University of Puerto Rico-Mayagüez (UPRM)

The Electrical and Computer Engineering Department
(www.ece.uprm.edu)

Microrredes Eléctricas

Profesor: Fabio Andrade, PhD

Universidad de Puerto Rico - Mayagüez

UPR founded in 1903,

Now: 11 campuses

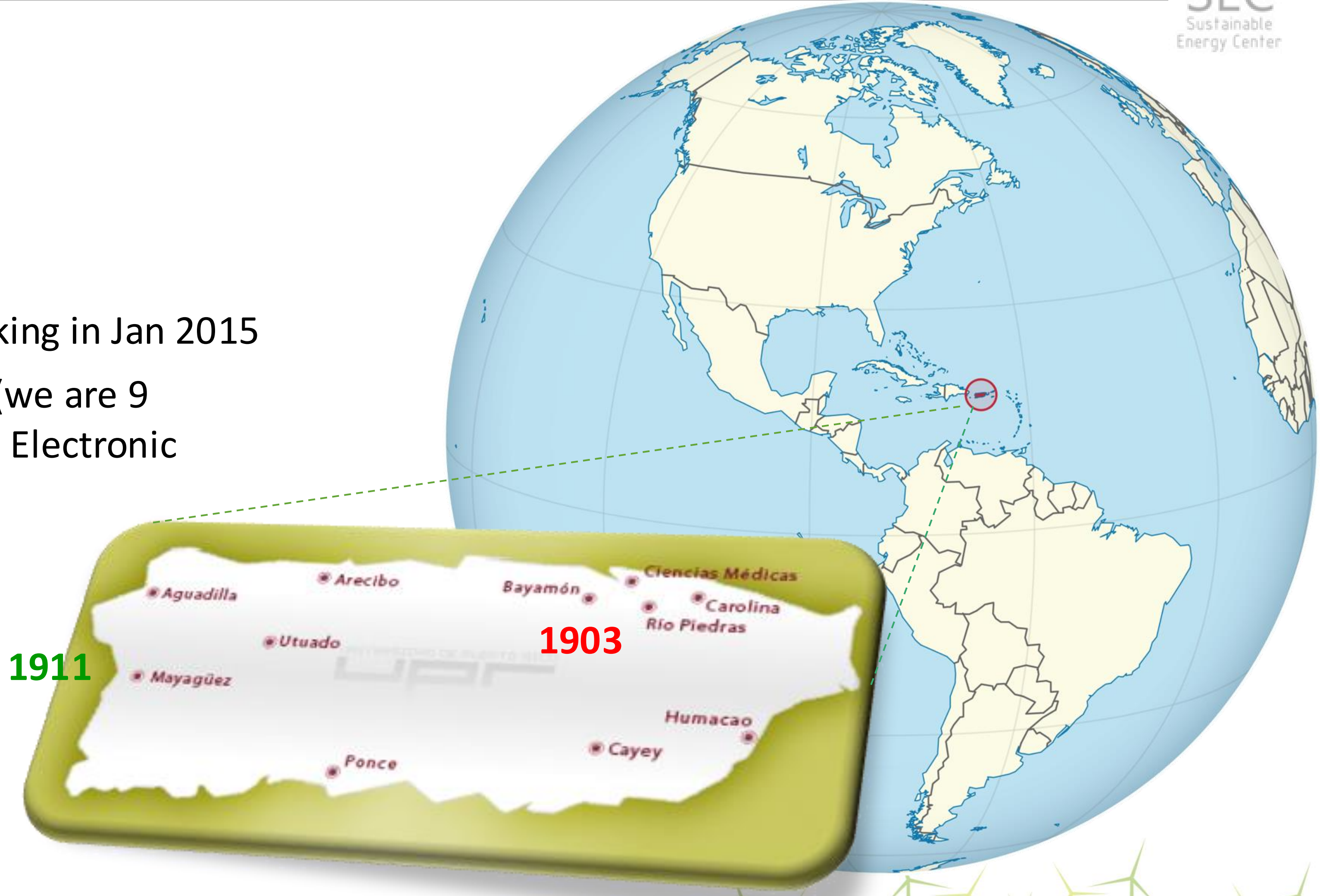
UPR Mayagüez

Electrical and Computer Eng. Dept.: Started working in Jan 2015

Currently I'm the coordinator of the Power Area (we are 9 Professors) and also collaborate with Control and Electronic areas

Teaching Experience includes:

- INEL 5417: Power Electronics Applied to Renewable Energy Systems
- INEL 4416: Power Electronics
- INEL 6085: Advanced Power Electronics
- INEL 6058: High Frequency Power Converters
- INEL 8496: Distributed Energy Resources



POWER ENGINEERING FACULTY

Erick Aponte, D. Eng., Rensselaer Polytechnic Institute

Marcel Castro, Ph.D. Howard University, Washington DC

Adriana Luna, Ph.D. Aalborg University Denmark

Fabio Andrade, PhD, Universitat Politècnica de Catalunya, Spain

POWER ENGINEERING FACULTY

José R. Cedeño, Ph.D.
Ohio State University

Efraín O'Neill, Ph.D.
Arizona State University

Lionel Orama, D. Eng.,
Rensselaer Polytechnic Institute

Eduardo Ortiz, PhD
Michigan State University

Agustín Irizarry, PhD
Iowa State University

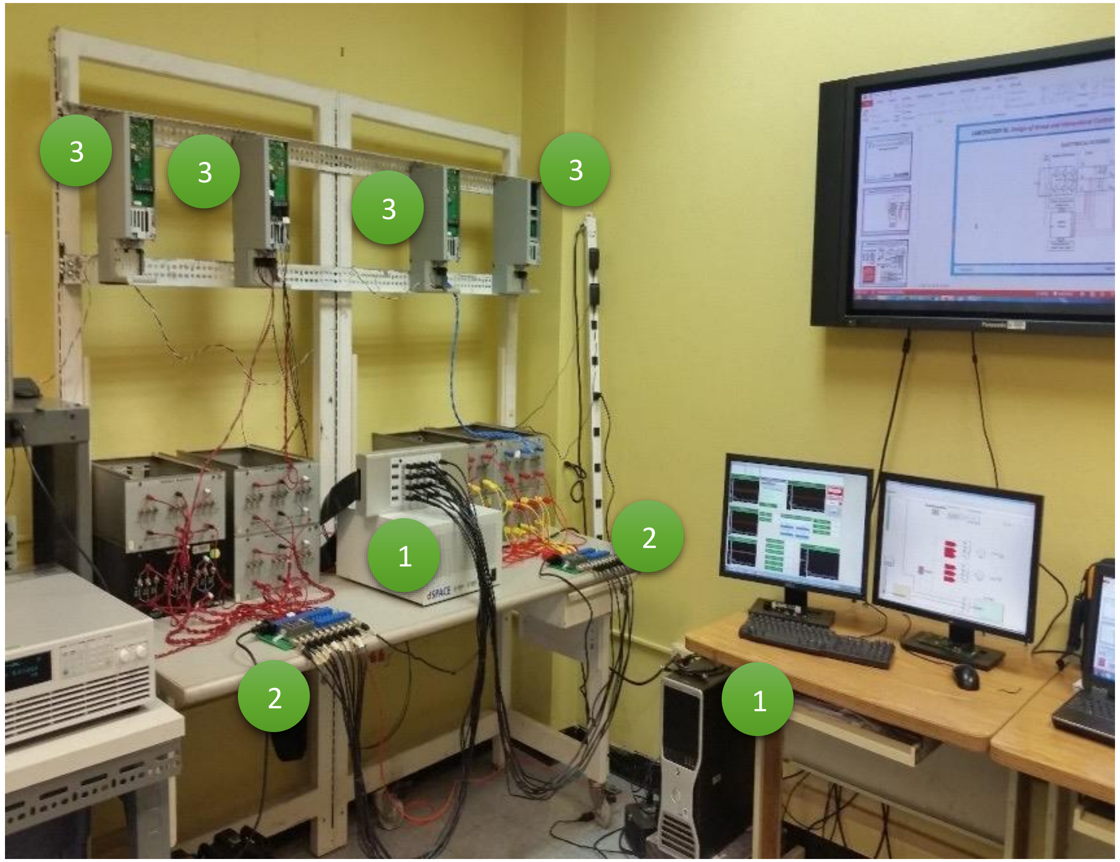
First Microgrid Lab at CID212

Seed funds

Co-PI at **NSF CRISP Type 2: Interdependent Electric and Cloud Services for Sustainable, Reliable, and Open Smart Grids**.

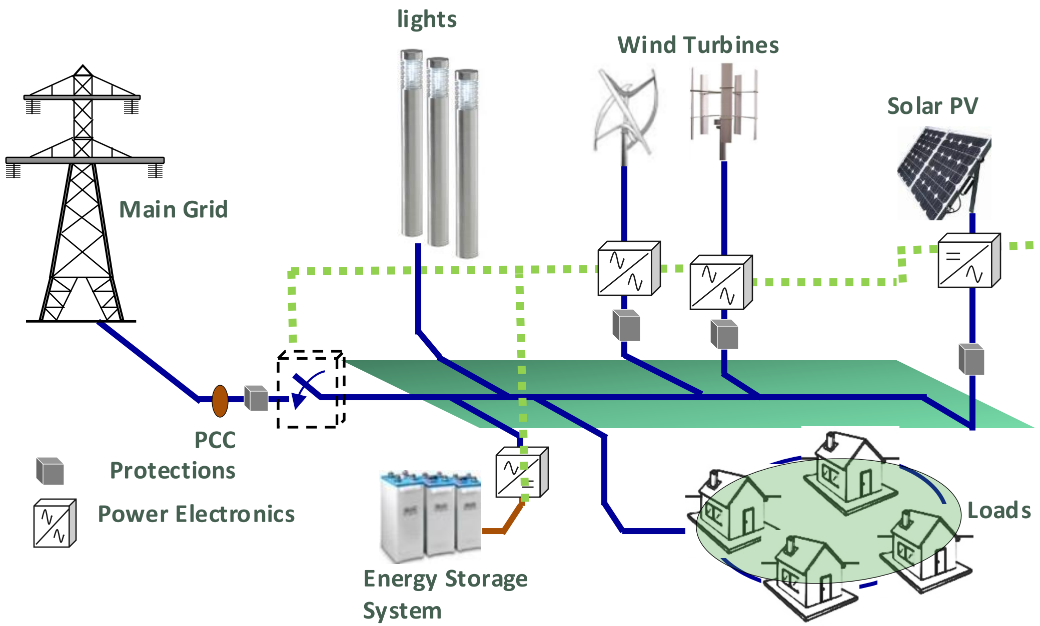
Grant No. ACI-1541106.

GridEd - The Center for Grid Engineering Education

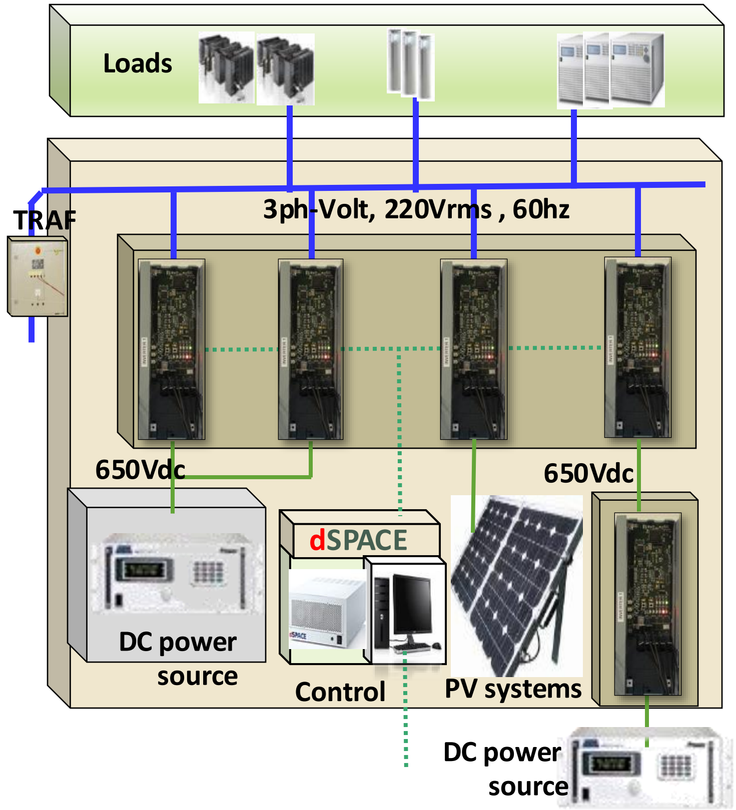


1. dSPACE System: Renewable Power models + Centralized Control systems
2. PWMs + 3 phases Current & Voltage sensor boards
3. DC/AC Converter 2.2kVA + Power Filter

NSF MRI: Development of a Real-world Microgrid Simulation/Testing AC Microgrid Instrument



Tertiary Control	Islanding detection	Electric Market	Power flow power	
Secondary Control	Grid on/off Operation	Synchronization	Power quality control	
Primary Control	MPPT	Virtual Impedance loop	P/Q droop method	
	DC voltage Control	PWM	PLL	Inner current and voltage loops



Grant No. ACI-1541106.

PI at NSF MRI: Development of a Real-world Microgrid Simulation / Testing Instrument, $355,640.00 (09/15/2018 – 31/08/2020)

NSF MRI Instrument:

Summer 2017

Hurricane MARIA Sept 2017

Ago 2018 MRI Grant

Dic 2018

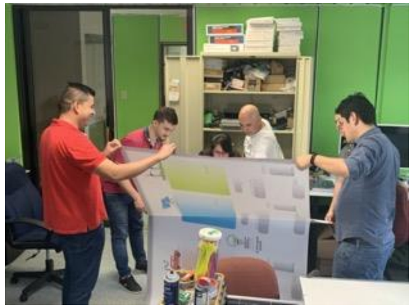
NSF MRI Instrument:

Jan
2019

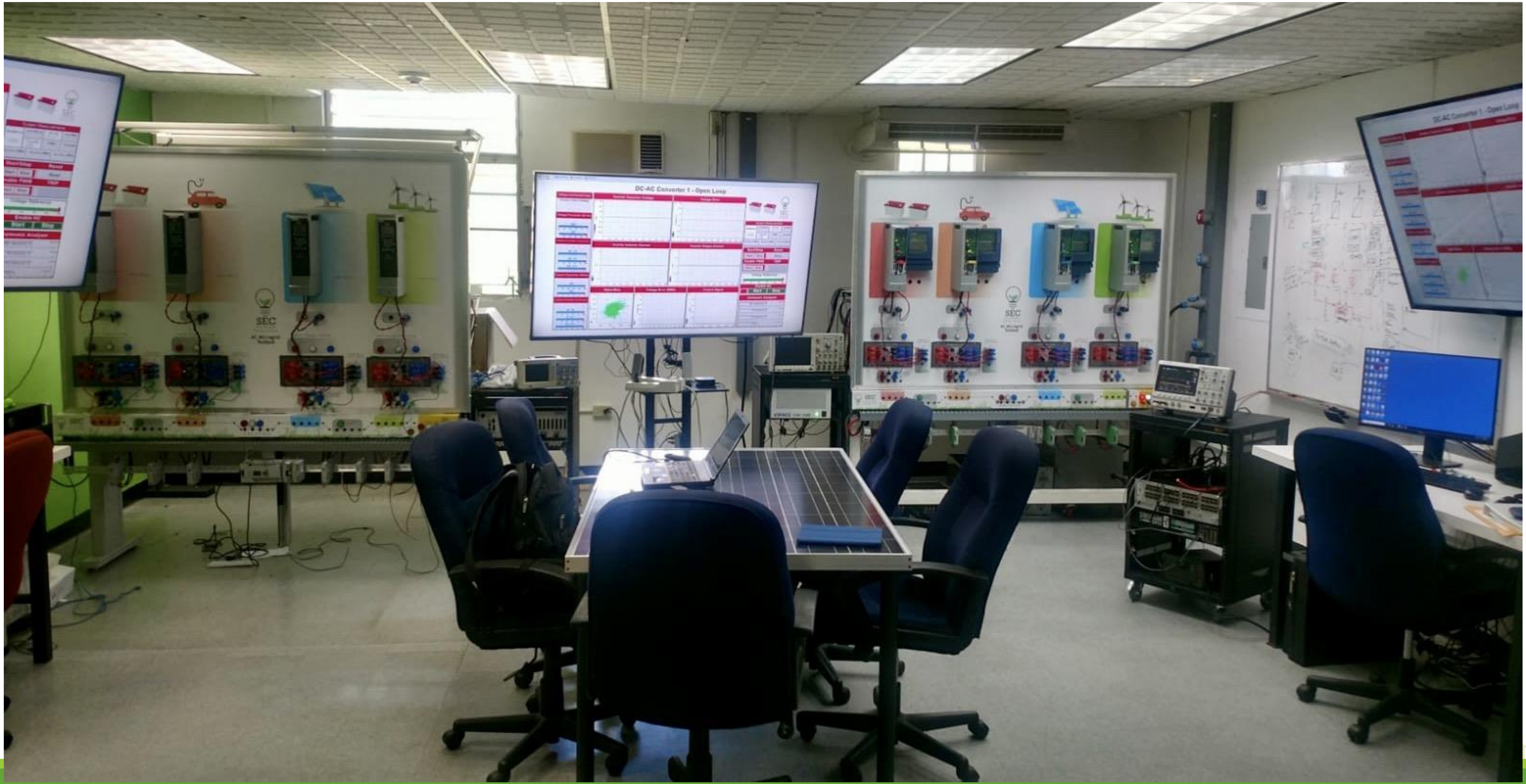
Earthquakes
Jan 2020

COVID Pandemic
Mar 2020

July 2020

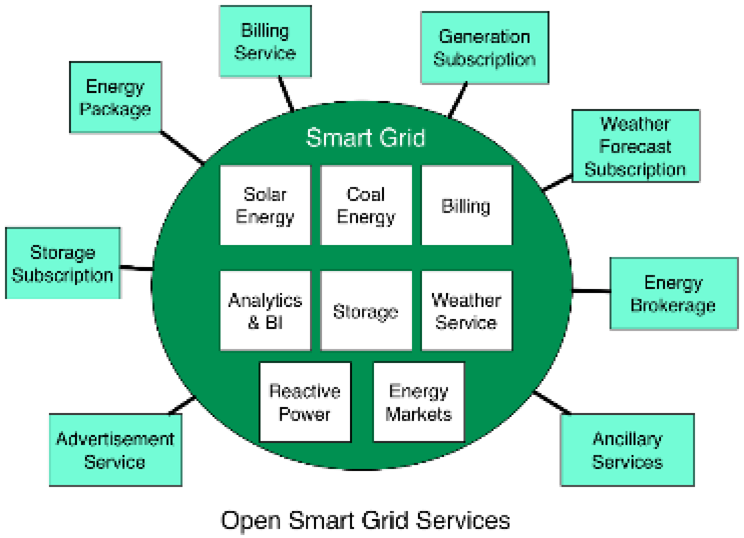


Current Microgrid Laboratory at CID208

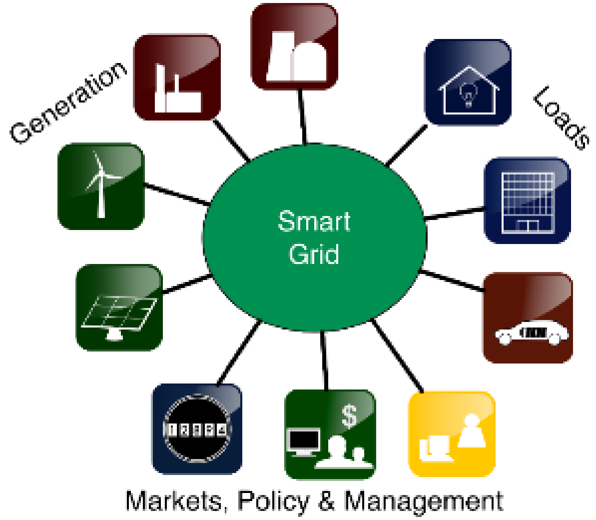


CRISP Type 2: Interdependent Electric and Cloud Services for Sustainable, Reliable, and Open Smart Grids

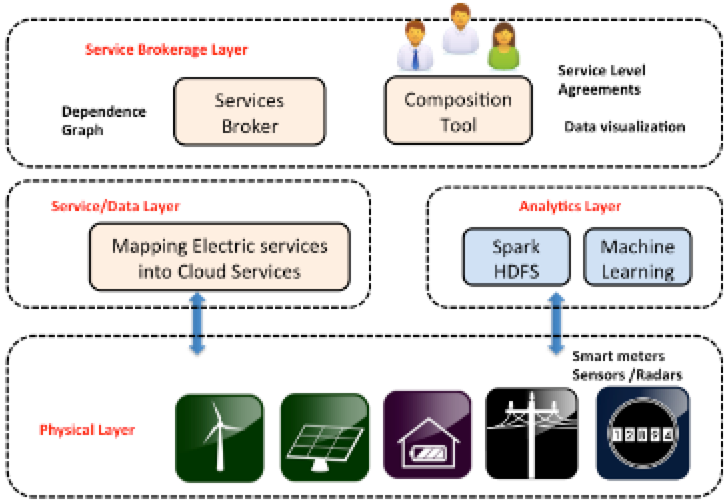
Proposed Open Access Smart Grid



Smart Grid Concept



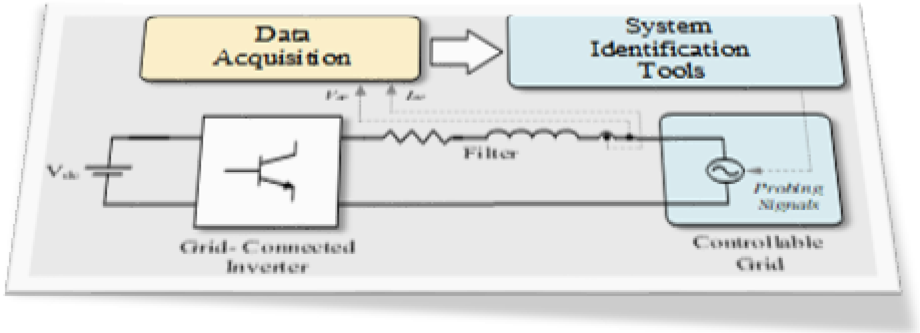
Proposed Software System Infrastructure

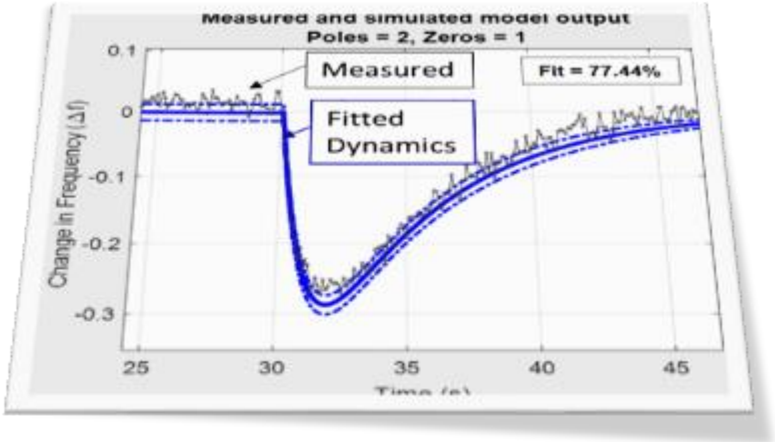


Grant No. ACI-1541106.

Co-PI at NSF CRISP Type 2: Interdependent Electric and Cloud Services for Sustainable, Reliable, and Open Smart Grids, $1,499,988.00 (09/15/2015 – 08/31/2019)

Development and Validation of Models to Assess Dynamic Response of Converter-Dominated Power Systems across Multiple Spatiotemporal Scales





This proposal will bridge power systems and power electronics domains to develop research programs at UAF, SDSU, and UPRM in dynamic (tens of milliseconds to 30 seconds timeframe) and transient (milliseconds to hundreds of milliseconds timeframe) level modeling of converter-dominated power systems. These programs will focus on exploring the use of converter-coupled generator models of varying complexity and detail for dynamic and transient timeframe power system simulations, and they will include a strong component of experimental validation.

Resilient Operation Of Networked Community Microgrids With High Solar Penetration

UNIVERSITY OF CENTRAL FLORIDA

THE UNIVERSITY OF TENNESSEE KNOXVILLE

OAK RIDGE National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

38 Años de Autogestión Solidaria y Humanitaria CASA PUEBLO

Iluminando a Adjuntas y Puerto Rico con el SOL

RECINTO UNIVERSITARIO DE MAYAGÜEZ – UNIVERSIDAD DE PUERTO RICO

HONNOLD FOUNDATION

This project proposes a novel development and evaluation of a microgrid controller (MGC) that coordinates the cluster operation of the Adjuntas MG to achieve high resiliency and cost-effective operation. Two operation modes are considered – normal and self-healing.

Developing socially and economically generative, resilient PV-energy systems for low- and moderate-income communities: Applications for Puerto Rico

SEC Sustainable Energy Center

Project Team	University of Puerto Rico-Mayaguez
Arizona State University	Cecilio Ortiz Marla Perez Lugo Fabio Andrade Marcel Castro
Clark Miller Elisabeth Graffy Kris Mayes Richard King Christiana Honsberg	**National Renewable Energy Laboratory** Benjamin Sigrin Meghan Mooney

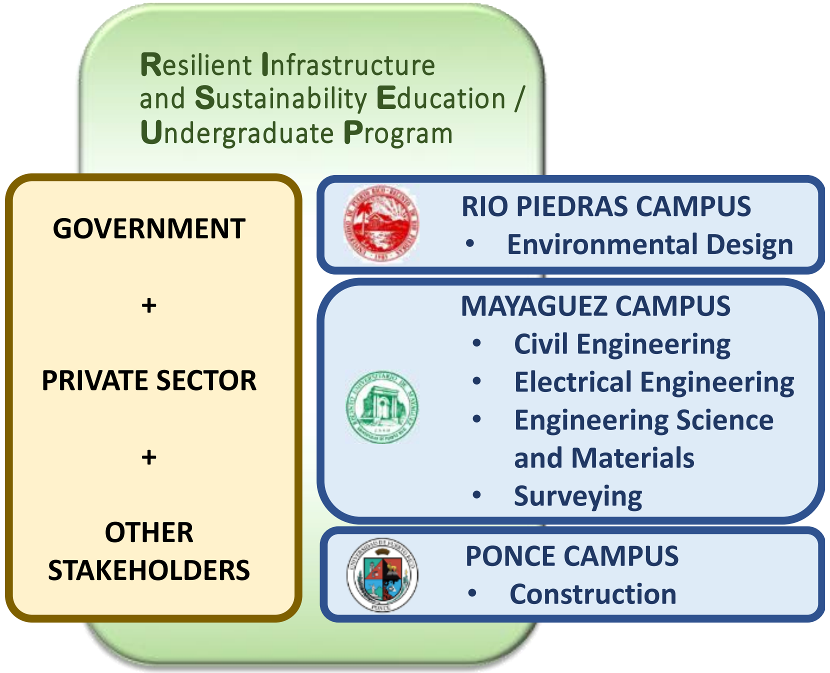
(04/2019 – 03/2022)

The project proposes **innovative pathways** for accelerating photovoltaic (PV) technology adoption among **low- and moderate-income (LMI) communities** in ways that generate positive social and economic benefits, including higher levels of energy security and socio-economic resilience.

U.S. DEPARTMENT OF ENERGY | Office of Science

Collaborative Research on Resilient Infrastructure and Sustainability Education - Undergraduate Program (RISE-UP)

We propose to develop an interdisciplinary Resilient Infrastructure and Sustainability Education – Undergraduate Program (RISE-UP). The program will provide the intellectual and practical academic space to generate case study research and turn them into hands-on solutions for real problems/projects, starting with the ones generated by the impact of Hurricanes Irma and Maria.



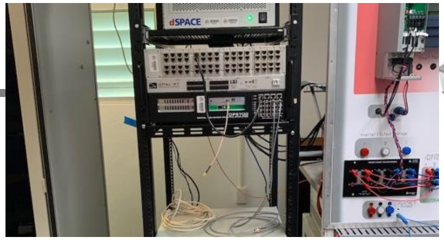
http://riseup.upr.edu

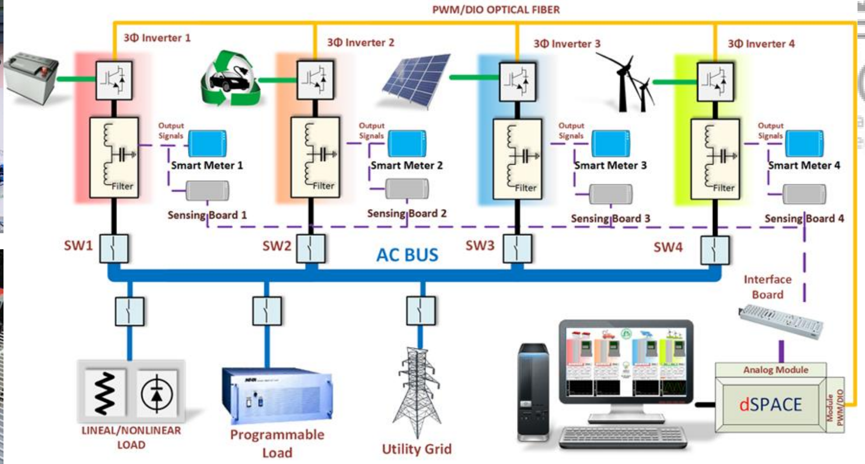
Senior Personnel at **NSF Building Capacity: A Collaborative Undergraduate STEM Program in Resilient and Sustainable Infrastructure,** $1,111,530.00 (10/01/2018 – 09/30/2023)

Grant No. ACI-1832468.

