University of Pittsburgh

10TH ANNUAL PITT ELECTRIC POWER INDUSTRY CONFERENCE
Presented by the Swanson School of Engineering & the Center for Energy

Graduate Student Symposium

Session Moderator:
Dr. Brandon M. Grainger

10th Annual Electric Power Industry Conference
Swanson School of Engineering
Graduate Student Symposium
November 16th, 2015














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Power Electronic Converter Design and Device Analysis

Ansel Barchowsky

Joseph Kozak

Alvaro Cardoza

Christopher Scioscia

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A 2kW, High Power-Density (100W/in3), GaN-Based, Modular Multilevel Converter

Ansel Barchowsky

Electro-Thermal Characterization of Power Semiconductor Devices

Joseph P. Kozak

Power Source Buffering using a Triangular Modular Multilevel Converter with Energy Storage

Alvaro Cardoza

Enhanced Reliability of APDN Architecture Utilizing Resonant Power Converter Topologies

Christopher Scioscia

A 2kW, High Power-Density (100W/in3), GaN-Based, Modular Multilevel Converter

Prepared by: Ansel Barchowsky

Ph.D. Student

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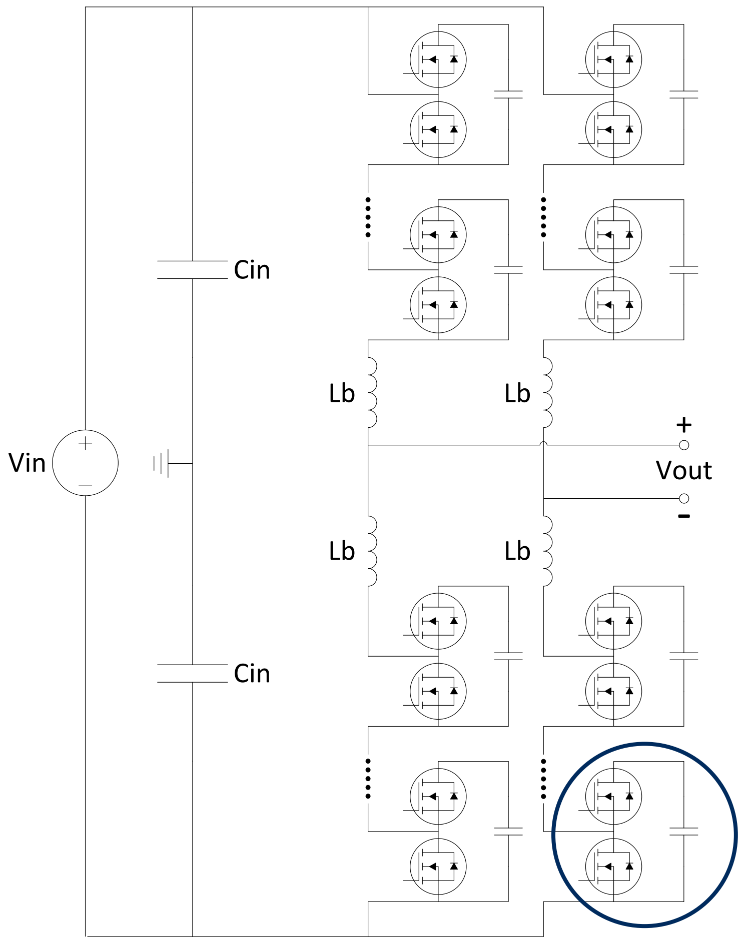
Power Electronic Converter Design and Device Analysis

A 2kW, High Power-Density, GaN-Based, MMC

MMC Topology for Low Voltage, High Density Conversion



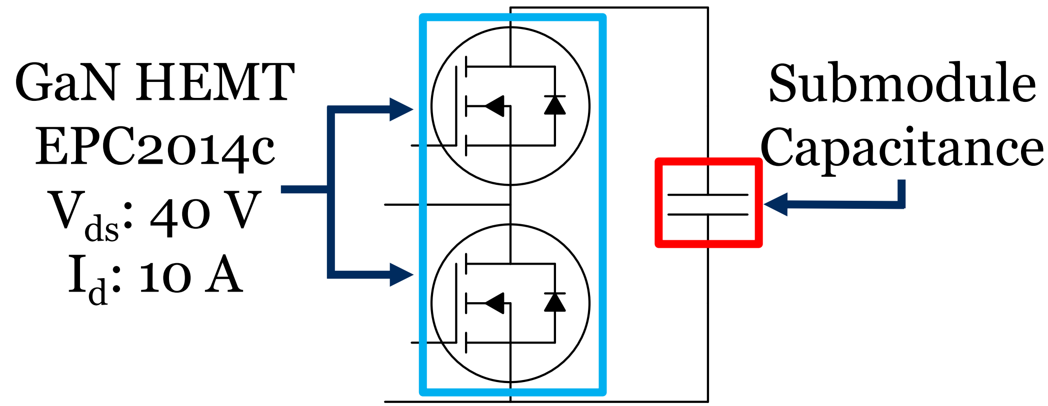
- High power-density is crucial in applications with limited volume
- There are a number of technical challenges to achieve high-density designs
- MMC topologies provide advantages in high-density design:
  - Small energy switching events
  - Low power semiconductor devices
  - Minimal filtering requirements
  - Modularity

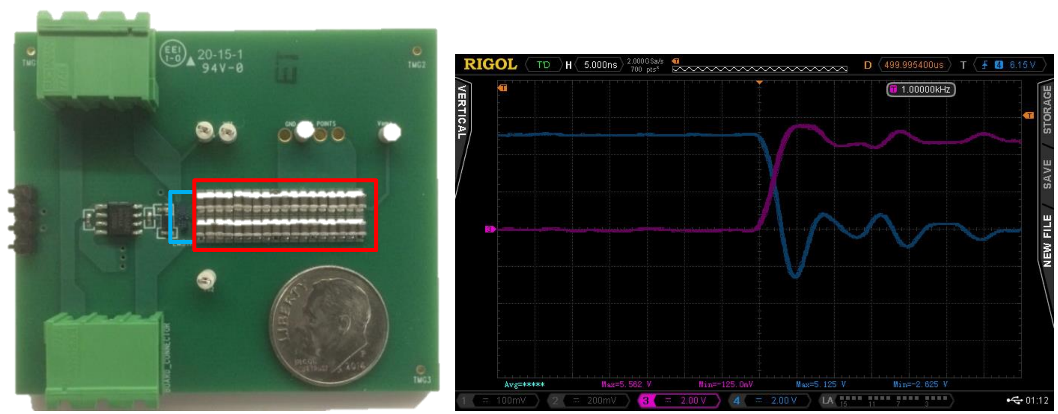
Power Electronic Converter Design and Device Analysis

A 2kW, High Power-Density, GaN-Based, MMC

Converter Ratings and Submodule Design

Converter Ratings	
Parameter	**Value**
Power Rating	2 kVA
Input Voltage (DC)	450V
Output Voltage (AC)	240 V
Output Frequency	60 Hz
Cell Capacitance	1.54 mF
Cell Voltage	30 V
Cells per Arm	14



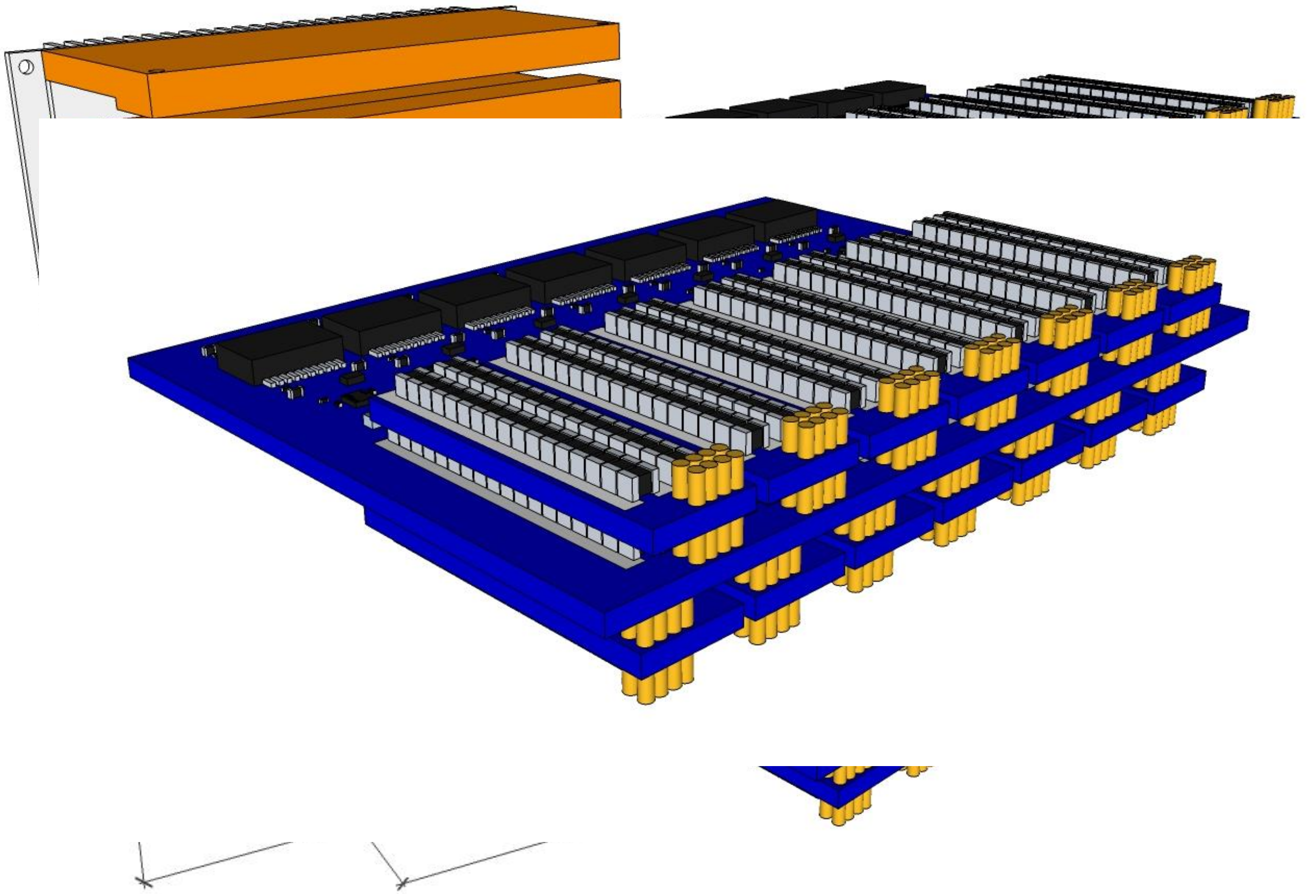


Prototype submodule and experimental switching characteristic

Power Electronic Converter Design and Device Analysis

A 2kW, High Power-Density, GaN-Based, MMC

Converter Fabrication and Layout



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Electro-Thermal Characterization of Power Semiconductor Devices

Prepared by: Joseph P. Kozak
M.S. Student

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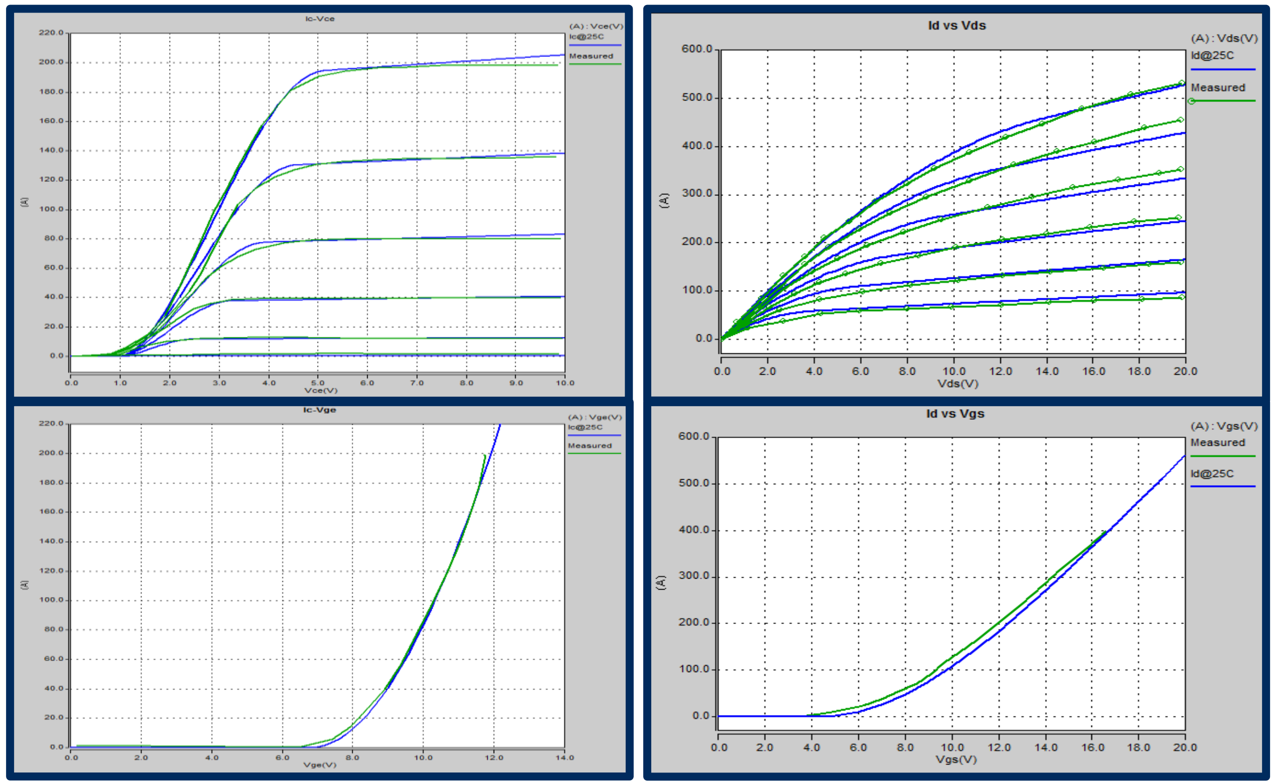
Power Electronic Converter Design and Device Analysis

Electro-Thermal Characterization of Power Semiconductors

Parameter Comparison

- Using Saber RD, the developed model was compared to the data from manufacturer specifications
- Graphs show the I-V characteristics of the created models
- By manipulating the parameters, the models will change output characteristics
- The graphs depict the strong relationship between the created model and manufacturer data



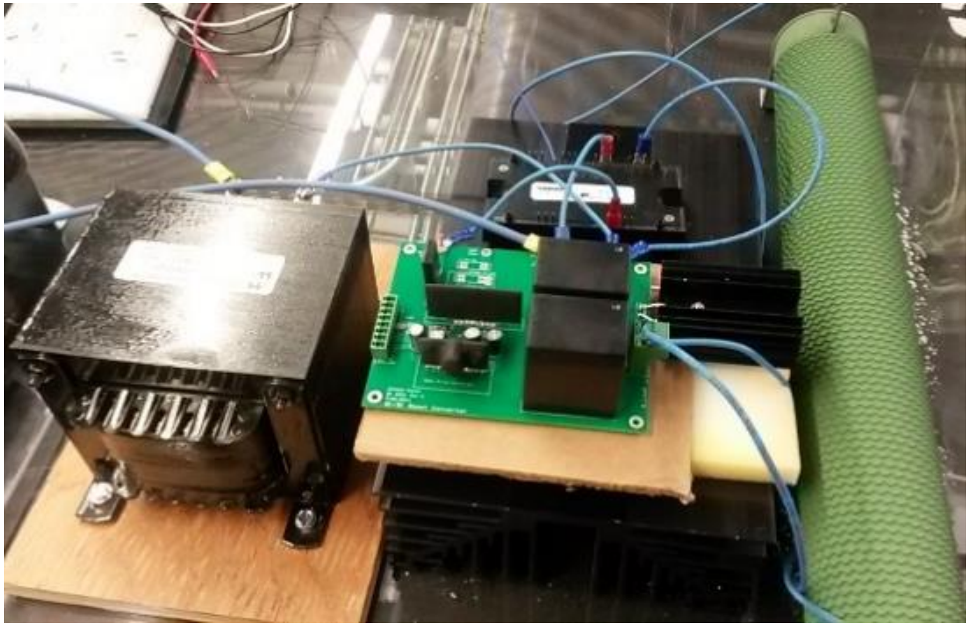
IGBT

MOSFET

Power Electronic Converter Design and Device Analysis

Electro-Thermal Characterization of Power Semiconductors

Experimental Set-Up



Parameter	Numerical Quantity
Input Voltage, V_{in}	220 V (max)
Output Voltage, V_{out}	440 V (max)
Duty Cycle, d	50%
Frequency, f	1000 Hz – 25000 Hz
Load Capacitor, C	220uF (EZPE50117MTA)
Load Resistor, R	103 Ω
Filter Inductor, L	30mH (195P20)
Power Diode	18A, 1.2kV (ISL9R18120G2)

