Power Electronics, Smart Grid, Grid Modernization and Beyond

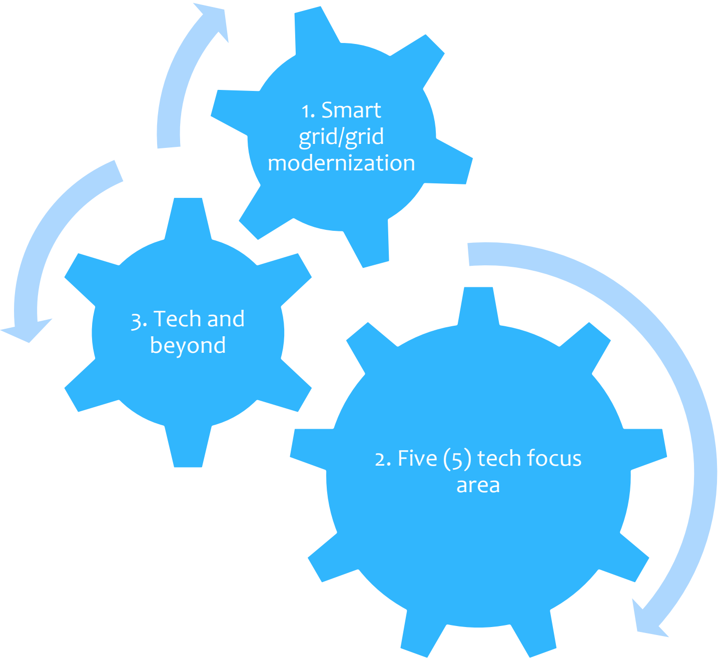
D. Tan, PhD, FIEEE

April 24, 2020

TPES
Electronics & Energy

Outline

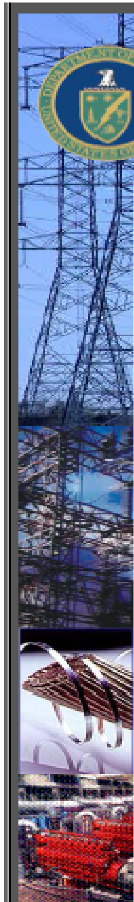
1. The smart grid and grid modernization
   * A dual innovation path
   * Storage: the last missing piece
2. Technology focus areas (TFAs)
   * Microgrids: Ultimate assets for utilities
   * Substation: Focal point for renewable integration and grid performance enhancement
   * Flexible electronic large 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



SusTech

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

3

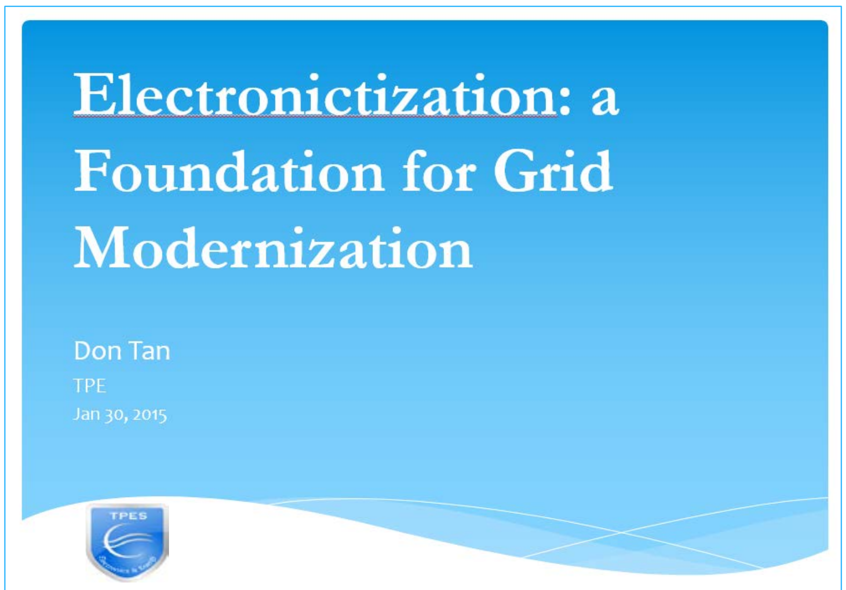
If you would summarize all seven abilities, it is one word: digitization

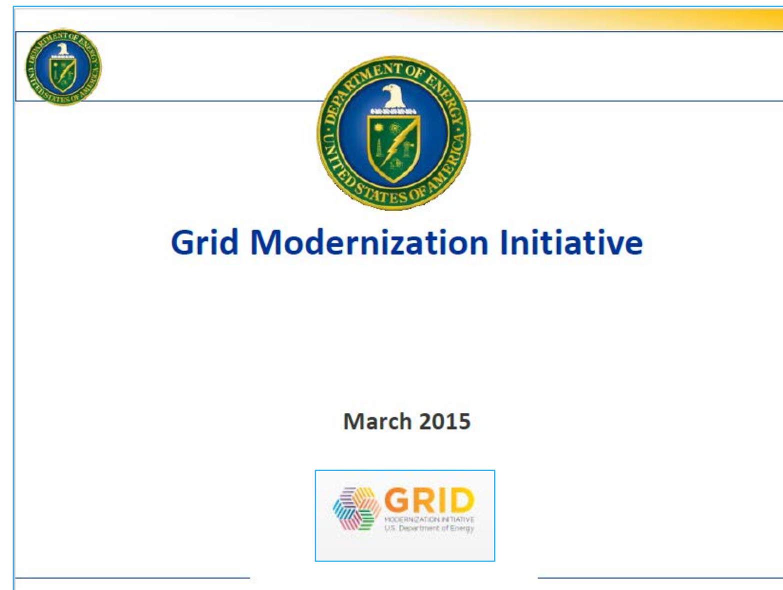
But the grid is aging …

D. Tan, "Electronictization for grid modernization," EE Dept. Distinguished Speaker Series, UCR, Jan., 2015

The Smart Grid and Grid Modernization

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





D. Tan, "Electronictization – A Foundation for Grid Modernization," *Chinese Journal of Electrical Engineering*, Vol. 1, No.1, March, 2016 , pp. 1 - 8 (Invited)

Grid Modernization: From EE to EEE

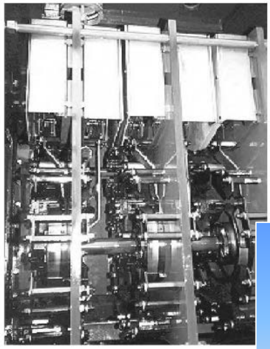
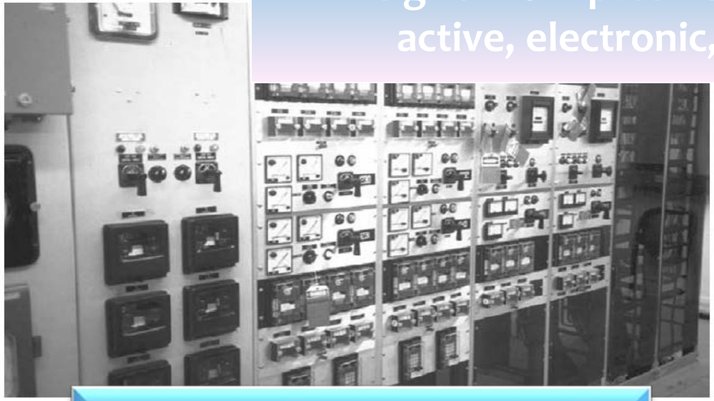


Figure 4-20. Tap changer.



Electric and Electromechanical

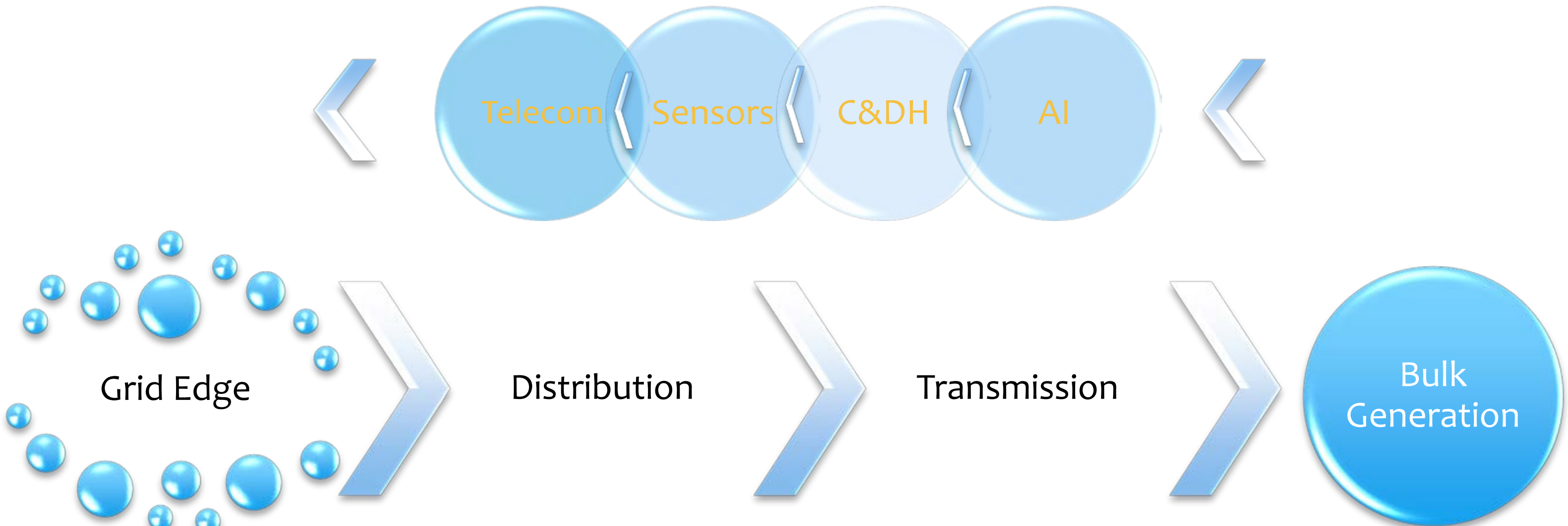
Electronic → Active → Dynamic

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

Electronic, Electric and Electromechanical

D. Tan, "Electronictization – A Foundation for Grid Modernization," *Chinese Journal of Electrical Engineering*, Vol. 1, No.1, March, 2016 , pp. 1 - 8 (Invited)

