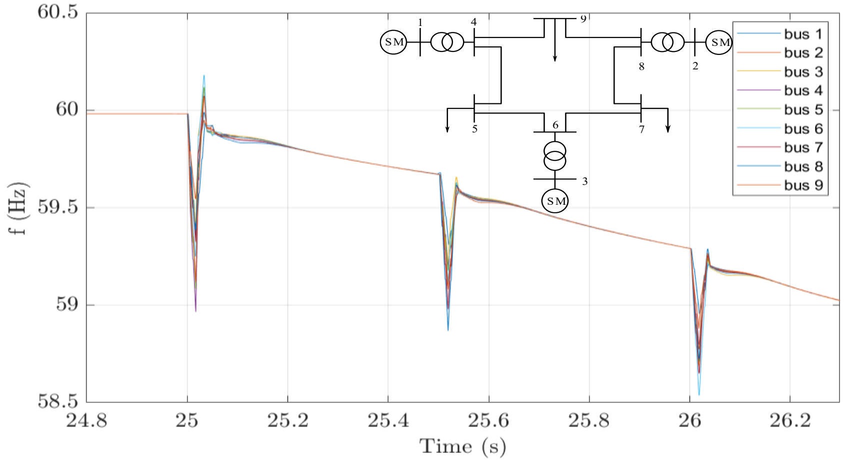
- In AC system, **average power** transfer between two nodes requires **identical frequencies,** different frequencies ⇒ **average power = 0**
- Power flow from SG to grid depends on angle difference δ :
  - SGs have large Xd, results in low ${}^{\Delta P}/_{\Delta\delta}$, benign to disturbances
  - GFM IBR small X filters give high ${}^{\Delta P}/_{\Delta\delta}$, 20X response

Controlling Power Flow with the Angle of the Voltage

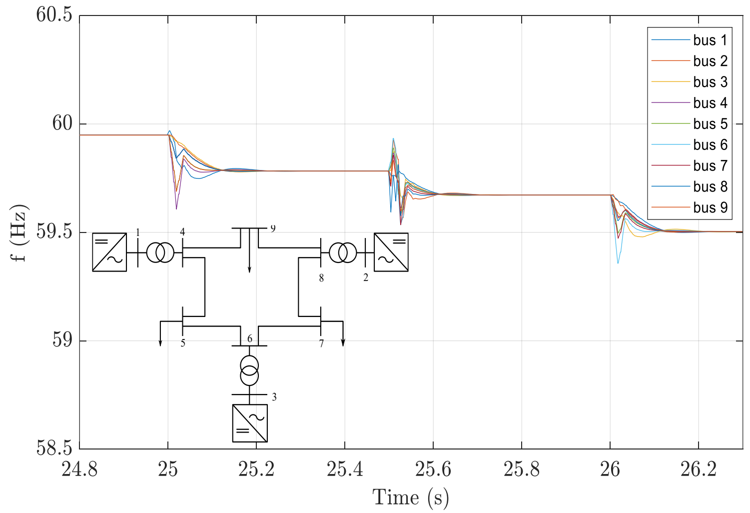


What is frequency?…*revisiting concept for IBR-rich systems*

- Angles of multiple SGs rapidly lock due to damper winding (within ROCOF limits), allowing SGs to deliver power even as system slowly moves to final P/f ‘droop’ state – frequency is ‘DC’



9-bus IEEE system w/ SGs - three load steps at three different times



- GFM IBR frequencies post-disturbance are all different as measured
- Can cause interactions & instability.
- Tuning requires detailed system and controller info – **not scalable**

Multi-IBR Systems

Hawaii: Nov 21, 2021

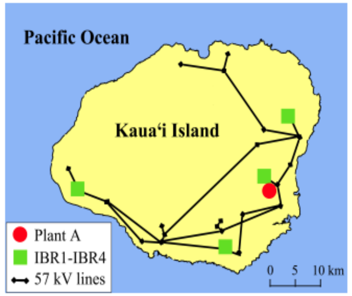
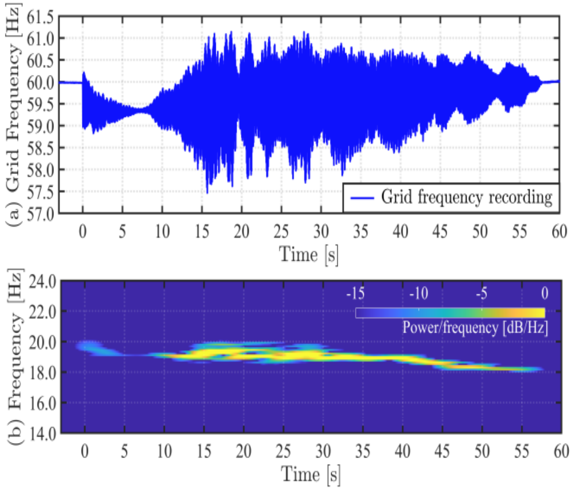


TABLE I
KIUC GENERATION MIX
BEFORE AND AFTER EVENT

Time	$t = 0^{-}$ s	$t = 60$ s
Plant A	60.6%	0.0% ↓
IBR1	4.1%	14.0% ↑
IBR2	4.6%	21.0% ↑
IBR3	0.0%	14.0% ↑
IBR4	4.1%	23.0% ↑
Biomass	13.7%	14.0% ↑
Hydros	13.0%	13.0% –



- Tripping of largest SG with 60% load share caused frequency excursions and oscillations at ~**19 Hz.**
- IBR 1,2,3: GFLs; **IBR4: GFM (VSM)**
- Fast Frequency Response mandated for GFLs (**IBR 1 and IBR 2)** reduced damping, but GFM stabilized the system at t=57 sec

Loss of Stability with High GFL IBR Penetration

- Assuring system stability at high penetration levels can be challenging — even w/ GFM!
- Many grid operators/vendors confirm challenge of assuring a stable system, even with GFMs. Model-based re-tuning using simulations may be possible **- but is not scalable**

Modeling Inverters at Scale

- Complex large order IBR model – e.g., balanced 3 phase inverter needs 15 states, for N inverters, need 15N states – **not scalable**
- Models do not hold under unbalance and harmonic conditions
- Reduced-order aggregate models difficult **- IBRs from different vendors and ratings – no guarantees of stability**