- Designed and constructed DC/DC Boost Converter
- Swept frequency to analyze electrical performance of system with varied transistors
- Recorded Temperature performance to compare between transistors

Power Electronic Converter Design and Device Analysis

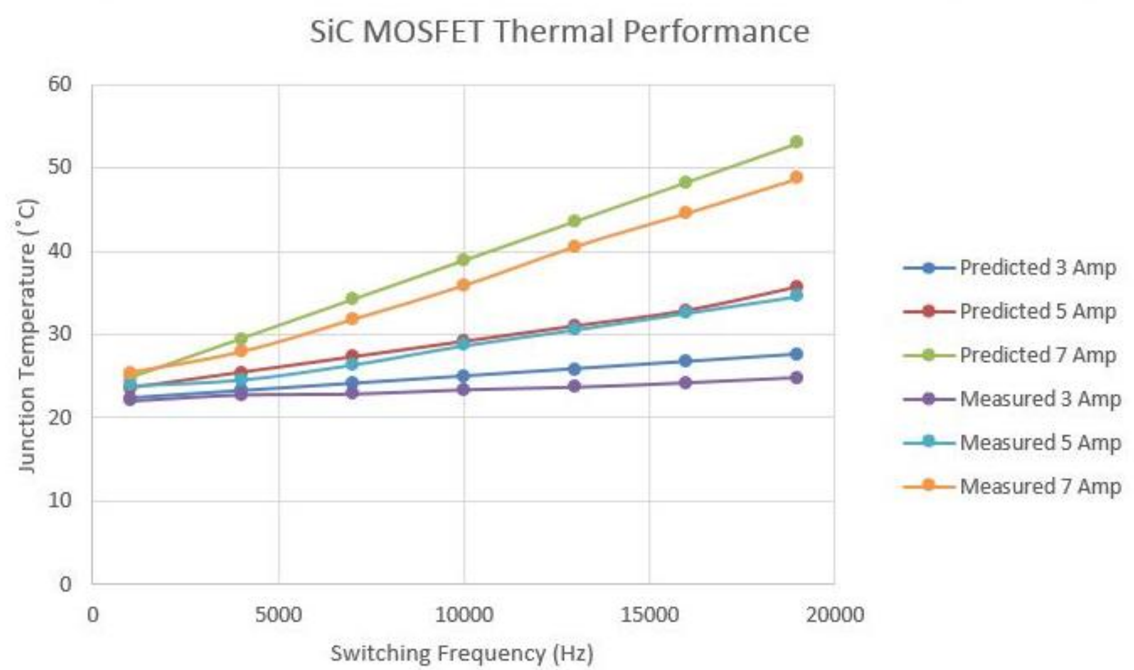
Electro-Thermal Characterization of Power Semiconductors

Thermal Prediction and Measurement of SiC MOSFET

- Using known parameters can accurately predict the Junction Temperature of a SiC MOSFET

- Mathematical expression that relates switching and conduction losses to changes in temperature

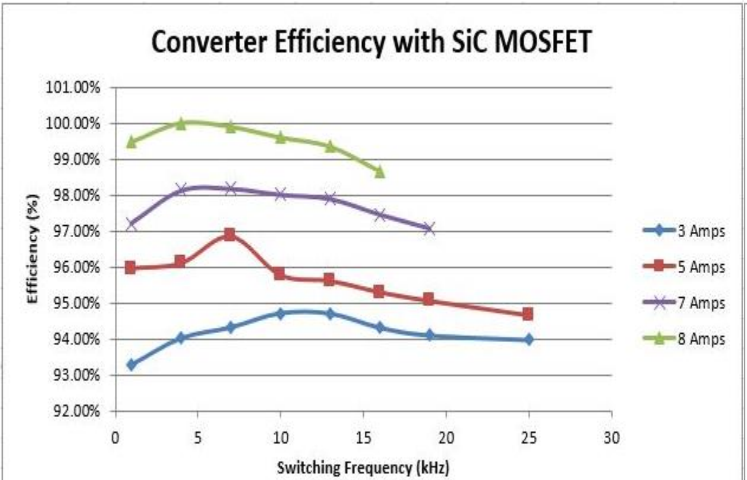
$$E_S f_s + R_{on}\, I_{DS}^2 = \frac{T_J - T_A}{\Theta_{JA}}$$

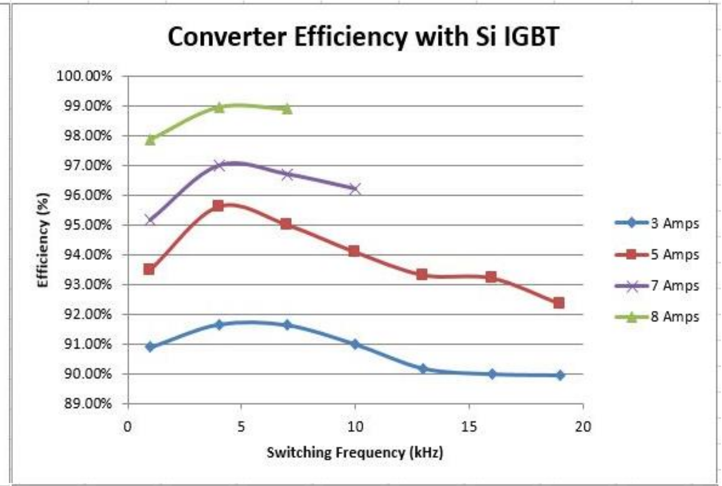


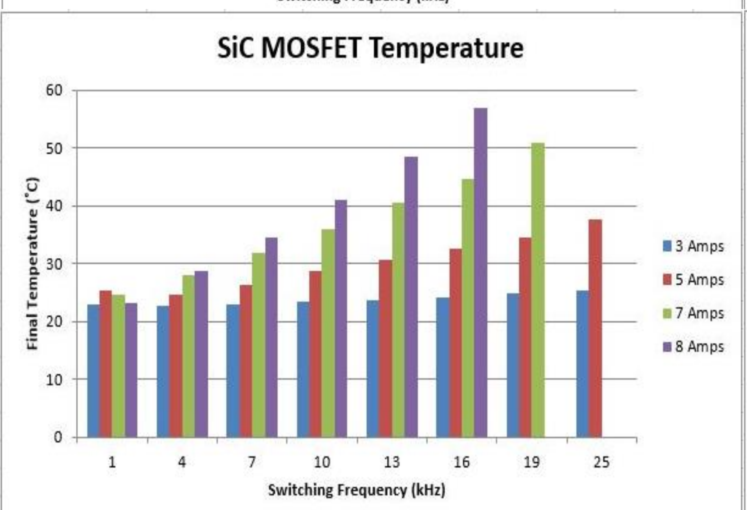
Power Electronic Converter Design and Device Analysis

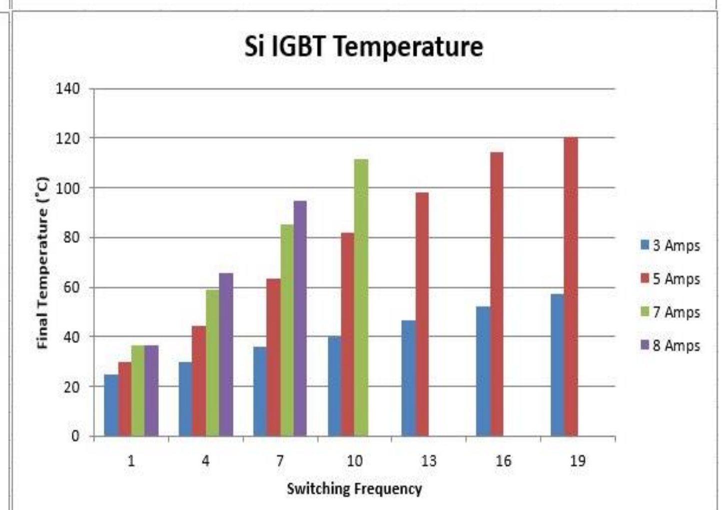
Electro-Thermal Characterization of Power Semiconductors

Device Performance Comparison Conclusions









- Better electrical efficiency from SiC MOSFET
- SiC MOSFET can operate with much smaller thermal management system
- Si IGBT was unable to operate under certain test conditions without risk of damaging the device

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Power Source Buffering using a Triangular Modular Multilevel Converter with Energy Storage

Prepared by: Alvaro Cardoza
M.S. Student

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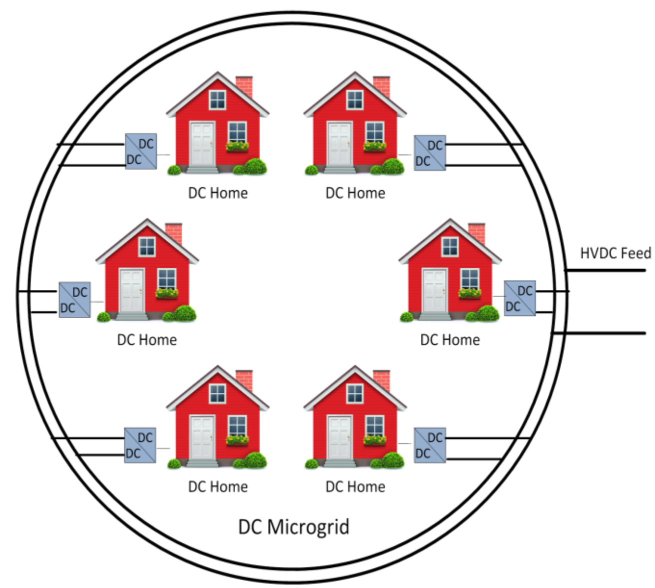
Power Electronic Converter Design and Device Analysis

Power Source Buffering using a TMMC with Energy Storage

Converter Motivation

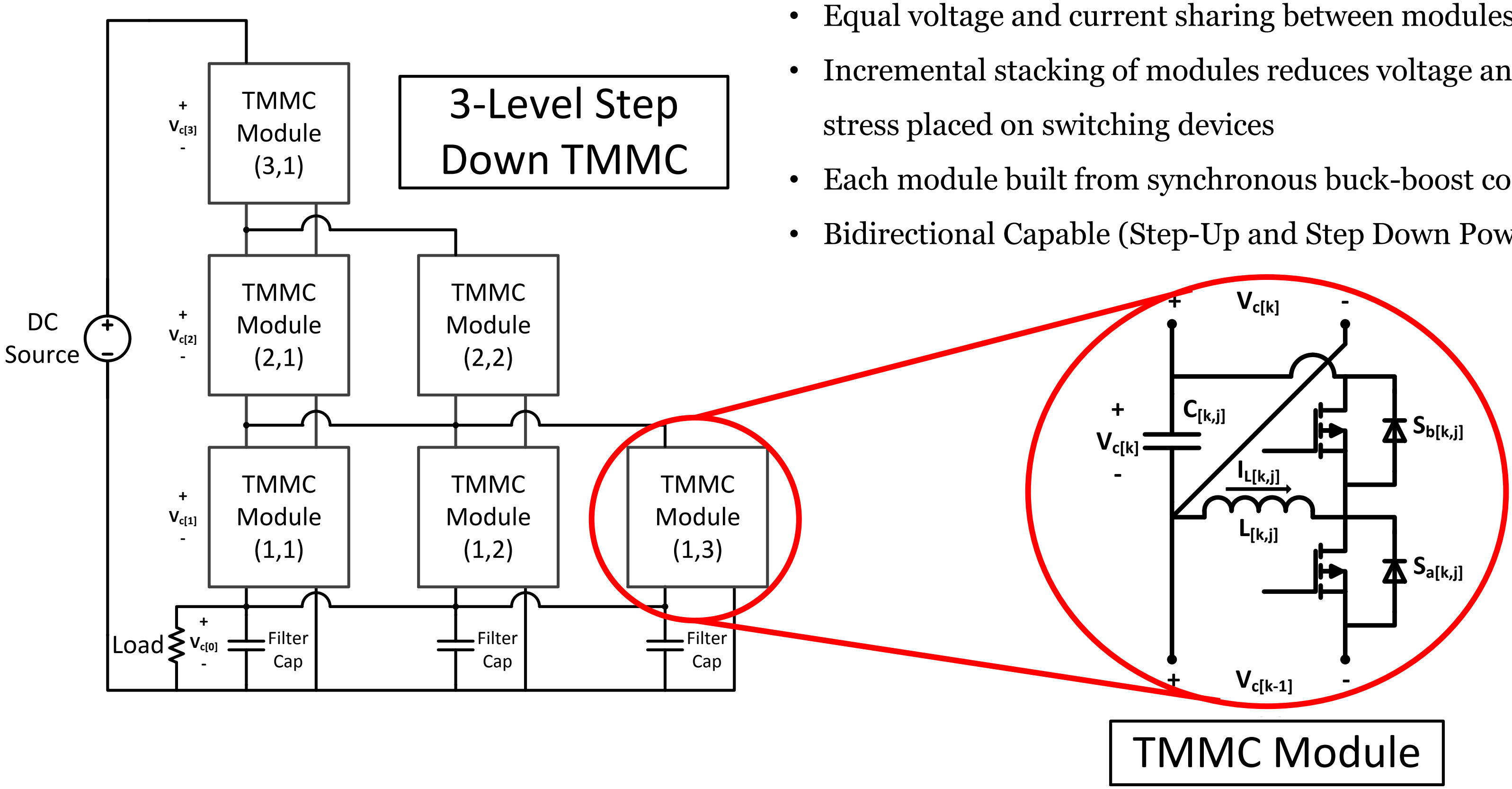
As grid development continues to incorporate DC technologies and diversify its generation sources with renewables, it is becoming increasingly more important to develop new interfacing devices to ensure adequate control and stability of the power grid.



Power Electronic Converter Design and Device Analysis

Power Source Buffering using a TMMC with Energy Storage

Topology Selection - TMMC



Triangular Modular Multilevel Converter

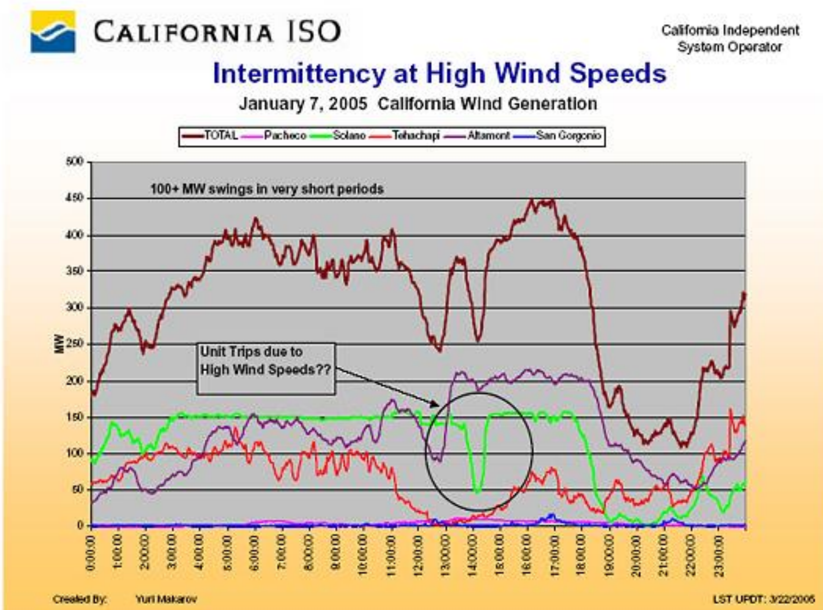
- Equal voltage and current sharing between modules
- Incremental stacking of modules reduces voltage and current stress placed on switching devices
- Each module built from synchronous buck-boost converters
- Bidirectional Capable (Step-Up and Step Down Power Flow)

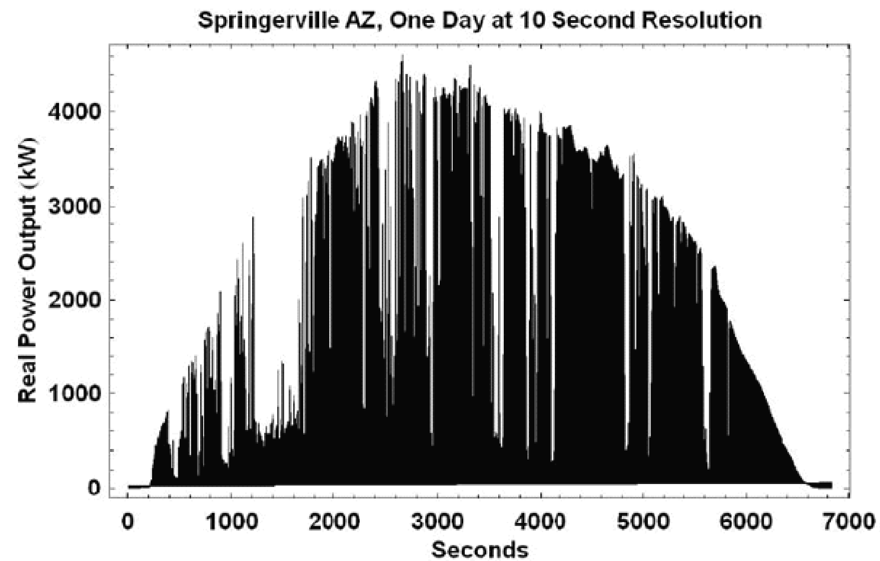
Power Electronic Converter Design and Device Analysis

Power Source Buffering using a TMMC with Energy Storage

Converter Applications – Renewable Generation

A converter with the ability to buffer connected input sources would be directly applicable for integrating inherently intermittent renewable generation sources.