UPRM's Microgrid Laboratory

Microgrid Laboratory





South Dakota State University · University of Alaska Fairbanks · Arizona State University · University of South Florida · Universidad del Valle · Universidad de Jaén · NREL National Renewable Energy Laboratory · Sandia National Laboratories · Oak Ridge National Laboratory · U.S. Department of Energy Office of Science · NSF · windmar · Casa Pueblo Adjuntas Puerto Rico


Solar House


Community Initiatives

Community Initiatives

UPRM ECE University of Puerto Rico - Mayagüez Electrical & Computer Engineering Department

University of Puerto Rico-Mayagüez (UPRM)

The Electrical and Computer Engineering Department

(www.ece.uprm.edu)

Education Activities

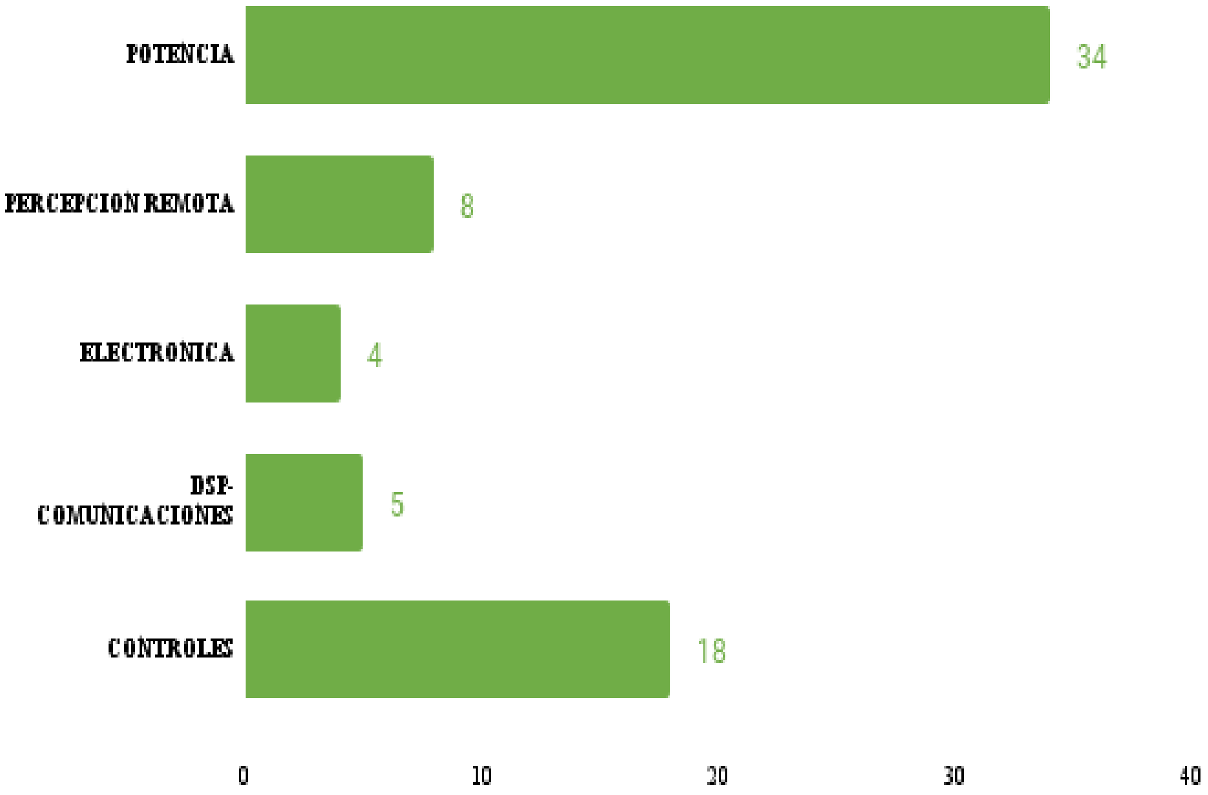
Research – PhD and Msc theses

Outreach – go to Communities

2019 EE Graduates (undergrad) per area

9 Power Faculty expertise:

- microgrids, renewable energy sources, power electronics, electric vehicles
- Distributed Generation (DG), islanding detection
- smart rural power systems, appropriate technology, responsible wellbeing
- power system optimization, evolutionary computation, T&D design,
- Illumination Engineering, electrical safety
- power systems dynamics, renewable energy resources
- power quality, social implications of technology



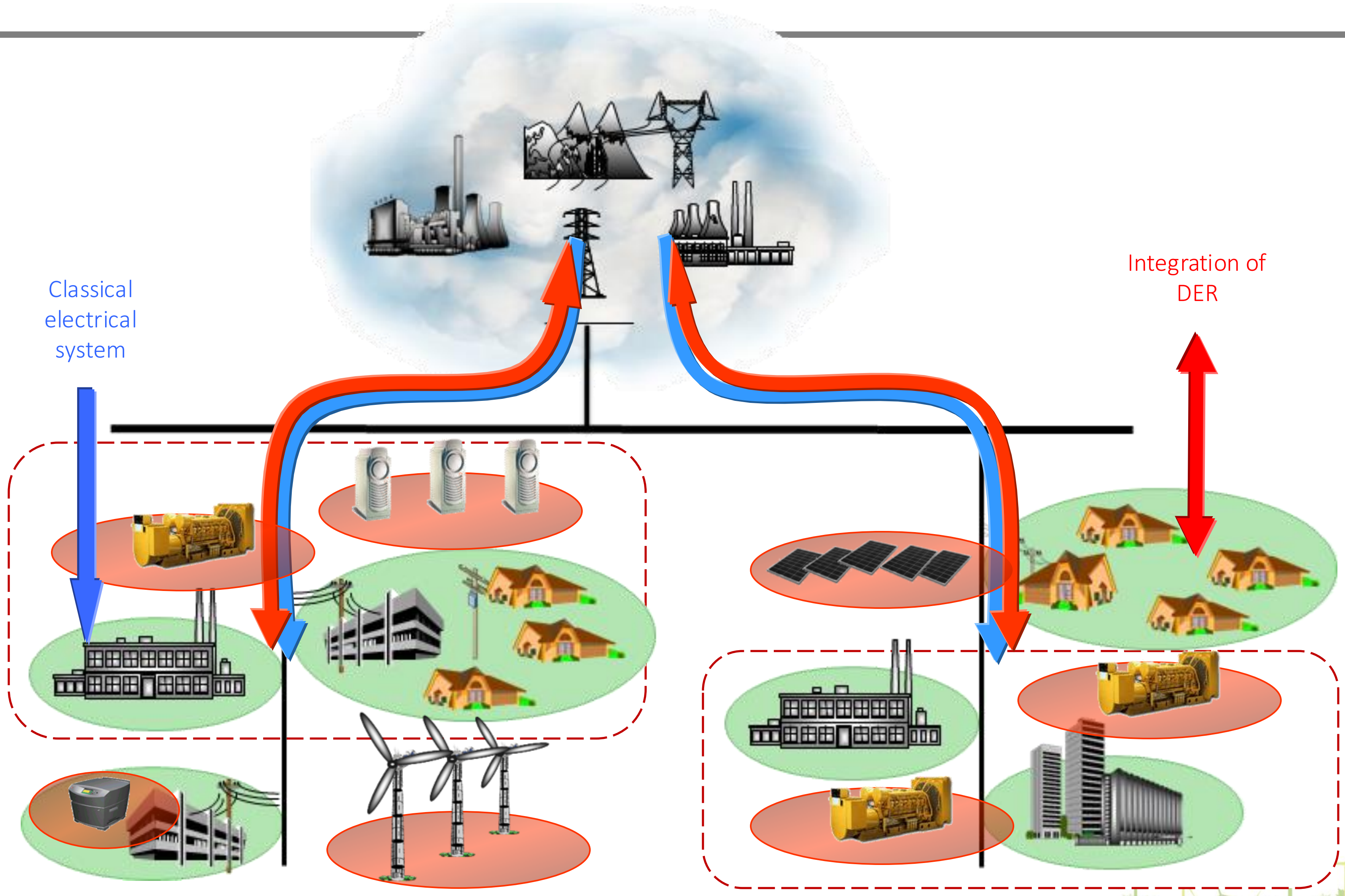
Undergraduate power engineering courses

Course code	Course title/description
INEL 4103	Circuit Analysis III (basic 3 phase balanced power)
INEL 4405	Electric Machines
INEL 4406	Electric Machines Laboratory
INEL 4407-08	Electric Systems Design I and II - elec sys design for buildings
INEL 4409	Illumination Engineering
INEL 4415	Power Systems Analysis (pwr flow, econ. dispatch, faults)
INEL 4416	Introduction to Power Electronics
INEL 4417	Alternative Energy Generation (renewables)
INEL 5406	Transmission and Distribution Systems Design
INEL 5408	Motors Control, drives
INEL 5415	Power System Protection
INEL 5417	Power Electronics applied to renewables

Graduate power engineering courses

Course code	Course title/description
INEL 5406	Transmission and Distribution Systems Design
INEL 5408	Motor Control
INEL 5415	Power System Protection
INEL 5417	Power Electronics applied to renewables
INEL 6025	Advanced Energy Conversion
INEL 6027	Power Systems Dynamics and Control
INEL 6028	Power Systems Optimization and Economic Operation
INEL 6058	High Frequency Power Converters
INEL 6066	Electric Drive Systems
INEL 6077	Surge Phenomena
INEL 6085	Advanced Power Electronics
INEL 6096	Power Quality

An Introduction to Microgrid Control



An Introduction to Microgrid Control

An Introduction to Microgrid Control

France
EDF
ARMINES
idea
SCALAGENT Distributed Technologies

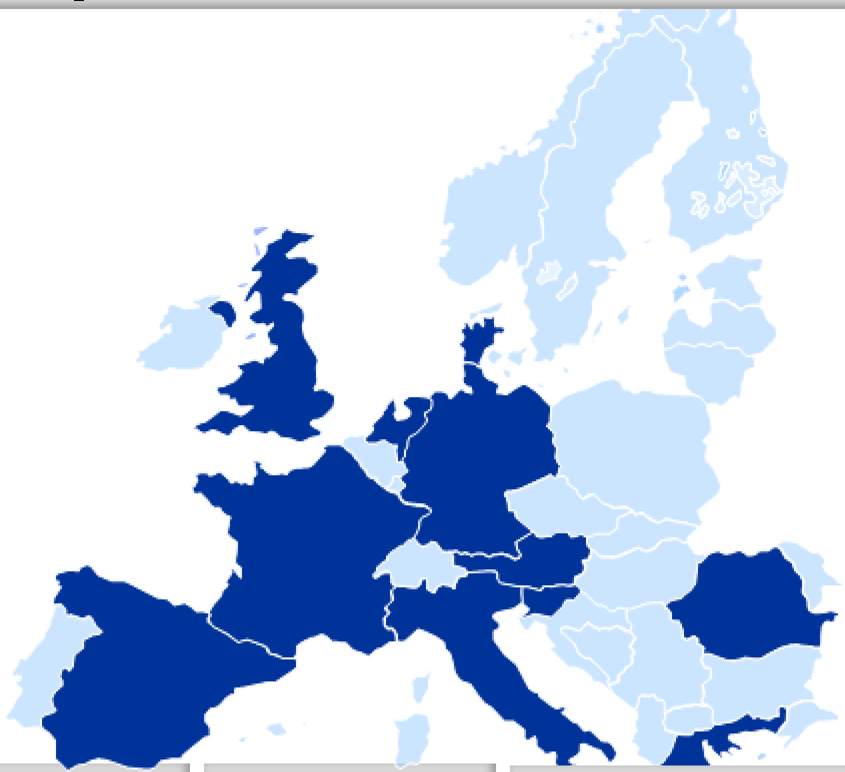
United Kingdom
EDF ENERGY
nationalgrid The power of action
PÖYRY
MANCHESTER 1824 The University of Manchester
Imperial College London

The Netherlands
ECN
vrije Universiteit amsterdam

Denmark
Microgrids seriously affect your brain www.aau.dk
AALBORG UNIVERSITY

Romania
ECRO

Athens
National and Kapodestrian UNIVERSITY OF ATHENS



Spain
UPC
IBERDROLA
RED ELÉCTRICA DE ESPAÑA

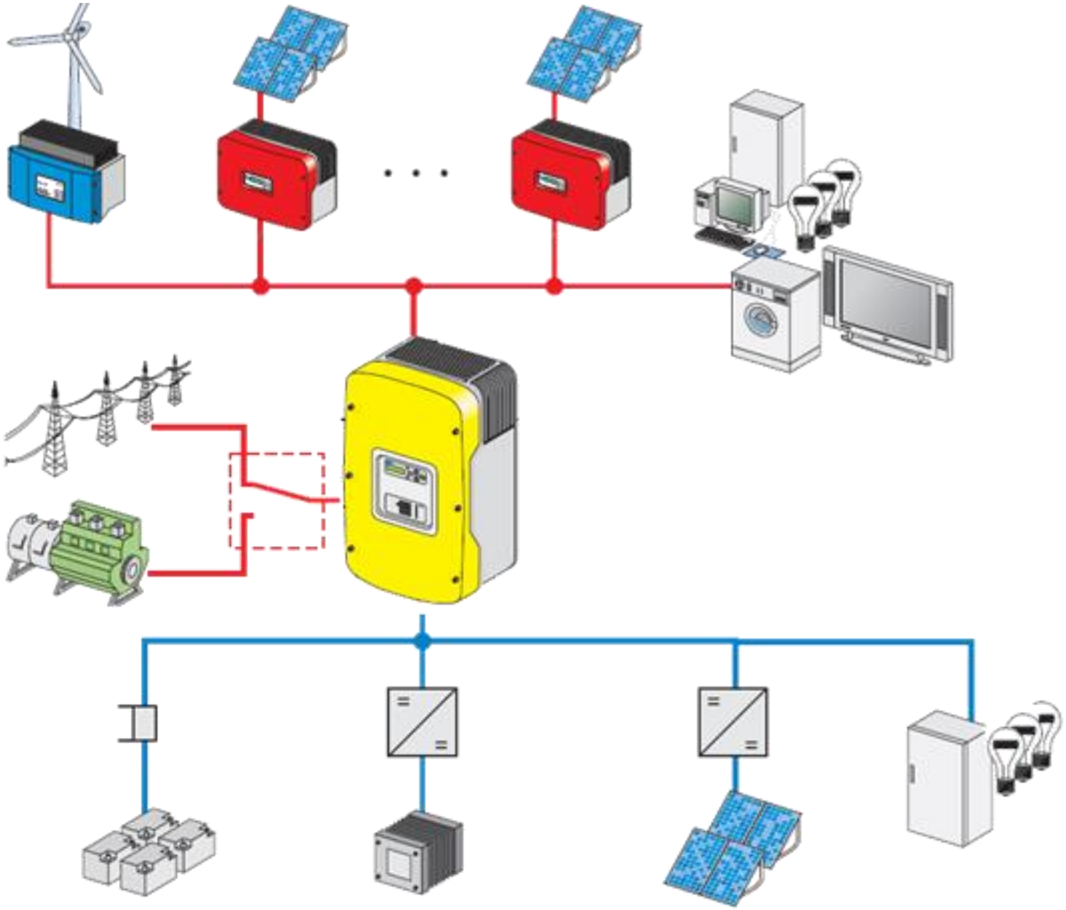
Germany
Schneider Electric
ISET

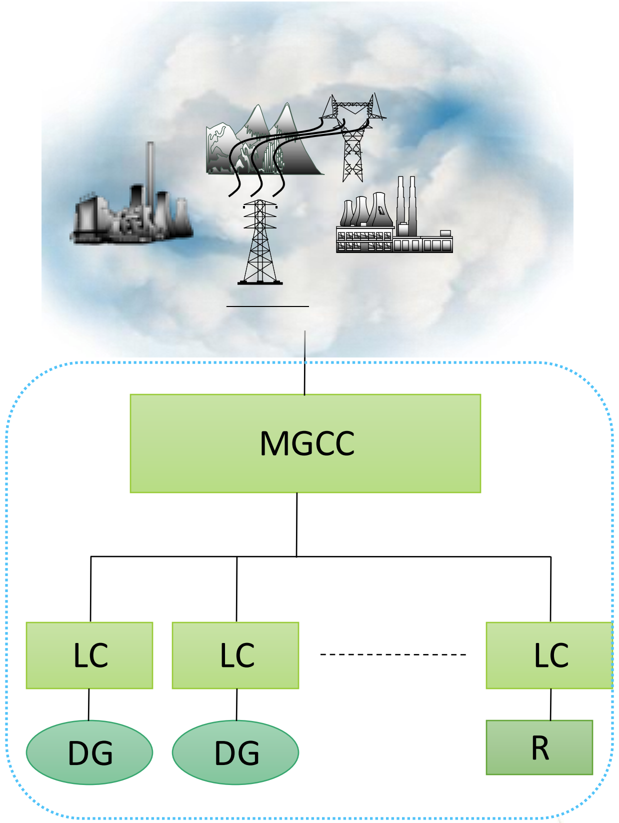
Austria
SIEMENS

Italia
CESI
RSE

An Introduction to Microgrid Control

"… MicroGrid concept assumes an aggregation of loads and microsources operating as a single system providing both power and heat. The majority of the microsources must be power electronic based to provide the required flexibility to insure operation as a single aggregated system …" [Lasseter et al, 2002]

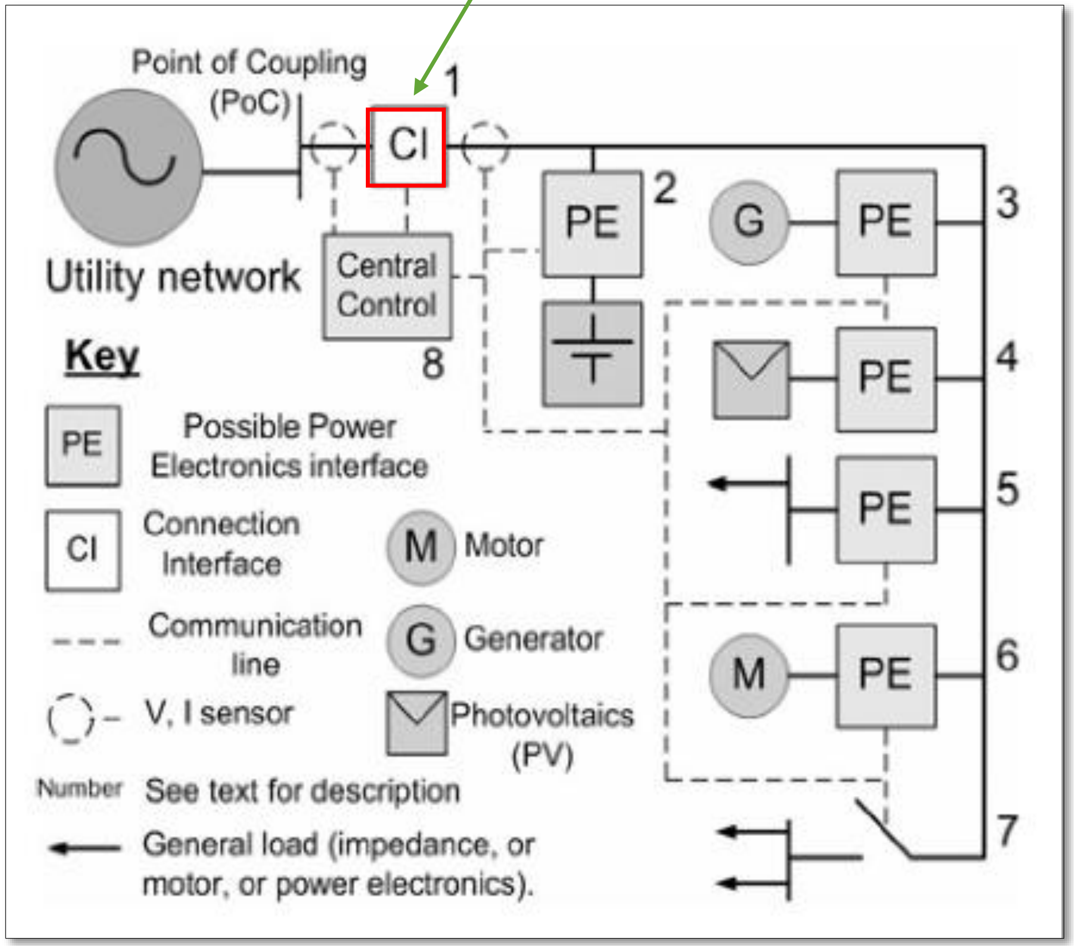




Microgrid *[Dimeas y Hatziargyriou, 2005]*

Microgrid Configurations

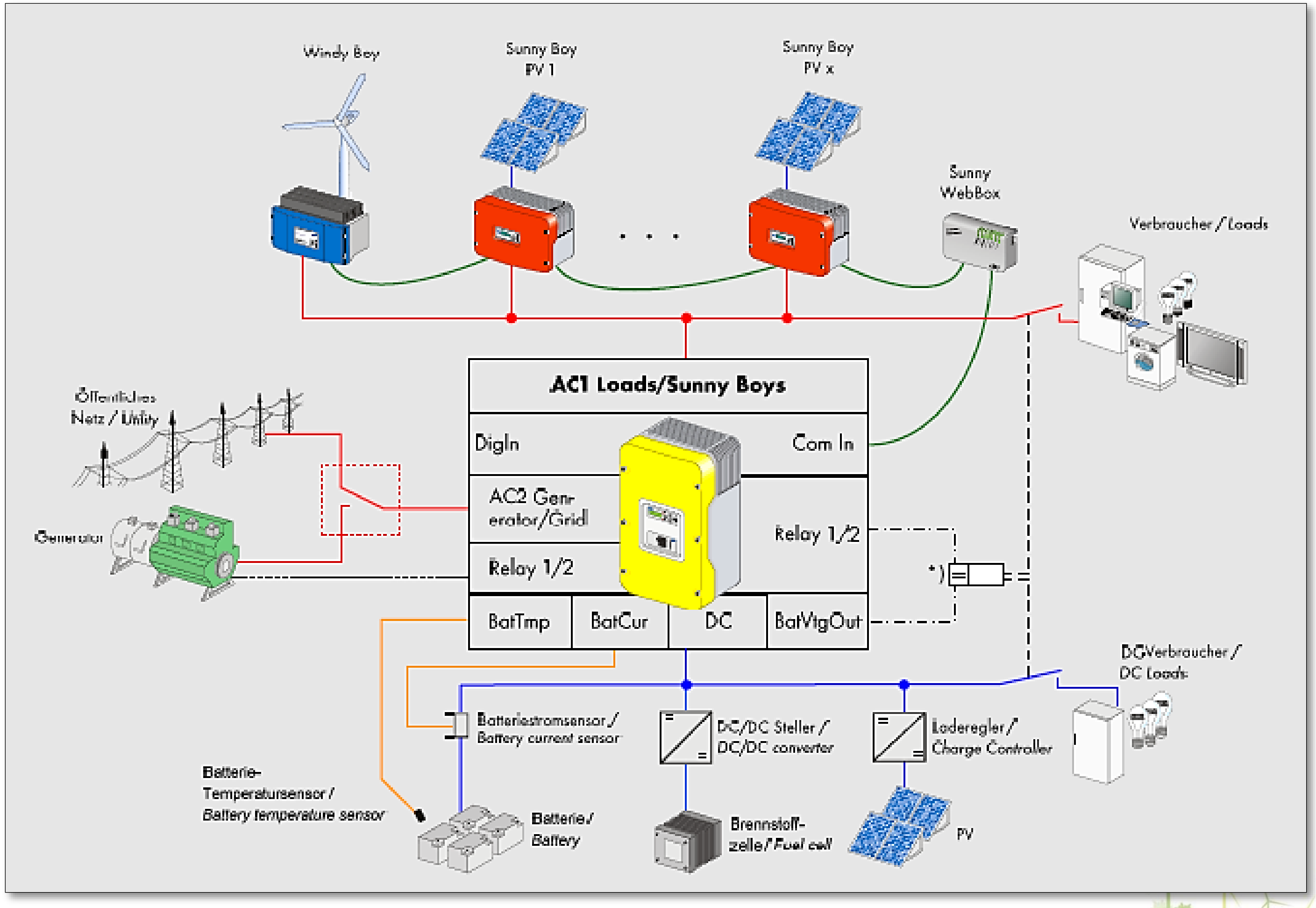
Connection interface (CI)



Microgrid Configurations

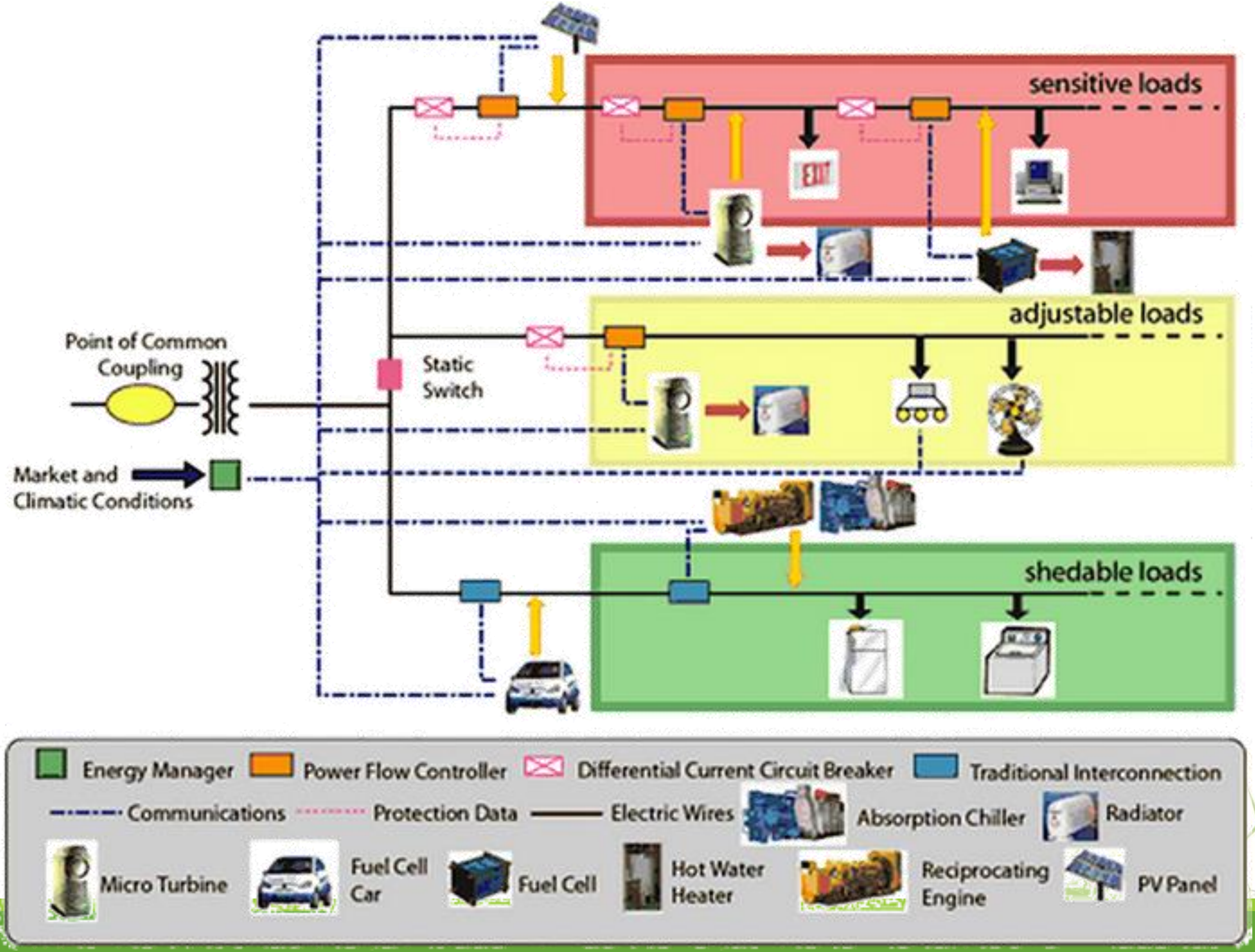
AC-DC Hybrid Microgrid

Hierarchy of loads



Microgrid Configurations

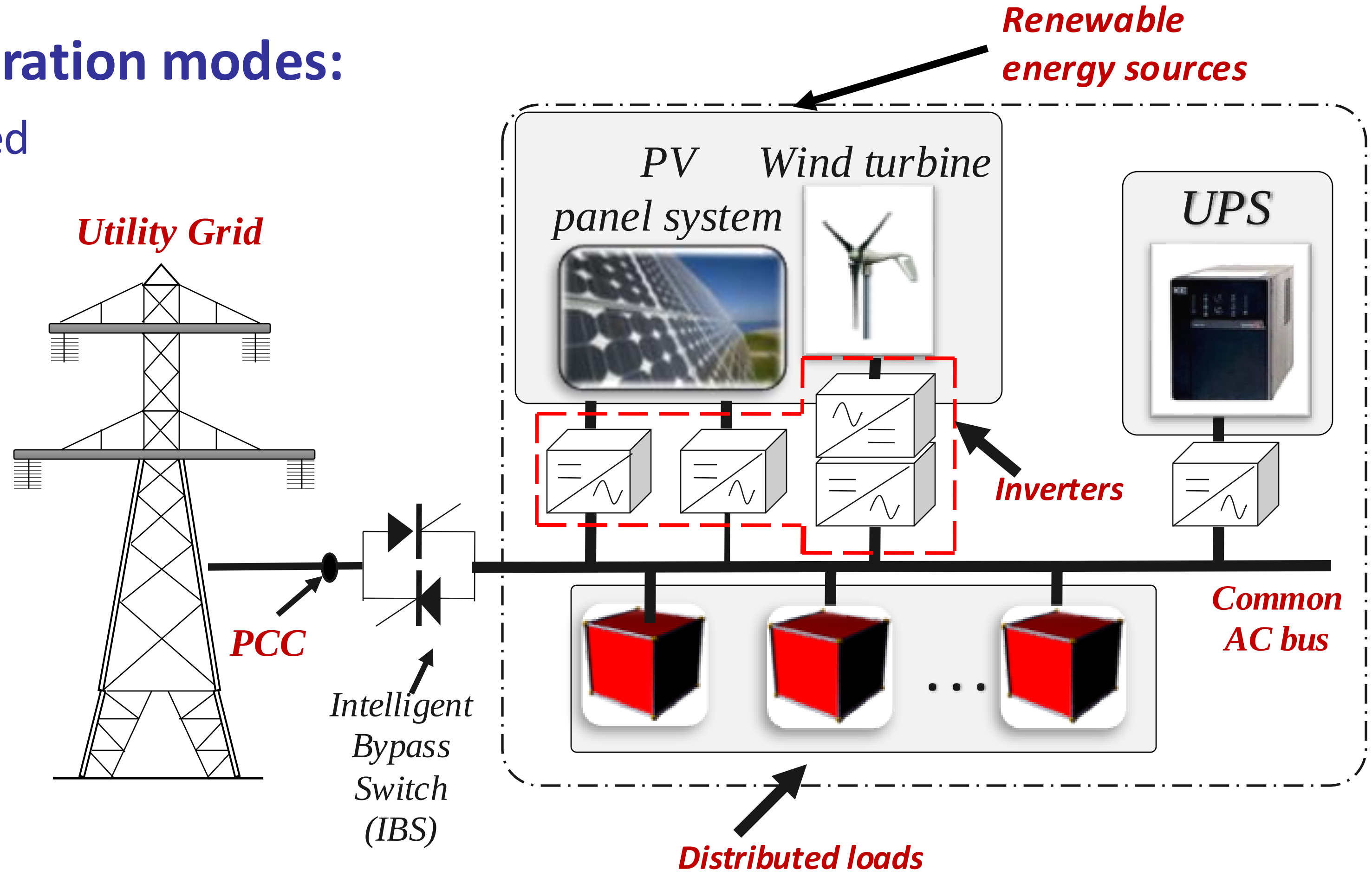
Microgrid proposed by the CERTS (Consortium for Electric Reliability Technology Solutions)