Evolution towards a Modern Electronic Grid



Structured Microgrids

MVDC

MVDC, & LVDC

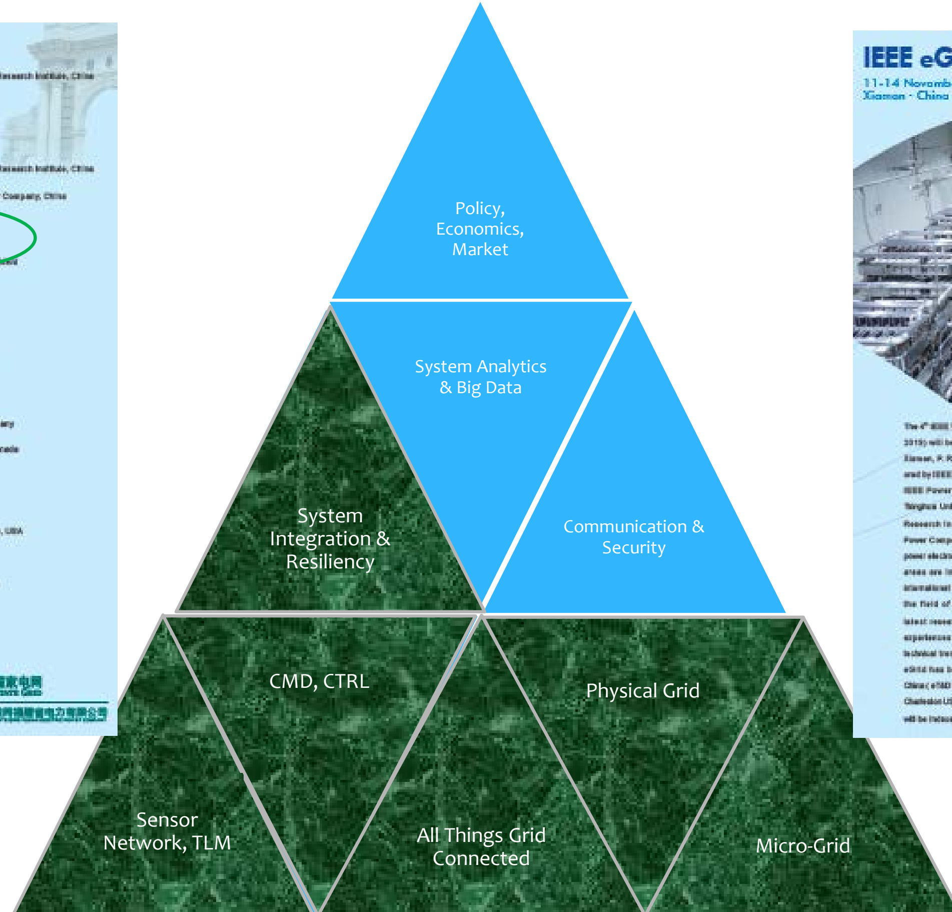
HVDC & HVAC

Asynchronous & Synchronous Generation

A dual innovation path needs to be pursued

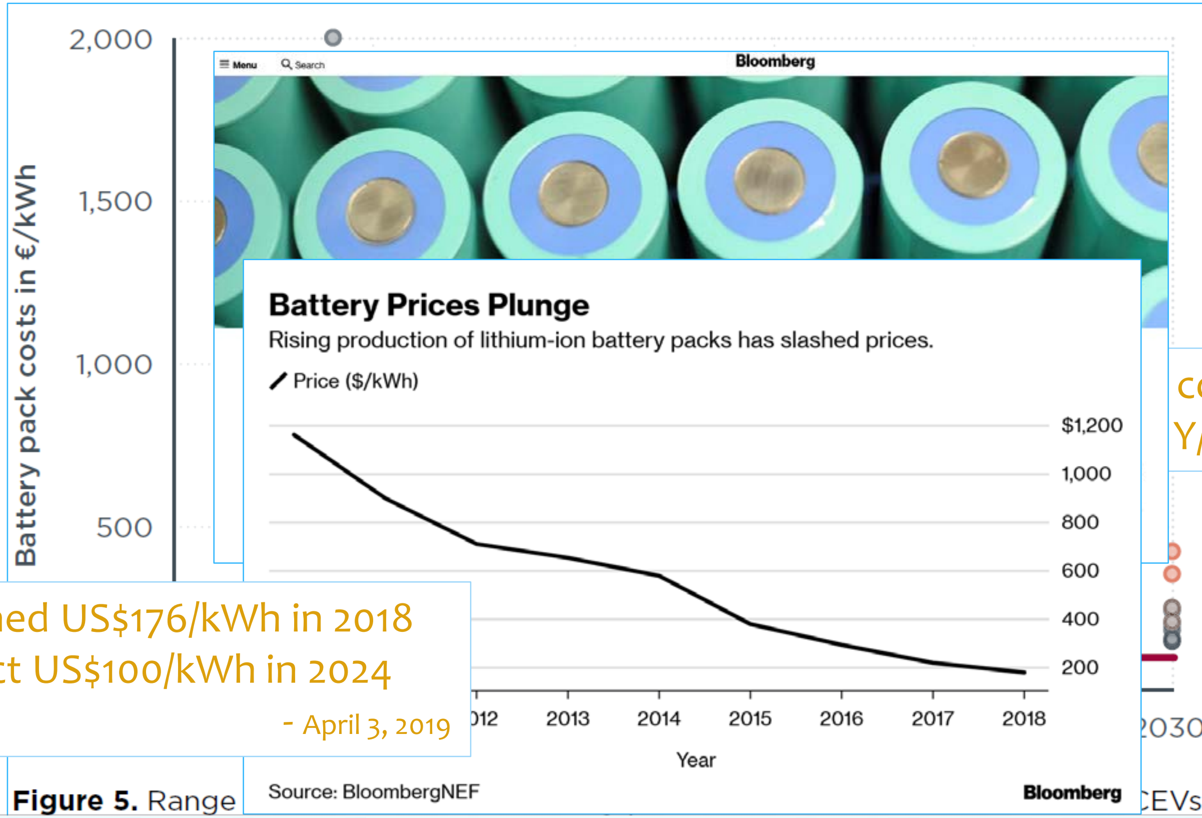
D. Tan, "Towards a (more) electronic power transmission and distribution (eT&D)," *CSEE Power Electronics & HVDC Conference*, Dec., 2016 (Invited Keynote)

Power Electronics: Laying the Foundation



D. Tan, "Electronictization – A Foundation for Grid Modernization," *Chinese Journal of Electrical Engineering*, Vol. 1, No.1, March, 2016 , pp. 1 - 8 (Invited)

Battery Cost Going Down Exponentially



cost will be
Y/E 2017

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

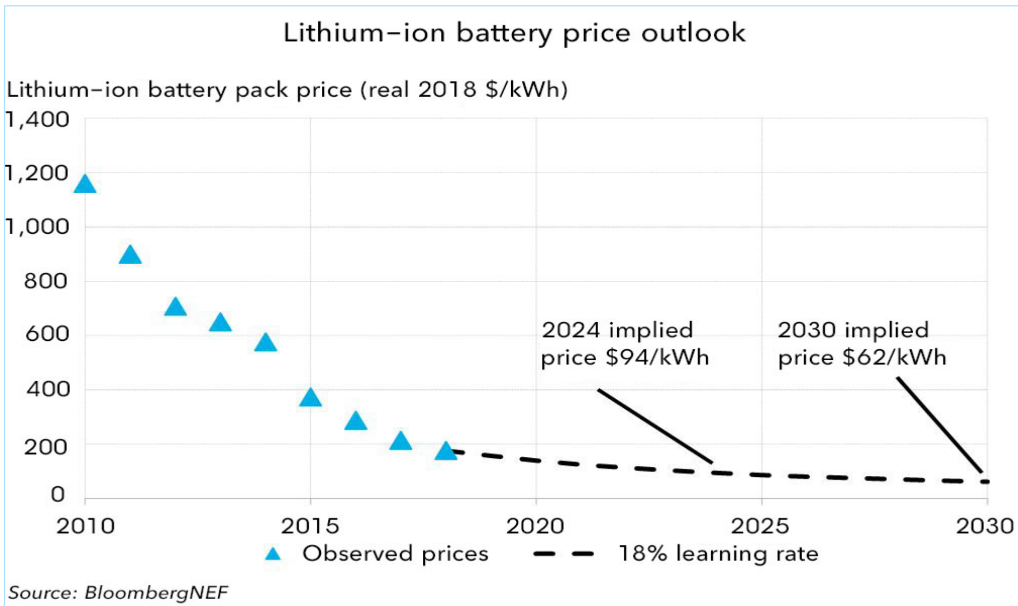
\- April 3, 2019

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

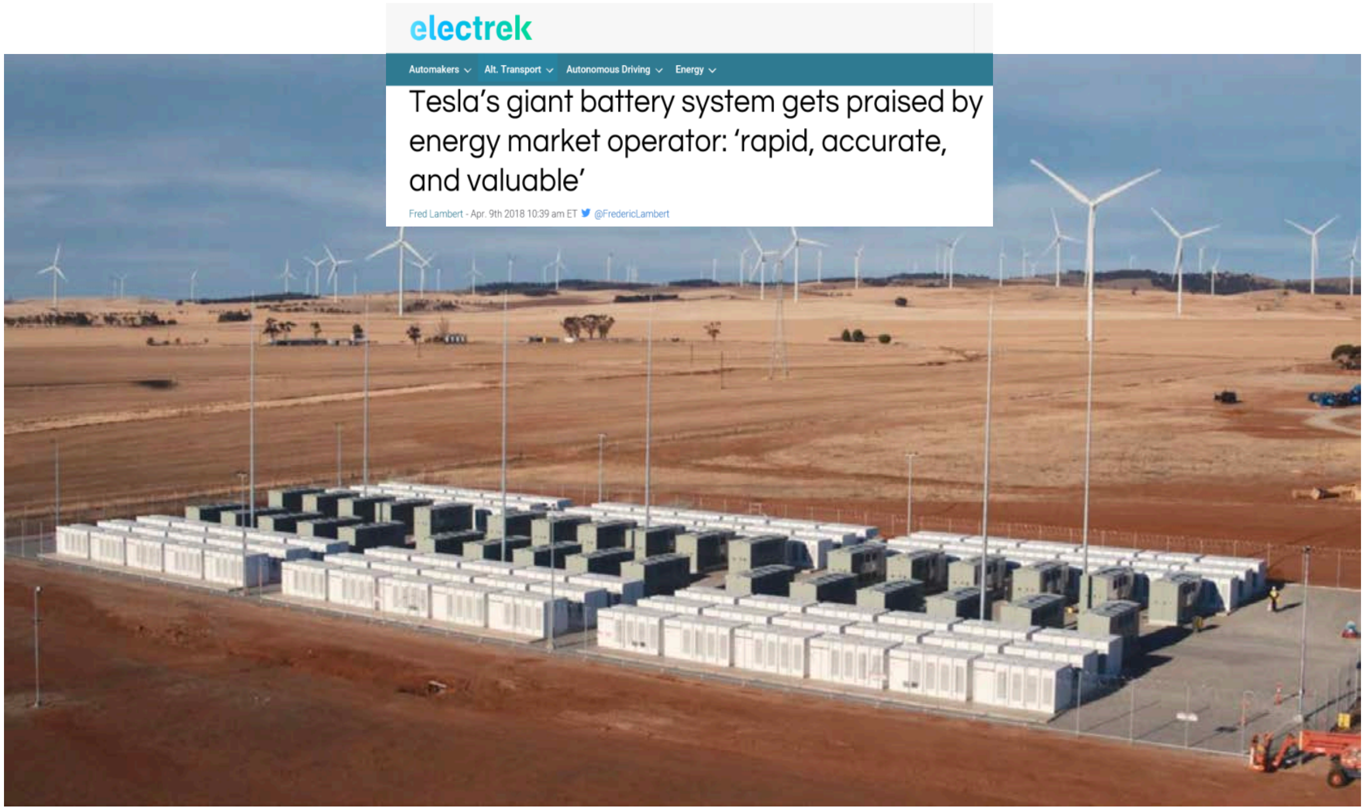
ICCT Working Report, "*Electrical vehicles: Literature review of technology cost and carbon emission,*" ICCT Working Report, 2016-14, July, 2017

Battery cost continues to fall

- Li-ion battery cost continues to drop



Batteries: Grid-Scale Deployment



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

D. Tan, "Batteries: the ultimate inertia for renewable integration," *IEEE T&D Show, April,* 2018 (Invited Super Session Panelist)

Batteries: “Rapid, accurate, and valuable”

Figure 1 Accuracy and speed of regulation FCAS response – large conventional steam turbine

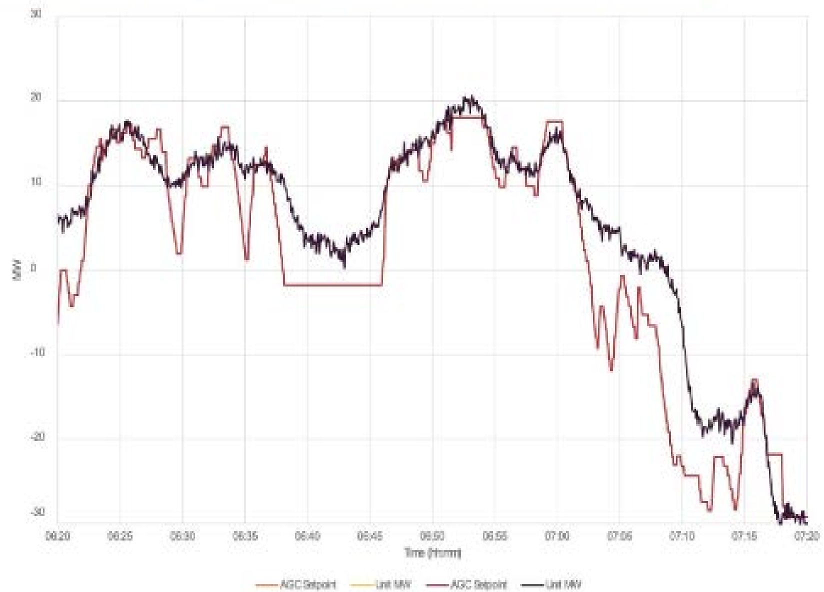
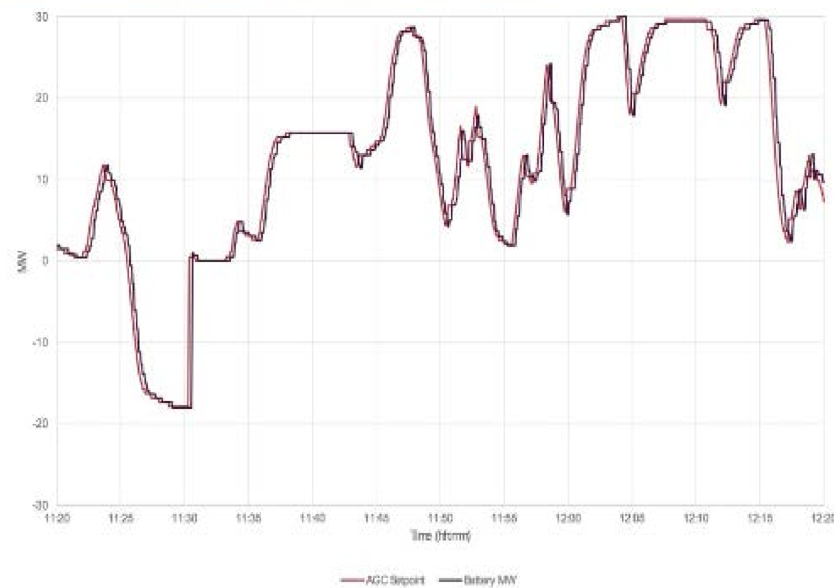


Figure 2 Accuracy and speed of regulation FCAS response – Hornsdale Power Reserve



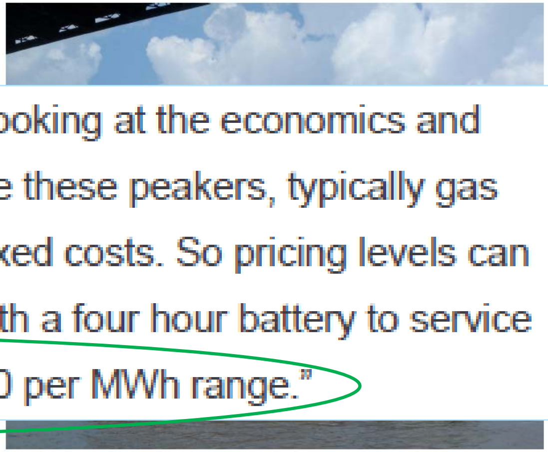
Battery: “The super inertia” for fast and accurate responses

“Initial operation of the Hornsdale power reserve battery energy storage system,” *Australian Energy Market Operator (AEMO)*, April 5, 2018

Solar/Battery: Displacing Gas Peaker Plants

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."



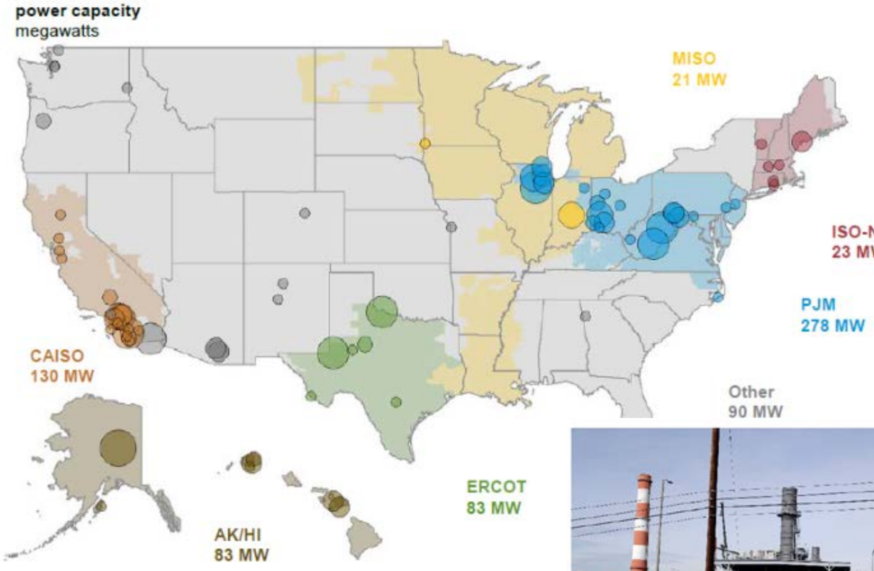
Peaker plants are only fired up for perhaps less than 20% of their operating lifetime, but they are at their most polluting in the period during which they ramp up, spewing pollutants and greenhouse gases (GHGs) into the air. Solar-plus-storage is now starting to fill that niche. Image: wiki / Jim Henderson

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

Shutterstock / Nutthapat Matphongtavorn



Grid-scale batteries are being installed coast-t from 2017 indicates. Source: U.S. Energy Inforr Battery Storage Market Trends, 2018.

