Graduate Student Symposium

Session Moderator:
Brandon Grainger, PhD

9th Annual Electric Power Industry Conference
University of Pittsburgh
Swanson School of Engineering
November 17th, 2014

Celebrating Student Achievement September 2012 to August 2014

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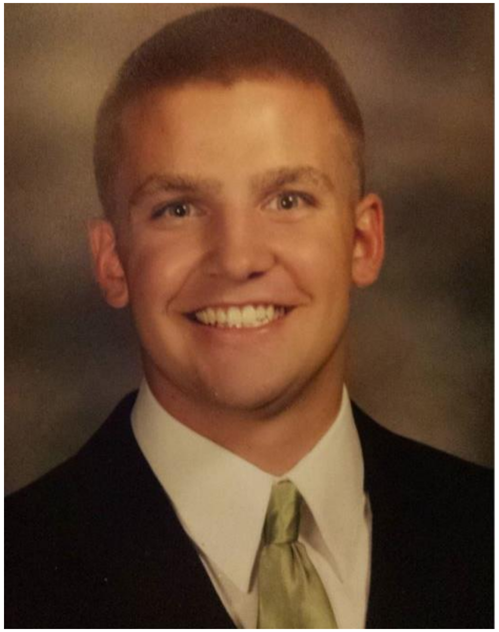
Undergraduate Student Researchers - Industry



Michael Doucette
Edison Engineer

Zachary Smith
Leadership Development Program

Andrew Lichauer
Testing Engineer

Powering Business Worldwide

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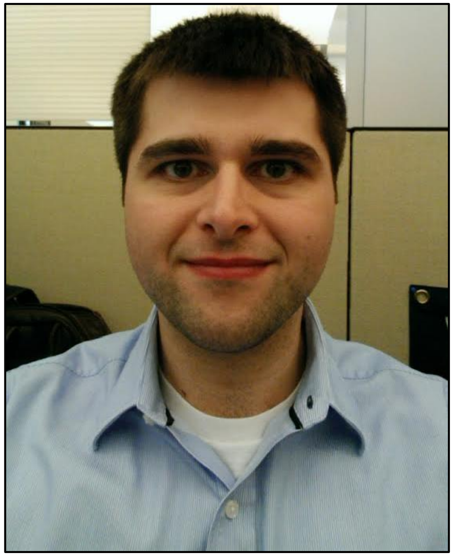
Graduate Student Researchers – Masters - Industry



Adam Sparacino
System Studies
Engineer

Benoit de Courreges
Electrical Engineer
(Paris, France)

Rusty Scioscia
Senior Application
Engineer

MITSUBISHI ELECTRIC

EDF

EATON
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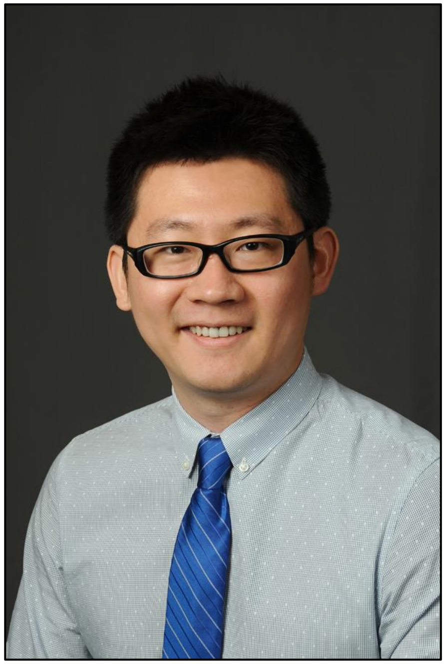
Graduate Student Researchers – PhD – Industry

Robert Kerestes
Senior Electrical Engineer

EMERSON

Emmanuel Taylor
Electrical Engineer

U.S. DEPARTMENT OF ENERGY



Ang Li
Consultant

SIEMENS

Graduate Student Researchers – PhD – Academia

Raghav Khanna
Visiting
Assistant Professor

Brandon Grainger
Research
Assistant Professor

Hussain Bassi
Assistant Professor
(Saudi Arabia)

Research & Development Activity

Session Moderator:
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Presented by the Swanson School of Engineering & the Center for Energy

DC Microgrid Control and Communication Development

Shimeng Huang
Brandon Grainger
Velin Kounev
Qinhao Zhang
Alvaro Cardoza

9th Annual Electric Power Industry Conference
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ABB

Systematic Solution for MTDC Modeling and Control Design

Shimeng Huang

DC Microgrid Constant Power Load Controller Design

Brandon Grainger, PhD

Secure Communication Architecture

Velin Kounev

Modern Control in Power Systems Applications

Qin-Hao Zhang

Bidirectional DC/DC Converter Design

Alvaro Cardoza

HILLMAN FAMILY FOUNDATIONS

University of Pittsburgh

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A Systematic Solution for MTDC Modeling and Control Design

Prepared by: Shimeng Huang
Ph.D. Student

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November 17th, 2014

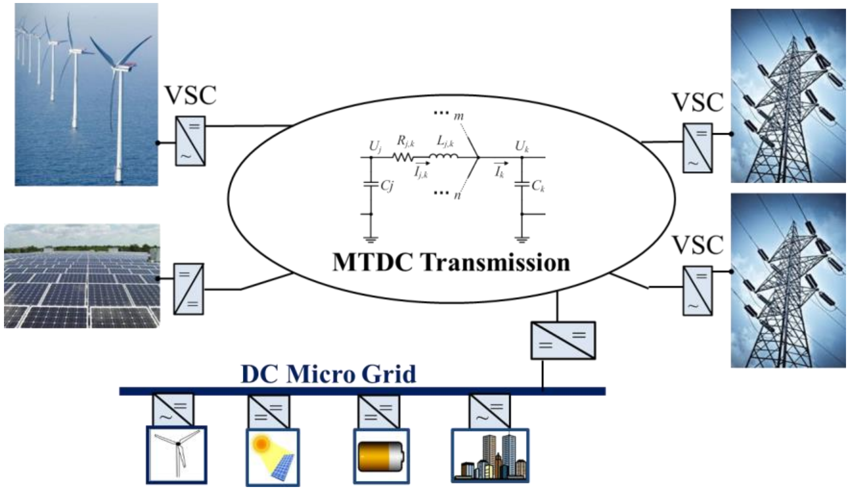
DC and Hybrid Systems Analysis

Multi-Terminal DC Controls

A systematic solution for MTDC modeling and control design

Feature

- Automatic model generation
- Configurable controller model
- Smart control design
- Enable fast evaluation of system configurations
- Explore and optimize different control schemes.

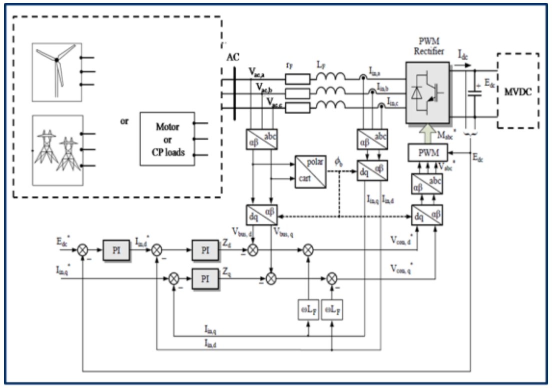


MTDC systems have great potential in transmission and distribution applications.

DC and Hybrid Systems Analysis

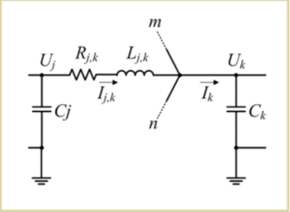
Multi-Terminal DC Controls

A two-stage modeling method that is generalizable to arbitrary MTDC configurations

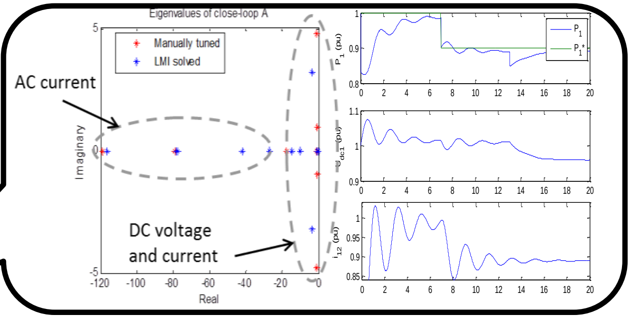


Subsystem

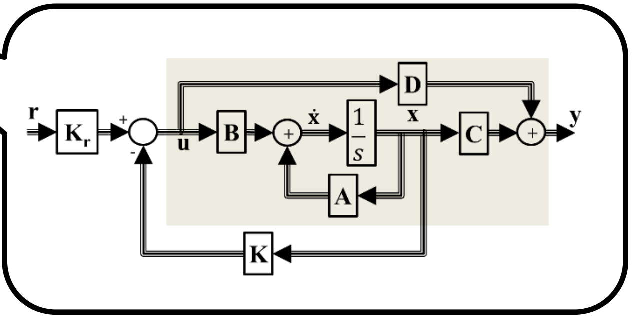
$$\begin{bmatrix}\dot{\mathbf{x}}_1\\ \dot{\mathbf{x}}_2\\ \vdots\\ \dot{\mathbf{x}}_N\\ \dot{\mathbf{x}}_c\end{bmatrix} = \begin{bmatrix} \boxed{\mathbf{A}_{11}} & 0 & \cdots & 0 & \mathbf{A}_{1c}\\ 0 & \mathbf{A}_{22} & \cdots & 0 & \mathbf{A}_{2c}\\ \vdots & \vdots & \ddots & \vdots & \vdots\\ 0 & 0 & \cdots & \mathbf{A}_{NN} & \mathbf{A}_{Nc}\\ \mathbf{A}_{c1} & \mathbf{A}_{c2} & \cdots & \mathbf{A}_{cN} & \mathbf{A}_{cc}\end{bmatrix}\begin{bmatrix}\mathbf{x}_1\\ \mathbf{x}_2\\ \vdots\\ \mathbf{x}_N\\ \mathbf{x}_c\end{bmatrix}+\begin{bmatrix}\mathbf{B}_1 & 0 & \cdots & 0\\ 0 & \mathbf{B}_2 & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & B_N\\ 0 & 0 & \cdots & 0\end{bmatrix}\begin{bmatrix}\mathbf{u}_1\\ \mathbf{u}_2\\ \vdots\\ \mathbf{u}_N\end{bmatrix}$$



Coupling



Identify sources of instability

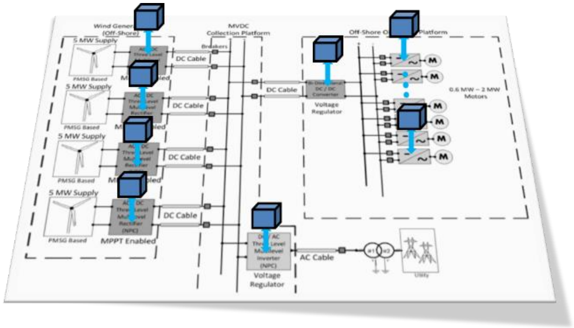


Optimizing control gains

DC and Hybrid Systems Analysis

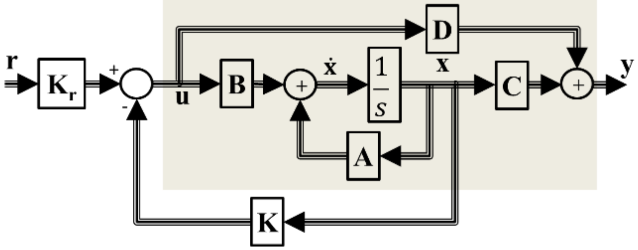
Multi-Terminal DC Controls

Explore different controller architectures and optimize control parameters

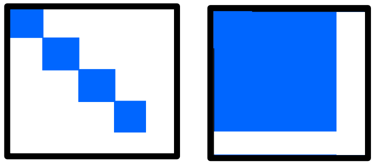


Generated model captures the relative location of signals

$$\begin{bmatrix}\dot{\mathbf{x}}_1\\ \dot{\mathbf{x}}_2\\ \vdots\\ \dot{\mathbf{x}}_N\\ \dot{\mathbf{x}}_c\end{bmatrix} = \begin{bmatrix} \boxed{\mathbf{A}_{11}} & 0 & \cdots & 0 & \mathbf{A}_{1c}\\ 0 & \mathbf{A}_{22} & \cdots & 0 & \mathbf{A}_{2c}\\ \vdots & \vdots & \ddots & \vdots & \vdots\\ 0 & 0 & \cdots & \mathbf{A}_{NN} & \mathbf{A}_{Nc}\\ \mathbf{A}_{c1} & \mathbf{A}_{c2} & \cdots & \mathbf{A}_{cN} & \mathbf{A}_{cc}\end{bmatrix} \begin{bmatrix}\mathbf{x}_1\\ \mathbf{x}_2\\ \vdots\\ \mathbf{x}_N\\ \mathbf{x}_c\end{bmatrix} + \begin{bmatrix}\mathbf{B}_1 & 0 & \cdots & 0\\ 0 & \mathbf{B}_2 & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & B_N\\ 0 & 0 & \cdots & 0\end{bmatrix} \begin{bmatrix}\mathbf{u}_1\\ \mathbf{u}_2\\ \vdots\\ \mathbf{u}_N\end{bmatrix}$$



Control structure can be easily specified through nonzero pattern of a gain matrix

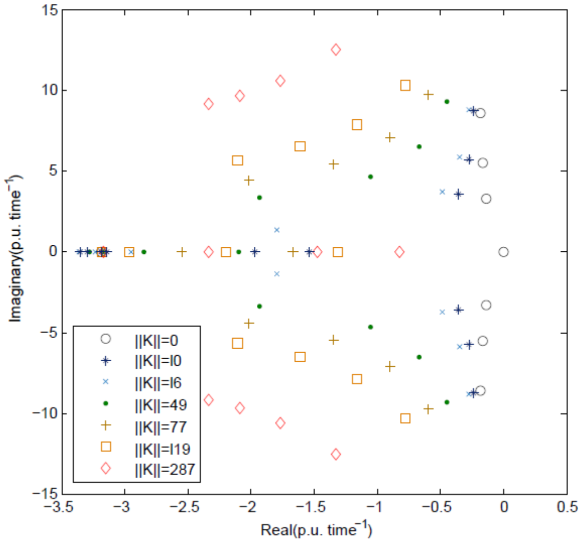


- Control gains can be optimized by LMI-based algorithm
- Linear controller easy to implement
- Tune classic controllers, e.g. droop gains
- Design control in a smart grid

DC and Hybrid Systems Analysis

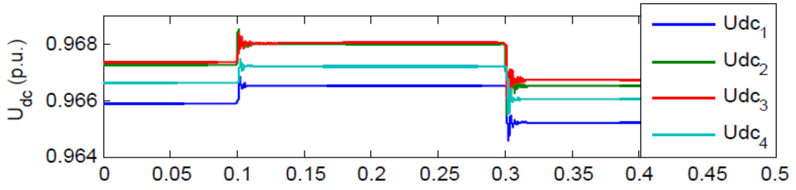
Multi-Terminal DC Controls

LMI optimization can coordinate multiple controllers

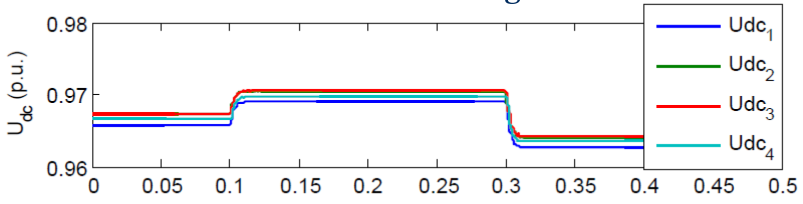


Trade-off local and system control goals

Distributed controllers with local observation



Distributed controllers with global observation



Coordinate controllers at different terminals

DC Microgrid Constant Power Load Controller Design

Prepared by: Brandon Grainger, PhD

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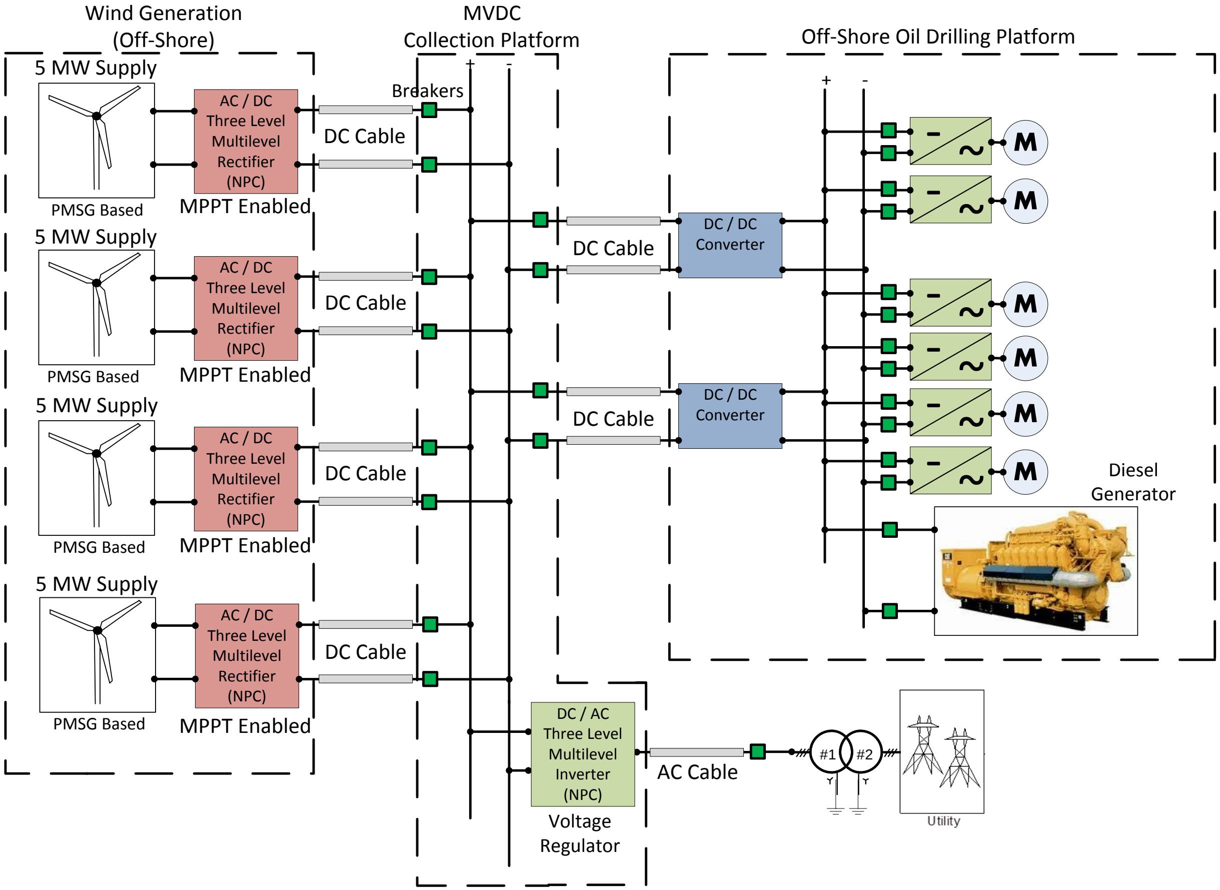
DC Microgrid Control and Communications Development

DC Microgrid Constant Power Load Controller Design



"….the next big change we are starting to see is a move from ***AC to DC making the subsea electrical power supply more economical and convenient.*** Using HVDC converters we will be able to send power hundreds of kilometers offshore. Who knows, maybe we will even supply this power from a ***renewable source*** some day." – *GE Power Conversion*

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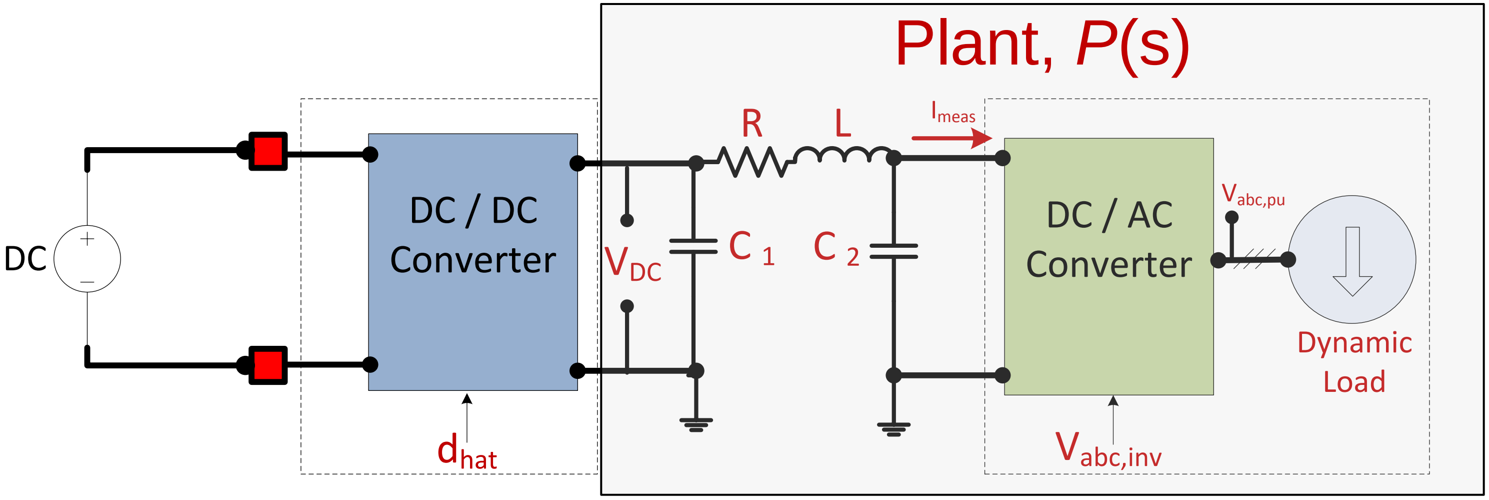
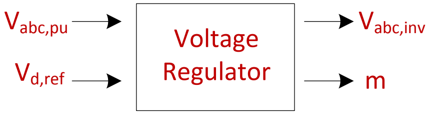
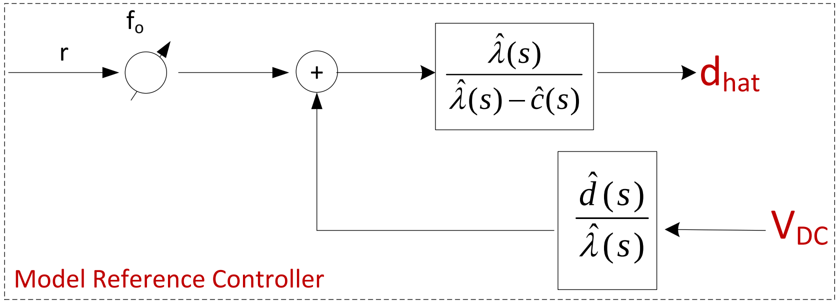
DC Microgrid Constant Power Load Controller Design





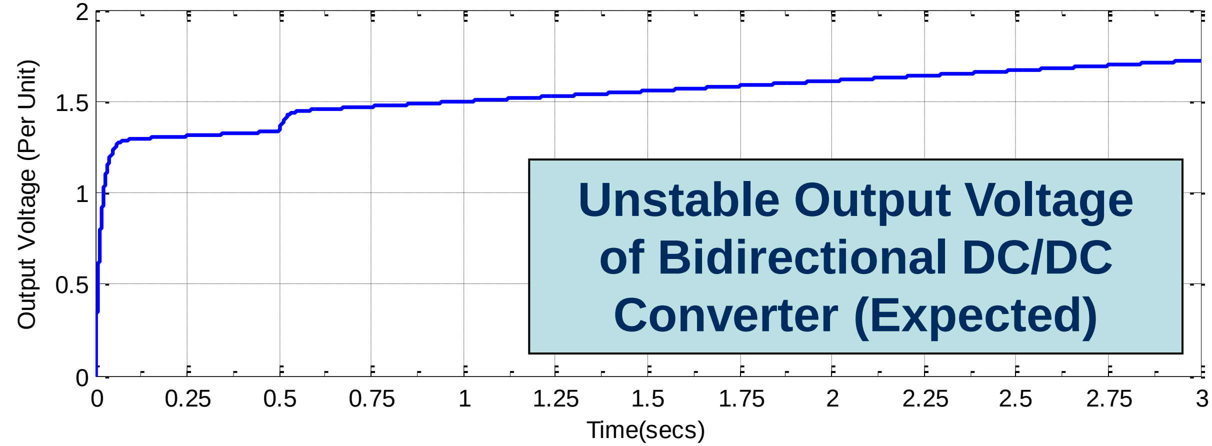


Electric Circuit Model with Controllers

DC Microgrid Control and Communications Development

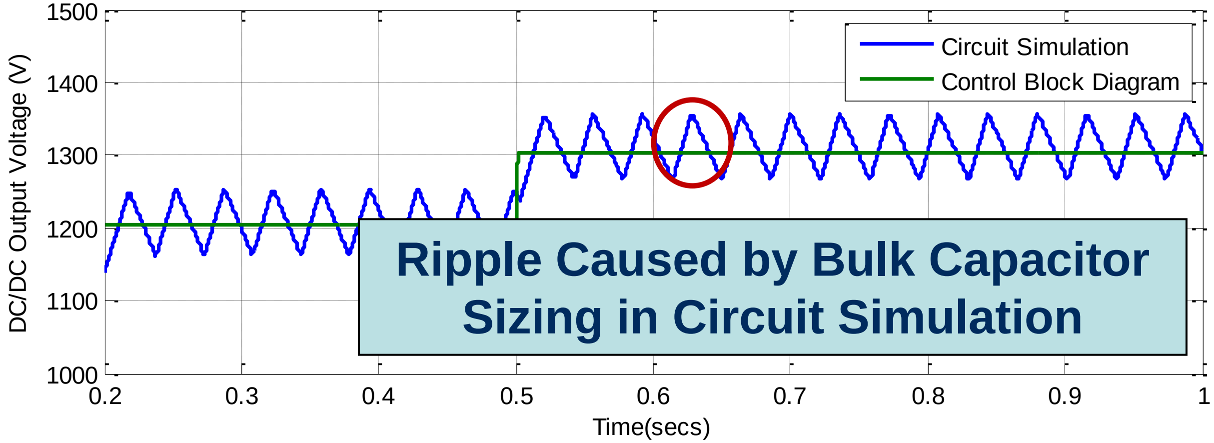
DC Microgrid Constant Power Load Controller Design

- Comparison of MRC method with traditional Proportional Derivative (PD) control



Unstable Output Voltage of Bidirectional DC/DC Converter (Expected)

Per unit voltage, step response unstable, PD control causes indefinite increase.

