Power Electronics, Smart Grid, Grid Modernization and Beyond

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Outline

1. The smart grid and grid modernization
   * A dual innovation path
   * Storage: the last missing piece

2. Technology focus areas (TFAs)
   * Microgrids: Ultimate assets for utilities
   * Substation: Focal point for renewable integration and grid performance enhancement
   * Flexible electronic large power transformers/on-line sensors/IoT-connected communication
   * Transportation electrification.smart infrastructure
   * Energy-based active control

3. Technology Development and beyond
   * Data analytics for renewable forecasting
   * Smart meter analytics and flexible demand response
   * Machine learning for MW power design
   * Big data for asset management and prediction of equipment failure
   * AI for grid-scale resiliency and fault recovery
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Smart Grid and Grid Modernization
The Smart Grid and Grid Modernization

Smart Grid Functions

Defined under EISA 2007 to have the abilities to:

- Develop, store, send and receive digital information concerning electricity use, costs, prices, time of use, nature of use, storage, or other information relevant to device, grid, or utility operations

- Measure or monitor electricity use as a function of time of day and power quality characteristics; store, synthesize or report that information by digital means

- Sense and localize disruptions or changes in power flows for enabling automatic protective responses to sustain reliability and security of grid operations

- Detect, prevent, communicate, respond to, or recover from system security threats (cyber-security threats and terrorism), using digital information, media, and devices

- Respond by any appliance or machine to such signals, measurements, or communications automatically or in a manner programmed by its owner or operator without independent human intervention

- Use digital information to operate functionalities on the electric utility grid that were previously electro-mechanical or manual

- Use digital controls to manage and modify electricity demand, enable congestion management, assist in voltage control, provide operating reserves, and provide frequency regulation

But the grid is aging ...

If you would summarize all seven abilities, it is one word: digitization.

The Smart Grid and Grid Modernization

* Jan, 2015, UC Riverside talk → Grid modernization by D. Tan
* March, 2015 → DoE grid modernization initiative (GMI)

Electronictization: a Foundation for Grid Modernization

Don Tan
TPE
Jan 30, 2015

Power Electronics & Systems (PE&S), as a system of technologies, brings a suite of technologies to help transform the grid from passive, electric, and electro-mechanical to active, electronic, electric, and electro-mechanical.
Evolution towards a Modern Electronic Grid

A dual innovation path needs to be pursued

D. Tan, “Towards a (more) electronic power transmission and distribution (eT&D),” CSEE Power Electronics & HVDC Conference, Dec., 2016 (Invited Keynote)
Power Electronics: Laying the Foundation

Battery Cost Going Down Exponentially

- Reached US$176/kWh in 2018
- Project US$100/kWh in 2024

At US$100/kWh, an EV can be more cost effective than an ICE car

Battery cost continues to fall

* Li-ion battery cost continues to drop

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Lithium–ion battery price outlook

Lithium–ion battery pack price (real 2018 $/kWh)

2010 2015 2020 2025 2030

2024 implied price $94/kWh
2030 implied price $62/kWh

Source: BloombergNEF
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Batteries: Grid-Scale Deployment

Battery: “The last missing piece (asset) of the puzzle” for grid modernization

Batteries: “Rapid, accurate, and valuable”

“Initial operation of the Hornsdale power reserve battery energy storage system,” Australian Energy Market Operator (AEMO), April 5, 2018
8minutenergy: ‘We can do solar peaker plants at half the cost of gas’

“However, to fill that evening peak, we need storage. You start looking at the economics and power prices in that evening peak can be very high, just because these peakers, typically gas peakers, are now pushed into a shorter period to recover their fixed costs. So pricing levels can be well over US$100 per MWh and we can build a solar plant with a four hour battery to service that peak. We can build that somewhere in the US$50 to US$60 per MWh range.”
Utilities are investing in big batteries

Utilities are starting to invest in big batteries instead of building new power plants

