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Introduction to Power Electronic Technologies in Distributed Energy Resources

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Tutorial Outline

- Transition in Power Systems and Need for Flexible Resources
- Introduction to Distributed Energy Resources (DERs) and IEEE Technology Roadmap of Power Electronics for DERs (ITRD)
- WBG Devices for DERs
- Power System Support Functions for DERs
    - Voltage Regulation
    - Frequency Regulation
    - Voltage Ride-Through
    - Frequency Ride-Through
- Conclusions

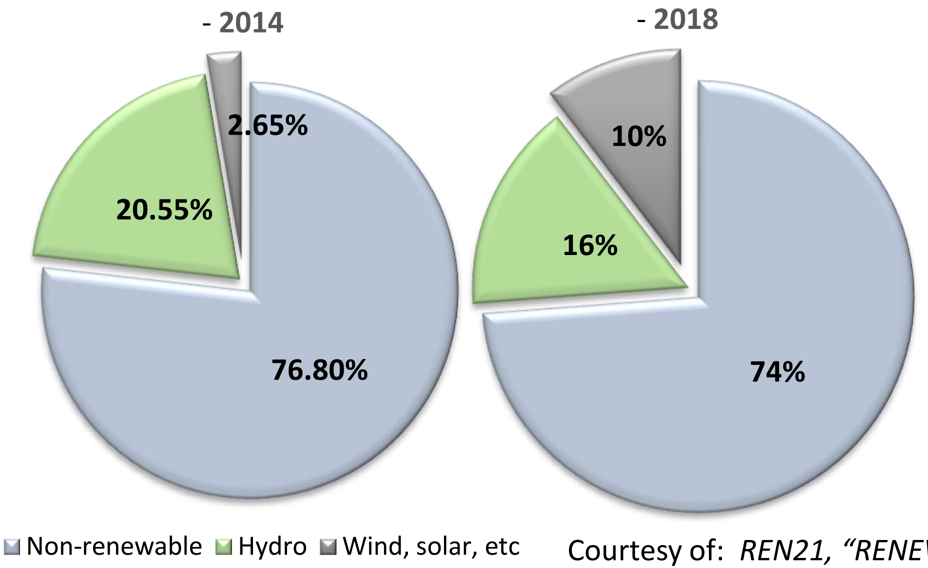
Power Systems in Transition

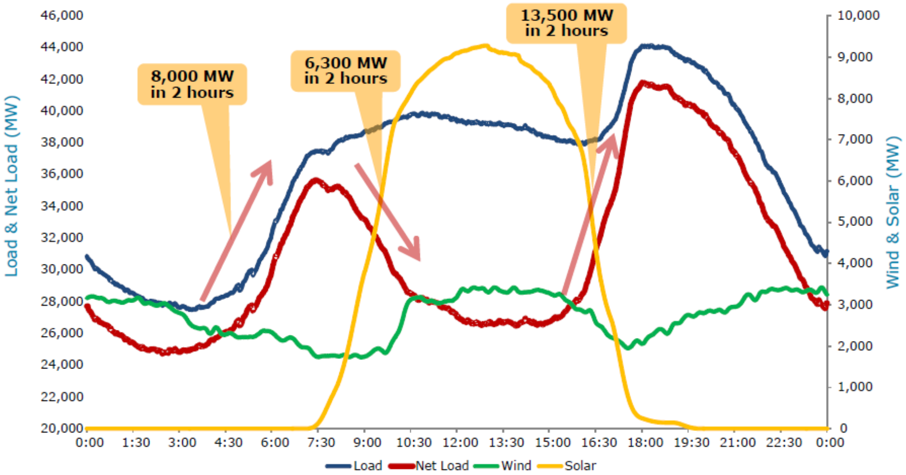
- Mega-trends in power systems
  - High carbon → Low carbon
  - Electrification → +Transportation
  - Energy → +Services

Canadian Parliament 1884

- Stability
- Security
- Reliability
- Affordability
- Resiliency
- Sustainability
- **Flexibility**

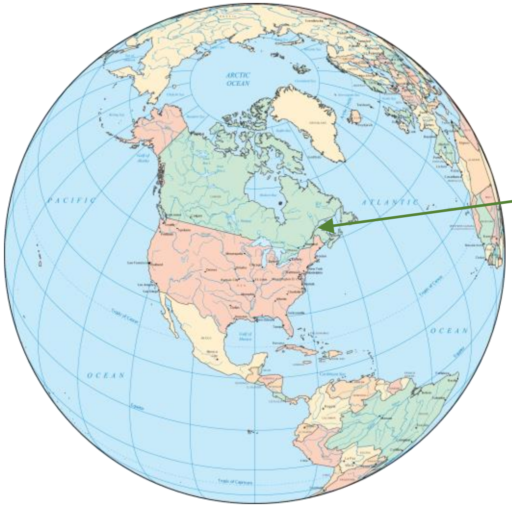
Global Renewable Energy Share

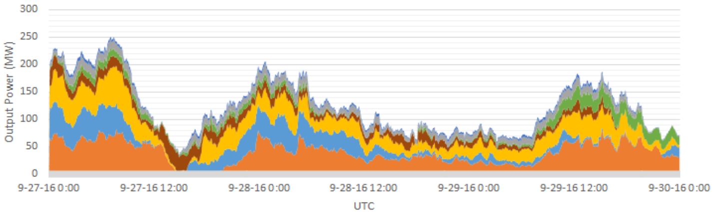




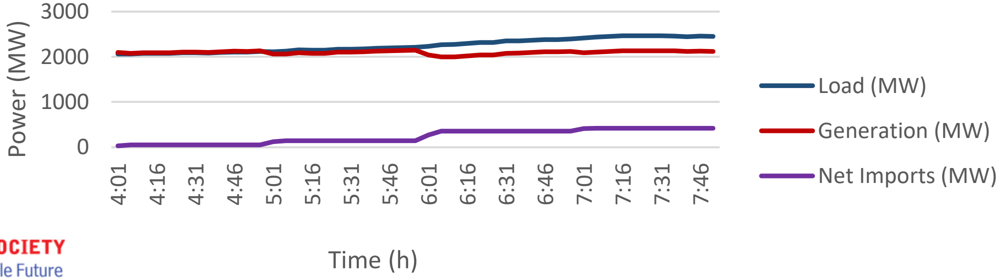
Courtesy of: *REN21, "RENEWABLES 2019 GLOBAL STATUS REPORT."*