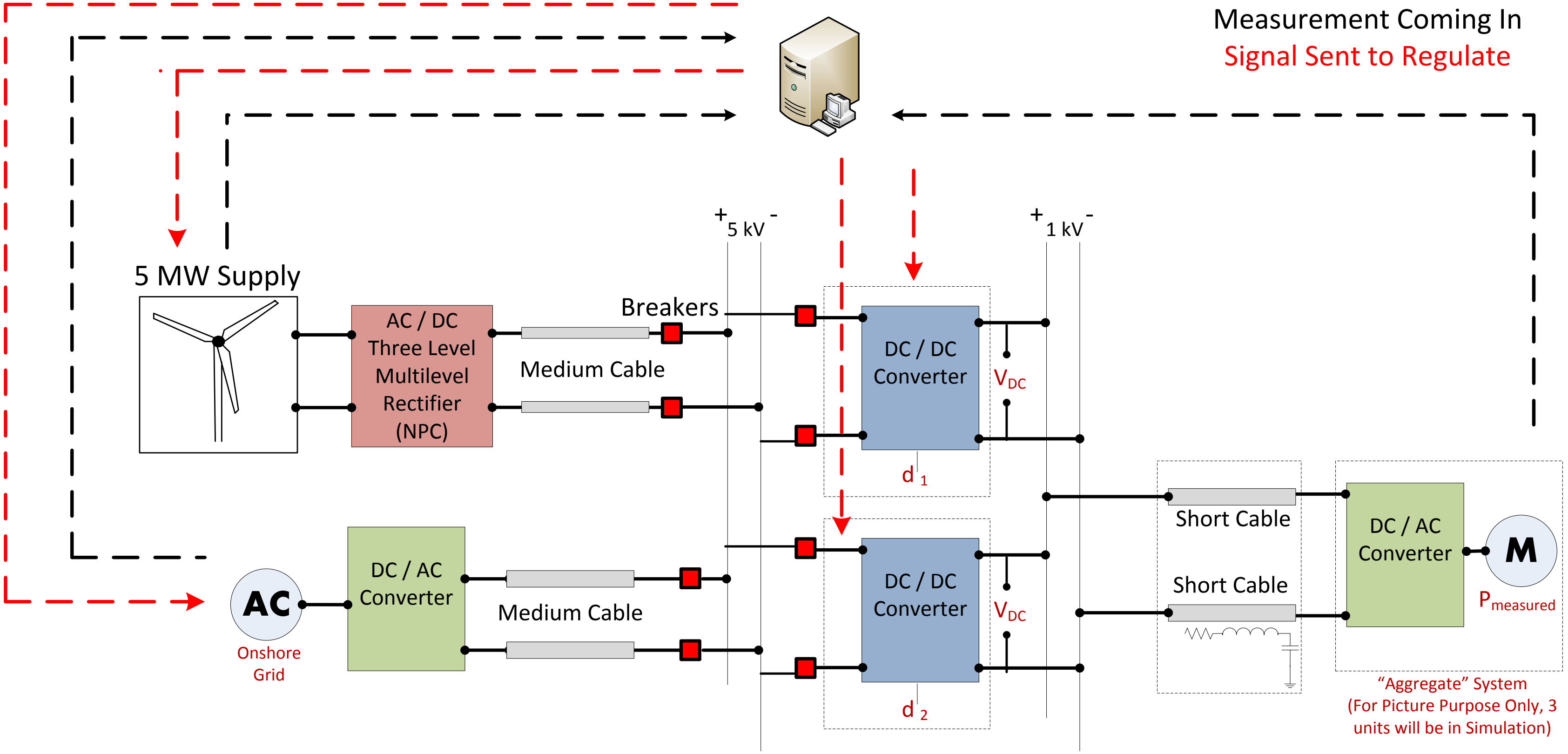


Ripple Caused by Bulk Capacitor Sizing in Circuit Simulation

Same voltage, step response, stabilized with MRC design.

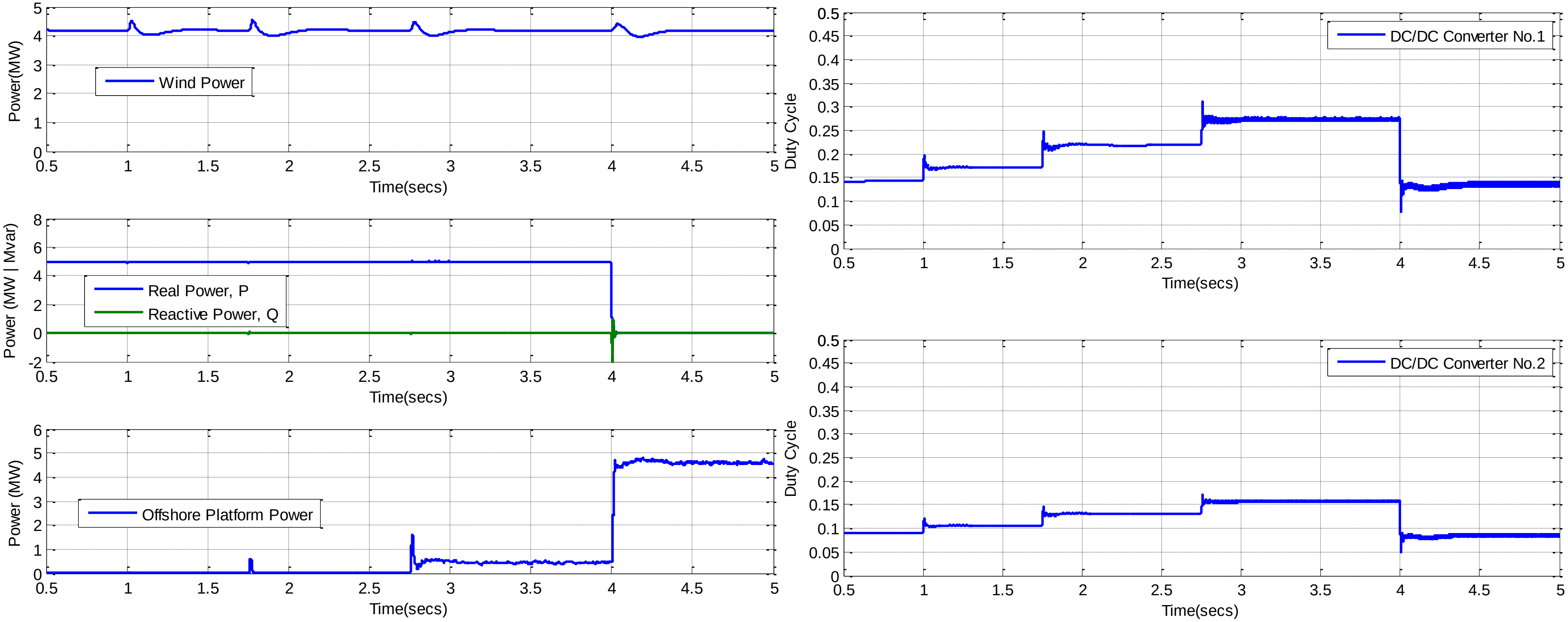
DC Microgrid Control and Communications Development
DC Microgrid Constant Power Load Controller Design

- Three mechanisms in the microgrid for power generation regulation: (1) Blade pitch (2) DC/DC converter duty cycle, and (3) power reference of grid connected converter.



DC Microgrid Control and Communications Development

DC Microgrid Constant Power Load Controller Design



- **Take away: Bidirectional DC/DC converter duty cycle is an indicator of the relationship between load demand and available power generation. The AC system analogy is system frequency acting as the same indicator.**

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Secure Communication Architecture

Prepared by: Velin Kounev

Ph.D. Student

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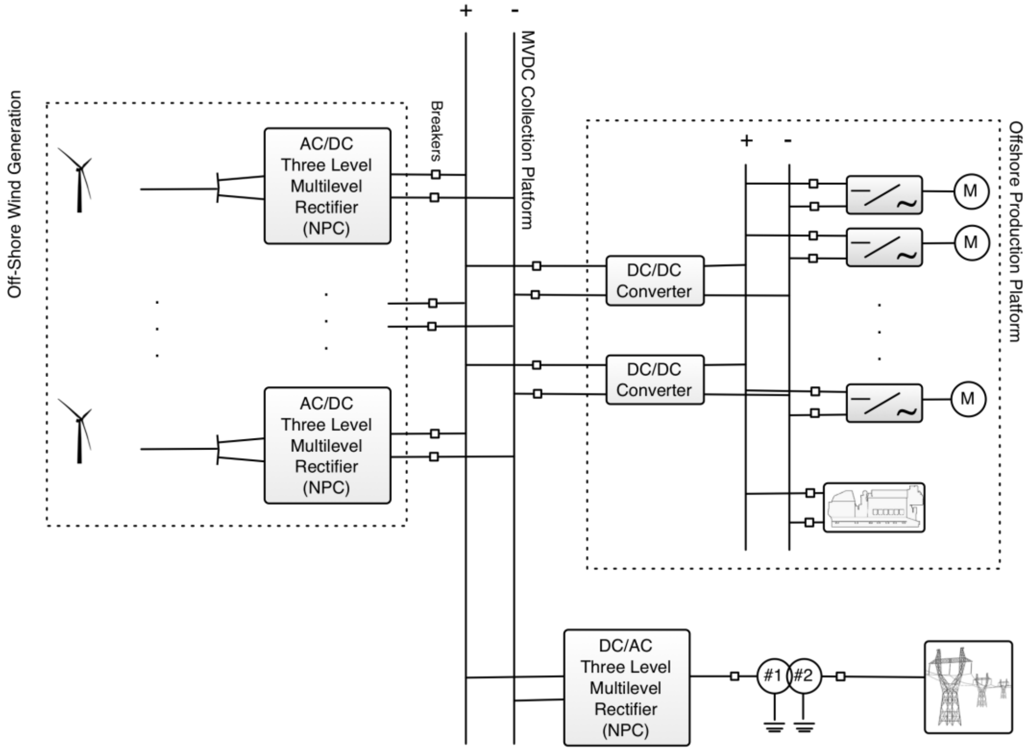
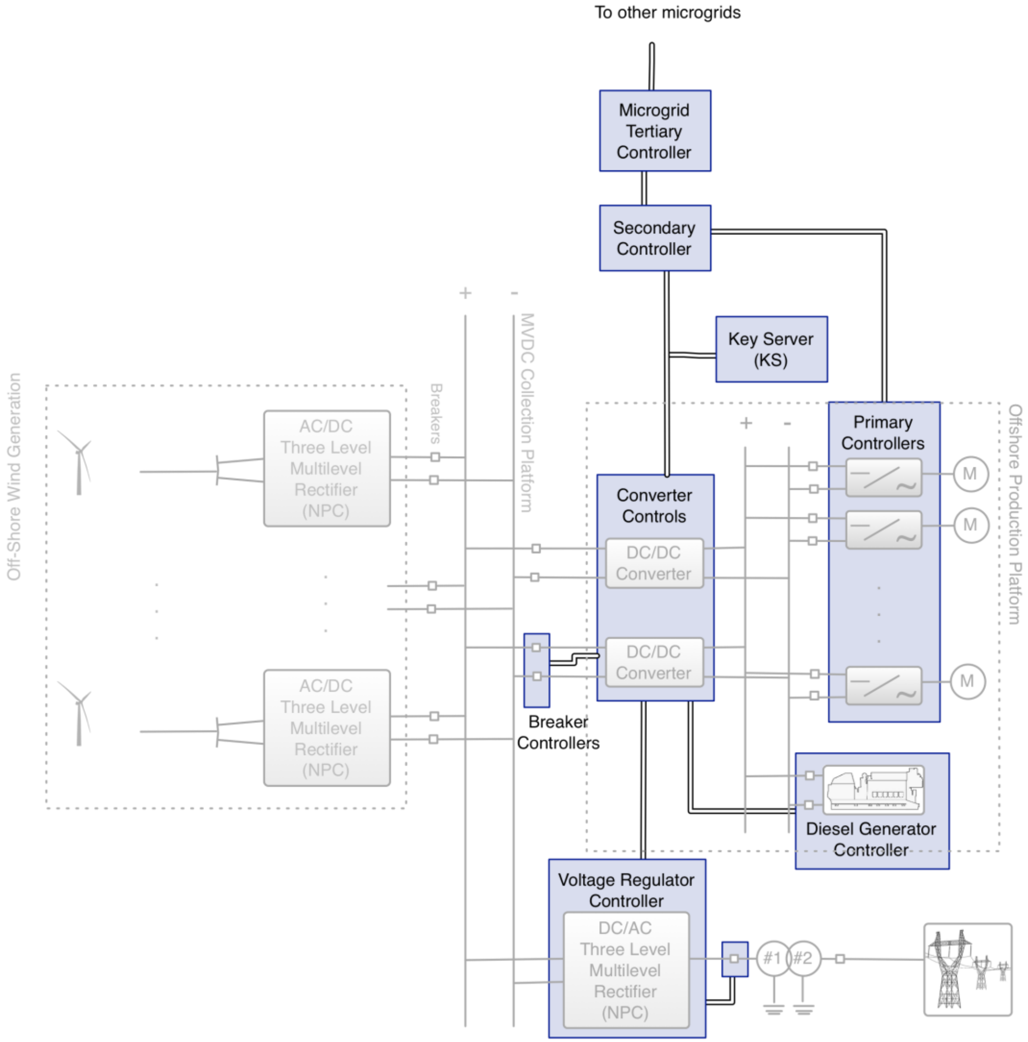
Secure Communication Architecture



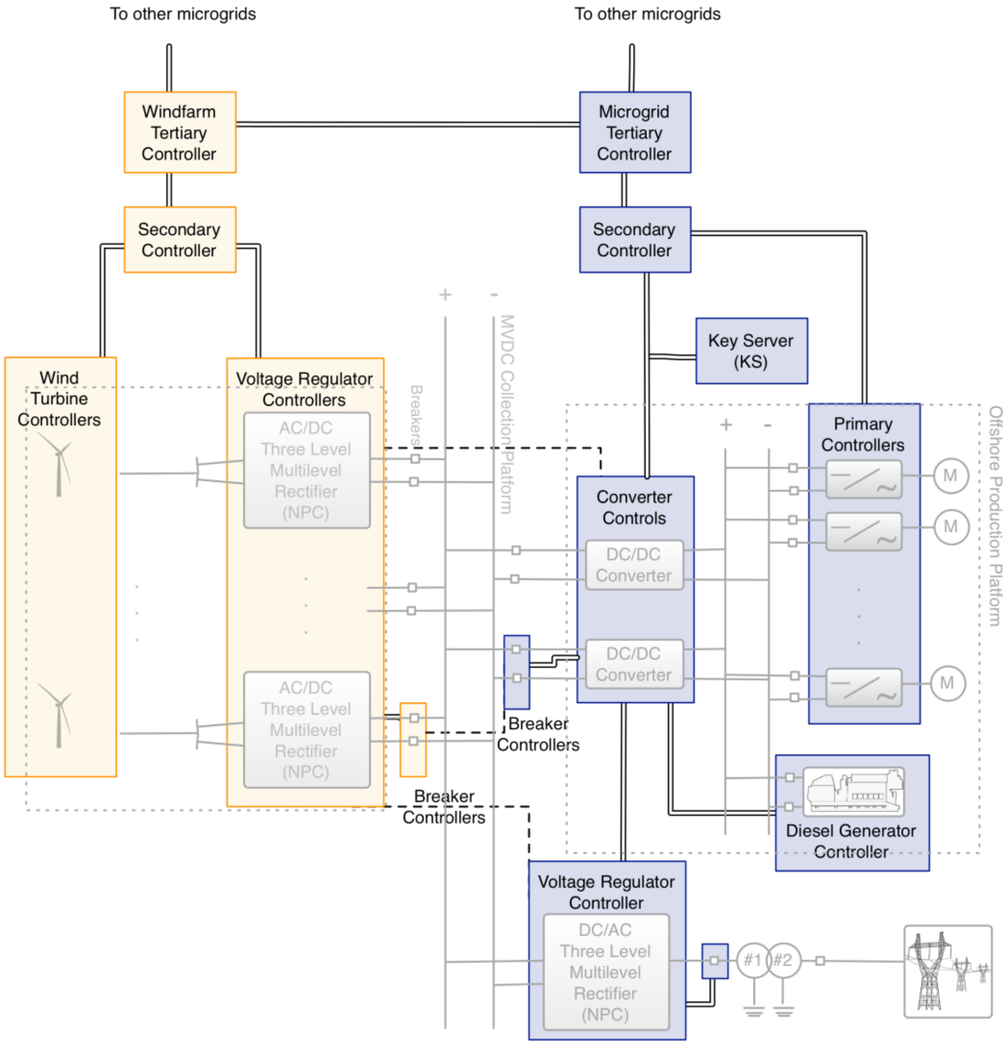
DC Microgrid Control and Communications Development

Secure Communication Architecture



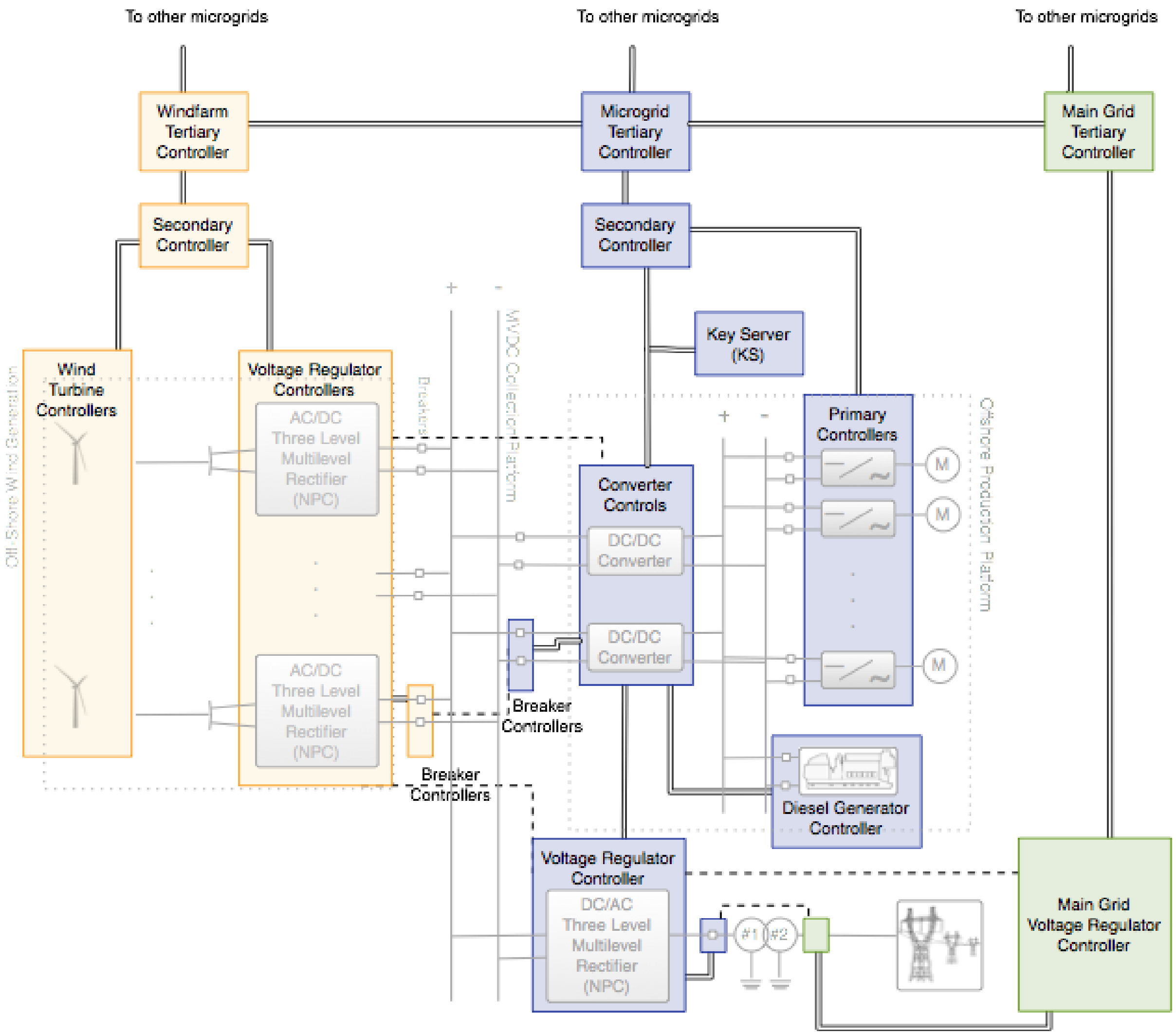
DC Microgrid Control and Communications Development

Secure Communication Architecture



DC Microgrid Control and Communications Development

Secure Communication Architecture

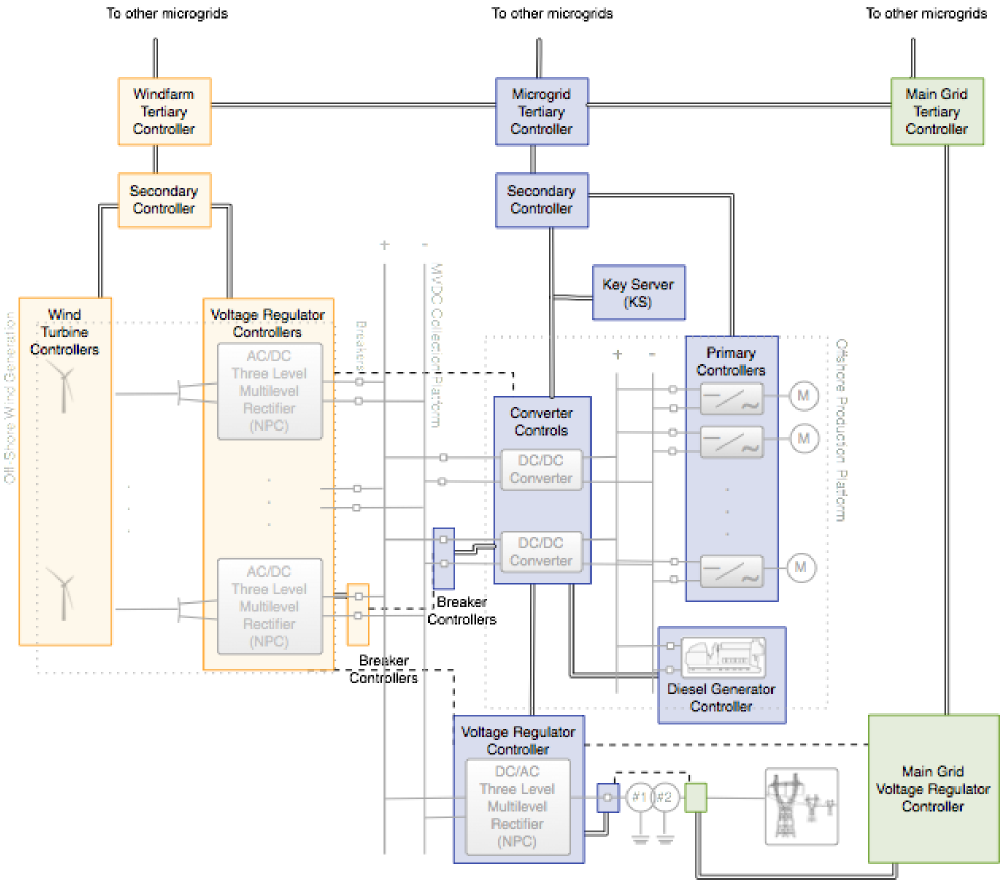


DC Microgrid Control and Communications Development

Secure Communication Architecture

Microgrid Communication Challenges

- Real-time end-to-end delay (3 ms)
- High availability (99.999%)
- Multicast / Broadcast
- Devices have limited computational resources (600 MHz)
- Device lifetime is measured in decades
- Need for secure trusted communication with devices owned by different organizations

