Flexible Scalable Electricity Solutions for Off-Grid Communities

Deepak Divan Joseph Benzaquen
Center for Distributed Energy, Georgia Tech

DOE Energy Storage Peer Review
10/13/2022

GT Center for Distributed Energy

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

Georgia Tech Center for Distributed Energy

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

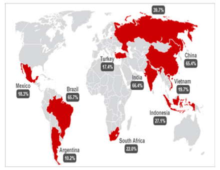

Smart Wires

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

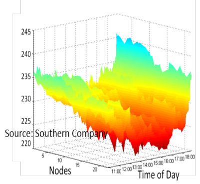

4 kV MVSI for Large PV Farms


7.2 kV 50 kVA SST

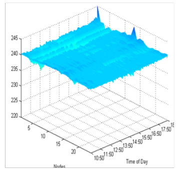
5 kV DC Grid Building Block
7.2 kV 50 kVA Grid Connected SST
4 kV MVSI for Large PV Farms
Triports for PV/Storage/Grid
MVSI with Integrated Storage
Microgrid-Grid Interface Device

Decentralized Grid Control Techniques & Markets

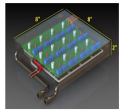
Grid Edge Volt VAR Control
Collaborative Control
High PV Integration
DER Micro grid Impact
Self-Pricing Island Grids
Virtual Power Plants

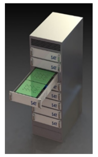


Feeder Voltage w/o and with GE Control


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)

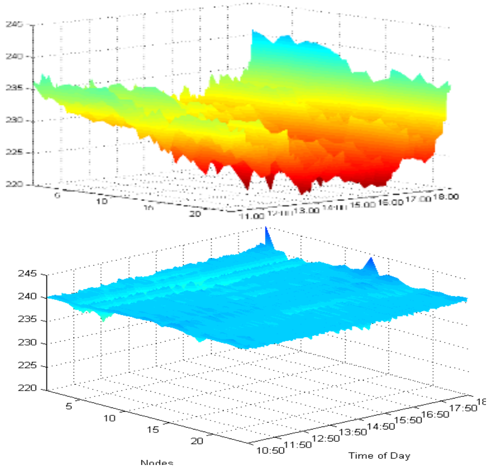
Low-Cost Communications
Cyber-Security
Data Management
AMI Data Analytics
Global Sensor Networks
Cloud Based GAMMA System


GAMMA Platform


Gamma kernel

Primary Drivers

Digitalization Decentralization Decarbonization



COLLABORATIVE CONTROL
Varentec (Sentient)

POWER FLOW CONTROL
Smart Wires


GAMMA kernel

GRID EDGE SENSE & CONTROL
GAMMA

MULTIPORT ENERGY HUB
Grid Block

Need for Energy Equity and Resiliency

Georgia Tech | Center for Distributed Energy

- While most of us take the power grid for granted, there are communities that are off-grid, or live with poor-quality unreliable power
- This includes thousands of people, many living in Native American nations, or in remote areas where it is difficult to provide and maintain service
- High-impact low-frequency events (e.g., climate change, hurricanes, flooding, wildfires, cascading outages or cyber-physical events) can cause extended outages on the grid, with disproportionate impact on poorer communities.
- There is a need for a cost-effective flexible equitable solution for providing power to these communities, such that their quality of life is maintained

Navajo home being fitted with PV power

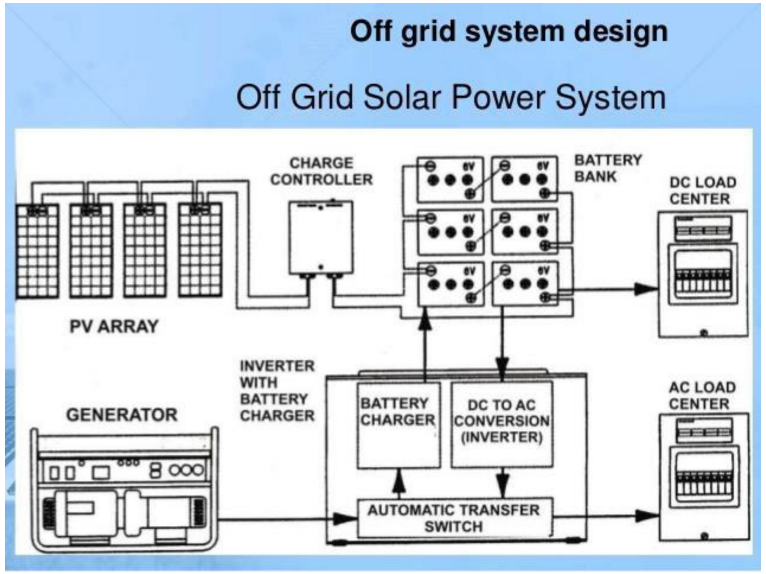
HILF events and grid impact

Example Off-Grid Electricity Solution

What are the Available Options?

Georgia Tech | Center for Distributed Energy

- Resilience solutions typically include diesel generators and microgrids, which are expensive and require skilled technicians to install and operate the systems – challenging for small communities or single homes
- The other alternative is a solar home system, using PV panels & batteries – typical off-grid home may need 1 kW to >10 kW at 120 volts 60 Hz
- Typical off-grid homeowner would like to:
  - Sustain critical loads, such as lighting, phones, refrigerators and TV/internet connectivity for sustained periods of time
  - Power high-rated loads such as tools, microwaves & appliances as needed
  - Start small and low-cost, expand as needed
  - High flexibility to fulfill daily requirements
  - Avoid high costs related to installation, operation, repair and disposal
- Existing state of the art solutions use PV panels, batteries, and power converters to supply single homes and are large, bulky and very expensive, poses safety hazard, is limited in expansion capability, often home rewiring – requires skilled technician to install



Typical solar home system installation

DOE Sandia Project Objectives

Georgia Tech | Center for Distributed Energy

VISION: Safe, flexible, reliable, and resilient plug-n-play building block, that can be used individually or scaled as needed, to address a range of applications and fulfill the electric power needs of off-grid and poor-grid homes and communities.

Storyboarding the Requirements:

Worked with the Derrick Terry of the Navajo Tribal Utility Authority (NTUA) and Sandia to better understand the needs, pain- points and use-cases that are typical for an energy constrained community such as the Navajo Nation

- Plug and play allows rapid installation and minimum down-time in resiliency situations
- Touch safe (48 VDC) batteries and PV panels allow homeowners to self-install the system
- Multi-port operation: 120 V AC, solar, batteries, grid, and loads – managing all simultaneously
- Flexible – can support individual loads, or can be stacked to support a house
- Can automatically form a microgrid with other homes if needed
- Automatically supports grid-connected, microgrid, and portable power applications
- Can export power to the grid (if allowed by utility)
- Monitoring and control of the system via cell phones
- Baked in safety and cybersecurity
- No skilled technicians needed to install, operate and maintain – 'PhD in the Box'