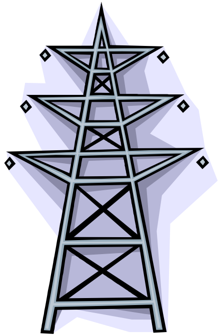
Power System Operation in the Context of an Interconnected Large Grid - NPCC





NB Power Load, Generation, and Import:





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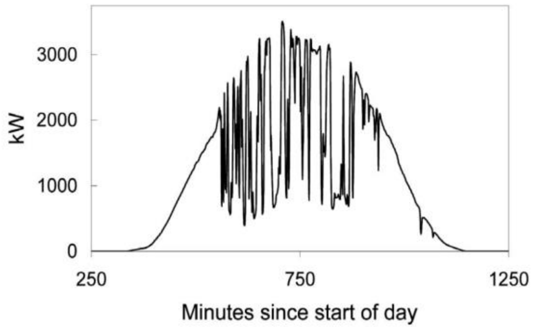
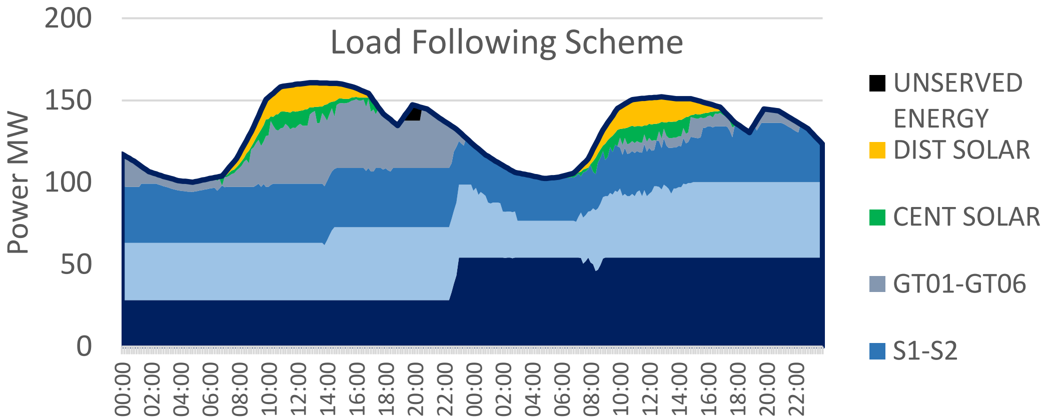
Power System Operation in an Isolated Small System - Barbados





- Fast ramping events from PV systems
- Existing generators cannot cope fast events
- Large deviation of frequency/voltage
  → shedding loads → adding batteries
- Wind integration: 10-20% more resources
- Need more flexible system resources – where can we find additional flexible resources ???

...from Distributed Energy Resources (DERs)

- General definition of DERs: (small & medium) energy resources connected to distribution networks for producing electricity, consuming electricity in a controlled manner, or improving energy efficiency
- Portfolios of DERs: distributed generation (DG) systems, electricity storage facilities (incl. EVs), managed loads (e.g. demand response, energy efficiency, directly controlled loads)

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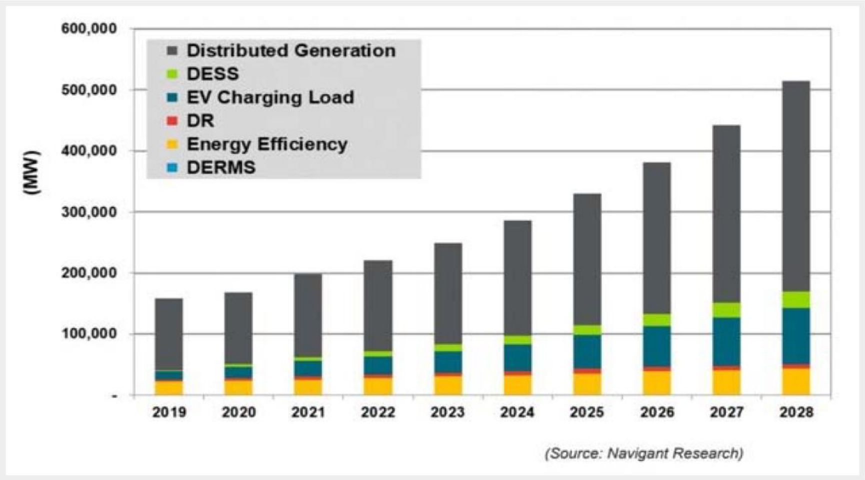
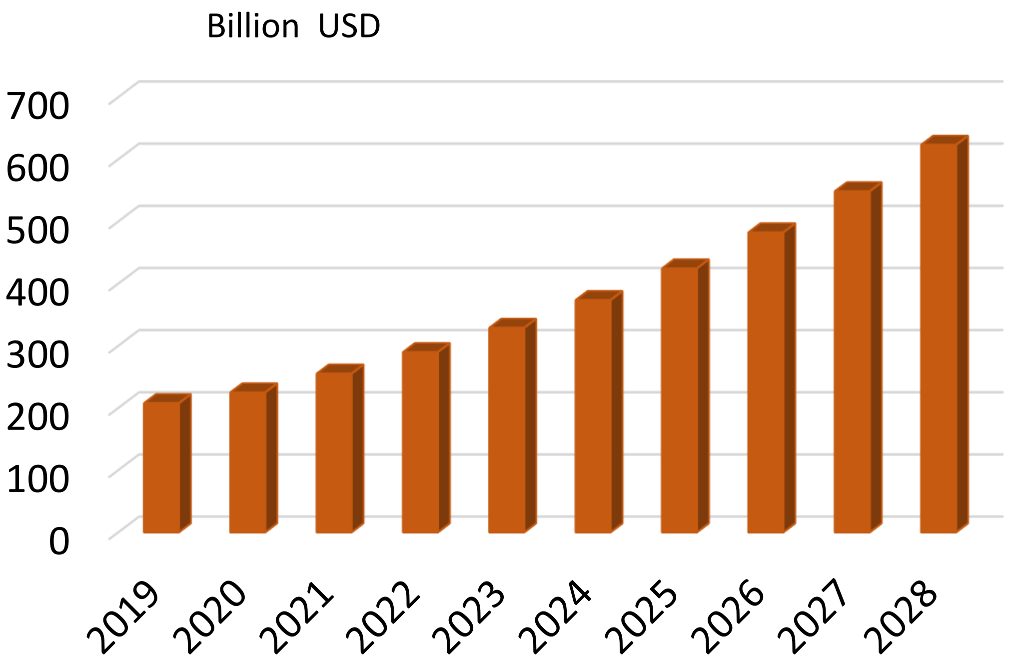
Global DER Market Growth – Huge Potential

Annual Installed Total Distributed Energy Resource Power Capacity by Technology, World Markets: 2019-2028



Courtesy of "Distributed Energy Generation Market Size Report, 2020-2027" by Grant View Research, and "Navigant Research Report", 2019.