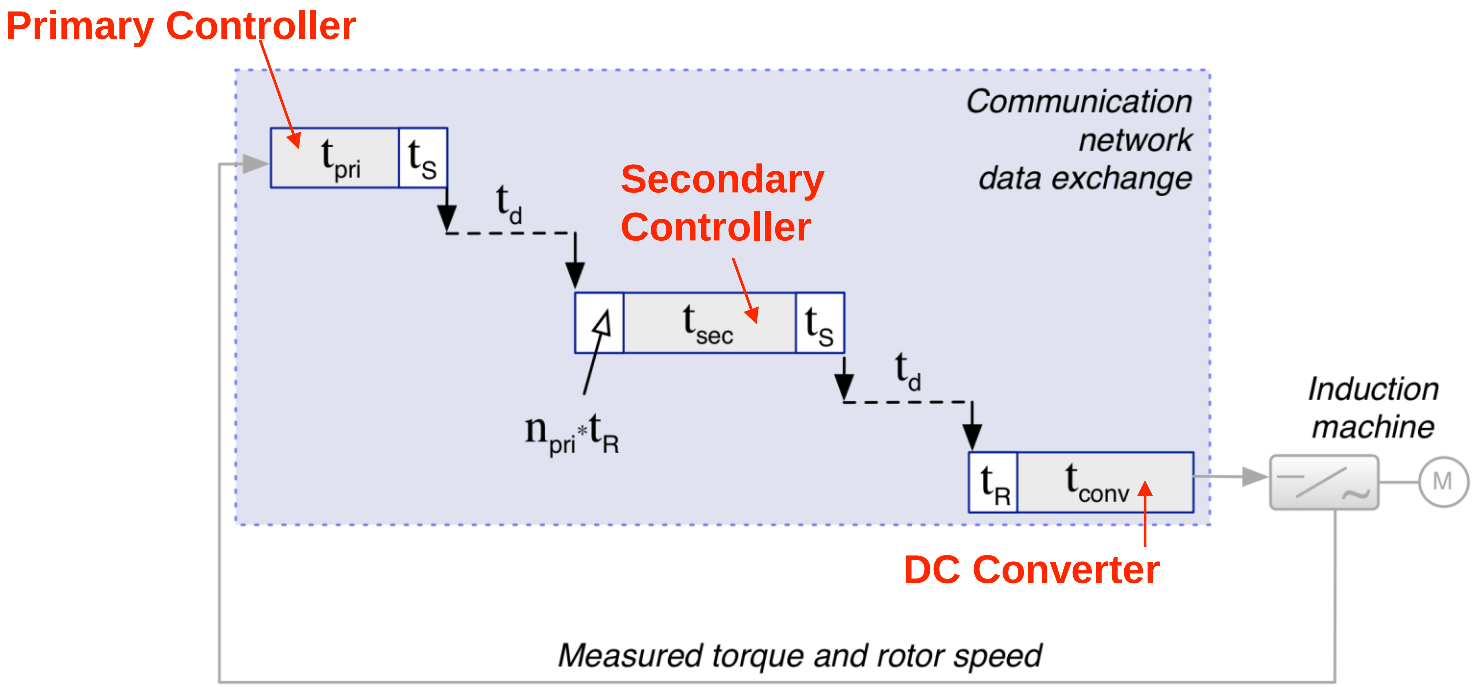


DC Microgrid Control and Communications Development

Secure Communication Architecture

Our proposed solution

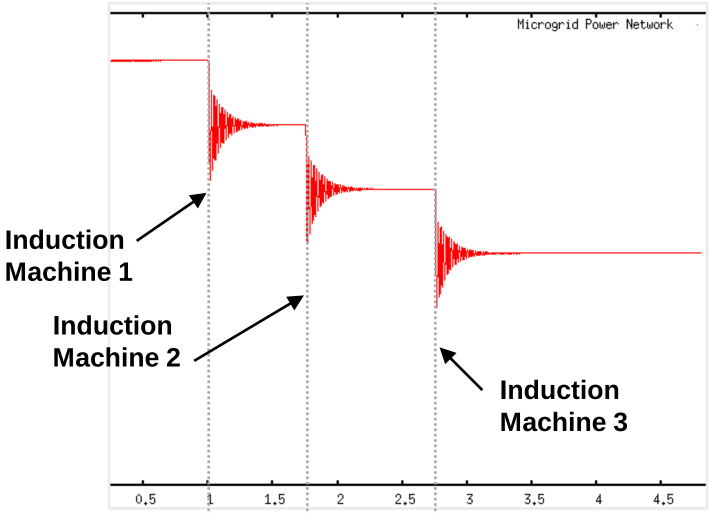
- **Real-time performance in compliance with IEC 61850 (3ms end-to-end delay)**
- **Provides confidentiality and authentication (NIST recommended 192-bit AES & CMAC)**
- **The protocol supports multicast communication**
- **Co-simulation environment**



DC Microgrid Control and Communications Development

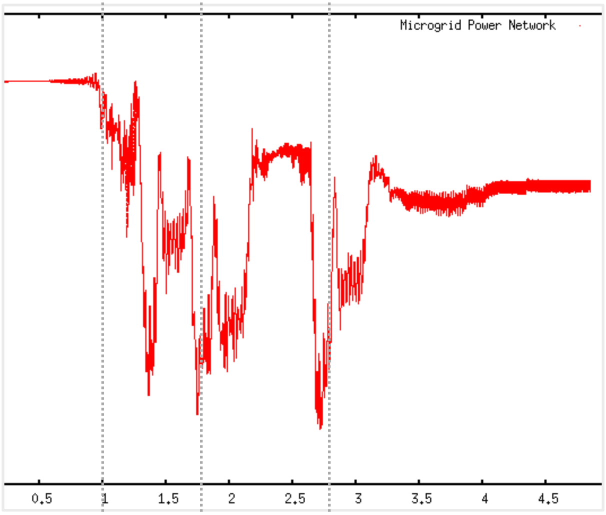
Secure Communication Architecture

Microgrid power control simulation results without delays in the distributed control loop



Microgrid power control simulation results with delays

- **Transmission and Propagation**
- **Authentication and Verification**
- **Encryption and Description**
- **Embedded OS**



Modern Control in Power System Applications

Qin-hao Zhang
Ph.D. Student

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DC Microgrid Control and Communications Development

Modern Control in Power System Applications

Controller Benefits: Built-in Intelligence for an Evolving Grid

- **PID control is simple to implement and accomplishes the control object effectively. These controllers are widely adopted in practice.**

- **Practical concerns encountered in the evolving power system:**
  - Nonlinearities
  - Uncertainty and measurement errors in the power system

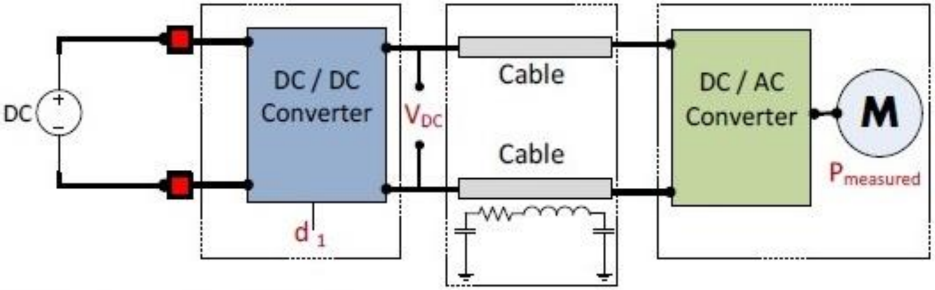
- **Modern control technique provides an alternative solution:**
  - State feedback approach for handling communication delays in power electronic systems
  - Model reference adaptive control for optimizing maximum power point tracking algorithms in photovoltaic systems.

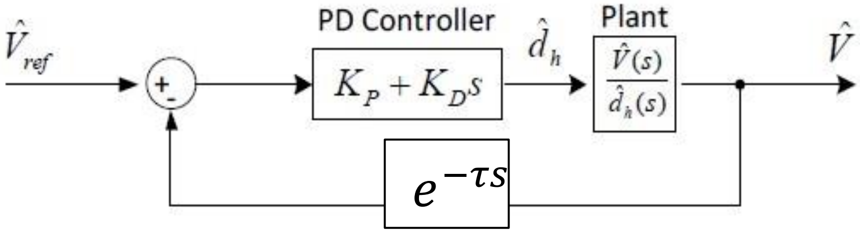
DC Microgrid Control and Communications Development

Modern Control in Power System Applications

Modern Control Theory to Represent Complex System Dynamics

- Proportional-Derivative controls are traditionally 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.
- State space equations are a commonly used modern control approach easily handled 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).





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

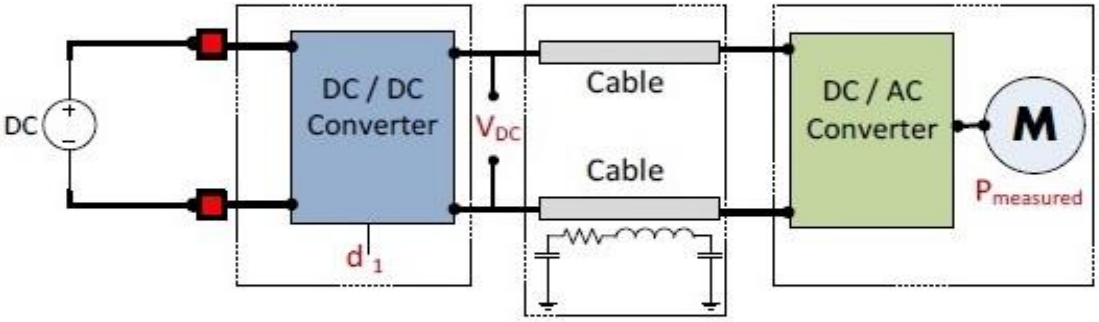
DC Microgrid Control and Communications Development

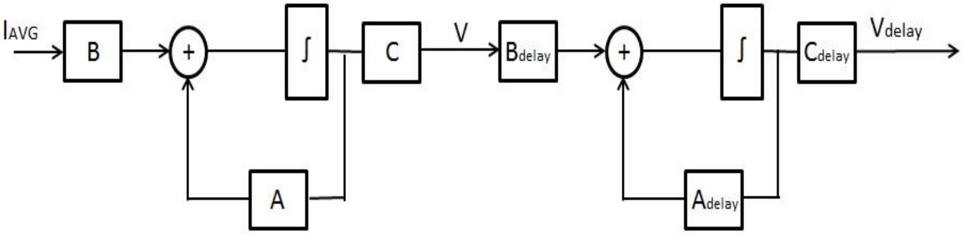
Modern Control in Power System Applications

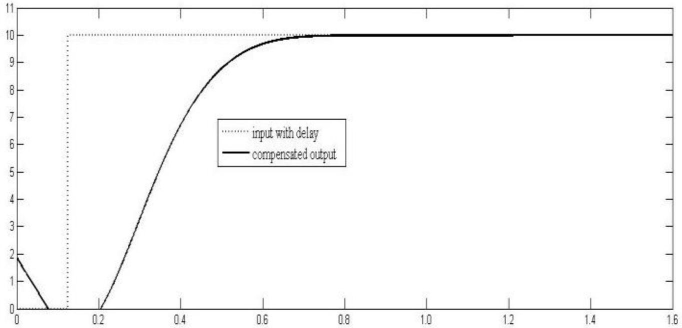
State Feedback Controller Design Accounting for Communication Delays

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

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







- State space representation includes all system information in one equation

- Result of the voltage output by using full state space feedback

DC Microgrid Control and Communications Development

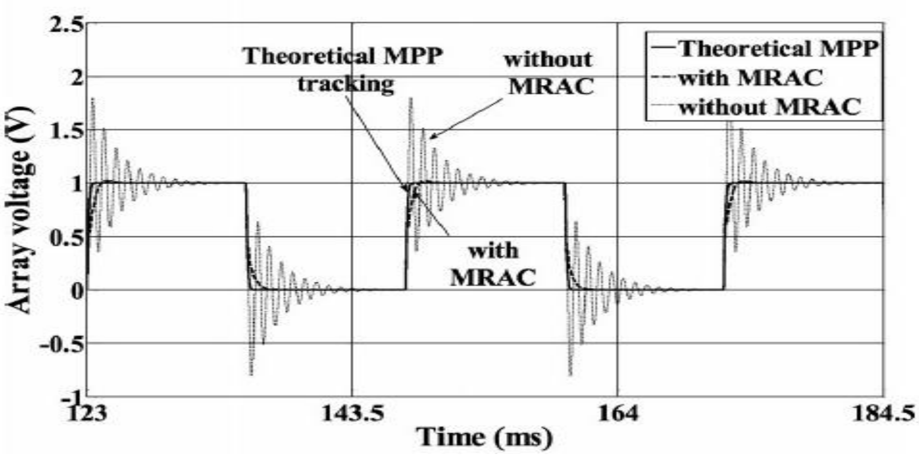
Modern Control in Power System Applications

Optimization of MPPT algorithm for Photovoltaic System Design

- Using system identification, the variation of the PV voltage output due to the change of duty cycle or the grid current change can be identified.

$$\hat{v}_{PV} = G_{v_{pload}}\hat{d} + G_{V_{pload}}\hat{\imath}_{load}$$

- Model Reference Adaptive Control optimizes the transient performance of the voltage when the system converges to the optimal set-point. Improved solar panel efficiency is a direct outcome.



Bidirectional DC-DC Converter Design: Single-Input, Multiple Output Converter

Prepared by: Alvaro Cardoza
M.S. Student

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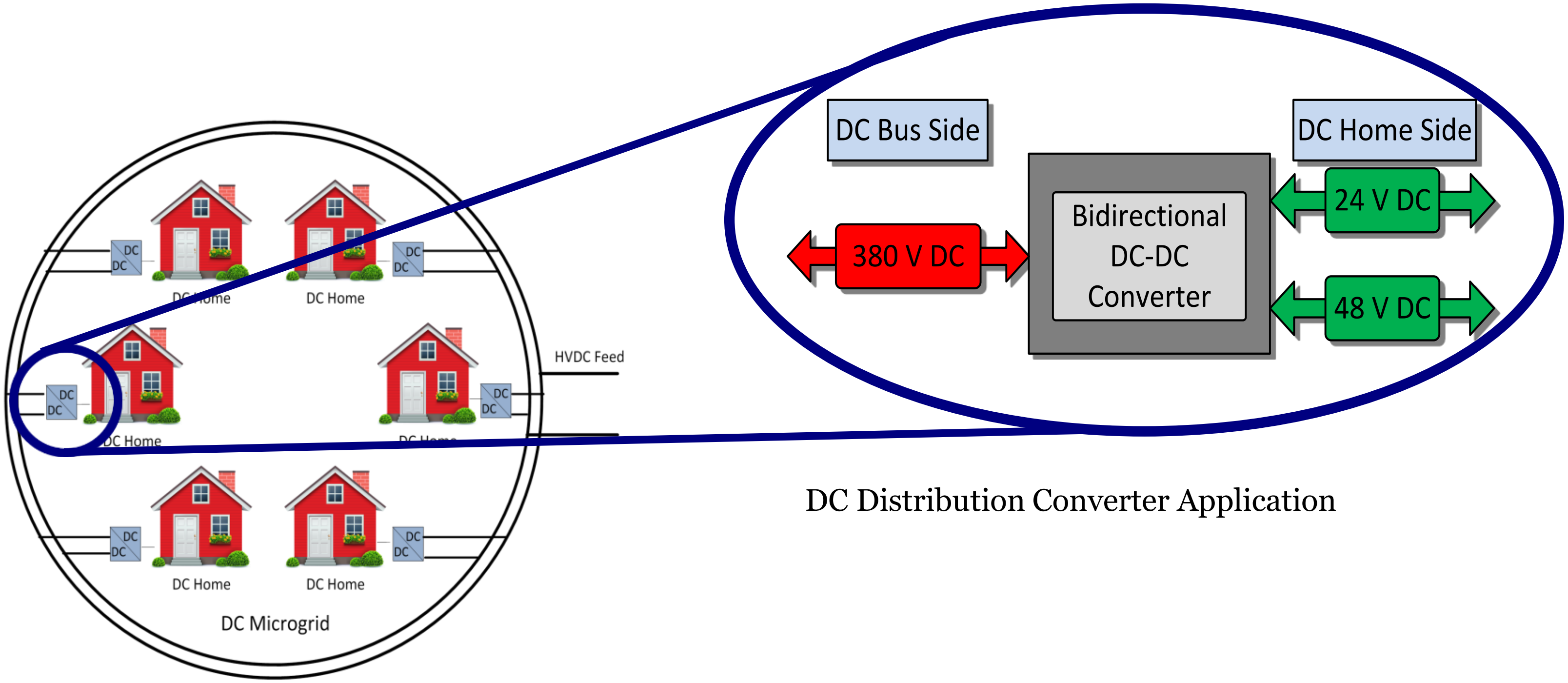
DC Microgrid Control and Communications Development

Bidirectional DC-DC Converter Design: Single-Input, Multiple Output

Converter Background

Desired Features

- Bidirectional power flow
- Single input from grid
- Two (or more) outputs sent to house
- Dynamic response to fault events
- Steps up/down voltage to desired levels
- Isolation with no physical transformer



DC Distribution Converter Application

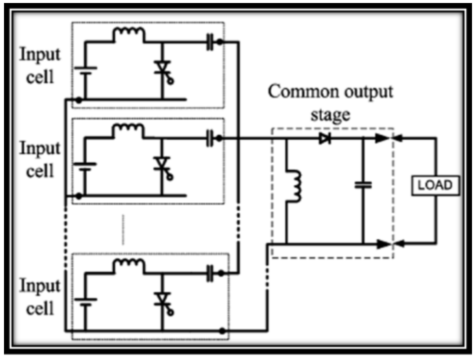
DC Microgrid Control and Communications Development

Bidirectional DC-DC Converter Design: Single-Input, Multiple Output

Topology Investigation

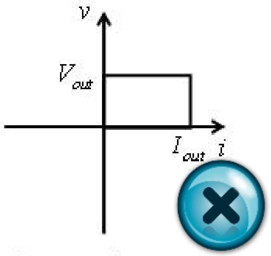
4 Rules for Feasible Multiple-Input DC-DC Converters

1. All Feasible Input Cells Must Contain at Least 1 Independently Controlled Forward Conducting and Bidirectional Blocking Switch
2. There Must Not be a Redundancy of Parallel Switches
3. Common-Stage Capacitor Voltage Should Not Depend on Input Voltage (May be Relaxed as long as Both Cap Ends are Not Connected to Common Stage)
4. Both Ends of Input Source Should Not Be Terminals of the Input Cell

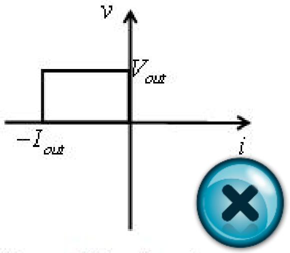


Multiple-Input SEPIC Converter

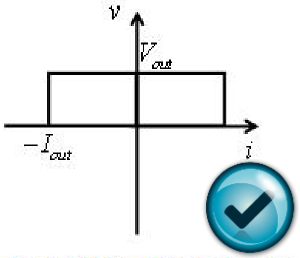
In order to achieve bidirectional power flow, converter operation must be multi-quadrant:



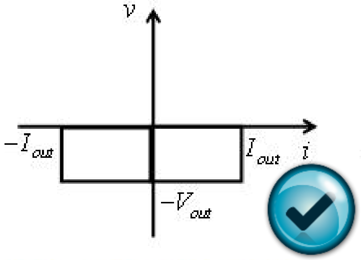
First Quadrant



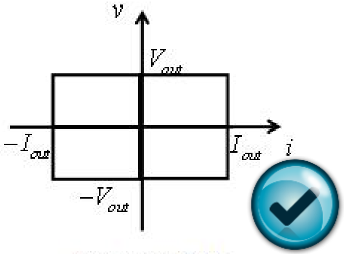
Second Quadrant



First and Second Quadrant



Third and Fourth Quadrant



Four Quadrant

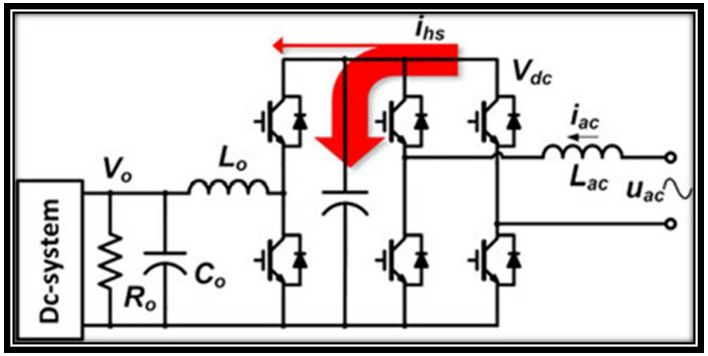
DC Microgrid Control and Communications Development

Bidirectional DC-DC Converter Design: Single-Input, Multiple Output

Decoupling and Control

The use of a properly sized DC-link capacitor allows for desired isolation and decoupling assuming the capacitor follows two main guidelines:

- For low frequency noise mitigation, the input grid peak voltage must be smaller than that of the DC-link voltage
- For high frequency noise mitigation, the second-stage impedance must be greater than the DC-link impedance



Decoupling DC-Link Capacitor

Droop control is one method of maintaining a reliable energy supply. This is a common control strategy for microgrid environments. The method below is an example of typical droop control:

Conventional Grid-based Control

- Conventional P/*f* Droop (CPFD) Control – Used for active power sharing

$$f = f_{nom} - K_P(P - P_{nom})$$

DC Microgrid Control and Communications Development

Bidirectional DC-DC Converter Design: Single-Input, Multiple Output

Converter Applications

An innovative multi-port DC-DC converter provides additional functionality to residential and commercial buildings, which exist in a DC distribution network.

- Bidirectional converters enable power flow from available grid generation to building loads as well as from building-side generation back into the grid
- This feature is especially useful for islanded operation where each building load can aid in maintaining a stable microgrid
- DC-DC converter interfaces can act as a replacement for building circuit panels, adding protection and isolation between buildings and grids

Potential sources of on-site generation include:

- Photovoltaics
- Plug-in Hybrid Electric Vehicles or Electric Vehicles
- Residential/Commercial Wind (Although Less Common)

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Direct Current Architecture for Modern Power Systems

Chris Scioscia
Joseph Kozak, Ansel Barchowsky
Augustin Cremer

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HILLMAN FAMILY FOUNDATIONS

DC AMPS: Focus and Takeaways

Chris Scioscia

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Ansel Barchowsky

Characterization between SiC MOSFET and Si IGBT in a DC/DC Boost Converter

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A Novel 380V DC Topology for Increased Efficiency in Cell Tower Applications

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DC AMPS: Focus and Takeaways

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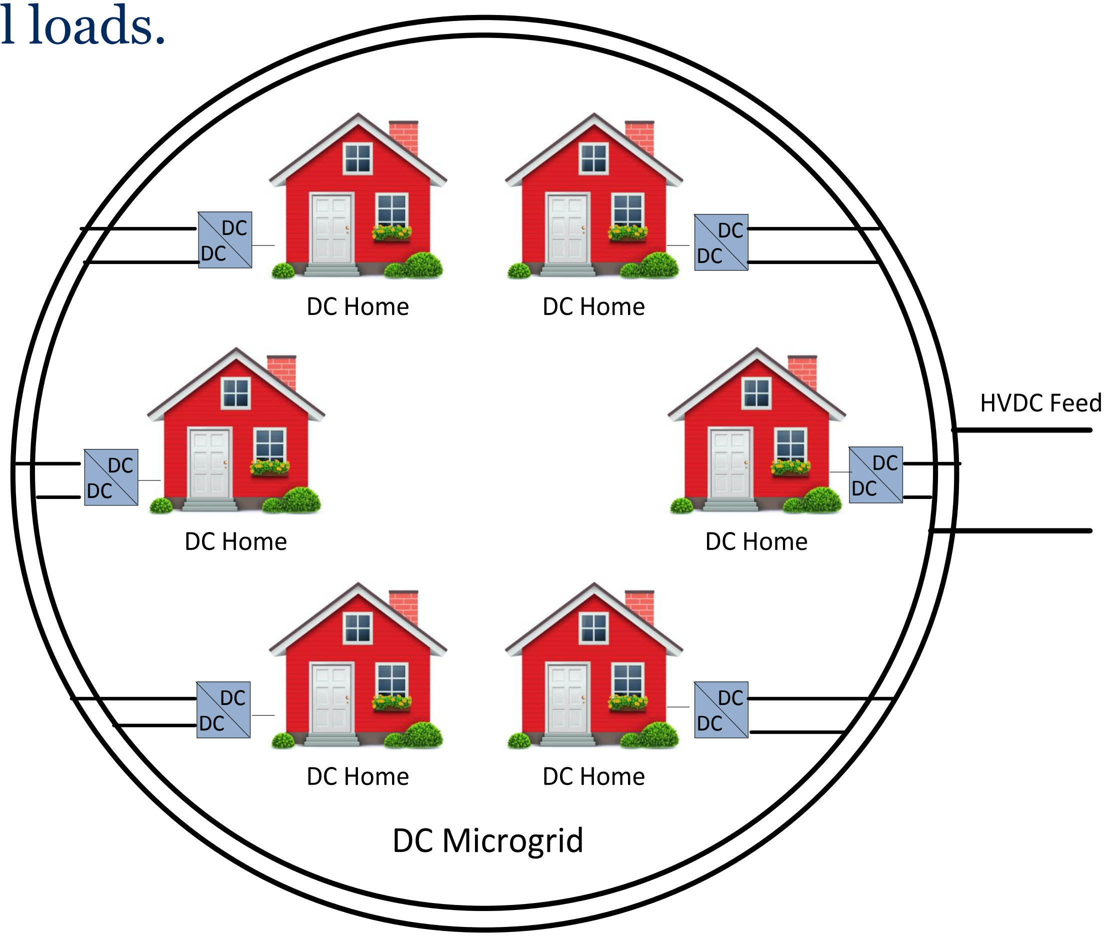
Direct Current Architecture for Modern Power Systems

DC AMPS: Focus and Takeaways

DC Microgrids and the Future Home

- DC power is inherently compatible with renewal sources and majority of residential loads.