Source: *J. Apt and A. Curtright, "The Spectrum of Power from Utility-Scale Wind Farms and Solar Photovoltaic Arrays," Jan. 2004.*
Y. Makarov and D. Hawkins, " Wind Generation and Grid Operations: Experience and Perspective," CAISO Corp., March 2005. Presentation.

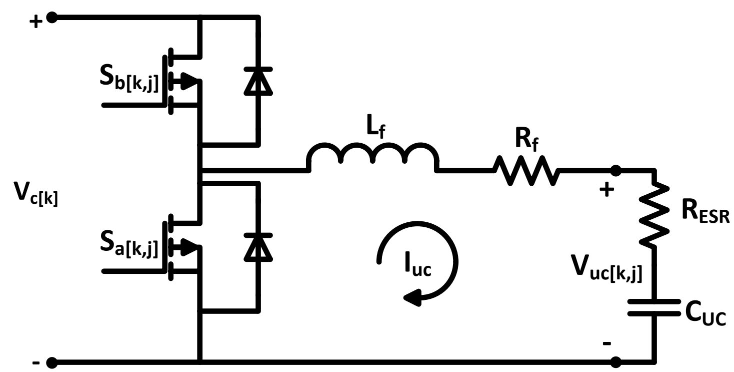
Power Electronic Converter Design and Device Analysis

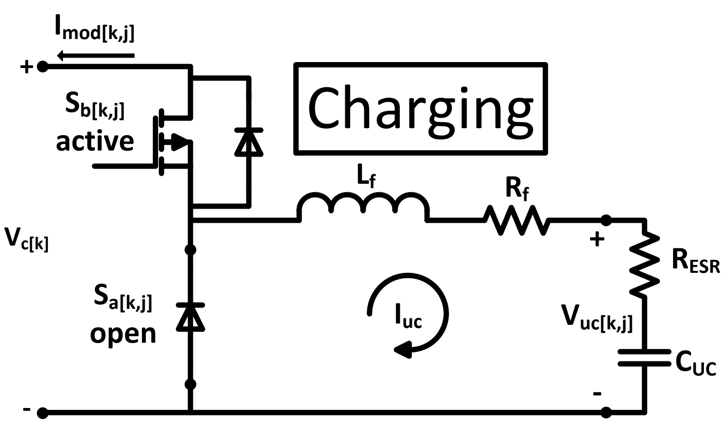
Power Source Buffering using a TMMC with Energy Storage

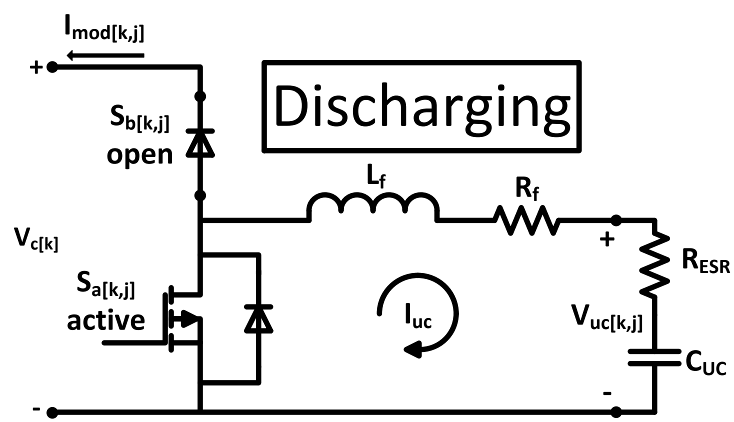
Energy Storage – Integrating Ultracapacitors

Ultracapacitors (UC) were integrated using a converter capable of buck & boost operations

- UC's ideal for transients lasting seconds to minutes
- Quick charge / discharge cycling
- Long cycle lifespan
- High power density







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Enhanced Reliability of APDN Architecture Utilizing Resonant Power Converter Topologies

Prepared by: Christopher Scioscia
M.S. Student

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Power Electronic Converter Design and Device Analysis

Enhanced Availability of APDN Architecture Utilizing a Resonant Power Converter Topology

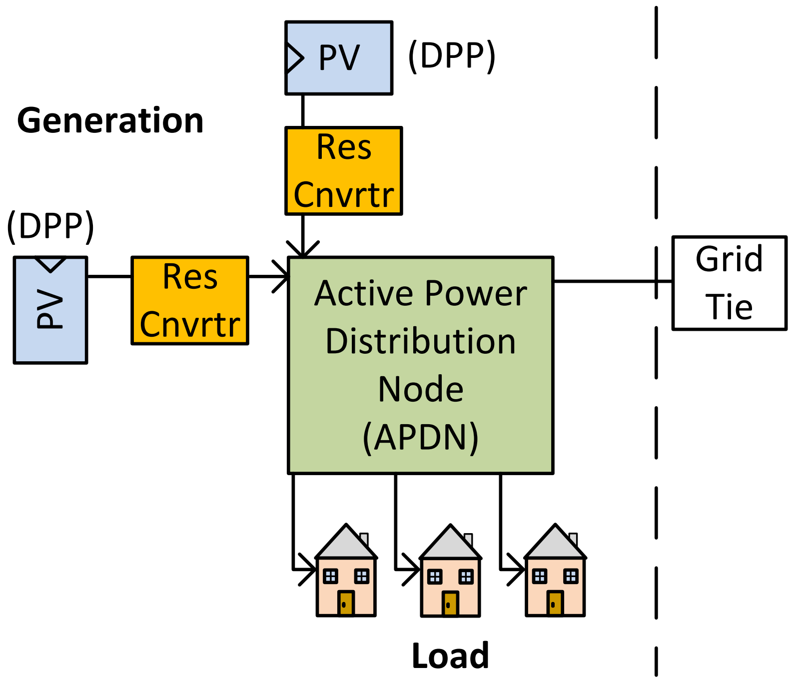
Research Motivation

- Improve reliability and availability in microgrid setting
- Enhance weak grid with smart converter features

Areas of Interest:

- Distributed Power Processing (DPP)
- Resonant Conversion

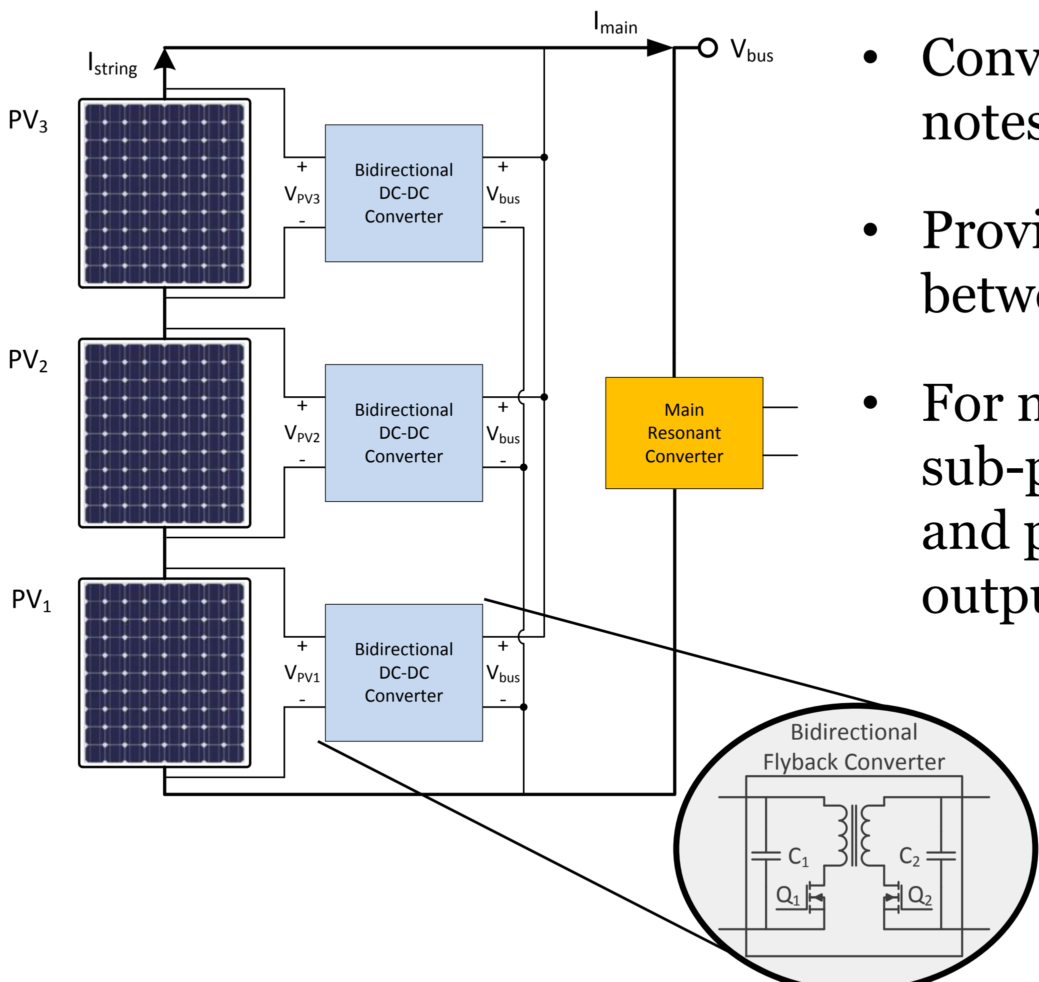
Example Microgrid with APDN



Power Electronic Converter Design and Device Analysis

Enhanced Availability of APDN Architecture Utilizing a Resonant Power Converter Topology

Distributed Power Processing (DPP)



- Converters at intermediate notes
- Provides difference in power between panels
- For mismatches up to 25%, sub-panel efficiency >98% and provides 32% higher output power [1]

[1] C. Olalla, D. Clement, R. Rodriguez, and D. Maksimovic, "Architectures and Control of Submodule Integrated DC-DC Converters for Photovoltaic Applications", *IEEE Transactions on Power Electronics*, Vol. 28, No. 6, pp 2980-2997, June 2013

Power Electronic Converter Design and Device Analysis

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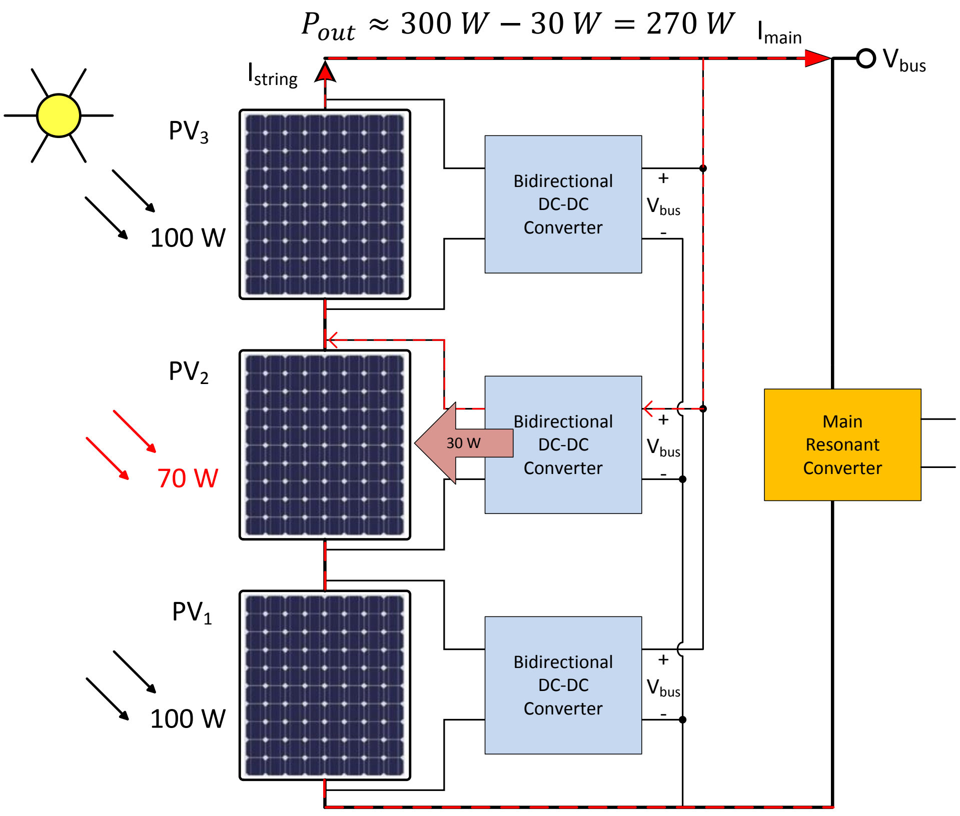
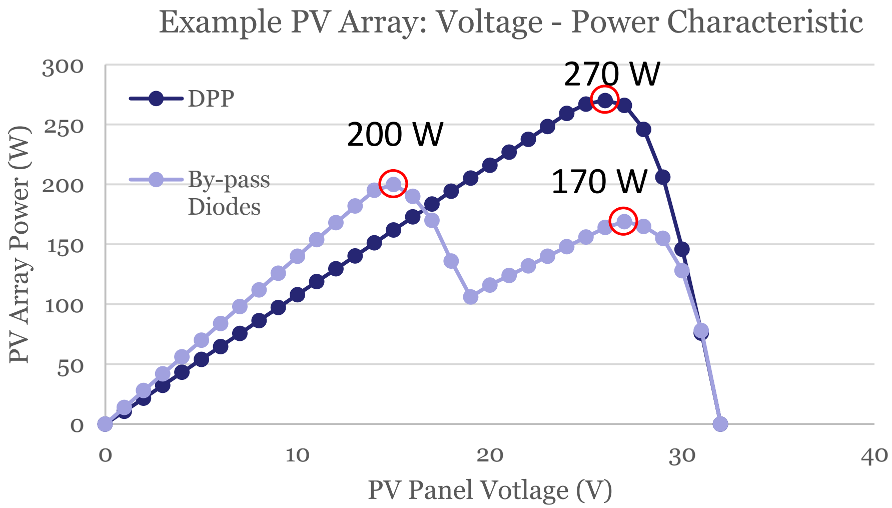
Distributed Power Processing (DPP)



Example:

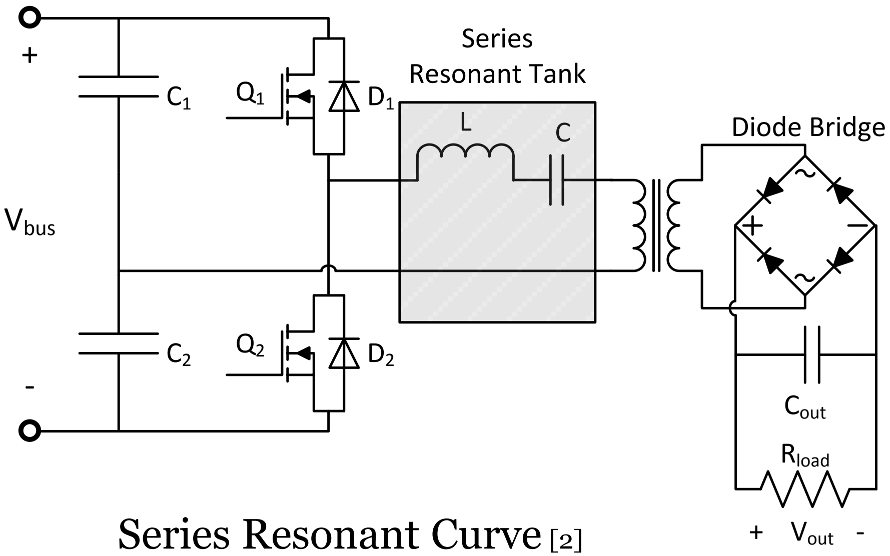
- 100 W rated solar panels
- 30% gradient mismatch



