Power Electronics and Distributed Control for the Future Grid
Prof Deepak Divan, Director – Center for Distributed Energy, Georgia Tech

Enabling Advanced Power Electronics Technologies for the Next Generation Electric Utility Grid
Workshop at Sandia Labs
Transitioning from Today’s Grid

Centralized Grid – Scheduled Generation Follows Load

How Do We Improve on 100+ Years of Success?
- Slow control & unidirectional power flows
  – power electronics control
- Large investment exists in generation and T&D
  – overlay/augment strategy
- ‘Exponential’ technologies impact grid integrity
  – unstoppable, challenge & opportunity
- Economies of scale – 100’s MW, 100’s kV
  – make viable at small scale
- Poor dynamic balancing results in asset overbuild
  – real-time pricing & decentralized controls
- Cost of resiliency is very high
  – low-cost bottom-up grid architecture

US will spend $100’sB in new infrastructure. Should it be more of the same? What can and should change?

Exponential Technologies
Computation, PV solar, wind, power semis, storage, microcontrollers, sensors, IoT, communication technologies, online services, social media, mobile pay, block-chain

Mexico Utility Solar - 2017
800 MW @ 1.7¢/kWhr

Price Volatility

Prosumers

Storage & EVs
GT Center for Distributed Energy

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

Platform Initiatives

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

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

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

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

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

**Global Asset Monitoring Management & Analytics (GAMMA)**
- Low-Cost Communications
- Cyber-Security
- Data Management
- AMI Data Analytics
- Global Sensor Networks
- Cloud Based GAMMA System

Emerging Technology: D-Light
Top 10 Emerging Markets Source: Global Intelligence Alliance
Feeder Voltage w/o and with GE Control
Gamma kernel
Hybrid Transformers: \( P/Q/V/I/Z \) control

Standard Transformer Augmented With Fractionally-Rated (8\%) Converter ..DOE Projects

- Uses standard large power transformer and widely available BTB converter
- Allows scaling to 100’s of kV and 100’s of MW with low-cost & small footprint
- Fail-normal approach retains basic functionality in case of converter failure.
- High impact at 10,000 bus system and Texas system (simulations)
- Reduces cost and size for \( P/Q/V/I/Z \) control by 6X as compared with HVDC Light

**13 kV 1 MW Field Demonstration**

- System meets BIL, fault current, and provides \( P/Q/I/V/Z \) control

**DOE Project: DE-AR0000229**
**DOE Project: DE-AR0000765**
**DOE Project: DE-OE0000855**
Transmission Power Flow Control ... *Smart Wires*

- Real-time control of transmission power flows on individual lines
- Smart Wires proved a new paradigm of distributed grid control
- Smart Wires has raised ~$150 M, and is seeing good traction
- Proven on 230-350 kV/2000 A systems with 65 kA fault current

**Grid-Edge VAR Control**

- LTC set at 240V (1.0 pu)
- **TOP-DOWN CONTROL**
- **EDGE-UP CONTROL**
  - Volatile
  - Smooth
  - Limited Grid-Side Control Range
  - Unprecedented Control

**ARPA-E Projects**

- Source: Southern Company and Varentec

Decentralized Grid-Edge Volt-VAR Control ... **Varentec**

- Real-time decentralized grid-edge VVC
- Funded by KV, Bill Gates with >$40M
- Approved by Hawaii and Colorado PUC
- Increases PV penetration by >100% (HECO)

**Proven at 20+ utilities**

- 5 MW 12 mile line
- 421 Transformers
- 4760 KVA
- 91 * 10 kVAR Units

- 0-10 kVAR injection

**Source:** Southern Company and Varentec
Soft Switching Solid State Transformers (S4T)

Transformative solid state transformer with AC or DC input/output

- 25 kVA building block, 97% eff.
- 480-600 VAC, 600-800 VDC
- Parallel to multi MW level
- HF transformer isolation
- Bidirectional universal converter
- Sinusoidal/filtered input/output
- ZVS, low dv/dt, low EMI

S4T ... Applications:
1. 5 kV MVDC networks
2. 7.2 kV 50 kVA SST
3. 300 kW MVSi PV Farm
4. PV-Batt-Grid Triport
5. Industrial – MV SST
6. DC Fast Charging

DOE & ARPA-E Projects
- 25 kVA S4T Module
- 25 kVA S4T Module
- 25 kVA S4T Module
- 25 kVA S4T Module

Proposed MVSI topology - DOE

7.2 kV AC to 240 V AC 50 kVA Solid State transformer

90 kV BIL and 1 kA fault current
Grid Support: Virtual Resources

- Dynamic balancing (virtual storage)
  - Hydro-DER balancing (Norway/Germany/Denmark)
  - Demand Control (thermal, G2V, feeder level VVC)
  - Power flow control (reduce curtailment of wind/solar)
  - Ramp rate control (CA duck curve)
  - Virtual inertia for grid support
- Grid supporting appliances – grid as a ‘living ecosystem’
- Real time pricing for prosumers (grid support functions)