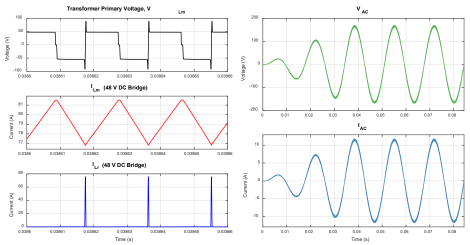
AC Cube — Circuit Topology Selection

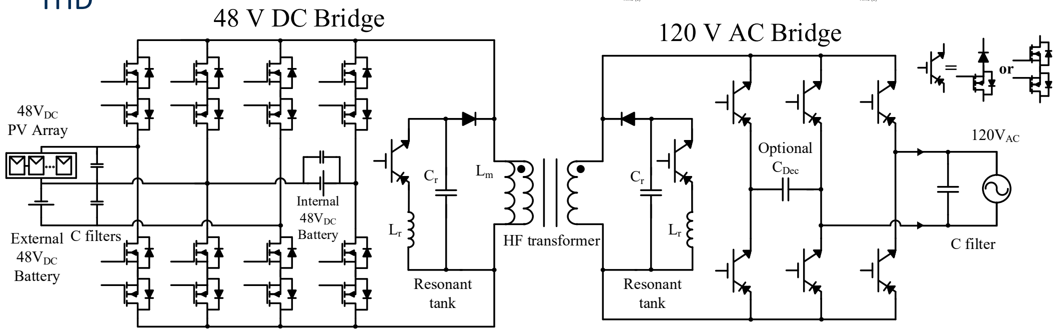
Requirements Driving the Topology Selection:

- Multi-port capability
- Ease to parallel
- Efficiency (>97%)
- Cost, < 150$/kW (Converter) + <150$/kWh (Battery)
- Reduced switch count / passives

Dyna-C-type S4T adaptation:

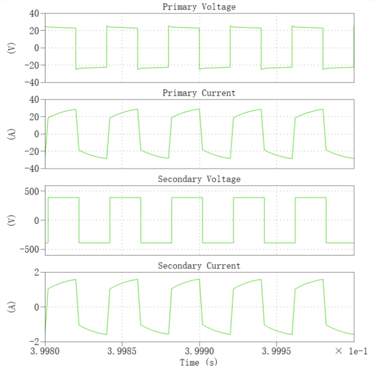
- Single-stage
- CSI topology for easy paralleling
- Expected efficiency of 95%
- Soft-switching S4T topology for high efficiency, low EMI, low THD

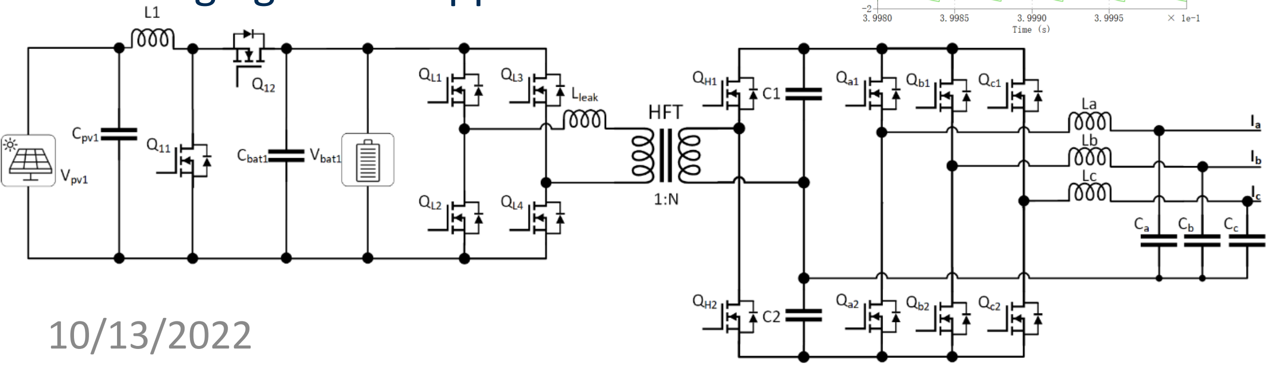




DAB + VSI:

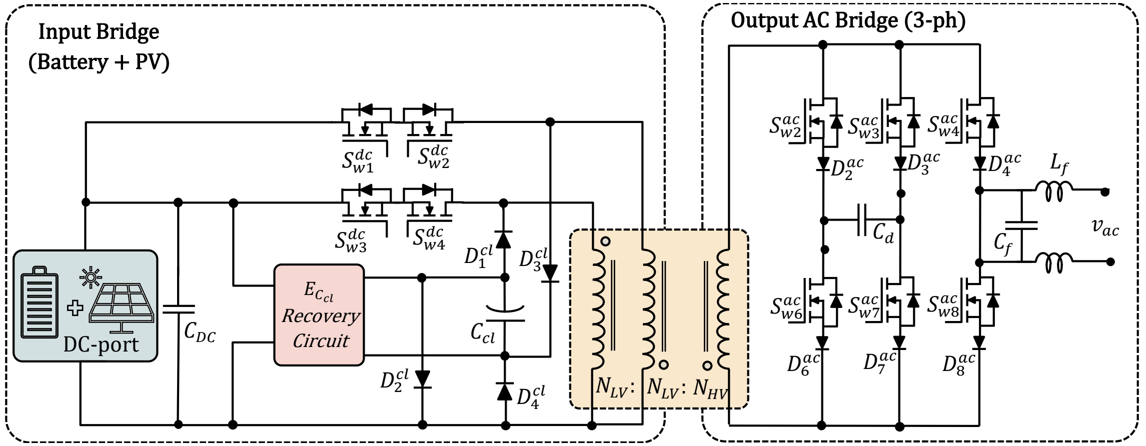
- Multi-stage converter
- VSI AC-output paralleling complexity
- Hard-switching VSI
- Size and cost of capacitors
- Managing 120Hz ripple





Dyna-C-type S4T adaptation:

- Single-stage
- CSI topology for easy paralleling
- Expected efficiency of 97.4%
- Similar S4T benefits with lower component count



AC Cube Technical Specifications (PRD)

Georgia Tech Center for Distributed Energy

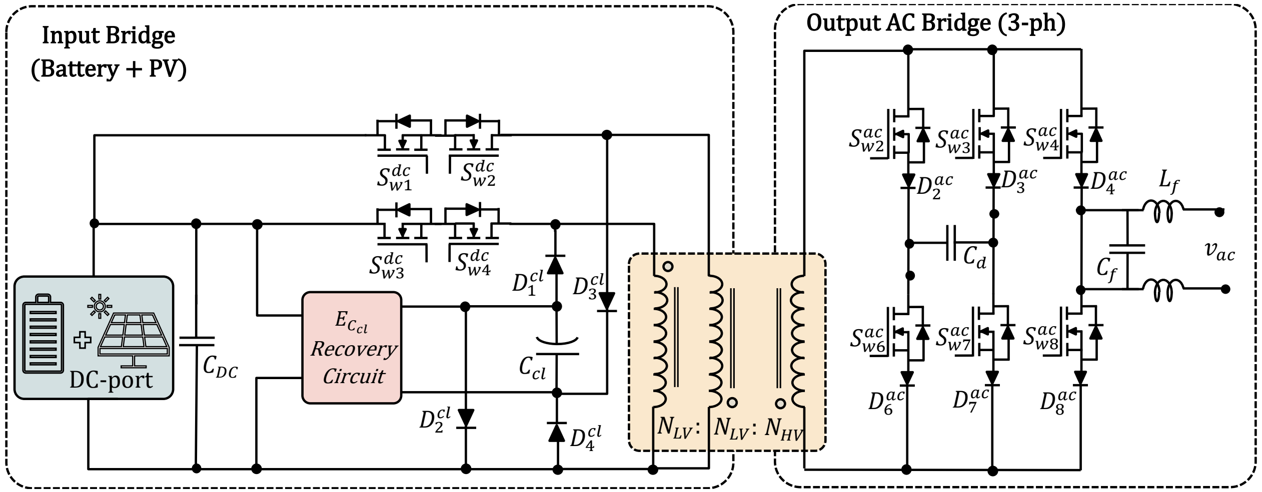
Category	Parameter	Value			Unit
		Min.	Typ.	Max	
Output	Continuous AC Output Power			1250	W
	Operating RMS AC Output Voltage		120		V (AC)
	Operating AC Output Frequency	58	60	62	Hz
	Current Harmonic Distortion			< 5	% THD
	Power Factor	0.85 lagging		0.85 leading	
	Grid Connected Power Return		1000		W
Input	DC Input Voltage Operating Range	24	48	60	V (DC)
	Maximum PV Power			1000	W
	Maximum External Battery Power			1000	W
	Integrated Battery Voltage (<48V)	41.6	48.1 (nominal)	54.6	V (DC)
	Integrated Battery Energy		1000		Wh
	AC Line Input	108	120	132	VAC