Jeremiah Johnson and Joseph F. DeCarolis
Thursday, February 28, 2019 - 1:00am

Grid-scale batteries are being installed coast-to-coast across the United States, a trend that grew in 2017. Source: U.S. Energy Information Administration, Battery Storage Market Trends, 2018.
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Technology Focus Areas
Technology Focus Areas (TFAs)

1. Microgrids: Ultimate utility assets
2. Substation: Focal point for renewable integration, grid performance enhancement, and self diagnostics with grid impedance measurement
3. Flexible electronic large power transformers (FeLPT): on-line sensors and IoT-enabled command & communication
4. Smart infrastructure: Transportation electrification interface such as ultra-fast charging stations, etc.
5. Energy-based active control
**TFA 1: Structured Microgrids (SµGs)**

*Definition can be readily extended for multi-port cases*

**DoE Update:** The microgrid may be defined as the resources – generation, storage, and loads, - within a boundary that are managed by a controller.

D. Ton and I. Reilly, “Microgrid controller initiatives,” IEEE power and energy magazine, July/August, 2017, pp. 24-31

**DoE:** A group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid (and can) connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.

**Extension of the DoE Definition***

Integrated with loads, energy sources, storage devices, sensors, and data bus, a structured microgrid is an autonomous subsystem that features

1. Balanced energy over the intended operation/capacity
2. Reconfigurable for stand alone or grid connected
3. Resilient with fault tolerance/fault isolation
4. Bidirectional power flow
5. Modular/scalable

Emerging System Applications and Technological Trends in Power Electronics

Power electronics is increasingly cutting across traditional boundaries

by Don Tan

This article examines six emerging system applications, which include green energy systems integration; smart homes; all things connected; transportation electrification; renewable integration; and structured microgrids. The first major technology trend playing a crucial role in shaping the emerging system applications includes safe and secure power conversion, control, and power system integration.

Title of the article: Emerging system applications of PE in the integration of green energy systems, Figures 2 and 3 illustrate the concept of green energy system integration.

WBG devices going mainstream

Microgrid: A concept in an autonomous electric power system; it can be dc or ac, a hybrid of dc and ac, a battery or WBG microgrid is integrated with loads, energy storage, energy systems, microgrids, and other distributed energy resources that includes the following features:

- A balance of energy over the extended operation and capacity
- Reconfigurability for stand-alone or smart microgrids
- Strengths in fault tolerance and fault isolation
- A distributed power flow
- Scalability and reliability
- Low power goes monolithic
- High power goes modular

Star homes, buildings and cities

Transportation electrification

SµGs: Local and Global Benefits

SµGs: CHP – An Early Adaptor

- Combined Heat and Power (CHP) generation provides
  - Reliable baseload power
  - Gas line weather proof
  - Heat captured for hot water, chilled water and steam product (heating)
- With CHP powers the baseload, renewables can be integrated
  - Solar, wind, and storage
  - Demand response
  - EV ultrafast charging
- SµGs
  - Industry, campus, district, and many others

UCSD campus µG reduced the electricity cost by $80 m per year

SmGs: Resiliency

- Frequent extreme weather events, Hurricane Harvey?!

Microgrids can turn mostly-idle back-up generation assets into cash generators

(Invited Keynote)
SµGs: Remote Energy Access

Electricity means modernization and prosperity – SµGs are perfect vehicles for remote energy access

TFA 2: Flexible Substations

Configured as a multi-terminal SM:
1. Electronic power transformer
2. Renewable integration
3. Interconnect to the grid
4. Energy storage to maintain balance
5. Multi-time scale autonomous control
6. Wireless communication

A SM for a campus/building/community
1. Electronic power transformer
2. Renewable integration
3. Interconnect to the feeder
4. Energy storage to maintain balance
5. Multi-time scale autonomous control
6. Wireless communication

Configured as a Two-terminal SM:
1. Electronic power intertie or UPFC
2. Renewable integration
3. Interconnect to the feeder
4. Energy storage to maintain balance
5. Wireless communication

Flexible Hybrid Transformer Concept

* Hybrid transformer

Figure 7 Conceptual illustration of the proposed flexible hybrid transformer with renewables system (HT-R)