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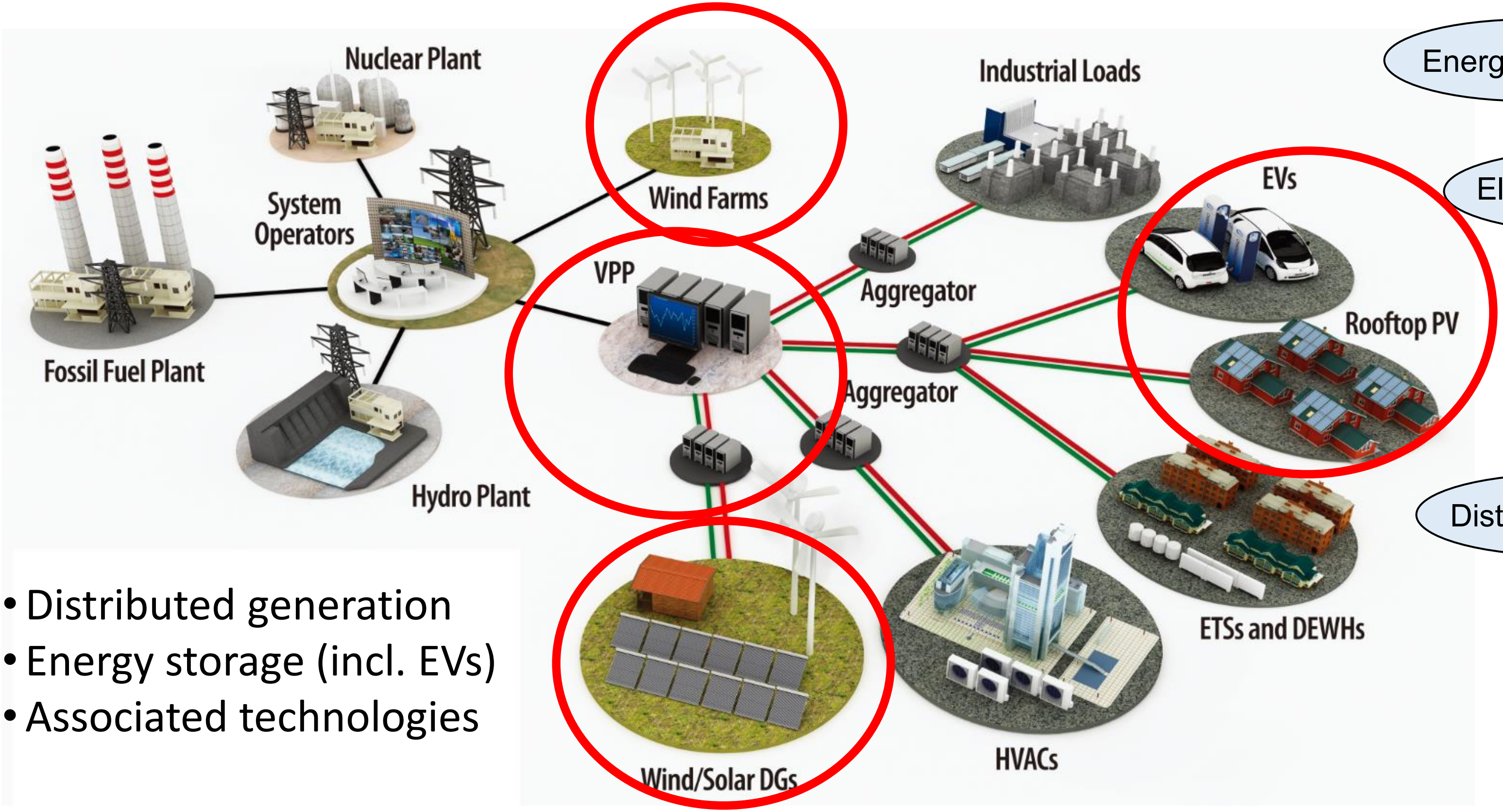
DERs to Support Power Systems

Resources / DERs	Generation Capacity	Voltage Regulation	Frequency Regulation	Load Following	Balancing	Reserve	Black Start
DG + Smart Inverters	☾	●	●	⊗	⊗	☾	⊗
Battery Storage & EVs	●	●	●	●	●	●	●
Demand Response	☾	⊗	⊗	⊗	●	●	⊗
Direct Load Control	☾	?	●	●	●	●	⊗
Indirect Load Control	⊗	⊗	⊗	☾	☾	⊗	⊗
Energy Efficiency	☾	⊗	⊗	⊗	⊗	⊗	⊗

Power Electronics Based DERs as Integral Part of Power Systems



Energy Storage

Electric Vehicles

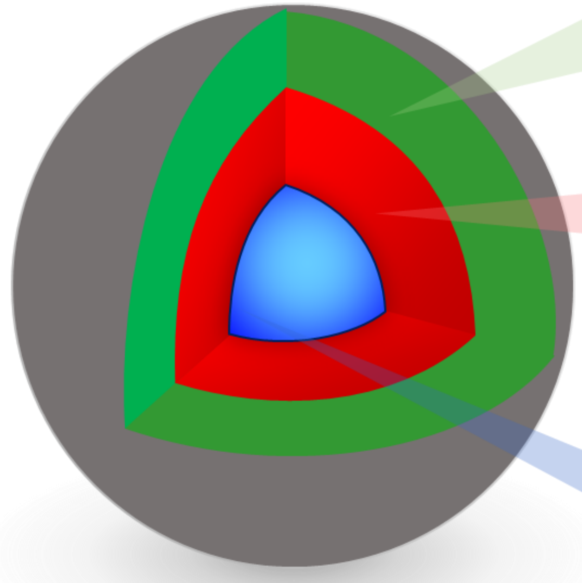
Distributed Gen.