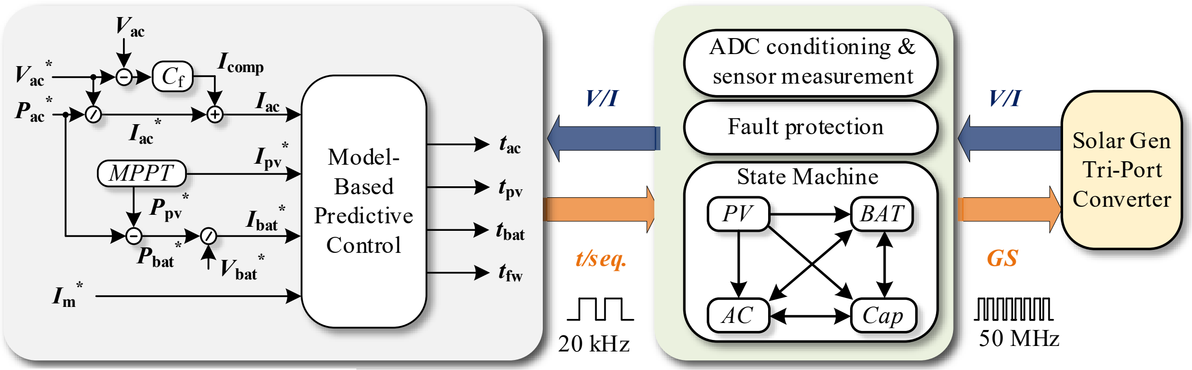
Category	Parameter	Value			Unit
		Min.	Typ.	Max	
Efficiency	Peak Efficiency (One-Way)			> 96	%
Environment	Permissible Ambient Temperature	-20 (-4)		+50 (122)	°C (°F)
	Relative Humidity	4		100	%
	Enclosure	TBD			
Form Factor	Dimensions [W x D x H]	12 x 10 x 8			in
	Weight			< 15	lb
Control Interface	Communication Protocol	Bluetooth (GAMMA) to cloud. Serial comms between AC Cubes when connected. Smart-phone app for user interface			
Protections	DC Over-Current Protection	Software current limiting 100 A Fused Inputs at battery			
	AC Over-Current Protection	Software current limiting AC Circuit Breakers Relay switches to AC grid when available			

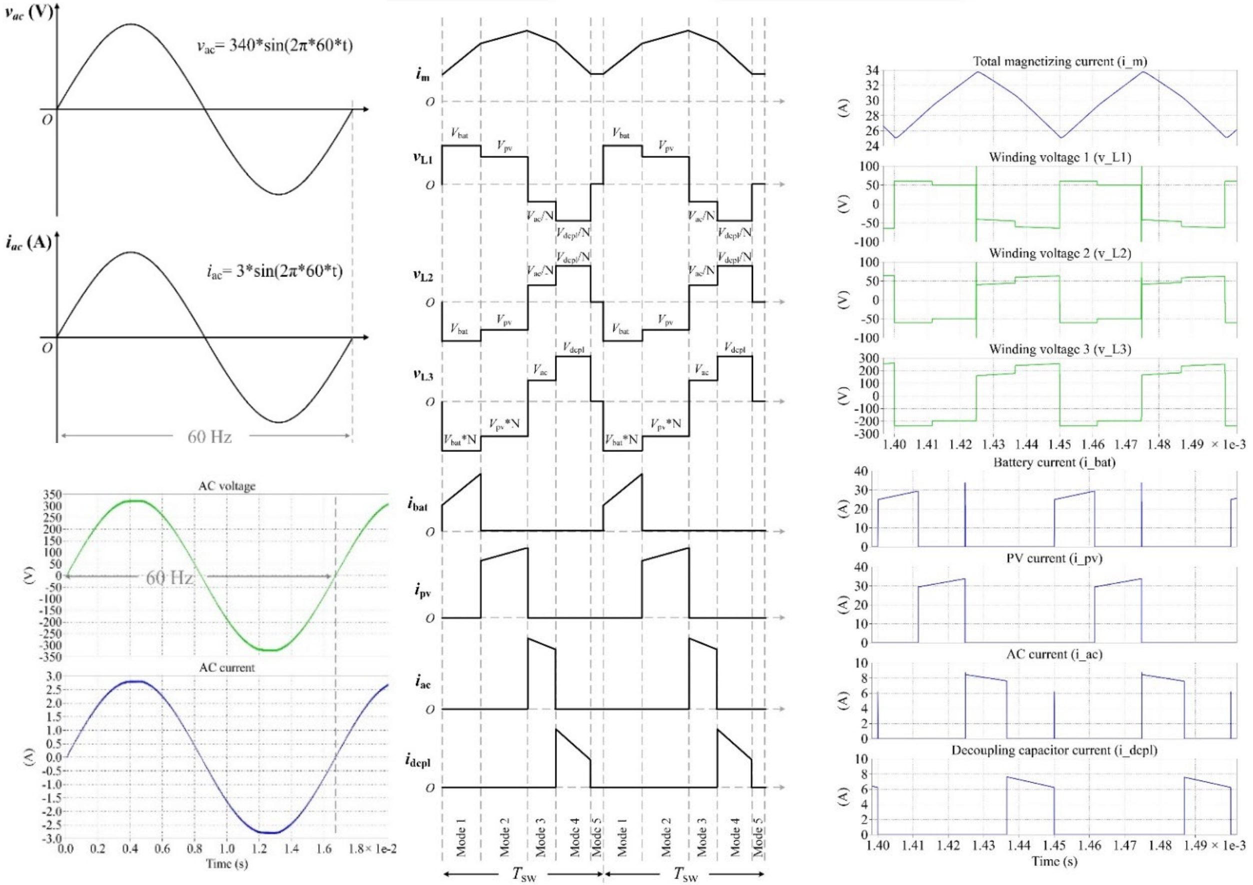
Feedback Requested

AC Cube — Controller Design (MPC+SVPWM)