What is Inertia?...revisiting the concept for IBR-rich systems

- 100s of large MW-scale SGs provide inertia (H~5 secs) that is constant & defined by physics - with IBRs, there is loss of inertia
- Classical SG stability is assessed with constant inertia, how will IBR based systems behave? (detailed models proprietary or don't exist)
- IBR can provide control-based inertia (constant, adaptive, or zero) – challenging to integrate with system model, but can assist with major disturbances such as frequency/phase jumps & faults

IBRs at Scale… *impending trouble?*

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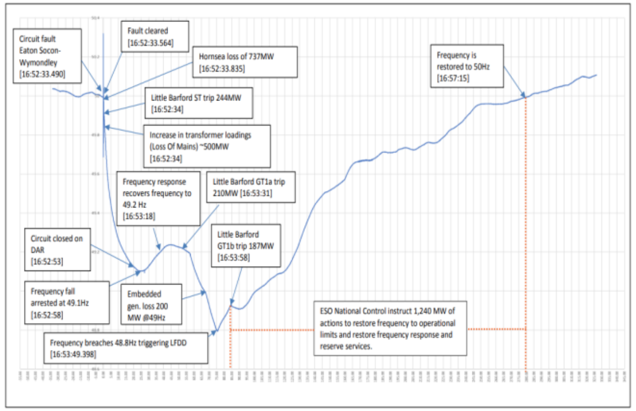
- System stability at high penetration levels is challenging — even w/ GFM!
- Multiple grid operators & vendors confirm the challenge of maintaining a stable system with even 4 to 5 GFM inverters. Current model-based strategy of retuning and validation through simulations is proving inadequate – **major concerns for scaling**
- European operators are installing 1500 GW-sec of synchronous condensers - necessary inertia for ROCOF
- How do we ensure cybersecurity in massively distributed and decentralized grid?
- Detailed simulations with high-number of IBRs across all contingencies are extremely time consuming and computationally demanding — after all the studies, stability cannot be guaranteed!

UK: Aug 9, 2019

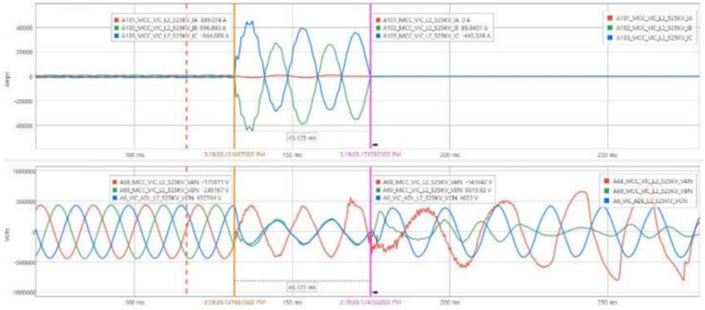
- Unbalanced line-ground fault happened due to lightning strikes
- Tripping of a 737 MW wind power plant (cause: capability limits of wind plant not sufficient to sustain the large oscillation)
- Followed by a large RoCoF ⇒ tripping of other SG and wind



~1.1 million customers without electricity for 15-45 minutes

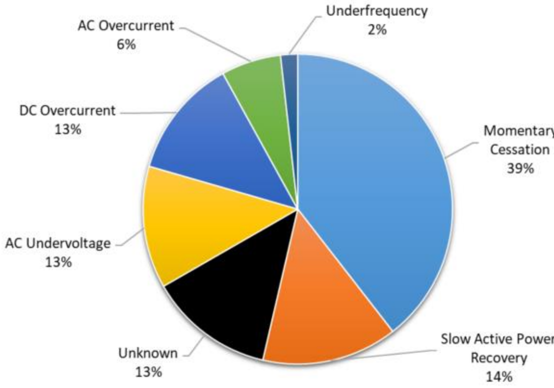
Abnormal Operating Scenarios (NERC report Apr. 2022):

- Abnormal operation conditions such as unbalances, faults (symmetrical/asymmetrical), harmonics, and phase-jumps remain a challenge



Phase-to-Phase Fault on 500-kV Line

Loss of 765 MW of solar PV resources (27 facilities)
Loss of 145 MW of DERs



Causes of Inverter Tripping

UNIFI Consortium

DOE-SETO Funded ($25M)

Vision: Conduct research and development, demo concepts at scale, author best practices and standards, train next-generation workforce

Purpose: Future power systems with any mix of machines and IBRs at any scale that are affordable, secure, reliable, clean, & resilient

Goal: Forum to address fundamental challenges in seamless integration of GFM technologies into power systems of the future

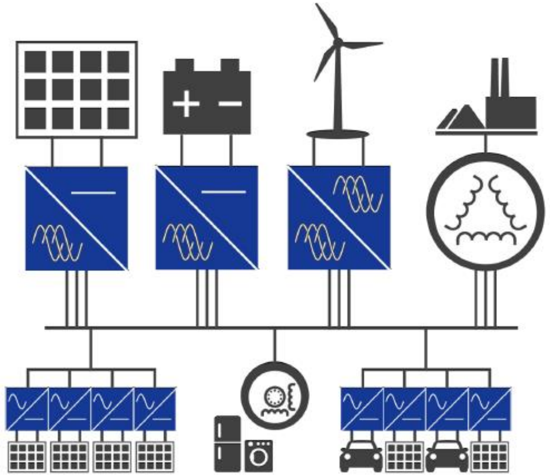
unifi consortium | universal interoperability for grid-forming inverters

Sustained engagement of researchers and practitioners was critical in interconnecting generators to realize the grid as we know it today