Microgrid operation

Microgrid operation modes:

- Grid connected
- Islanded

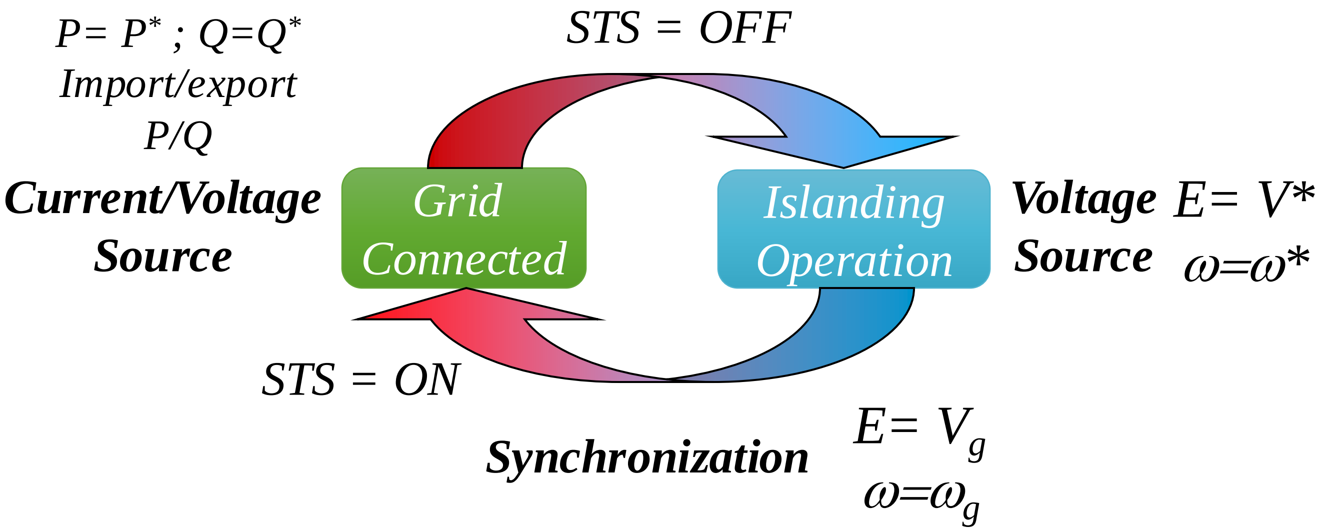


Typical structure of a flexible microgrid

Microgrid operation

Islanded / Grid-connected operation

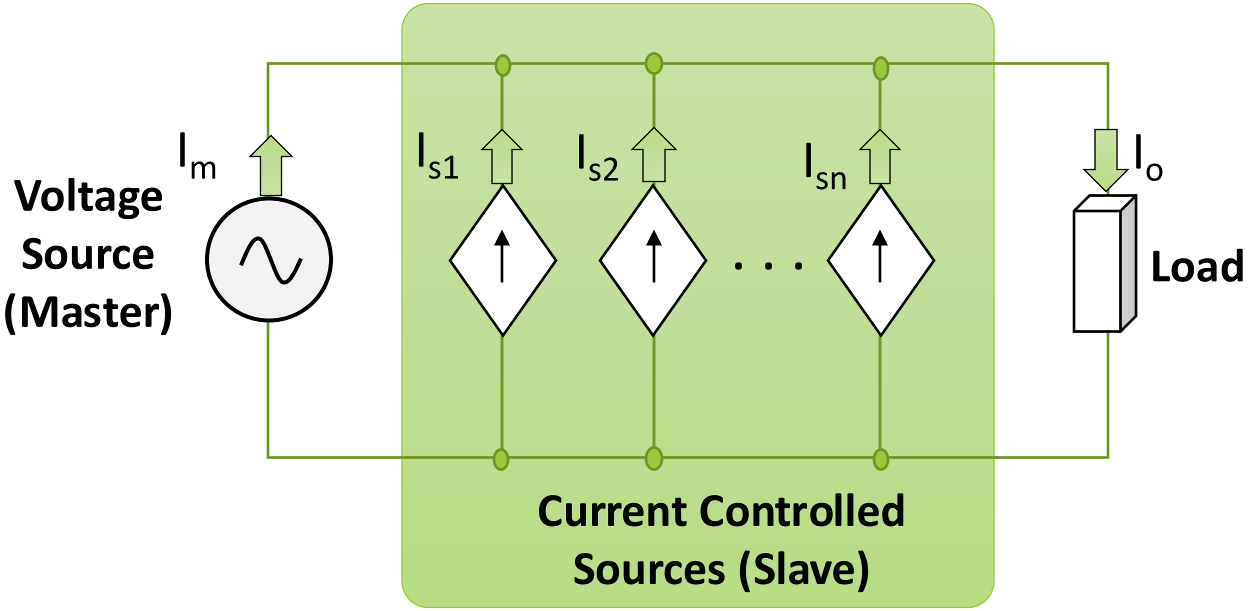
- Operation modes and transfers of the flexible microgrid and Static Transfer Switch (STS)



From grid-connected an islanded modes, it is necessary a smooth transition.
For both modes, the converters could work as voltage sources!

Microgrid operation

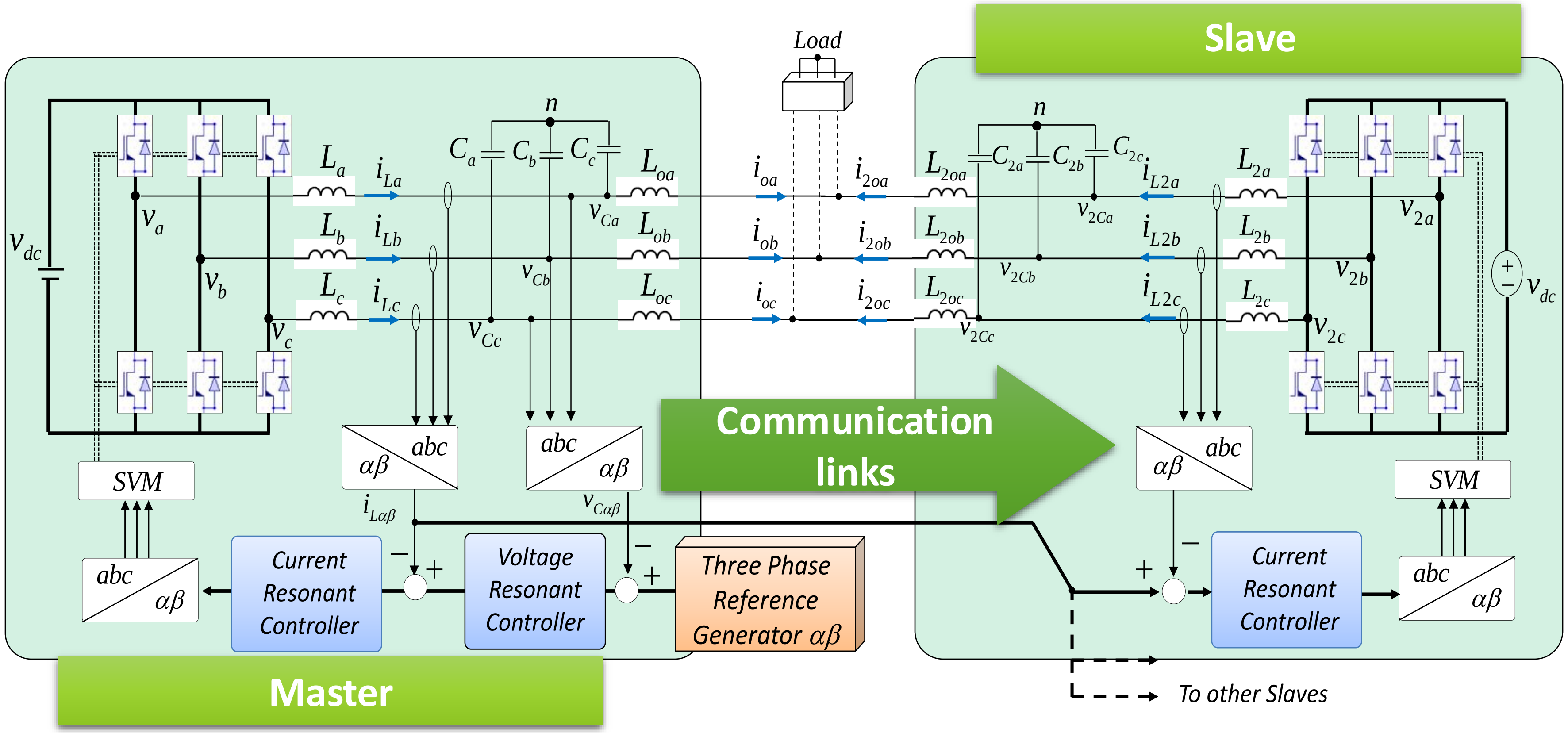
Master-slave control



Woo-Cheol Lee "A Master and Slave Control Strategy for Parallel Operation of Three-Phase UPS Systems with Different Ratings"

Microgrid operation

Master-Slave control

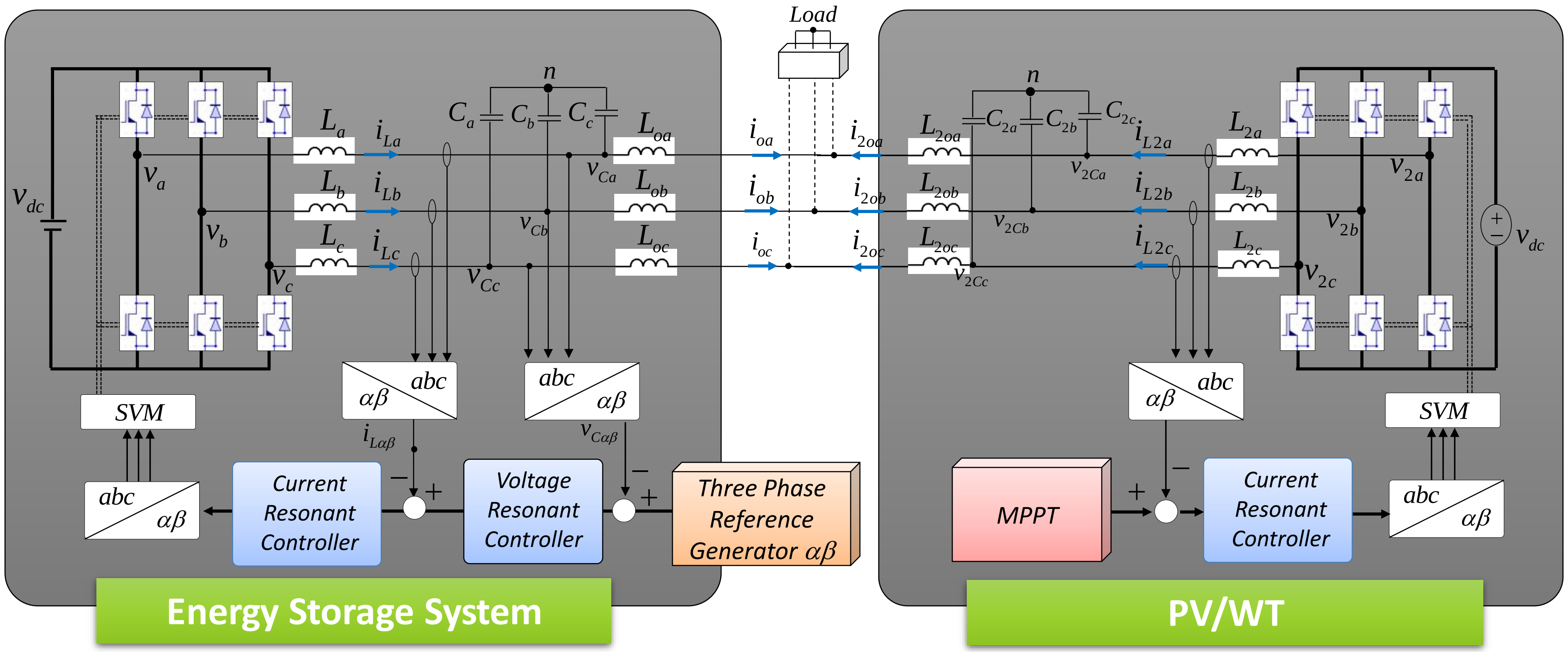


This technique ensures exact current sharing,

but needs for high-speed communications.

Microgrid operation

Master-slave control



- Voltage source: grid forming units
- Current source: MPPT units. WT and PV

Current sharing is not necessary in this system

University of Puerto Rico-Mayagüez (UPRM)

The Electrical and Computer Engineering Department

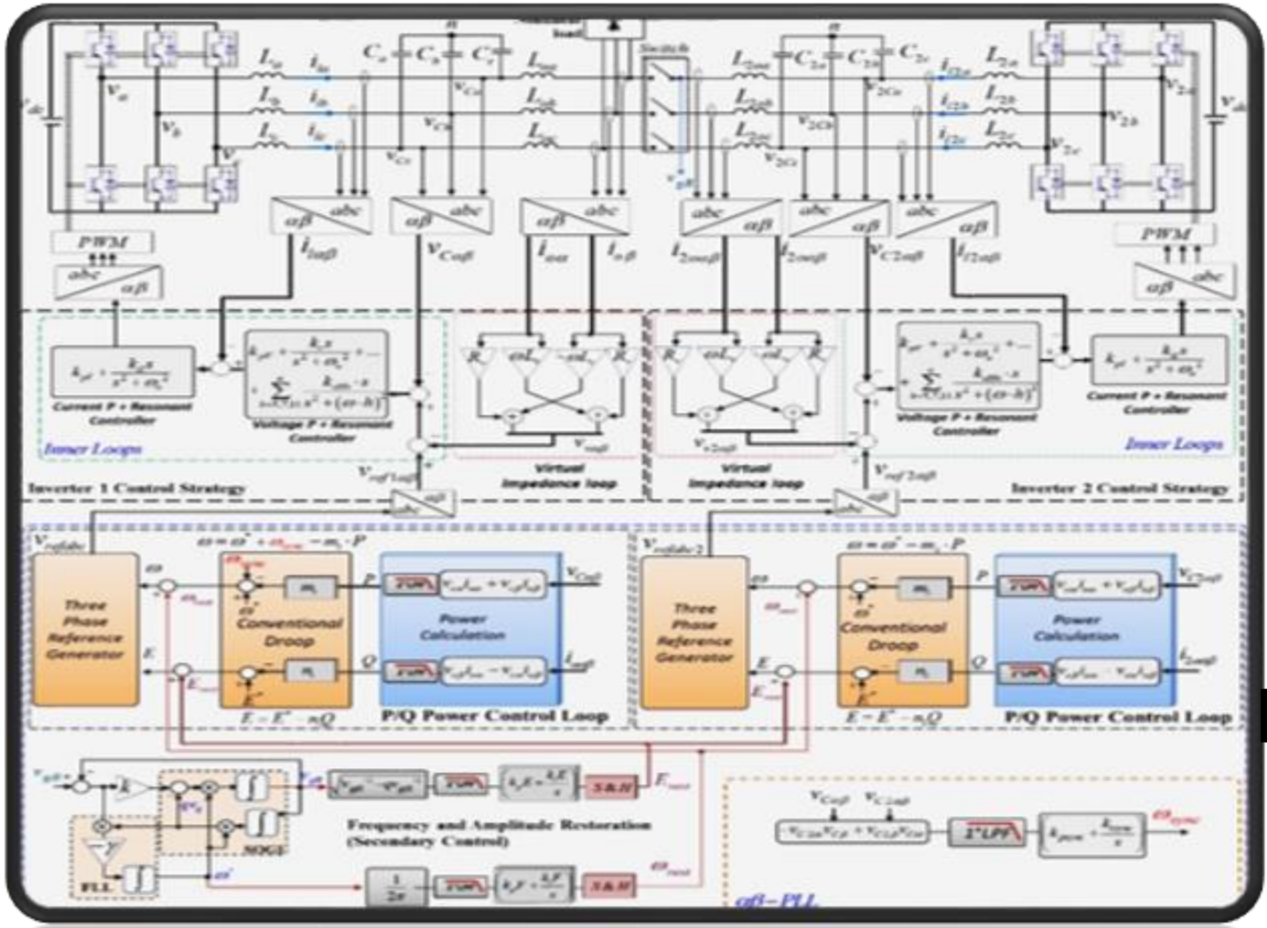
(www.ece.uprm.edu)