- Distributed generation
- Energy storage (incl. EVs)
- Associated technologies

Evolution of Standards – DER Interconnection Requirements

	1990's	2000's	2010's ~ 2020
Evolution of DER Standards	IEEE 519-1992 ANSI C84.1-1995 UL 1741-1999	IEEE 929-2000 IEEE 1547-2003 UL 1741-2010 CSA C22.2 No.107.1-01	IEEE 1547a-2014 & 2018 & 2020; IEEE 2030.2 UL 1741 SA & CA Rule 21 & HI Rule 14H (U.S.) CSA C22.3 No.9 (Canada) EN 50438:2013 & EN 50549:2019 (Europe)
DER Interconnection Requirements	Compliance with power system specifications: *Voltage range* *Frequency range* *Synchronization* *THD (harmonics)*	+ Safety & protection: *Not to regulate voltage* *Anti-islanding* *Narrow power factor* *Dis- and re-connection* + Power quality: *THD&TDD (harmonics)* *Flicker* *DC injection*	+ System support functions: *V & f regulation* *V & f ride-through* *Power curtailment* *Ramp rate* *Wider power factor* *Grid forming* *Black start*

Evolution of DER Inverters - Past, Present and Future



System Support Functions

- Active Power Control
  - * Frequency Regulation
  - * Ramp Rate Adjustment
- Reactive Power Control
  - * Voltage Regulation
  - * Power Factor Adjustment
- Black Start
- Harmonic Compensation

Local Control Functions

- Monitoring & Control
- Resource Optimiz. (MPPT)
- Volt/Freq Ride Through
- Anti-Islanding/Protection
- Grid Synchronization

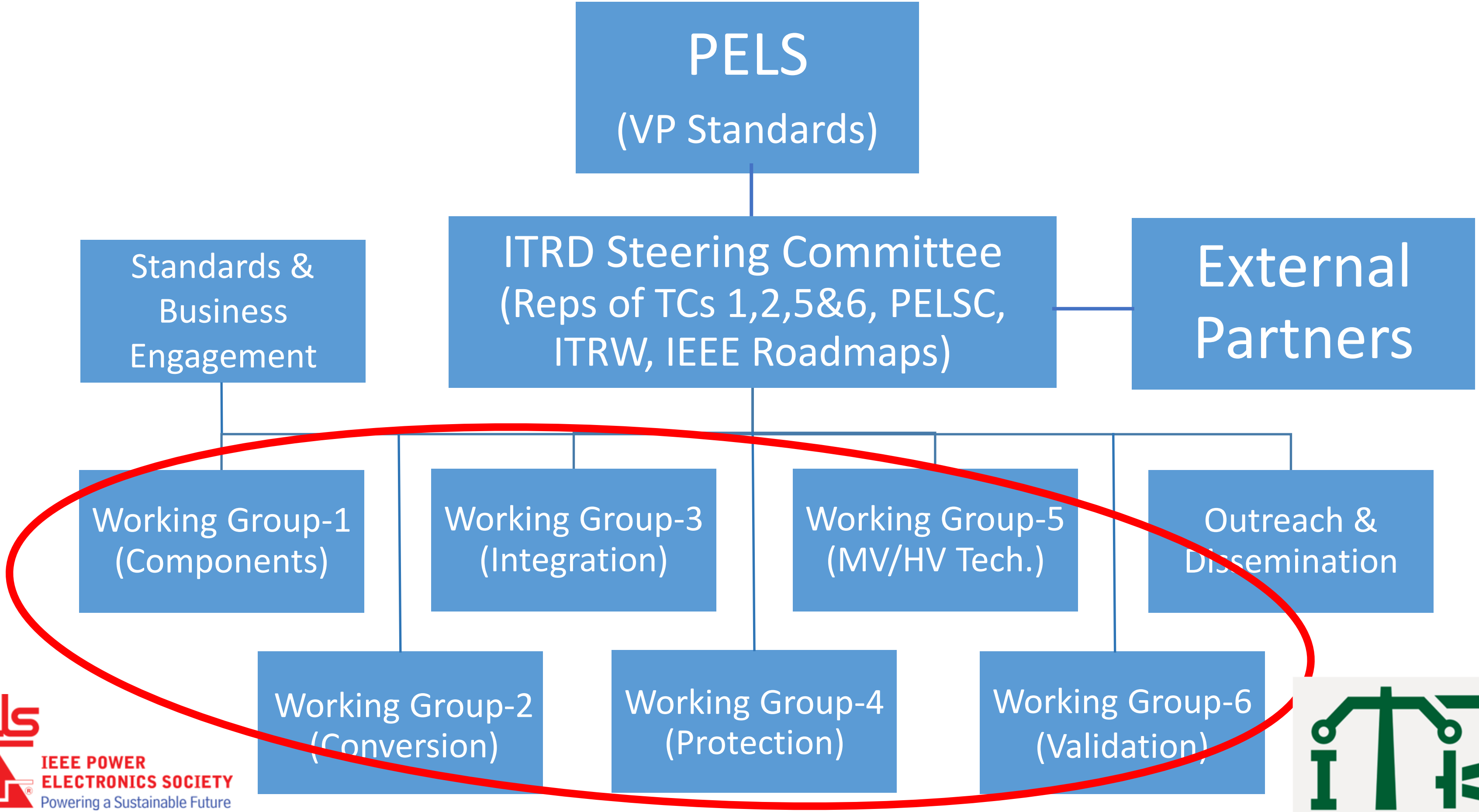
Basic Functions

- Power Conversion (PWM)
- Fault Protection
- V, I, ϕ Controls

IEEE Technology Roadmap of Power Electronics for Distributed Energy Resources

- Technology roadmaps – consensus documents in projecting long-term and strategic technological developments and associated solutions of a field
- ITRD – One of the IEEE Roadmaps
  - An initiative (project) of the IEEE Power Electronics Society (PELS) of 3 years (2020-22)
  - Focusing on technologies of Power Electronics for Distributed Energy Resources (DERs)
  - ITRD Committee with over 110 members and 6 working groups (and growing)
- ITRD outcomes - White Papers and associated publications to capture the (projected) long term technological developments and applications, as reference and guidance to engineers in power electronics (+ identifying opportunities for new standards)

ITRD Organizational Structure



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Interested in Contributing to ITRD?