UNIFI provides a platform for such engagement to realize the grid of the future

Joint meeting of the UNIFI Consortium at Georgia Tech on Jan 24/25, 2023

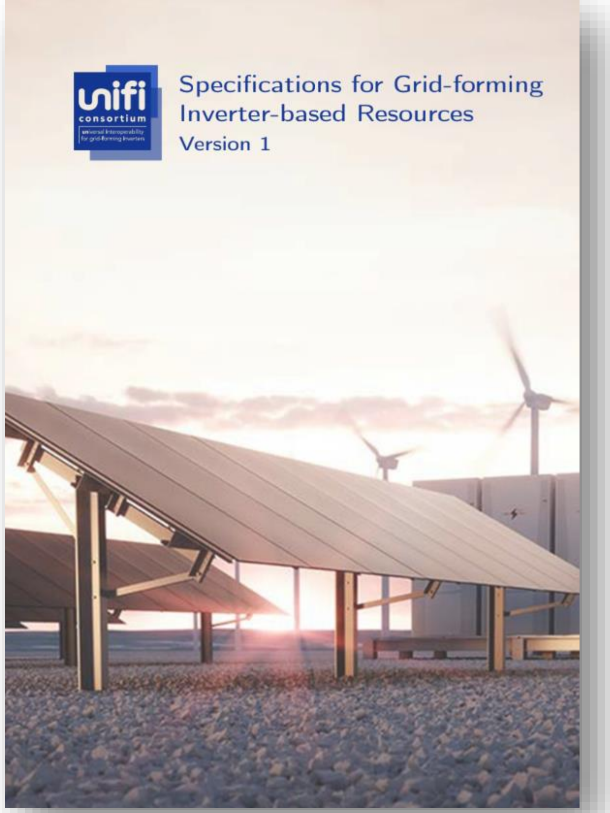
Thrusts	Areas	Area Leads
Research & Development (R&D)	modeling & simulation	PNNL, Cal, EPRI, ASU
	controls	SIEMENS, MISO
	hardware	W, NC STATE UNIVERSITY, Danfoss
	integration & validation	UAF
Demonstration & Commercialization (D&C)	20+MW demo	ComEd, Hawaiian Electric, ISO new england
	IP management	GT, SIEMENS
	domestic products	GT, HITACHI ABB
	standards	EPRI, ISO new england
Outreach & Training (O&T)	education	VT, M, ASU
	workforce development	T, EPRI
	communication	W, M
	events	W, EPRI



unifi will unify

- New & Old (GFM with GFL+Machines)
- Local & Global (controls)
- Slow & Fast (timescales of operation)
- Big & Small (inverters to aggregations)
- Solar, Wind, & Storage (technologies)

UNIFI SPECS, COMPLIANCE, AND VALIDATION



Release Date. December 15, 2022

- Started as a high-level document
- With agreement on parameters, detailed technical specifications and metrics can be derived

Purpose: create alignment between all stakeholders while also being inclusive of legacy industrial practices, the UNIFI consortium has been diligently articulating an ongoing list of UNIFI universal principles and specifications that frame a forward-looking description of the desired functionality of a future IBR-rich grid

Performance Requirements for Operation Within Normal Grid Operating Conditions:

- Autonomously Support the Grid
- Dispatchability of Power Output
- Provide Positive Damping of Voltage and Freq Oscillations
- Active and Reactive Power Sharing across Generation Resources
- Robust Operation in Grids with Low System Strength
- Voltage Balancing

Desirable Properties & UNIFI Universal Principles

Performance Requirements for Operation Outside Normal Conditions:

- Ride-through Behavior (system-wide stability, self-protection, and optimality)
- Response to Asymmetrical Faults
- Response to Abnormal Frequency
- Response to Phase Jumps and Voltage Steps
- Intentional Islanding

Quantifiable validation metrics/criteria (e.g., input/output functions)

Quantifiable validation metrics/criteria (e.g., input/output functions)

Use Cases: representative transmission, distribution, and microgrid scenarios (compliant with current practices and standards)

CHALLENGE: GFM INTEROPERABILITY

Current Status:

- Today's IBRs have achieved reasonable performance – switching frequency, control bandwidth, HF passivity, etc. However, all control architecture and controllers are proprietary – even GFM controls are non-standard with no assurance of interoperability
- Most IBR-IBR or IBR-Grid interactions occur in the "slow control layer(s)". Need to ensure that unit- and system-level objectives (e.g., stability in multi-IBR systems) are achieved under normal, transient, and fault conditions for <u>geo-dispersed multi-vendor IBR systems</u>

Transactive Layer

e.g., <0.01 Hz

- Economic Dispatch
- Power Flow Optimization

- Grid Operator
- Plant Controller

Slow Loop

e.g., 0.1-60 Hz

e.g., Droop, VSM, dVOC, etc.

- Ensuring execution of grid operator dispatch
- Mange/Pacify interactions
- Rules for collaboration

Fast Loop

e.g., >100 Hz

e.g., Voltage/current loops, protection, switching scheme

Switching (PWM) scheme, voltage & current controller loops – minimum requirement (Rules) to participate:

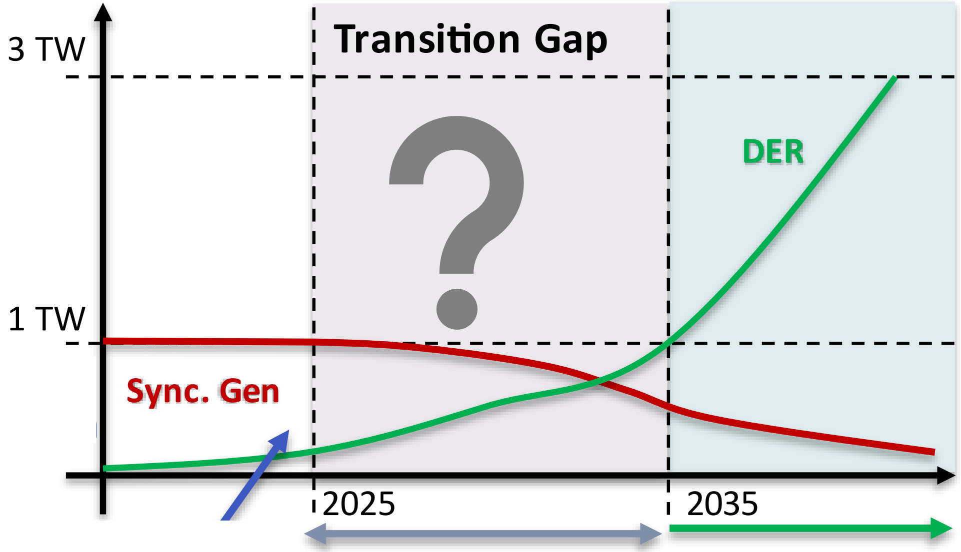
- Minimize HF interactions (> nominal frequency) with other inverters and grid apparatus (e.g., passivity)
- Handle Non-ideal conditions (unbalance, harmonics)
- Current limiting (low harmonics) / Inverter protection
- Execute upper-layer(s) commands with specified fidelity
- Manage large/fast transients w/ recommended practices