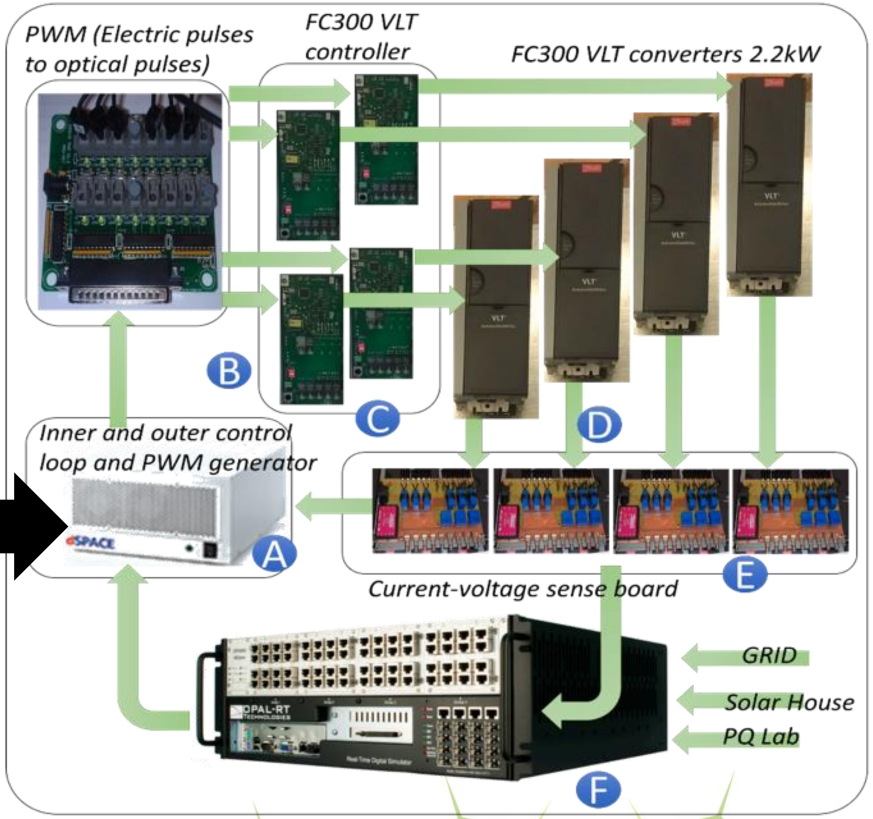
Education Activities

Research – PhD and Msc theses

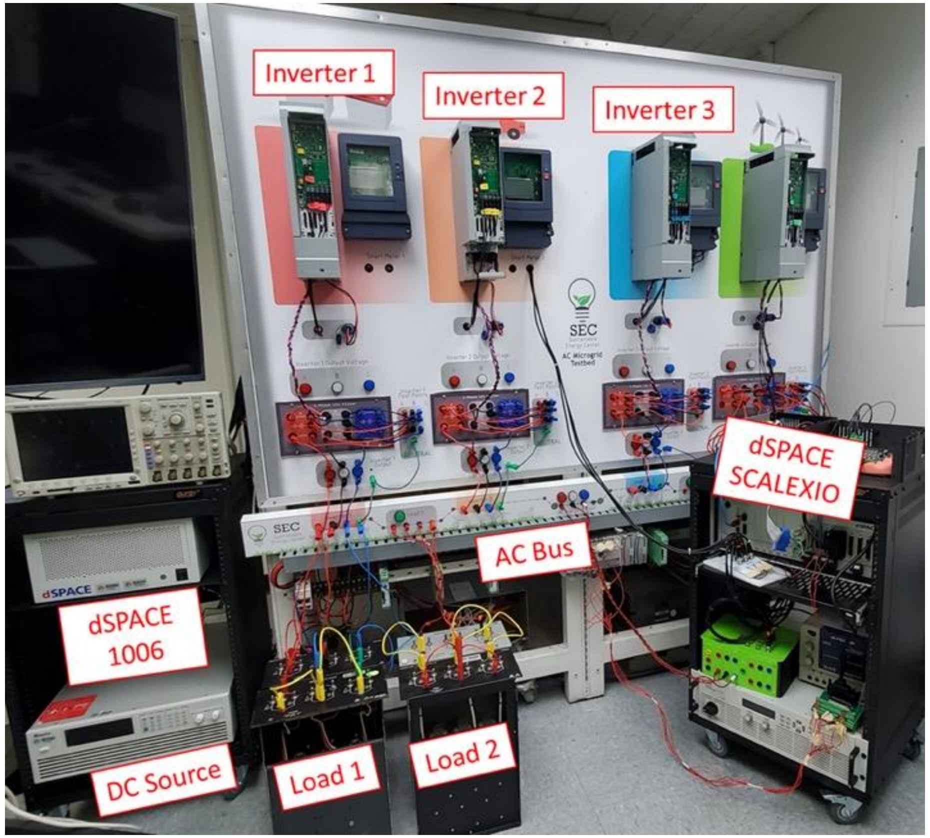
Outreach – go to Communities

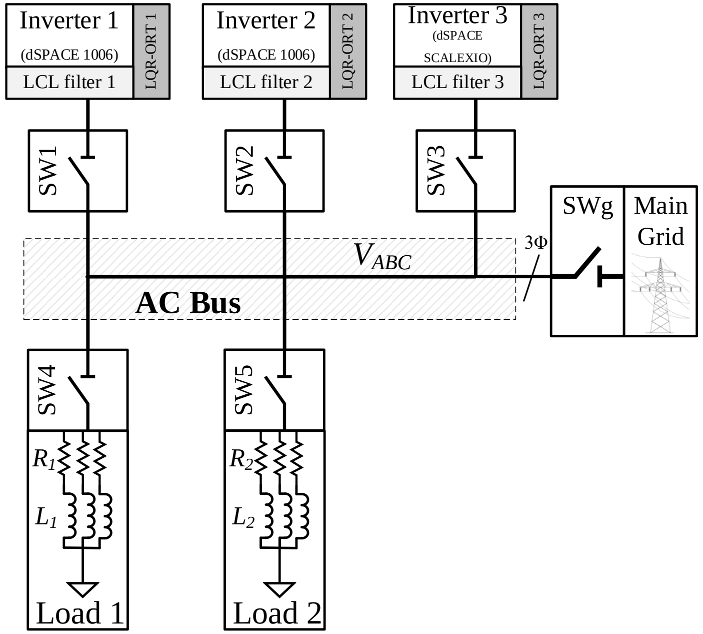
Research Activities

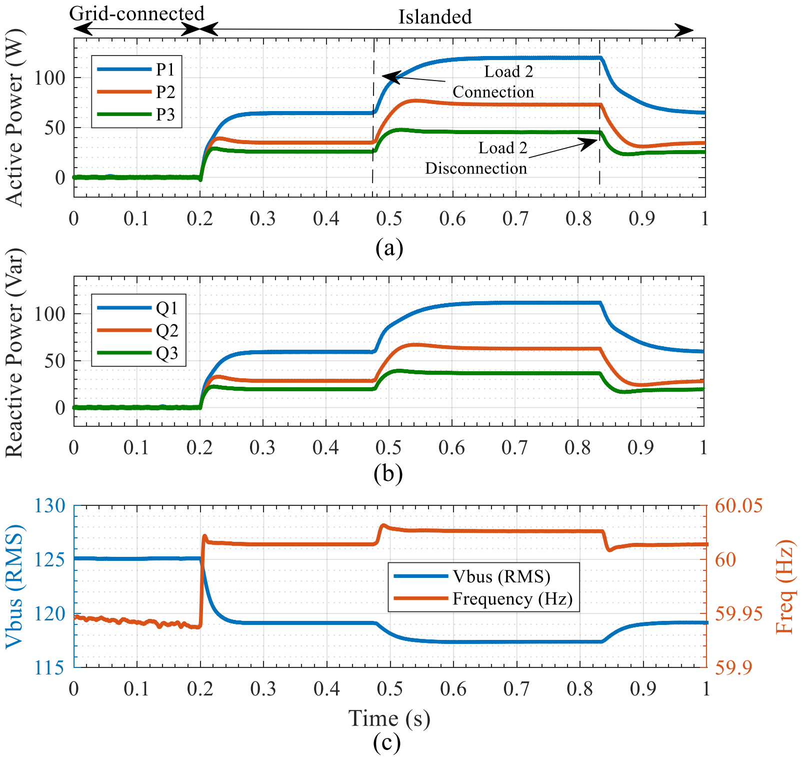




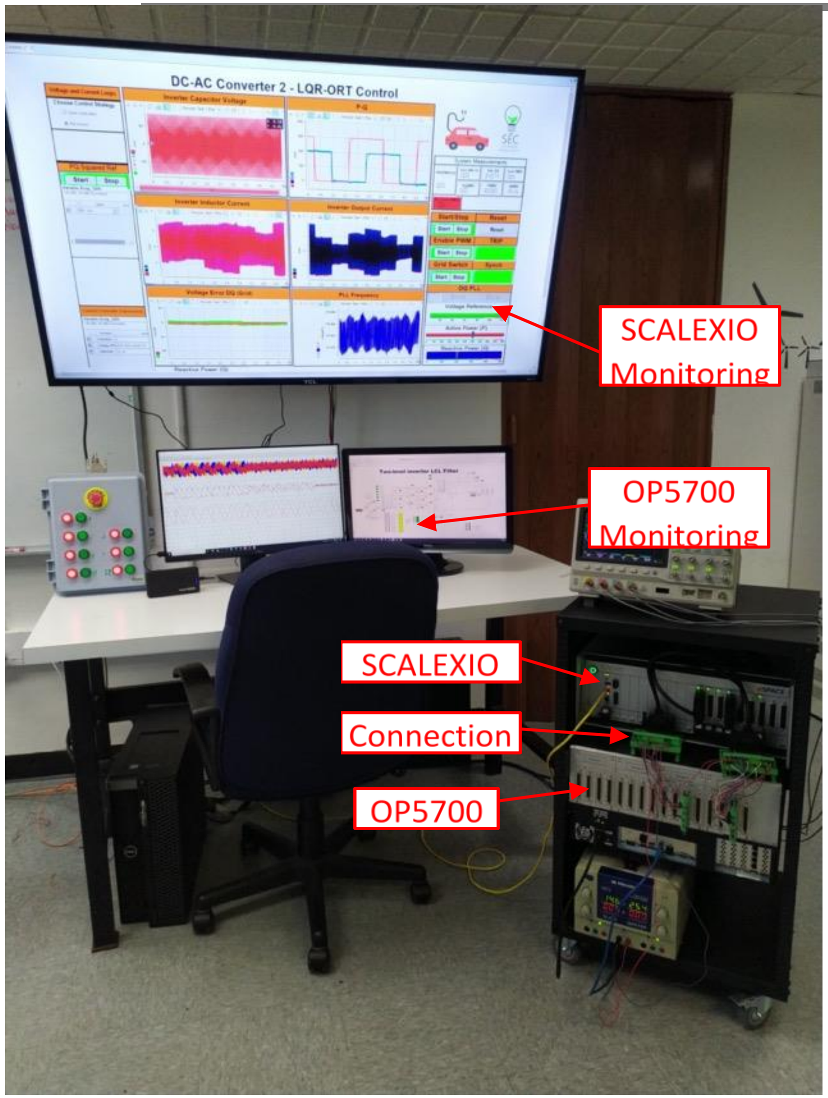
Research Activities

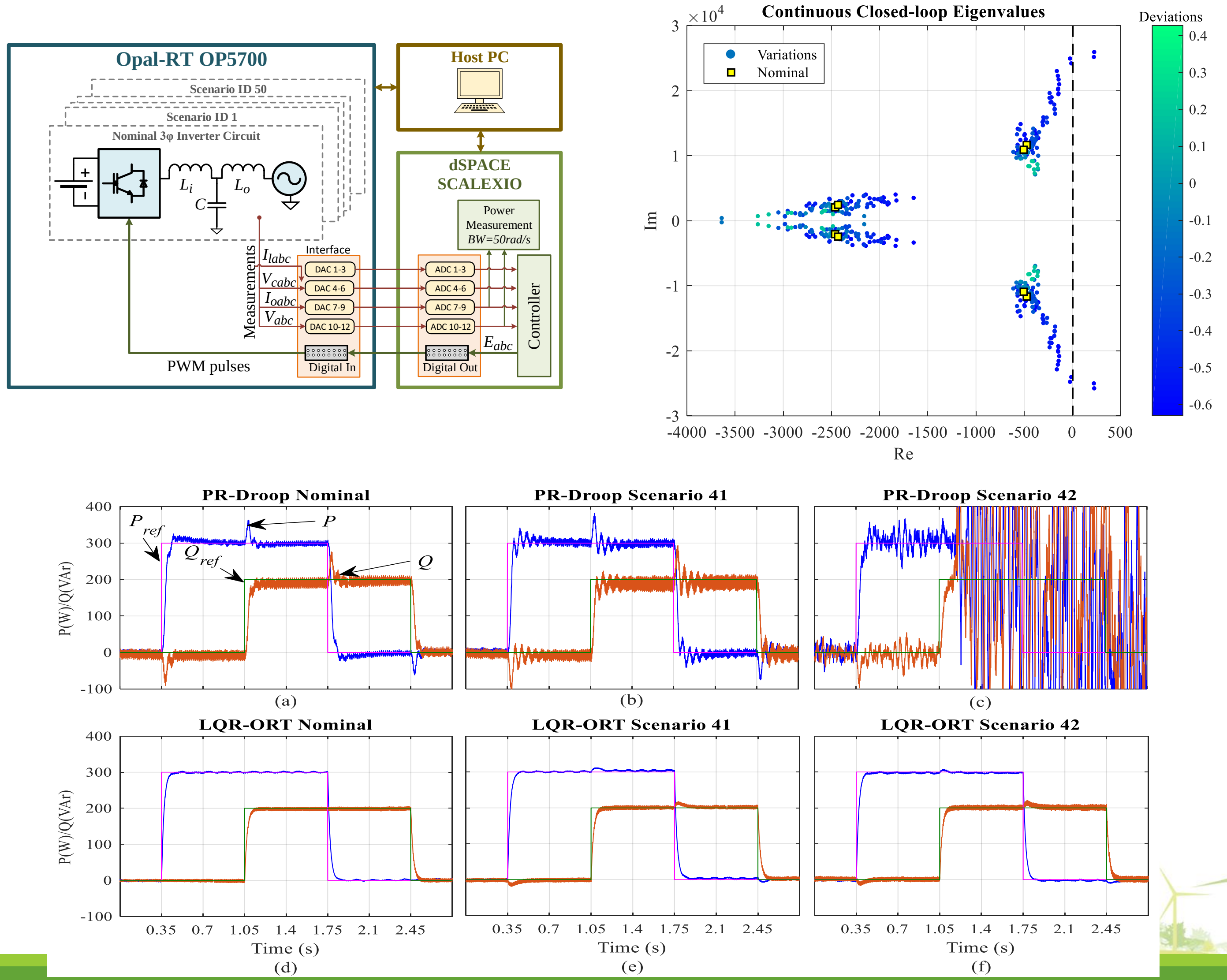






Research Activities





AN INTEGRATED POWER SHARING CONTROL METHOD FOR THREE-PHASE INVERTER-BASED GENERATORS IN ISLANDED MICROGRIDS

A dissertation submitted in partial fulfillment of the requirements for the degree of:

Doctor of Philosophy

in

Electrical Engineering

University of Puerto Rico at Mayagüez

Electrical and Computer Engineering Department

Juan Felipe Patarroyo Montenegro, Ph.D. Candidate

Advisor: Dr. Fabio Andrade Rengifo

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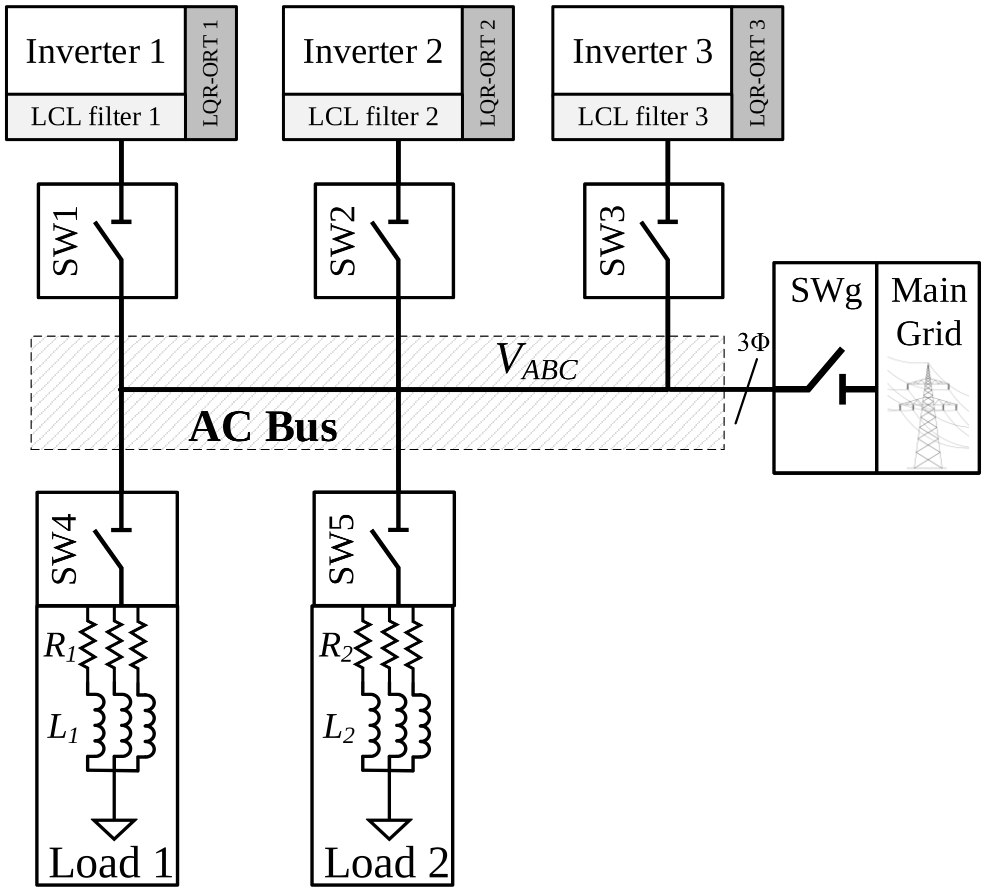
Proposed Microgrid Scenario



Microgrid Parameters

Parameter	Symbol	Value
Grid Voltage	V	$120V_{RMS}$
DC bus Voltage	V_{dc}	$350V$
Grid Frequency	$f\ (\omega_c)$	$60Hz\ (376.99\ rad/s)$
Output Inductance	L_{o1}, L_{o2}, L_{o3}	$1.8mH, 1.8mH, 3.6mH$
Input Inductance	L_{i1}, L_{i2}, L_{i3}	$1.8mH, 5.4mH, 3.6mH$
Filter Capacitance	C_1, C_2, C_3	$8.8\mu F$
PWM Frequency	f_{PWM}	$10kHz$
Sampling Period	T_s	$100\mu s$
Load 1	R_1, L_1	$85.7\Omega, 0.46H$
Load 2	R_2, L_2	$171.43\Omega, 0.53H$

Microgrid Models

$$\begin{bmatrix}\dot{V}_{cd}\\ \dot{V}_{cq}\\ \dot{I}_{ld}\\ \dot{I}_{lq}\\ \dot{I}_{od}\\ \dot{I}_{oq}\end{bmatrix} = \begin{bmatrix} 0 & \omega_c & 1/C & 0 & -1/C & 0\\ -\omega_c & 0 & 0 & 1/C & 0 & -1/C\\ -1/L_i & 0 & 0 & \omega_c & 0 & 0\\ 0 & -1/L_i & -\omega_c & 0 & 0 & 0\\ 1/L_o & 0 & 0 & 0 & 0 & \omega_c\\ 0 & 1/L_o & 0 & 0 & -\omega_c & 0\end{bmatrix}\begin{bmatrix}V_{cd}\\ V_{cq}\\ I_{ld}\\ I_{lq}\\ I_{od}\\ I_{oq}\end{bmatrix} + \begin{bmatrix}0 & 0\\ 0 & 0\\ 1/L_i & 0\\ 0 & 1/L_i\\ 0 & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}E_d\\ E_q\end{bmatrix} + \begin{bmatrix}0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ -1/L_o & 0\\ 0 & -1/L_o\end{bmatrix}\begin{bmatrix}V_d\\ V_q\end{bmatrix}$$

Grid-connected

$$\begin{bmatrix}\dot{V}_{c1}\\ \dot{I}_{l1}\\ \dot{I}_{o1}\\ \dot{V}_{c2}\\ \dot{I}_{l2}\\ \dot{I}_{o2}\\ \dot{V}_{c3}\\ \dot{I}_{l3}\\ \dot{I}_{o3}\end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C_1} & -\frac{1}{C_1} & 0 & 0 & 0 & 0 & 0 & 0\\ -\frac{1}{L_{i1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ \frac{L_{d1}}{L_t} & 0 & -\frac{RL_{o2}L_{o3}}{L_t} & -\frac{LL_{o3}}{L_t} & 0 & -\frac{RL_{o2}L_{o3}}{L_t} & -\frac{LL_{o2}}{L_t} & 0 & -\frac{RL_{o2}L_{o3}}{L_t}\\ 0 & 0 & 0 & 0 & \frac{1}{C_2} & -\frac{1}{C_2} & 0 & 0 & 0\\ 0 & 0 & 0 & -\frac{1}{L_{i2}} & 0 & 0 & 0 & 0 & 0\\ -\frac{LL_{o3}}{Lt} & 0 & -\frac{RL_{o1}L_{o3}}{L_t} & \frac{L_{d2}}{L_t} & 0 & -\frac{RL_{o1}L_{o3}}{L_t} & -\frac{LL_{o1}}{L_t} & 0 & -\frac{RL_{o1}L_{o3}}{L_t}\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_3} & -\frac{1}{C_3}\\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_{i3}} & 0 & 0\\ -\frac{LL_{o2}}{L_t} & 0 & -\frac{RL_{o1}L_{o2}}{L_t} & -\frac{LL_{o1}}{L_t} & 0 & -\frac{RL_{o1}L_{o2}}{L_t} & \frac{L_{d3}}{L_t} & 0 & -\frac{RL_{o1}L_{o2}}{L_t}\end{bmatrix}\begin{bmatrix}V_{c1}\\ I_{l1}\\ I_{o1}\\ V_{c2}\\ I_{l2}\\ I_{o2}\\ V_{c3}\\ I_{l3}\\ I_{o3}\end{bmatrix} + \begin{bmatrix}0 & 0 & 0\\ \frac{1}{L_{i1}} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\\ 0 & \frac{1}{L_{i2}} & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & \frac{1}{L_{i3}}\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}E_1\\ E_2\\ E_3\end{bmatrix}$$

Islanded

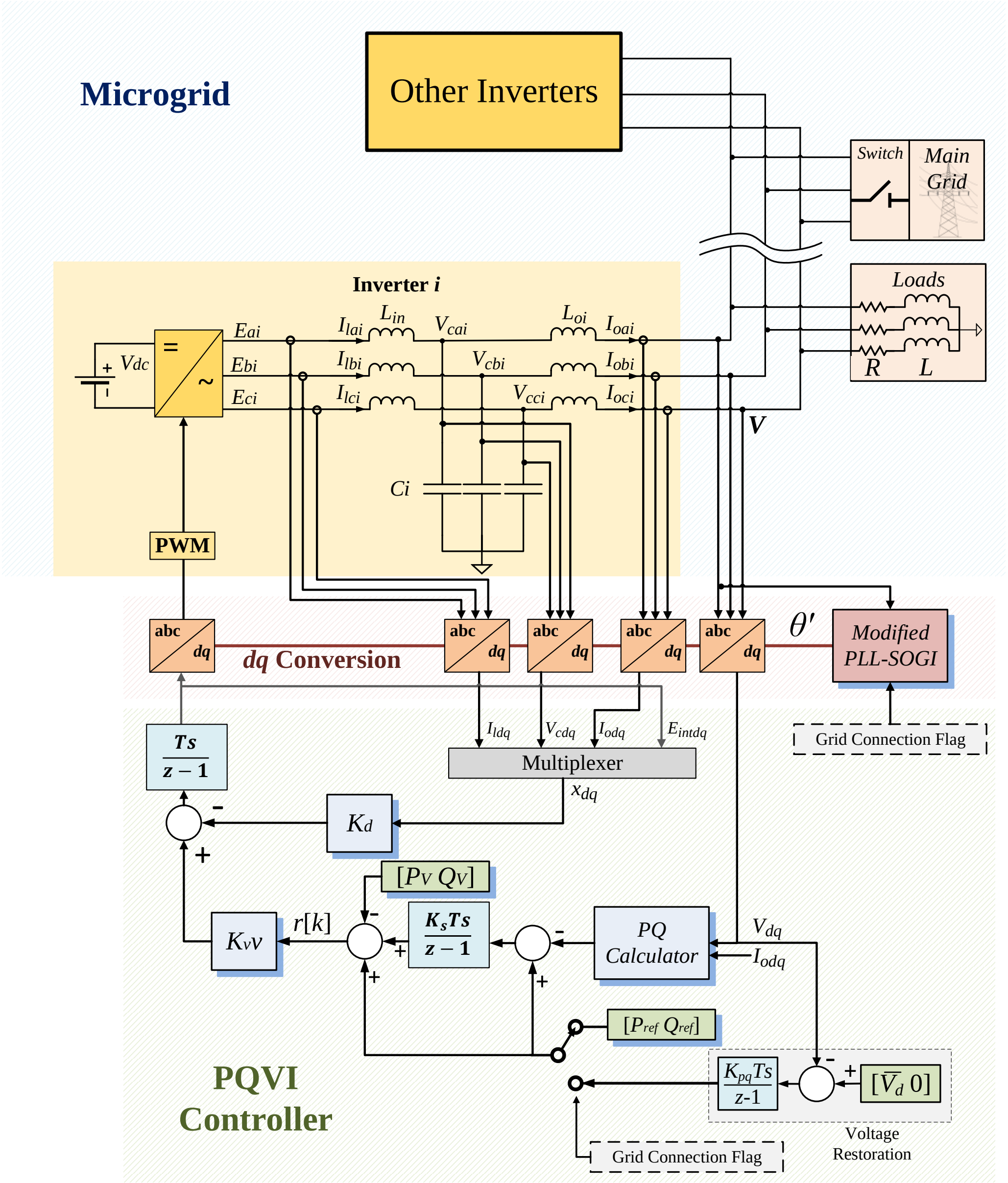
where:

$$L_t = L(L_{o1}L_{o2} + L_{o1}L_{o3} + L_{o2}L_{o3} + L_{o1}L_{o2}L_{o3})$$

$$L_{d1} = LL_{o2} + L_{o2}L_{o3} + LL_{o3}$$

$$L_{d2} = LL_{o1} + L_{o1}L_{o3} + LL_{o3}$$

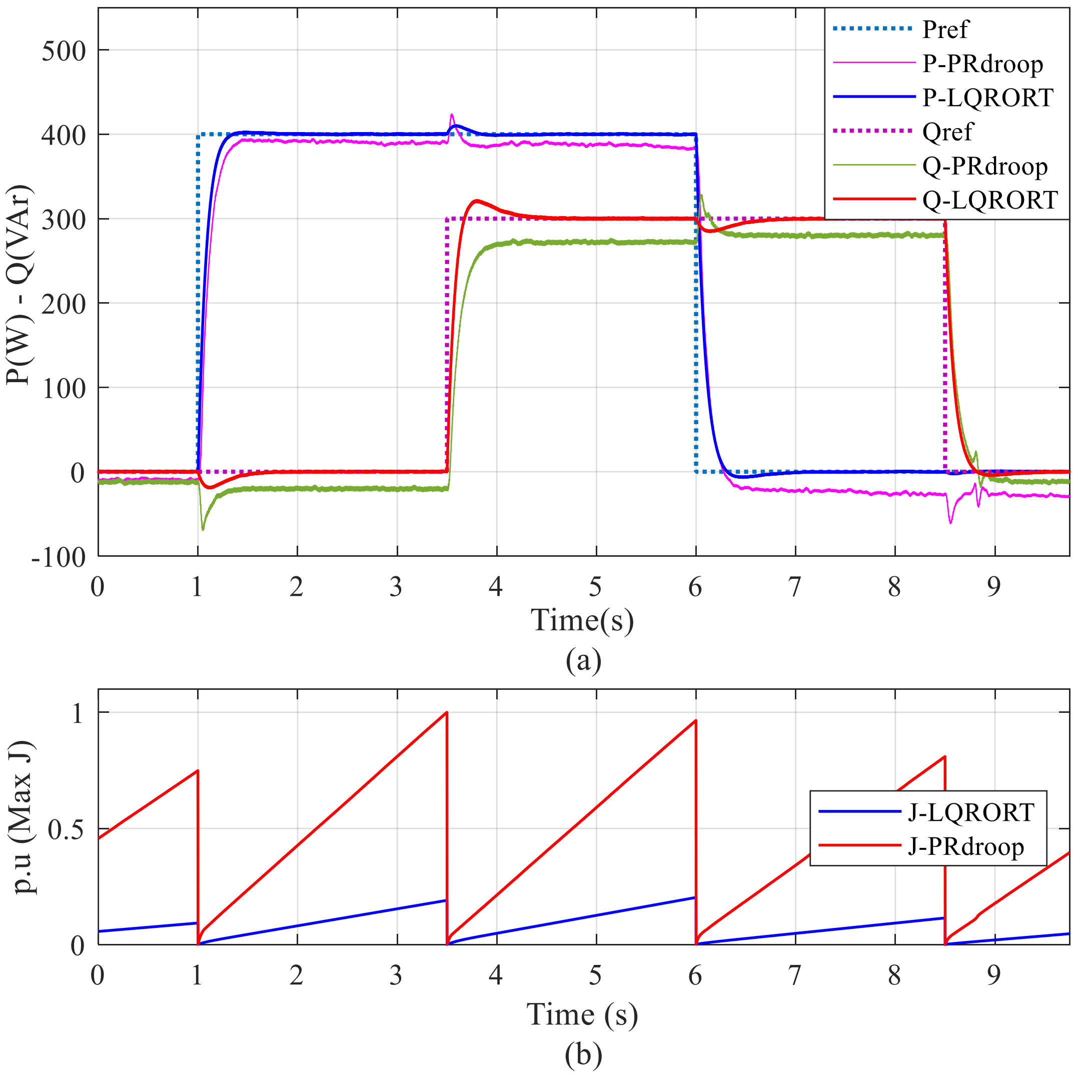
$$L_{d3} = LL_{o1} + L_{o1}L_{o2} + LL_{o2}$$

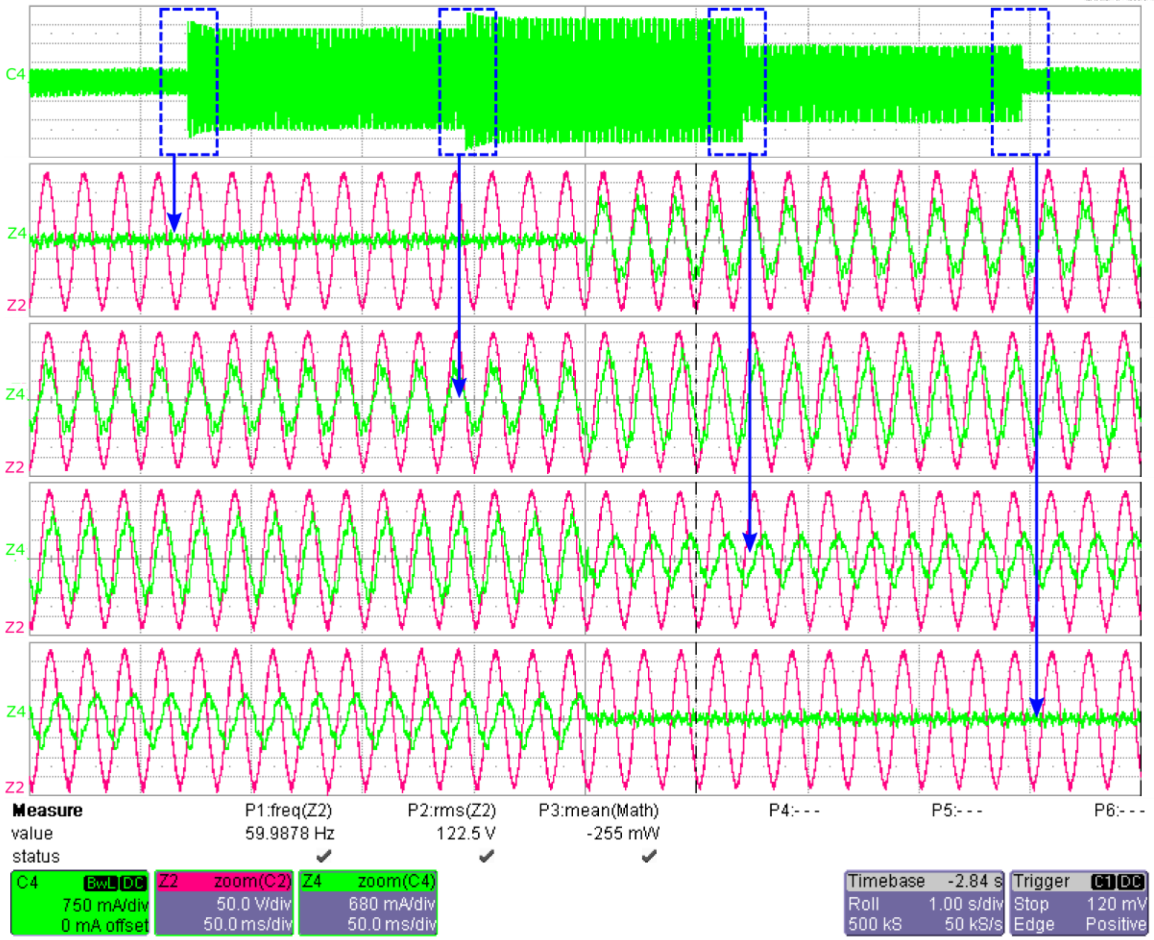


Control Parameters

Parameter	Symbol	Value
Error Weighting Matrix	Q_{p1}, Q_{p2}, Q_{p3}	$\{5, 4.9, 4.8\} \times 10^3 \times I_{2\times2}$
Input Weighting Matrix	R_{p1}, R_{p2}, R_{p3}	$\{0.2, 0.15, 0.18\} \times I_{2\times2}$
Inner Integrator Gain	K_{i1}, K_{i2}, K_{i3}	1
Outer Integrator Gain	K_{s1}, K_{s2}, K_{s3}	5
SOGI gain	K_{SG}	0.7
PLL Proportional Gain	K_{pP}	0.28307
PLL Integral Gain	K_{iP}	7.5102
Frequency Restoration Gain	K_f	100
Power Rating	S_1, S_2, S_3	$500, 1000, 1500\, VA$
Voltage Restoration Gain (Active)	K_{p1}, K_{p2}, K_{p3}	1000, 2000, 3000
Voltage Restoration Gain (Reactive)	K_{q1}, K_{q2}, K_{q3}	−1000, −2000, −3000

Grid-connected Mode Experimental Results





CONTRIBUTION TO THE POWER-SHARING CONTROL STRATEGIES FOR MICROGRIDS

A dissertation submitted in partial fulfillment of the requirements for the degree of:
Doctor of Philosophy
in
Electrical Engineering

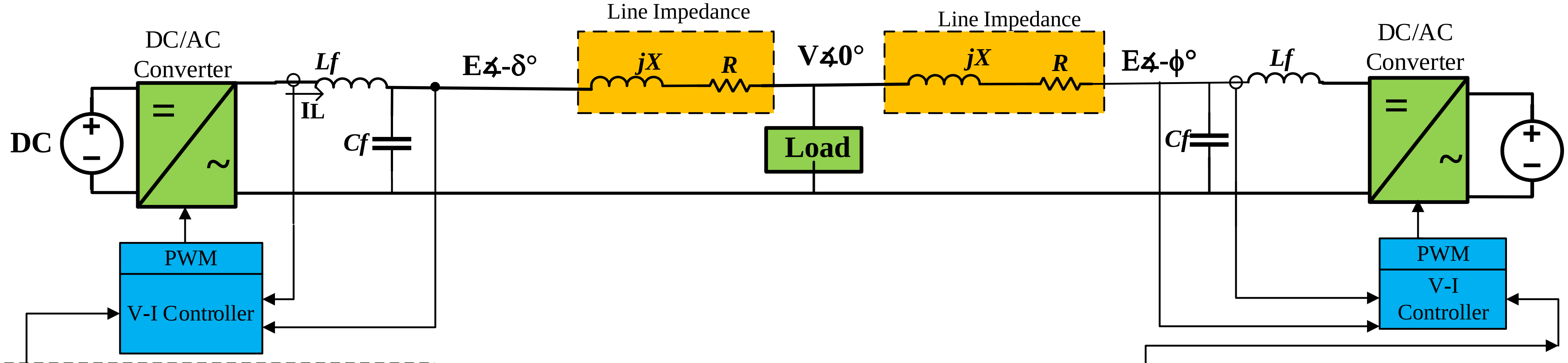
University of Puerto Rico at Mayagüez

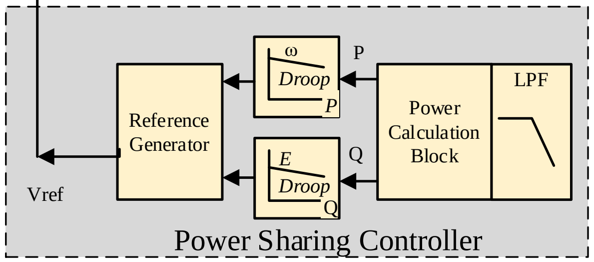
Electrical and Computer Engineering Department