- Sign-up to the ITRD Committee and join WGs/Committees (a simple form):

☞https://app.smartsheet.com/b/form/a5fe3dfc0d5c47e688d9ce369bcfd788

☞https://www.ieee-pels.org/programs-projects

The International Technology Roadmap for Wide Bandgap Power Semiconductors (ITRW) ›

Empower a Billion Lives

Cyber-Physical Security Initiative

IEEE International Technology Roadmap of Power Electronics for Distributed Energy Resources (ITRD)

IEEE International Technology Roadmap of Power Electronics for Distributed Energy Resources (ITRD)

Distributed energy resources are rapidly growing in grids with power electronics technologies enabling additional functionalities and value-added services. The Power Electronics Society has launched the project to develop the IEEE International Technology Roadmap of Power Electronics for Distributed Energy Resources (ITRD). This International Roadmap will form working groups in distributed energy resources, coordinate with the IEEE Roadmapping Project, IEEE Technical Societies, and other stakeholders to produce a roadmap that will provide reference and guidance to engineers in power electronics by identifying the future research, technology developments, and applications of distributed energy resources. The ITRD is dedicated to providing a reliable and comprehensive roadmap serving academia, industry, national labs, and research organizations.

The PELS ITRD group is currently calling for stakeholders from industry (manufacturers, technology providers, consultants, and utilities), national labs and research institutions, academia/students and professional associations to work together to provide guidance and foresight for distributed energy resources and begin the development of working groups to produce a background whitepaper in this focus area.

To become engaged with this project please submit your information **HERE**

- Contract:

Jane Celusak <j.celusak@ieee.org> Project Manager

or Liuchen Chang <LChang@unb.ca>

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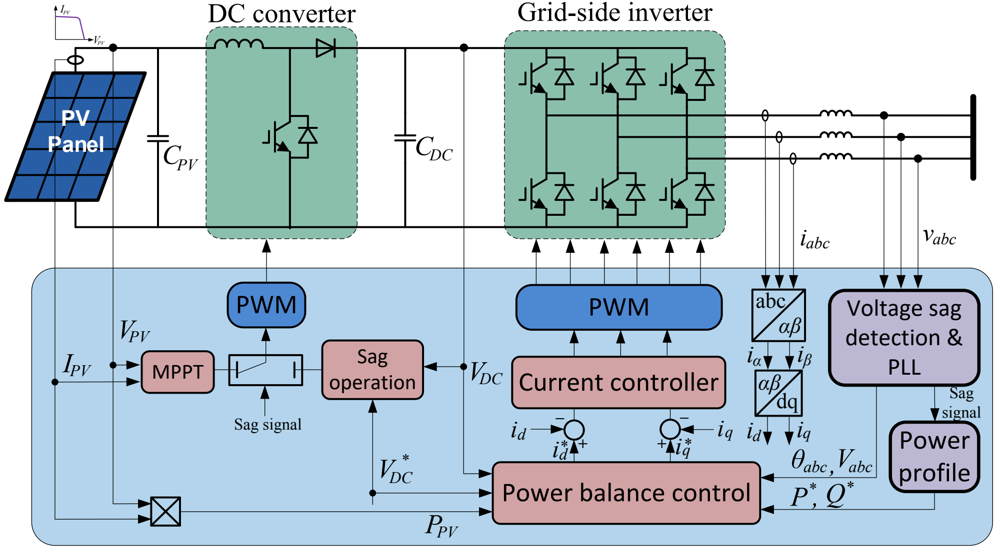
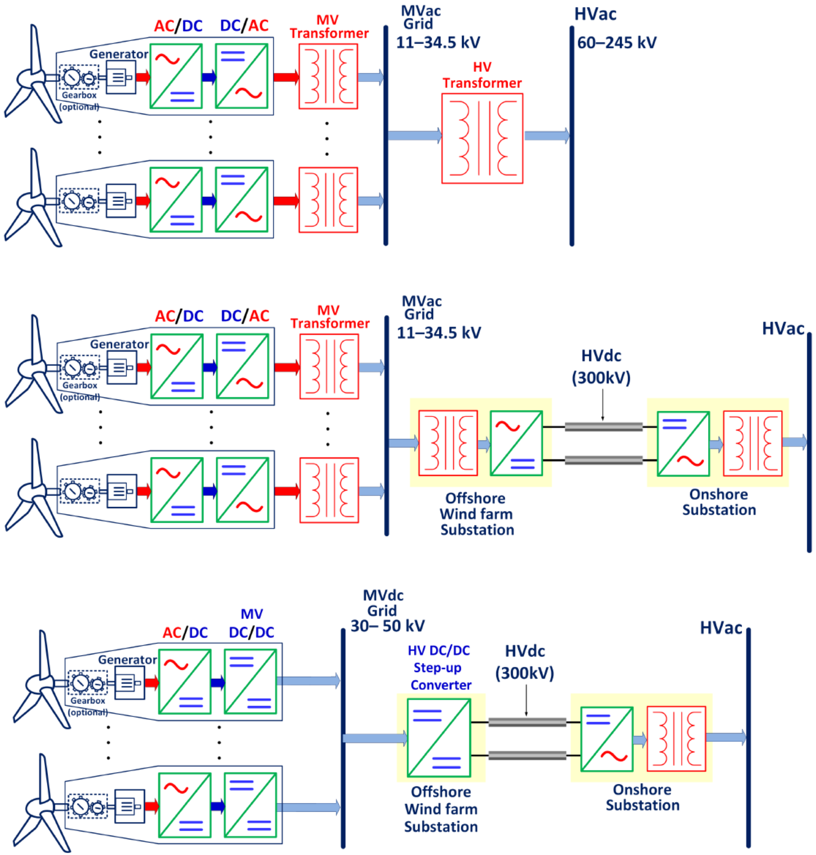
DER Power Converters – Conversion, Interface & Control