Industry Standard Inverter (1 kW to >1 MW)

Challenges:

- Interoperability; Scalability; Multi-vendor; Black-box inverter; Technology Migration
- Minimize low/medium frequency interactions between grid elements (IBRs and SGs)
- Loss of communication/Latency (ensure real-time-must-run)
- Assist in Transient & Fault-Recovery

Bridging the Energy Transition Gap



Deployed Technologies

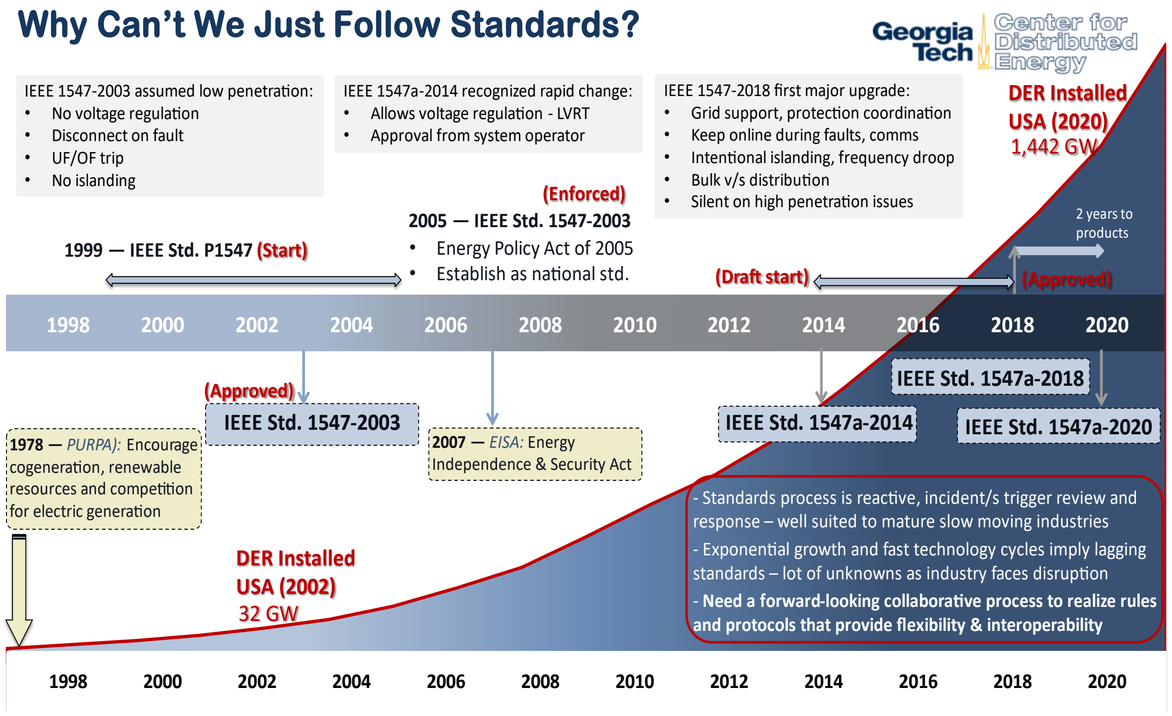
- Basic inverter (GFM/GFL) control
- Detailed EMT simulations of GFM IBRs
- High-performance GFM IBR hardware
- Device-level inverter control & protection
- Passive high frequency dynamics & impedance

Bridge Technologies

- Ensure the grid is stable and can integrate 1 TW of non-compliant IBRs, while standards for GFM are developed and compliant IBRs are deployed at scale

Needed Technologies

- Interoperability/stability of GFM/GFL/SGs
- GFM control under constraints, unbalance, harmonics
- Scalable system-level architectures and specifications
- Communication latency, security & resilience



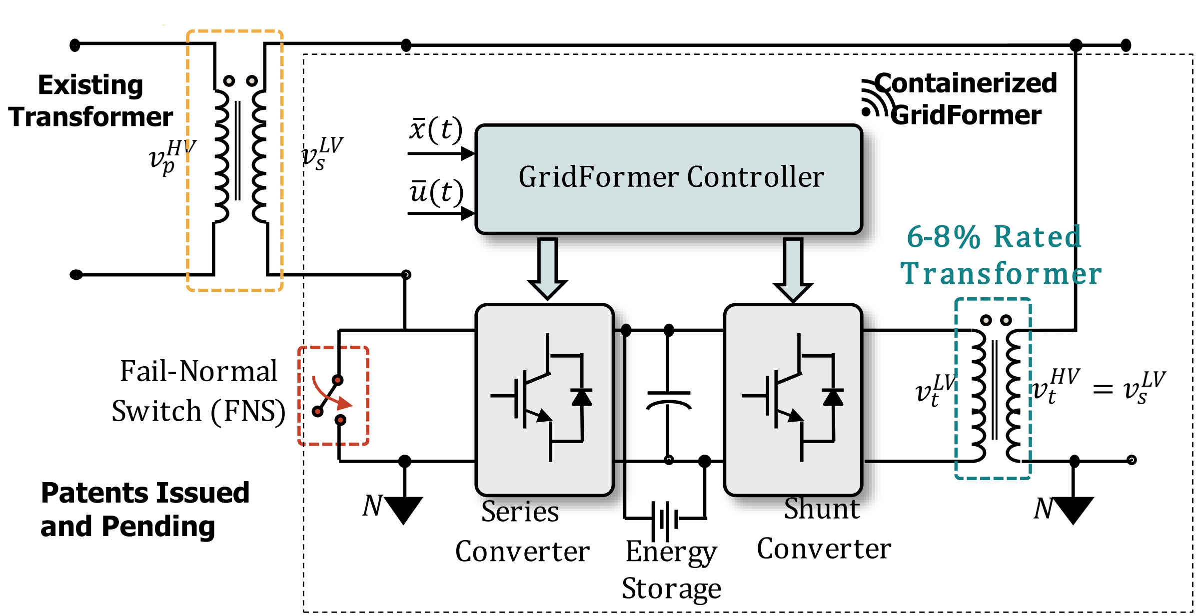
- ❑ There is a need for a utility asset in the near term that provides active grid control and stabilizes the grid to allow non-compliant IBRs to operate
- ❑ This <u>requires GFM capability, energy storage, and the ability to do series/shunt injection/damping</u> – EU is looking to add 1500 GW-sec of inertia to stabilize the grid in the interim (may not be all that is needed)