The Scattergood power plant in Los Angeles is one of three natural gas power plants slated to shut down by 2029. AP Photo/Marcio Jose Sanchez

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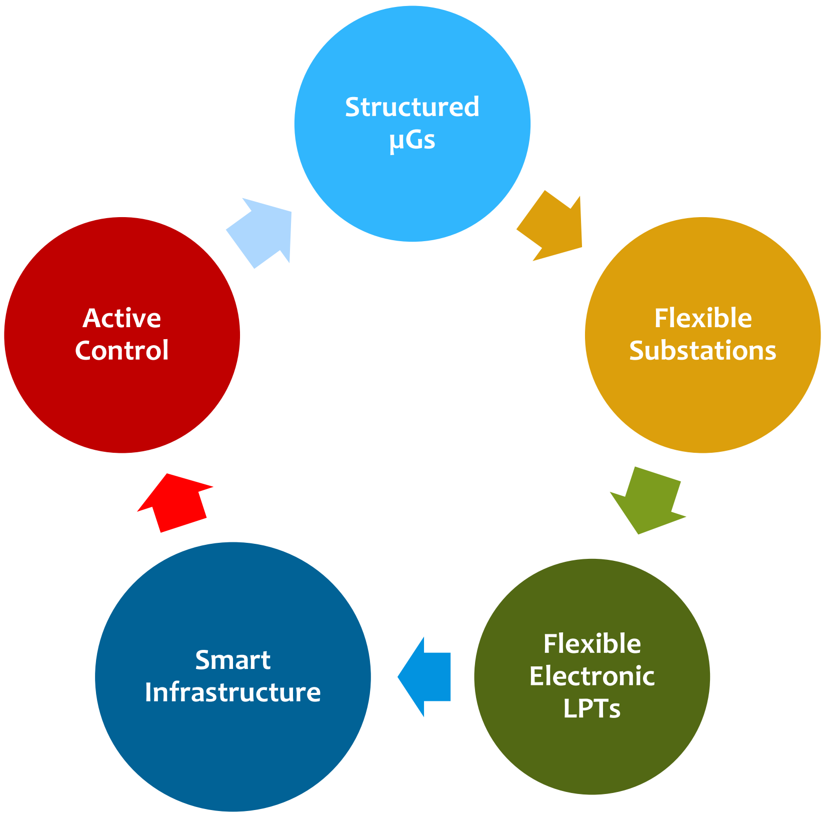
Technology Focus Areas

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

D. Tan, "Emerging system applications and technological trends in power electronics," *IEEE Power Electronics Magazine*, June, 2015, pp.38-47

SμGs : Local and Global Benefits

Emerging System Applications and Technological Trends in Power Electronics

Power electronics is increasingly cutting across traditional boundaries

by Don Tan

This article summarizes six emerging system applications, which include green energy system integrations; microgrids; all things grid connected; transportation electrification; smart homes, smart buildings, and smart cities; and energy harvesting. The four major technology trends playing a crucial role in driving the emerging system applications include adiabatic power conversion, monolithic power conversion, multilevel power converters, and wide-bandgap devices.

Evolution of Power Electronics

Power electronics (PE) is going through an exciting time, with increasingly widespread applications. I experienced this firsthand when I was the president of the IEEE Power Electronics Society (PELS) in 2013 and 2014. As I traveled from the United States to Asia, Europe, and the Pacific Islands, celebrating the 25th anniversary of PELS, one of the recurring themes was that people were asking what the future is for PE and what the emerging technical fields are going to be in the next five to ten years. To answer those questions, I presented a keynote speech at the plenary of the IEEE Applied Power Electronics Conference and Exposition

Digital Object Identifier 10.1109/MPEL.2015.2422051
Date of publication: 24 June 2015

power switching function effectively and efficiently.

Today, PE has outgrown its classic definition. It has evolved to include just about all aspects of electrical and electronic engineering, as shown in Figure 1(b). It includes analog and digital circuits, converter circuits, magnetic and electric machines, linear and nonlinear control, energy generation and storage, system engineering and integration, radio-frequency (RF) circuits, antennas, ICs and monolithic passives, and power semiconductors and ICs. Today, PE encompasses the typical coursework of any electrical and computer engineering program.

Wireless energy harvesting is a quintessential example of the ever-diversifying technical landscape of PE as a technology that crosscuts many fields of electrical engineering.

Green Energy System Integration

One of the most significant system applications of PE is the integration of green energy systems. Figure 2 illustrates the concept of green energy system integration. Solar and wind energy systems are maturing fast to penetrate deeply into the energy market to provide electricity for average consumers. The technologies for individual systems are mature, and recent trends are toward the integration of solar farms with wind farms, particularly with offshore wind farms. To transmit the power from offshore to onshore, new high-voltage dc (HVDC) transmission technology has been developed and deployed around the world. The new technology leverages the recent progress in PE, such as HV IGBTs and multilevel voltage-source converter (VSC) circuit topology. (More details on multilevel power are given in the "High Power Goes Multilevel" section.)

Relative to wind and solar energy systems, wave and tidal energy systems are less mature. Except for a few cases of deployments for tidal barrages, they are still in the demonstration and testing stage. The idea is to leverage wave and tidal energies to supplement the intermittency of wind and solar energies. The challenges are in the initial cost, transmission to shore, and environmental footprint. PE can help with underwater power converters and subsea cable for power control and distribution.

A more recent trend in system integration is the development and deployment of energy-storage devices and resources to enhance system performance, hardware reliability, and power availability. There are many forms of energy storage being used, such as batteries, pumped hydro, compressed air, flywheels, hydrogen, fuel cells, and thermal energy. Once all these technologies are successfully developed, deployed, and integrated, we will have truly sustainable energy systems for years to come. PE engineers will be the best system integration engineers since intimate knowledge about the system hardware is essential for the successful integration of any system.

Microgrids

A microgrid is an autonomous electric power subsystem. It can be dc, ac, or a hybrid of dc and ac. A structured microgrid is integrated with loads, energy sources, storage devices, sensors, and data buses, and is an autonomous subsystem that includes the following features:

- balance of energy over the intended operation and capacity
- reconfigurability for stand-alone or grid-connected operation
- resiliency with fault tolerance and fault isolation
- bidirectional power flow
- modularity and scalability.

There are many benefits that a microgrid can bring to a user locally. The local benefits of microgrids are as follows:

- enhanced energy efficiency
- reduced electricity cost
- improved power quality
- greater availability of power (particularly when grid tied)
- enhanced energy independence
- combined utility generation (gas, heat, water, and communication)
- environmental conservation using renewables locally
- creation of a natural platform for local generation and integration
- resiliency with redundancy and recovery
- building structure for the next higher-level grid(s).

Microgrids are beneficial to grid operators globally. Microgrids bring benefits globally to the grid by

- enhancing distributed generation with a high percentage of renewables
- enhancing distributed storage
- accommodating new demand from electric vehicles
- allowing smart metering to do transactive (dynamic) pricing
- enabling local energy management without burdening the grid bandwidth for communication
- preprocessing data locally to reduce the required grid capacity
- providing predictive local control to enhance grid stability
- using bidirectional flow to enhance energy availability to grid
- providing a balance between the distribution grid and microgrids
- using their ability to island.

DC microgrids are particularly advantageous for practice due to their many benefits, which include higher efficiency, more robust system operation, no impedance matching issues, no synchronization, simple waveforms, and a large body of knowledge in PE and systems being directly leveraged. Figure 3 shows an example of a resilient dc microgrid for mission-critical space applications [2].

- Renewable integration
- Structured microgrids
- All things grid connected
- Transportation electrification
- Smart homes, buildings and cities
- Power conversion goes adiabatic
- Low power goes monolithic
- High power goes multi-level
- WBG devices going main stream

D. Tan, "Emerging system applications and technological trends in power electronics," *IEEE Power Electronics Magazine*, June, 2015, pp.38-47

SµGs: CHP – An Early Adaptor

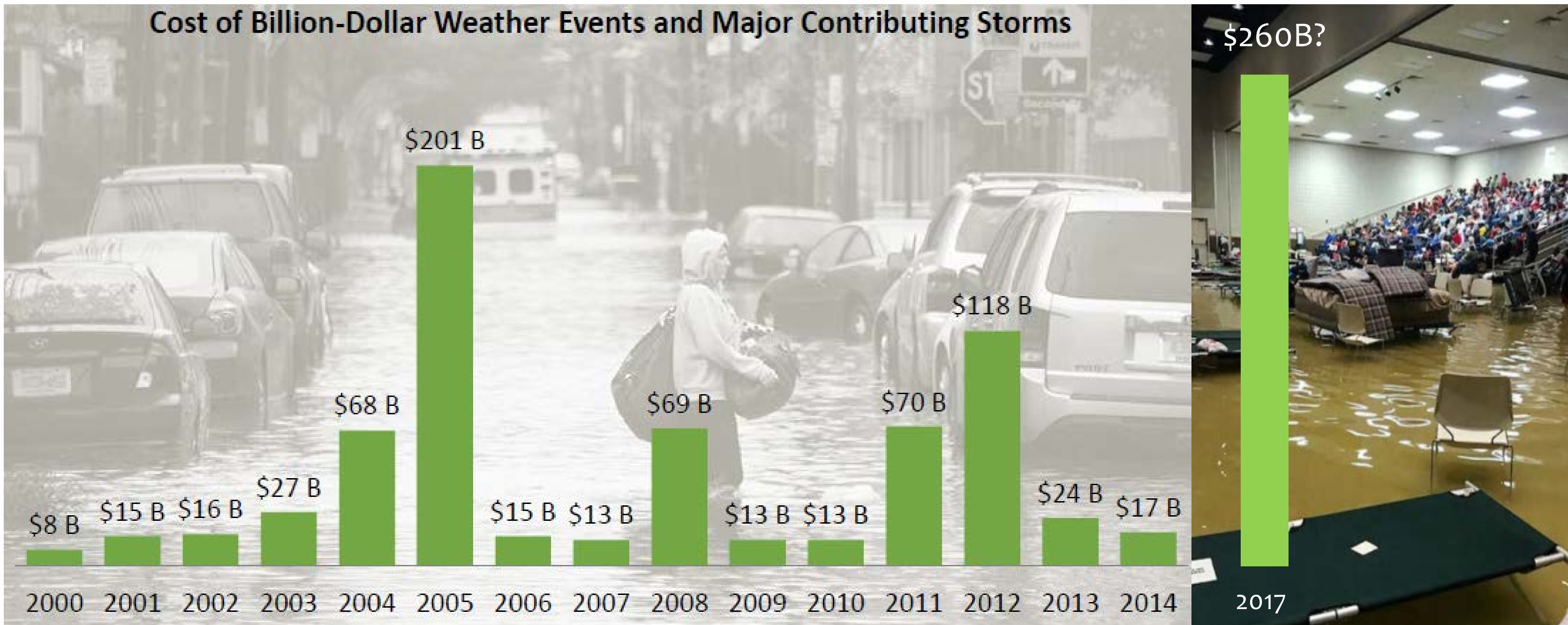
- Combined Heat and Power (CHP) generation provides
  - Reliable baseload power
  - Gas line weather proof
  - Heat captured for hot water, chilled water and steam product (heating)
- With CHP powers the baseload, renewables can be integrated
  - Solar, wind, and storage
  - Demand response
  - EV ultrafast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

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

D. Tan, "Structure microgrids: Invaluable assets for grid modernization," *IET APSCOM*, Nov, 2018 (Invited Opening Keynote)
A. Hampton, "Combined heat and power: the ideal anchor for microgrids," *IDEA Campus Conference*, Feb., 2016

SμGs: Resiliency

* Frequent extreme weather events, Hurricane Harvey?!



D. Tan, "Structure microgrids: Invaluable assets for grid modernization," *IET APSCOM*, Nov, 2018 (Invited Opening Keynote)
J. M. Carroll, "Maximizing microgrids: the top issues facing the ideal microgrids," *IDEA Conference*, 2016

SμGs: Utility Emergency Systems

Grid Cyber Security

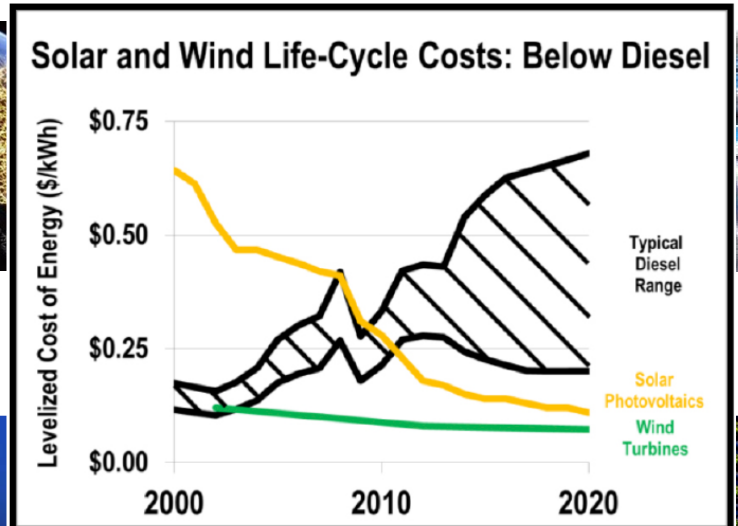
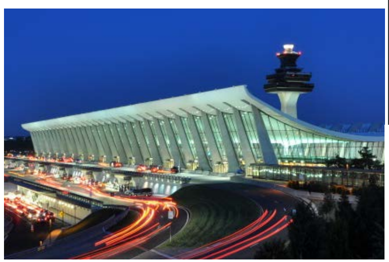


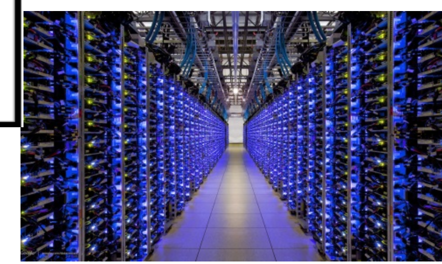
Figure 2: Life-cycle cost trends, diesel vs. renewables

Sources: International Energy Agency, Lawrence Berkeley National Laboratories, National Renewable Energy Laboratory, U.S. Energy Information Administration, Clean Edge, Caterpillar.