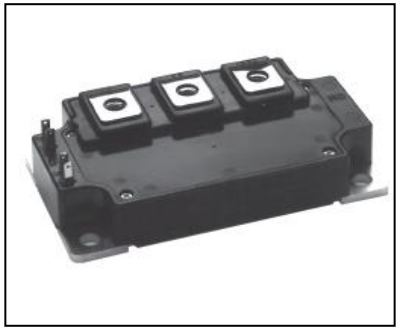


Direct Current Architecture for Modern Power Systems

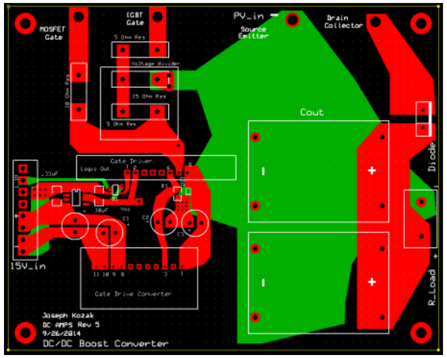
DC AMPS: Focus and Takeaways

Major Research Thrusts to Improve DC Home Design

Power Semiconductor Devices

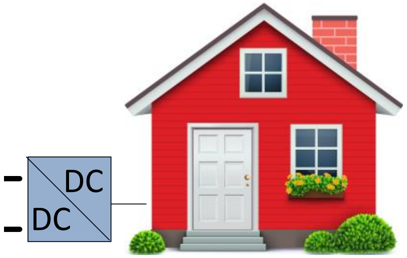


DC Power Converter Philosophy



DC System Control and Protection

DC Microgrid Design



DC Home

Direct Current Architecture for Modern Power Systems

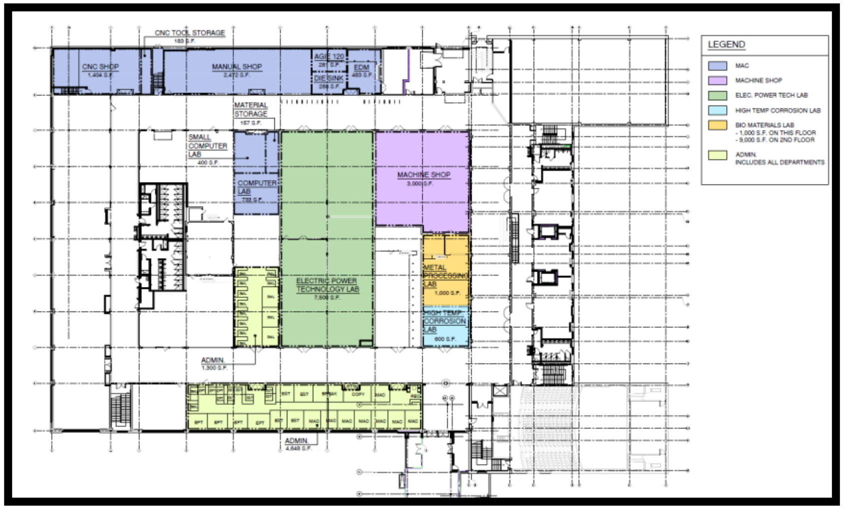
DC AMPS: Focus and Takeaways

Design Evaluations in Laboratory Setting

Electric Power Systems Lab

- Rating: 480 V, 200 A, 75 kVA
- Motor Control Center
- Energy Management/Power Quality
- Training and Teaching

Potential Electric Power Technology and Microgrid Lab



- 13.8 kV, 5 MW (or higher)
- Utility/Distribution Microgrid
- Hardware-in-the-Loop (RTDS)
- Automation / Protection

Direct Current Architecture for Modern Power Systems

DC AMPS: Focus and Takeaways

Community Involvement as Practices Emerge

- Community of knowledge to enhance adoption.
- Collaborations formed by academia and industry
- Priming the Pittsburgh region to be in a position of leadership in this arena
- Promote economic and job growth

NATIONAL ENGINEERING FORUM

NATIONAL ACADEMY OF SCIENCES

MILLCRAFT INVESTMENTS

Allegheny Conference on Community Development

LEADERSHIP PITTSBURGH INC.

IMBUTEC

GLOBAL LEARNING COUNCIL

Modeling and Characterization of False Turn-On in Wide Bandgap Semiconductors

Prepared by: Ansel Barchowsky
M.S. Student

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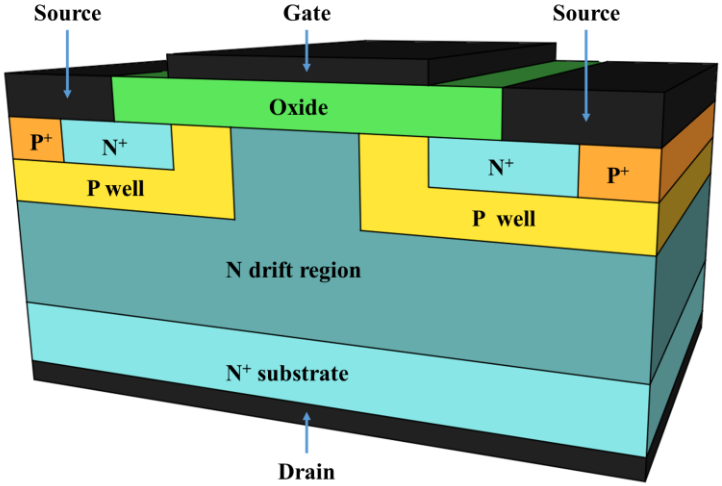
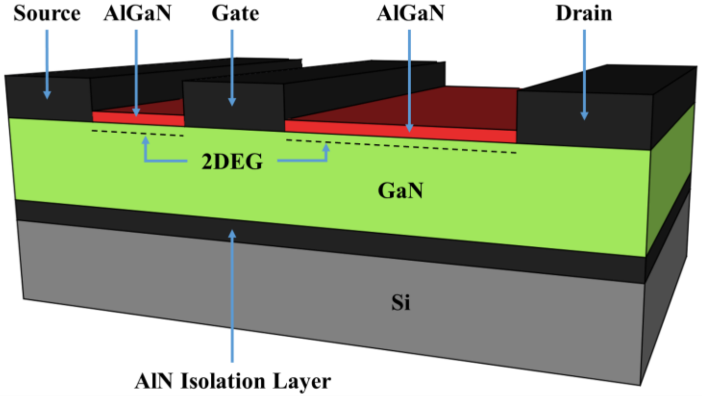
Direct Current Architecture for Modern Power Systems

False Turn-On in Wide Bandgap Semiconductors

Wide Bandgap Semiconductors in Power Electronics

- Benefits vs. Silicon:
  - Faster transition between on and off states
  - Lower switching losses, especially at high frequencies
  - Generally lower R_{ON} values
  - Better performance at high temperatures
- Transient Concerns During Switching
  - Voltage Overshoot
    - During turn-on, terminal gate voltage can exceed maximum ratings, destroying the device
  - Ringing
    - Repeated high frequency voltage oscillations can lead to secondary turn on of the device during turn-off
  - False Turn-On
    - High *dv/dt* transients induced on the drain terminal of a device can cause it to turn-on unintentionally



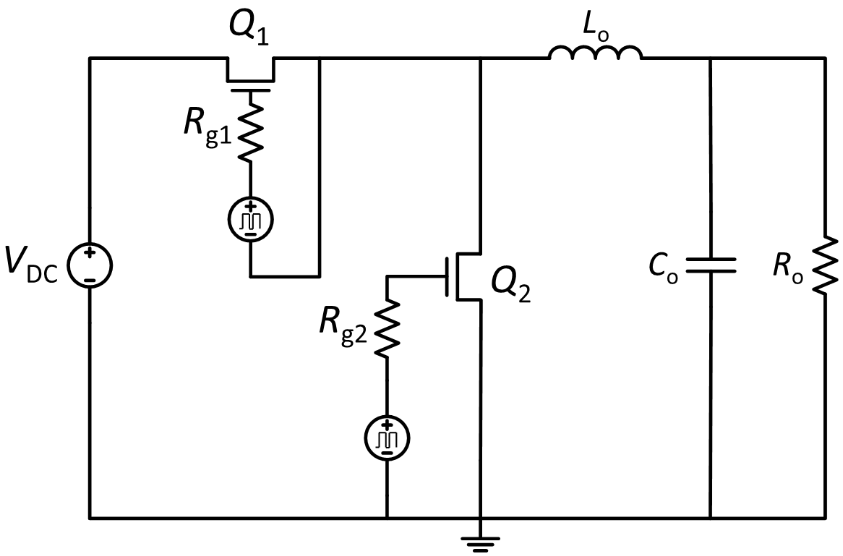


Top: SiC MOSFET **Bottom: GaN HEMT**

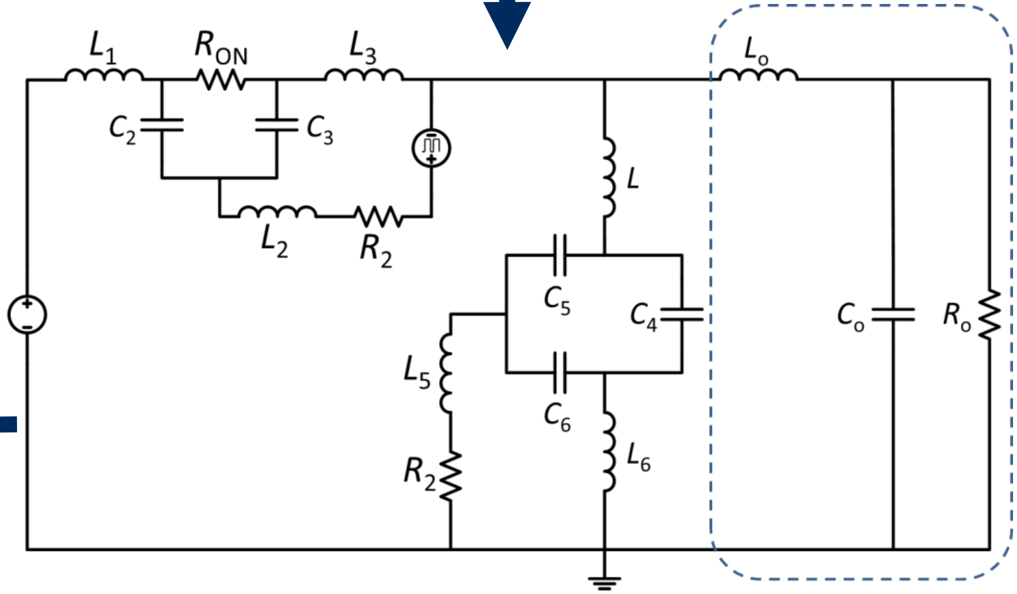
Direct Current Architecture for Modern Power Systems

False Turn-On in Wide Bandgap Semiconductors

Equivalent Circuit Model of Synchronous Buck Converter During Q_1 Turn-On



In this system, Q_1 is at it's moment of turn on and Q_2 is supposed to be off. The parasitic capacitances and inductances of the devices are modeled.



Extraction of State-Space Model

$$R_0 C_2 x_2 = R_0 x_1 - x_2 - x_3$$

$$+ L_2 \dot{x}_4 + L_3 \dot{x}_4 = -x_3 - R_1 x_4 +$$

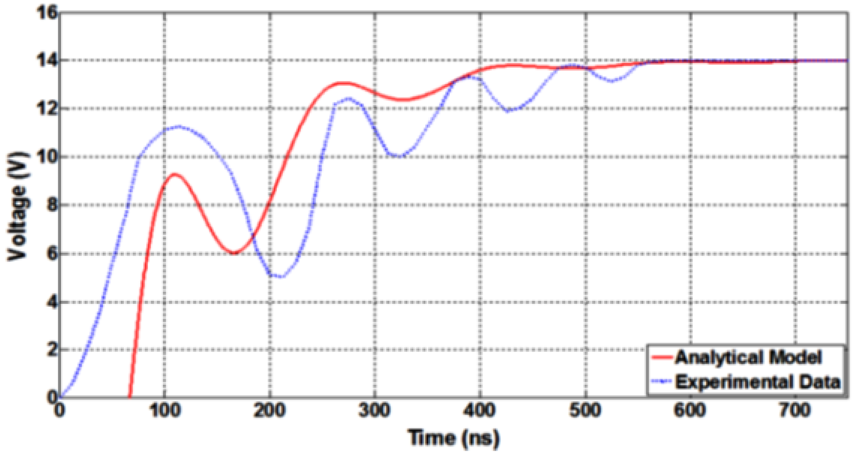
$$\dot{x}_{10} - L_6 \dot{x}_1 + L_6 \dot{x}_{10} = x_8 - R_2 x$$

$$C_2 \dot{x}_2 - C_3 \dot{x}_3 = -x_4$$

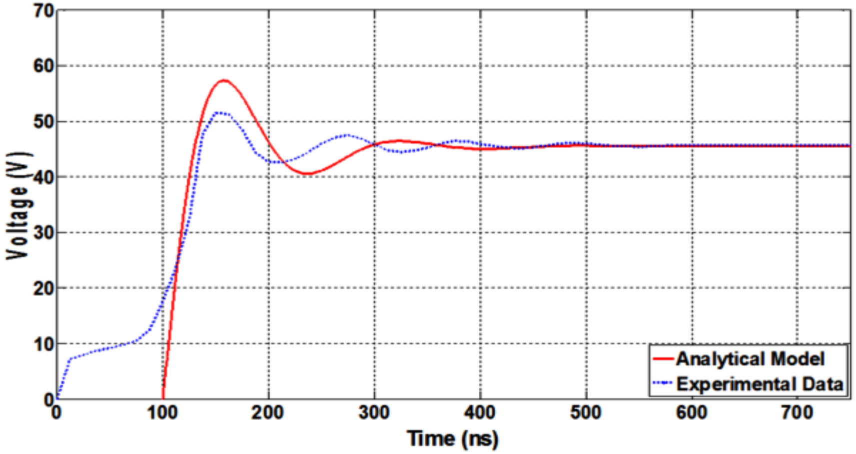
Direct Current Architecture for Modern Power Systems

False Turn-On in Wide Bandgap Semiconductors

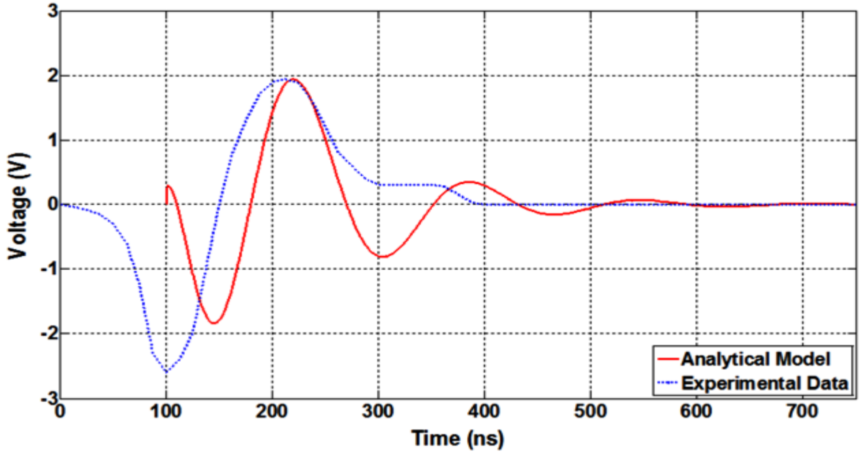
Validation of Analytical Model with Experimental Results



(1)



(3)



(2)

(1) V_{gs1} During Q_1 Turn-On

(2) V_{ds2} During Q_1 Turn-On

(3) V_{gs2} During Q_1 Turn-On – False Turn-On

Characterization between SiC MOSFET and Si IGBT in a DC/DC Boost Converter

Prepared by: Joseph Kozak
M.S. Student

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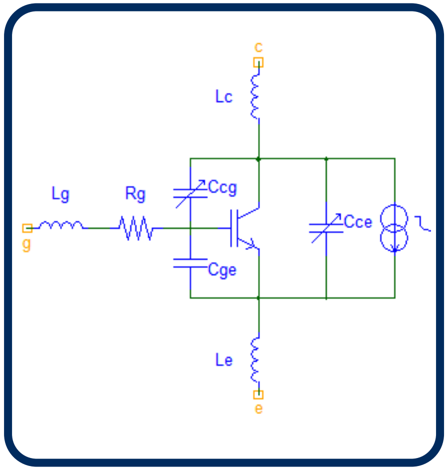
Direct Current Architecture for Modern Power Systems

SiC MOSFET and Si IGBT in DC/DC Boost Converter

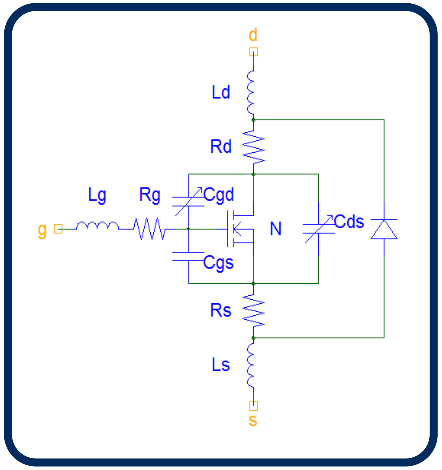
Model Creation in Synopsis SaberRD

IGBT



- Offers Diode, IGBT and MOSFET model creation
- Incorporated components include:
  - Resistances
  - threshold voltage
  - on resistance
  - Intrinsic capacitances
  - Parasitic inductances
- Shown are the MOSFET and IGBT models

MOSFET

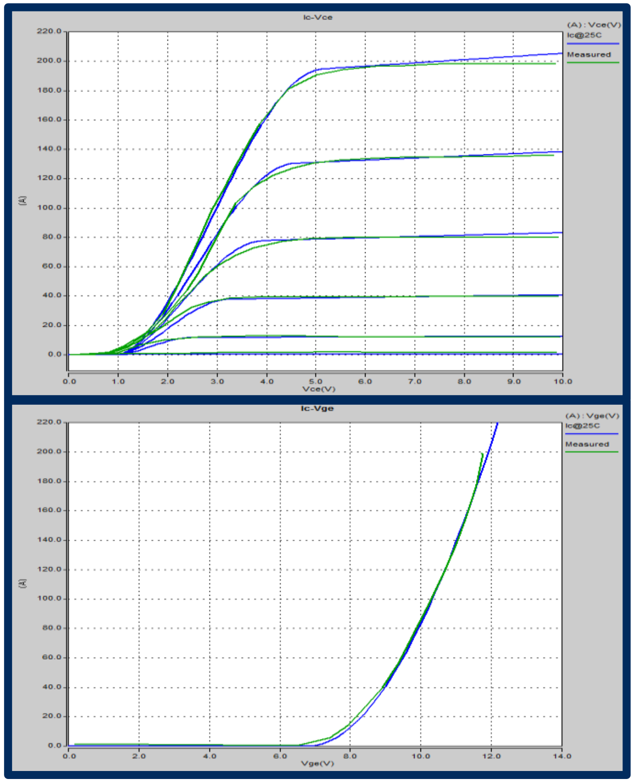


Direct Current Architecture for Modern Power Systems

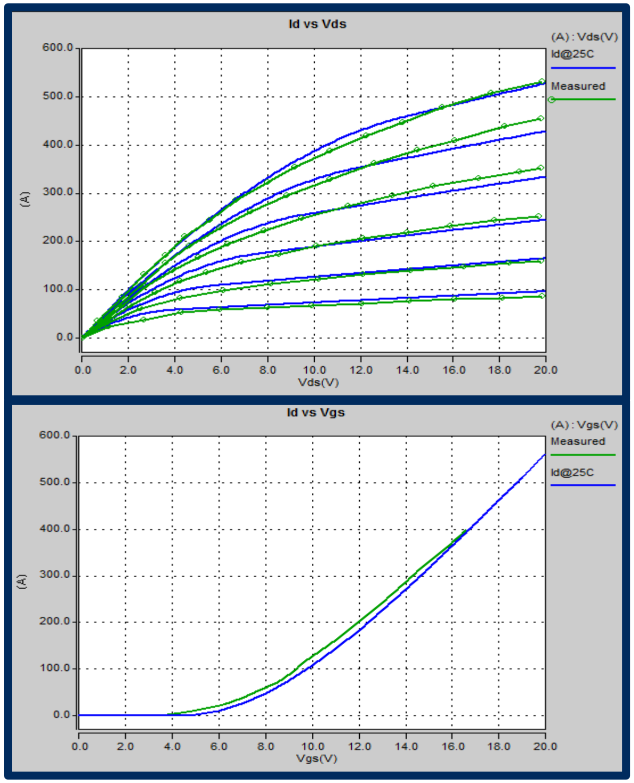
SiC MOSFET and Si IGBT in DC/DC Boost Converter

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

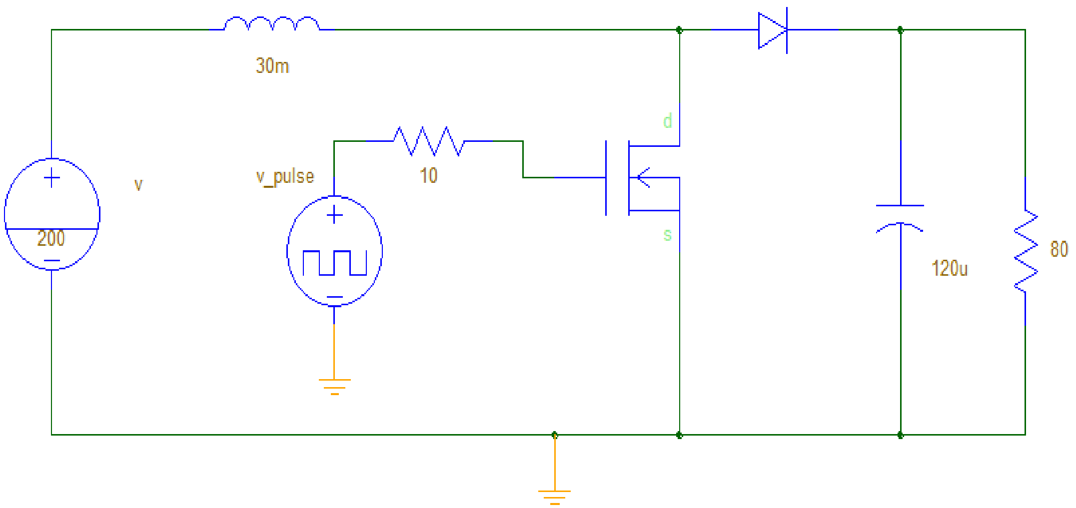


MOSFET

Direct Current Architecture for Modern Power Systems

SiC MOSFET and Si IGBT in DC/DC Boost Converter

DC Converter Topology



$V_{dc} = 300\ Volts$
$L = 100mH$
$C = 40uF$
$R_{load} = 500\ Ohm$

$R_{pulse} = 5\ Ohms$
$V_{pulse} = 20\ Volts$
$Duty\ Cycle_{Vpulse} = 0.5$

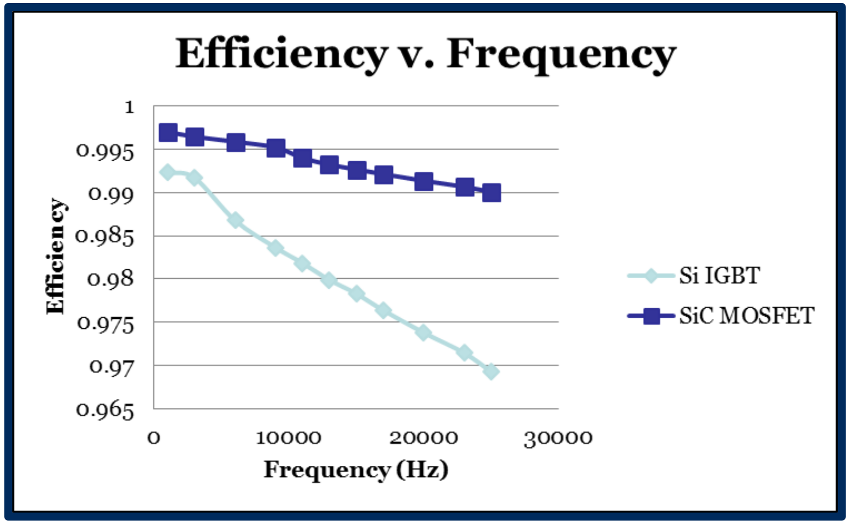
- DC/DC Boost converter has been designed for initial testing
- Used to simulate the electrical performance of the transistor models
- The design can be extrapolated to more complex circuits using the transistor models

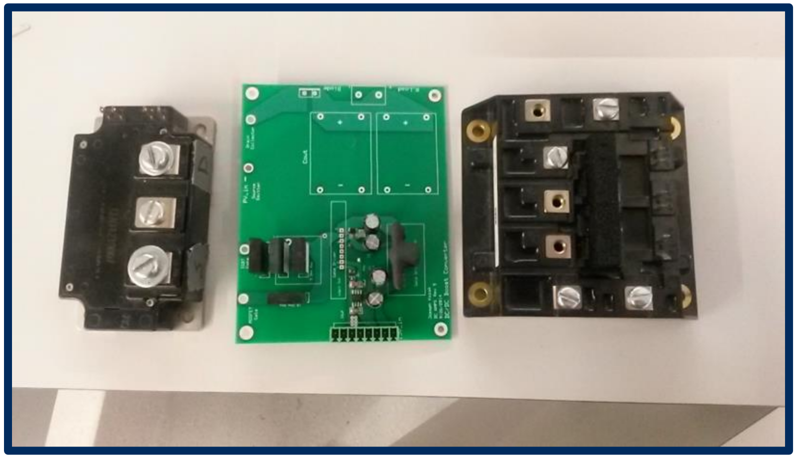
Direct Current Architecture for Modern Power Systems

SiC MOSFET and Si IGBT in DC/DC Boost Converter

Simulation Results

- The simulated results are consistent with known transistor properties
- DC Converter is under development to validate the simulated results





Physical DC Converter Development

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A Novel 380V DC Topology for Increased Efficiency in Cell Tower Applications