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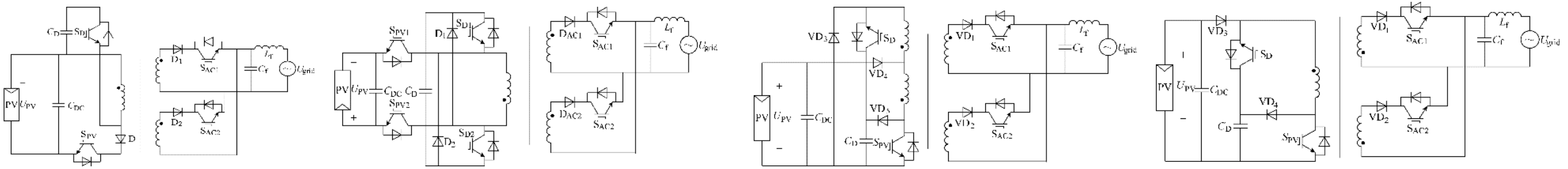
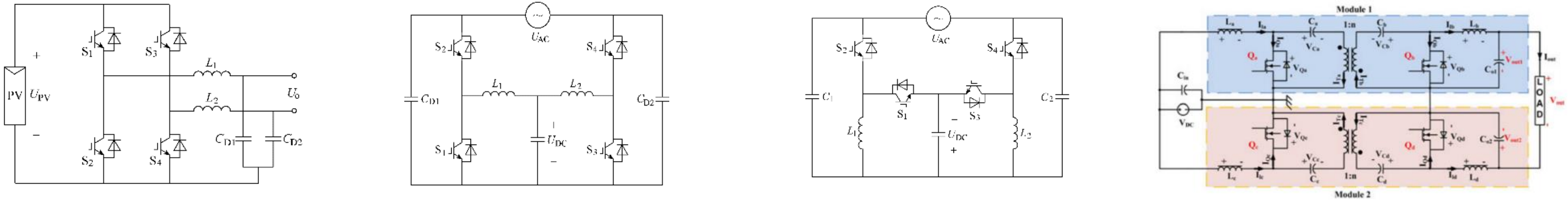
… So Many Topologies and Structures

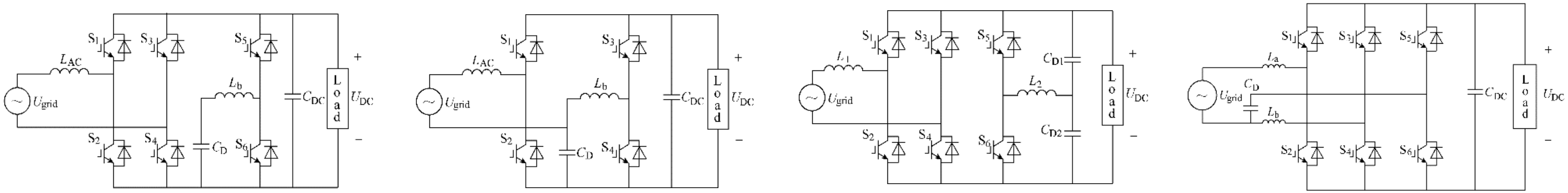
- Flyback-type single-phase power decoupling topologies



- Differential-type single-phase power decoupling topologies



- Bridge-type single-phase power decoupling topologies



DER Power Converter Advancements

- Performance-driven
- Function-driven

	(Currently) Prevailing Technologies	Emerging Technologies
Topologies	Two-lever Inductor-based Line frequency filters Low(er) frequency isolation Silicon devices	Multi-level Capacitor-based Active filters High(er) frequency isolation Wide-Bandgap devices
Frequency	10 kHz to 100 kHz	100 kHz to 10 MHz
Power Flow	Unidirectional	Four quadrant
Power Factor	Unity (narrow) power factor	Wide range compensation
Cooling	Forced air	Advanced thermal management
Integration	Panel mounted	Planar, modular, multicell

WBG Devices

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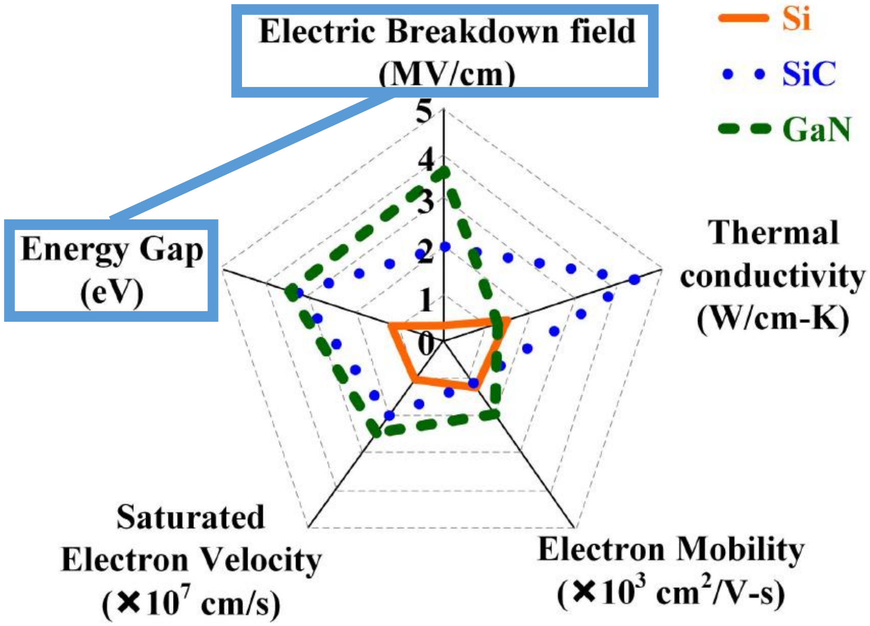
SiC and GaN Power Devices Allow for More Efficient and Novel Power Electronics