Daniel Darío Campo Ossa, Ph.D. Candidate

Advisor: Ph.D. Fabio Andrade Rengifo

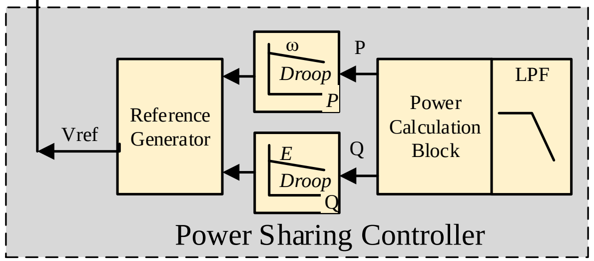
Problem Statement





$$P = \left(\frac{1}{(R^2 + X^2)}\right)(RE^2 - REV\cos\delta + XEV\sin\delta)$$

$$Q = \left(\frac{1}{(R^2 + X^2)}\right)(XE^2 - XEV\cos\delta - REV\sin\delta)$$



$$\omega = \omega_0 - m(P - P_0)$$
$$E = E_0 - n(Q - Q_0)$$

$$\omega = \omega_0 - m(P - P_0)$$
$$E = E_0 - n(Q - Q_0)$$

Proposed Controllers for Power-Sharing (Rotated Droop)

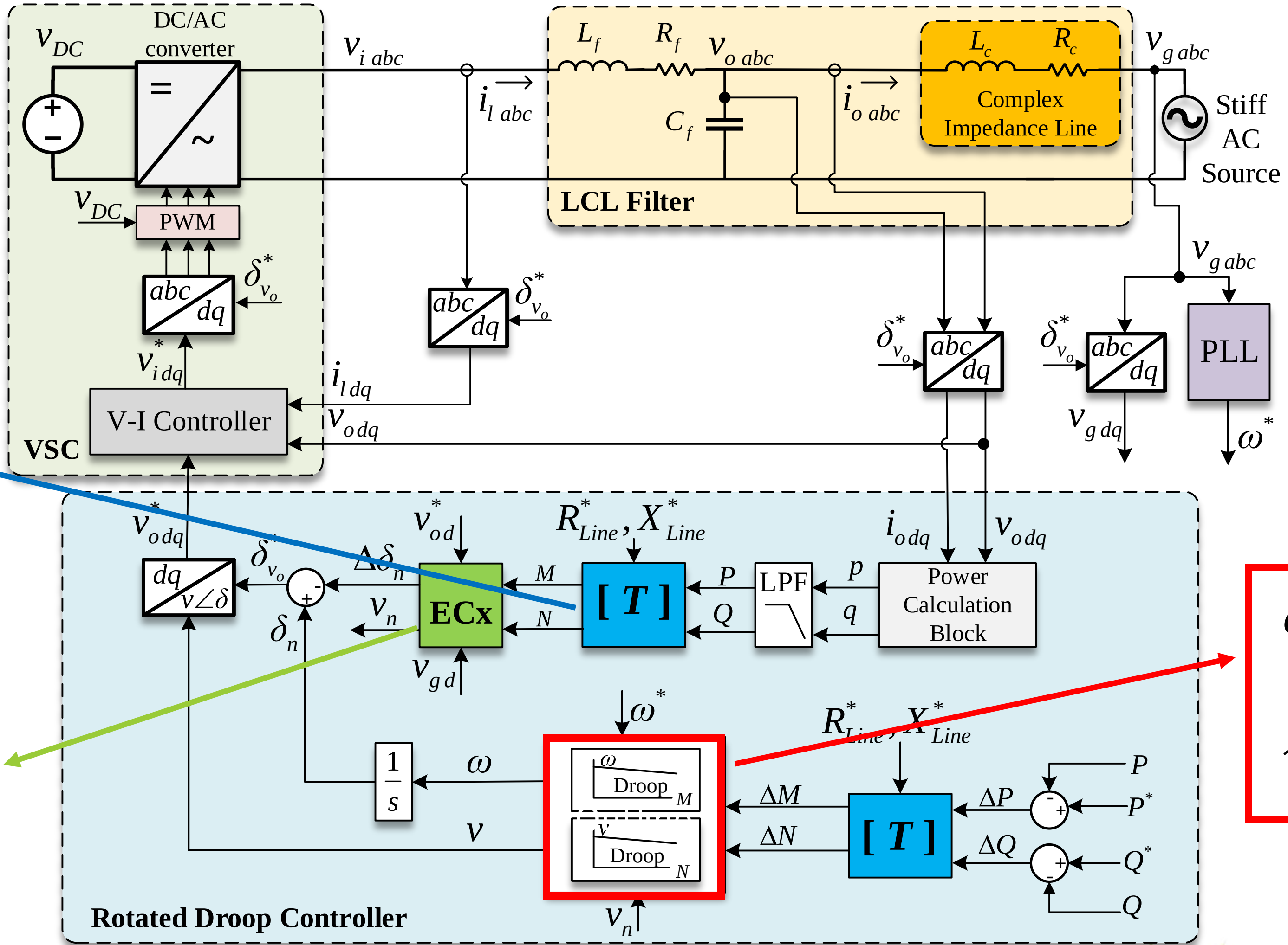
$$\begin{bmatrix} M \\ N \end{bmatrix} = \begin{bmatrix} X & -R \\ R & X \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix}$$

$$\begin{bmatrix} M \\ N \end{bmatrix} = [\mathrm{T}] \begin{bmatrix} P \\ Q \end{bmatrix}$$

ECx

$$\Delta\delta = \frac{M}{v_{od}^{*} v_{gd}}$$

$$v_n = \frac{v_{gd} + \sqrt[2]{\left(v_{gd}^2 + 4N\right)}}{2}$$



$$\omega - \omega^{*} = -k_m \Delta M$$

$$v - v_n = -k_n \Delta N$$

Proposed Controllers for Power-Sharing (Rotated VSG)

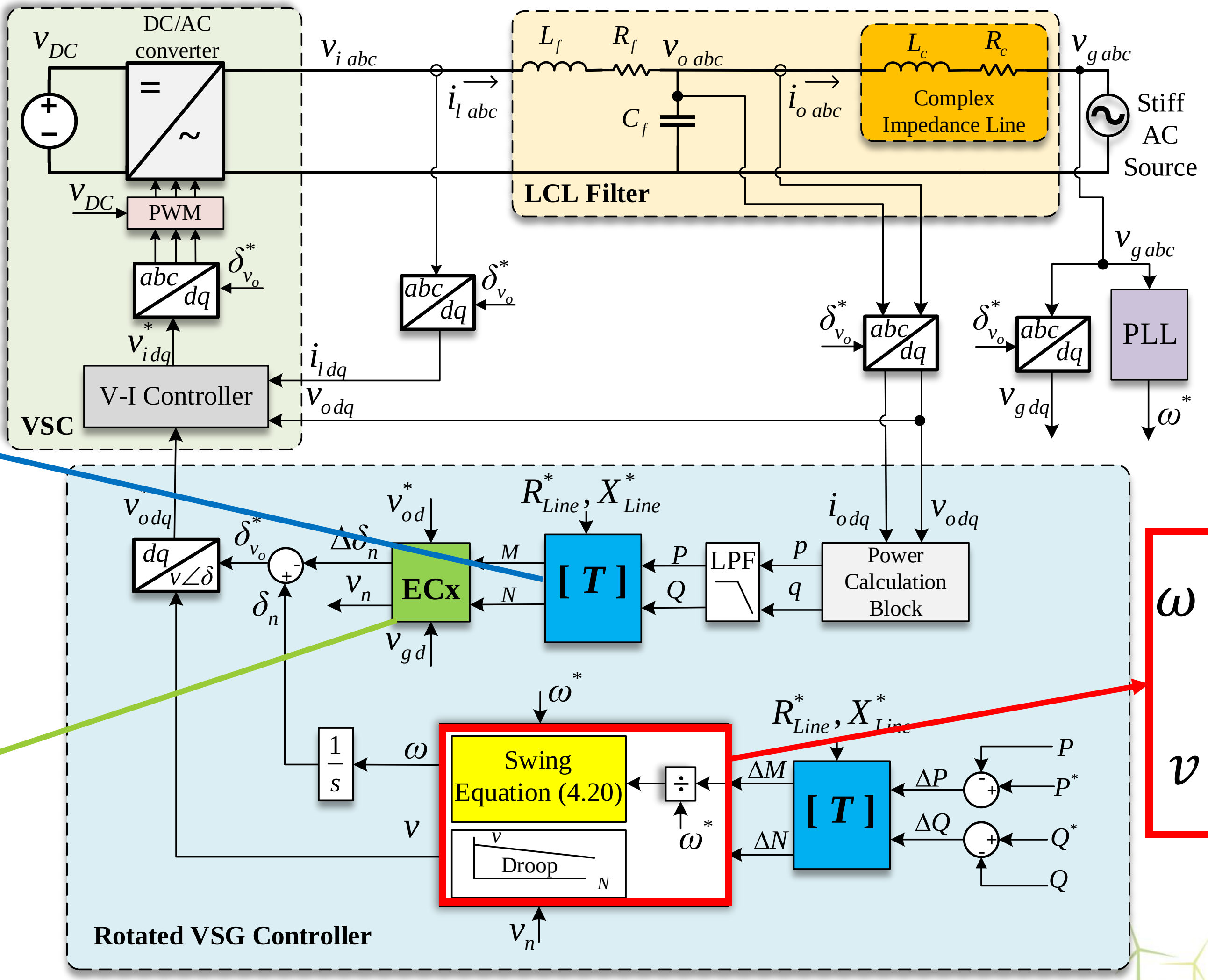
$$\begin{bmatrix} M \\ N \end{bmatrix} = \begin{bmatrix} X & -R \\ R & X \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix}$$

$$\begin{bmatrix} M \\ N \end{bmatrix} = [\mathrm{T}] \begin{bmatrix} P \\ Q \end{bmatrix}$$

ECx

$$\Delta\delta = \frac{M}{v_{od}^{*} v_{gd}}$$

$$v_n = \frac{v_{gd} + \sqrt[2]{\left(v_{gd}^2 + 4N\right)}}{2}$$



$$\omega - \omega^* = \left(\frac{1}{2\mathrm{H}s + \mathrm{K}_D}\right)\left(\frac{\Delta M}{\omega^*}\right)$$

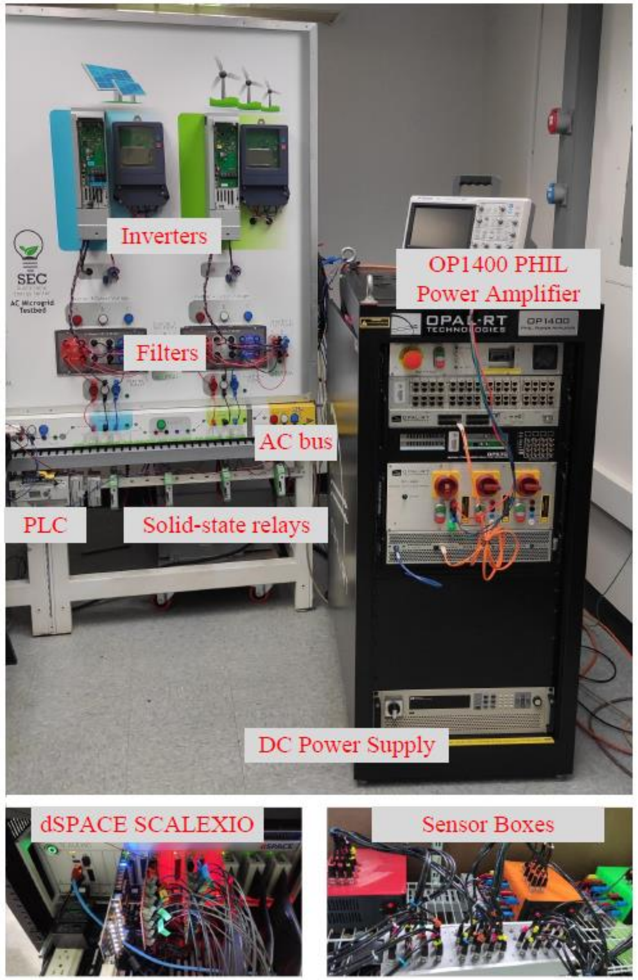
$$v - v_n = -k_n \Delta N$$

Experimental Results (Testbed)

System Parameters:

Parameter	Symbol	Value
Fundamental frequency	ω	376.99 rad/s
Cut-off frequency of measuring filter	ω_f	18.85 rad/s
Grid voltage (Stiff AC)	(V)	120 V_{RMS}
Inverter output voltage	(V_{od})	120.63 V_{RMS}
Filter Capacitance	C_f	8.8 μF
Filter Inductance	L_f	1.8 mH
Series Resistance of the filter inductor	R_f	0.18 Ω
Inductance of the line	L_c	0.0001H to 0.002H
Resistance of the line	R_c	0.2 Ω to 2.2 Ω
Frequency droop	K_m	0.001
Amplitude droop	K_n	0.02 to 0.04

Experimental testbed.

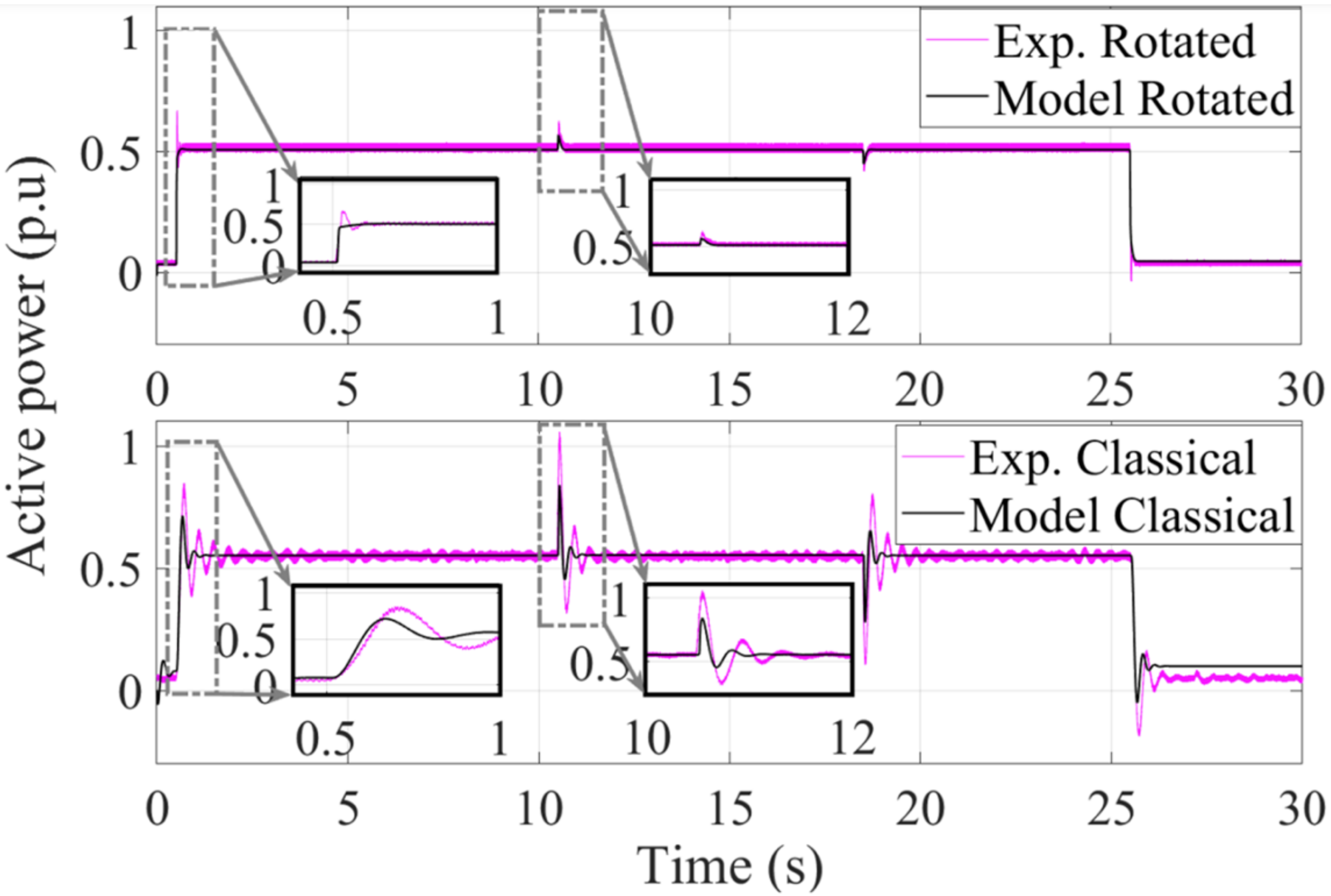


Experimental Results (Droop)

Both controllers used the same **Active power** step in the experimental testbed.

Active Power step = 500W

Parameter	Symbol	Value
Inductance of the line	L_c	0.0018H
Resistance of the line	R_c	2.2 Ω
Switching Frequency	f_s	10kHz
DC bus voltage	DC	400 V
Voltage Loop	k_{pV}, k_{rV}	0.35, 400
Current Loop	k_{pi}, k_{ri}	0.7, 100

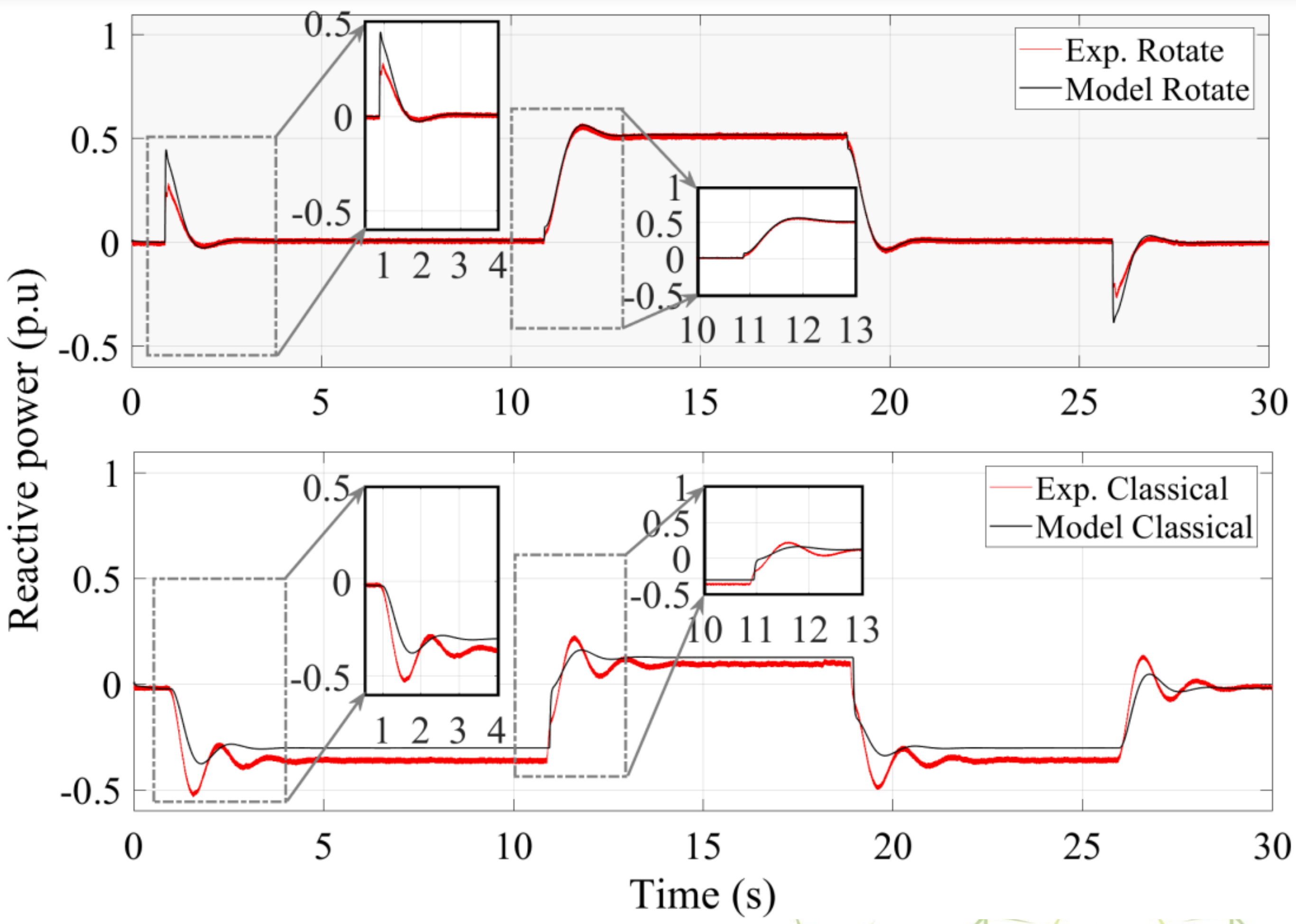


Experimental Results (VSG)

Both controllers used the same **Reactive power** step in the experimental testbed.

Ractive Power step = 200W

Parameter	Symbol	Value
Inductance of the line	L_c	0.0018H
Resistance of the line	R_c	2.2 Ω
Switching Frequency	f_s	10kHz
DC bus voltage	DC	400 V
Virtual inertia constant	H	1.42s
Damping coefficient	K_D	14.53
Voltage Loop	k_{pV}, k_{rV}	0.35, 400
Current Loop	k_{pi}, k_{ri}	0.7, 100



AGGREGATED INVERTER-BASED GENERATOR MODEL PARAMETERIZATION VIA ONLINE MOVING HORIZON ESTIMATION USING A DER_A SMOOTH MATHEMATICAL REPRESENTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of:

Doctor of Philosophy

in

Electrical Engineering

Jesus David Vasquez Plaza

Ph.D. Candidate

University of Puerto Rico at Mayagüez

Electrical and Computer Engineering Department

Advisor: Ph.D. Fabio Andrade Rengifo

Introduction: Parameterization IBGs Models

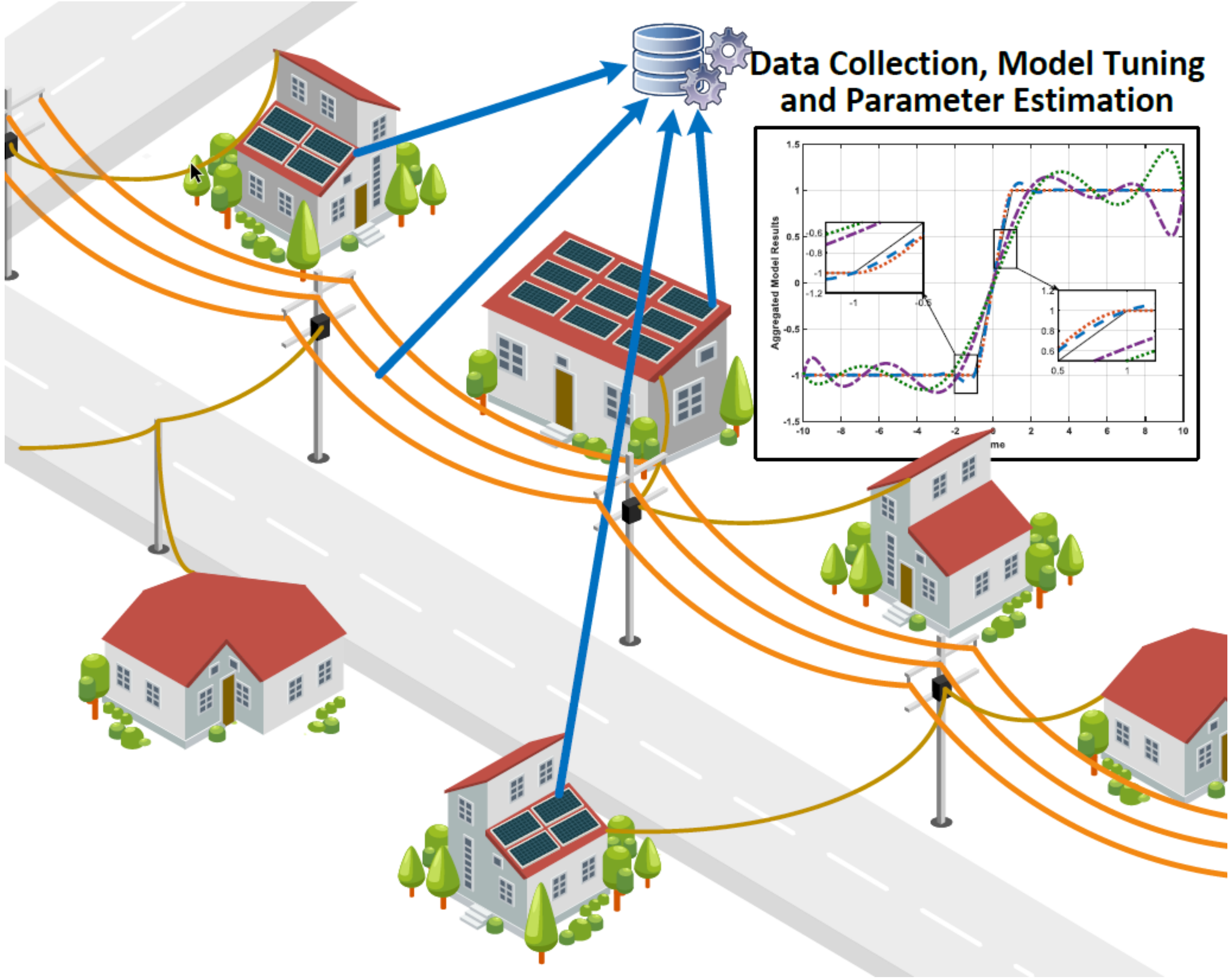


Figure 4: IBGs aggregated modeling illustration

- Aggregated models such as PVD1, DER_A, repc, among others, have been proposed to represent the dynamics of hundreds of IBGs.
- Identification of parameter values in aggregated models is a crucial and meticulous process, as they consist of several parameters whose estimation requires rigor in order to provide an accurate mathematical model.