Prepared by: Augustin Crémer
M.S. Student

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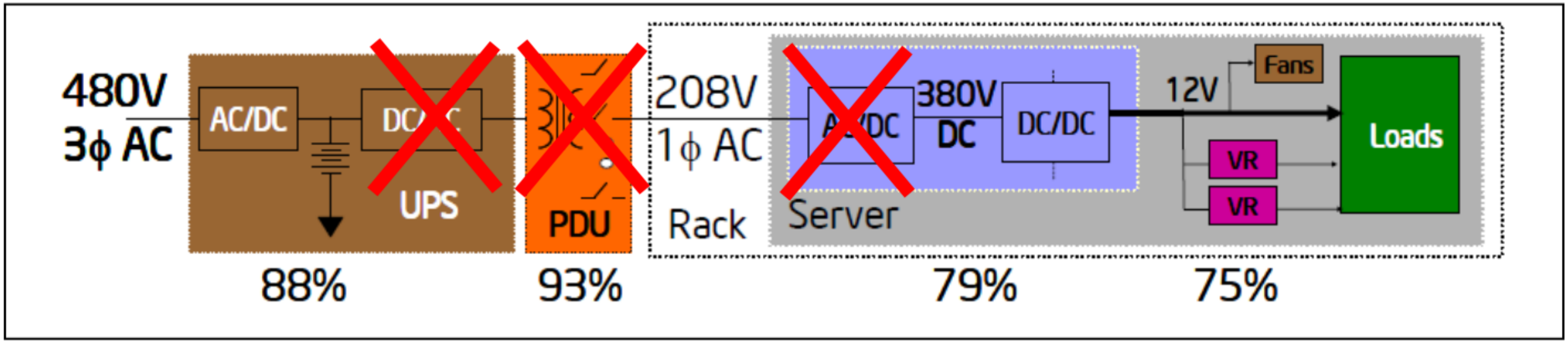
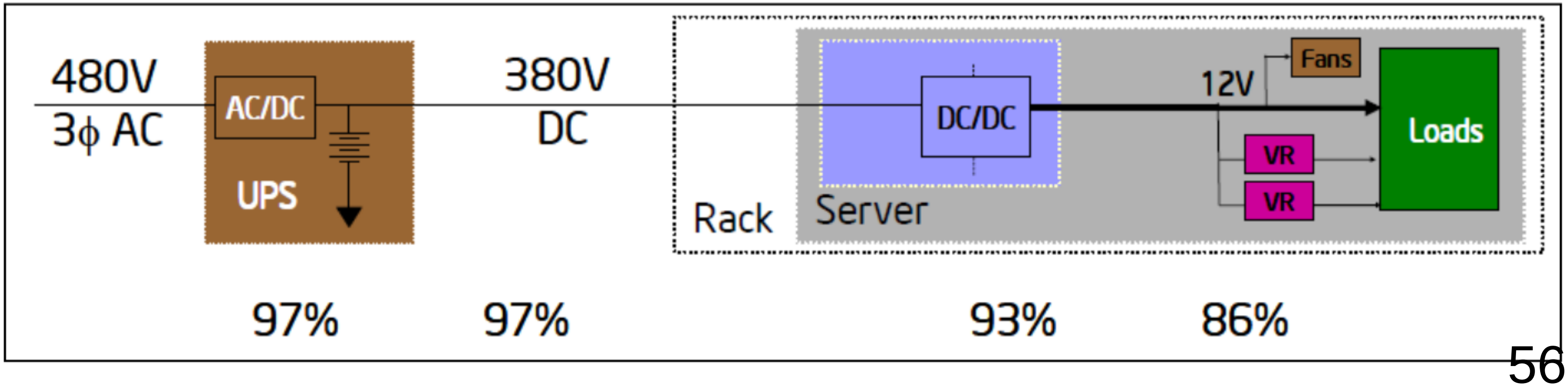
Direct Current Architecture for Modern Power Systems

A Novel 380 V DC Topology for Cell Towers

DC 380 V has shown great results in the data center industry



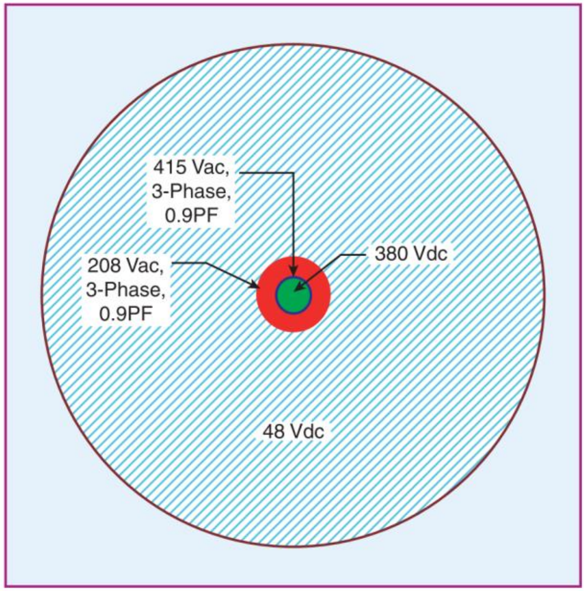


Direct Current Architecture for Modern Power Systems

A Novel 380 V DC Topology for Cell Towers

DC 380 V has shown great results in the data center industry

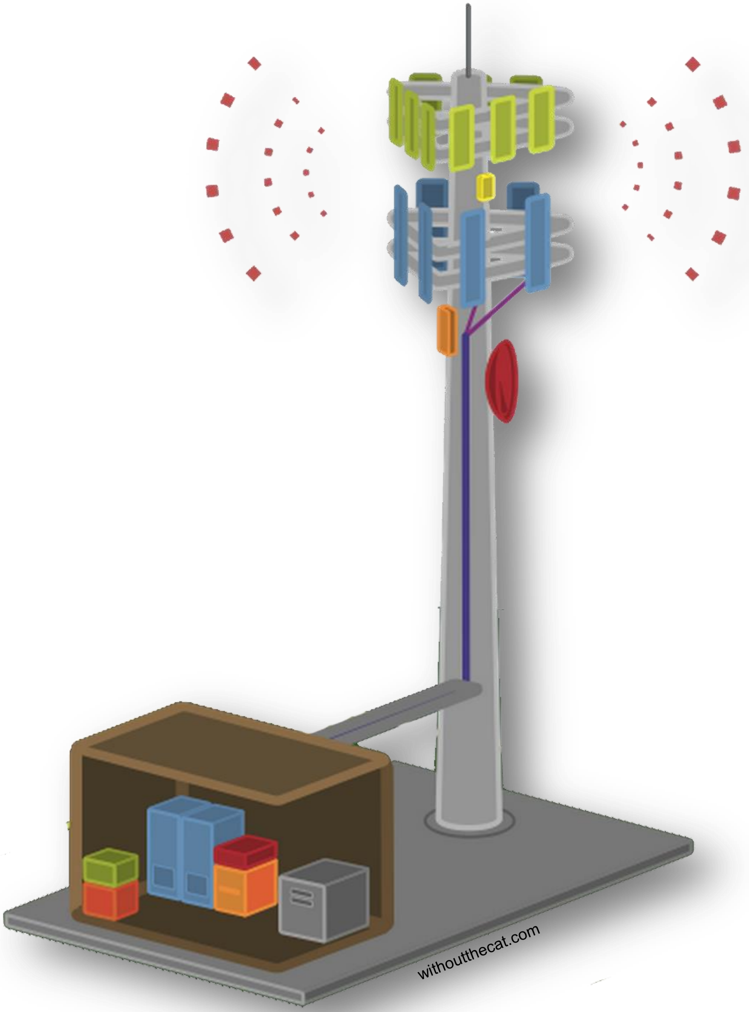
- Compared to a legacy 208 VAC system, 380 V DC offers
  - 10% efficiency increase
  - 25% lower footprint
  - 10% lower capital cost
  - 20% lower installation cost
  - Better renewable energy integration.



Direct Current Architecture for Modern Power Systems

A Novel 380 V DC Topology for Cell Towers

State of the art and expected benefits



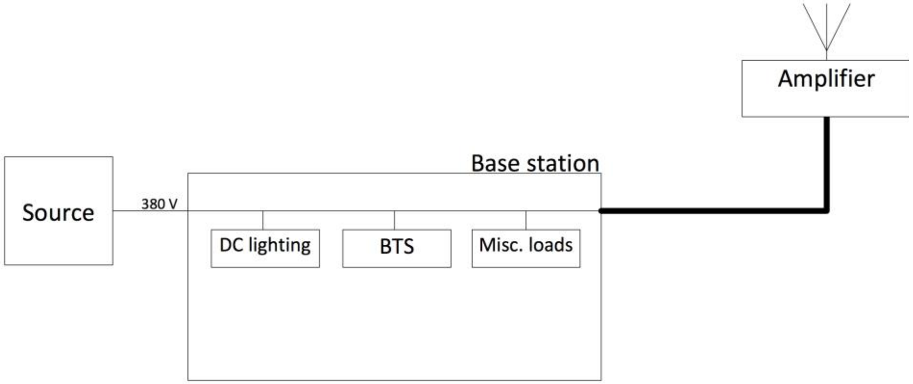
- 48 V DC offers great reliability and low conversion losses
  - Low voltage means high currents (several 10s of A)
    - Increased transmission losses up the pole
    - Increased copper costs.
- Expected benefits of a 380 V DC topology for cell towers
  - Increased efficiency
  - Lower footprint
  - Lower capital cost
  - Better renewable integration
    - Lower operational expenses for remote cell sites.

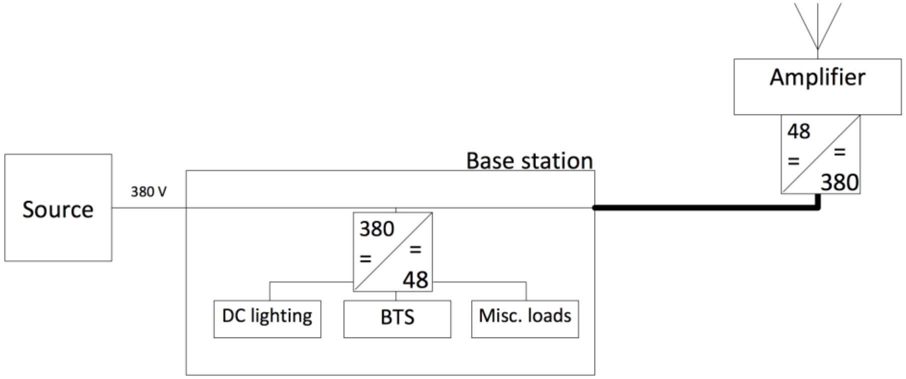
Direct Current Architecture for Modern Power Systems

A Novel 380 V DC Topology for Cell Towers

Objectives

- Analysis of different topologies
  - Full DC 380 V
  - Hybrid DC 380 – DC 48 V
- Quantification of the efficiency gain in comparison with a legacy 48 V DC architecture.





Power Electronics Systems Design, Protection, & Evaluation

Patrick T. Lewis, Hashim Al Hassan
Stephen M. Whaite
Laura Wieserman

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MITSUBISHI ELECTRIC
Changes for the Better

Modular Multilevel Converter Based High Voltage DC Protection

Patrick T Lewis

Fault Location Identification

Hashim Al Hassan

EATON
Powering Business Worldwide

Voltage Sag Generator for the Electric Power Systems Lab

Stephen Whaite

Fault Current and Overvoltage Calculations for the Inverter-Based Generation Using Symmetrical Components

Laura Wieserman

Modular Multilevel Converter Based High Voltage DC Protection

Prepared by: Patrick T. Lewis
M.S. Student

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Power Electronic Systems Design, Protection, & Evaluation

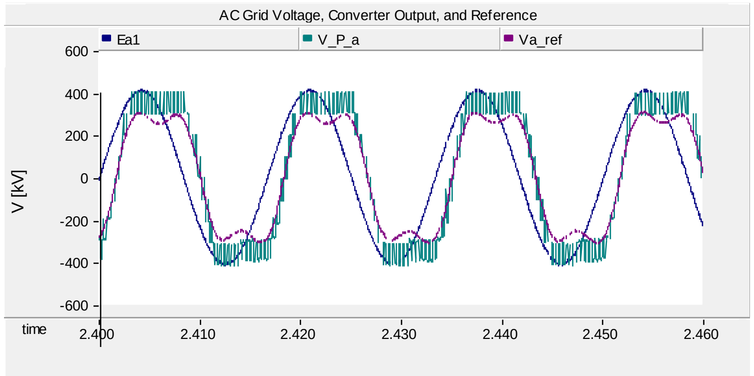
Modular Multilevel Converter Based HVDC Protection

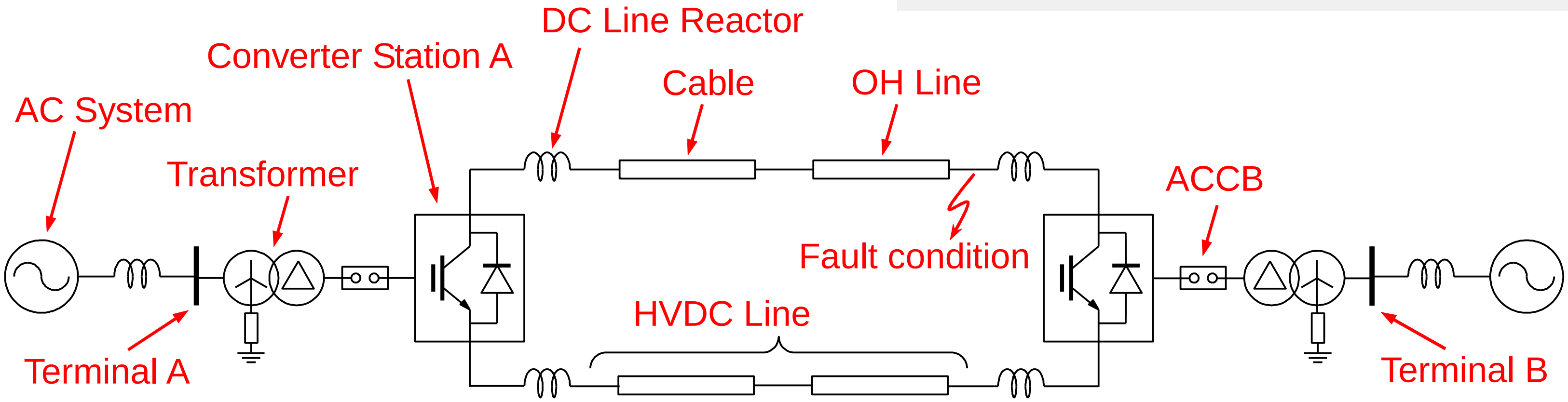
Research Background

Role of the University of Pittsburgh within HVDC technology development project with Mitsubishi Electric Corporation

1. HVDC System Modeling
2. DC Fault Analysis
3. DC Protection System Design
4. DC Protective Relaying Schemes

EPIC 2014: Validation of HVDC system model



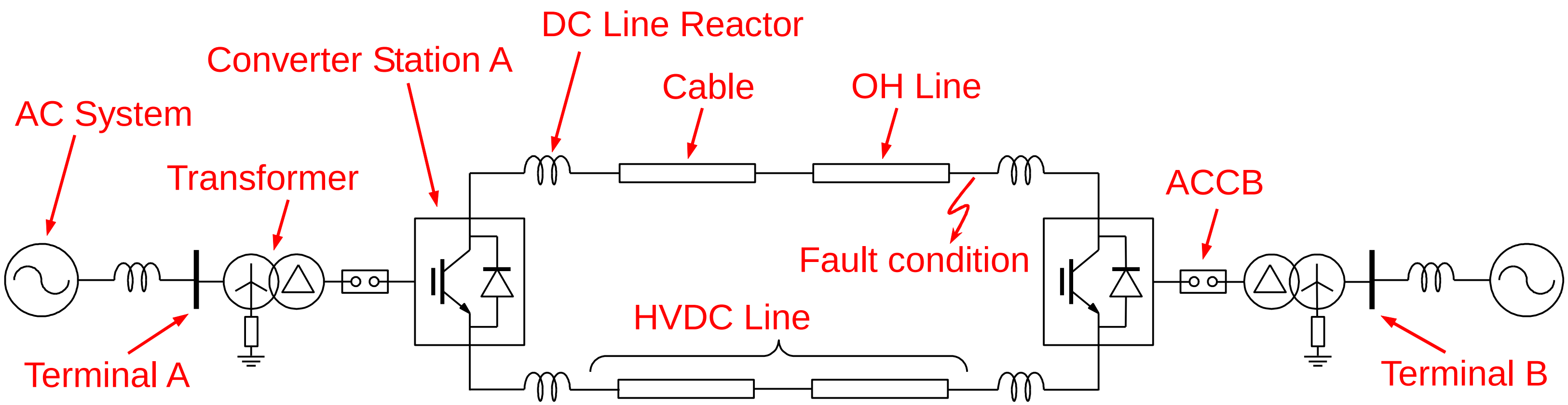


Power Electronic Systems Design, Protection, & Evaluation

Modular Multilevel Converter Based HVDC Protection

Research Motivation

- Need for MMC-HVDC transmission without a communication channel between terminals A and B
- Need for a fault section identification algorithm to avoid false reclosure of the AC circuit breakers in attempt to restart the system
- **Need for a solution to suppress circulating currents in the MMC topology**

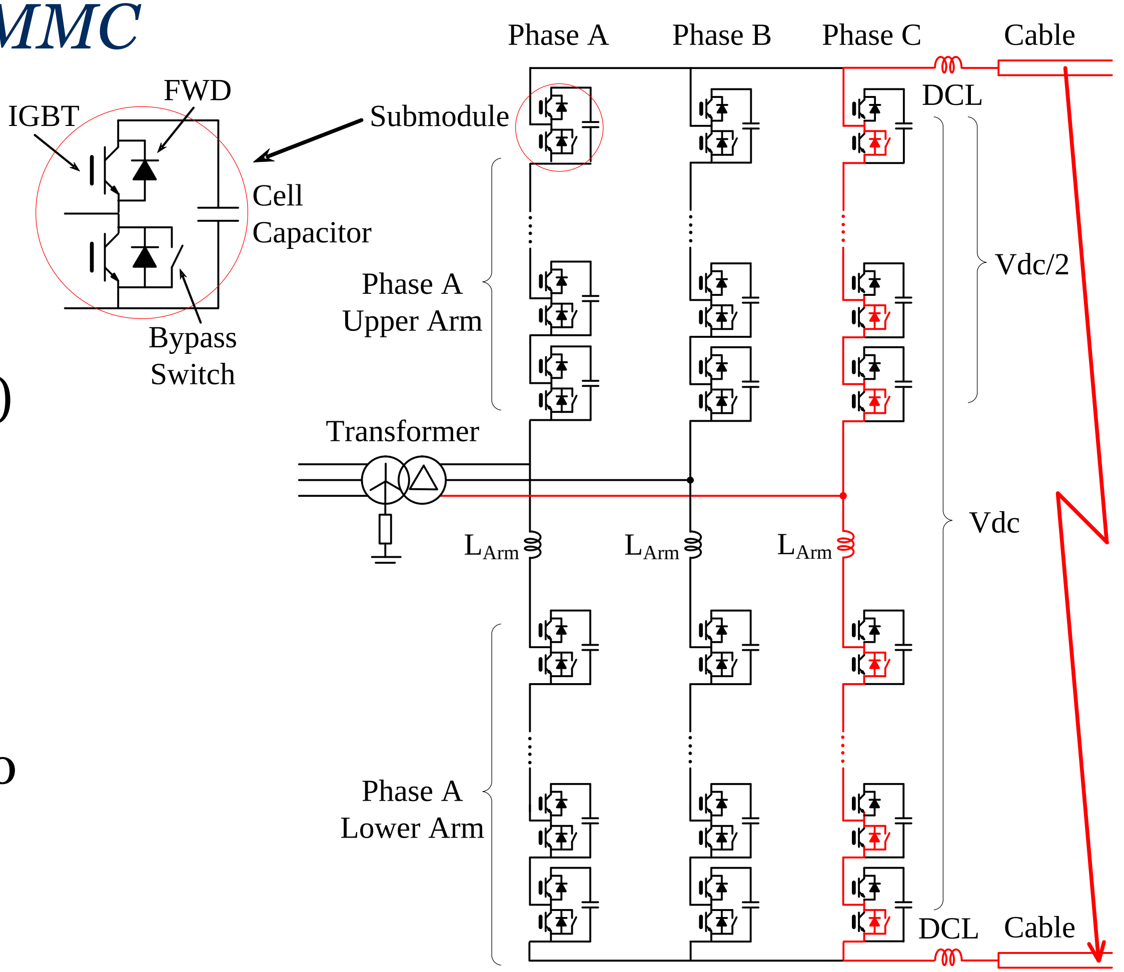


Power Electronic Systems Design, Protection, & Evaluation

Modular Multilevel Converter Based HVDC Protection

Circulating Currents in MMC

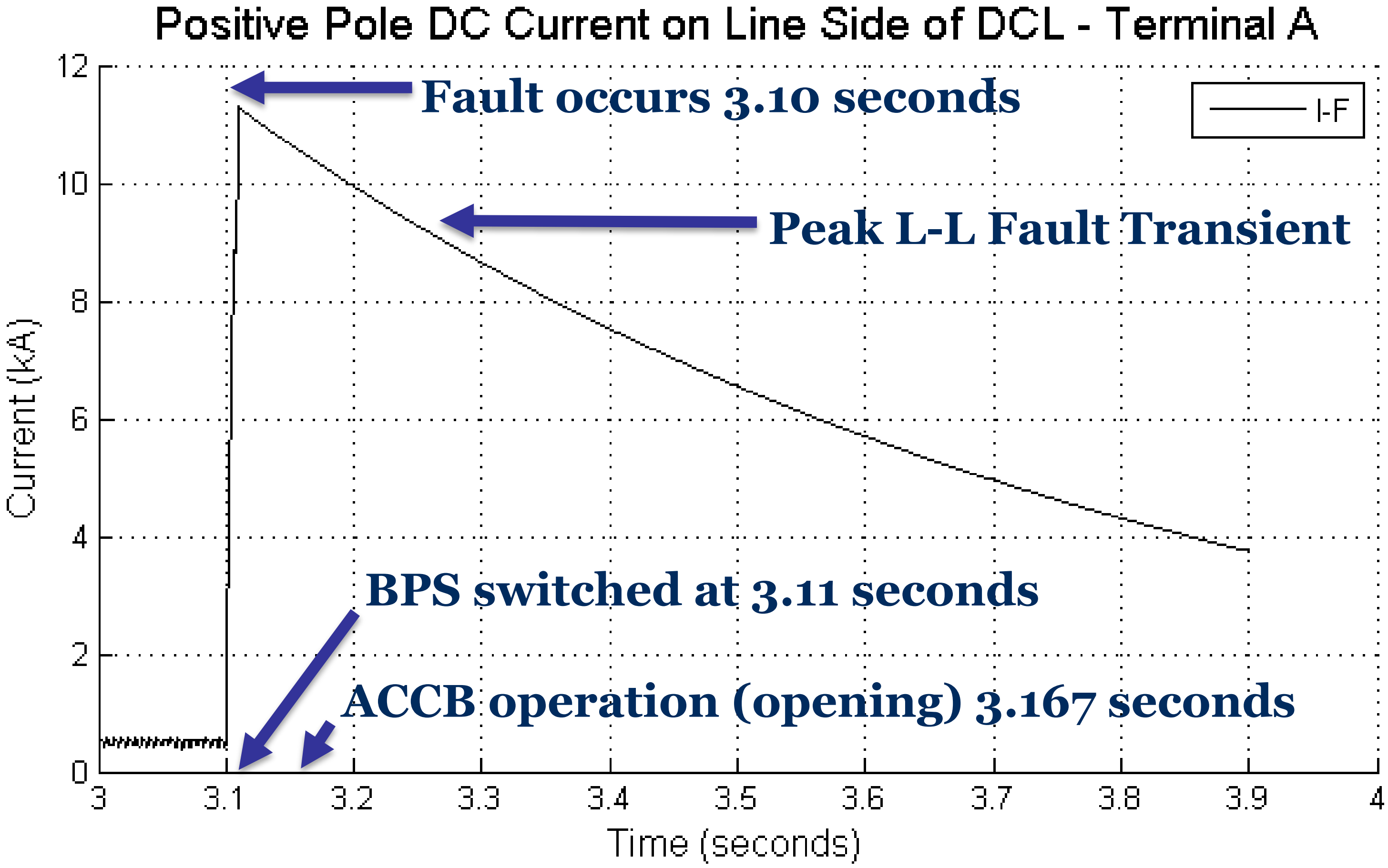
- Line-to-line fault on DC side of the system
- Circulating current path flows through BPS and freewheeling diodes (FWD)
- Gate blocking and bypass switch (BPS) protection
- Slow dissipation of this current delays restart time
- Need for a novel solution to suppress circulating currents more quickly



Power Electronic Systems Design, Protection, & Evaluation

Modular Multilevel Converter Based HVDC Protection

Circulating Currents to be Suppressed Quickly



Fault occurs 3.10 seconds

Peak L-L Fault Transient

BPS switched at 3.11 seconds

ACCB operation (opening) 3.167 seconds

Conceptual solutions being proven in simulation and hardware.