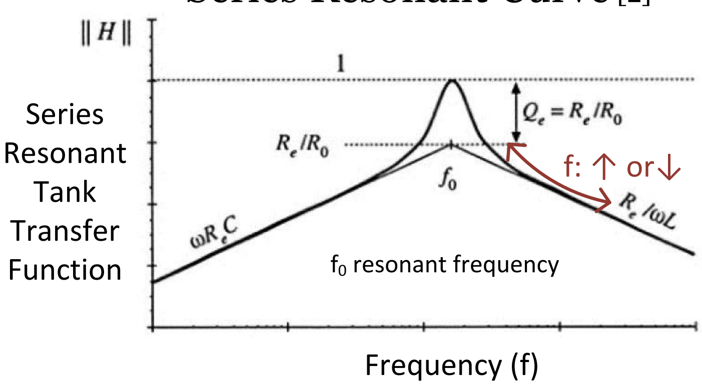
Power Electronic Converter Design and Device Analysis

Enhanced Availability of APDN Architecture Utilizing a Resonant Power Converter Topology

Series Resonant Power Converter



Series Resonant Curve [2]



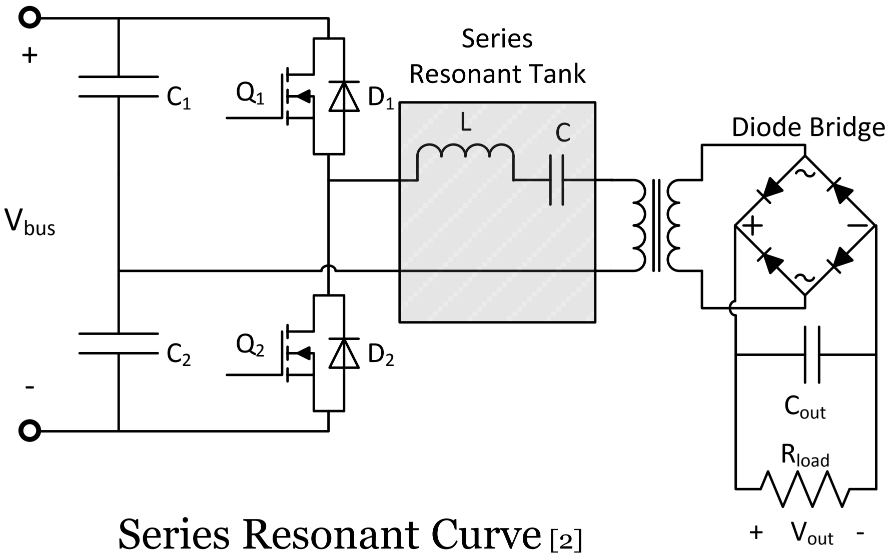
- Utilize impedance curve of resonant tank
- Match output power to load power by adjusting switching frequency

[2] R. Erickson and D. Maksimović, *Fundamentals of Power Electronics*, Second edition, Kluwer, New York, 2001

Power Electronic Converter Design and Device Analysis

Enhanced Availability of APDN Architecture Utilizing a Resonant Power Converter Topology

Series Resonant Power Converter



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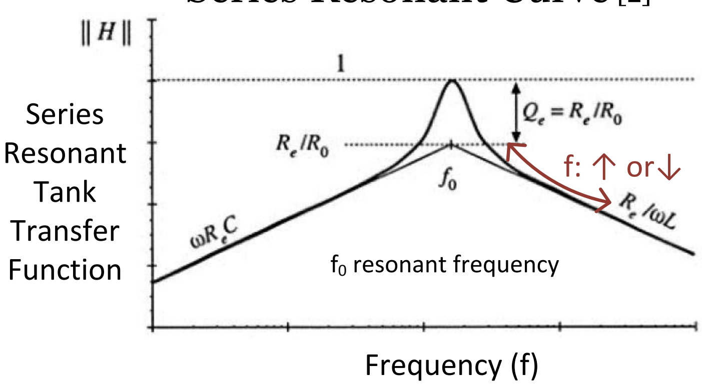

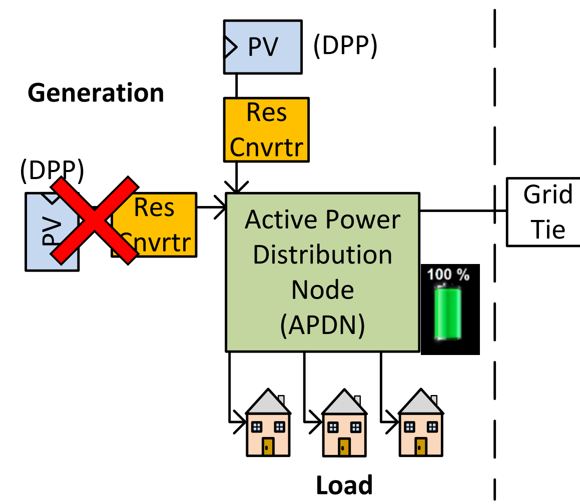

[2] R. Erickson and D. Maksimović, *Fundamentals of Power Electronics*, Second edition, Kluwer, New York, 2001

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Power Electronics Applications in Microgrids

Patrick T. Lewis

Stephanie P. Cortes

Qin-hao Zhang

Stephen M. Whaite

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Dynamic Reactive Current Support as a DG Inverter Function

Patrick T. Lewis

A Residential Energy Management Solution for EV Charging

Stephanie P. Cortes

DC Microgrid Control and Communications in Power System Applications

Qin-hao Zhang

Analysis and Control of the Synchronous Buck Converter With a Constant Power Load

Stephen M. Whaite

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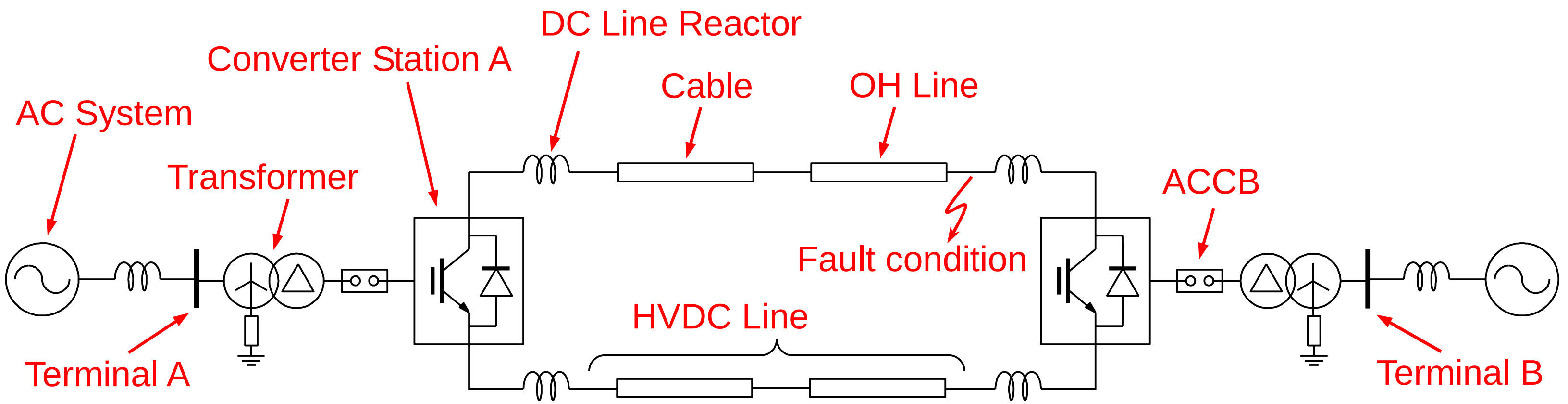
Power Electronic Applications in Microgrids

Dynamic Reactive Current Support as a DG Inverter Function

MELCO Joint Research Update

- First chapter of research collaboration between the University of Pittsburgh and Mitsubishi Electric has come to a close. Next stages of research thrusts are in discussion.
- Outcomes of the HVDC protection research:
  - Conference paper accepted and journal paper submitted
  - Patent application submitted for licensing the fault section identification protection algorithm

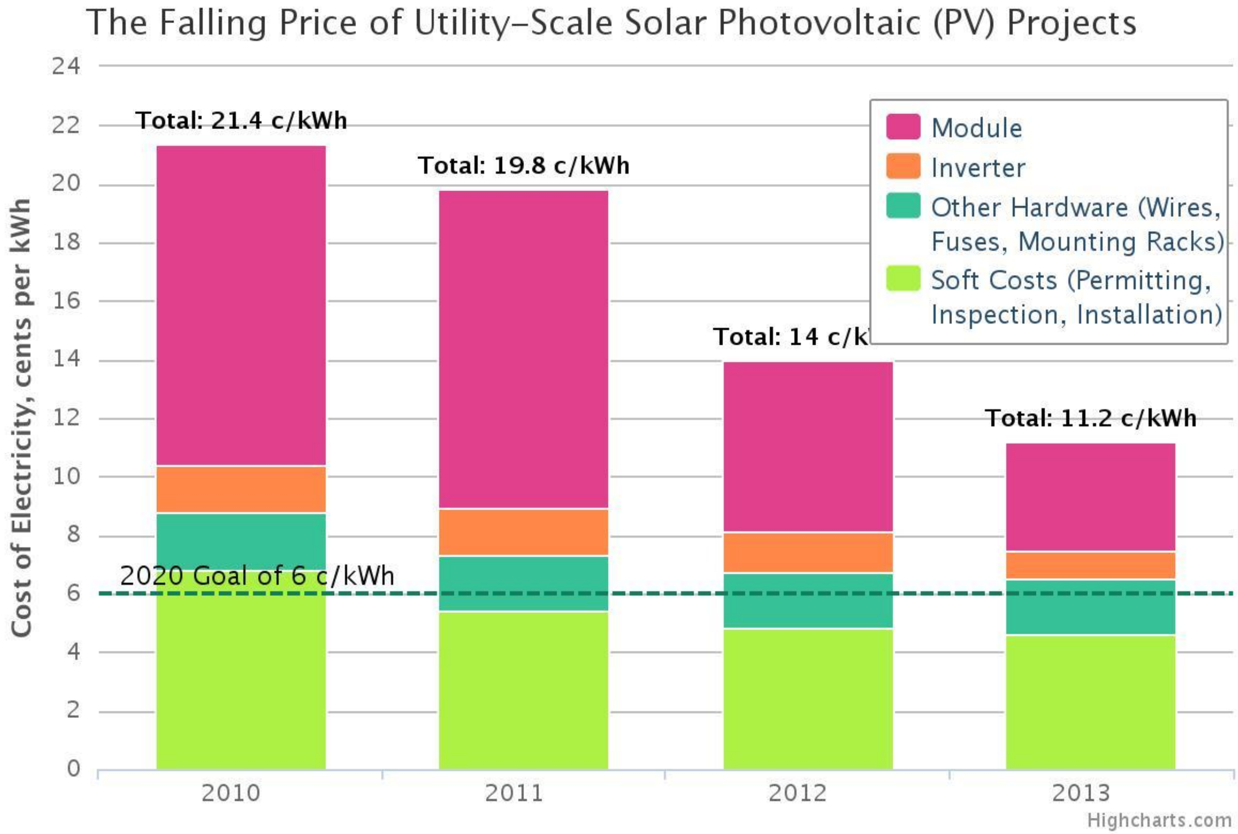


Power Electronic Applications in Microgrids

Dynamic Reactive Current Support as a DG Inverter Function

Research Background

- Increased penetration of distributed PV generation expected on the grid due to cost-competitiveness



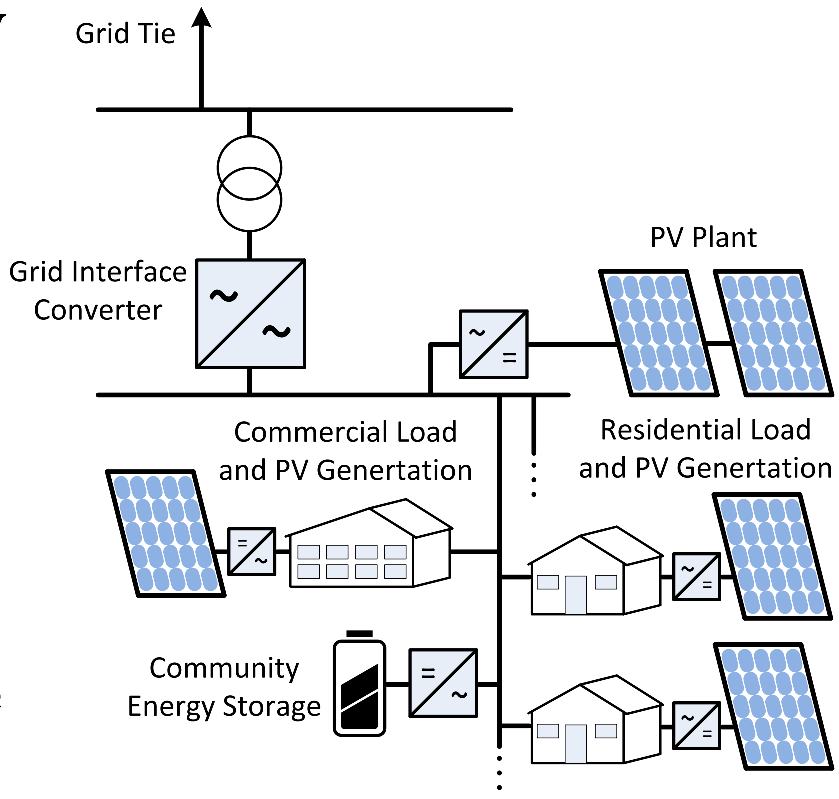
Source: NREL

Power Electronic Applications in Microgrids

Dynamic Reactive Current Support as a DG Inverter Function

Research Background

- In a microgrid, stability and resiliency issues arise during fault events or MG islanding transitions. The voltage rise or fall can cause undesired DG disconnection
- Voltage instability can be resolved with reactive current injection to remedy a voltage sag and with reactive current absorption for a voltage rise
- IEEE standard 1547 defines the stable ranges of voltage and frequency as interconnection specifications for distributed generation



Example of Community Microgrid

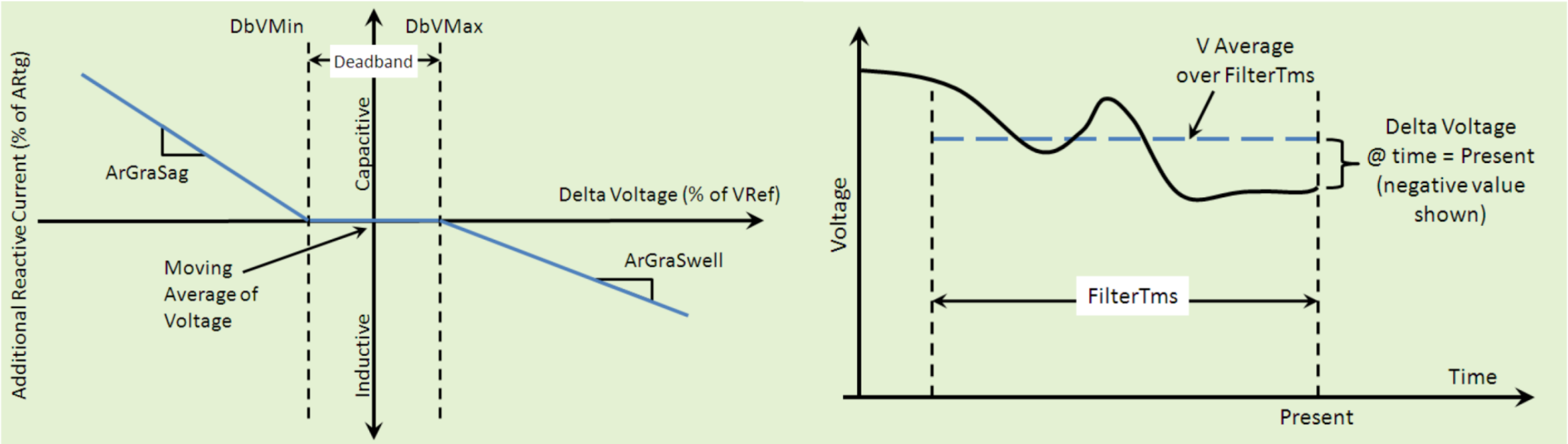
Power Electronic Applications in Microgrids

Dynamic Reactive Current Support as a DG Inverter Function

Reactive Current Injection as Grid Support

- During fault ride through event injecting sufficient reactive current must be determined according to the measured voltage at the grid

$$k = \frac{(I_q - I_{q0})/I_{rated}}{(1 - v_g)}, \qquad where\ I_q < I_{rated}$$