Aggregated Distributed Energy Resources (DER_A) Model

10 States
48 Parameters

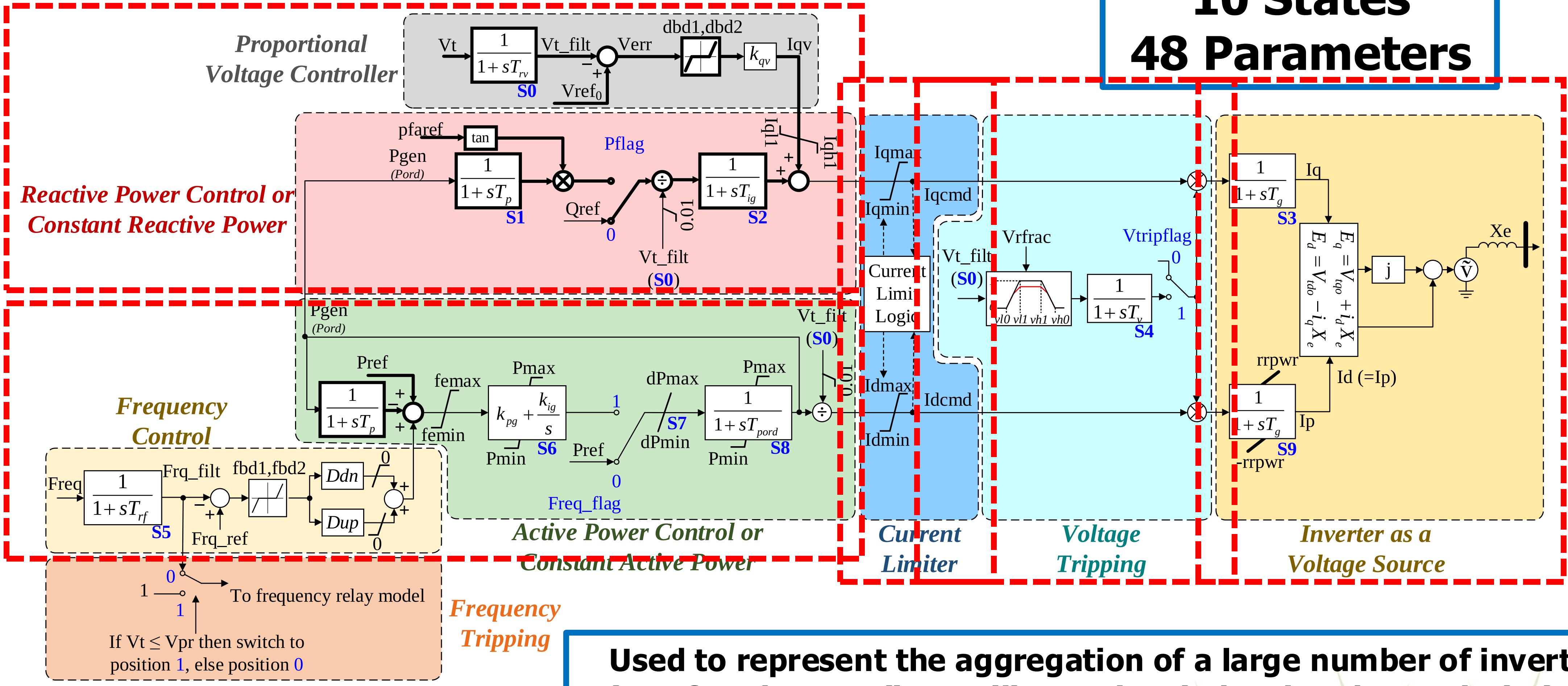
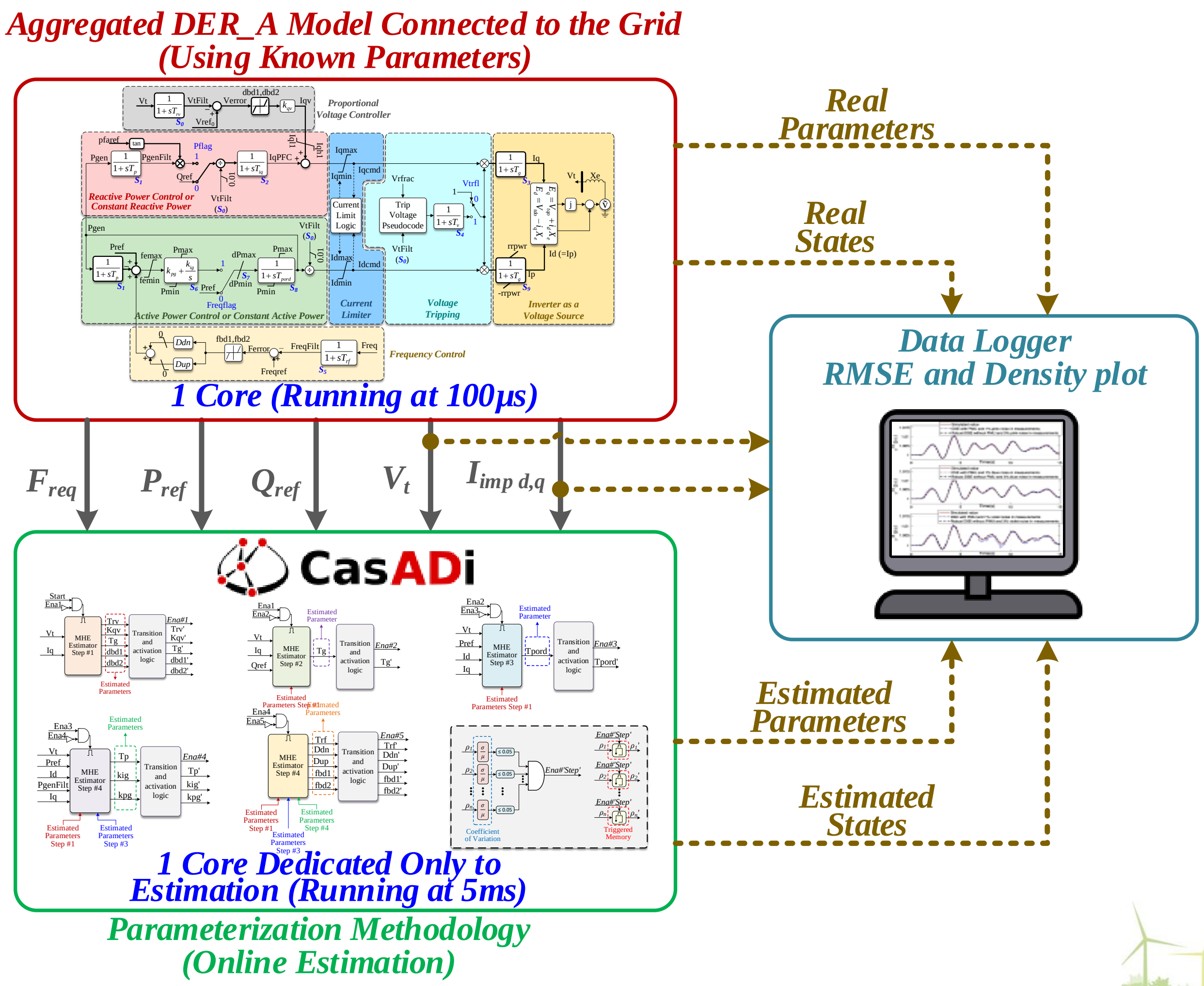


Figure 12: Overall structure for aggregated distributed energy resources (DER_A) model – EPRI [20]

Used to represent the aggregation of a large number of inverter-interfaced DERs. (i.e., utility-scale wind, solar photovoltaic (PV), and battery energy storage resources).

Results and Analysis - Parameterization Methodology Validation

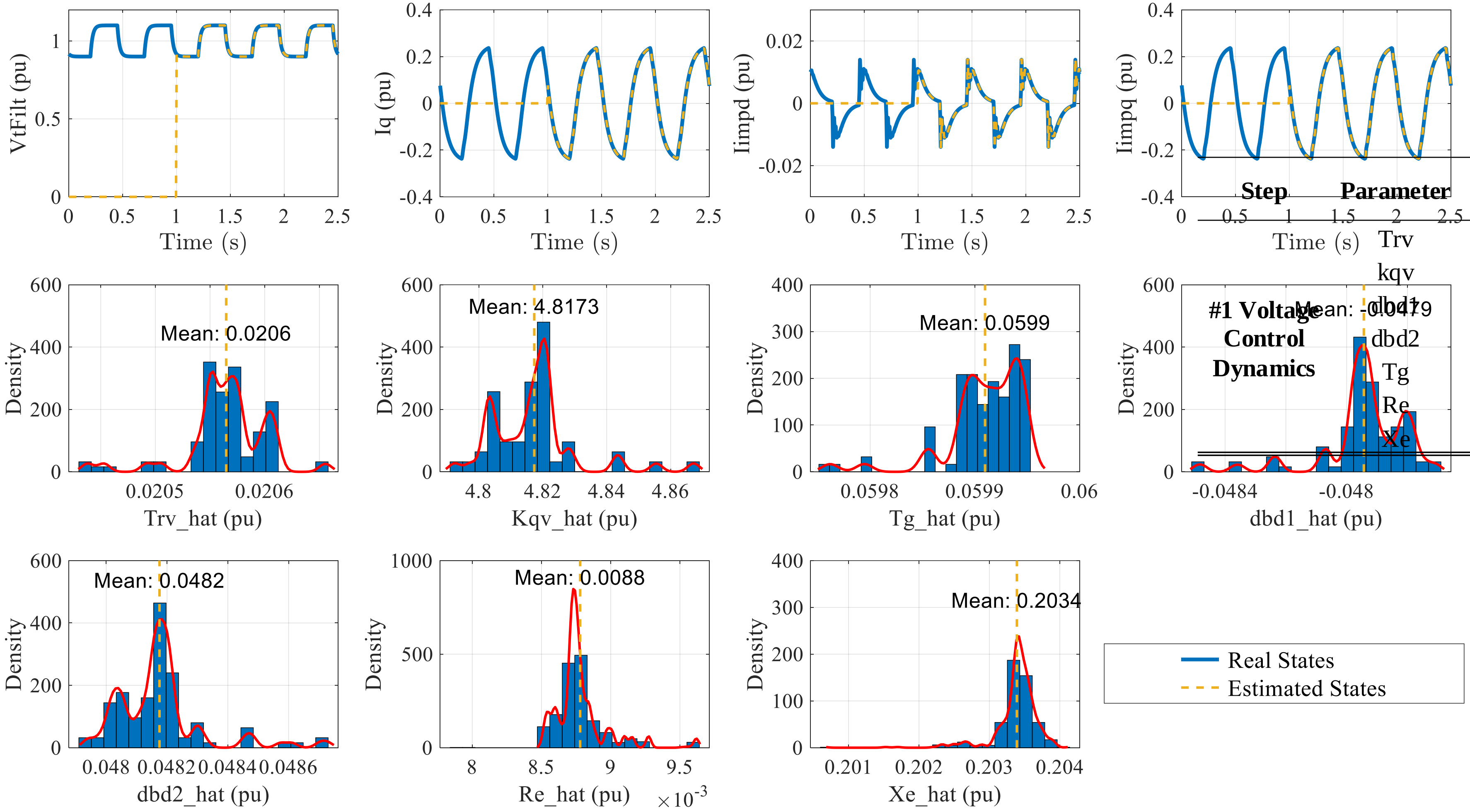
Proposed Methodology Validation Using Known Parameters



Results and Analysis - Parameterization Methodology Validation

Step # 1 – Voltage Control Dynamics (Using Known Parameters)

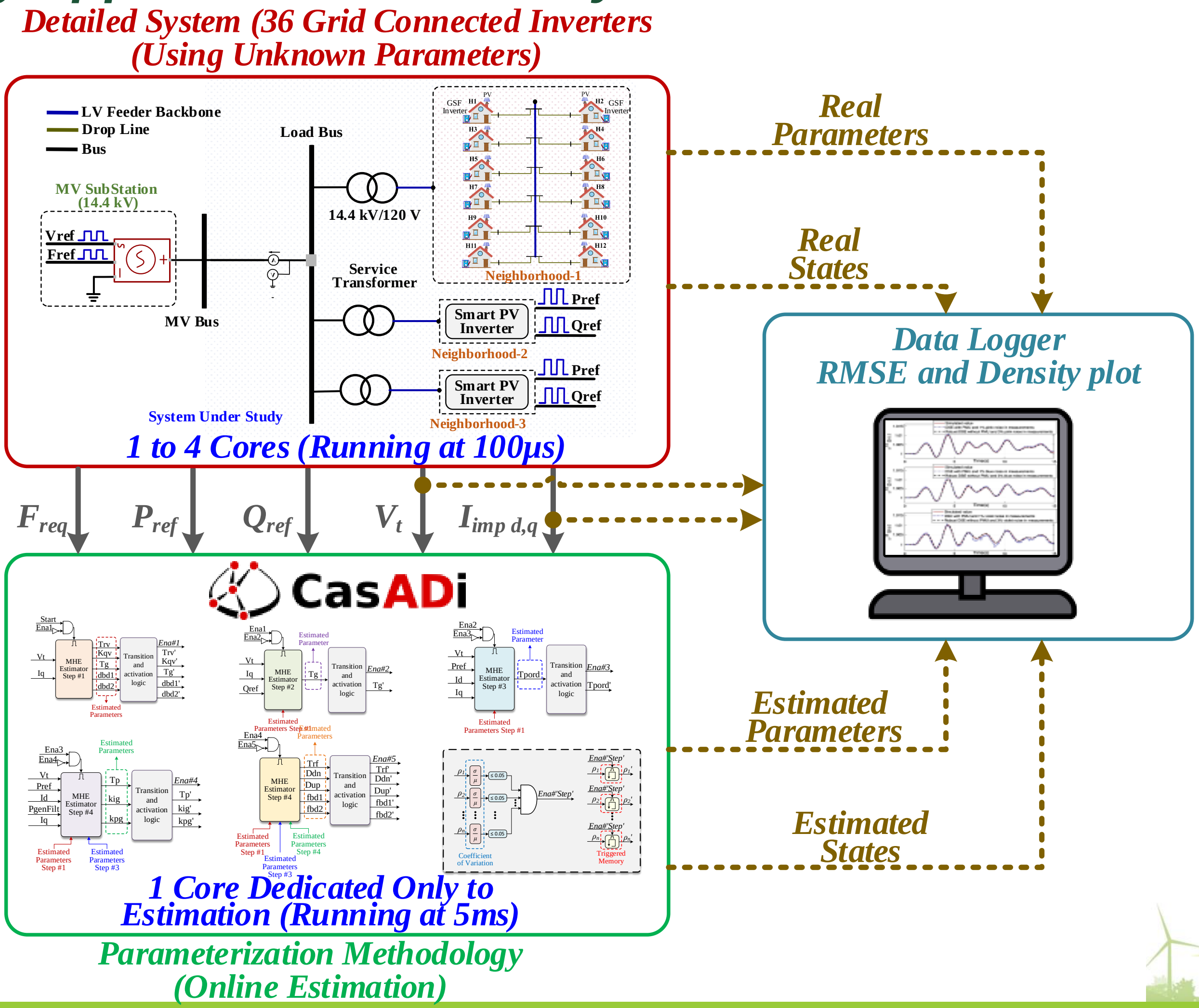
Parameterization with Known Parameters - Step #1: Voltage Control Dynamics



Step	Parameter	True Value	Estimated Value	State	Fit Based on NRMSE (%)
#1 Voltage Control Dynamics	Trv	0.02 s	0.0206 s		
	kqv	5 pu	4.8173 pu	VtFilt (S0)	99.0654
	dbd1	-0.05 pu	-0.0479 pu	Iq (S3)	99.5867
	dbd2	0.05 pu	0.0482 pu	Iimpd (S10)	96.3428
	Tg	0.06 s	0.0599 s	Iimpq (S11)	99.8867
	Re	0.01 pu	0.0088 pu		
	Xe	0.2 pu	0.2034 pu		

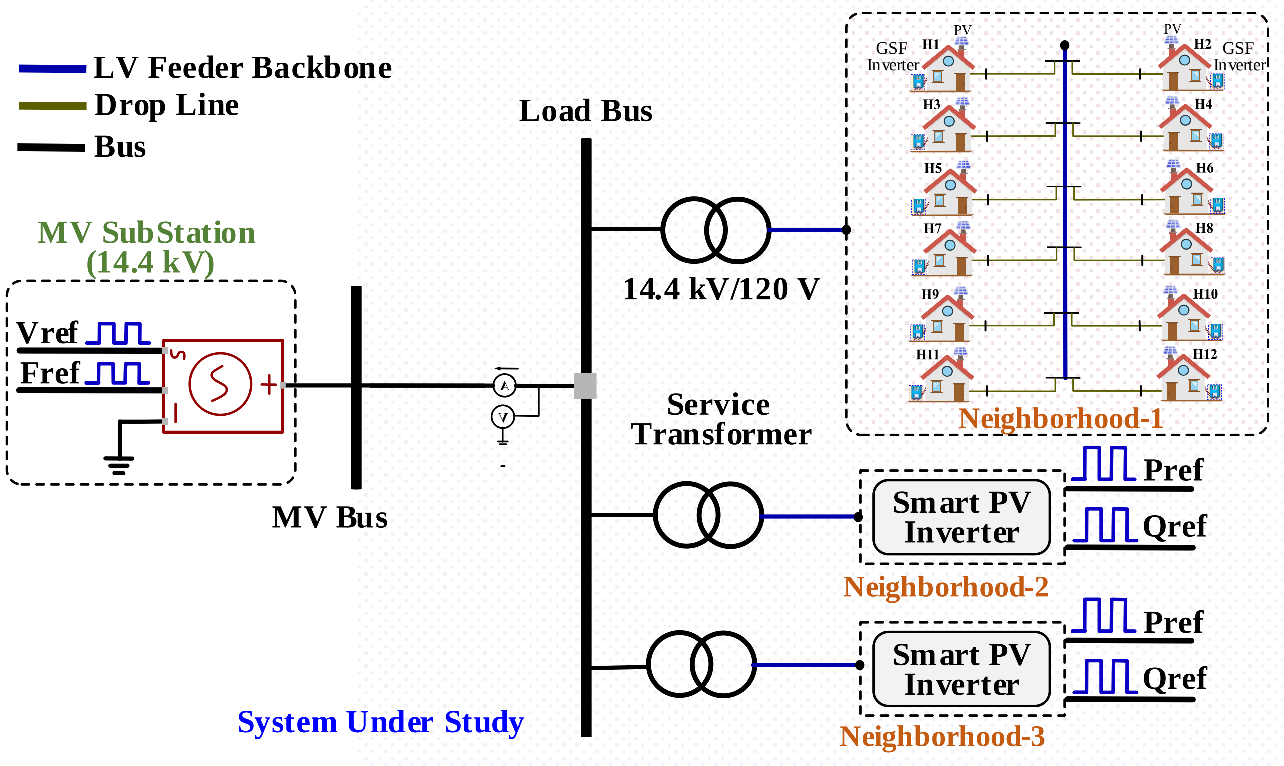
Results and Analysis - Parameterization Methodology Validation

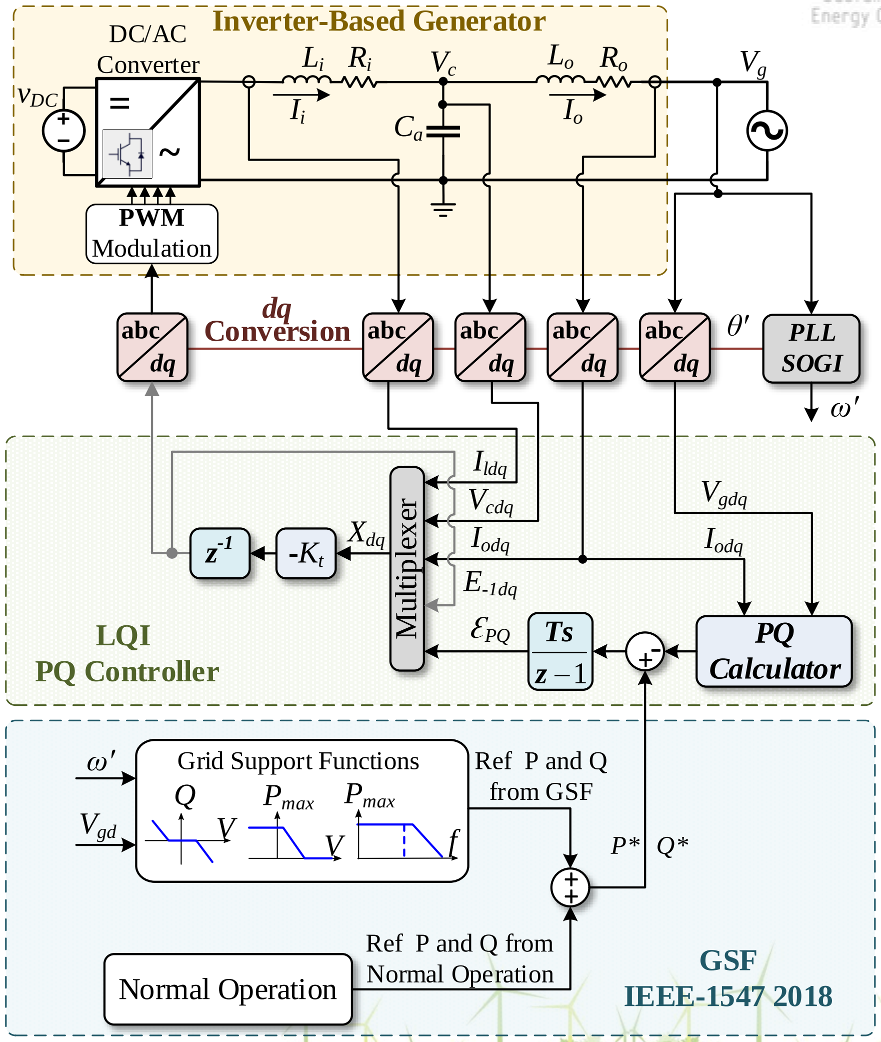
Proposed Methodology Applied to a Detailed System



Results and Analysis - Parameterization Methodology Validation

Proposed Methodology Applied to a Detailed System

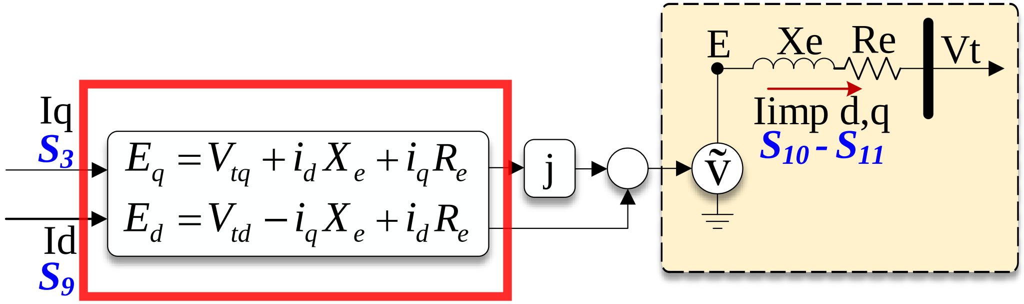


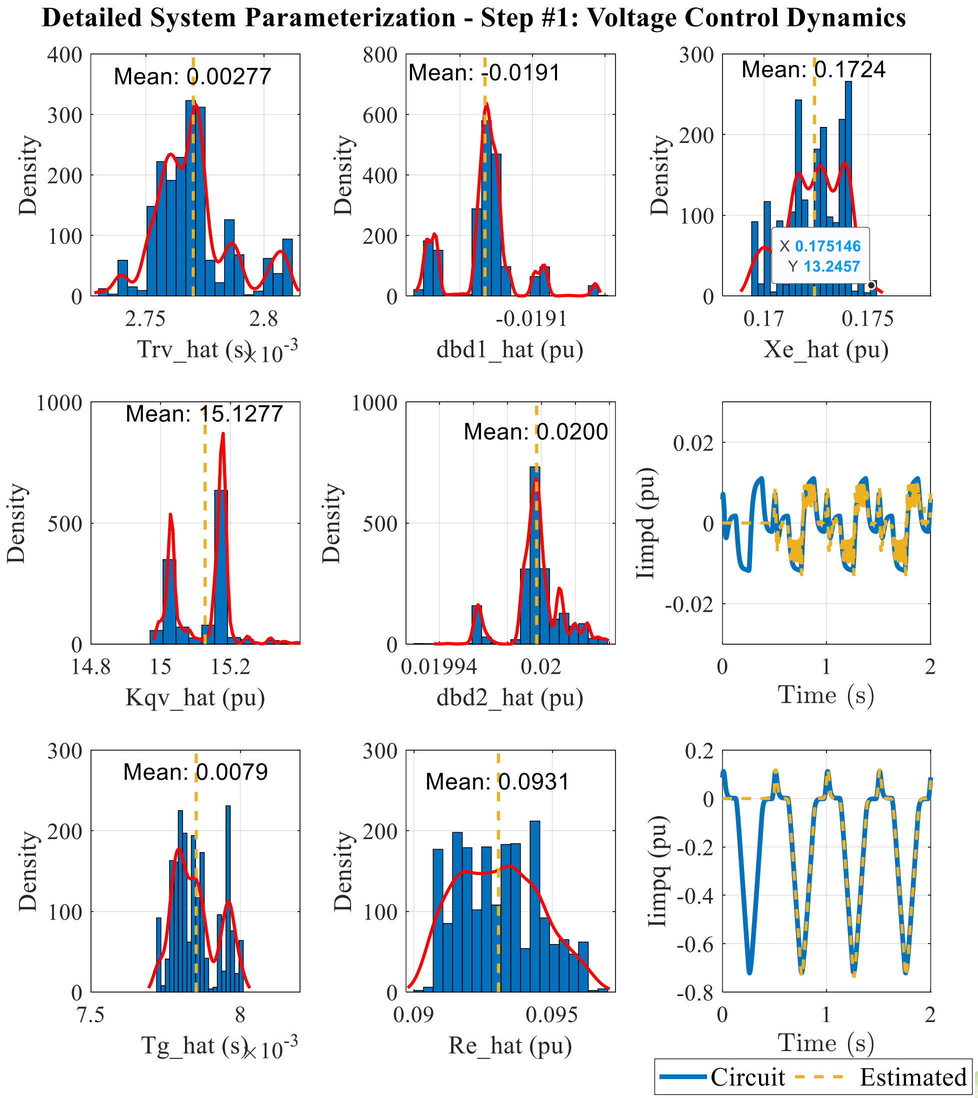


Results and Analysis - Parameterization Methodology Validation

Step # 1 – Voltage Control Dynamics (Methodology Applied to a Detailed System)

Step	Parameter	Default Value	Estimated Value	State	Fit Based on NRMSE (%)
#1 Voltage Control Dynamics	Trv	0.02 s	0.00277 s	Iimpd (S10)	50.7245
	kqv	5 pu	15.1277 pu		
	dbd1	-0.05 pu	-0.0191 pu		
	dbd2	0.05 pu	0.0200 pu	Iimpq (S11)	97.9008
	Tg	0.06 s	0.0079 pu		
	Re	N/A	0.0931 pu		
	Xe	0.2 pu	0.1724 pu		

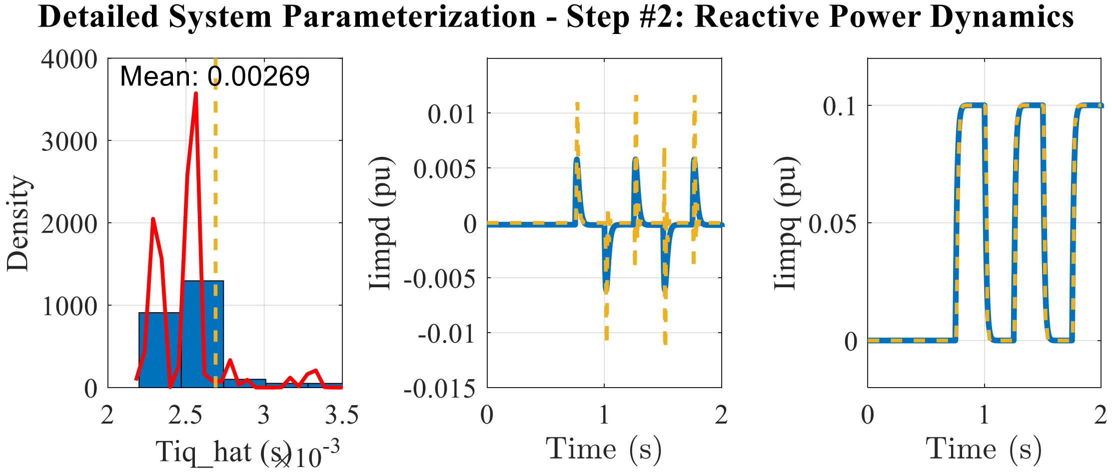


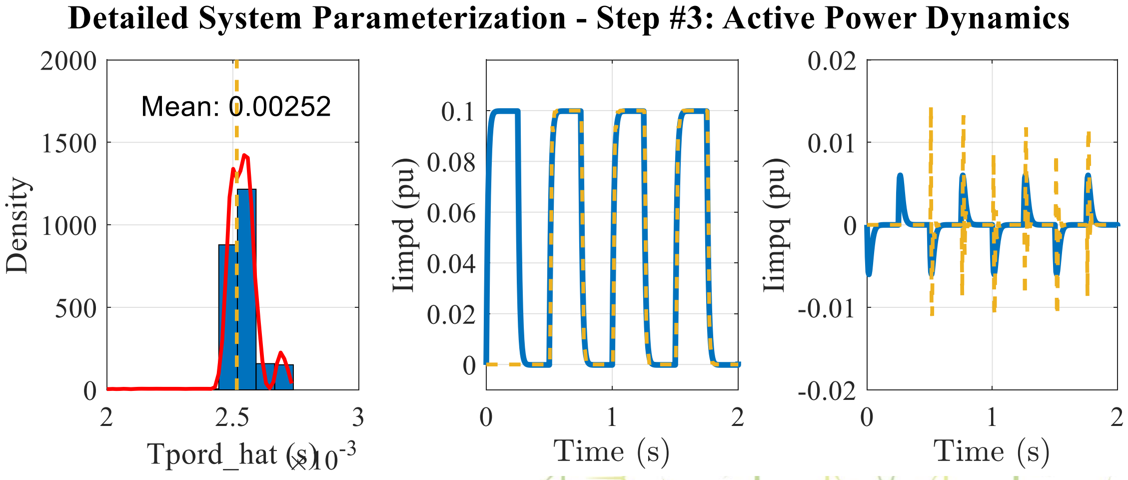


Results and Analysis - Parameterization Methodology Validation

Step # 2-3 – Reactive - Active Power Dynamics (Methodology Applied to a Detailed System)

Step	Parameter	Default Value	Estimated Value	State	Fit Based on NRMSE (%)
#2 Reactive Power Dynamics	Tiq	0.02 pu	0.0027 pu	Iimpd (S10)	51.1075
				Iimpq (S11)	96.6813
#3 Active Power Dynamics	Tpord	0.02 pu	0.0025 pu	Iimpd (S10)	96.2887
				Iimpq (S11)	52.1342





Microgrids for Resilience in Puerto Rico

Professors:

A. Irizarry-Rivera, E. O'Neill-Carrillo, F. Andrade, Marcel Castro Sitiriche

Students:

Omar F. Rodríguez, Yuly V. García, Robert García, Oscar Garzón, Daniel Cortez

University of Puerto Rico at Mayagüez (UPRM)
Department of Electrical and Computer Engineering

UPRM

Leading & executing the energy transition

- First DG and microgrid studies in Puerto Rico
- Emphasis on a more distributed power system
- Strong presence in energy policy discussions
- Collaborations with National Laboratories
- Sustainable energy projects: research, teaching, consulting, policy & outreach

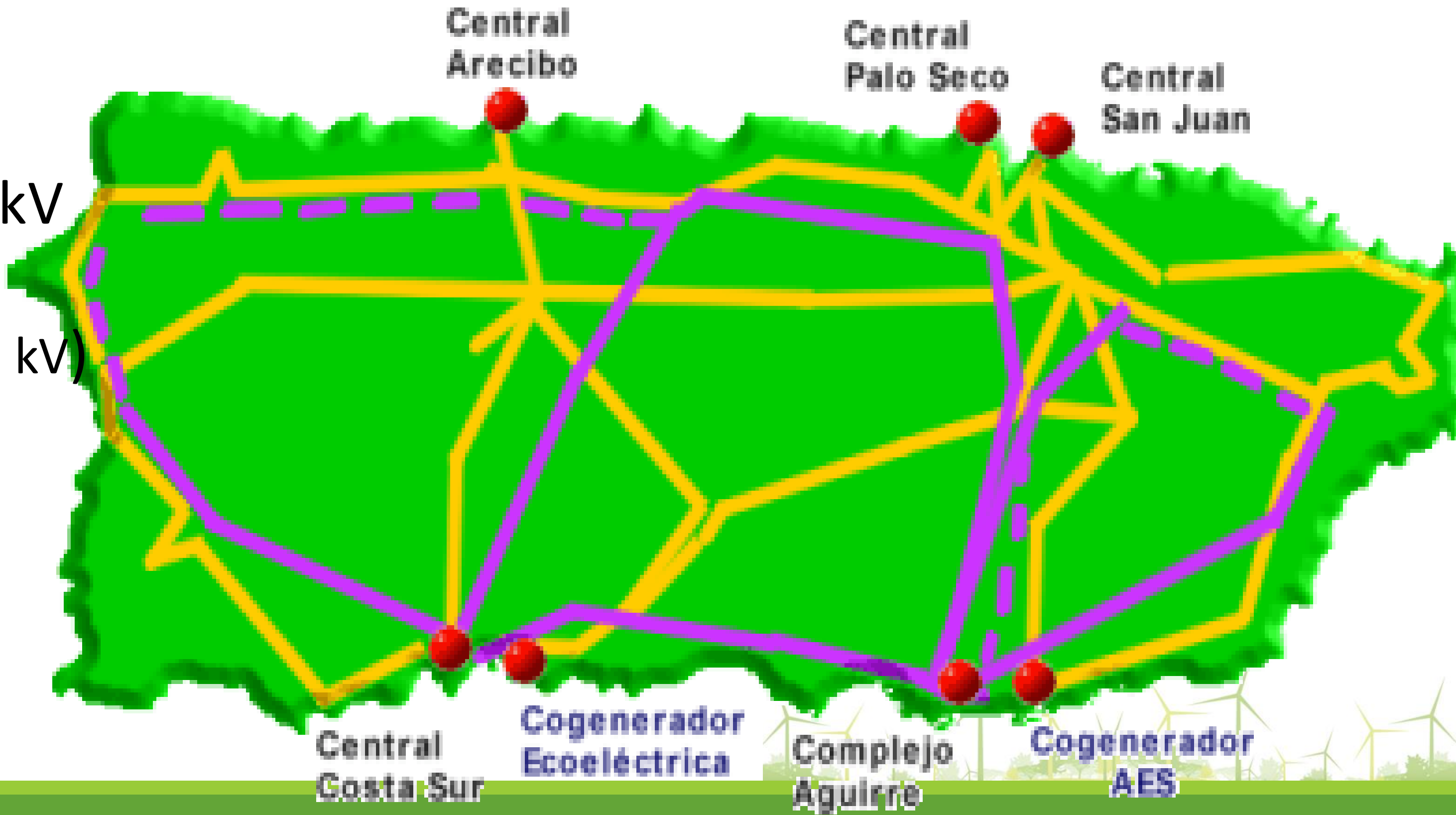
Community leaders during a Solar Communities Colloquium Bayamón, Puerto Rico, April 2017.