University of Pittsburgh

Fault Location Identification

Prepared by: Hashim Al Hassan
Ph.D. Student

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November 17th, 2014

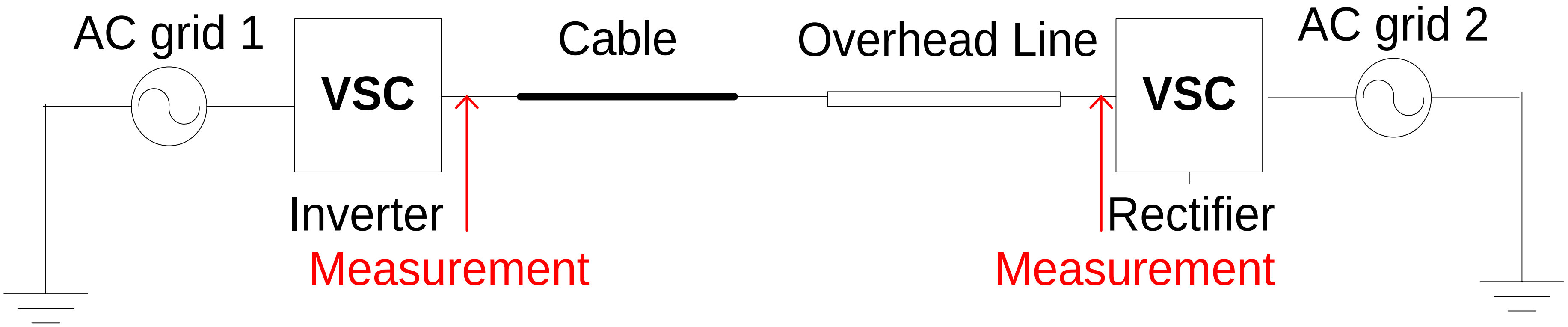
Power Electronic Systems Design, Protection, & Evaluation

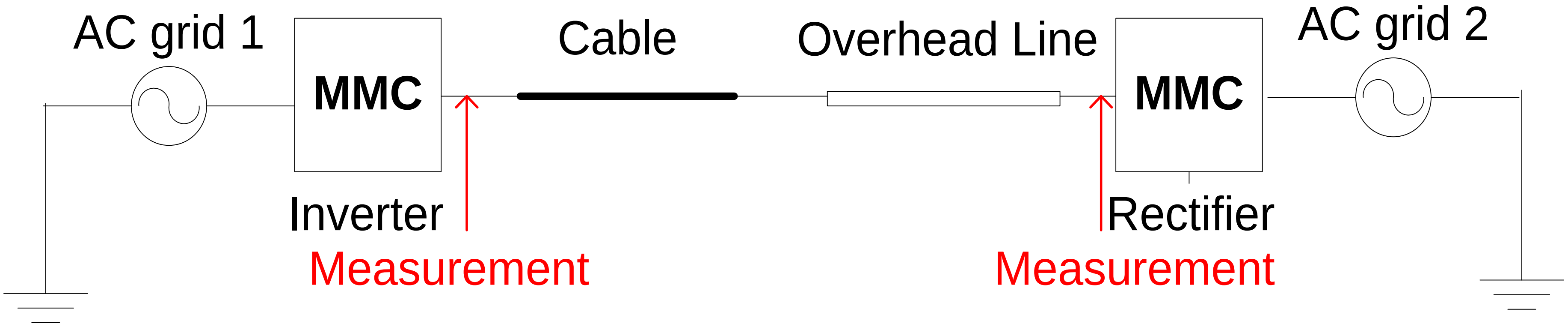
Fault Location Identification

Research Objective and Motivation

1. Fault Location Identification:
   - Reduce maintenance time and cost.
   - Identify weak points in the system.(preventative maintenance)
2. Fault Section Identification:
   - Increase Reliability by:
     - Operating reclosers for OH line faults.
     - Shutting down the system for cable faults.

Fault Location Identification System of Study

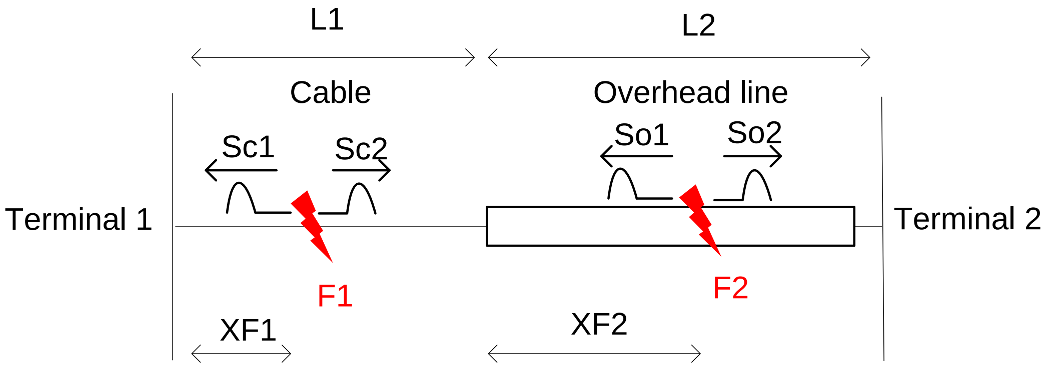


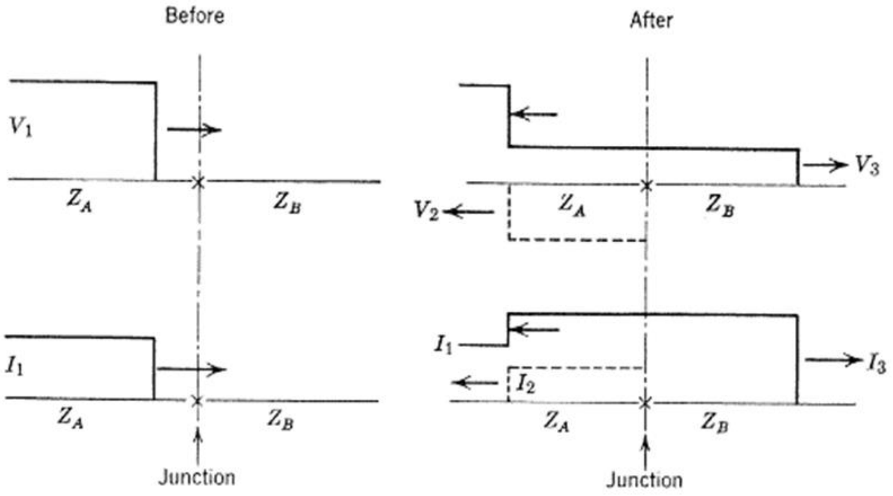


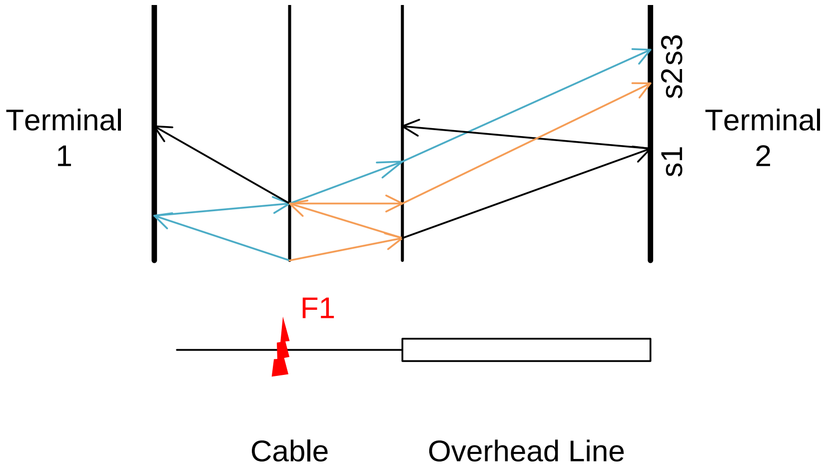
Power Electronic Systems Design, Protection, & Evaluation

Fault Location Identification

Travelling Wave Theory: Method Utilized for Research







Source: Allan Greenwood, Electrical Transients in Power Systems, Second edition, John Wiley & Sons, Inc. 1991

Conclusion and Current Research Direction

Conclusion:

- Extended Current Research on Fault Location Identification for a VSC-HVDC system with cable and overhead line segments.

- Developing a novel algorithm for fault section identification that can be implemented in current technology with no need for communication.

Current Research Direction:

- Power flow control for MTDC applied to wind farms and taking into account uncertainty.

Voltage Sag Generator for the Electric Power Systems Lab

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

9th Annual Electric Power Industry Conference
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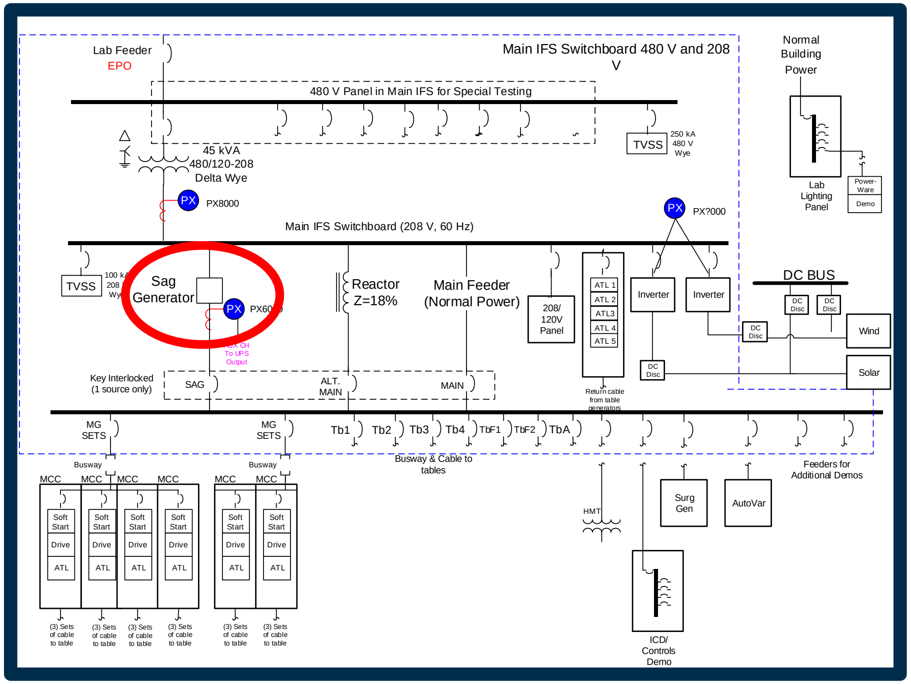
Graduate Student Symposium
November 17th, 2014

Power Electronic Systems Design, Protection, & Evaluation

Voltage Sag Generator for the Electric Power Systems Lab

Motivation

- A Voltage Sag Generator (VSG) was a part of the design concept for the Pitt Electric Power Systems Lab (EPSL).
- A VSG in the EPSL supports both the lab’s educational and research functions.
- Commercially available VSG units are prohibitively expensive.

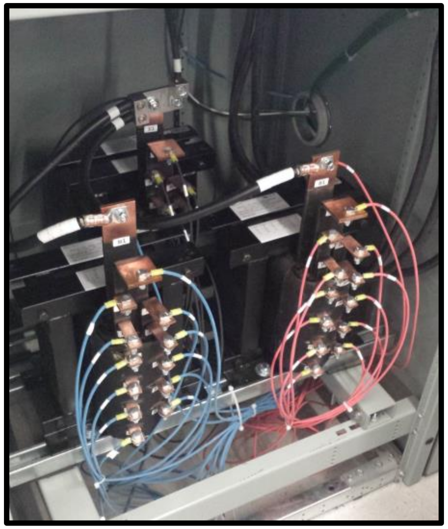


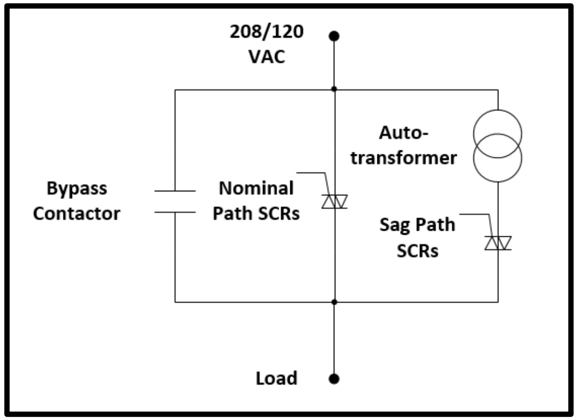
Power Electronic Systems Design, Protection, & Evaluation

Voltage Sag Generator for the Electric Power Systems Lab

Electrical Design

- Each phase of the VSG consists of two conduction paths for each, one at nominal voltage and one at sag voltage.
- Sag voltages are produced by fixed tap autotransformers with contactor tap selection.
- SCRs are used to switch between conduction paths
- The nominal path is rated for 150 A RMS, the full EPSL rated load



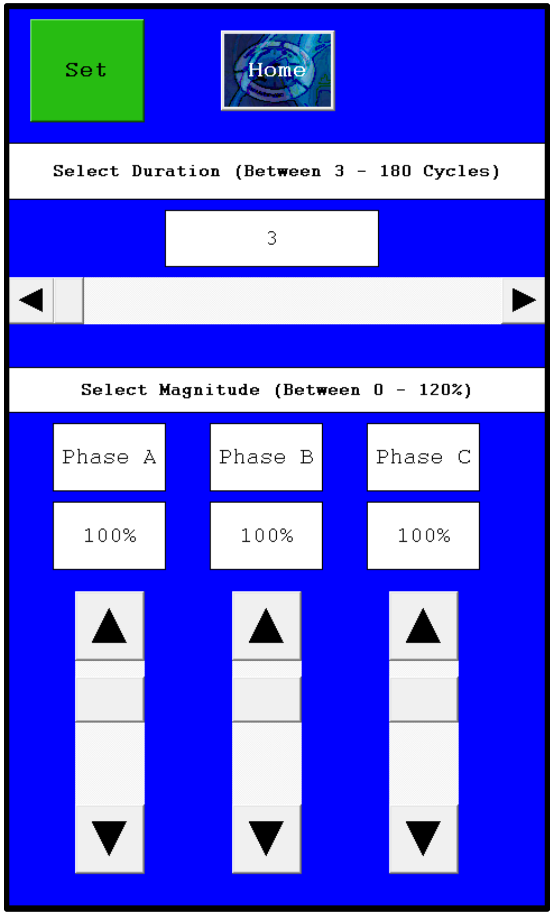


Power Electronic Systems Design, Protection, & Evaluation

Voltage Sag Generator for the Electric Power Systems Lab

Control Design

- A PLC with touchscreen HMI is used to control the VSG.
- The PLC controls the tap selection contactors and the SCR gate drivers.
- Transformer taps can be independently set for each phase, allowing unbalanced sags.
- Sag duration can be set between 3 and 180 cycles.



Select Duration (Between 3 - 180 Cycles)

3

Select Magnitude (Between 0 - 120%)

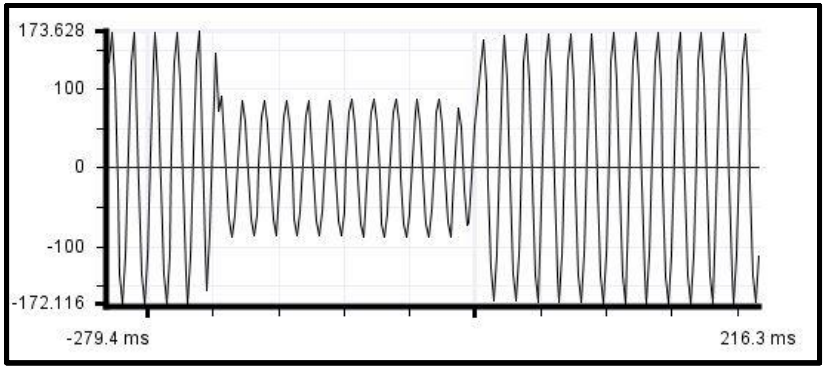
Phase A	Phase B	Phase C
100%	100%	100%

Power Electronic Systems Design, Protection, & Evaluation

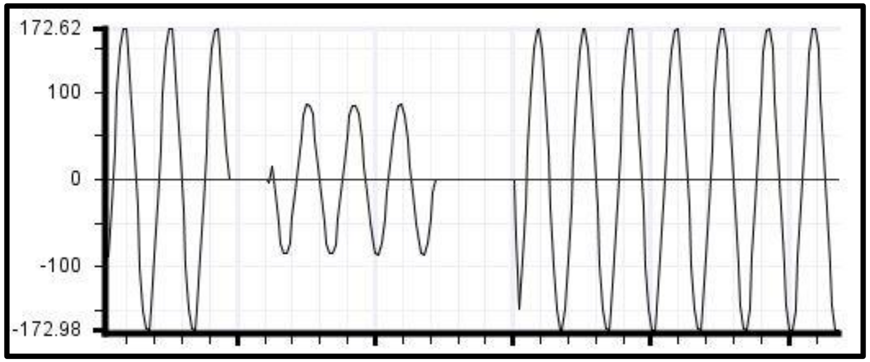
Voltage Sag Generator for the Electric Power Systems Lab

Test Results

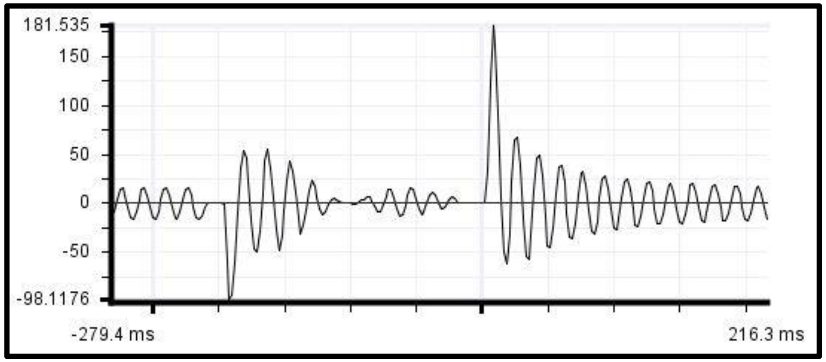
- The VSG has been tested with a variety of sag levels and durations.
- Using SCRs and a PLC necessitates a delay to ensure a current zero.



Phase L-N Voltage for 10 Cycle, 50% Sag w/ Inductive Motor Load



Phase L-N Voltage for 3 Cycle, 50% Sag w/ Resistive Load



Line Current for 10 Cycle, 50% Sag w/ Inductive Motor Load

Fault Current and Overvoltage Calculations for Inverter-Based Generation Using Symmetrical Components

Prepared by: Laura Wieserman
Ph.D. Student

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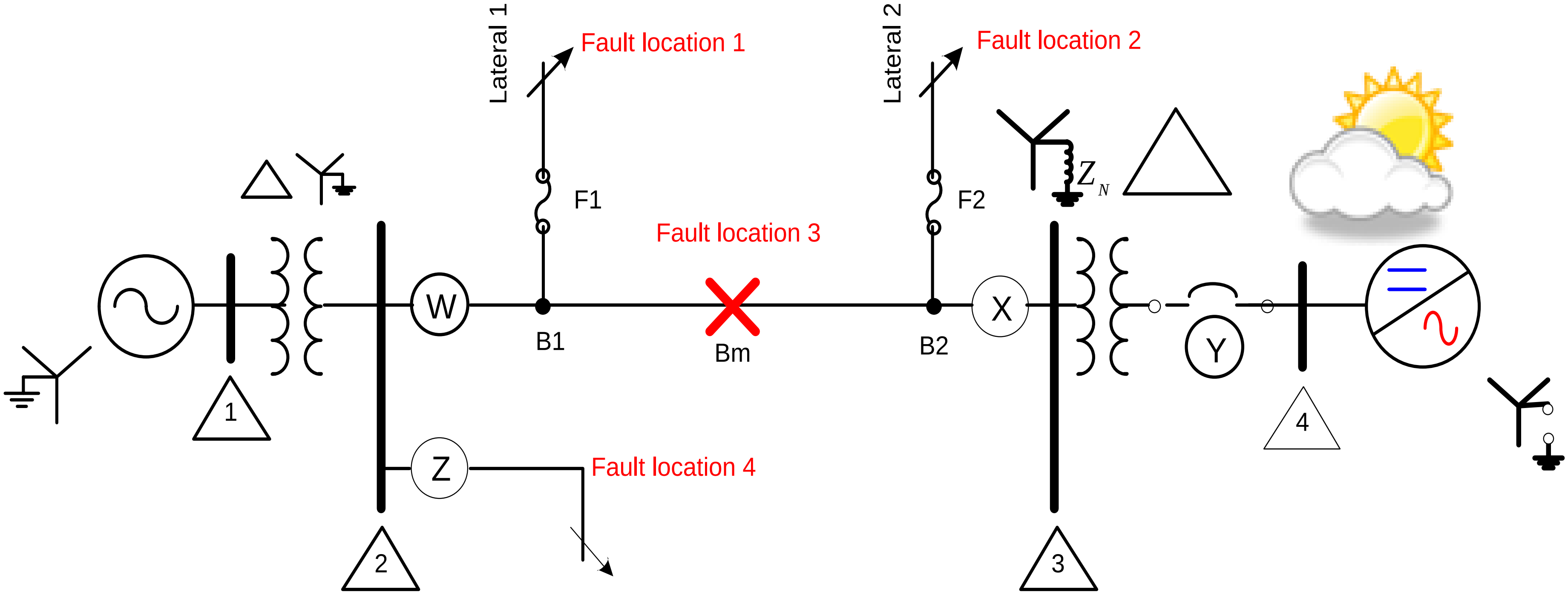
Fault Current and Overvoltage Calculations for Inverter-Based Generation

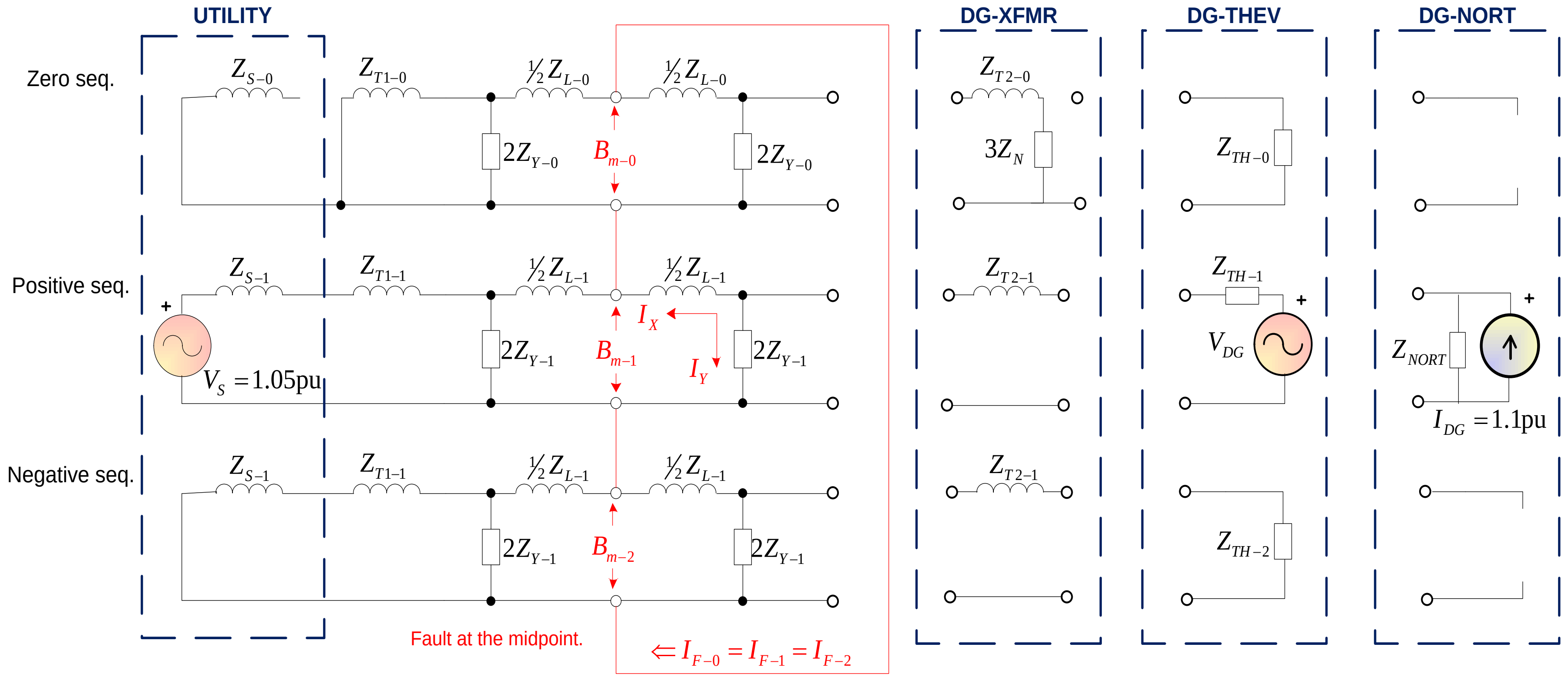
Test Feeder For Distributed Generation Symmetrical Component Analysis



Power Electronic Systems Design, Protection, & Evaluation

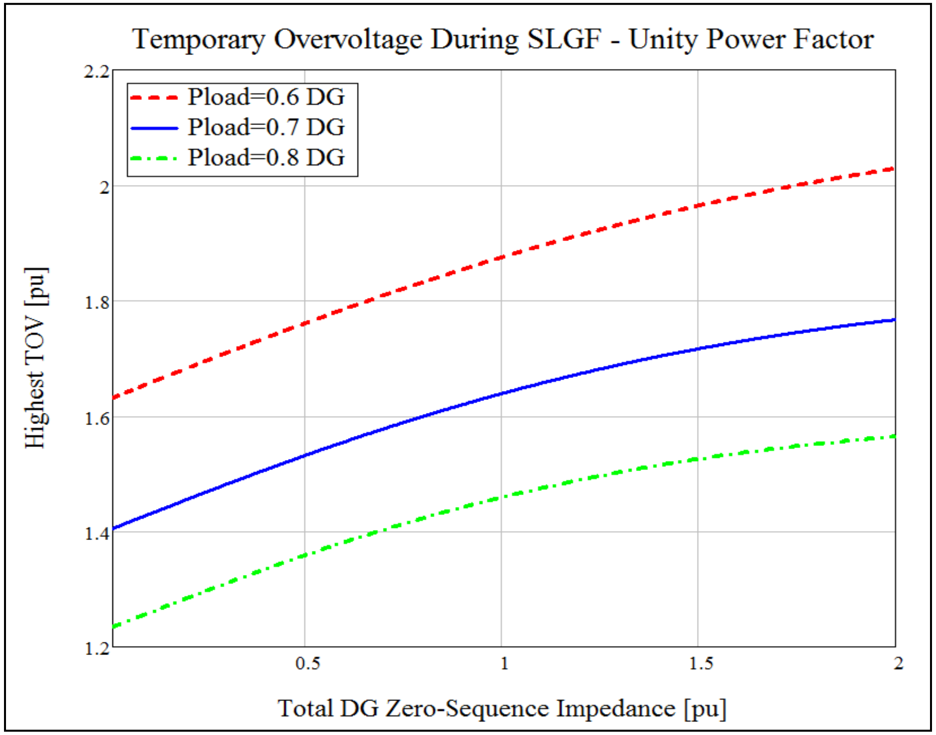
Fault Current and Overvoltage Calculations for Inverter-Based Generation

Symmetrical Component Calculations for Solar Inverter-based Generation.