Georgia Tech | Center for Distributed Energy



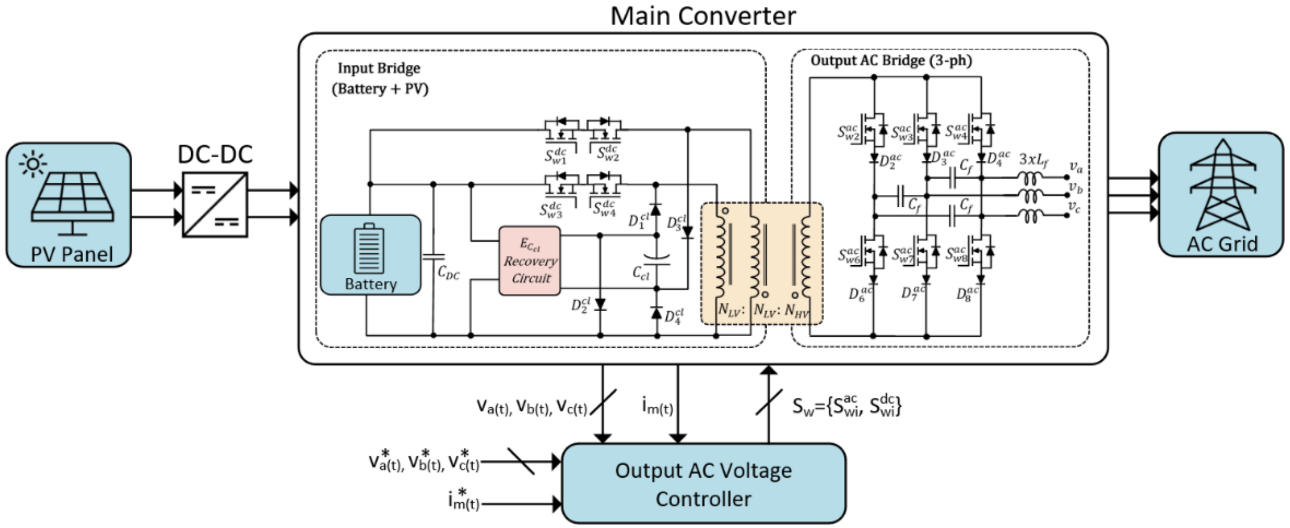




Model-Based Predictive Control with SVPWM:

- Development of the controller and switching state-machine for the new topology
- Single-phase operation simulation validation
- Bidirectional powerflow validation
- Constant switching-frequency operation

AC Cube — Controller Design



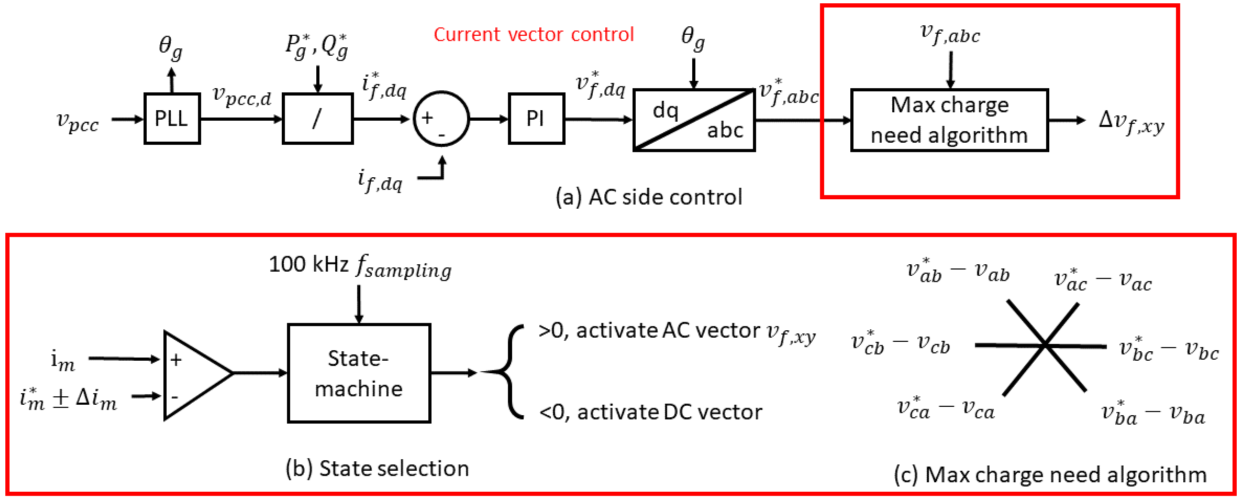


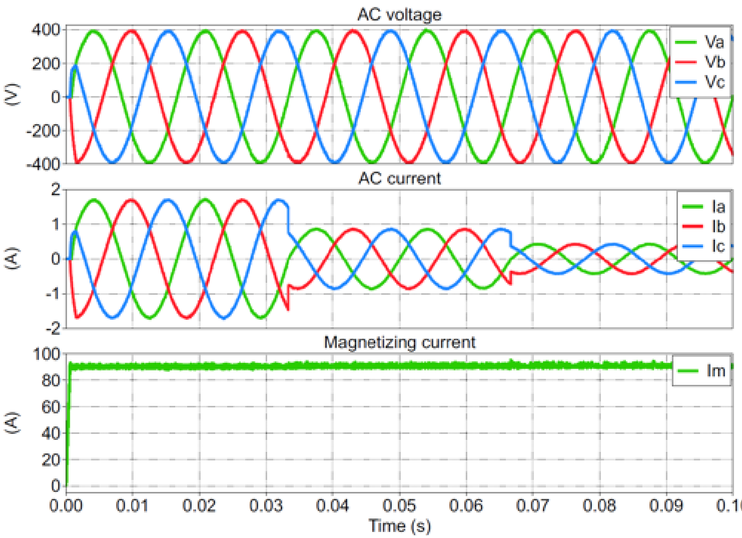
Table II: Comparison of controls

Control	THD	Running Time	Load transient (100% to 50%): Settling time	I_m overshoot	V_{ac} overshoot
PWM (20 kHz)	0.5%	2 min	78 us	5.5%	25%
Proposed (100 kHz)	1.0%	30 s	21 us	3.3%	5.8%

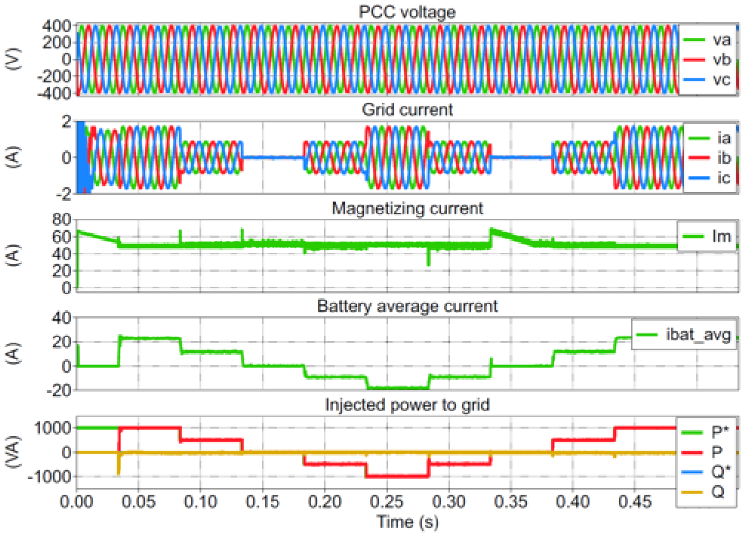
Average switching frequency of the proposed control [Hz]