Water Supply/Treatment



Airport/Traffic Contr



Data Centers

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

D. Tan, "Structure microgrids: Invaluable assets for utilities," 2nd *IEEE PELS/PES eT&D Workshop*, Nov., 2017 (Invited Keynote)

SμGs: Remote Energy Access

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

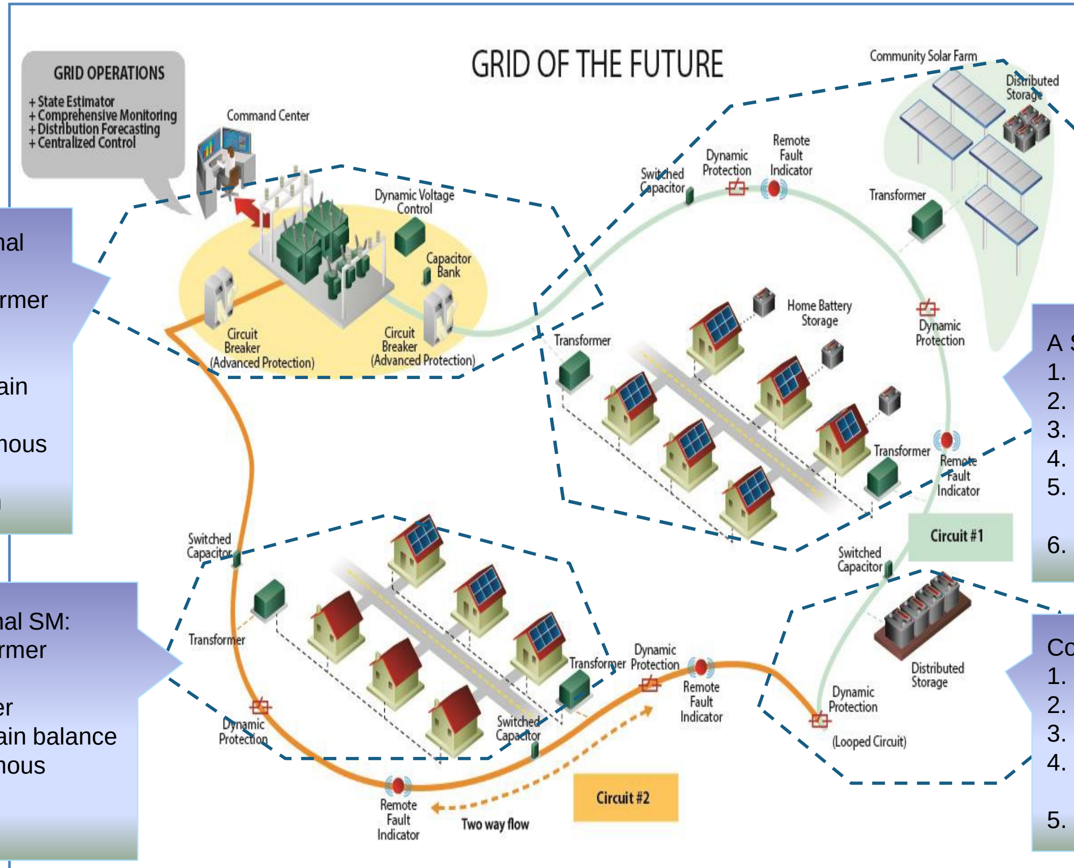
Lingshed is about 225 kilometers from Leh, population 31,000, the largest city in Ladakh.

D. Tan, "Structure microgrids: Invaluable assets for grid modernization," *IET APSCOM*, Nov, 2018 (Invited Opening Keynote)

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

Configured as a multi-terminal SM:
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



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. Energy storage to maintain balance
4. Multi-time scale autonomous control
5. Wireless communication

D. Tan, "Batteries: the ultimate inertia for renewable integration," *IEEE T&D Show*, 2018 (Invited Super Session Panelist)
Southern California Edison, "Grid modernization: Distribution system concept of operations," Version 1.0, January 2016

Flexible Hybrid Transformer Concept

* Hybrid transformer

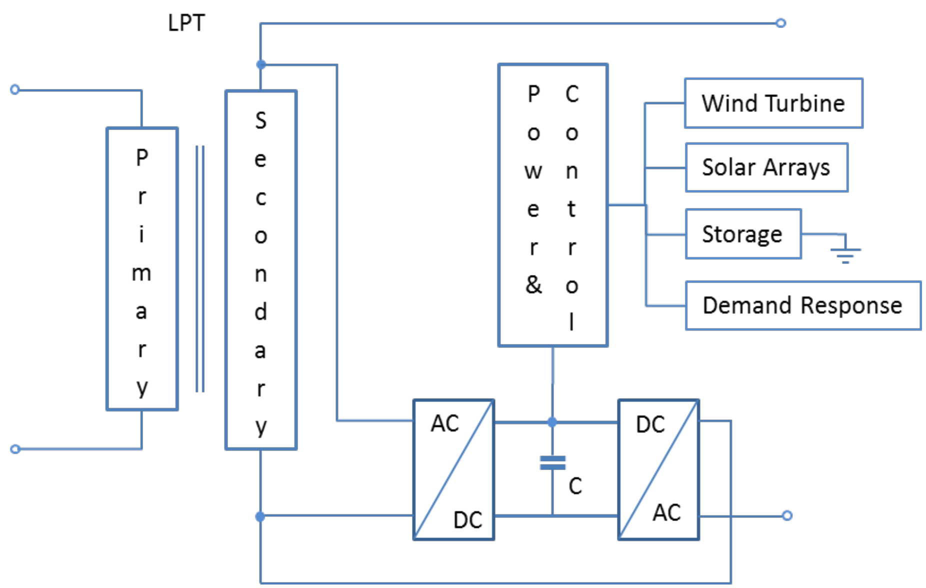


Figure 7 Conceptual illustration of the proposed flexible hybrid transformer with renewables system (HT-R)

D. Tan, "Flexible hybrid transformers with renewable energy integration," *E2 Systems White Paper*, Nov., 2017

A Solar Power Example

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

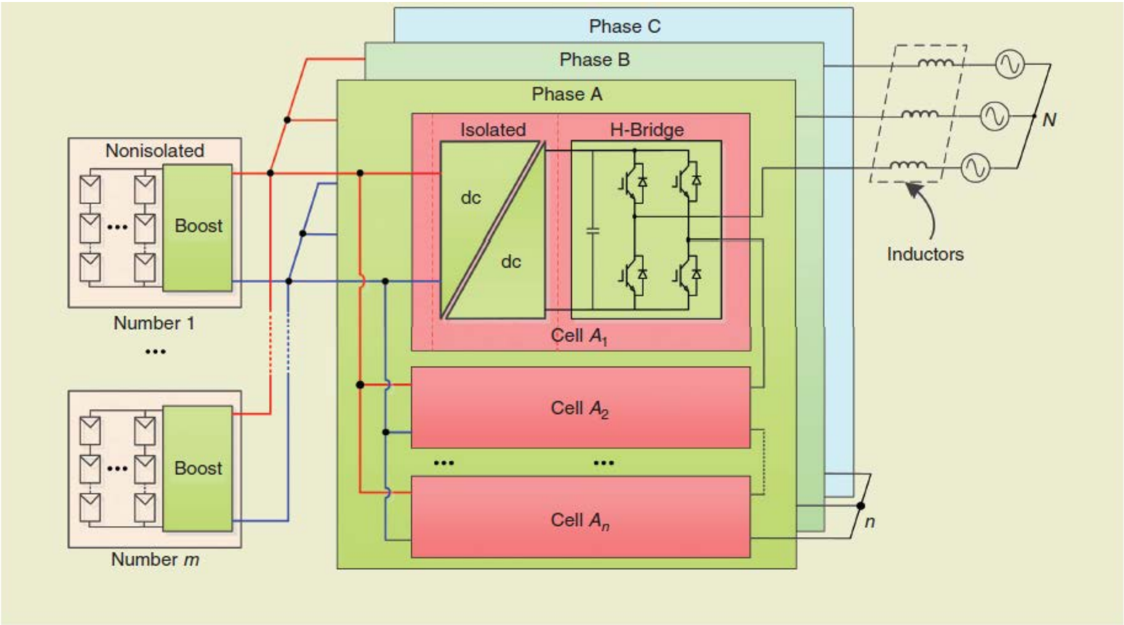
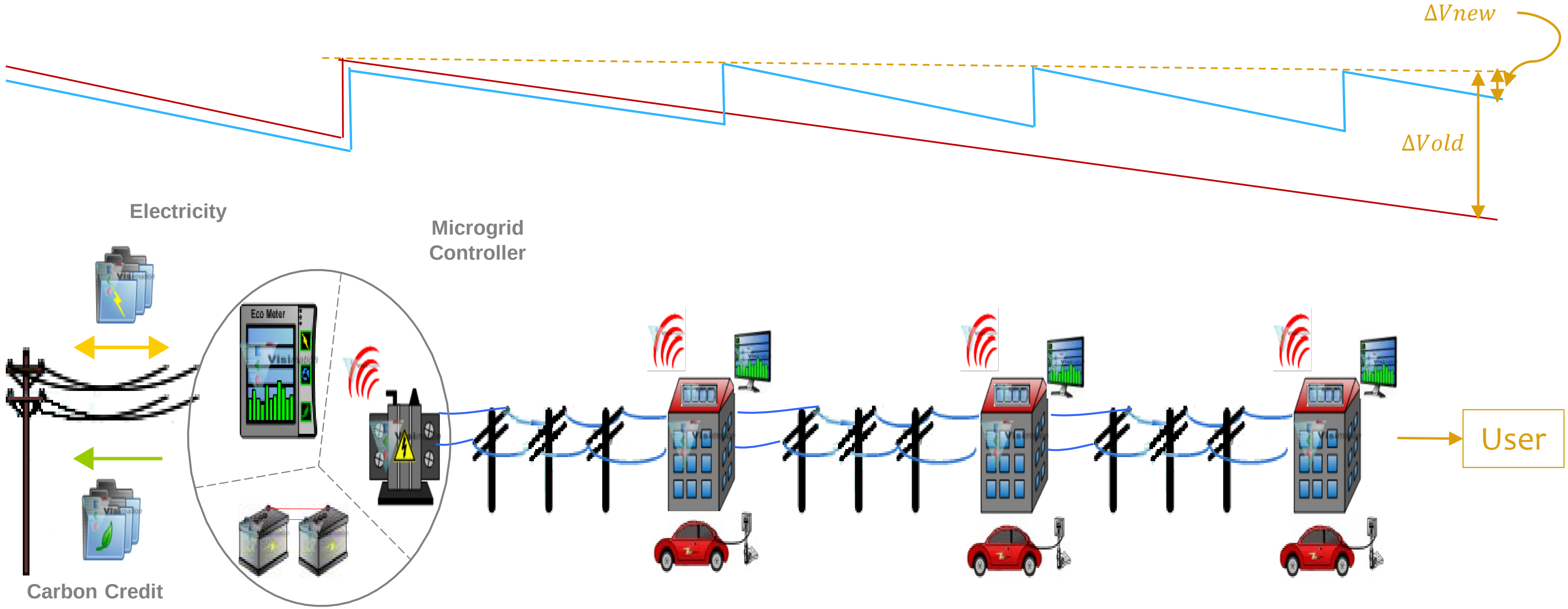


FIG 13 A typical dc bus, three-phase, isolated CHB grid-connected PV inverter.