**...cheaper than real resources**
Ad-Hoc Self-Organizing Grids … getting real!

- **Expandable**: Plug-n-play system expands as needed
- **Affordable**: Uses exponential technologies
- **Flexible**: Ad-hoc topology with variety of load/source
- **Dispersed**: Geographically dispersed w/ poor comms
- **Secure**: Baked in cyber-physical security
- **Autonomous**: Nodes act together to control microgrid
- **Dynamic-pricing**: Prosumer agents react to price signals
- **Grid-connect**: Utilizes grid power as cost dictates
- **Grid-disconnect**: Utility can load-shed microgrid
- **Grid-safe**: Grid support and no negative grid impact
- **Decentralized**: No central control – rule based
- **High-quality**: Bumpless islanding and reconnect
- **Resilient**: Bottom-up power restoration
- **Simple**: Easy field installation & maintenance
- **Marketplace**:
  - Prosumers own assets, act in self-interest
  - Prosumers billed on net consumption/generation
  - Investment signals to prosumers

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Decentralized Self-Pricing Microgrids

- **Intelligent**
- **Self-pricing**

- **Bottom-up modular grids**
- **Agnostic to topology**

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Lowest cost operation for consumers/prosumers and producers

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Courtesy: You Solar
The future grid can operate like a living ecosystem. Each node has intelligence and local visibility and influences the local environment based on simple rules for all nodes. All nodes operate in their own self-interest, but also act to sustain the system as a condition of market participation. System is cyber-secure, self-aware & flexible, does not need information on network configuration, status & generation. Real-time pricing information is derived at each node, allowing each node to optimize its behavior and investments. Surplus/scarcity of resources triggers price swings that govern consumption, stabilize the system and drive investments. Collective intelligence and slow coordination allows the group/system to solve problems that an isolated node cannot. Such a system is fractal, can be built from the bottom-up, and can realize high resiliency and availability at low cost.
Energy Access … the elephant in the room

- **3 Billion** people live in energy poverty, including **1.1 Billion people** without any access to electricity [1]

- **95% of utilities** in the Sub-Saharan Africa cannot recover their operational and capital costs [2]

- Only **1.8 million** people have tier 2 access (200 Wh<) using off-grid electric services [3]

Source: Bloomberg New Energy Finance. Figures refer to 2012 data [1]

**Net CO2 emission if the un-electrified 1.1 Billion get energy access**

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<th>CO2 emission (Gt)</th>
<th>No Access</th>
<th>Tier 1</th>
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**Absolute Environmental Catastrophe**

- Co2 emission if the un-electrified 1.1 Billion get energy access
IEEE Empower A Billion Lives Global Competition

www.empowerabillionlives.org

The Goal of the Competition
Foster interdisciplinary innovation in the global community to develop and demonstrate solutions to electricity access that are designed to scale, regionally relevant, holistic, and leverage 21st century technologies that feature exponentially declining prices.

What Are the Targeted Electricity Needs?
Tier 2 electricity access (200 Wh/day) and above including:
- **Household uses:** lighting and phone charging, telecommunication, entertainment, air circulation, refrigeration, water pumping, etc.
- **Community uses:** public lighting, water pumping & purification, etc.
- **Productive uses:** agricultural manufacturing, light manufacturing, commerce, etc.

WHO IS THE TARGET CUSTOMER GROUP?
- Off-grid or have access < 2 hours a day
- Purchasing power below global poverty line (< $1.90/day)
- > 90% live in rural areas
- < 50% have bank accounts
- < 50% have smartphones

WHO IS THIS COMPETITION FOR?
- Student teams, Research laboratories
- Small and medium-sized companies
- International corporations
- Nonprofit organizations
- Everyone!

COMPETITION TRACKS
- **EXISTING SOLUTIONS:** Solutions that are already commercially available, meeting the electricity needs of the target customer group, and have radical scaling potential.
- **EMERGING SINGLE-USER SOLUTIONS:** New solutions that meet minimum tier 2 needs of a single household in the target customer group.
- **EMERGING MULTI-USER SOLUTIONS:** Solutions that meet minimum tier 2 needs of a community of users. These devices are expected to be able to create, interconnect and manage a grid (including market functions) from the bottom up.

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<td>Nov 4-7, 2018</td>
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<td>Regional – EBL Joburg, S. Africa</td>
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<td>Regional – EBL Seville, Spain</td>
<td>Jan 22-24, 2019</td>
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<td>Global Final – EBL Baltimore, USA</td>
<td>Sept 2 – 5, 2019</td>
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Questions?
ddivan@gatech.edu