A paradigm shift seems to be occurring, but the utility industry is not recognizing the full implications of this change

Examples of Solutions

GridFormer — *New Approach to Stabilize & Manage High IBR Penetration Grids*

Georgia Tech | Center for Distributed Energy



GridFormer: Retrofit on Existing Transformers in Susbstations

GridFormer Example:

- 50 MW, 345 kV/132 kV connection
- 11 kV/4 MW GridFormer converter
- 0.5 MWh energy storage

0.5 MWh storage

MV AC Drive

GridFormer Capabilities

The 'GridFormer' integrates standard containerized **fractionally-rated** off-the-shelf GFM inverters and storage with already deployed transformers to realize:

- ❑ Steady-state control of power flows, voltage, impedance and VARs
- ❑ Grid forming capability, including inertial support, improving grid stability
- ❑ Series/parallel damping of oscillations, incl. interactions between regions
- ❑ Black-start capability

GridFormer Benefits:

- ❑ Allows deployment of IBRs to continue even while GFM inverters are developed into grid codes and standards
- ❑ Rapid low-risk deployment - improves steady state & transient response, can prolong current grid paradigm

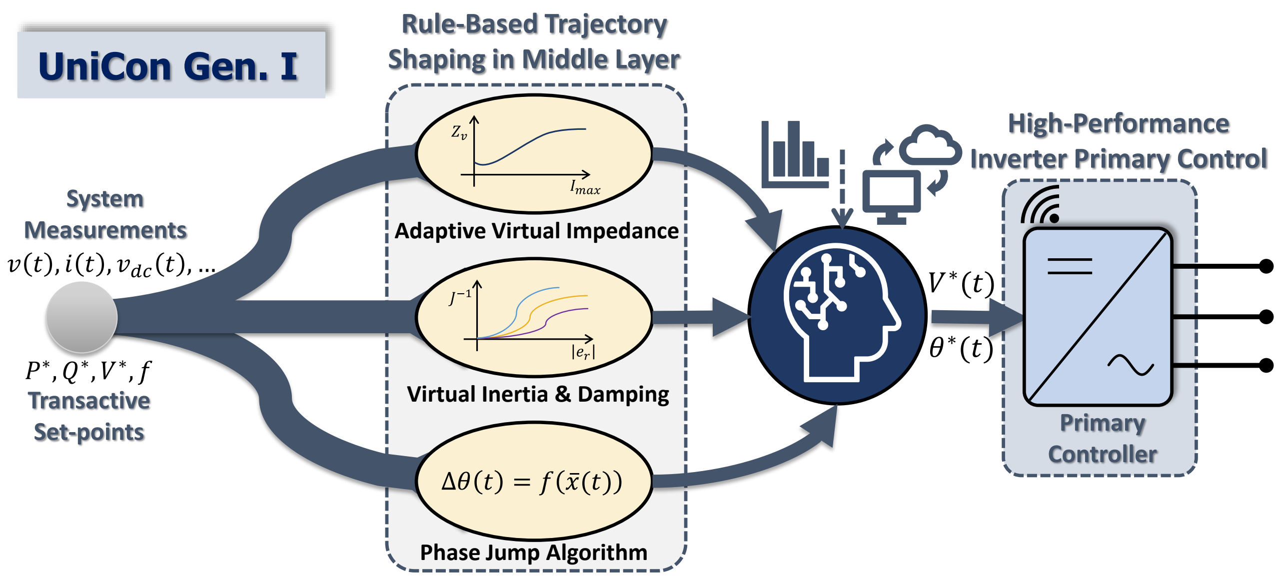
5 MW/22 kV prototype built & under test at e-grid (DOE) facility

Partners: GT-CDE, EPRI & Southern

Rule-Based Universal Control of Grid Connected Inverters

Georgia Tech Center for Distributed Energy

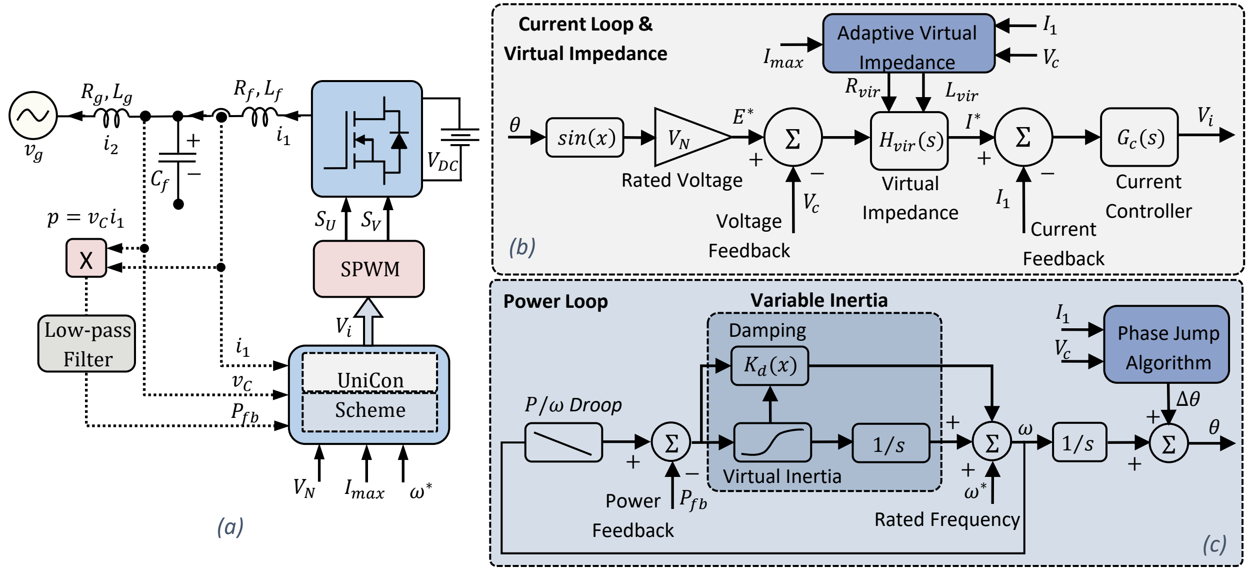
UniCon Gen. I



There is a need to fundamentally reimagine IBR controls!