Casa Pueblo-UPRM PV Lab. First interconnected system in PR, 2008

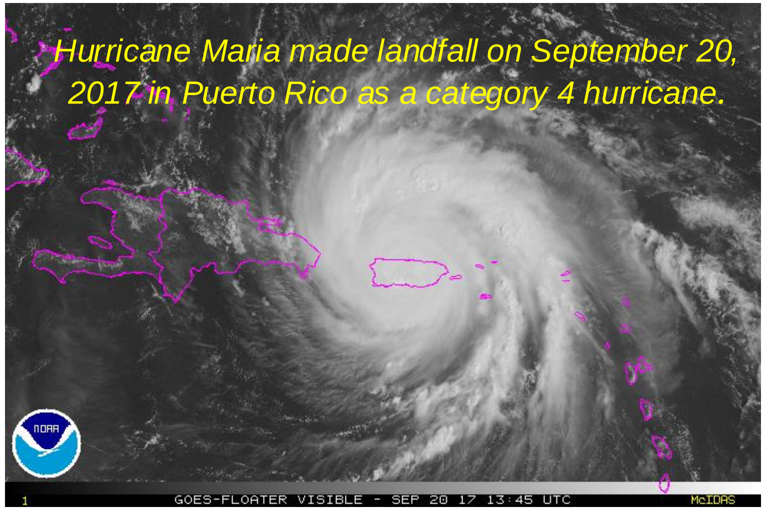
Villa Turabo: First Solar Community in PR

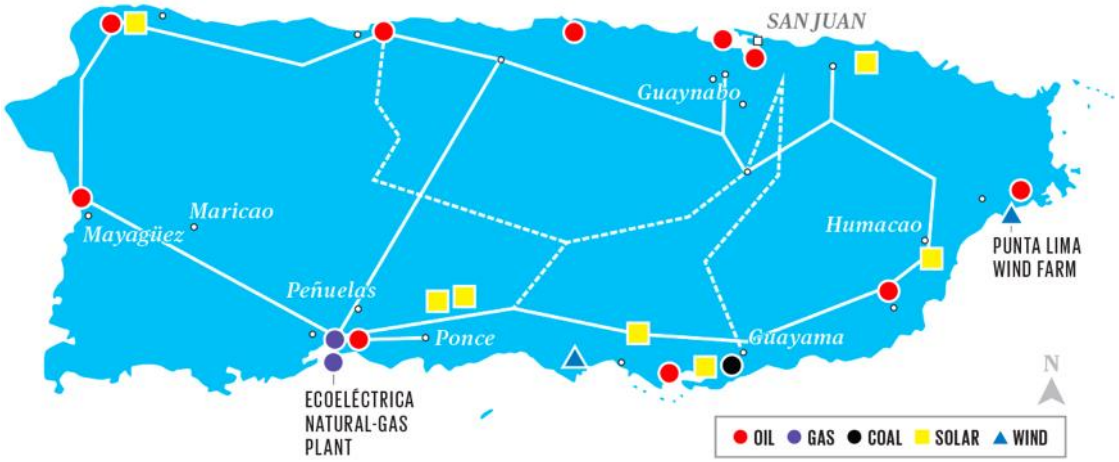
Challenges in Puerto Rico

- Physical limitations: Islanded system – no external support
- Power flows from South (generation) to North (demand)
- Dependence on imported fossil fuels (over 95%)
- Reduced demand
- Electric grid
  - Transmission voltages: 230 kV, 115 kV
  - Sub-transmission: 38 kV
  - Distribution (e.g., ***4.16 kV***, 8.32 kV, 13.2 kV)
- Bankrupted utility
- Legacy centralized system:
  - Not sustainable
  - Not resilient



Microgrids in Puerto Rico’s Reconstruction -Introduction





Rebuilding Puerto Rico's power grid: The inside story - M Gallucci - IEEE Spectrum, 2018
Hurricane Maria Effects on Puerto Rico Electric Power Infrastructure - A. Kwasinski, F. Andrade, M. Castro-Sitiriche, and E. O’Neill-Carrillo

Microgrids in Puerto Rico's Reconstruction After Maria….

Location of last 28,814 homes reconnected to the grid, partial (red) and completed (green)

Puerto Rico's context

After a disaster, rely only on your community

- Hurricanes & earthquakes
  - Usually, impacts to T&D & centralized power plants respectively
- Humid, hot, corrosive, drought conditions, strong/extreme winds (storms)
- Dated, conventional, low-inertia power systems
- Resilience is not valued properly
- Poor power quality
- Context and solutions are different from continental locations
  - Market pushes unsuitable "solutions", causing implementation problems, maintenance issues and confusion
  - "Poison the well" effect for other sustainable solutions

Oases of Light deployed after hurricane María
https://epics.ieee.org/solar-power-aid-puerto-rico/

E. O'Neill-Carrillo, Miguel A. Rivera-Quiñones. "Energy Policies in Puerto Rico and their Impact on the Likelihood of a Resilient and Sustainable Electric Power Infrastructure," *CENTRO*, Journal of the Center for Puerto Rican Studies, Hunter College, no. 3, vol. 30, 2018.

Lessons from hurricane María

Why did the power system fail? Why the slow response?

- *Centralized electric system*, Hurricane cat. 4 (1 mile shy of being cat. 5)
  - Islanded system, no external support
- Transmission system (230kV, 115 kV) destroyed in the eastern half of Puerto Rico.
  - No way to supply the north (highest demand) from power plants in the south
- Distribution systems (13.2, 8.32, 7.2 & 4.16 kV) destroyed or damaged in most areas
- Quotes from Federal leaders in charge of response
  - "*Figuring out what we needed, took us a long time*", "Should have used regional communications from the beginning", Described the organizational interactions as a "spaghetti chart", "Number of voltages in the system, the diversity of components, was a logistical nightmare"
- FEMA had no plan for a disaster like this in Puerto Rico
- Slow state government response, lack of proper planning
  - For example, over-reliance on cell phones and the internet
- Focus on the San Juan Metropolitan Area
  - Forgotten: Western and Central regions remained uncommunicated for days

Source: "Rebuilding Puerto Rico Energy Sector Summit", San Juan, PR, May 10, 2018 (Dr. Efraín O'Neill notes).

Lessons from hurricane María

What can be done

- Need to re-think disaster response in Puerto Rico
  - Need to create a shared disaster response vision
- Must get away from traditional contingency planning, into resilience planning
- Better management; need to communicate as frequently as possible
  - Avoid keeping people “in the dark”
- Must harden supporting infrastructures (e.g., communications)
- Standardization is critical to build a system that can be restored quicker
- Limit North-South transmission over the mountains
- *The centralized electric power model is insufficient*
  - ***NEED FOR A RESILIENT, DECENTRALIZED ELECTRIC POWER SYSTEM***

E. O’Neill-Carrillo, et al. “Stakeholder Perspectives on Increasing Electric Power Infrastructure Integrity.” *ASEE Annual Conference*, June 2019, Tampa.

A. Kwasinski, et al. "Hurricane Maria Effects on Puerto Rico Electric Power Infrastructure," in *IEEE Power and Energy Technology Systems Journal*, vol. 6, no. 1, March 2019

Rooftop PV Systems

Solar communities and community microgrids for resilience

Citizen empowerment → Technology → Social and environmental justice → Sustainable energy

Beyond technology: communities, with appropriate partnerships, can further local socio-economic initiatives to achieve energy sustainability, social and environmental justice.

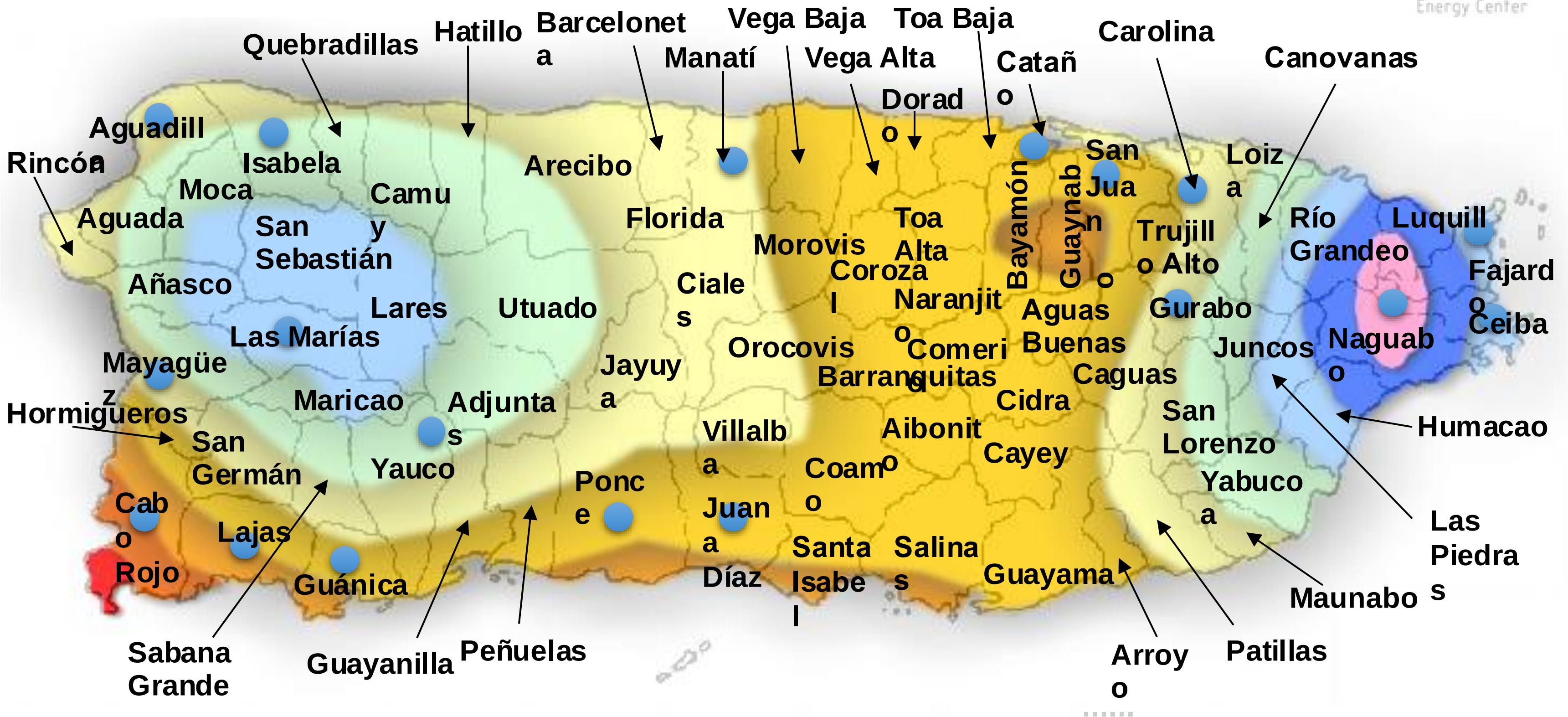
E. O'Neill-Carrillo, et al. "Community Energy Projects in the Caribbean: Advancing Socio-Economic Development and Energy Transitions," *IEEE Tech & Soc Mag*, vol. 38, no. 3, Sept. 2019.

E. O'Neill-Carrillo, et al.: "The Long Road to Community Microgrids," *IEEE Electrif Mag*, vol. 6, no. 4, Dec. 2018.

Solar resource in Puerto Rico

Estimated average insolation in Puerto Rico, kWh/m^2 per year

- Irizarry, O'Neill & Colucci, *Achievable Renewable Energy Targets for Puerto Rico's Renewable Energy Portfolio Standard*, 2009.



- 1495 → 3.4 h
- 1343 → 3.1 h
- 1191 → 2.7 h
- 1952 → 4.5 h
- 1800 → 4.1 h
- 1648 → 3.8 h
- 2408 → 5.5 h
- 2256 → 5.2 h
- 2104 → 4.8 h

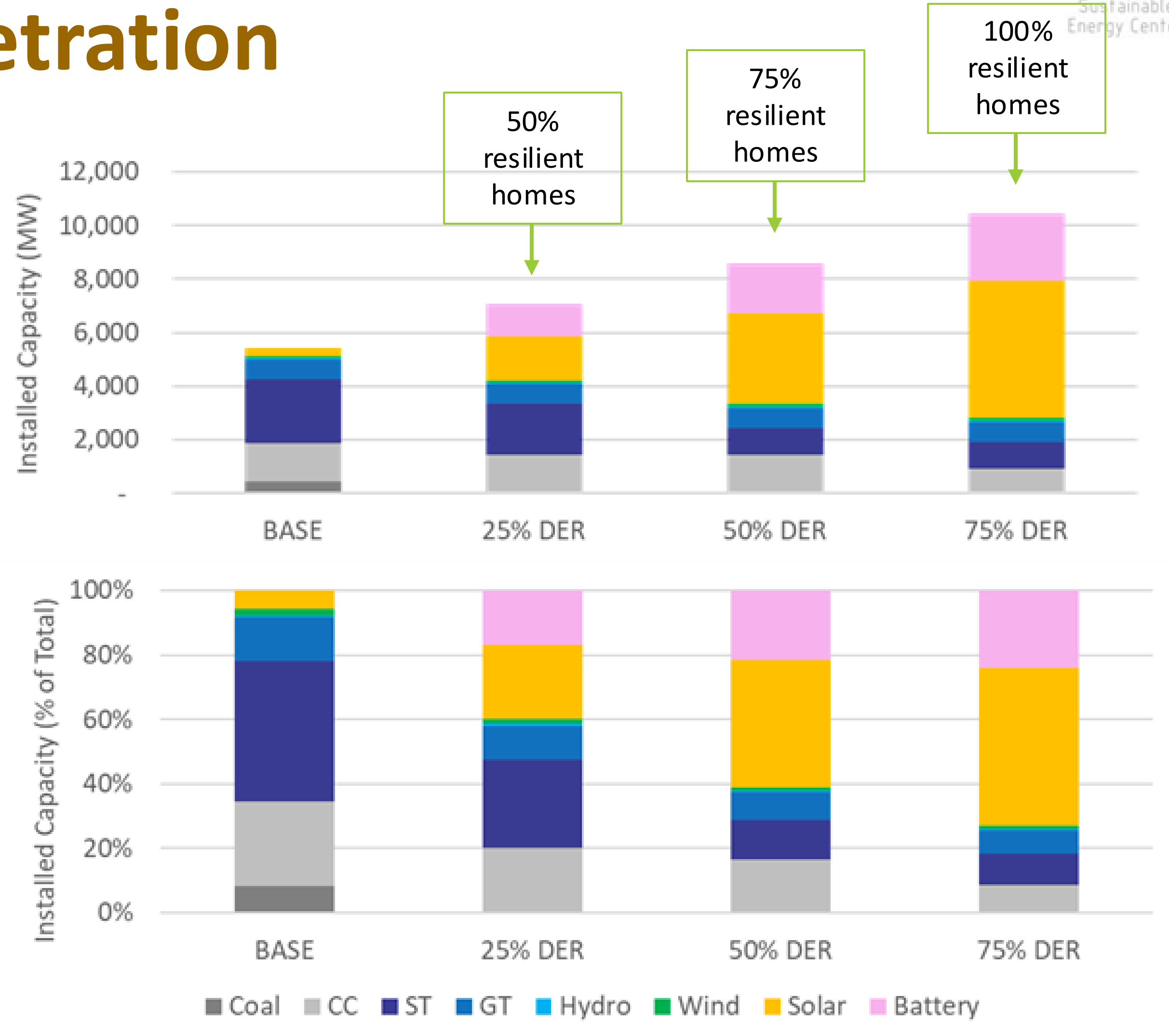
Source: https://www.uprm.edu/aret/

Integration of Distributed Solar

25%, 50% and 75% PV penetration

+2X peak demand

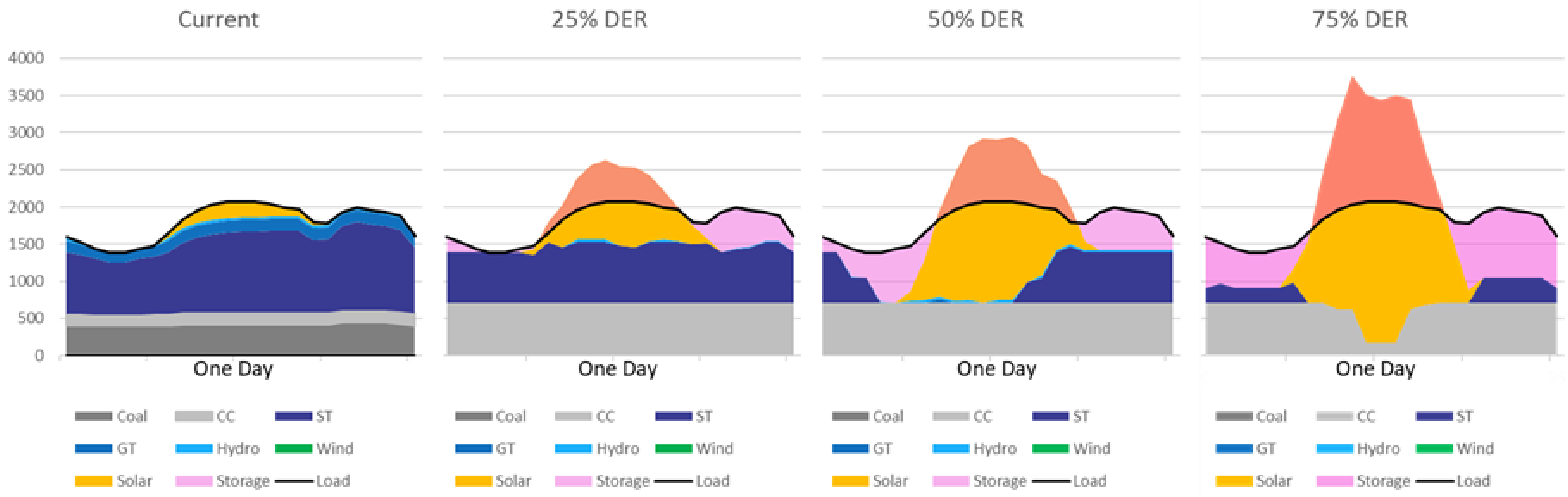
- 5,000 MW new PV
- Batteries ~5,300 MWh a 11,400 MWh
- Distributed Solar + Batteries dominate in scenarios with higher penetration.
- Fast-track retirement of older fossil fleet (coal & oil)



Source: "Estudio de Integración de Recurso Solar Distribuido en Puerto Rico" https://cambiopr.org/solmastechos/

Generation profile

Significant change in daily generation



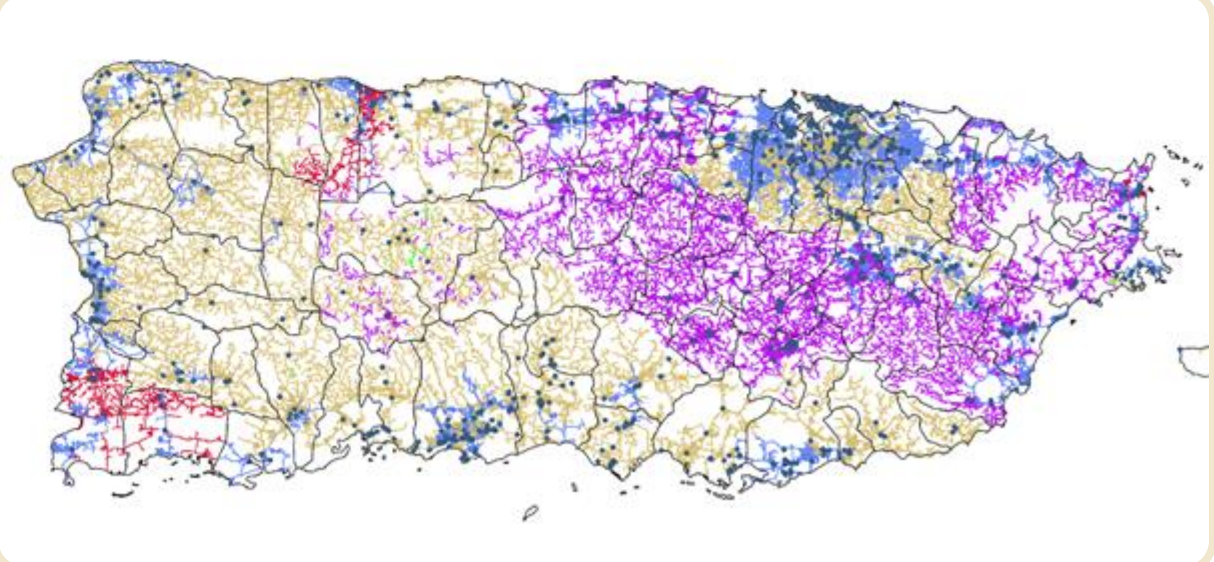
- ✓ Batteries supply peak demand in the afternoon/night and the mornings' ramps.
- ✓ Combined cycle fleet increases output to replace coal and older oil plants.
- ✓ Fossil fleet is reduced, main role in the 50% & 75% scenarios is regulation.

Source: "Estudio de Integración de Recurso Solar Distribuido en Puerto Rico" https://cambiopr.org/solmastechos/

Distribution System Analysis

912 feeders modeled (1,097 total, 89% of line miles)

- GIS data from the utility. OpenDSS model show to achieve 75% renewables we need:
- For line voltage or thermal violation change conductor (if change of conductor exceeds 2 sizes re build line) – **15%**
- For transformer back flow > 125% nominal for > 500 h change transformer – **4%**



Source: "Estudio de Integración de Recurso Solar Distribuido en Puerto Rico" https://cambiopr.org/solmastechos/

Integration of Distributed Solar

Very high penetration of distributed, rooftop solar photovoltaic plus batteries is feasible with modest investment in distribution system (relative to IRP)

- Deployment of 100% residential solar rooftops + batteries will provide 2700 MW, adding commercial (rooftop and carports) allows generation of 75% of total annual energy demand from renewable sources by 2035.
- fossil fuel imports reduced by $600 millions annually most fossil fired generation retired
- 70% reduction of CO_2 emissions
- Dependency on transmission systems is significantly reduced
- Cost is less than the proposed IRP…

Source: “Estudio de Integración de Recurso Solar Distribuido en Puerto Rico” https://cambiopr.org/solmastechos/

Recommendations

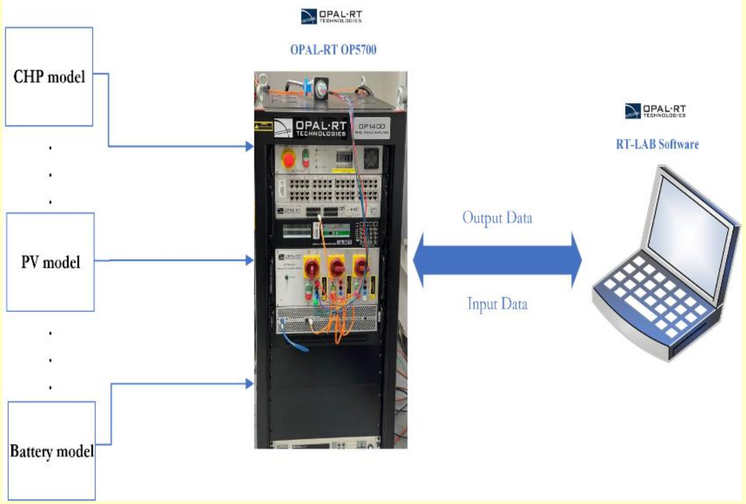
Planning and Operational Practice of Distribution Systems

- A more distributed power system in island, coastal, and remote communities
  - Solar communities and community microgrids
- Distributed energy for local resilience
- Widespread use of onsite renewable energy to yield LOCAL economic, social and environmental benefits
- A new role for conventional power system components
- A trained workforce, and an informed and active citizenry
- In Puerto Rico: Rooftop PV + storage residential cost (~ 20 cents/kWh) is less than grid price (34 cents/kWh today)
- Electric vehicles

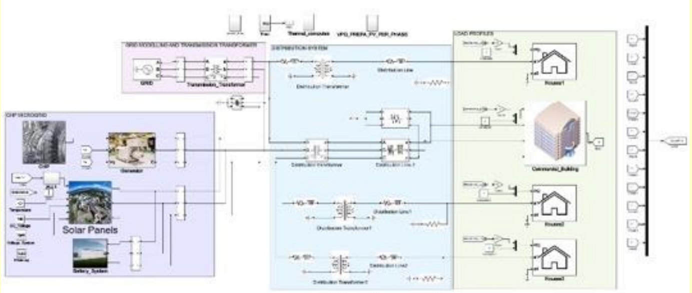
Master's Thesis: Feasibility analysis of microgrid implementation in compliance with the Puerto Rico 9028-PREB Regulation.

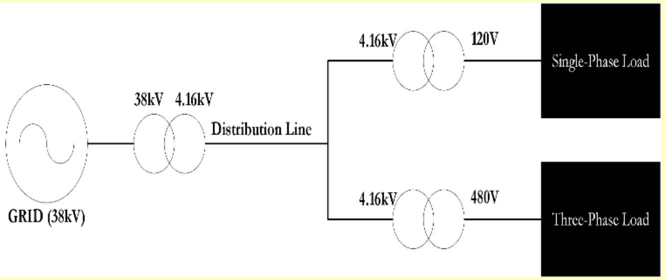
Deliverables

- Functional models (PV, battery, CHP models) of different distributed generators in MATLAB/Simulink (running in OPAL-RT).
- An extensive repository of MATLAB scripts and Simulink block diagrams to implement new possible scenarios such as: ramp rate strategies, system behavior, load demand and model behavior, etc.