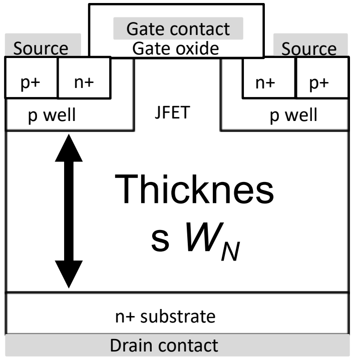


Device Thickness

$$W_N = \left(\frac{3}{2}\right)\left(\frac{V_B}{E_C}\right)$$

Device Resistance

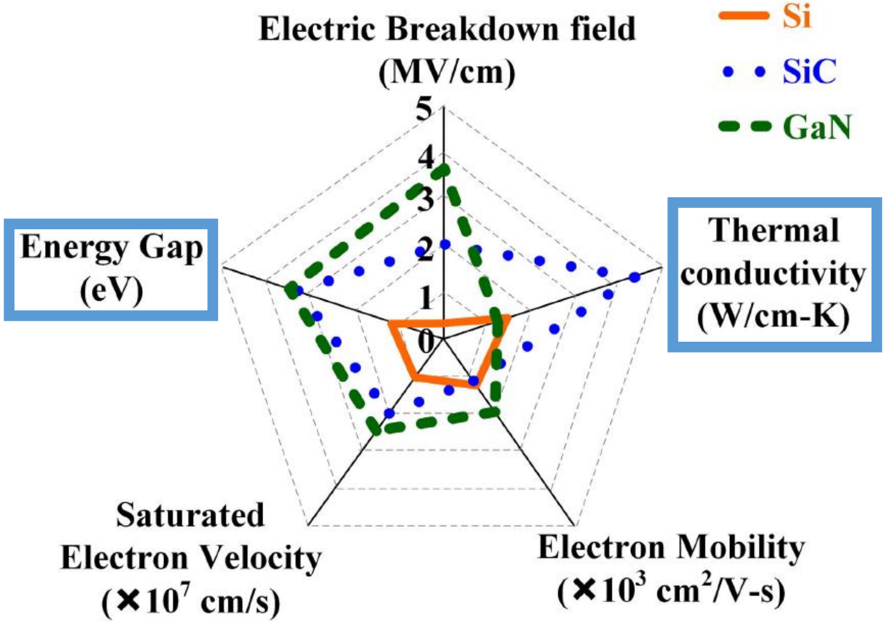
$$R_{ON,SP} = \left(\frac{3}{2}\right)^3 \frac{V_B^2}{\mu_N \varepsilon_S E_C^3}$$



Large Bandgap and Critical Electric Field allow for high voltage devices with thinner layers: lower resistance and associated conduction losses

Thinner layer and low specific on-resistance allow for smaller form factor that reduces capacitance: higher frequency operation, reduced size passives

Large Bandgap and Thermal Conductivity Enable Robust High Temperature Operation with Reduced Cooling

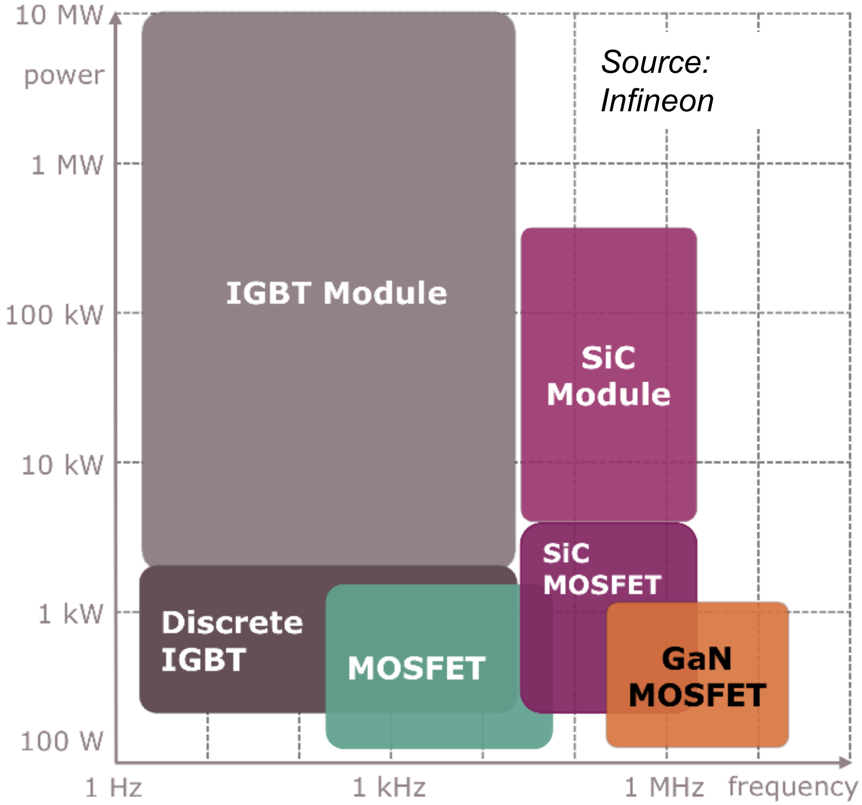


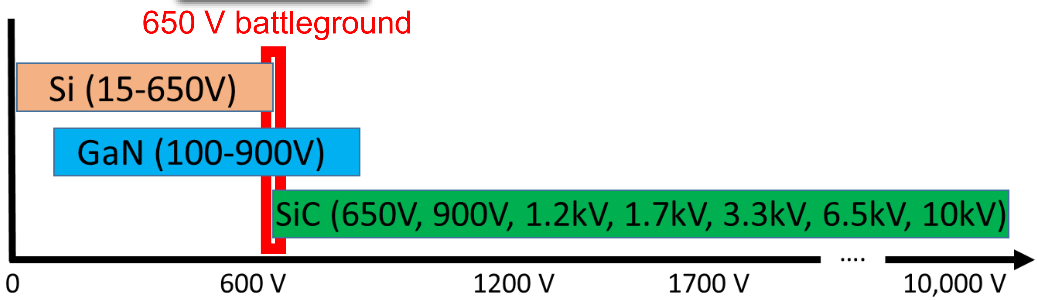
SiC/GaN devices enable **more efficient, lighter, smaller form factor** power electronics operating at high frequencies, and at elevated temperatures with reduced cooling.