UNIFI Principles Implemented by UniCon:

- Support grid as ecosystem, suppress interactions
- Universal power sharing / Dispatch-mode & Droop
- Fault-ride-through, fault current injection, fault recovery
- Plug-n-Play, RT control without low-latency communications



Universal Controller (UniCon) provides autonomous intelligent highly nonlinear control of grid connected inverters

New Paradigm — Rule-based universal control (UniCon) allows for flexible and adaptive behavior over a wide range of realistic operating conditions without any tuning, including:

- ✓ At-will connect/disconnect of inverters to the grid
- ✓ Automatically operate grid-connected or grid-islanded (GFM) under all conditions, poor (or no) topology knowledge
- ✓ Grid support: inertia as needed; oscillation/resonance damping; interactions w/ inverters, generators; phase-jumps
- ✓ Ability to do bottom-up black-start and form resilient and fractal microgrid clusters that coalesce or separate as needed
- ✓ Rule-based middle-layer allows operation with different primary controllers, possibly from different vendors

Universal IBR Autonomous Control

Georgia Tech Center for Distributed Energy

Random Sequence of Events

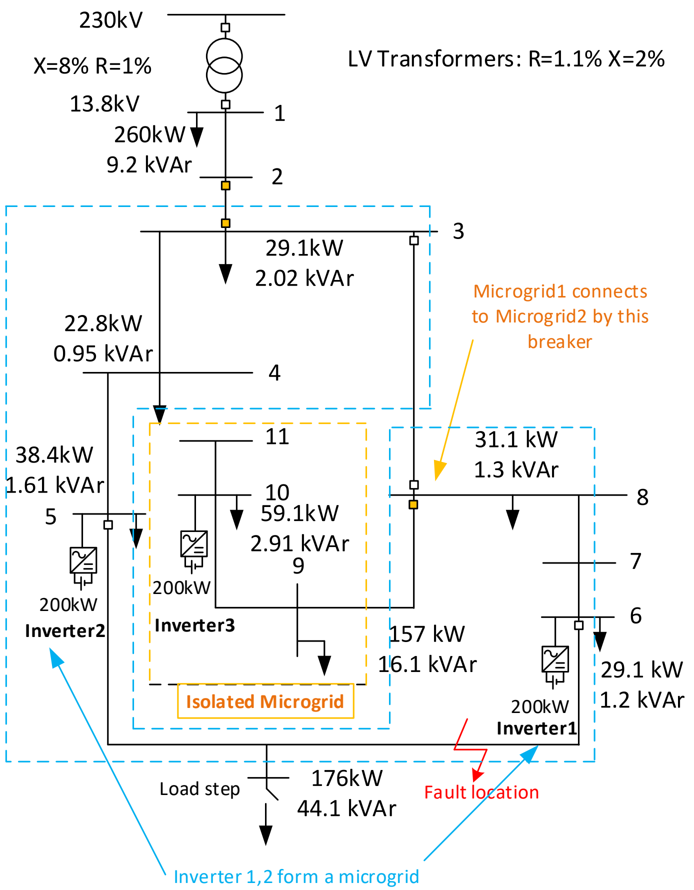
µG1 and µG2 interconnect

Load is added step-wise

Fault is applied

Fault is cleared after 0.5s

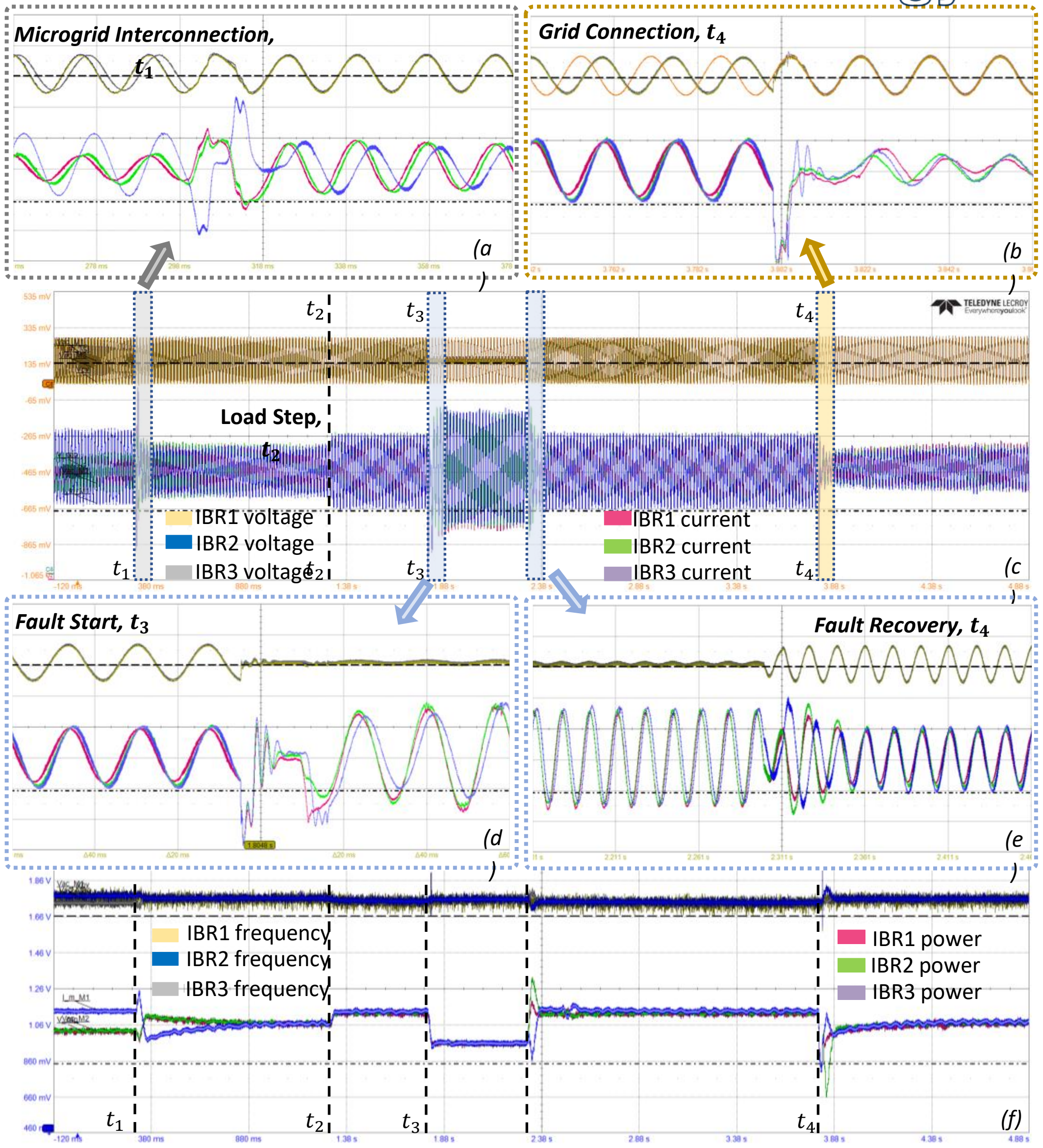
Microgrid connects to grid



Various use cases including single/multi-microgrid & grid-connected operation

Simulation, HIL & HW results validate UniCon can damp oscillations and operate in a stable manner with no communications.

C1, C3, C5: 630 V/div
C2, C4, C6: 283.3 A/div