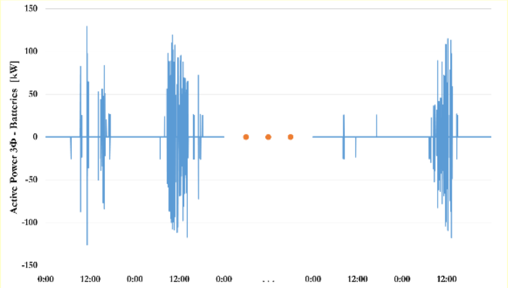


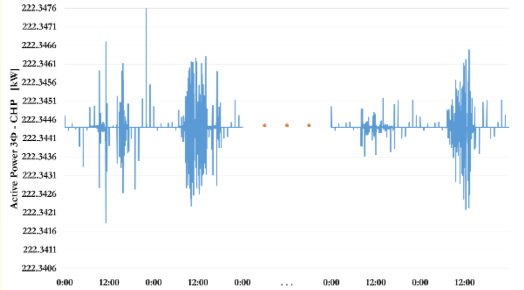
Platform Design

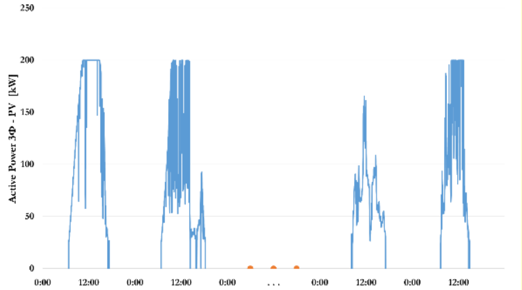




Results







*One publication whit Sandia National Laboratory (In progress).

Master's Thesis: Methodology to Implement a Microgrid in a University Campus

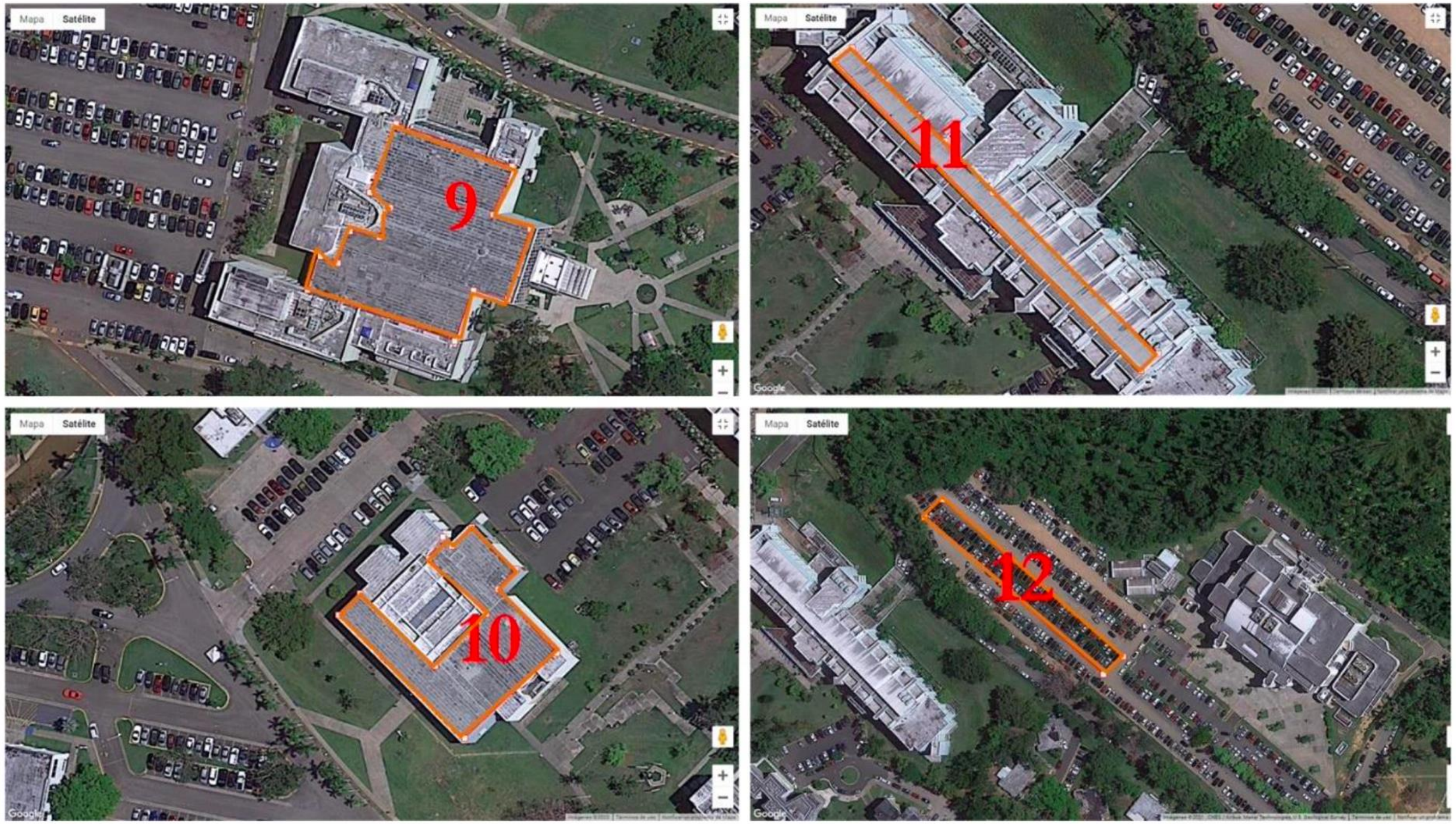
Determine the available energy resources

Electric design

Data collection

Microgrid design

Simulation 5

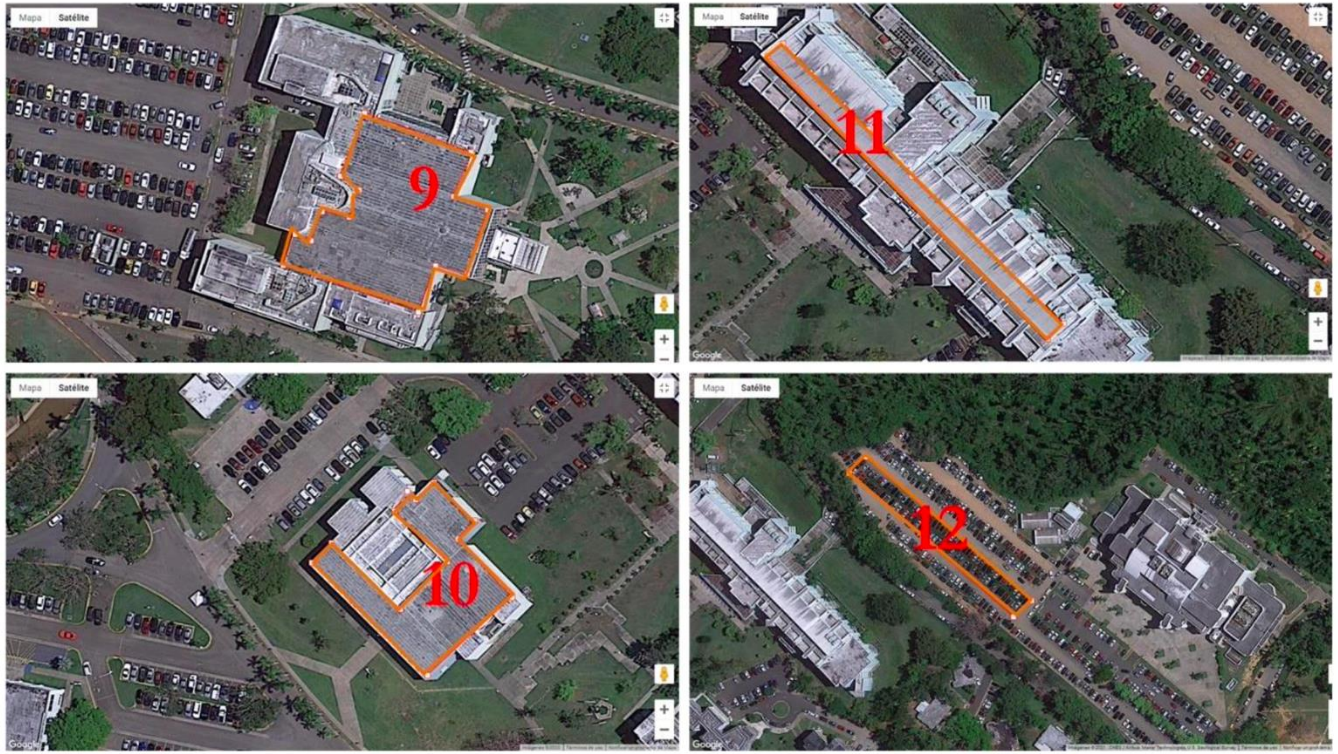


Microgrid behavior

Parkings

Rooftops

Master's Thesis: Methodology to Implement a Microgrid in a University Campus



Comparison between scenarios

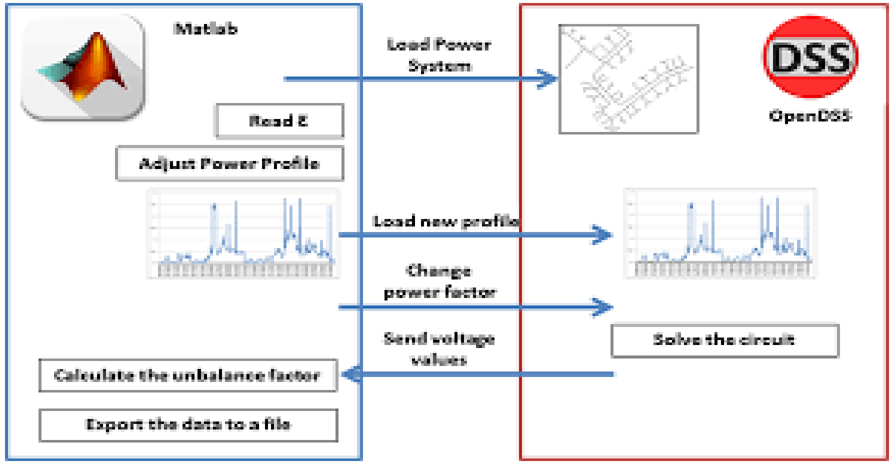
Scenario	Mode	Total Installed Capacity per microgrid [MW]	Estimated Initial Cost [Million USD]
PV	Grid connected	1.4	2.4
PV+ Bat	Islanding	3+3.94	5+4.7
CHP		0.8	1.7
PV+Bat+CHP		1.4+1.5+0.4	2.4+1.7+0.8

Fuel Consumption per year
Scenario 3
Natural Gas $ 191,000
Propane Gas $ 734,000

Scenario	Mode	Need Area [m^2]	Austerity Days	Load Interruption	
				State	Average duration per day [hours]
PV	Grid connected	10,000	No	N/A	N/A
PV+ Bat	Islanding	21,000+1,600	Yes	Yes	2.75
CHP		9	Yes	No	0
PV+Bat+CHP		10,000+625+12	Yes	Yes	1.48

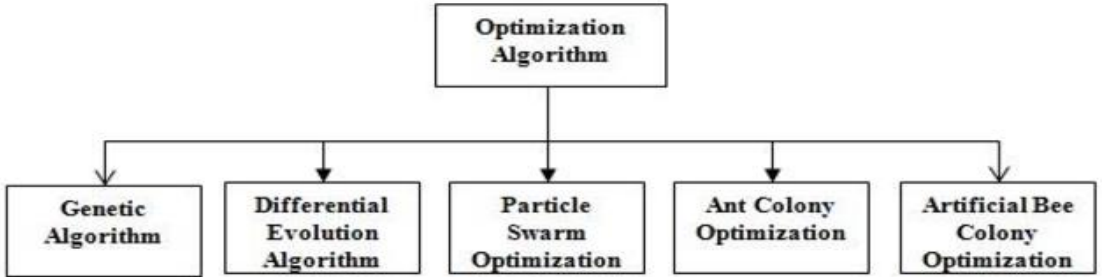
Master's Thesis: Optimal Integration Of Photovoltaic Generators Into The Puerto Rico Electrical Network

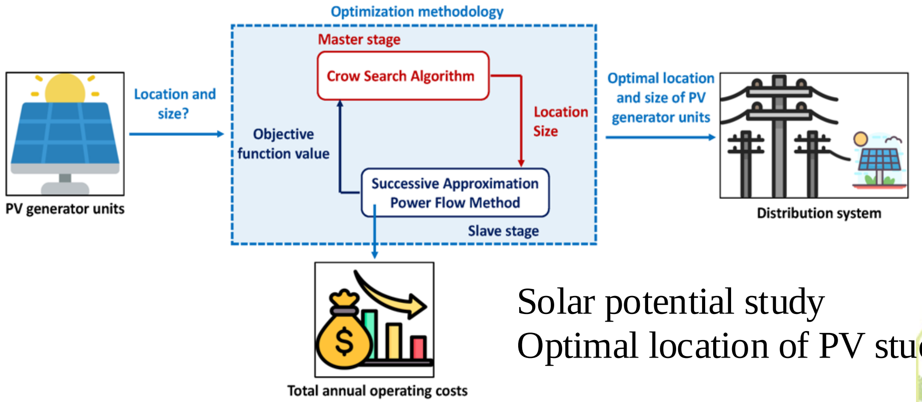
Modeling of electrical systems



Solve power flow
Operation
Power loss
Voltage profiles
Fails analyze
Interface with MATLAB
Data analyze
Distribution system analyze

Implementation of optimization algorithms



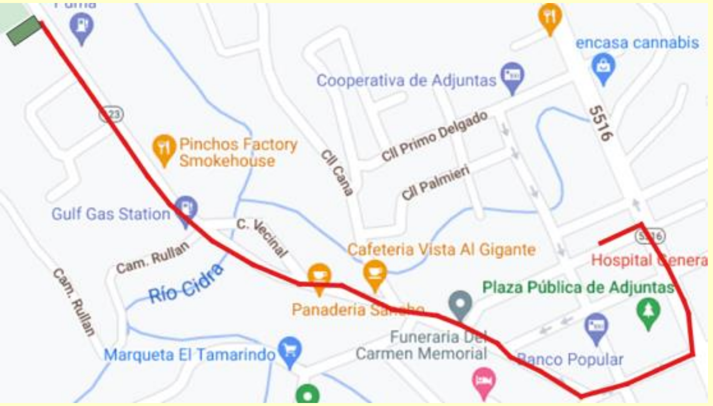


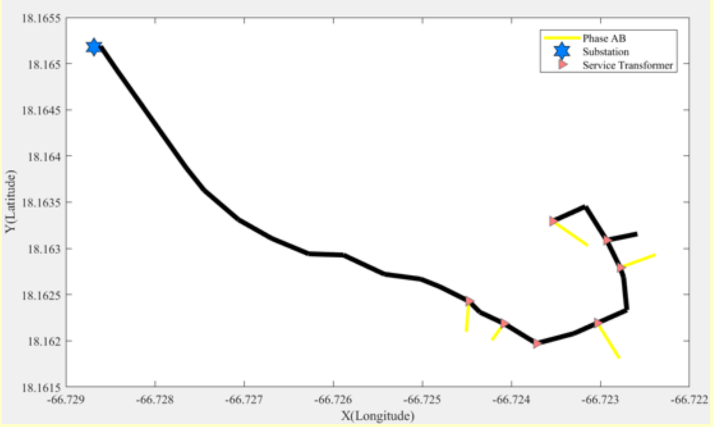
Solar potential study
Optimal location of PV study

Master's Thesis: OpenDss with Python and Matlab interface to simulate Adjuntas microgrid

Demographic

- Adjuntas is a town of Puerto Rico
- In the downtown, there are commercial and residential buildings
- On the rooftop of each building, there are solar photovoltaic panels





System Description

- 1 Substation 8202
- 2 Triphasic and 6 Monophasic Transformers
- 39 buses
- 64 Lines about 2 Miles of total length
- 2 Residencial and 13 Commercial loads
- 10 PVSystems
- Battery Storage System missing

Master's Thesis: Thesis: Analysis of the Solar Energy Potential on Roofs for A Low-Income community in Mayaguez Puerto Rico.

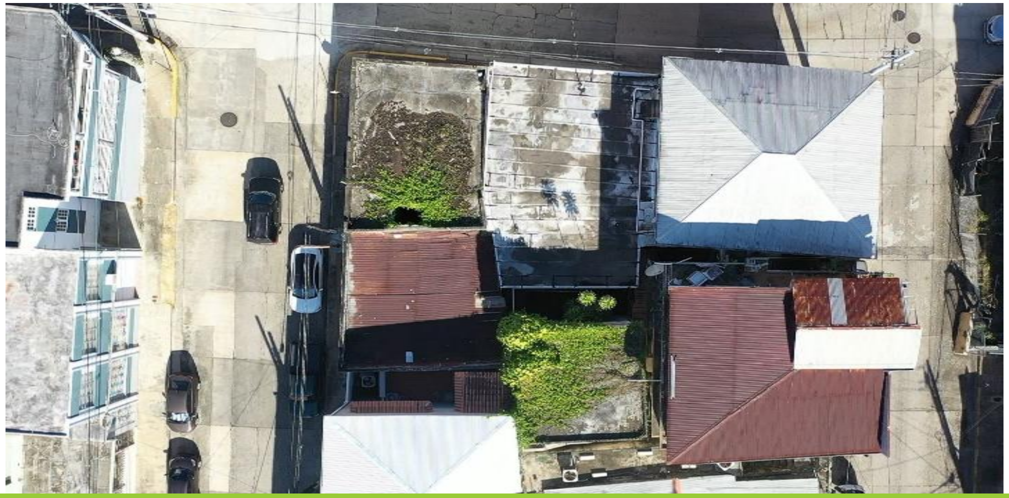
Photo: Fabio Andrade, June 2020.

Master's Thesis: Thesis: Analysis of the Solar Energy Potential on Roofs for A Low-Income community in Mayaguez Puerto Rico.

Photo: Fabio Andrade, June 2020.

Master's Thesis: Thesis: Analysis of the Solar Energy Potential on Roofs for A Low-Income community in Mayaguez Puerto Rico.

Current state of the rooftops.



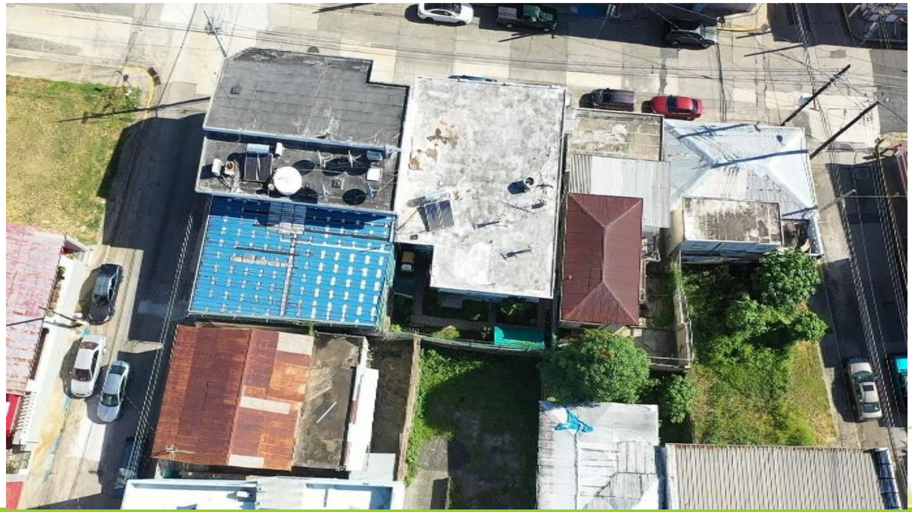


Photo: Fabio Andrade, June 2020.

Data collection

- The community was divided into 33 sections as shown in Figure. Each section has an average between 30 and 50 houses.

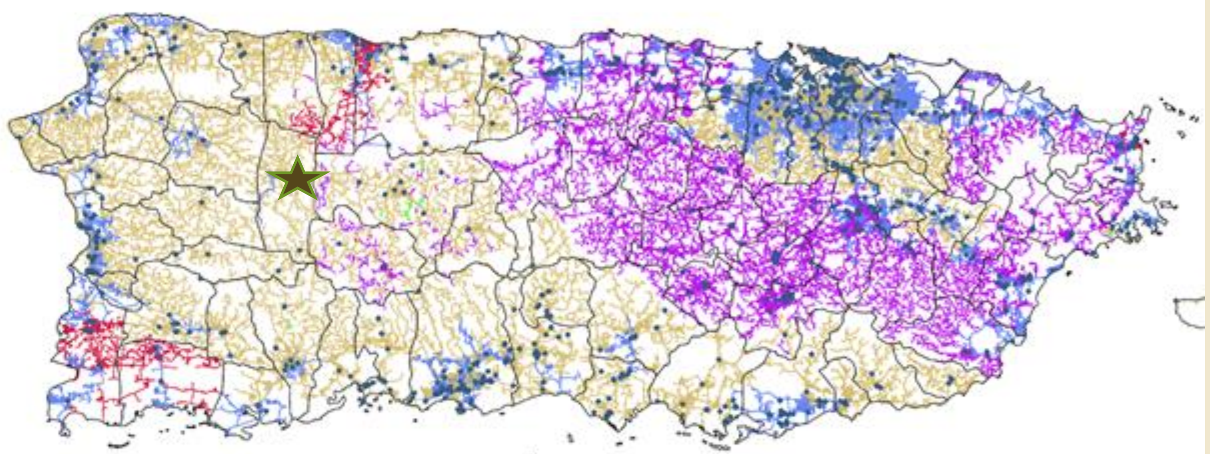
Barrio la Salud	
Section	**Houses**
33	1188

Master's Thesis: Thesis: Analysis of the Solar Energy Potential on Roofs for A Low-Income community in Mayaguez Puerto Rico.

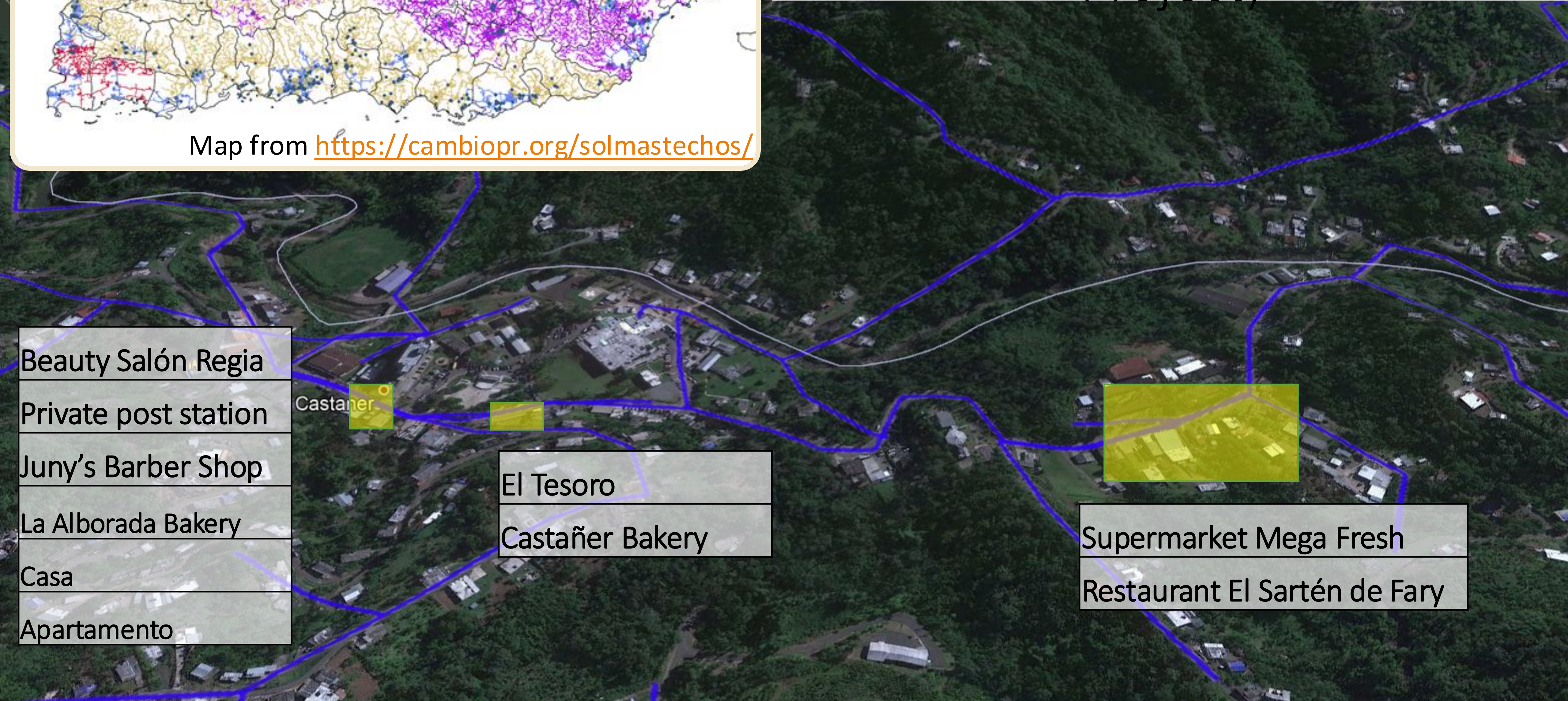
Solar potential map.

Source: Google Project Sunroof.

Example: Castañer Microgrid (Pilot Project)



Map from https://cambiopr.org/solmastechos/



Energy Demand

Building	Demand (kWh)
Beauty Salon Regia	6
Private post office	4
Juny's Barber Shop	34
La Alborada Bakery & Restaurant	97
House	5
Apartment	5
Total	**151**

Cost without microgrid

- Normal conditions: $0.24/kWh (currently, $0.29/kWh)
  Cost without microgrid (from utility)

  $1,000 per month ($12,000 annual)

- After hurricane María: $1.20/kWh
  Cost of electricity without microgrid (back-up generator)

  $5,350 monthly ($65,000 annual)
  - Cost of diesel: $0.68 per liter
  - Liters per hour: 10 L

- Annual demand: 55 MWh

Normal conditions: Cost with microgrid

- Similar to electricity from the utility before (currently, ***<u>below</u>***)
- $0.24/kWh
- Estimated investment: $180,000

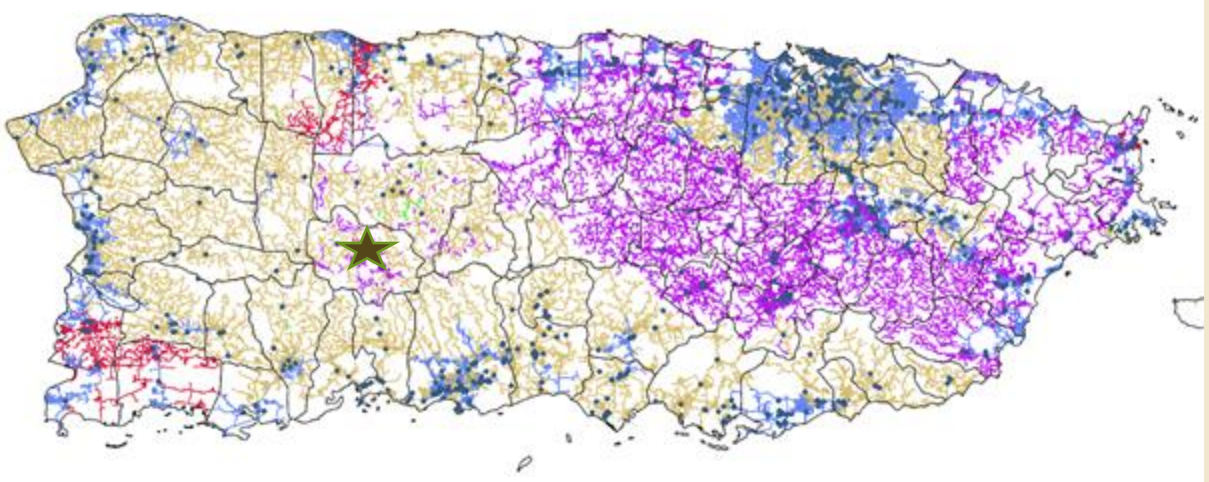
RESILIENT OPERATION OF NETWORKED COMMUNITY MICROGRIDS WITH HIGH SOLAR PENETRATION

U.S. DEPARTMENT OF ENERGY | Office of Science

SEC Sustainable Energy Center

TOPIC AREA 5.1: RESILIENT COMMUNITY MICROGRIDS

This project proposes a novel development and evaluation of a microgrid controller (MGC) that coordinates the cluster operation of the Adjuntas MG to achieve high resilience and cost-effective operation. Two operation modes are considered: normal and self-healing.



Map from https://cambiopr.org/solmastechos/

Example: Adjuntas Microgrids

Data collection

The main loads are being monitored; the meters collect voltages, active and reactive power for each of the phases.

Simulink Model