DC side 25%	DC side 50%	DC side 100%	AC side 25%	AC side 50%	AC side 100%
3 k	6 k	10 k	30 k	28 k	24 k

High-bandwidth + low computational burden



(a) Load-tied [proposed control $f_{samp} = 100kHz$]



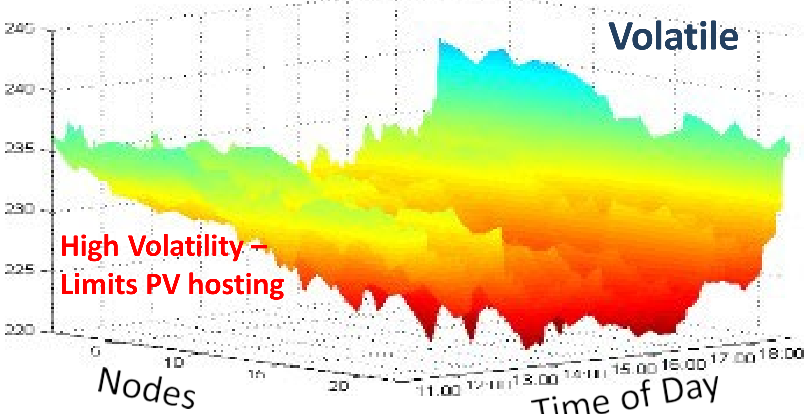
(b) Grid-tied [proposed control $f_{samp} = 100kHz$]

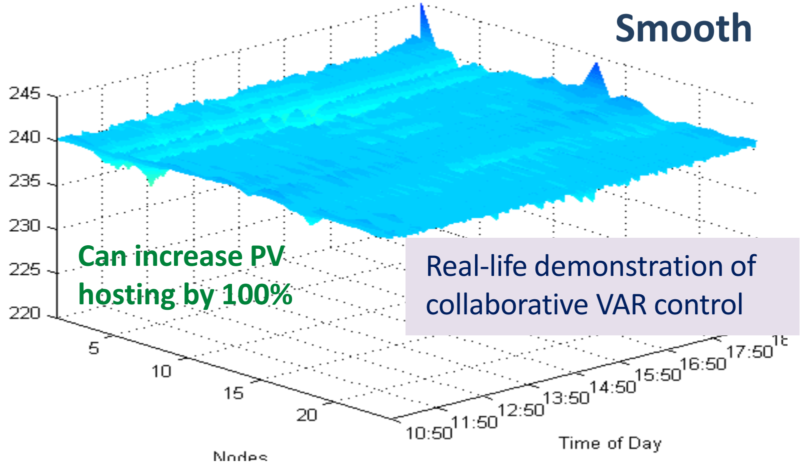
Collaborative Control for Grid as an Ecosystem

Georgia Tech Center for Distributed Energy

- Centralized control of a future grid with millions of intelligent DERs (storage) will be challenging – complexity, comms latency, security
- ‘Collaborative Control’ allows edge devices (inverters) to use local measurements and standard ‘rules’, acting in real-time to fulfill individual goals, and collaborating to sustain the grid ecosystem
- System is constantly changing, and devices need to act without real-time knowledge of system topology/state or low-latency comms
- Fundamentally different paradigm: today devices view the grid as a resource – with an ecosystem, all need to act to sustain it (priority)

Source: Southern Company and Varentec



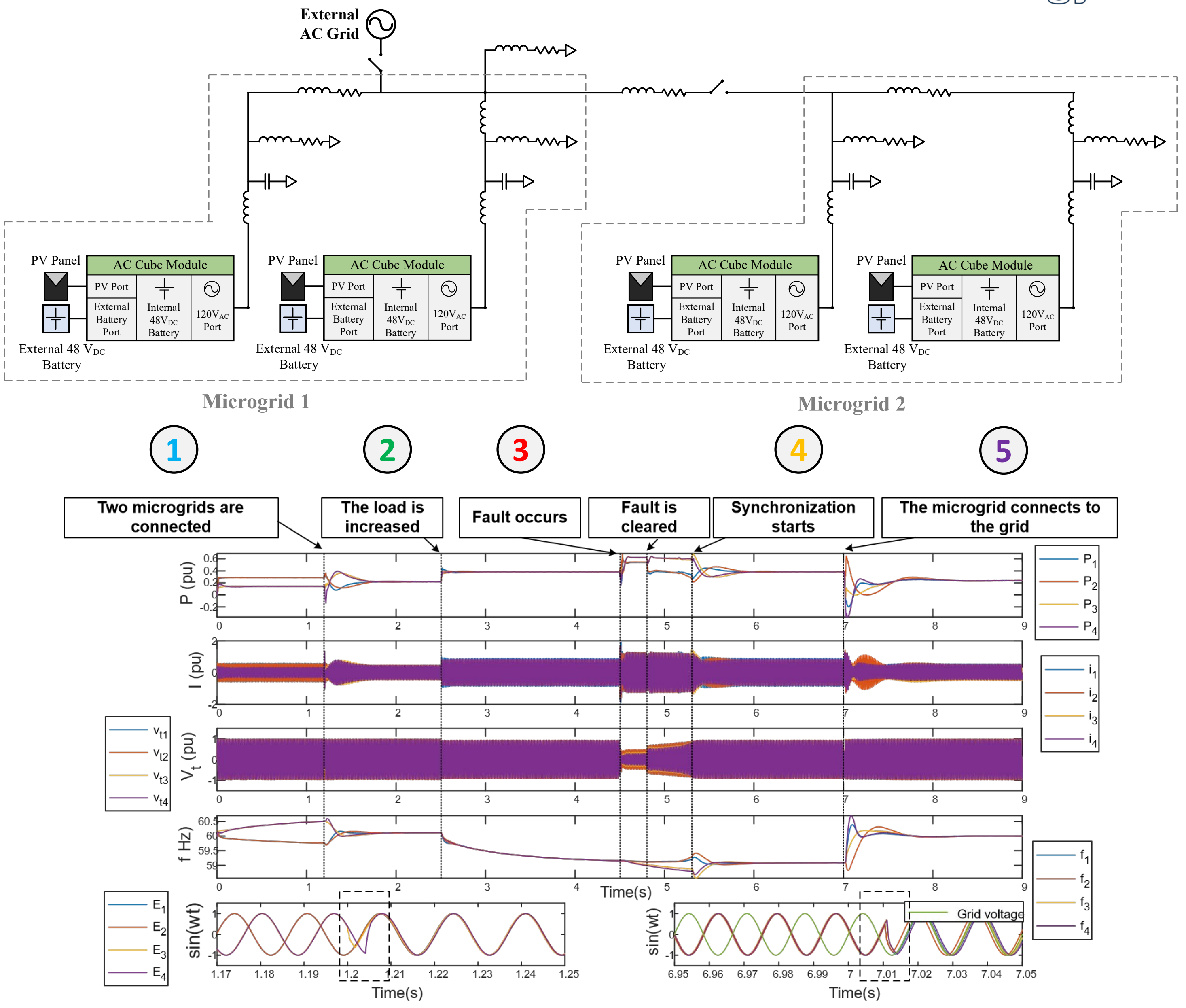


Examples of collaboration without communications

Autonomous inverters that collaborate with minimal system knowledge, don’t interact, operate over wide range of conditions & coordinate with slow secure comms