Comprehensive scenario to test UniCon performance. a) Micrograds interconnection. b) Grid connection. c) Voltage and current (full transient). d) Fault start. e) Fault recovery. f) Active power and frequency transient (full transient)

C1, C3, C5: 0.46 Hz/div C2,C4,C6 : 44.5 kW/div

EVERSOL – *Practical Scalable Dispatchable Solar*

- Plug-n-play modules (4x500W PV panels+2.5 kWh) practical, affordable dispatchable solar energy at any scale (2 kW – 100 MW+)

- Arbitrarily interconnect Eversol units to form a utility scale plant, or a decentralized industrial/commercial plant, or community microgrid

- Edge-intelligent, interoperable, decentralized, flexible, no fire risk, lower installation, commissioning, maintenance and O&M costs

- Many value streams: energy arbitrage, market participation, resiliency, grid support/stabilization, microgrids, peaker plants, reduced transmission build

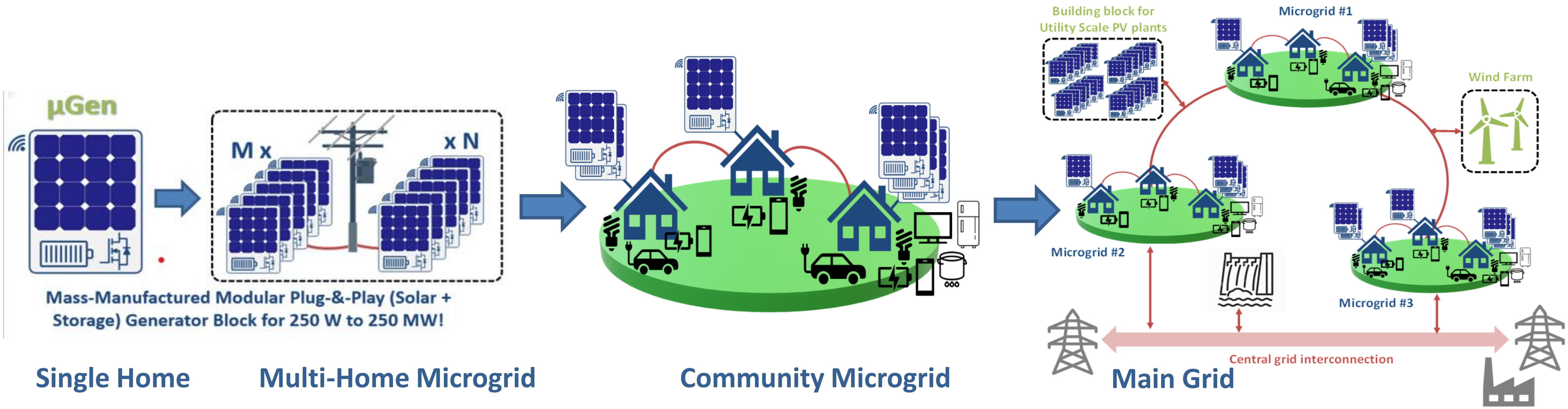
Industrial/Warehouse Generation in Metro Atlanta – Utility Dispatched
- 500 warehouses @ 2 MW PV plus 2 (up to 8) hours of storage
- 1000 MW peak/1200 GWh/yr generation for resiliency/peaker plant
- Provides resiliency for facility plus grid services to Southern
- Charge 10-20 EVs/facility (10,000 across Atlanta) without new grid build
- Low cost, optimized, no fire risk, dispatch under utility control
- Replaces 3000-4000 acres of ground-based PV + storage at lower cost

2 kW grid inverter, 2.5 kWh/unit

Patents Pending

Modular Grid Ecosystem - *Bottom-up Scalable Plug-n-Play*

Georgia Tech | Center for Distributed Energy



Decentralized Autonomous Control of Millions of Inverters

- Devices 'collaborate' to sustain grid (or microgrid) as an ecosystem, sharing energy as needed & available
- 'Real-Time Must Run' functionality without low-latency communications or accurate system knowledge