A Solar Power Example

* Modular scalable back-to-back converters for grid control, interconnect, and fault isolation

![Diagram of a solar power example](image)

Substation Automation and Modernization

* Feeder/Substation μGs voltage profile

$\Delta V_{new} < \Delta V_{old}$ → Week grid will be a thing in the past


C. Schweagerl, “Technical, economic and environmental benefits of microgrids operation,” Siemens, Jan., 2010
TFA 3: Flexible electronic LPT (FeLPT)

* Modular scalable back-to-back (BtB) converters for grid control, interconnect, and fault isolation
* Flexible Transformer
  * 3M Converter (3MC): Modular, Multi-level, and Multi-timescale

D. Tan, “A modular, scalable back-to-back power converter (MS BtB PC) for grid control, interconnect, and fault-isolation,” E2 System White Paper, Nov., 2017
D. Tan, “Towards a (more) electronic power transmission and distribution (eT&D),” CSEE Power Electronics & HVDC Conference, Dec., 2016 (Invited Keynote)
TFA 4: Electrification and Smart Infrastructure

* Powering smart manufacturing
Middlebrook Flying Capacitor Converter

D. Tan, "Switched-Capacitor Circuits: Coming of Age," IEEE PELS LAC Relaunch Meeting, April, 2019 (invited)

Fig. 3. Generalized $N$-stage voltage-divider Čuk converter.

\[
\frac{D_k}{N(1-D_k)} = M = \frac{D_1}{1-D_1}
\]

which leads to

\[
D_k = \frac{N D_1}{1 + D_1(N-1)}
\]

and

\[
D_k = \frac{NM}{1 + NM}
\]

\[
D_1 = \frac{M}{1 + M}
\]

Partial power processing

Fig. 4. $N$-stage converter. (a) During driving transistor off-time, $N$ capacitors are charged in series. (b) During transistor on-time, $N$ capacitors are discharged in parallel.

Voltage divider/multiplier

FeLPT: Built for eT&D

Bulk Generation (Wholesale)

- Energy arbitrage
- Ancillary services
  - Frequency regulation
  - Spinning reserve
  - Supplemental reserves
  - Ramping (new)
- Capacity
  - Peak energy
  - Flexibility (new)
- Reliability
  - Volt/Var support
  - Black start
  - Frequency response

Utilities (eT&D)

- Upgrade deferral
  - Reduce circuit and line overloading
  - Congestion relief
- Resiliency
  - Outage mitigation
  - Back-up power
- Power Quality
  - Fault ride-through
- Ancillary services
  - Frequency regulation
  - Spinning reserve
  - Supplemental reserves
  - Demand response
  - Black start

Grid Edge (End Users)

- Demand response
- Optimize retail rates
- Power quality
- Critical load
- Renewables on site
- Peak shaving
- Energy shifting
- Resiliency
- Islanding
- Reactive power

TFA 4: Electrification and Smart Infrastructure

* Data/Telecom Centers: Modular and Scalable

Ultra-Fast Charging: Efficient Architecture

SµGs integrate renewables for ultra-fast charging and grid support

On-Line Grid Voltage and Current Sensors

Smart Meters and PMUs

IEEE/ANSI Medium Voltage Outdoor Instrument Transformers

15 kV voltage/current combined line post sensor

D. Tan, “Towards a (more) electronic power transmission and distribution (eT&D),” CSEE Power Electronics & HVDC Conference, Dec., 2016 (Invited Keynote)
TFA 5: Active Control and Transactive Energy

* Scalable 5-level of controls


“NREL Integrate,” Siemens-OMNITRIC Group Industry Day Workshop, March 2017
First Resilient, Islanded, Remote Microgrid

* Flight-proven technology

Fuse Clearing and Dead Bus Recovery

**Fuse Clearing**

The bus holds minimum voltage even with a hard short

- Battery 1
- Batteries
- BDRs
- Loads
- PDU
- Regulated Primary Bus Voltage
- 6 x 7.5A
- 8 x 7.5A
- Shorted capacitor

21.84V min @ PDU output vs. 20 V min allowable.
21.80 V min @ CCM, 20.99 V min @ SCM vs. 19.5 V allowable