X. Zhang, T. Zhao, W. Mao, D. Tan and L. Chang, "Multilevel Inverters for Grid-Connected Photovoltaic Applications: Examining Emerging Trends," *IEEE Power Electronics Magazine*, vol. 5, no. 4, Dec. 2018, pp. 32-41

Substation Automation and Modernization

* Feeder/Substation µGs voltage profile

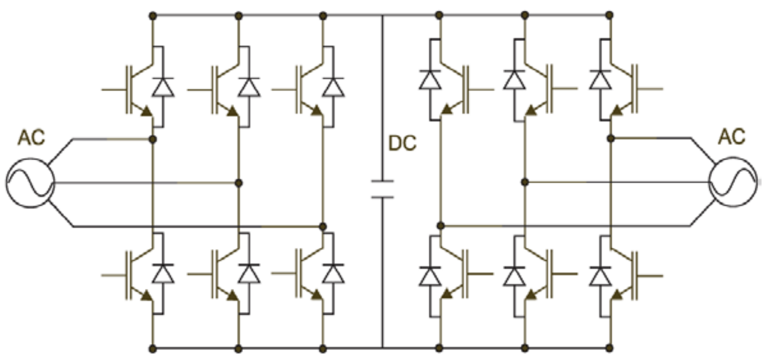


$\Delta Vnew$ << $\Delta Vold$ → Week grid will be a thing in the past

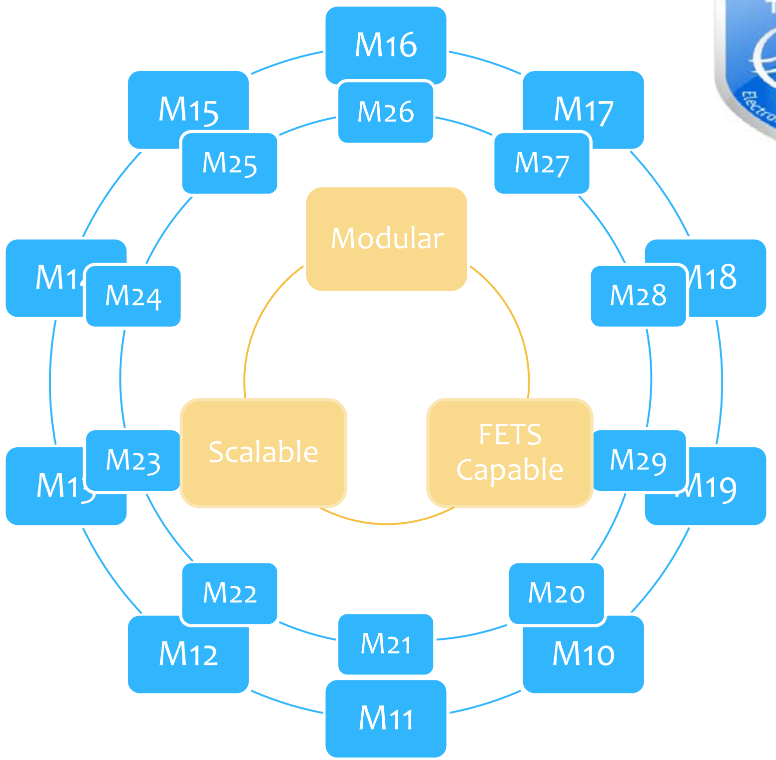
D. Tan, "Structure microgrids: Invaluable assets for utilities," 2nd *IEEE PELS/PES eT&D Workshop*, Nov., 2017 (Invited Keynote)
C. Schweagerl, "Technical, economic and environmental benefits of microgrids operation," *Siemens*, Jan., 2010

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



A Simple BtB Illustration



FETS – Flexible Electronic (AC/DC) Transmission System

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

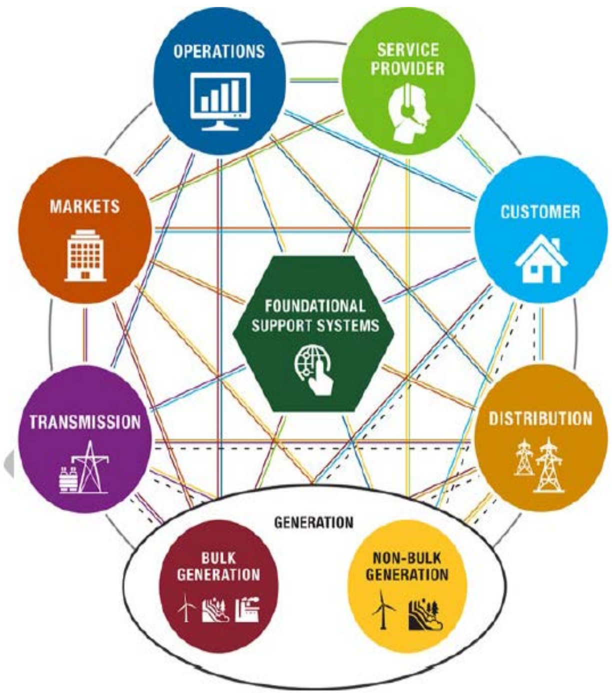
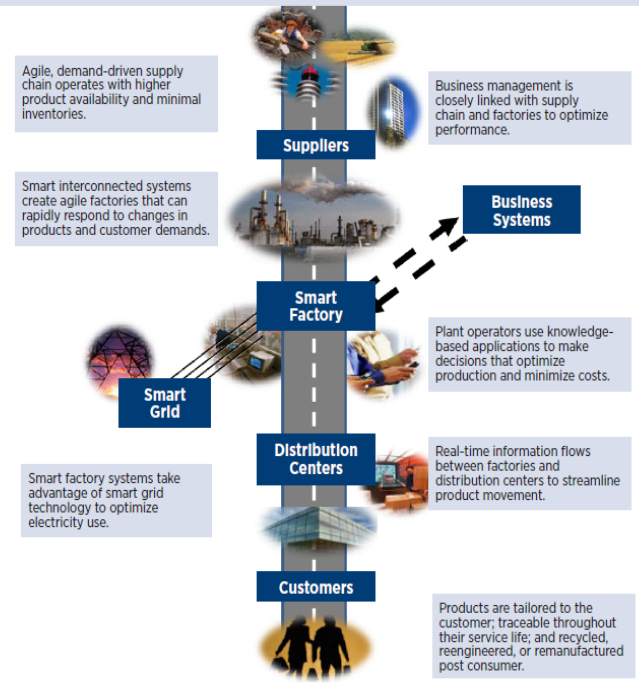


Figure 2-1. Concept of the Smart Manufacturing Enterprise

Smart, modern factories are interconnected with suppliers, distributors, customers, and business systems via information technology (data, voice, mobile, etc.) to create a highly optimized and competitive business enterprise.



Middlebrook Flying Capacitor Converter

D. Tan, “Switched-Capacitor Circuits: Coming of Age,” *IEEE PELS LAC Relaunch Meeting*, April, 2019 (Invited)

Partial power processing

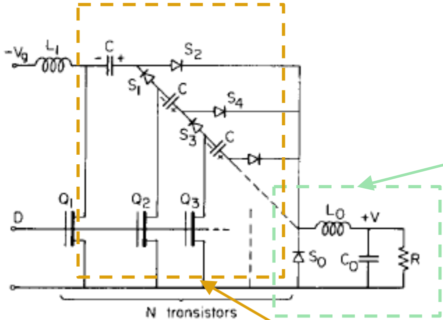


Fig. 3. Generalized N-stage voltage-divider Ćuk converter.

$$\frac{D_N}{N(1-D_N)} = M = \frac{D_1}{1-D_1} \quad (1)$$

which leads to

$$D_N = \frac{ND_1}{1 + D_1(N-1)} \quad (2)$$

and

$$D_N = \frac{NM}{1+NM} \qquad D_1 = \frac{M}{1+M}. \quad (3)$$

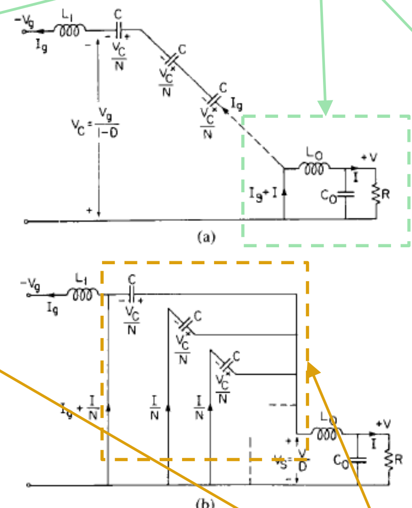


Fig. 4. N-stage converter. (a) During driving transistor off-time, N capacitors are charged in series. (b) During transistor on-time, N capacitors are discharged in parallel.

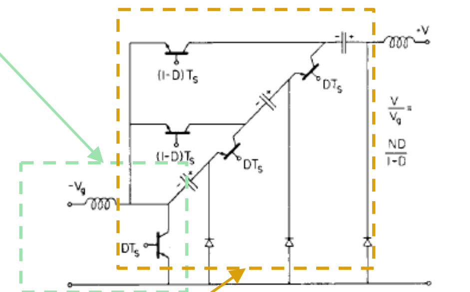


Fig. 10. Principle of three-stage voltage-multiplier Ćuk converter.

Voltage divider/multiplier

R. D. Middlebrook, "Transformerless DC-to-DC converters with large conversion ratios," in *IEEE Transactions on Power Electronics*, vol. 3, no. 4, Oct. 1988, pp. 484-488

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

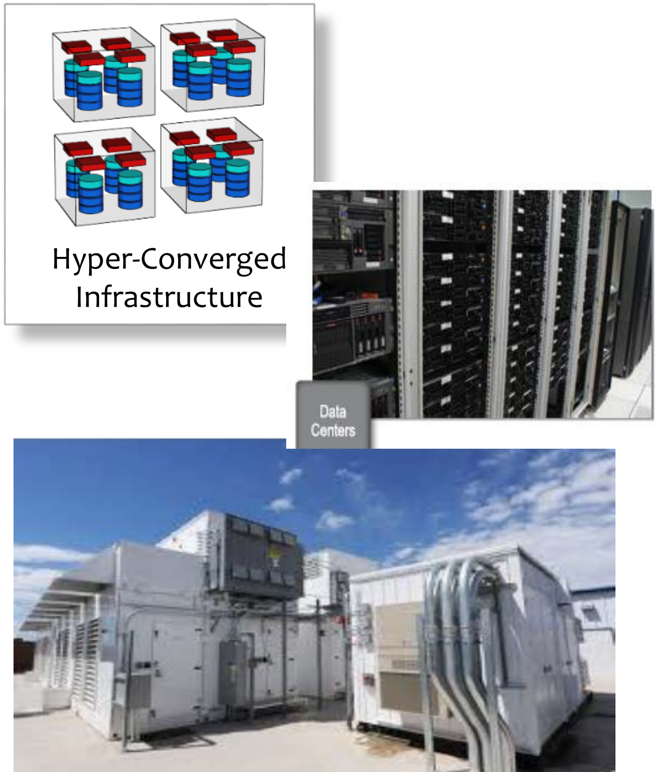
Grid Edge (End Users)

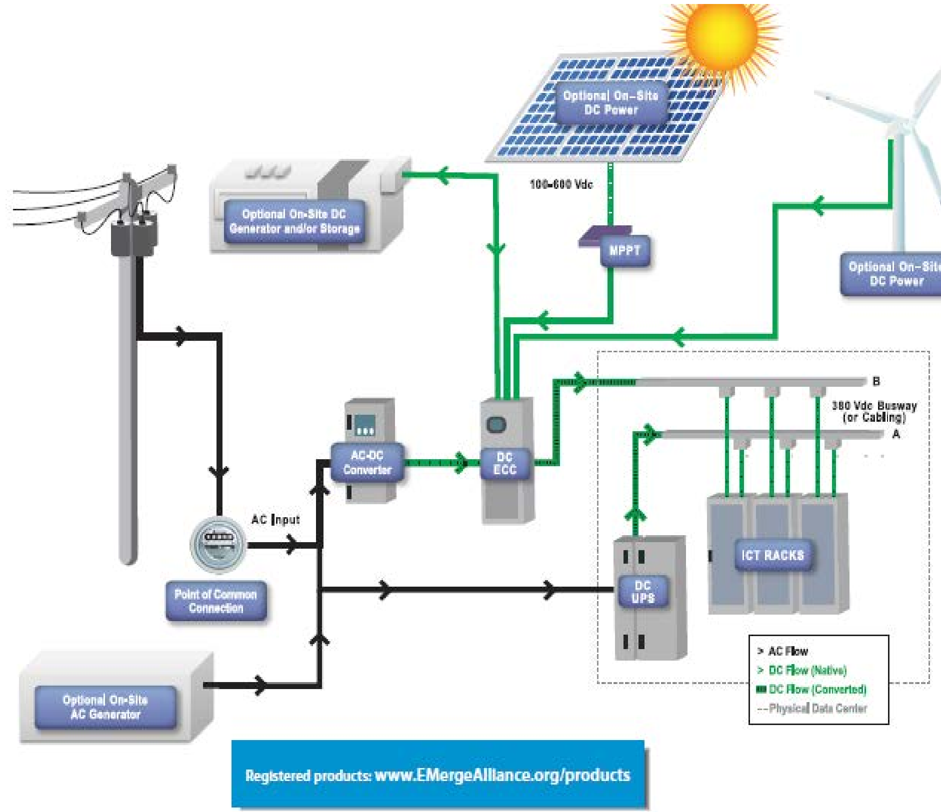
- **Demand response**
- **Optimize retail rates**
- **Power quality**
- **Critical load**
- **Renewables on site**
- **Peak shaving**
- **Energy shifting**
- **Resiliency**
- **Islanding**
- **Reactive power**

D. Tan, "Structure microgrids: Invaluable assets for utilities," 2nd *IEEE PELS/PES eT&D Workshop*, Nov., 2017 (Invited Keynote)

TFA 4: Electrification and Smart Infrastructure

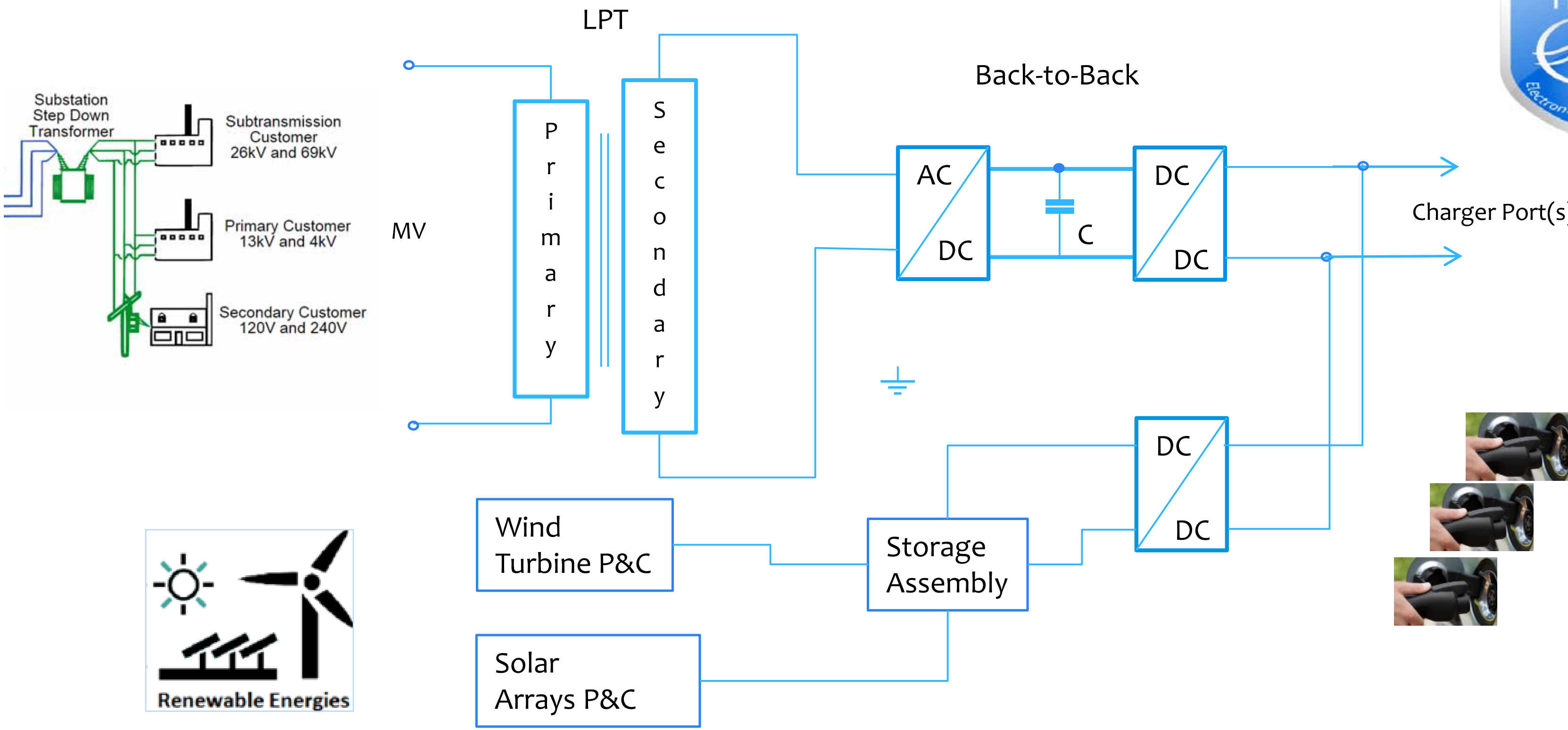
* Data/Telecom Centers: Modular and Scalable