Source: Seal B., “Common Functions for Smart Inverters, Version 3” *Electric Power Research Institute*, Feb 2014
Source: Yongheng Yang; Huai Wang; Blaabjerg, F., "Reactive Power Injection Strategies for Single-Phase Photovoltaic Systems Considering Grid Requirements,“ in *Industry Applications, IEEE Transactions on* , vol.50, no.6, pp.4065-4076, Nov.-Dec. 2014

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A Residential Energy Management Solution for EV Charging

Prepared by: Stephanie P. Cortes
Sr. Undergraduate Student

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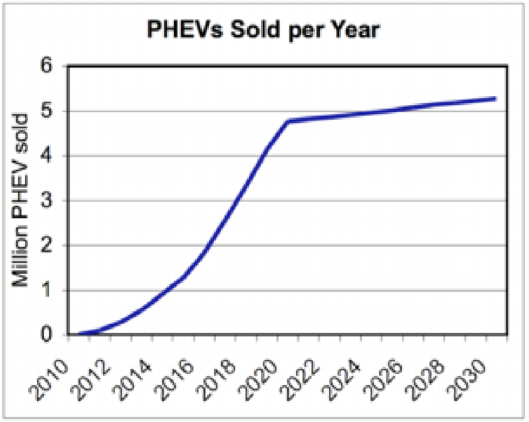
Power Electronic Applications in Microgrids

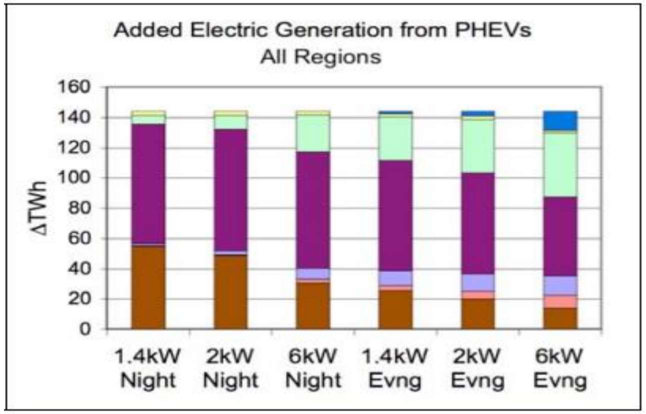
A Residential Energy Management Solution for EV Charging

Research Motivation

- Electric vehicles (EVs) – a promising solution to:
  - Reduce greenhouse gas emissions from the transportation sector
  - Increase economic independence from non-renewable resources
- Concerns:
  - Rapid increases in peak electrical consumption from a home or business
  - Transformer and feeder overloads
- Emerging solution: Vehicle-to-Grid
  - Neglects variability of human behavior and expectations



Projected number of PHEVs sold per year.



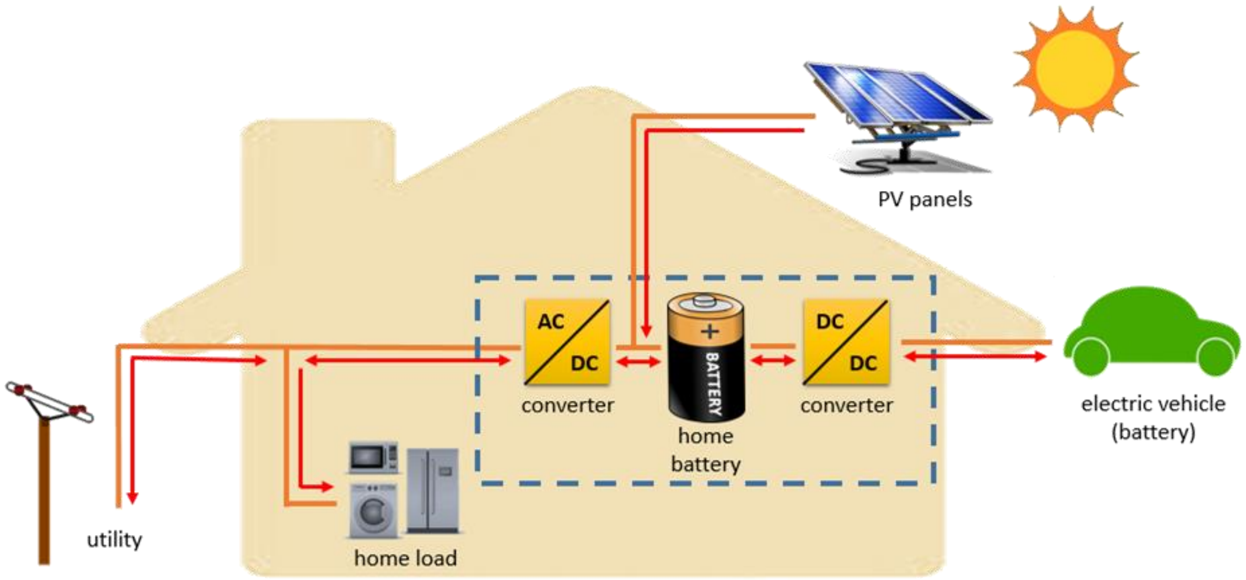
Projected 2030 requirements for new generation to meet PHEV demand.

Source: S.W. Hadley, A. Tsvetkova. "Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation." *Oak Ridge National Laboratory*, January 2008, ORNL/TM-2007/150.

Power Electronic Applications in Microgrids

A Residential Energy Management Solution for EV Charging

Proposed System



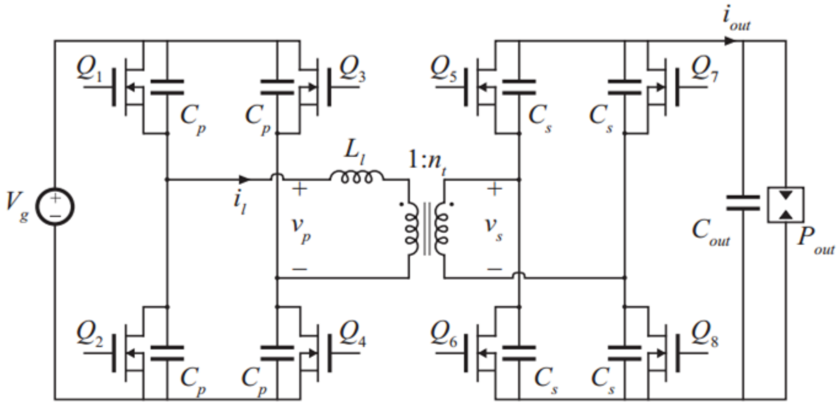
- Control strategy to manage bi-directional flow between EV and home battery
- Increased charging automation reduces grid impacts and importance of time-of-day charging by providing a buffer for the EV system
- Facilitates integration of renewable resources to charging infrastructure

Power Electronic Applications in Microgrids

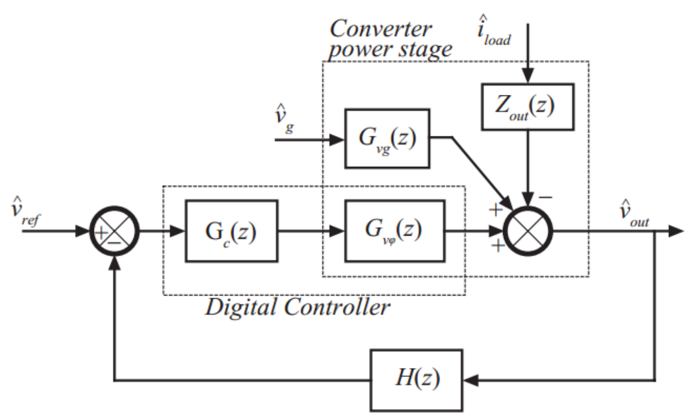
A Residential Energy Management Solution for EV Charging

Current Progress and Aims

- Development of energy management system
  - Full bridge isolated DC/DC converter
  - Evaluation of multiple energy storage models
- Simulation of converter circuit (PLECS) and control system (MATLAB/Simulink)
- Verify operation of system in hardware
- Optimize energy management system



DAB converter schematic.



Small-signal, discrete-time, closed-loop control block diagram of DAB converter.

Source: D.J. Costinett. "Analysis and Design of High Efficiency, High Conversion Ratio, DC-DC Power Converters." PhD dissertation, Dept. ECE Eng., Univ. Colorado, 2013.

DC Microgrid Control and Communications in Power System Applications

Prepared by: Qin-hao Zhang
Ph.D. Student

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Power Electronic Applications in Microgrids

DC Microgrid Control and Communications

Controller Tasks: Built-in Intelligence for an Evolving Grid

- **PI controller is not effectively useful to address stability issue in nonlinear system:**
  - Power electronic device
  - Constant Power Load

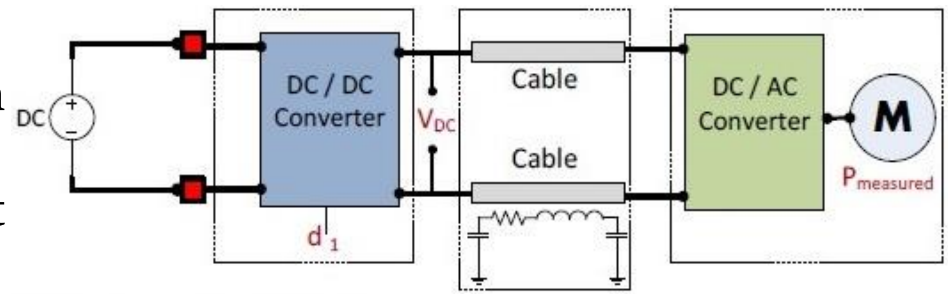
- **Modern control technique provides a better solution:**
  - State feedback approach for handling communication delays in power electronic systems
  - Model reference adaptive control for optimizing maximum power point tracking algorithms in photovoltaic systems.

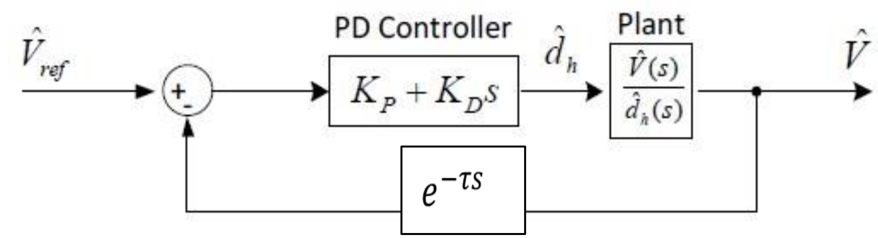
Power Electronic Applications in Microgrids

DC Microgrid Control and Communications

Modern Control Theory Representing Complex Dynamics

- Proportional-Derivative controls are used to improve system stability.
- Introducing a communication system on top of the electrical infrastructure vastly increases the order of the plant dynamics that need to be controlled and regulated.
- Modern control approach can easily handle with modern computers. This approach is an explicit way to compact the system dynamic equations in matrix form.
- State variables are measurable quantities within the power system (voltage and current as examples) and easy to implement.





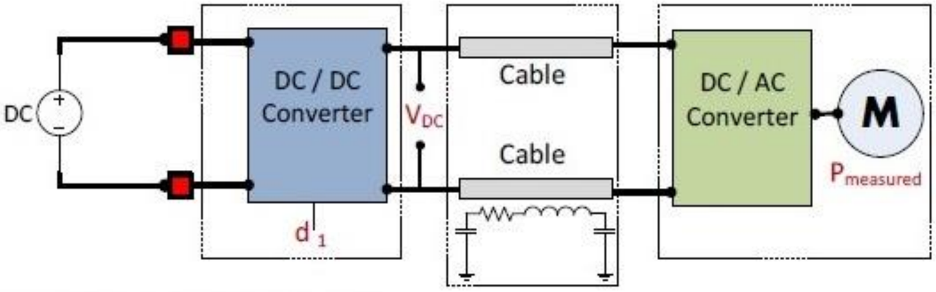
$$\begin{bmatrix} \dot{V}_1 \\ V_2 \\ \cdots \\ i_1 \\ i_2 \end{bmatrix} = A \begin{bmatrix} V_1 \\ V_2 \\ \cdots \\ i_1 \\ i_2 \end{bmatrix} + B\hat{d} \qquad V_{out} = C \begin{bmatrix} V_1 \\ V_2 \\ \cdots \\ i_1 \\ i_2 \end{bmatrix}$$

Power Electronic Applications in Microgrids

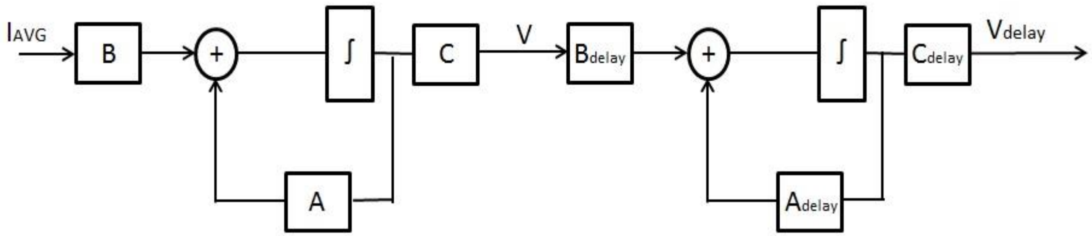
DC Microgrid Control and Communications

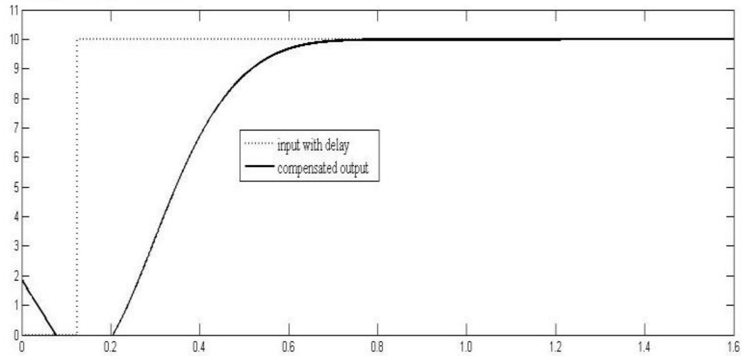
State Feedback Controller Design Accounting for Communication Delays

- The control law is derived based on the state variables previously outlined:



$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$
$$u = -Kx$$





- State space representation using all system information in one equation
- Result of the voltage output by using full state space feedback

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Analysis and Control of the Synchronous Buck Converter With A Constant Power Load

Prepared by: Stephen M. Whaite
M.S. Student

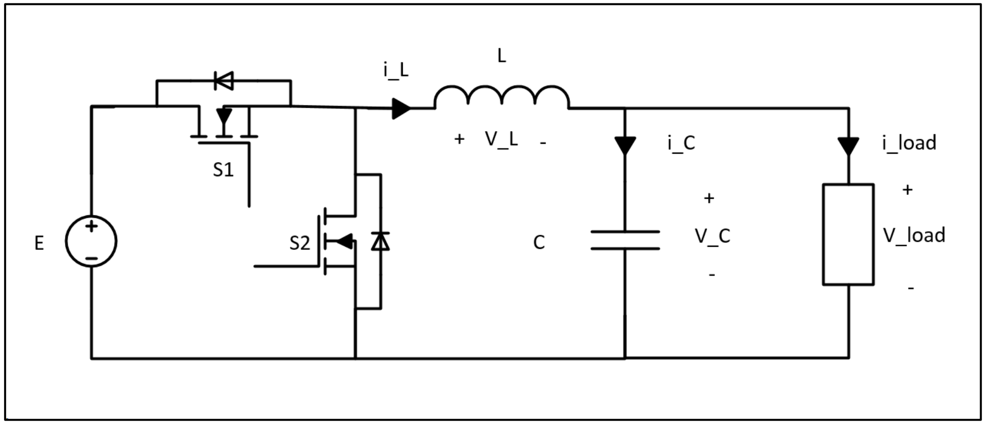
10th Annual Electric Power Industry Conference
Swanson School of Engineering
Graduate Student Symposium
November 16th, 2015