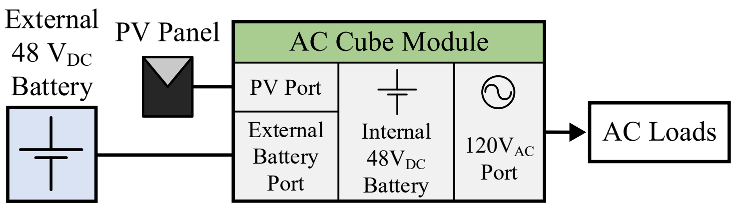
Collaborative Microgrid Control

- The AC Cube features a variety of standalone, grid-following, grid-firming, and grid-forming operational modes
- Proposed universal control strategy incorporates P-F droop and <u>ability to connect/disconnect at will with grid or other AC Cubes</u>
- Preliminary simulations on a 4-module system (2 microgrids each with 2 modules) evidence stability of the proposed control strategy during:
    1. Connection of multiple islanded microgrids
    2. Load step changes
    3. Grid fault conditions
    4. Re-synchronization following grid fault clearance
    5. Connection of microgrid clusters to external grid



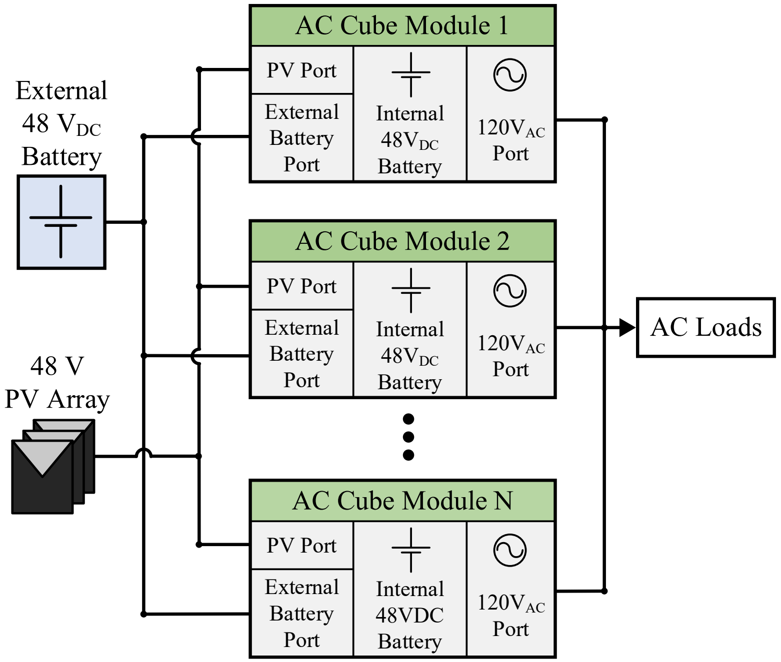
AC Cube - Use Scenarios

Georgia Tech Center for Distributed Energy

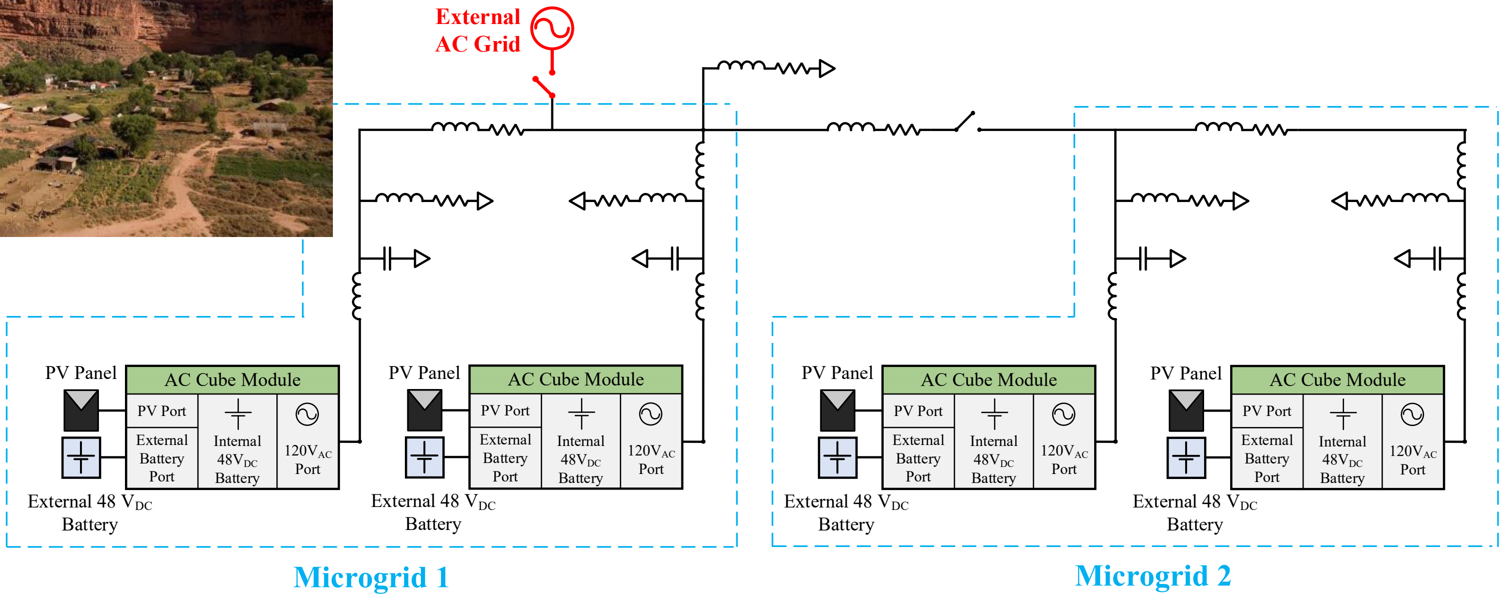


1a. Standalone Single AC Cube Module

3. For emergency deployments in resiliency conditions, ship or airdrop, and rapidly deploy using plug-n-play modules.



1b. Standalone Stacked AC Cube Modules



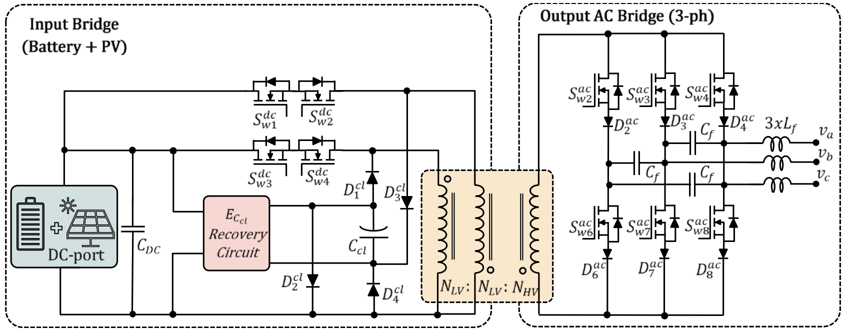
2. Two Microgrid Systems with Two AC Cubes Each