D. Tan, "Structure microgrids: Invaluable assets for grid modernization," *IET APSCOM*, Nov, 2018 (Invited Opening Keynote)
"DC Microgrids: advanced distribution platforms for flexibility, Savings, and Sustainability in buildings," Emerge Alliance Visions, 2011

Ultra-Fast Charging: Efficient Architecture

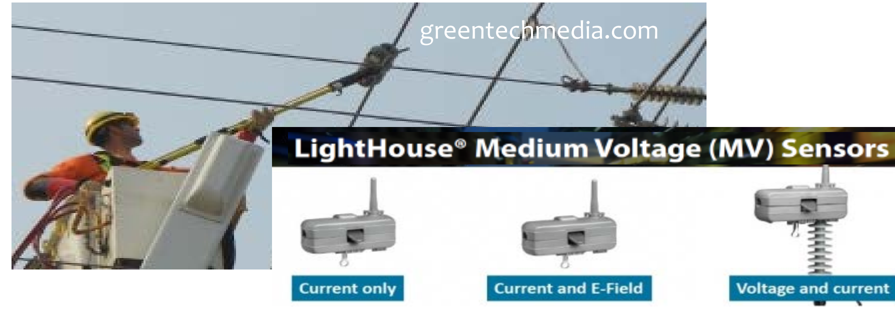


SµGs integrate renewables for ultra-fast charging and grid support

D. Tan, "Challenges in ultra-fast charging stations," *IEEE ITEC Asia-Pacific*, Aug., 2017 (Invited Keynote)

On-Line Grid Voltage and Current Sensors

Smart Meters and PMUs



tollgrade.com

new.abb.com

15 kV voltage/current combined line post sensor

arteche.com

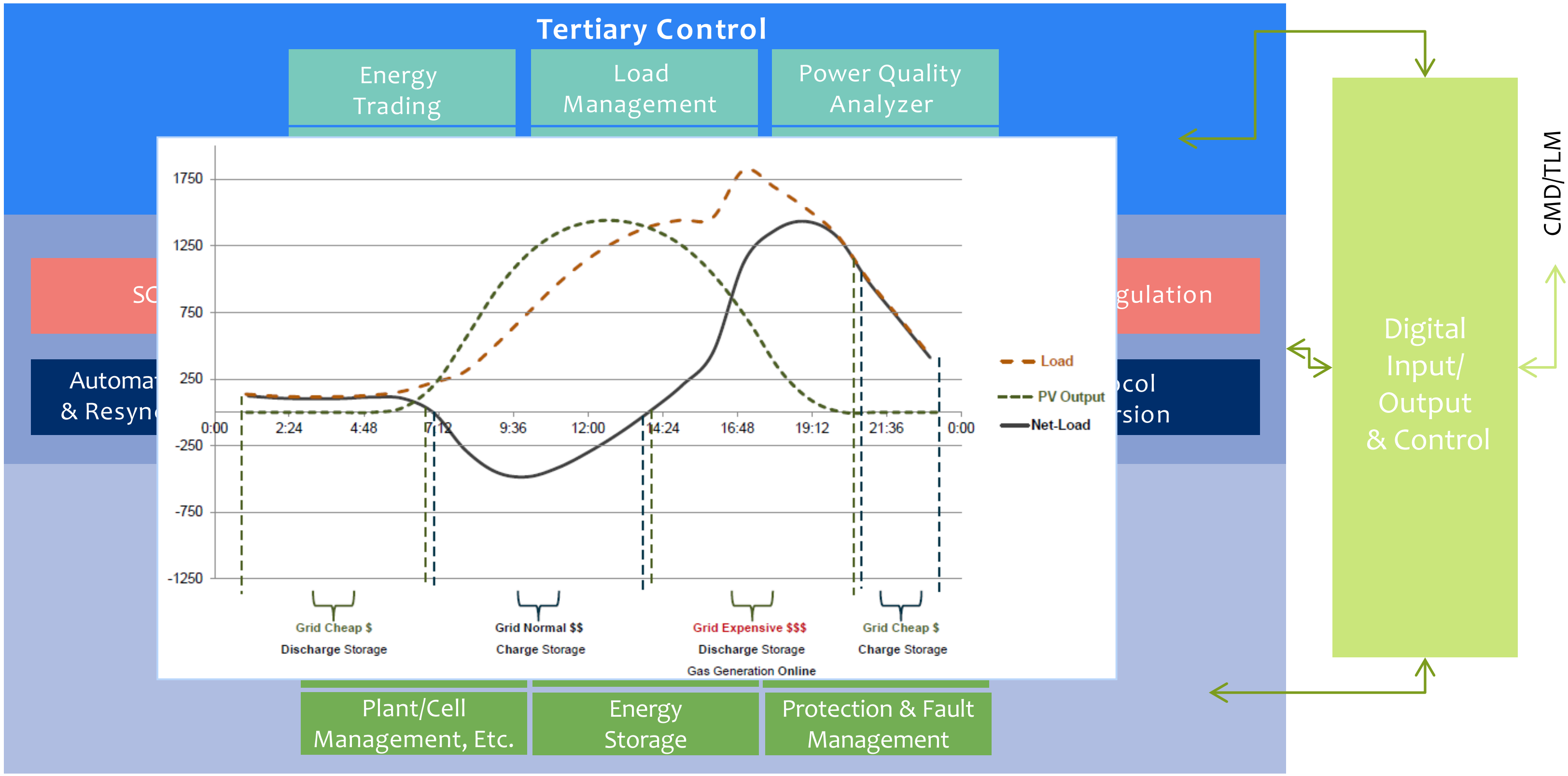
IEEE/ANSI Medium Voltage Outdoor Instrument Transformers

lindsey-usa.com/sensors

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

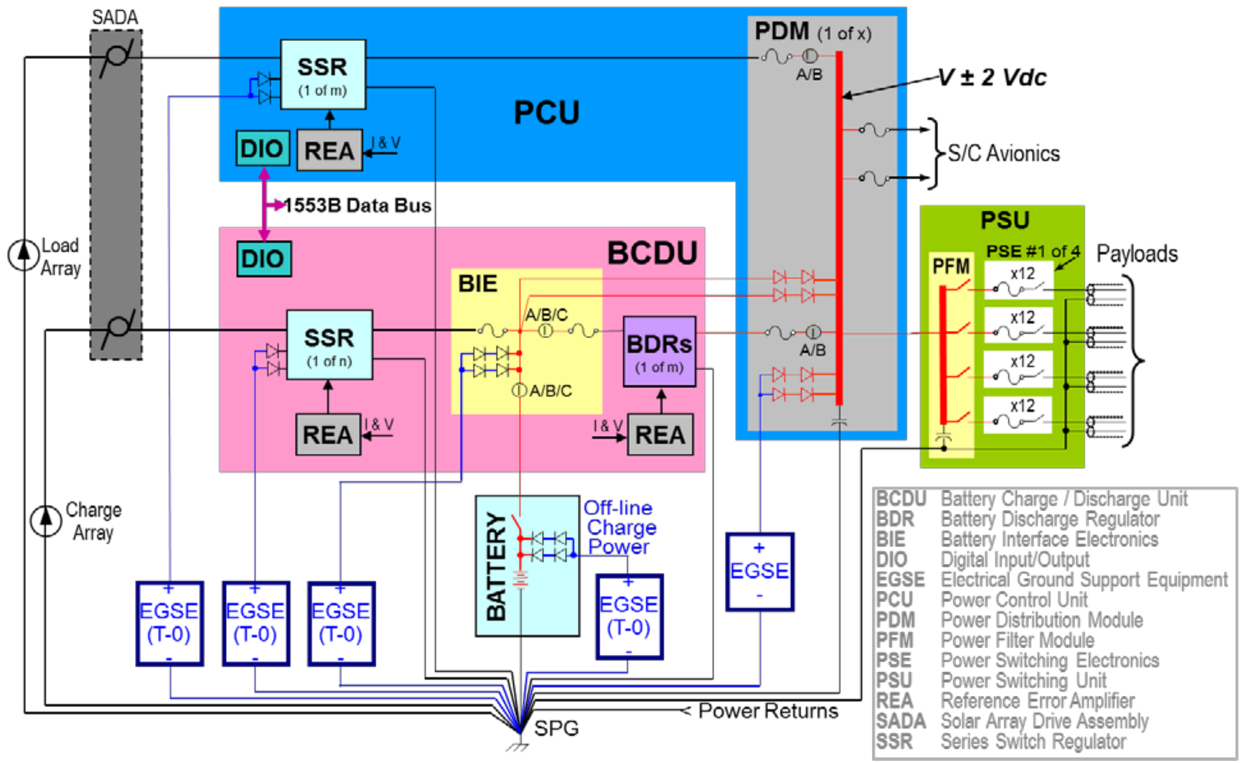
* Scalable 5-level of controls



D. Tan, "Structure microgrids: Invaluable assets for grid modernization," *IET APSCOM*, Nov, 2018 (Invited Opening Keynote)
M. Clout, "DER optimization, dispatch, tertiary control/monitoring strategies," *Siemens*, 2016
"NREL Integrate," *Siemens-OMNETRIC Group Industry Day Workshop*, March 2017

First Resilient, Islanded, Remote Microgrid

* Flight-proven technology



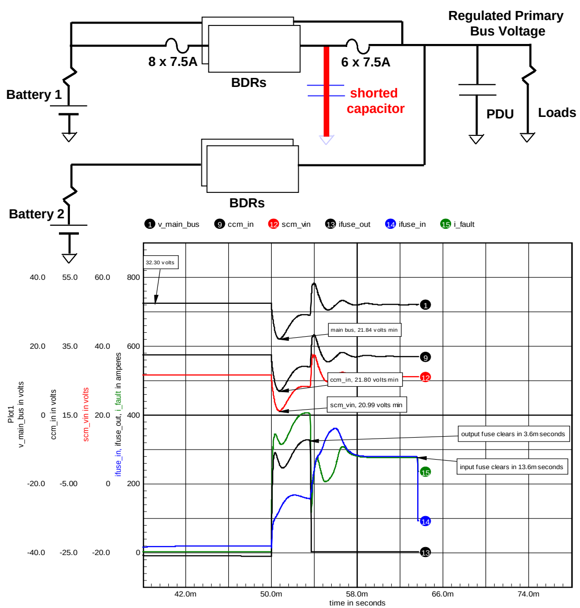
A resilient microgrid proven in deployment, saving national assets in US$B's

D. Tan, et al, "A first resilient DC-dominated microgrid for mission-critical space applications," *IEEE JESTPE*, Dec., 2016, pp. 1147-1157 (Invited)

Fuse Clearing and Dead Bus Recovery

- Fuse Clearing

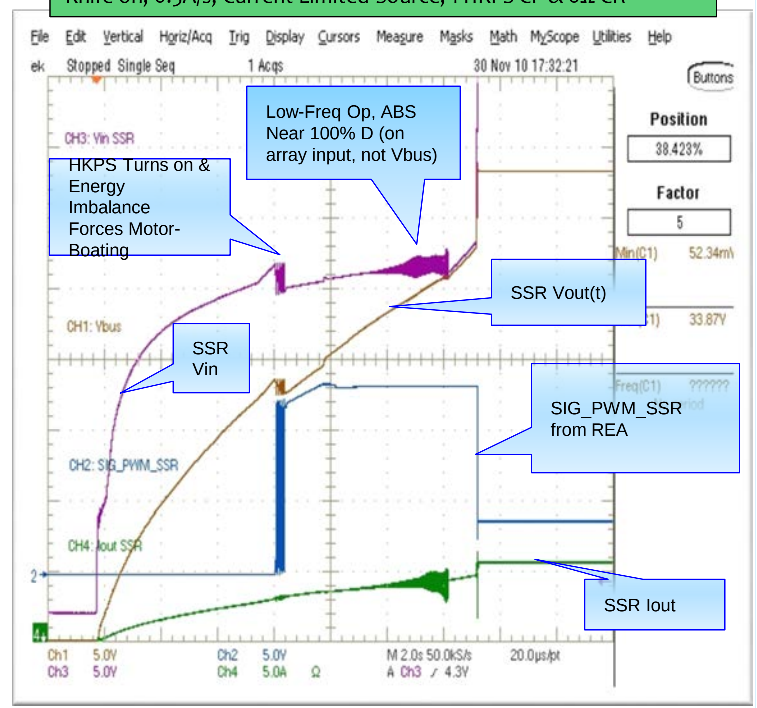
The bus holds minimum voltage even with a hard short