**Dead Bus Recovery**

Knife-on, 0.5A/s, Current-Limited Source, 1 HKPS CP & 6Ω CR

- HKPS Turns on & Energy Imbalance Forces Motor-Boating
- Low-Freq Op, ABS Near 100% D (on array input, not Vbus)
- SSR Vout(t)
- SSR Vin
- SIG_PWM_SSR from REA
- SSR Iout

Recovery is an orderly transition w/ a current-limited source

"An vision that is scalable for future grids."
Transactive Energy Enabled by $\text{S\muGs}$

$3\text{MC}$ – $3\text{M}$ Converter
$\text{AMC}$ – Area microgrid control
$\text{RES}$ – Renewable energy source
$\text{G}$ – Generators
$\text{S}$ – Storage
$\text{L}$ - Loads

$\text{S\muG}$: An enabler for cyber-physical and real-time transactive energy with bilateral P2P contract network and substitutability

Technology Advancement and Beyond

* Data analytics by Deep Learning for renewable forecasting

D. Tan, “Powering smart factories,” CATS Panel on Smart Manufacturing, May, 2018 (Invited Keynote)

“IBM announces cloud-based enterprise-wide analytics for energy companies,” Winder Power Engineering & Development, Feb., 2015
AI Enables Smarter Grid & Asset Cost Deferral

- Big data for asset management and prediction of equipment failure by Deep Learning (99% rate was reported)

D. Tan, “Powering smart factories,” CATS Panel on Smart Manufacturing, May, 2018 (Invited Keynote)
Technology Advancement and Beyond

- Smart meter analytics and flexible demand response: Descriptive, predictive and prescriptive (3Ps)
- Load analysis, load forecasting, load management, privacy and cyber security with Deep Learning and Reinforcement Learning


“How demand response can benefit from the growth in microgrids,” OpenADR Alliance Webinar, June 2015
Machine Learning for MW Power Design

- Machine learning for MW power design

Z. Zhao, D. Tan and K. Li, "Transient Behaviors of Multiscale Megawatt Power Electronics Systems - Part I: Characteristics and Analysis," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 1, March 2019, pp. 7-17

Z. Zhao, D. Tan, K. Li and L. Yuan, "Transient Behaviors of Multiscale Megawatt Power Electronics Systems - Part II: Design Techniques and Practical Applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 1, March 2019, pp. 18-29
SµGs with Machine Learning for Energy Balance

* AI for grid-scale resiliency, fault management and recovery

- Energy monitoring
- Fixed rules for energy balancing
- Big data for flexibility and robustness to maximize economic returns
- Machine learning for community demands

SµGs plus AI will enable breakthroughs in grid impedance online self-determination, using a combination of traditional model-based methods with new data-driven analytics

D. Tan, “Powering smart factories,” CATS Panel on Smart Manufacturing, May, 2018 (Invited Keynote)
B. Cornelusse, “Optimization and machine learning for smart microgrids,” Liege University, Sep., 2017
Work Force Development

Advanced Analytics Throughout the Enterprise: Personas

Citizen Data Scientists / Line of Business / Domain Expert
Business users who have little to no knowledge of analytics but understand the value of data. They need more than Excel and traditional BI tools but are challenged by data prep and visualization.

Line of Business Specialists, Consumer of Data Science
They use analytics for quality control, process monitoring and optimization. They generally have a scientific or engineering background but are not programmers.

Data Scientists / Statisticians
If they are under 30 they call themselves data scientists. Over 30, they call themselves statisticians. Deep understanding of mathematics and statistics. May or may not be programmers.

Experts, Managers, and Executives
These individuals span the spectrum and industries but are generally in charge of applying analytics to run their businesses and make strategic decisions.

Industry 4.0, 5G, and ABC \(\rightarrow\) eGrid \(\rightarrow\) Large demand on new workforces

D. Tan, “Powering smart factories,” CATS Panel on Smart Manufacturing, May, 2018 (Invited Keynote)
TPE: Technical Performance Excellence