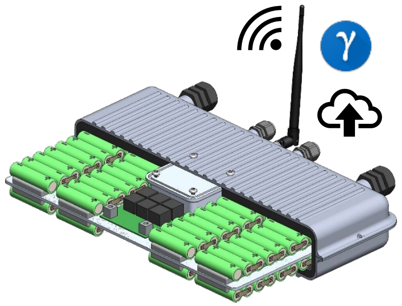
AC-Cube Hardware Development & HIL Testing

Georgia Tech Center for Distributed Energy

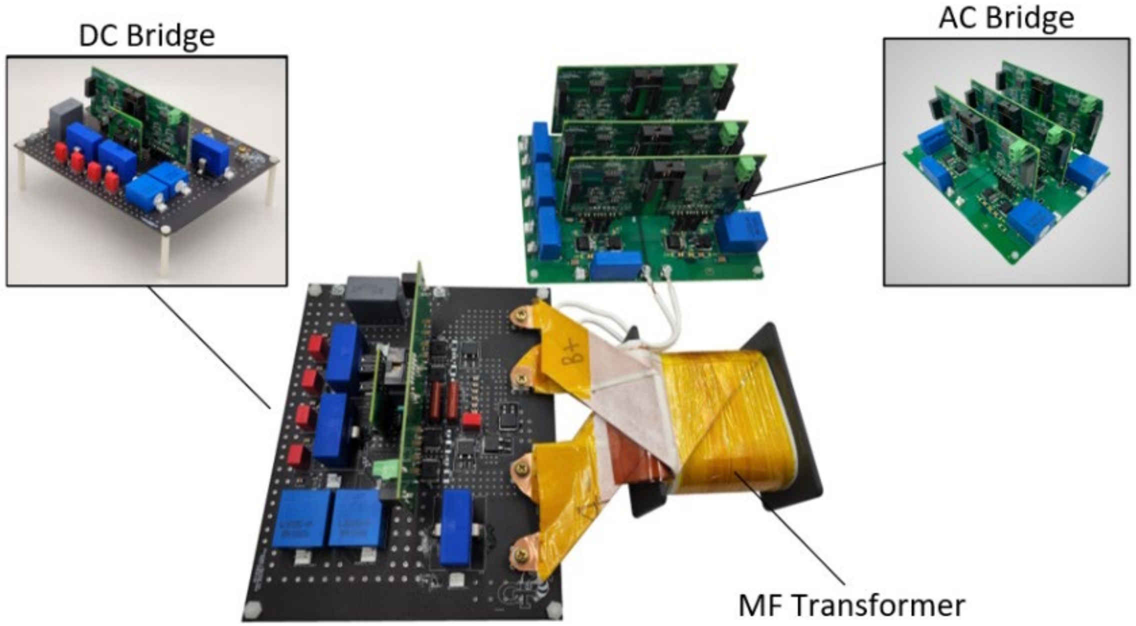
AC-Cube Circuit Schematic & Packaging

- Bi-directional multiport current-source-inverter (500 W/1 kW)
- Low-switch count with galvanic isolation & high efficiency.
- Grid connect at 480 volts 3 phase, 4-8 hours of storage (@60%)

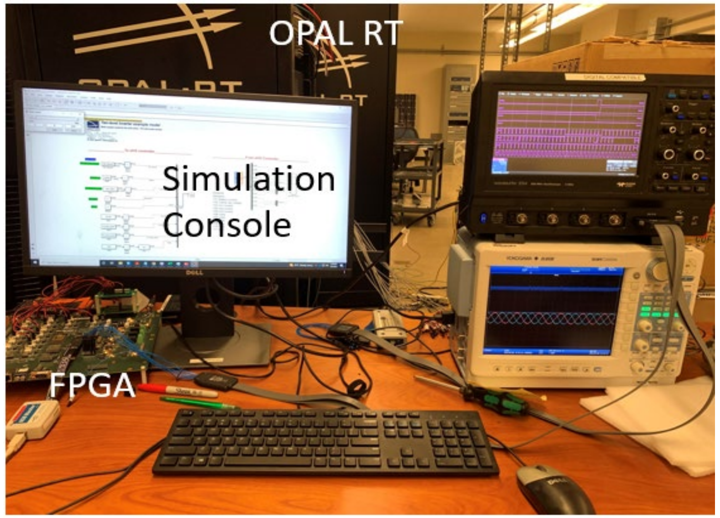


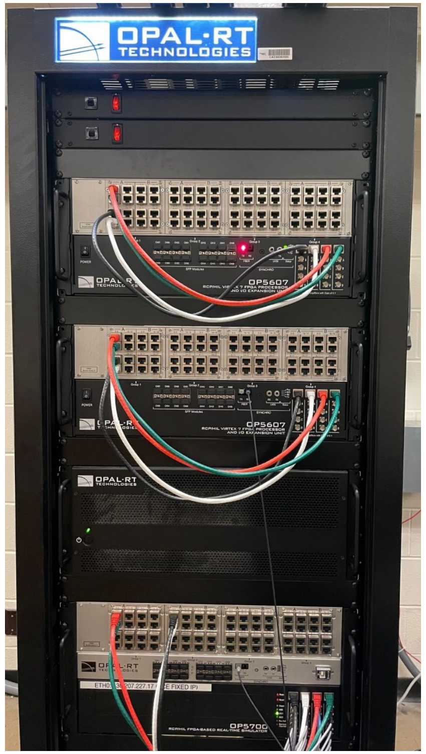


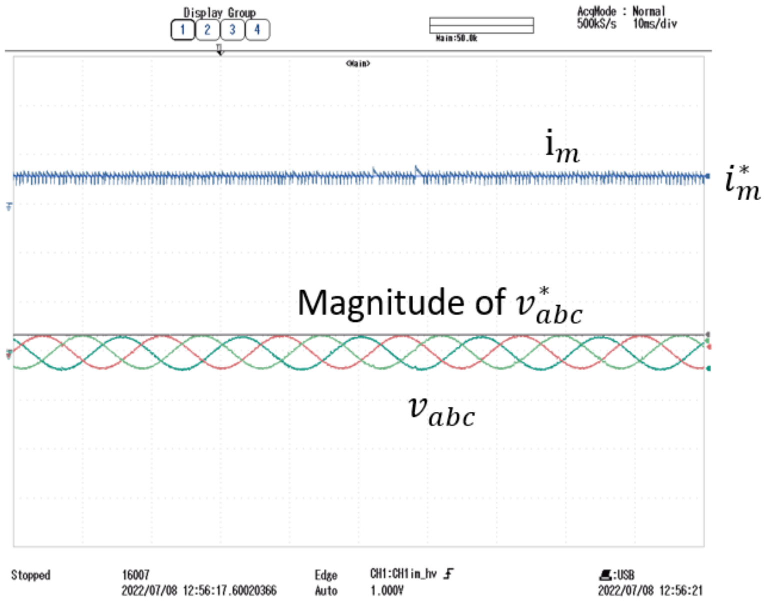
Hardware Prototype

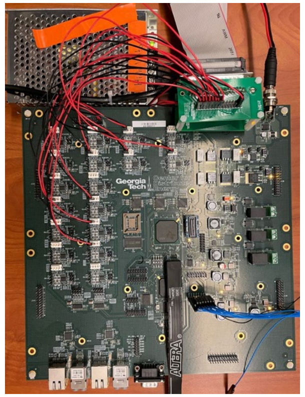


Simulation & HIL









Strong Alignment with Needs of Navajo Nation

Georgia Tech | Center for Distributed Energy

- Significant alignment between the needs of the Navajo Nation and the presented capabilities, use cases, install options, and specifications of the AC Cube, a safe, portable, affordable, and reliable AC power source.