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

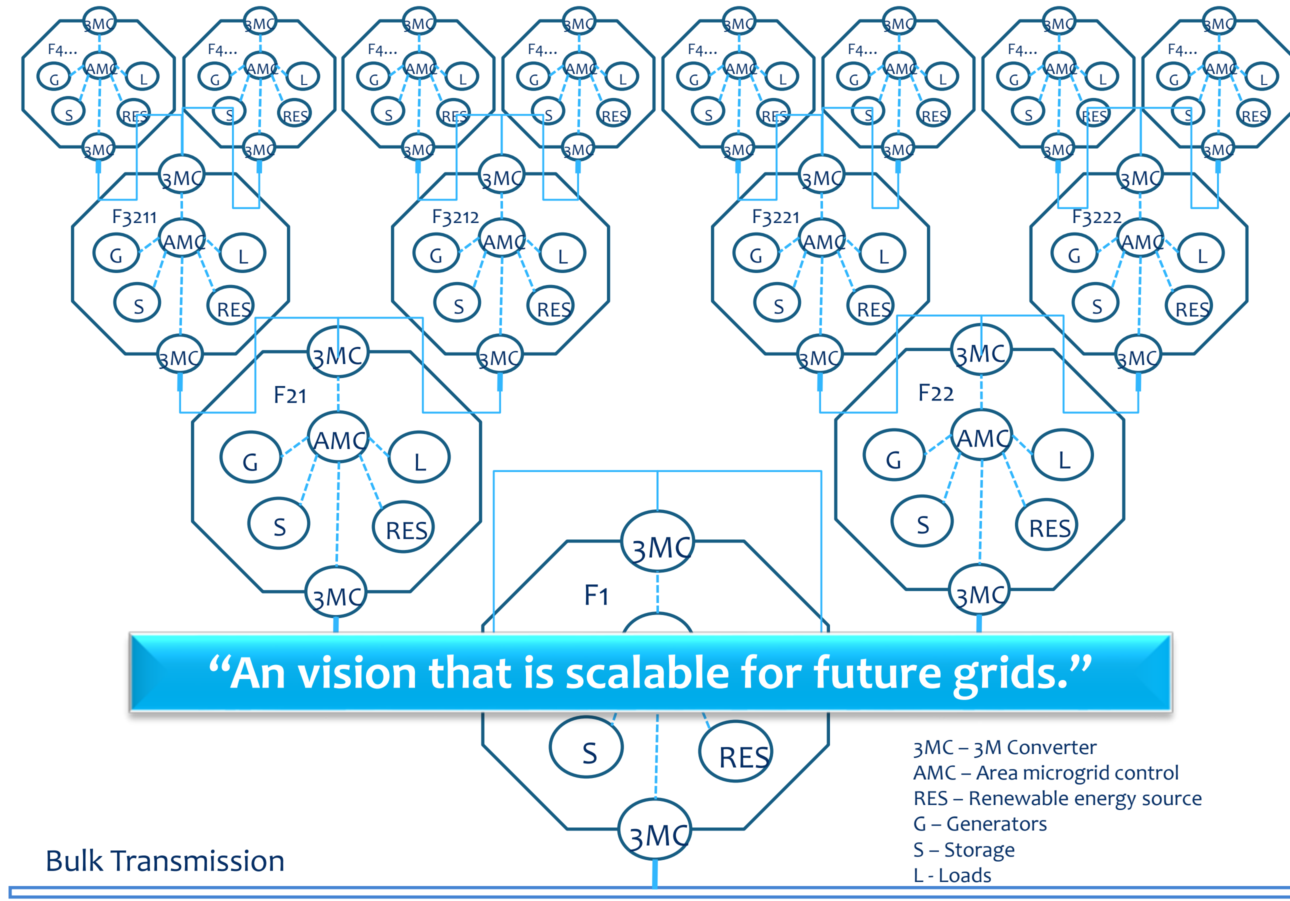


The bus holds its minimum voltage with a hard short

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

D. Tan, et al, "A first resilient DC-dominated microgrid for mission-critical space applications," *IEEE JESTPE*, Dec., 2016, pp. 1147-1157 (Invited)

A Fractal Radial Distribution with SμGs

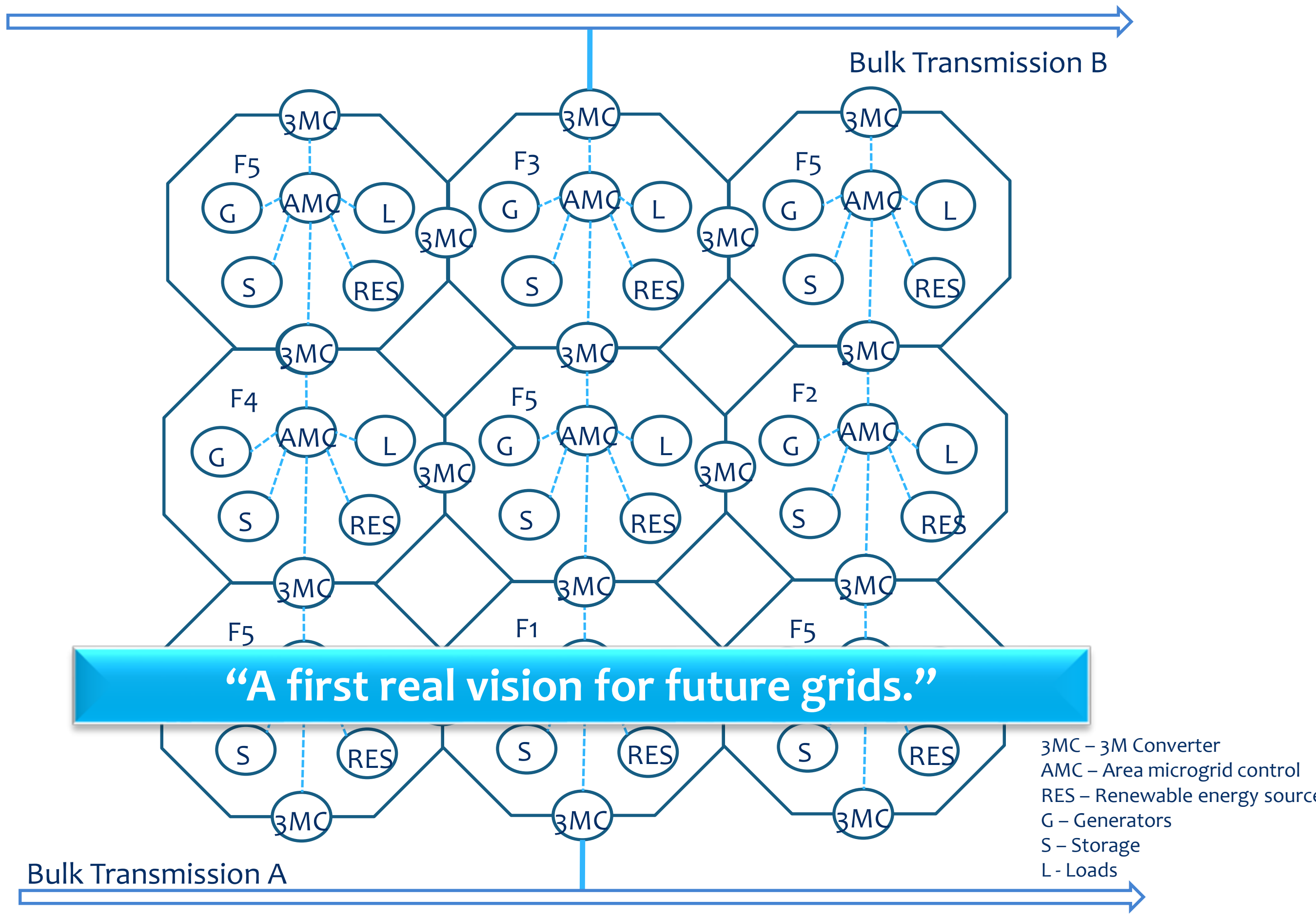


"An vision that is scalable for future grids."

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

D. Tan and Damir Novosel, "Six basic characteristics of modern power grid," *Southern Power System Technology*, Vol. 11, No. 10, Oct., 2017, pp. (Invited)

A Fractal Mesh Distribution with SμGs

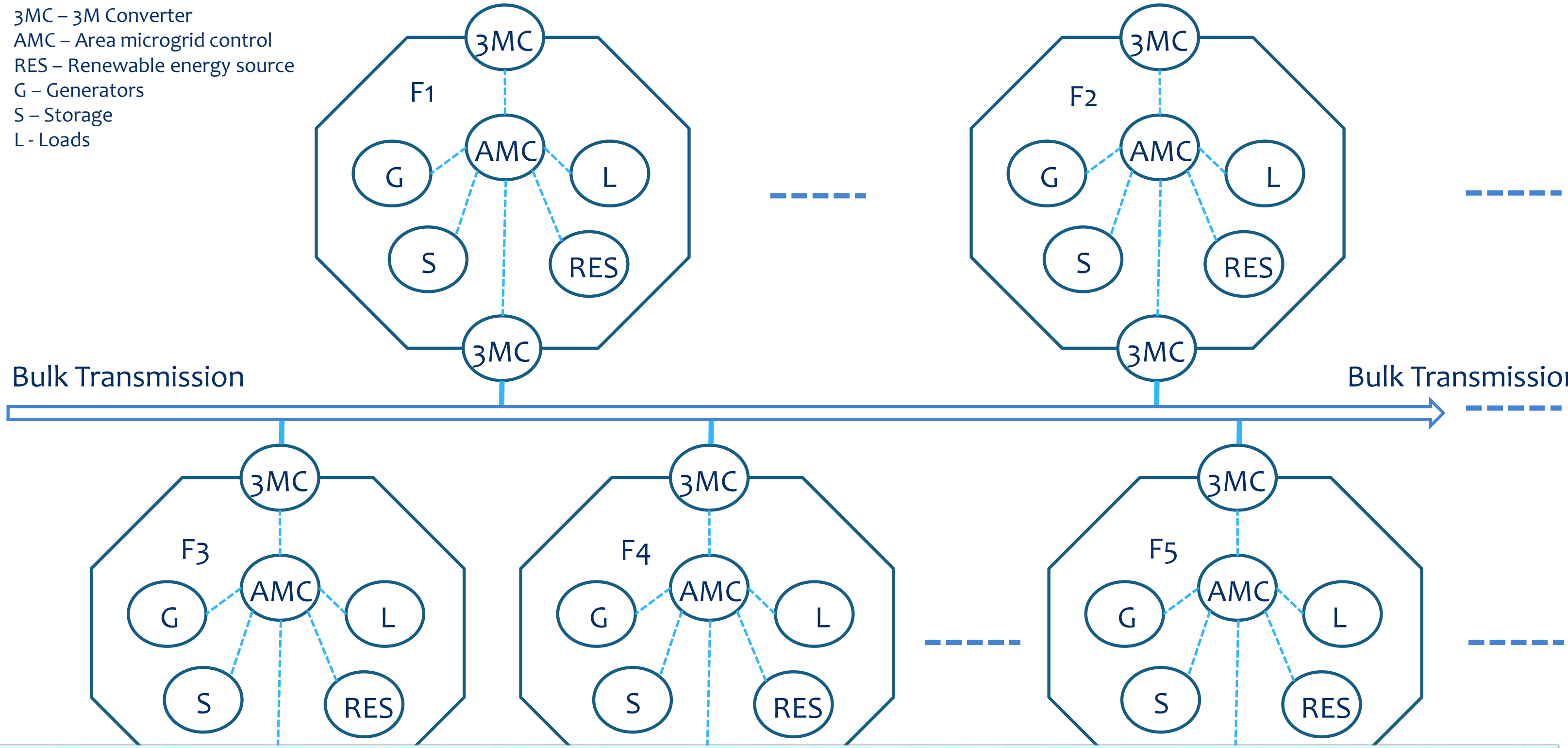


“A first real vision for future grids.”

D. Tan and Damir Novosel, “Six basic characteristics of modern power grid,” *Southern Power System Technology*, Vol. 11, No. 10, Oct., 2017, pp. (Invited)

Transactive Energy Enabled by SμGs

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



SμG: An enabler for cyber-physical and real-time transactive energy with bilateral P2P contract network and substitutability

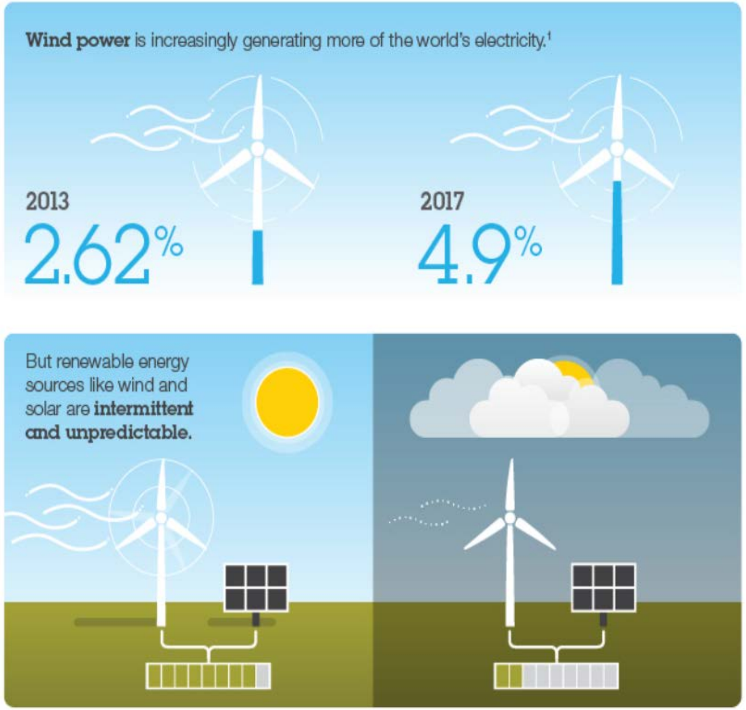
D. Tan and Damir Novosel, "Six basic characteristics of modern power grid," *Southern Power System Technology*, Vol. 11, No. 10, Oct., 2017, pp. 1-8 (Invited)