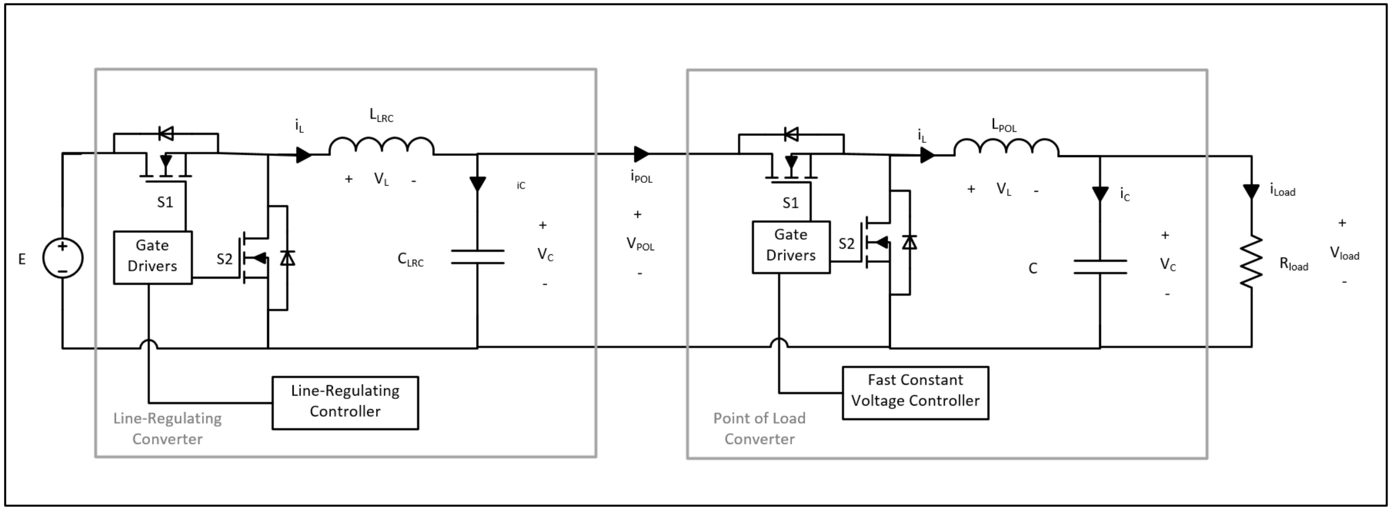
Power Electronic Applications in Microgrids

Analysis and Control of the Synchronous Buck Converter with a Constant Power Load

The System

- Synchronous Buck Converter
- Cascaded Converters
- Constant Power Load Behavior

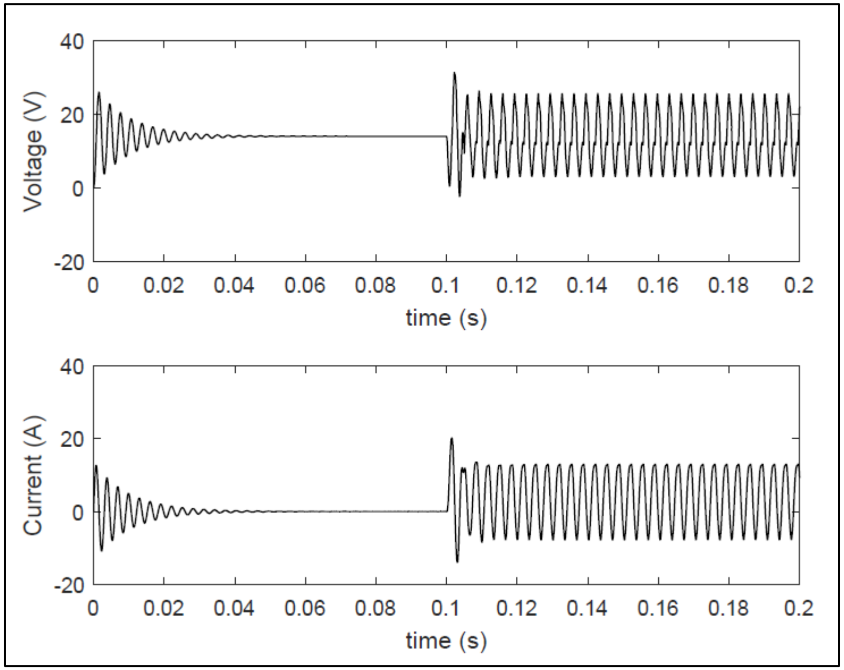




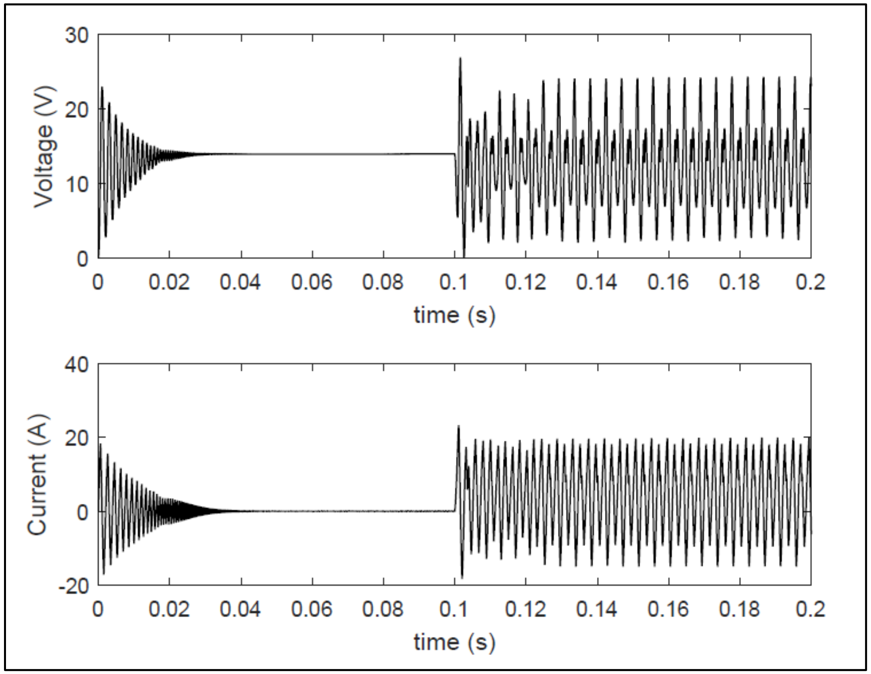
$$I_{Load} = \frac{P_{CPL}}{V_{Load}}$$

Power Electronic Applications in Microgrids
Analysis and Control of the Synchronous Buck Converter with a Constant Power Load
The Problem

Constant Duty Cycle



PI Control

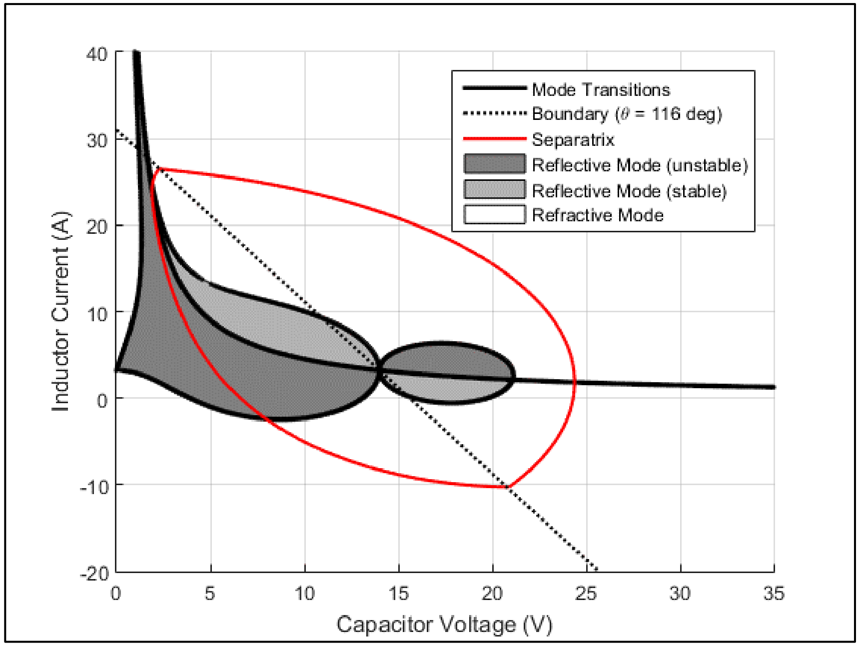


Power Electronic Applications in Microgrids

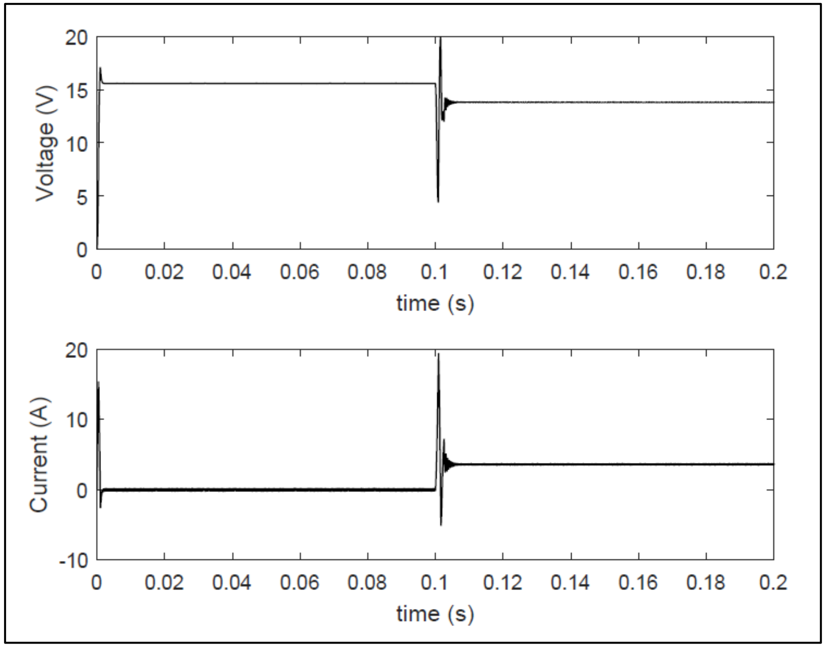
Analysis and Control of the Synchronous Buck Converter with a Constant Power Load

Boundary Control

Controller Definition



Controller Performance

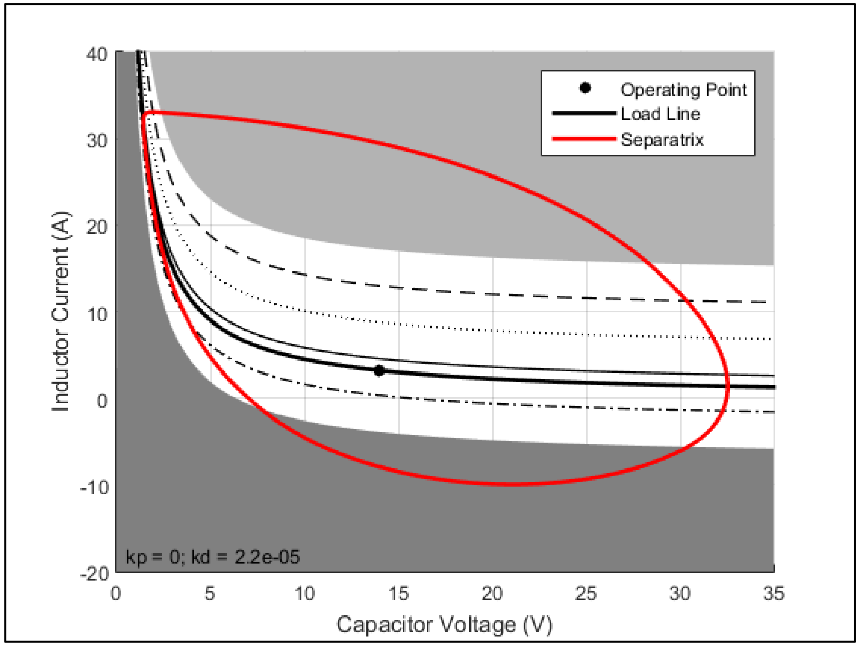


Power Electronic Applications in Microgrids

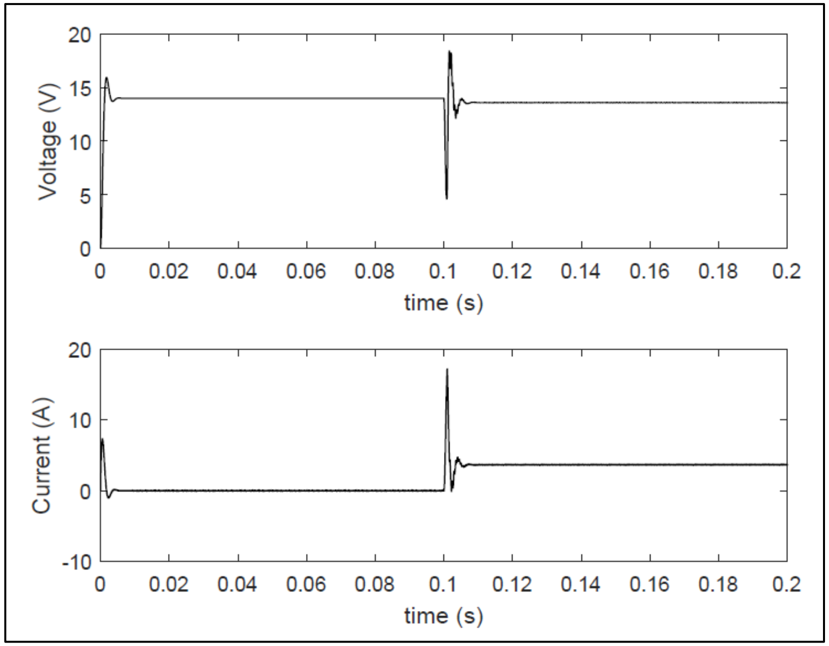
Analysis and Control of the Synchronous Buck Converter with a Constant Power Load

Derivative Control

Controller Definition



Controller Performance



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Photovoltaic Modeling, Testing and System Integration

Cedric Ofakem
Laura Wieserman
Andrew Reiman
Andrew Bulman

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November 16th, 2015

Overvoltages Associated with Photovoltaic Inverter Transients

Cedric Ofakem

Modeling Photovoltaic Inverter Transients using the Hammerstein-Wiener Method

Laura Wieserman

Distribution Modeling for Feeder Analytics and Distributed Energy Resource (DER) Integration

Andrew Reimen

DC Microgrid Development for Renewable Energy & Battery Storage Integration

Andrew Bulman

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Overvoltages Associated with Photovoltaic Inverter Transients

Prepared by: Cedric Ofakem
M.S. Student

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Photovoltaic Modeling, Testing and System Integration

Overvoltages Associated with PV Inverter Transients

Background

Why is a transient model necessary for PV inverters?

- Provide better prediction of inverter behavior in order to perform protection studies.
- Enable more accurate planning and interconnection studies by power system engineers.

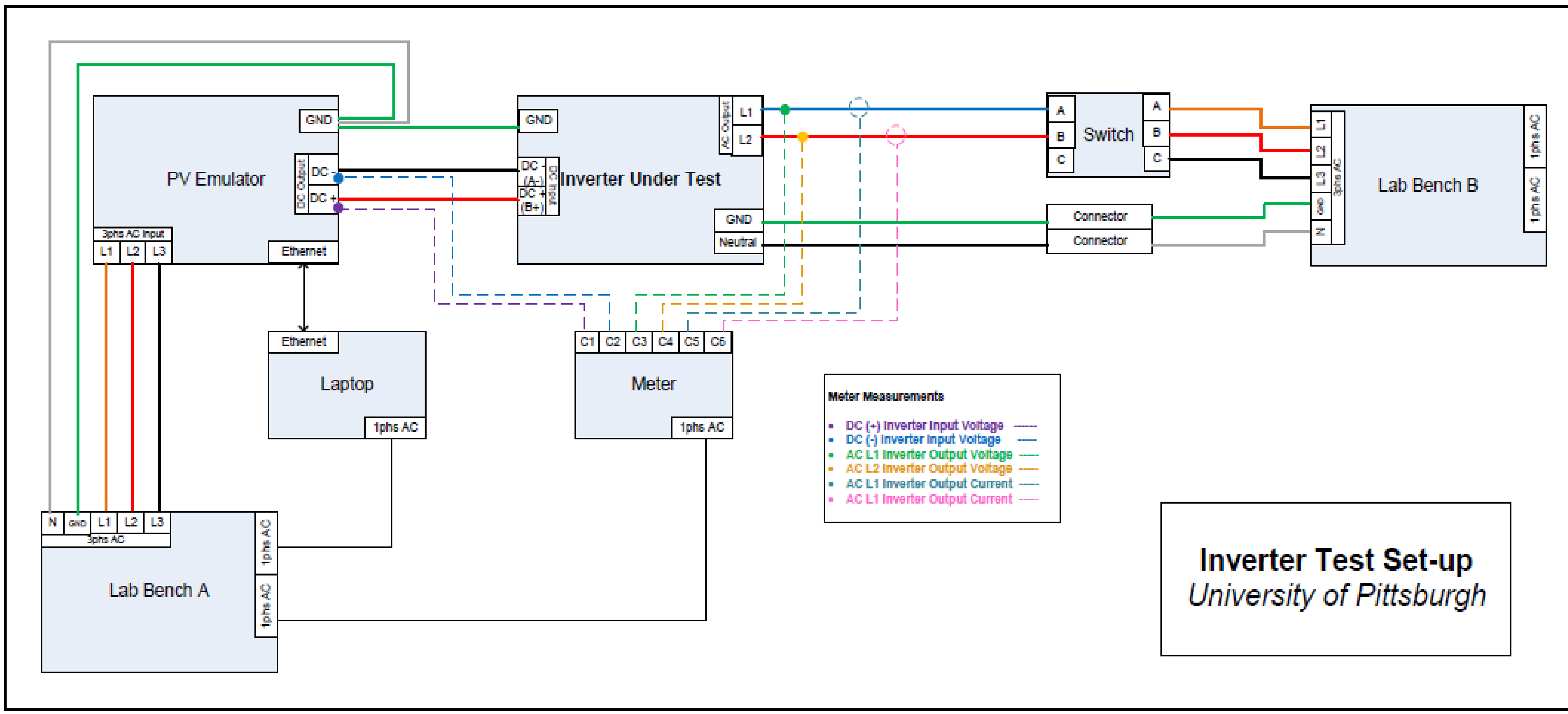
Increase in penetration and inaccurate planning models will cause unreliable system protection, leading to possible mis-operation and mis-coordination of relaying equipment. Valid transient models are necessary for planning and studying the impact of increased PV renewable penetration on the electric power grid.