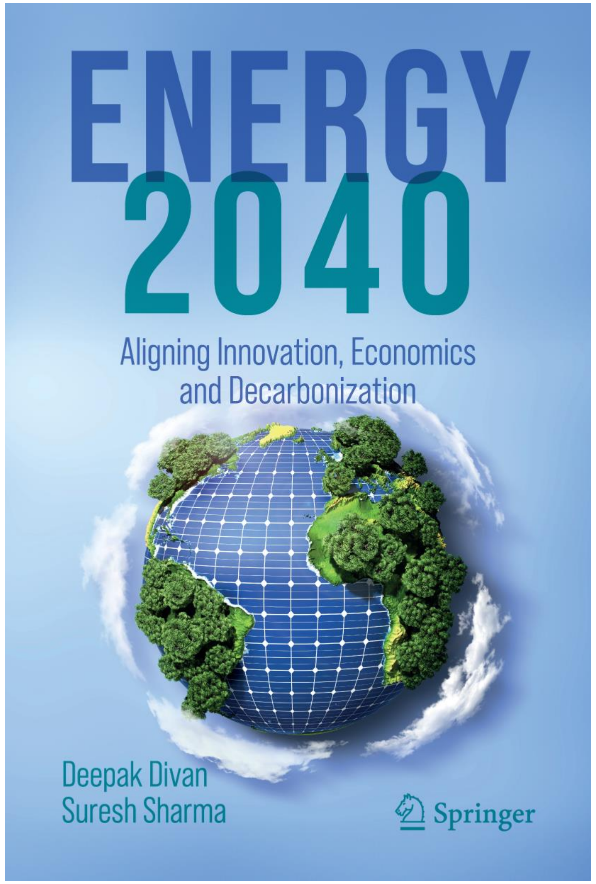
750 million in LDCs live off-grid – opportunity to leapfrog today's grid

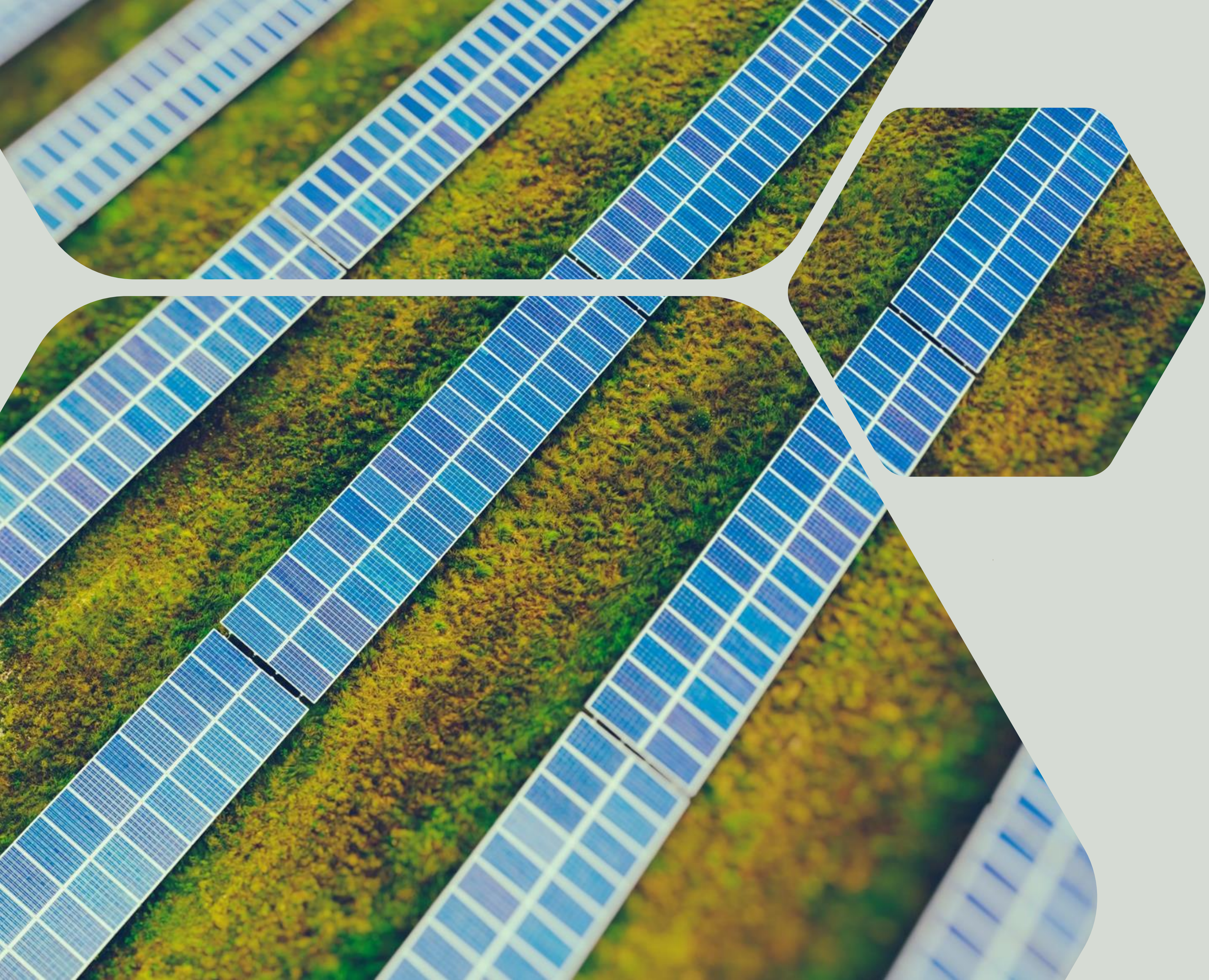
Such a scalable system seems aspirational and impossible - but is now viable!

Key Takeaways

- 21st century 'exponential technologies' with steep learning rates, are the primary drivers of this accelerating and irreversible energy transition
- Traditional utility practices and processes will likely be disrupted by this move from centralized control to distributed and decentralized control – new utility paradigm
- Rapid replacement of synchronous generators with IBRs is causing issues, especially at high penetration levels - grid dynamics & stability may be impacted
- GFL IBRs proven at scale, but will not support the grid at high penetration levels – GFM IBRs are not yet standard and have raised concerns about scaling
- Grid operators and utilities require definite validation processes and tests for IBRs that will guarantee stability under all corner cases – these do not exist
- A 'universal' middle layer control may allow multi-vendor multi-technology IBRs to interoperate and achieve a stable and flexible DER dominant grid [EPRI 2021 Report]
- Policy & regulation needed to enable 'grid as an ecosystem', where distribution and transmission resources collaborate to sustain the grid

Divan & Sharma - Springer





Questions?

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