Power Electronic Systems Design, Protection, & Evaluation
Fault Current and Overvoltage Calculations for Inverter-Based Generation

Grounding does affect the TOV and may achieve approx. a 0.2pu reduction in TOV



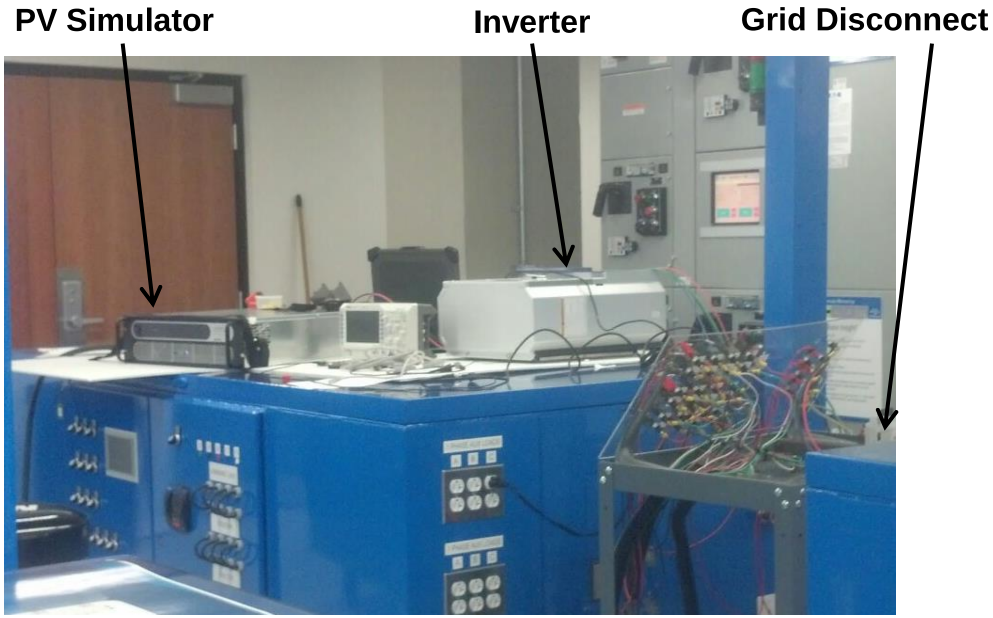
WORST-CASE TOV DURING SLGF AS A FUNCTION OF DG GROUNDING IMPEDANCE AND FEEDER LOAD, UNITY POWER FACTOR.

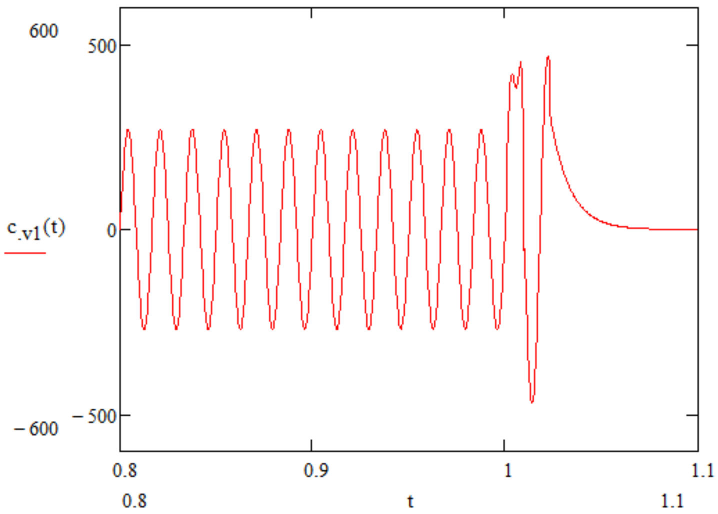
- Grounding alone is NOT enough to reduce the TOV’s to the desired maximum of 1.38 p.u. TOV on the system.
- A significant load is necessary to further reduce the overvoltages.
- A load greater than 80% of the DG would be needed for acceptable TOV with a wye-grounded/delta transformer, or 90% with an 8-Ohm neutral impedance in the ground connection.

Power Electronic Systems Design, Protection, & Evaluation

Fault Current and Overvoltage Calculations for Inverter-Based Generation

Inverter Open Circuit Testing in the Lab





```
AX:     =  -11.40ms
AY:     =  386.0 V
BX:     =  40.40ms
BY:     =  178.0 V
BX-AX:  =  51.80ms
BY-AY:  =  -208.0 V
1/|dX|: =  19.30 Hz
```

```
AX:     =  17.80ms
AY:     =  386.0 V
BX:     =  60.80ms
BY:     =  178.0 V
BX-AX:  =  43.00ms
BY-AY:  =  -208.0 V
1/|dX|: =  23.25 Hz
```

$$c_{v1}(t) := \left| \begin{array}{l} f1(t) \quad \text{if } t < 1.005 \\ f2[t-(1.005)] \quad \text{if } 1 < t < 1.0098 \\ f_{test}[t-(1.0097)] \quad \text{if } 1.0097 < t < 1.0097 + \dfrac{1}{75} \\ f_{test2}\left[t-\left(1.0097+\dfrac{1}{75}\right)\right] \quad \text{otherwise} \end{array} \right.$$

Modernizing a Legacy AC Power System Design for the 21st Century

Stephen Abate
Andrew Reiman
Matthew Korytowski

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EPRI ELECTRIC POWER RESEARCH INSTITUTE

Smart Inverter Settings for Improving Distribution Feeder Performance

Stephen Abate

FirstEnergy®

Feeder Analytics and DER Integration

Andrew Reiman

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

Integration of Offshore Wind Power to the U.S. Electric Grid

Matthew Korytowski

University of Pittsburgh

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Smart Inverter Settings for Improving Distribution Feeder Performance

Prepared by: Stephen Abate
M.S. Student

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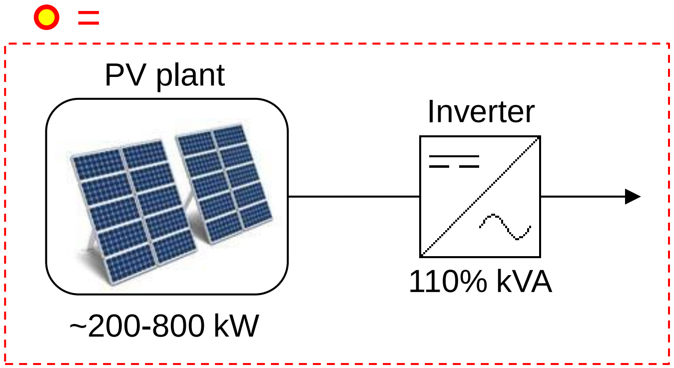
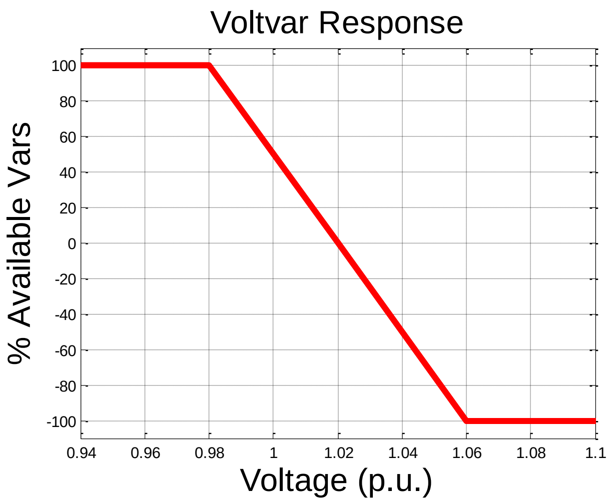
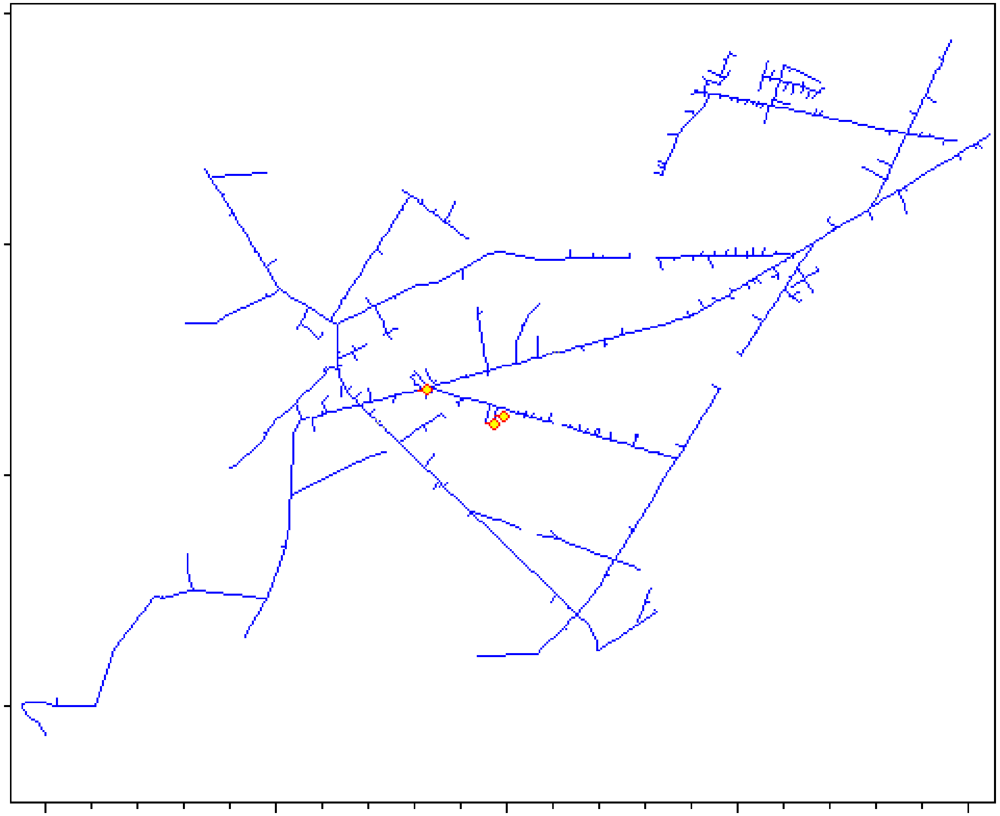
Smart Inverter Settings for Improving Distribution Feeder Performance

Smart Inverters provide reactive power support in response to voltage changes







Distribution circuit diagram

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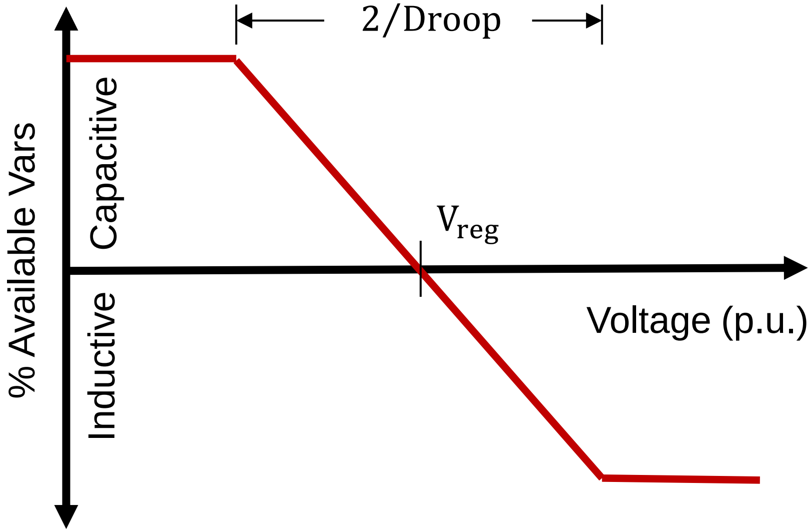
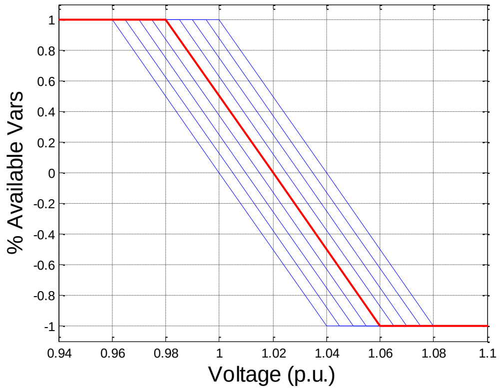
Smart Inverter Settings for Improving Distribution Feeder Performance

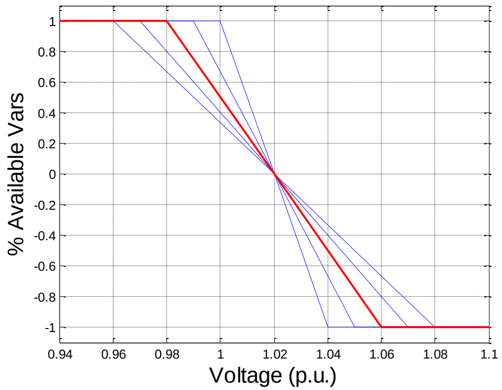
Properly chosen settings can improve distribution feeder metrics



Varying V_{reg}



Varying Droop



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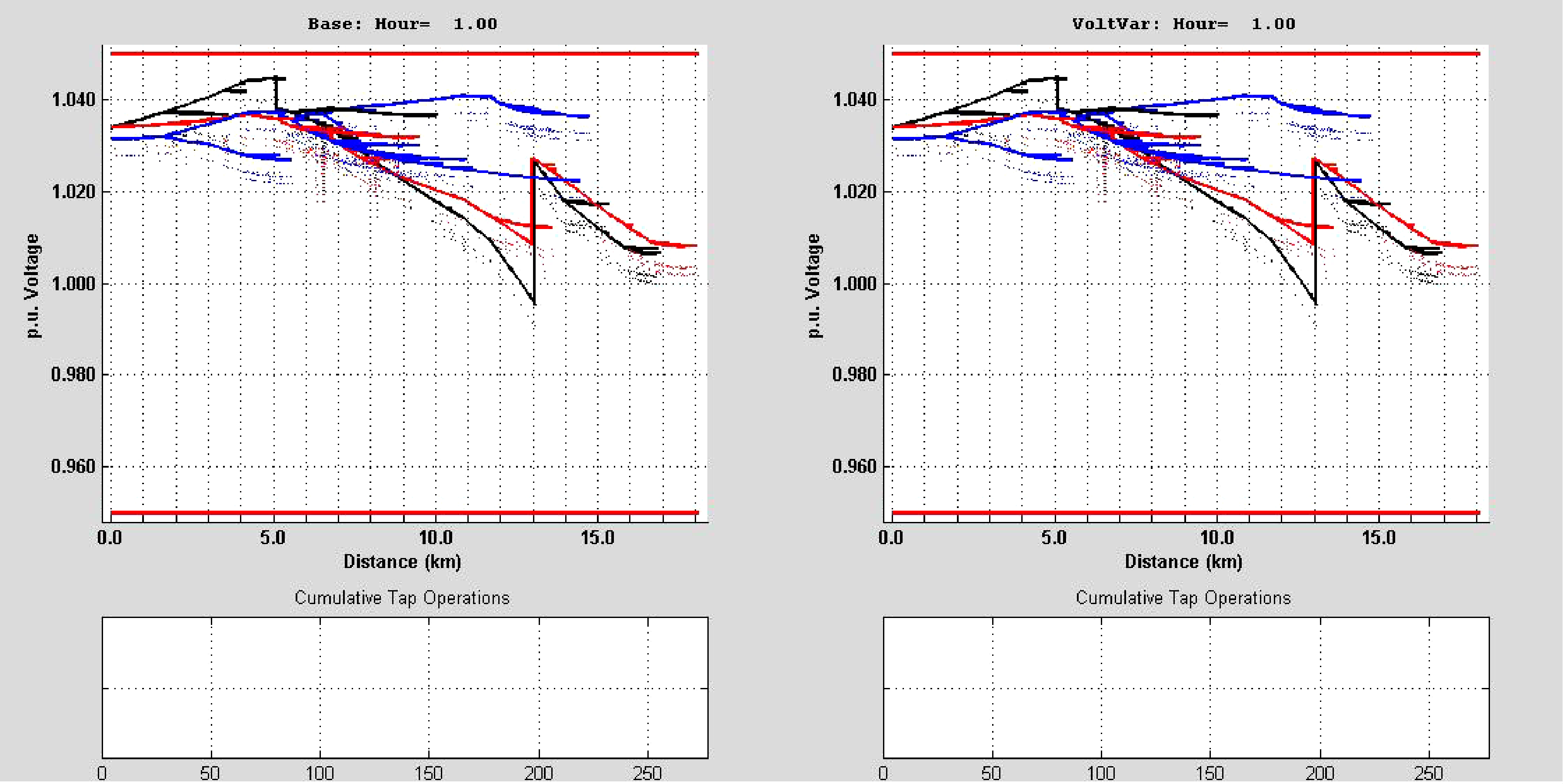
Smart Inverter Settings for Improving Distribution Feeder Performance

Properly chosen settings can improve distribution feeder metrics (Example: Reducing regulator tap changes)



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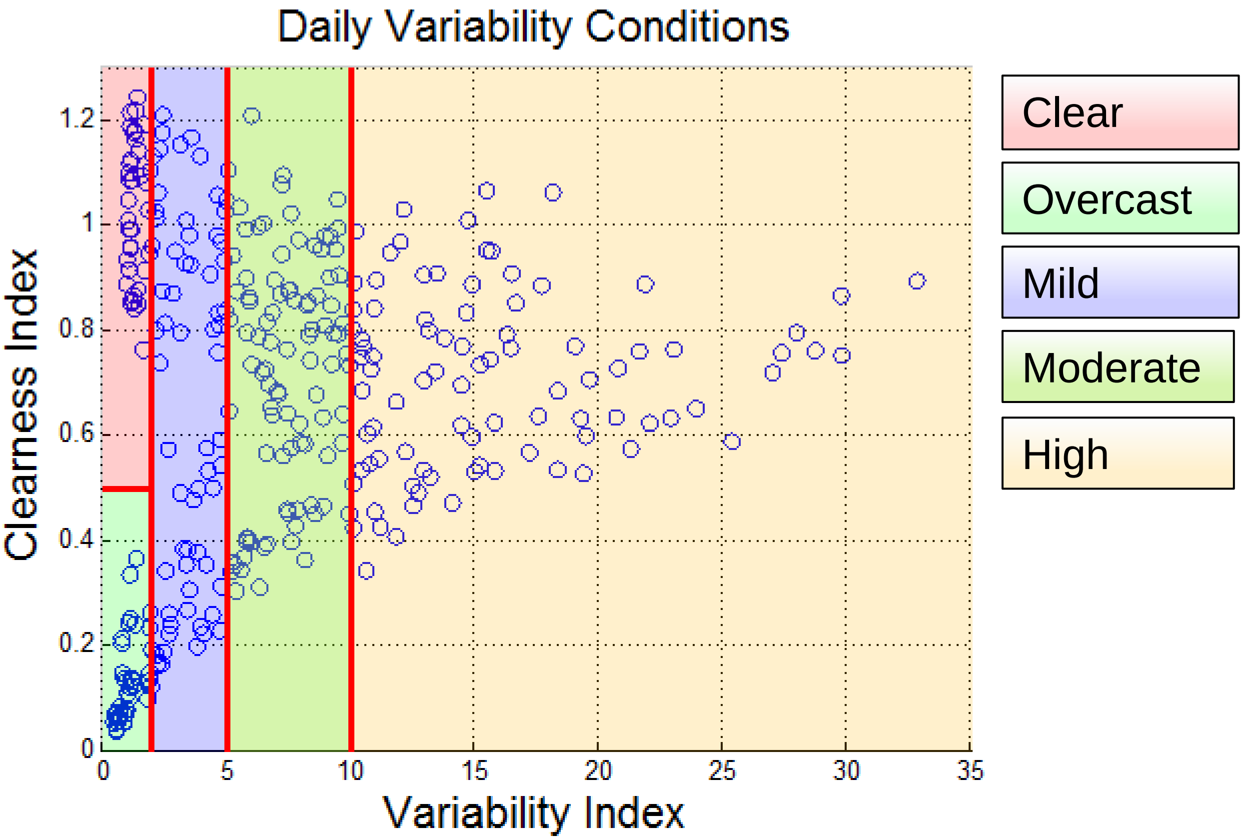
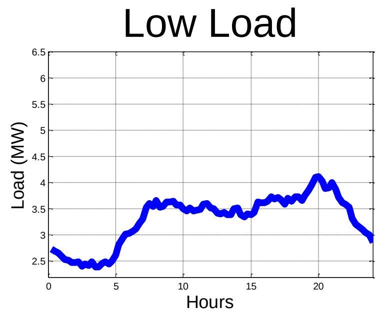
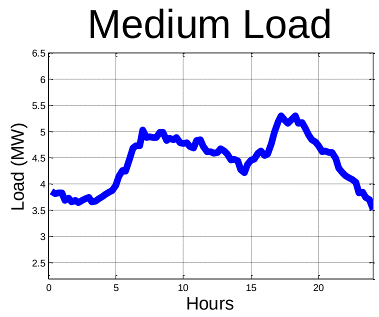
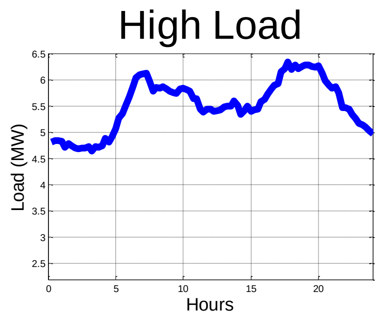
Smart Inverter Settings for Improving Distribution Feeder Performance

Days can be categorized based on solar parameters and load level









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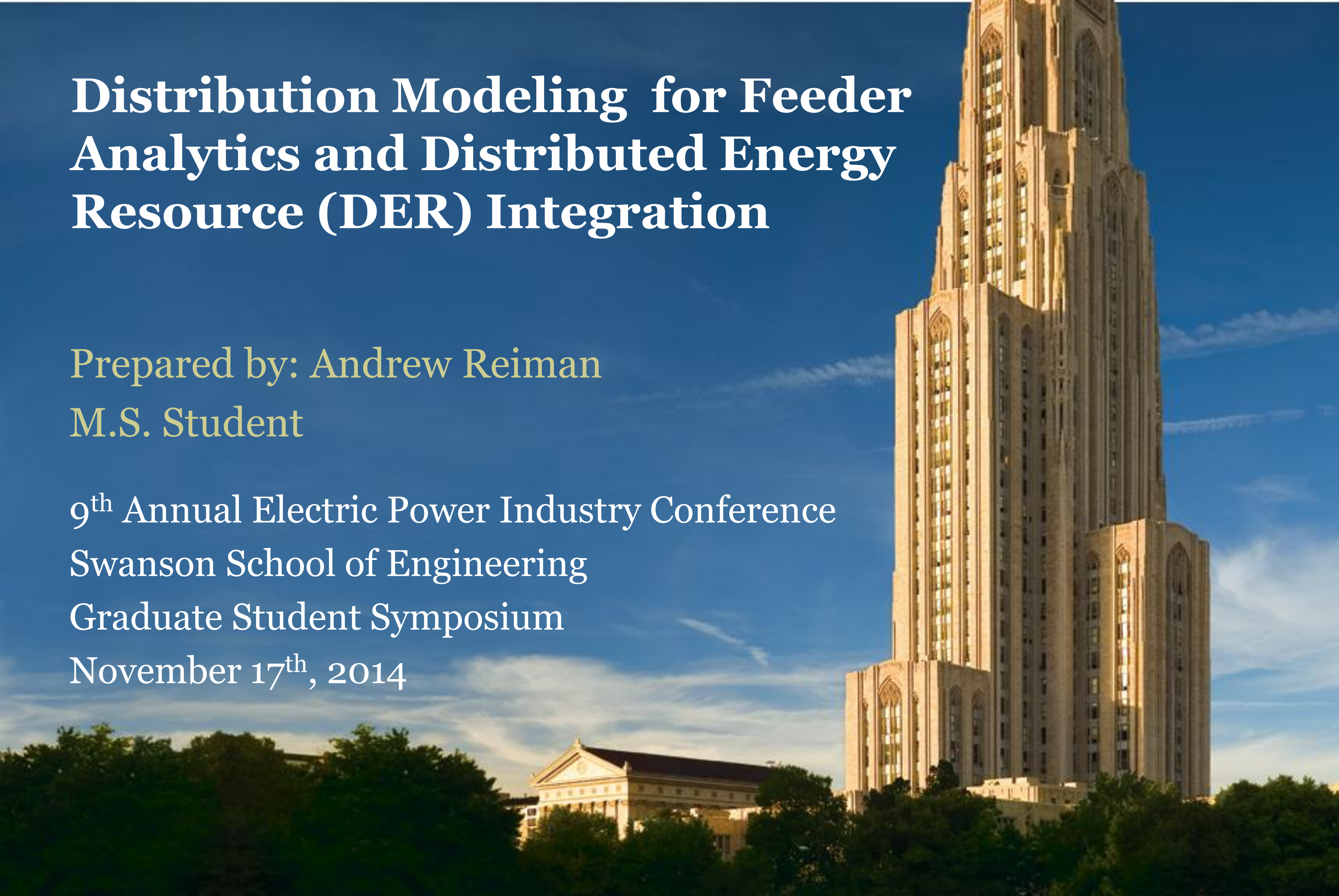