Photovoltaic Modeling, Testing and System Integration

Overvoltages Associated with PV Inverter Transients

Test Set-Up

One-line Diagram for Inverter Testing

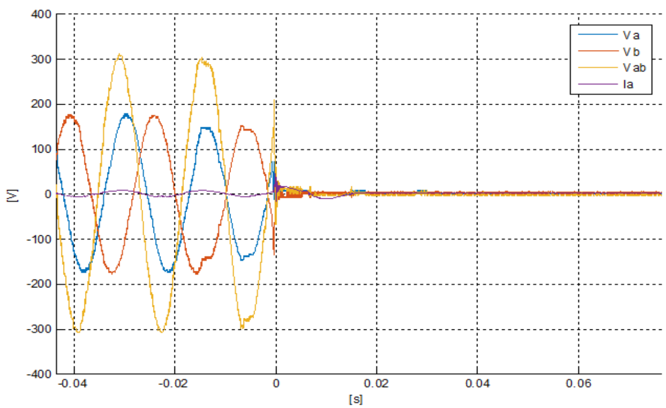


Photovoltaic Modeling, Testing and System Integration

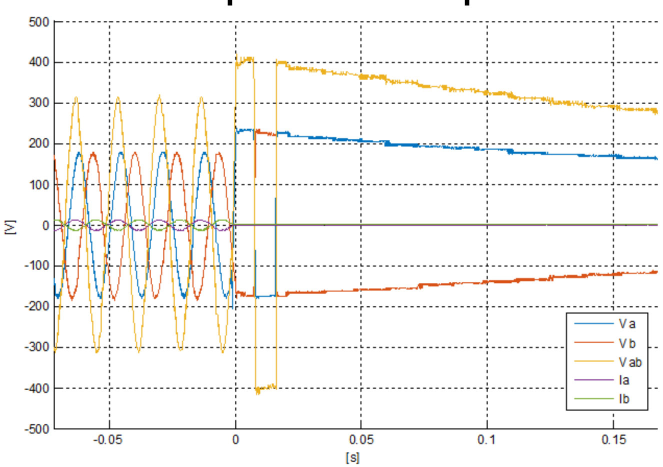
Overvoltages Associated with PV Inverter Transients

Results

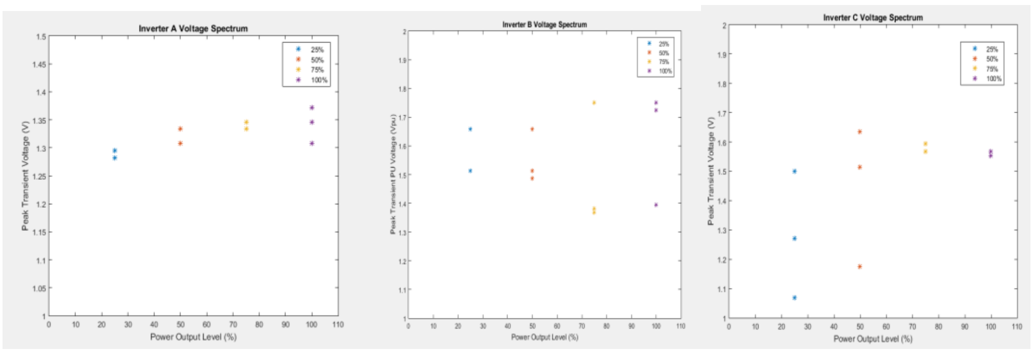
Short-circuit sample



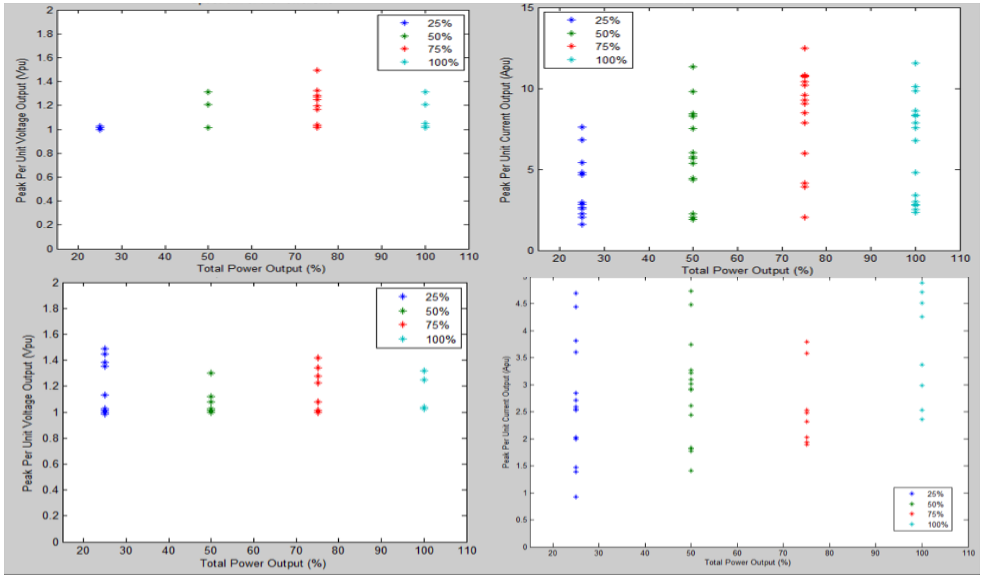
Open-circuit sample



Overvoltage Spectrum Plots (OC Tests)



Overvoltage and Overcurrent Spectrum Plots (SC Tests)



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Modeling Photovoltaic Inverter Transients using the Hammerstein-Wiener Method

Prepared by: Laura Wieserman

Ph.D. Student

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Photovoltaic Modeling, Testing and System Integration

Modeling Photovoltaic Inverter Transients using the Hammerstein-Wiener Method

Inverter Model for Studies

OpenDSS – Distribution System Simulator

- Multipurpose distribution system analysis tool
- Open Source Software

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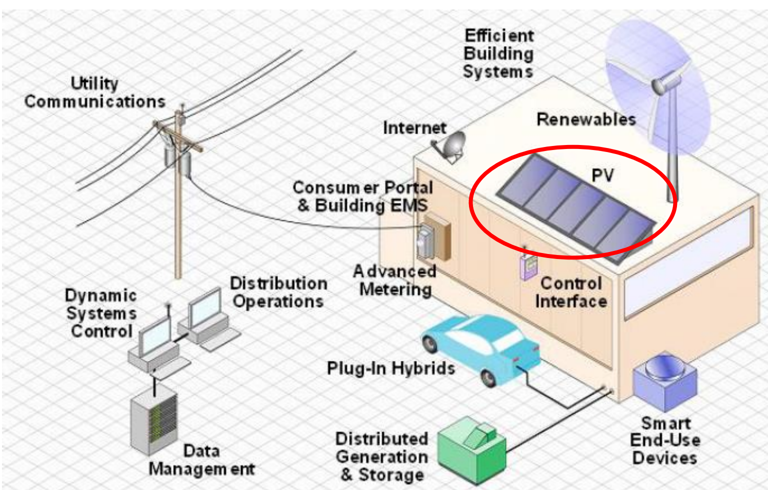


Planning and
Interconnection Studies

Photovoltaic Modeling, Testing and System Integration

Modeling Photovoltaic Inverter Transients using the Hammerstein-Wiener Method

Lab Set-Up

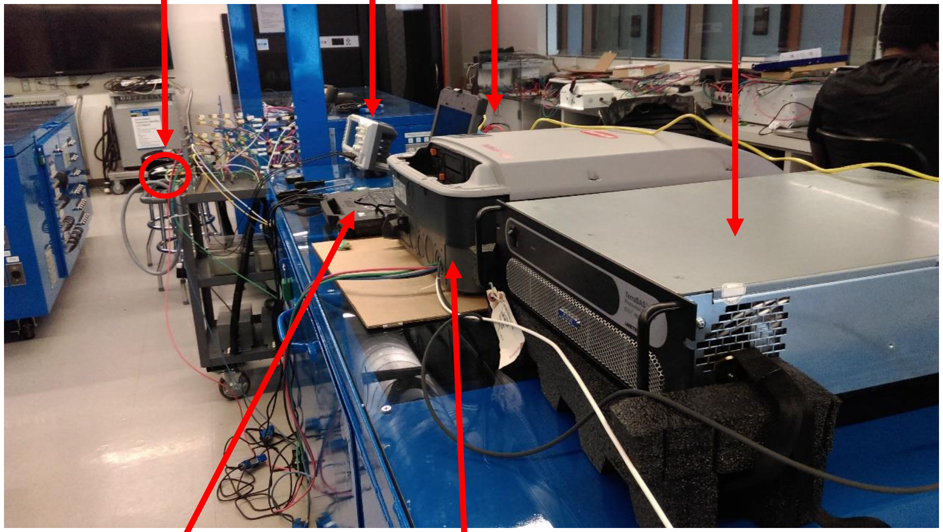
OC Switch

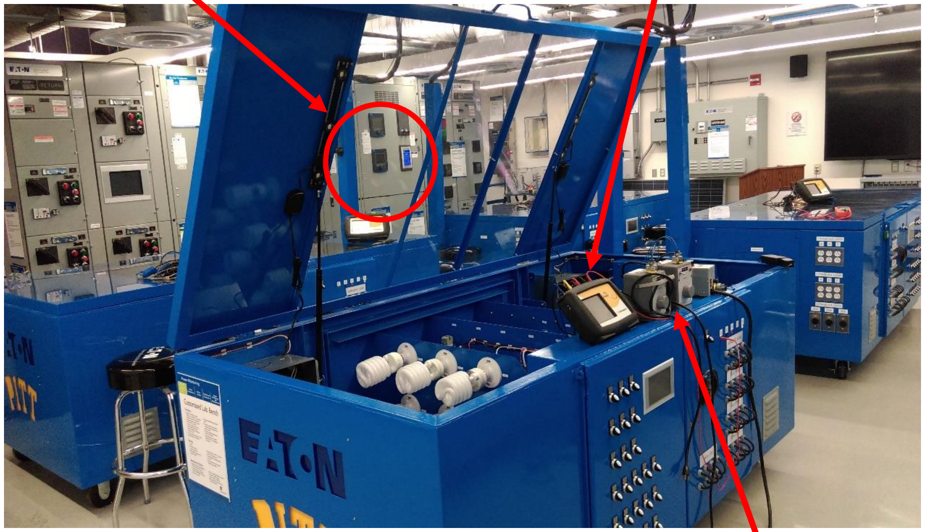
Two scopes

PV Emulator

Sag Generator

Monitoring Voltage/Current/Power





Emulator Control

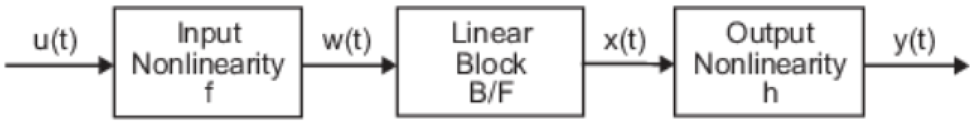
Inverter Under Test

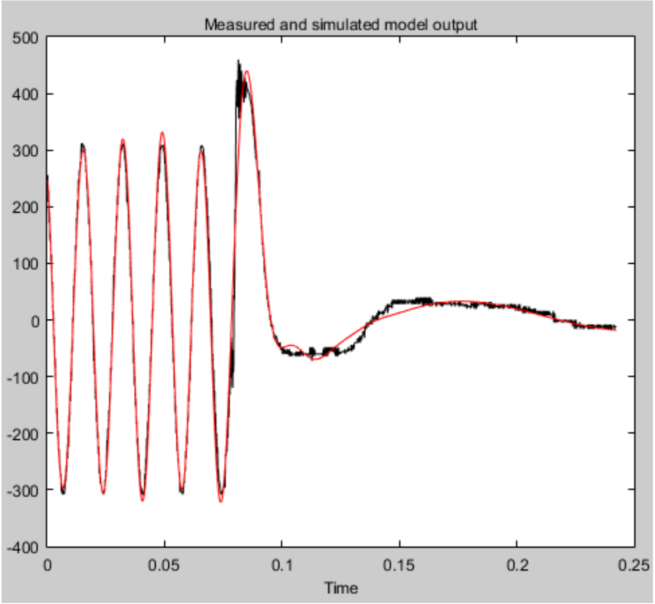
3 single-phase autotransformers

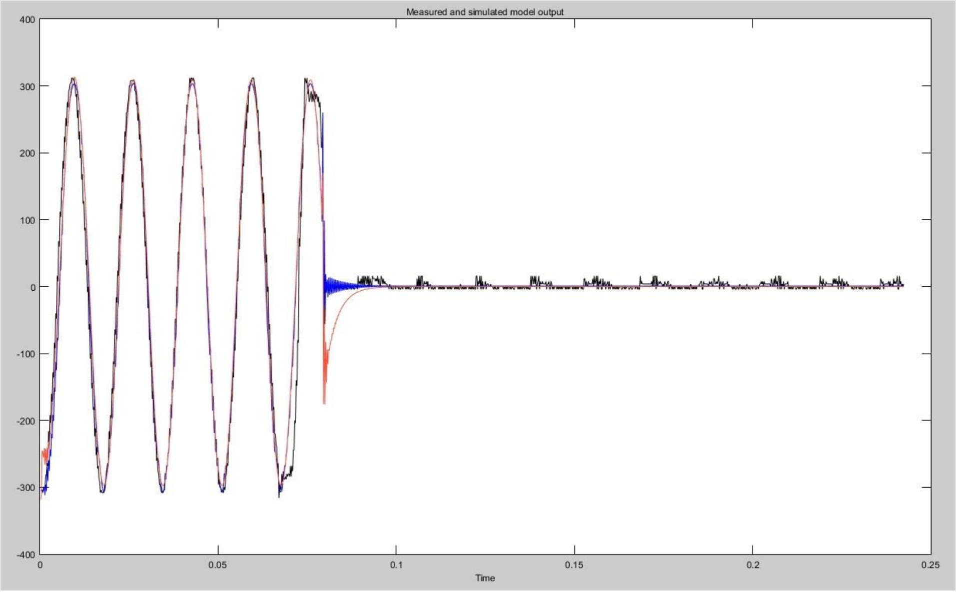
Photovoltaic Modeling, Testing and System Integration

Modeling Photovoltaic Inverter Transients using the Hammerstein-Wiener Method

System Identification Framework







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Distribution Modeling for Feeder Analytics and Distributed Energy Resource (DER) Integration