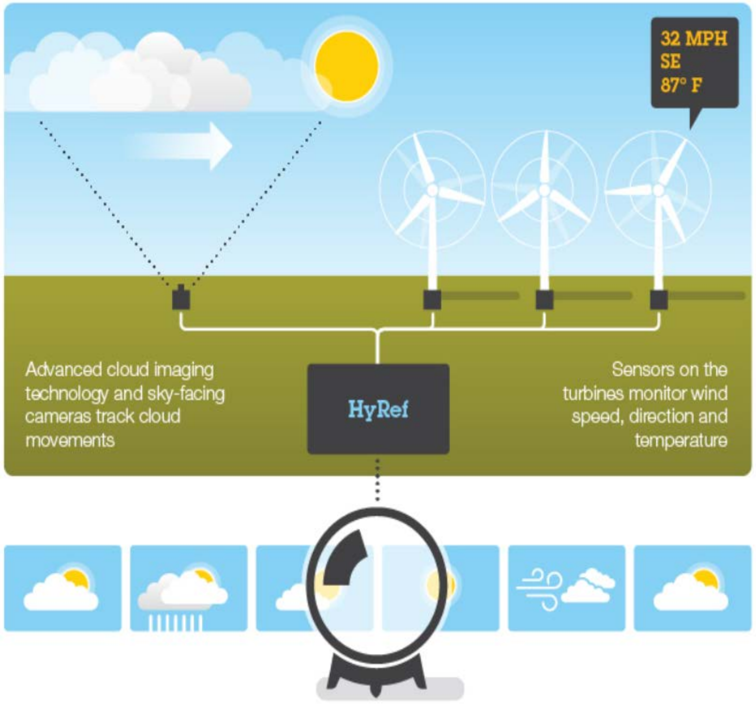
SusTech

Technology Advancement and Beyond

Technology Advancement and Beyond

* Data analytics by Deep Learning for renewable forecasting

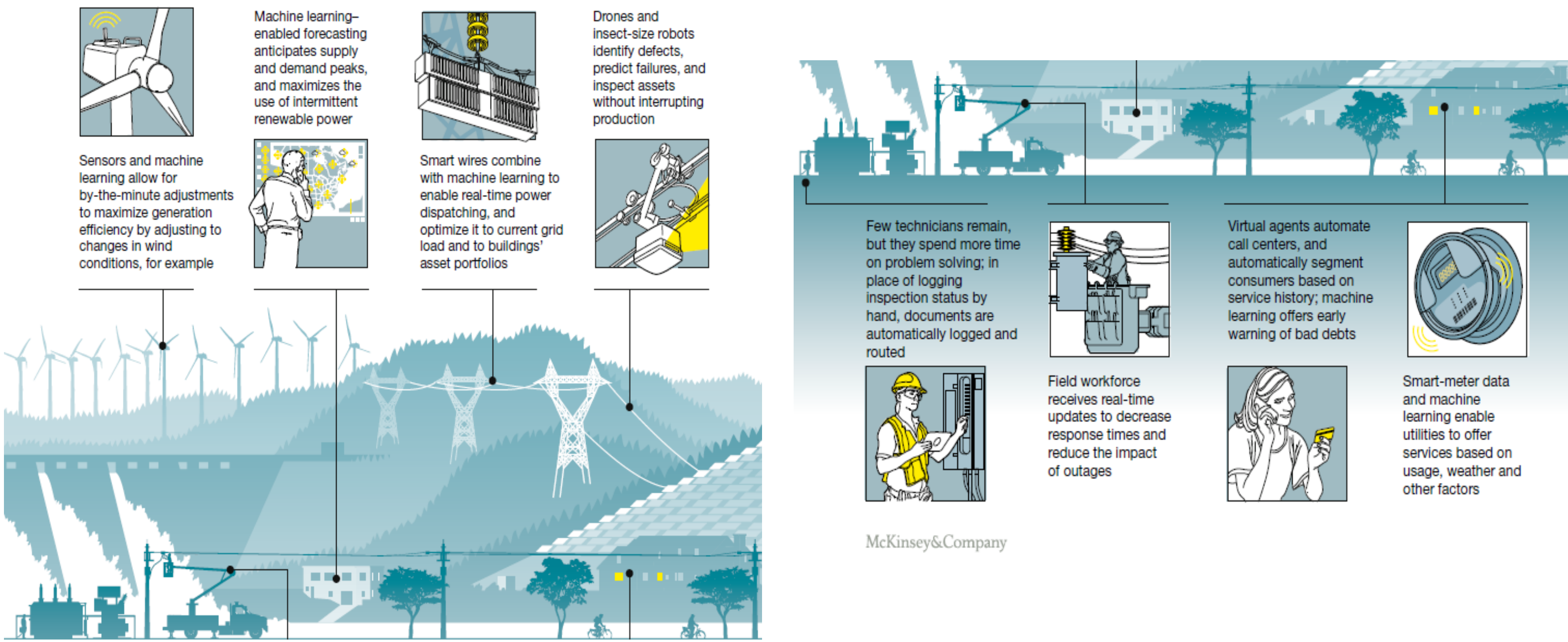




D. Tan, "Powering smart factories," *CATS Panel on Smart Manufacturing*, May, 2018 (Invited Keynote)
"IBM announces cloud-based enterprise-wide analytics for energy companies," Winder Power Engineering & Development, Feb., 2015

AI Enables Smarter Grid & Asset Cost Deferral

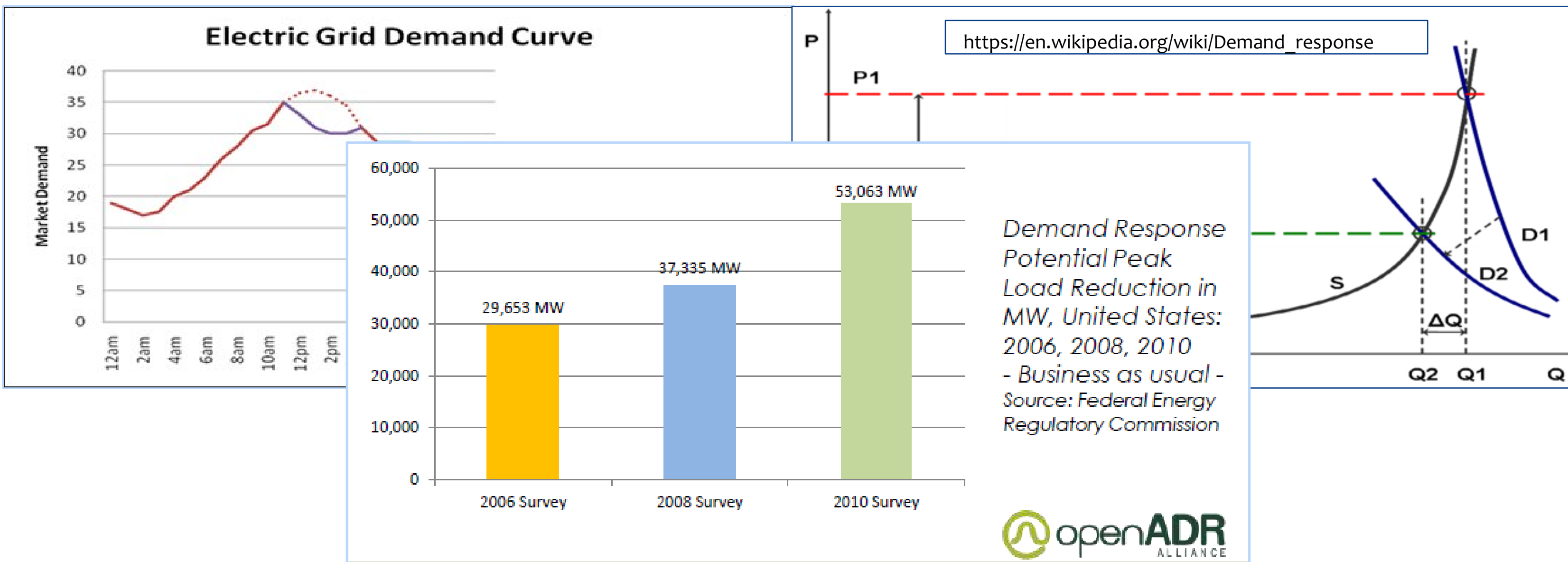
* Big data for asset management and prediction of equipment failure by Deep Learning (99% rate was reported)



D. Tan, "Powering smart factories," *CATS Panel on Smart Manufacturing*, May, 2018 (Invited Keynote)
"Artificial intelligence: the next digital frontier," *Discussion Paper, McKinsey Global Institute,* McKinsey & Company,2017

Technology Advancement and Beyond

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



D. Tan, "Structure microgrids: Invaluable assets for grid modernization," *IET APSCOM*, Nov, 2018 (Invited Opening Keynote)

"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

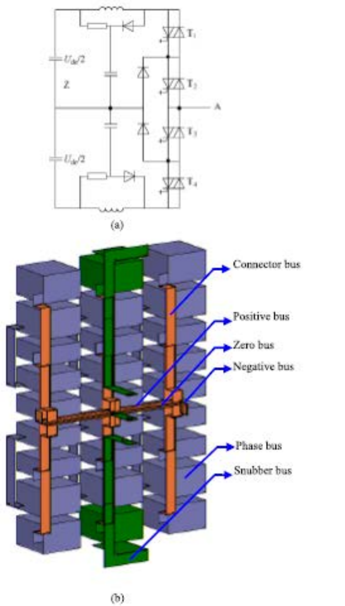


Fig. 2. Main-power-loop structure of one power electronics system [16]. (a) Circuit of the three-level NPC bridge. (b) Physical structure of the three-level NPC inverter.

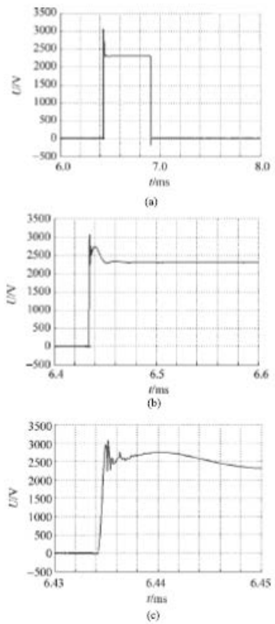


Fig. 3. Turn-off voltage across one IGCT measured at different t scales [19]. (a) 200 μs/div. (b) 20 μs/div. (c) 2 μs/div.

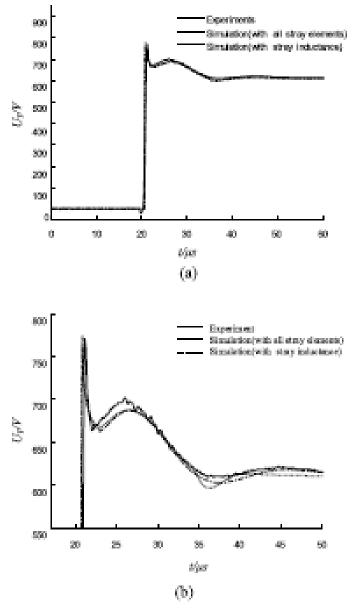


Fig. 7. Comparison of the turn-off voltage by experiments and simulations (a) Overall waveforms. (b) Zoomed-in waveforms.

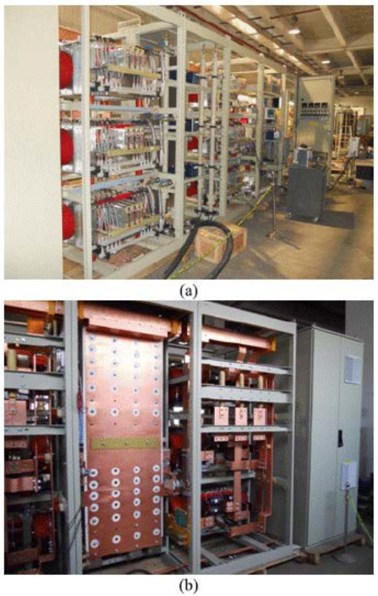


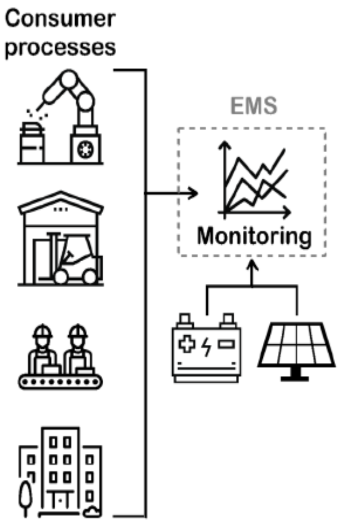
Fig. 21. Two kinds of bus-bar structures in electric traction converter. (a) Conductor-connected bus-bar structure. (b) Laminated bus-bar structure.

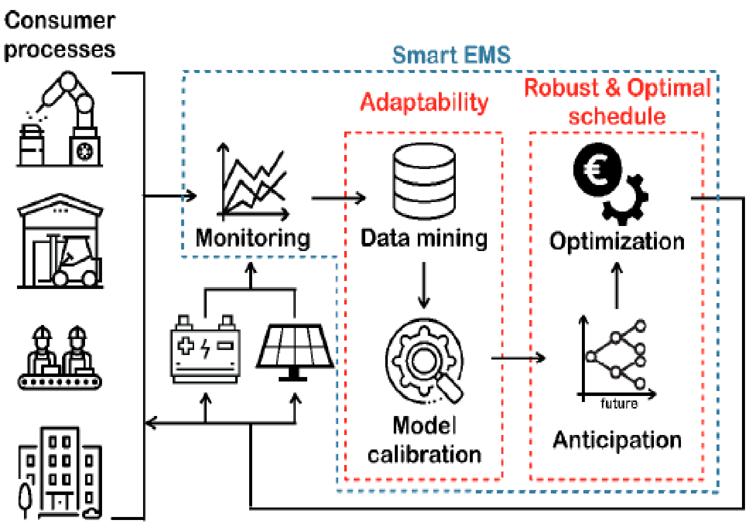
Z. Zhao, D. Tan and K. Li, "Transient Behaviors of Multiscale Megawatt Power Electronics Systems - Part I: Characteristics and Analysis,“ *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 1, March 2019, pp. 7-17

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

Industry 4.0, 5G, and ABC → eGrid → Large demand on new workforces

D. Tan, "Powering smart factories," *CATS Panel on Smart Manufacturing*, May, 2018 (Invited Keynote)
T. Hill, "Machine learning techniques in manufacturing: applications and caveats," Dell, 2017

TPE:
Technical Performance Excellence