- Alignment validated by Derrick Terry of the Navajo Tribal Utility Authority, whose inputs drive specifications of the AC Cube

- AC Cube delivers low-cost AC power while being uniquely suited to the following requirements of the Navajo Nation:
  - Intrinsic safety for rapid installation by electrically untrained members
  - Highly portable and mobile, enabling plug-and-play AC power as community members travel to engage with family and participate in community ceremonies
  - Stacking of modules enables output power scalability and incremental investments
  - Ultra-low hardware and installation cost
  - System intelligence enables wide variety of user installation options, and grid-forming and grid-following operating modes
  - High efficiency and high reliability
  - Integrated power monitoring enables “distributed utility” service-based models through NTUA

AC Cube Attributes and Project Timeline

Georgia Tech | Center for Distributed Energy

- AC Cube delivers low-cost AC power while being uniquely suited to the following requirements of the Navajo Nation and for resilient communities:
  - Intrinsic safety for rapid installation by electrically untrained members
  - Portable plug-and-play AC power for work and community ceremonies
  - Stacking of modules enables output power scalability and incremental investments
  - Low hardware and installation cost, rapid install, flexible configurability
  - Collaborative control enables variety of grid-forming, grid-following & microgrid operating modes
  - Integrated power monitoring enables “distributed utility” service-based models through NTUA

No.	Task	Duration
Yr 1	Work with NTUA to develop detailed specification. Develop concept for solution.	Aug. 2020 – Sep. 2020
Yr 2	Prove new elements to validate function. Detailed design of AC Cube. Simulate AC Cube for functionality. Detailed mechanical design of device and system. Procure and assemble first prototype AC Cube.	Oct. 2020 – Nov. 2022 (Delayed by NCE executions and supply chain issues)
Yr 3	Build and demonstrate fully functional prototype at CDE. Build two AC Cubes after validation. Opal-RT demonstration of AC Cube based microgrid system. Demonstrate a multi AC Cube system in lab, including internal/external storage and adhoc microgrid functionality. Ship prototype to Sandia. Write final report.	Nov. 2022 – Apr. 2023

IEEE Empower a Billion Lives - II

Energy Access needs new fresh thinking – holistic solutions, high-impact, scalable and lower cost

IEEE
EMPOWER
A BILLION LIVES
An IEEE-PELS Initiative

Key Challenge:

- 3 billion live in extreme energy poverty, ~1 billion live off-grid (only 15 million have Tier 2 (>200Wh/day)
- Solving energy access with today's solutions will result in 3.7 Gtons of CO_2 emission – not OK
- Existing assumptions relying on grid extension, SHS & microgrids are not working out as expected

IEEE Empower a Billion Lives (EBL) is an interdisciplinary global competition to develop/demonstrate innovative solutions to energy poverty & resiliency.

Teams are invited from across the globe and from all walks of life, including companies, research organizations, entrepreneurial startups, as well as student teams from colleges and universities.

Challenges:

- **Don't need energy – need livelihood and services**
- Factors - low purchasing power, aspirations, neighbors
- Low-tech users, interoperability, tech-obsolescence
- Last-mile sale, commission and maintain challenges
- Scalable - start small & grow as needed
- Need flexible and sustainable business models.

Participating in EBL-II is easy. Log on to www.empowerabillionlives.org to register your team. Review the requirements and submit a brief 3-page Concept Paper in the required format by Nov 1, 2021.

Building on the success of Empower a Billion Lives – I (EBL-I), IEEE PELS has launched EBL-II. EBL-I was held in 2019 and attracted over 450 teams from 70 countries. Over $500,000 was awarded to teams in prizes and support. Grand prize of $100,000 was won by Team SoULS from IIT Bombay, India

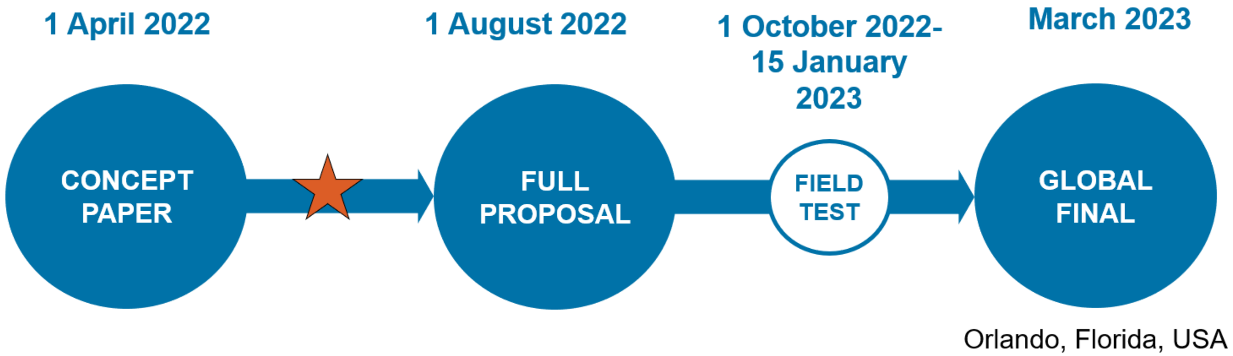
Empower a Billion Lives II

www.empowerabillionlives.org

Teams are invited from across the globe and from all walks of life, including companies, research organizations, entrepreneurial startups, as well as student teams from colleges and universities

- Targeting two groups as consumers of energy access solutions: the single family and the community.
- Teams can compete along the following 6 tracks, noting that solutions may fit into more than one track:

- **TRACK D: DECENTRALIZED UTILITY MODEL**
- **TRACK C: CENTRALIZED UTILITY MODEL**
- **TRACK A: AUTOMATION-CENTRIC SOLUTION**
- **TRACK P: END-USE ENERGY (PRODUCTIVE USE)**
- **TRACK E: ENABLING TECHNOLOGIES**
- **TRACK S: STUDENT TEAMS**



IEEE Advancing Technology for Humanity · IEEE Empower a Billion Lives – An IEEE-PELS Initiative · IEEE Power Electronics Society – Powering a Sustainable Future · IEEE Control Systems Society · Life Is On Schneider Electric

Conclusions

Georgia Tech | Center for Distributed Energy

- **VISION:** A future grid that realizes reliability and resiliency from the grid edge, and access to low-cost energy from the bulk power system, when it is available
- One key element to achieve this goal is a flexible plug-n-play power-brick which addresses the needs of off-grid communities, such as the Navajo Nation, as well as community resiliency after an HILF event
- The 1.25 kW, 1 kWh AC Cube module provides such a building block and supports most residential loads, and multiple modules can be connected in parallel to increase output power and run time
- The AC Cube eliminates the need for skilled technician install and operation through a plug-n-play design, use of advanced collaborative controls, and intrinsic electrical safety
- The proposed universal control scheme enables both stand-alone and grid-connected applications, enabling a variety of system installation possibilities in resiliency and contingency scenarios

Project members would like to thank Dr Imre Gyuk from DOE for his guidance and support, and Stan Atcitty from Sandia Labs for his guidance and technical leadership

Georgia Tech Center for Distributed Energy

Questions?

ddivan@gatech.edu