Distribution Modeling for Feeder Analytics and Distributed Energy Resource (DER) Integration

Prepared by: Andrew Reiman
M.S. Student

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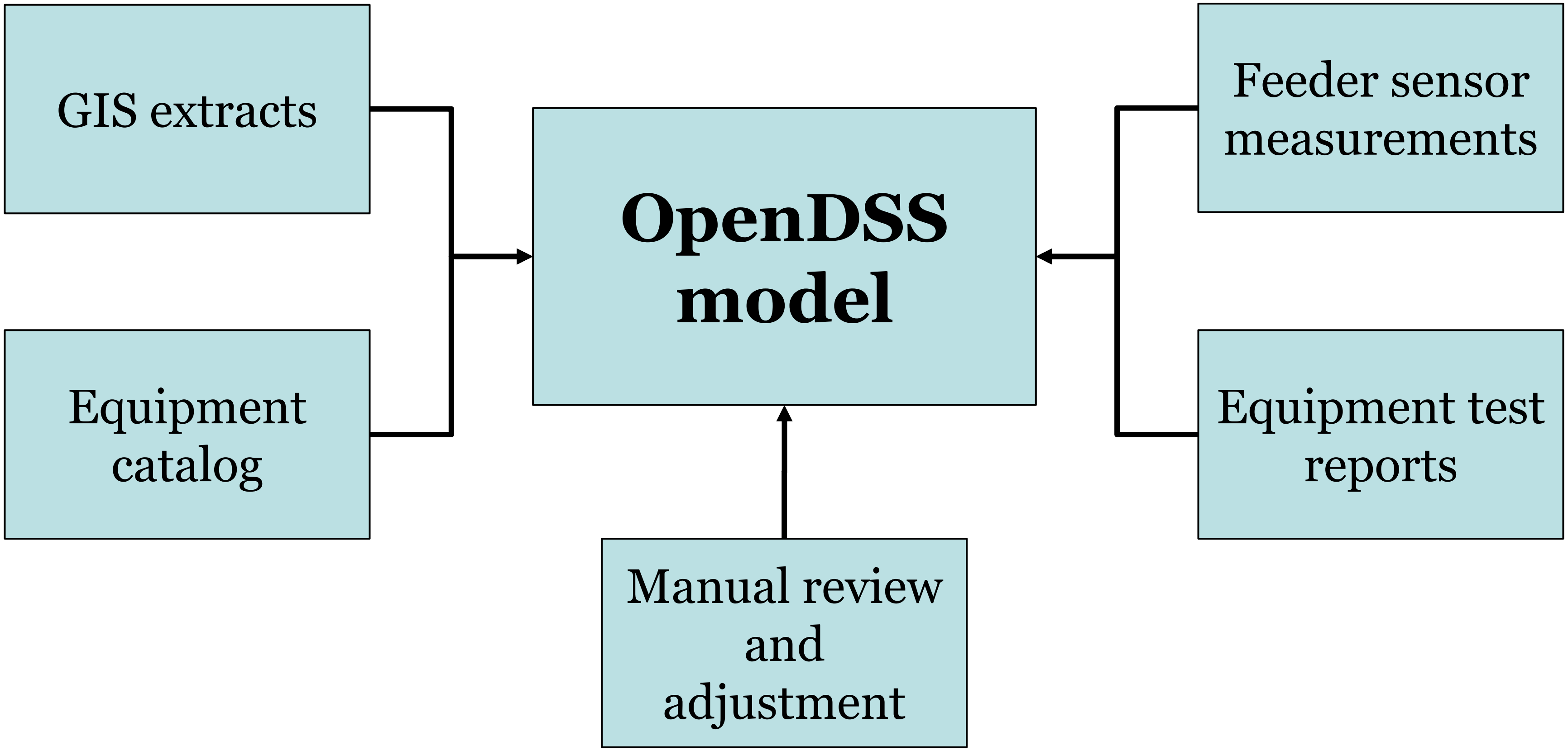
Feeder Analytics and DER Integration

OpenDSS models are created using scripted methods starting with GIS data.



GIS extracts

Equipment catalog

OpenDSS model

Feeder sensor measurements

Equipment test reports

Manual review and adjustment

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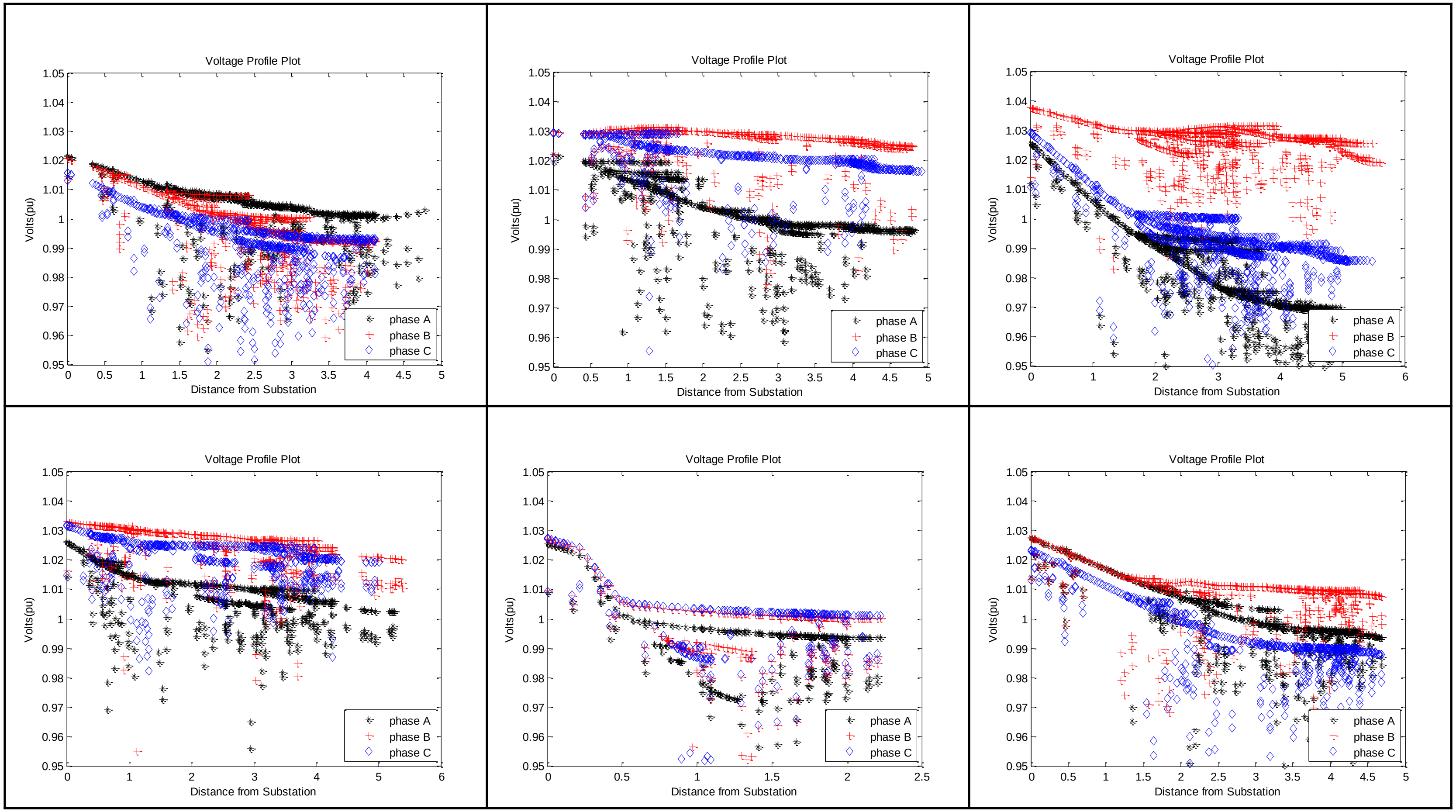
Feeder Analytics and DER Integration

Automatic model generation allows targeted analysis to be performed efficiently.



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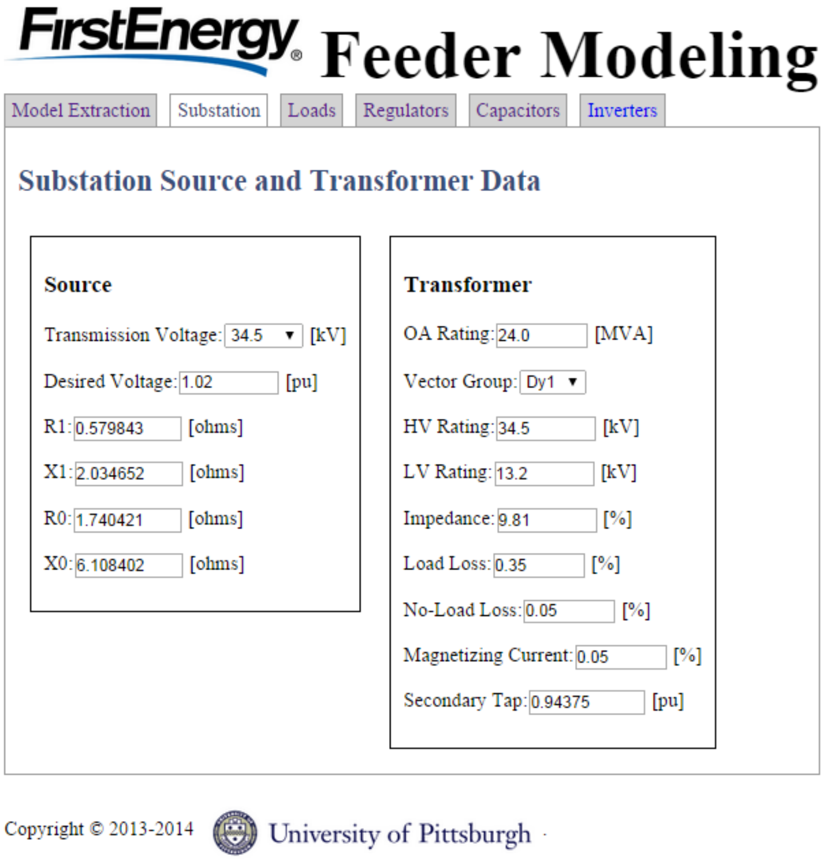
Feeder Analytics and DER Integration

A web browser interface will allow users to create and access models on a server.



Feeder Modeling

Substation Source and Transformer Data

Source

Transmission Voltage: 34.5 [kV]

Desired Voltage: 1.02 [pu]

R1: 0.579843 [ohms]

X1: 2.034652 [ohms]

R0: 1.740421 [ohms]

X0: 6.108402 [ohms]

Transformer

OA Rating: 24.0 [MVA]

Vector Group: Dy1

HV Rating: 34.5 [kV]

LV Rating: 13.2 [kV]

Impedance: 9.81 [%]

Load Loss: 0.35 [%]

No-Load Loss: 0.05 [%]

Magnetizing Current: 0.05 [%]

Secondary Tap: 0.94375 [pu]

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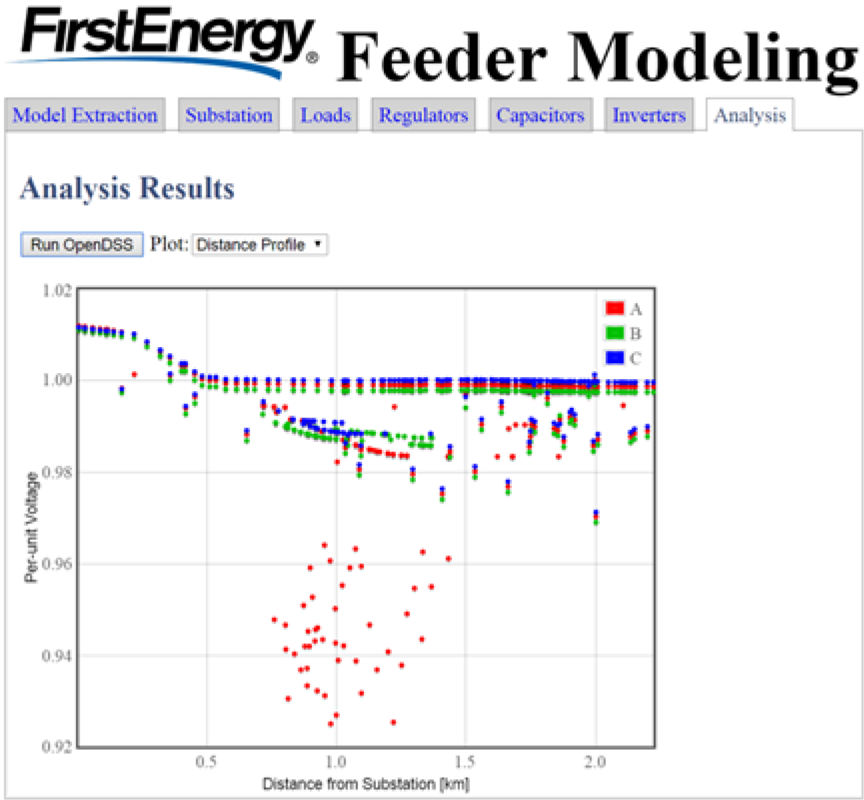

Feeder Modeling

Analysis Results

Plot: Distance Profile

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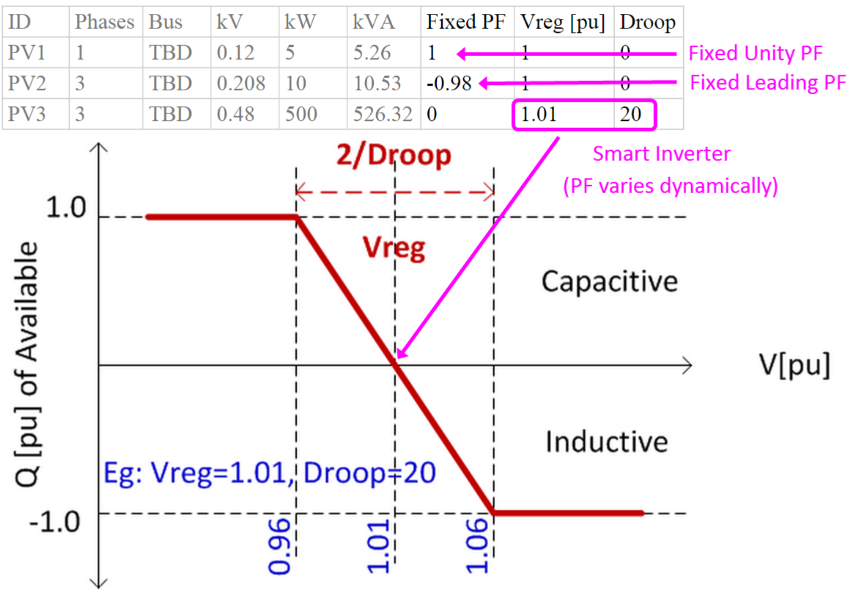
Feeder Analytics and DER Integration

Impact studies described in IEEE 1547.7-2013 can be performed.

DER Inverter Data



ID	Phases	Bus	kV	kW	kVA	Fixed PF	Vreg [pu]	Droop
PV1	1	TBD	0.12	5	5.26	1	~~1~~	~~0~~
PV2	3	TBD	0.208	10	10.53	-0.98	~~1~~	~~0~~
PV3	3	TBD	0.48	500	526.32	0	1.01	20

Fixed Unity PF

Fixed Leading PF

Smart Inverter
(PF varies dynamically)

Eg: Vreg=1.01, Droop=20

IEEE 1547.7 Studies Supported:

- C1 (steady state)
- C3 (operational characteristics)
- S1 (quasistatic)
- Data collection described in section 10 has been automated.

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Integration of Offshore Wind Power to the U.S. Electric Grid

Prepared by: Matthew Korytowski
Ph.D. Student

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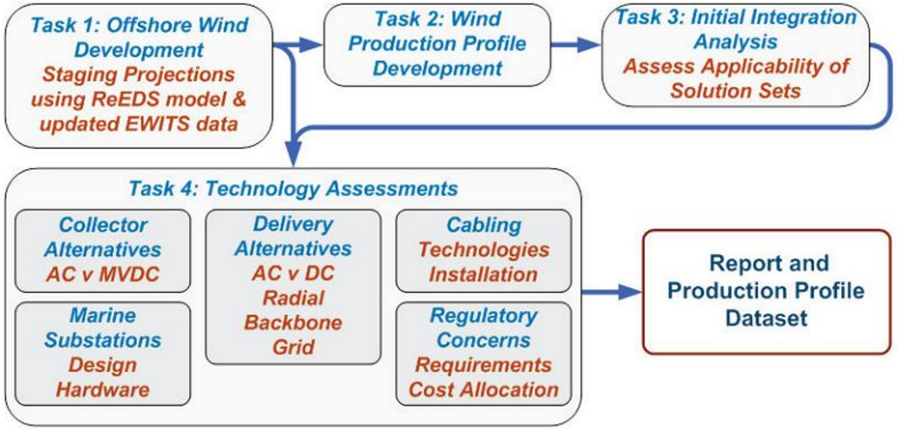
Modernizing a Legacy AC Power System Design for the 21st Century

Overview of NOWEGIS

Two critical objectives: (1) Reduce cost of energy, (2) Reduce deployment times

- National Offshore Wind Energy Grid Interconnection Study
- Identify and help address market barriers
- Considered resources, technologies, regulatory environment
- Team: ABB, AWS Truepower, Duke Energy, NREL, Pitt



Task 1: Offshore Wind Development
Staging Projections using ReEDS model & updated EWITS data

Task 2: Wind Production Profile Development

Task 3: Initial Integration Analysis
Assess Applicability of Solution Sets

Task 4: Technology Assessments

Collector Alternatives
AC v MVDC

Marine Substations
Design
Hardware

Delivery Alternatives
AC v DC
Radial
Backbone
Grid

Cabling Technologies
Installation

Regulatory Concerns
Requirements
Cost Allocation

Report and Production Profile Dataset

Modernizing a Legacy AC Power System Design for the 21st Century

Brief Discussion of Four Main Tasks

Each team focused on a particular task based on their expertise.

- **Task 1**: Offshore wind development staging projections
  - Built upon EWITS, updated to reflect current trends and new areas
- **Task 2**: Wind production profile development
  - Simulations performed to determine anticipated wind power profiles
- **Task 3**: Initial integration analysis
  - Assessed integration impacts of offshore wind
- **Task 4**: Technology assessments
  - Evaluated offshore wind energy collection and delivery topologies

Modernizing a Legacy AC Power System Design for the 21st Century

Key Results and Observations (1-4)

Eight key results spanning across integration, technology, resource, regulations.

1. Sufficient offshore wind energy in U.S.
2. Land-based study methods appropriate for offshore
3. Appropriate technologies exist for interconnections
4. Offshore wind energy may provide significant value

Modernizing a Legacy AC Power System Design for the 21st Century

Key Results and Observations (5-8)

Eight key results spanning across integration, technology, resource, regulations.

5. State policies are critical to encourage investment
6. Reductions in permitting and siting process needed
7. Current organizational structure may hinder progress
8. R&D promise to help reduce initial capital investment

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Community Outreach

Session Moderator:
Brandon Grainger, PhD

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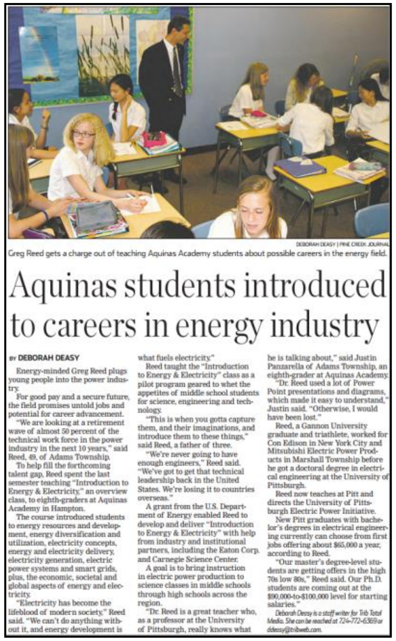
Outreach Activities

- **K-12 STEM – Middle/High School Curriculum Development on “Introduction to Energy and Electricity”**
  - Part of DOE 152 (Electric Power Sector Workforce Training Grant)
  - Univ. of Pittsburgh / Aquinas Academy (Gibsonia PA) Partnership
    - Pilot program, launched Spring 2013 Term
  - Key Topics (Lessons/Lectures)
    1. Energy Overview
    2. Energy Resources & Development
    3. Energy Diversification and Utilization
    4. Electricity Concepts
    5. Energy & Electricity Delivery
    6. Electricity Generation
    7. Electric Power Systems & Smart Grids including Tours of Eaton and Pitt Labs
    8. Economic, Societal, and Global Aspects



DEBORAH DEASY | PINE CREEK JOURNAL

Greg Reed gets a charge out of teaching Aquinas Academy students about possible careers in the energy field.

Aquinas students introduced to careers in energy industry

BY DEBORAH DEASY

Energy-minded Greg Reed plugs young people into the power industry.

For good pay and a secure future, the field promises untold jobs and potential for career advancement.

“We are looking at a retirement wave of almost 50 percent of the technical work force in the power industry in the next 10 years,” said Reed, 49, of Adams Township.

To help fill the forthcoming talent gap, Reed spent the last semester teaching “Introduction to Energy & Electricity,” an overview class, to eighth-graders at Aquinas Academy in Hampton.

The course introduced students to energy resources and development, energy diversification and utilization, electricity concepts, energy and electricity delivery, electricity generation, electric power systems and smart grids, plus, the economic, societal and global aspects of energy and electricity.

“Electricity has become the lifeblood of modern society,” Reed said. “We can't do anything without it, and energy development is what fuels electricity.”

Reed taught the “Introduction to Energy & Electricity” class as a pilot program geared to whet the appetites of middle school students for science, engineering and technology.

“This is when you gotta capture them, and their imaginations, and introduce them to these things,” said Reed, a father of three.

“We're never going to have enough engineers,” Reed said. “We've got to get that technical leadership back in the United States. We're losing it to countries overseas.”

A grant from the U.S. Department of Energy enabled Reed to develop and deliver “Introduction to Energy & Electricity” with help from industry and institutional partners, including the Eaton Corp. and Carnegie Science Center.

A goal is to bring instruction in electric power production to science classes in middle schools through high schools across the region.

“Dr. Reed is a great teacher who, as a professor at the University of Pittsburgh, really knows what he is talking about,” said Justin Panzarella of Adams Township, an eighth-grader at Aquinas Academy.

“Dr. Reed used a lot of Power Point presentations and diagrams, which made it easy to understand,” Justin said. “Otherwise, I would have been lost.”

Reed, a Gannon University graduate and triathlete, worked for Con Edison in New York City and Mitsubishi Electric Power Products in Marshall Township before he got a doctoral degree in electrical engineering at the University of Pittsburgh.

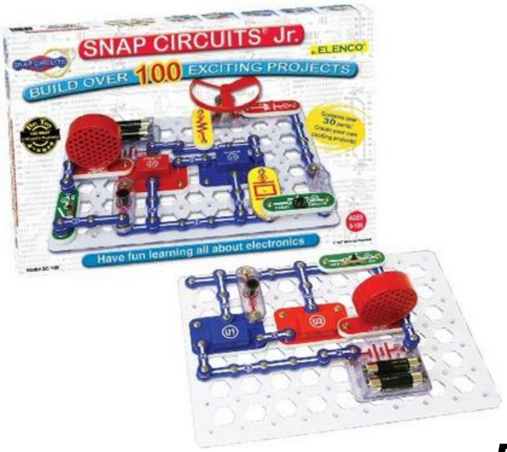
Reed now teaches at Pitt and directs the University of Pittsburgh Electric Power Initiative.

New Pitt graduates with bachelor's degrees in electrical engineering currently can choose from first jobs offering about $65,000 a year, according to Reed.

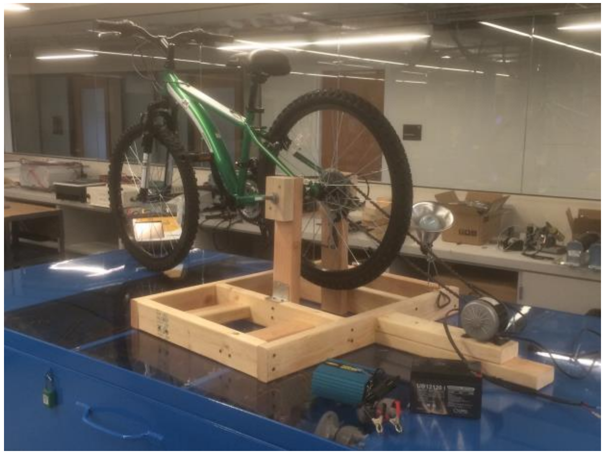
“Our master's degree-level students are getting offers in the high 70s low 80s,” Reed said. Our Ph.D. students are coming out at the $90,000-to-$100,000 level for starting salaries.”

Deborah Deasy is a staff writer for Trib Total Media. She can be reached at 724-772-6369 or ddeasy@tribweb.com.

Outreach Activities



Pitt graduate students building radios with middle school children



Bike Generated Electricity

SciencePalooza 2014 !

Science Lab Mobile Bus

Questions?

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