Prepared by: Andrew Reiman
Ph.D. Student

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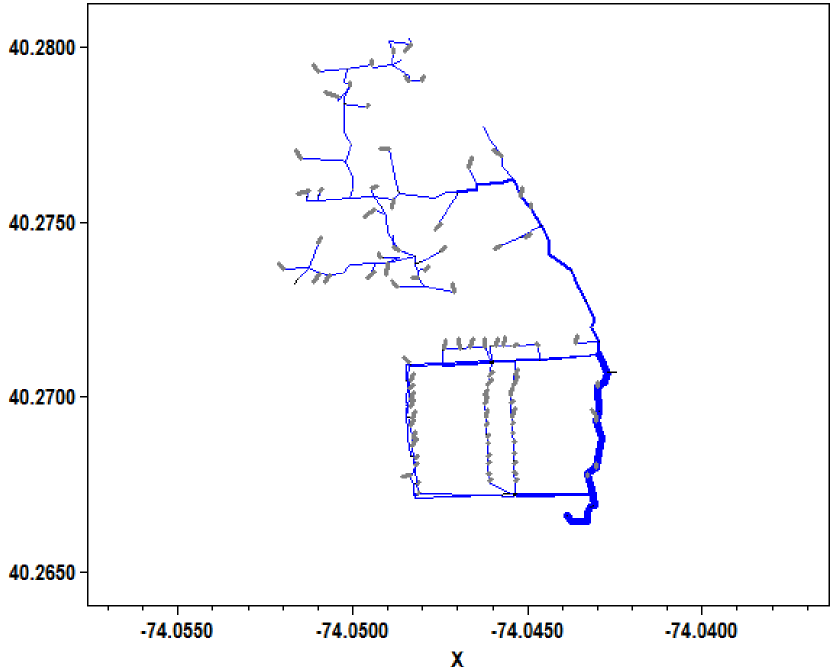
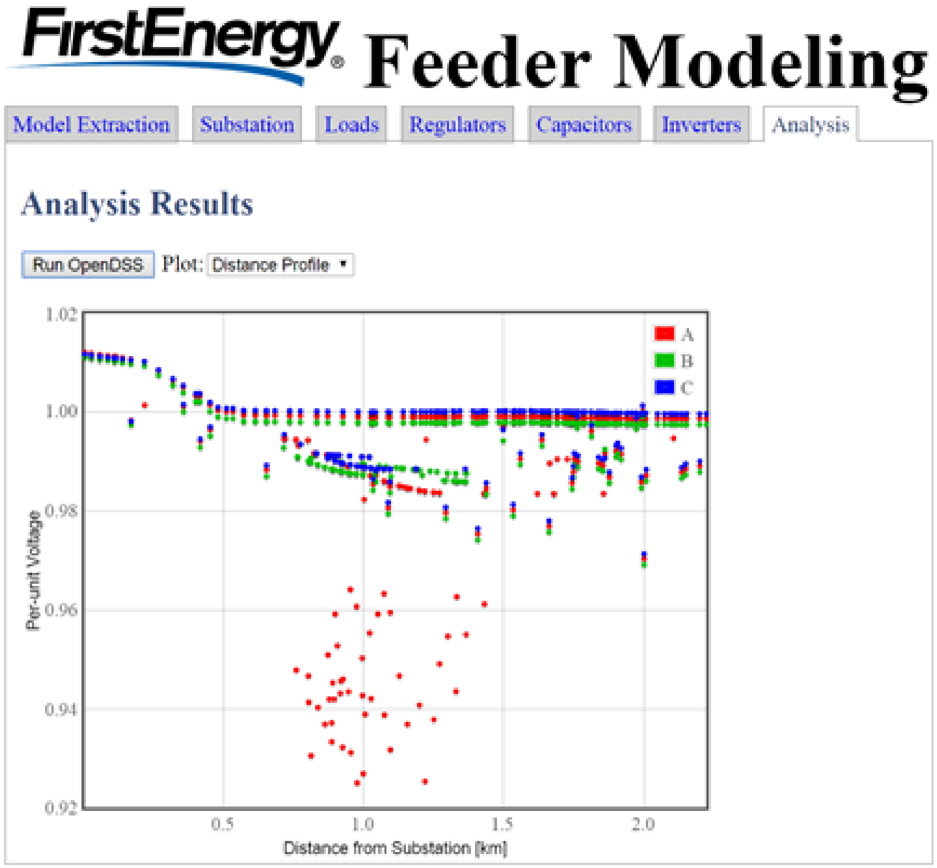
Photovoltaic Modeling, Testing and System Integration

Feeder Analytics and DER Integration

Applet has been deployed to company server

- Integration is ongoing
- 20 circuits tested now, 100+ circuits by year end

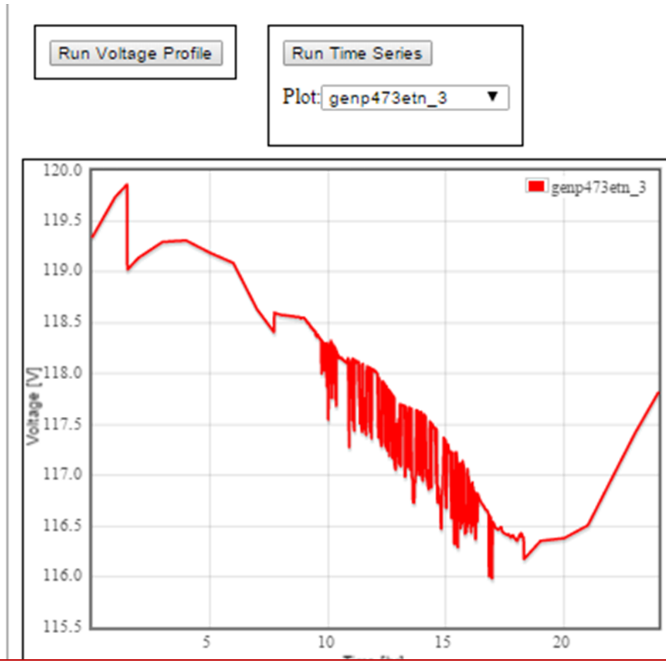


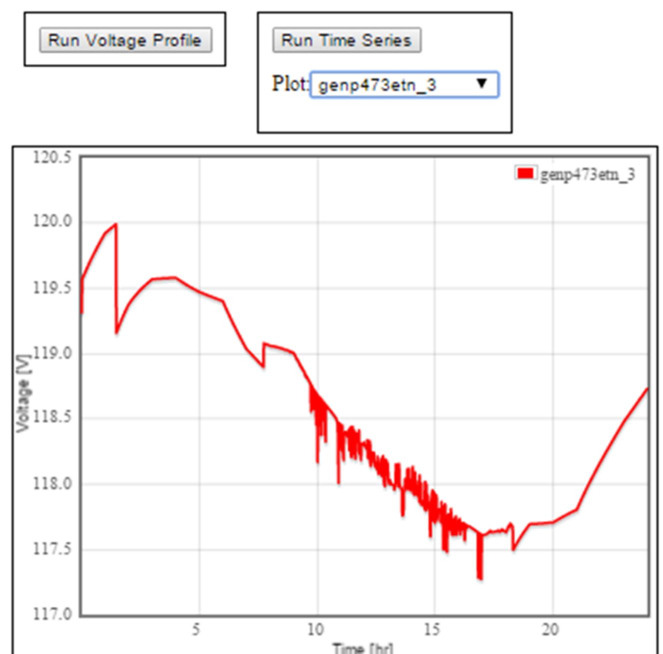


Photovoltaic Modeling, Testing and System Integration

Feeder Analytics and DER Integration

Automatic model generation allows targeted analysis to be performed efficiently





Generator Data

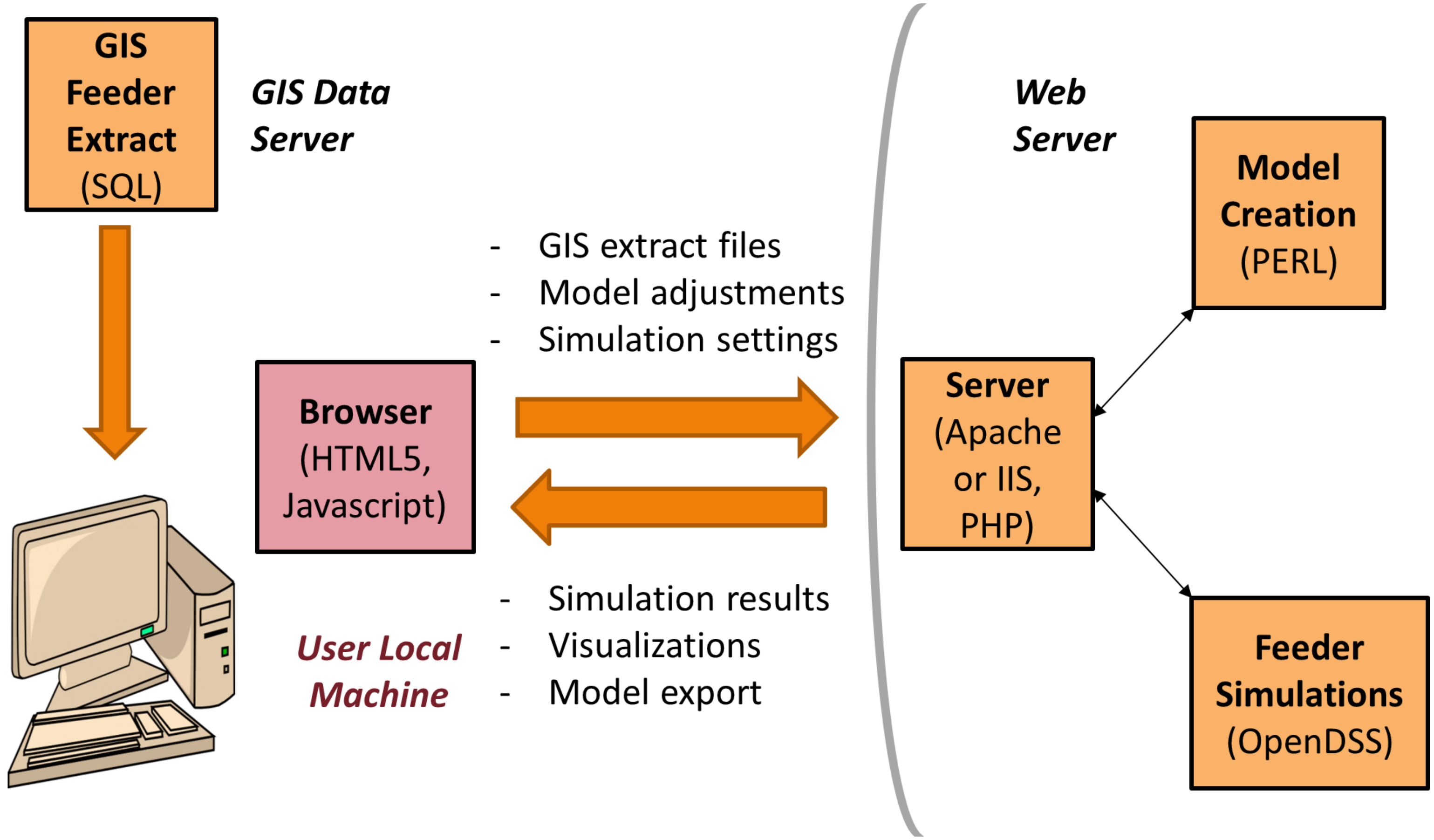
ID	Phases	Bus	kV	kW	kVA	Fixed PF	Vreg [pu]	Droop
genP386ETN	3	518988810	0.208	27.00	28.42	1.0000	1	0
genP473ETN	3	518988812	0.208	19.00	20.00	1.0000	1	0
genP386ETN_3	1	518988810.1.2	0.240	30.00	31.58	1.0000	1	0
genBT1748ETN	3	518983610	0.208	63.00	66.32	1.0000	1	0

Phases	Bus	kV	kW	kVA	Fixed PF	Vreg [pu]	Droop
3	518988810	0.208	27.00	28.42	1.0000	1	20
3	518988812	0.208	19.00	20.00	1.0000	1	20
1	518988810.1.2	0.240	30.00	31.58	1.0000	1	20
3	518983610	0.208	63.00	66.32	1.0000	1	20

Photovoltaic Modeling, Testing and System Integration

Feeder Analytics and DER Integration

OpenDSS models are created using scripted methods starting with GIS data



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DC Microgrid Development for Renewable Energy and Battery Storage Integration

Prepared by: Andrew Bulman
M.S. Student

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Photovoltaic Modeling, Testing and System Integration

DC Microgrid Development for Renewable Energy and Battery Storage Integration

Project Overview

- A collaboration of Pittsburgh based companies to develop a DC based microgrid at a Pitt Ohio trucking facility in Harmar, PA
- Goal was to create a viable system architecture for integrating the existing AC power system with renewable energy resources (50 kW of solar power and 5 kW of wind power) distributed through a 380 Vdc backbone.

Photovoltaic Modeling, Testing and System Integration

DC Microgrid Development for Renewable Energy and Battery Storage Integration

Project Motivation

- Promote the Pittsburgh region as a global leader in knowledge, innovation, research and development, education and manufacturing related to DC power

PITT OHIO
SUPPLY CHAIN ▪ GROUND ▪ LTL ▪ TL

PITT SWANSON ENGINEERING
ELECTRIC POWER SYSTEMS LAB

UNIVERSAL
ELECTRIC CORPORATION

WindStax™
Wind Power Systems

ASR
ADAM SOLAR RESOURCES

Sargent Electric Company

EATON
Powering Business Worldwide

elecyr
Saving The Power

PCTI
A Power Conversion Company

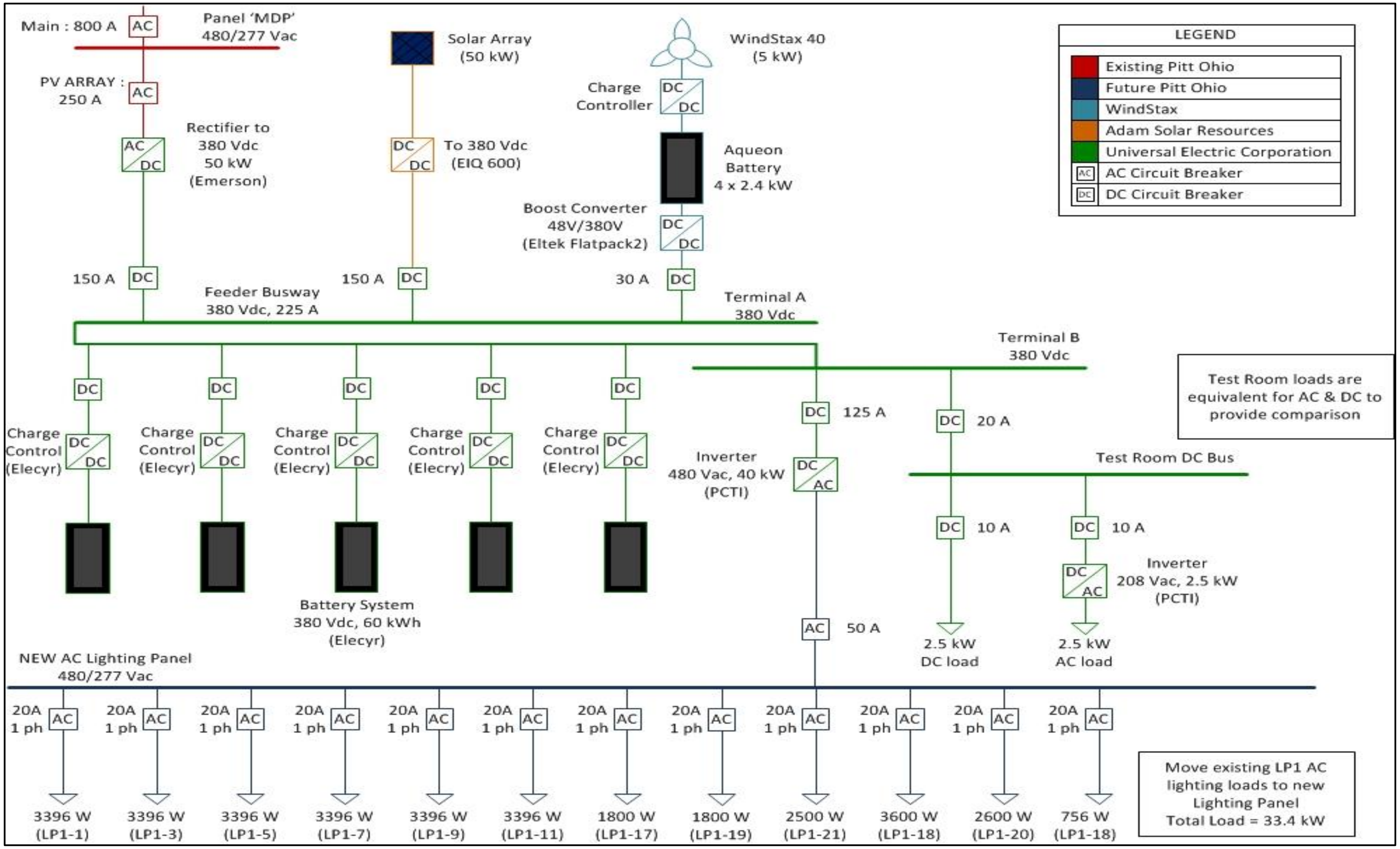
AQUION ENERGY

BDA Engineering, Inc.

Photovoltaic Modeling, Testing and System Integration

DC Microgrid Development for Renewable Energy and Battery Storage Integration

System Overview



Photovoltaic Modeling, Testing and System Integration

DC Microgrid Development for Renewable Energy and Battery Storage Integration

Current Research Direction

- Recent extension of the partnership for a new PITT OHIO distribution facility in Parma, OH
- Begun initial R&D activities toward potential electric trucking fleet concepts

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Questions?

Join all the graduate students at the poster session starting at 4:00pm today.

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