Large Bandgap results in relatively low intrinsic carrier concentration: low leakage and robust high temperature operation

Large Thermal Conductivity: high power operation with reduced cooling requirements

Selection of Si, SiC, or GaN is Application Specific and Driven by Voltage, Current, Frequency, Efficiency, and Cost Considerations



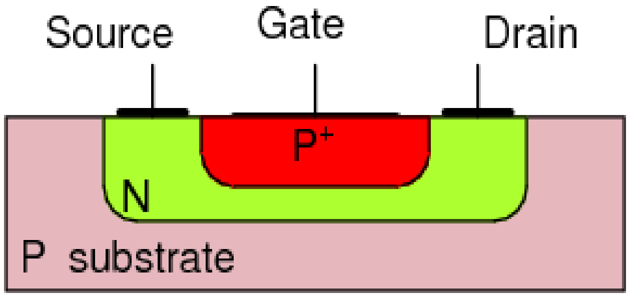


Si, GaN, and SiC all compete in the lucrative 650 V range:

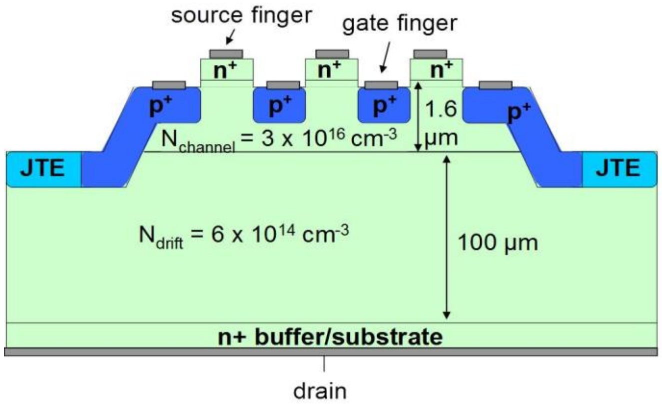
- *Si* is reliable, rugged, cheap, and capable of high current
- *GaN* offers efficient high-frequency operation at reasonable cost
- *SiC* is efficient and operates at high current and frequency

SiC Power Devices are Ideally Suited for High-power DER System Applications (35 kV, 1 MW)

High-Voltage (+900 V) SiC Power Devices are of Vertical Configuration



Lateral devices have system integration advantages but necessitate impractically large areas for high blocking voltage capability



Vertical device drift layer thickness can be tailored for high blocking voltage with no corresponding lateral device area increase

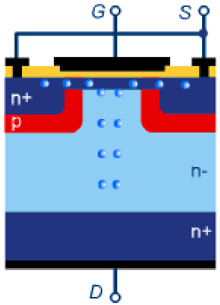
- Lateral devices with high blocking voltage capability necessitate large areas because of the required large drift length, defined as the gate to drain spacing. This increases cell-pitch and R_{on}.
- Beyond 900 V rating, vertical configuration is practical in SiC and GaN devices. Blocking voltage capability is determined by the thickness and doping of the vertical drift layer.

Voltage and Switching Frequency Requirements Drive Unipolar vs. Bipolar Device Selection

SiC: Unipolar devices to 10 kV, Bipolar Devices practical > 10 kV

Current flow in **unipolar** devices is due to only one type of charge carriers (electrons or holes) majority carriers. Unipolar devices have higher conduction losses and lower switching losses.

MOSFET

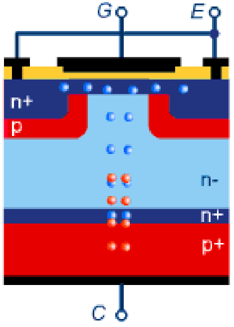


- During conduction, only one type of charge carrier flows: higher on-state resistance.
- Majority only conduction enables fast switching: lower switching losses

$$R_{on\text{-}sp} = \frac{W_D}{q\, N_D\, \mu_n}$$

Current flow in **bipolar** devices is due to both types of charge carriers, electrons and holes. Bipolar devices have *lower conduction losses and higher switching losses.

IGBT

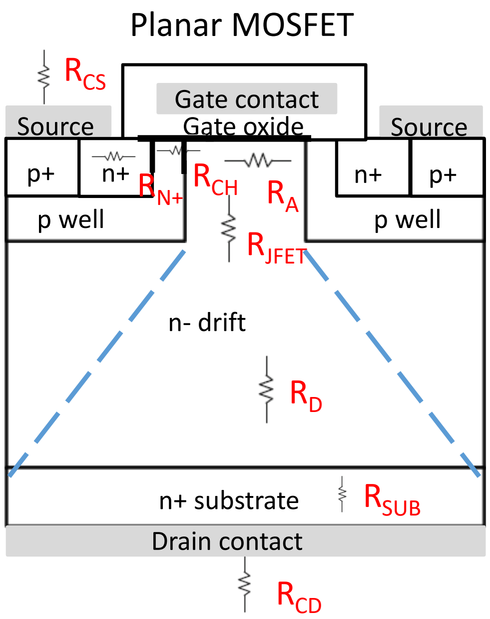


$$R_{on-sp} = \frac{W_{PT}}{q(\mu_n N_D + \mu_p N_P)}$$

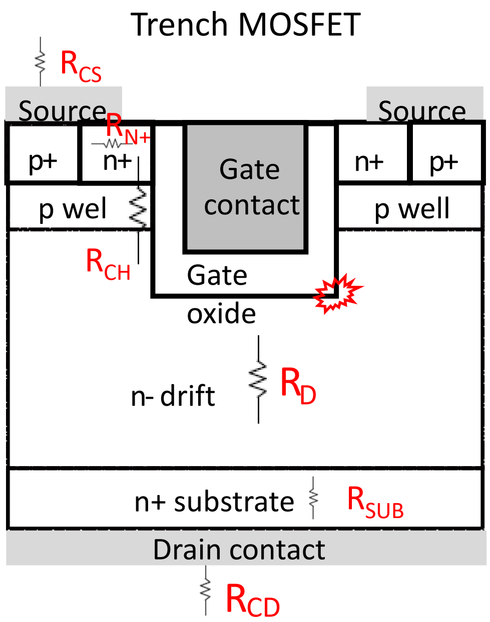
- During conduction, holes from the collector *p*+ region are injected into the *n*- region: the accumulated charge reduces on-state resistance.
- Bipolar conduction results in slower switching as minority carriers also need to be swept during transition: higher switching losses

*The knee voltage of bipolar conduction contributes to bipolar device loss at low voltages

650-1700 V SiC MOSFETs are Commercially Available in Planar and Trench Configurations and are Dominant in SiC-based Systems



$R_{ON,D} = R_{CS} + R_{N+} + R_{CH} + \mathbf{R_A + R_{JFET}} + R_D + R_{SUB} + R_{CD}$



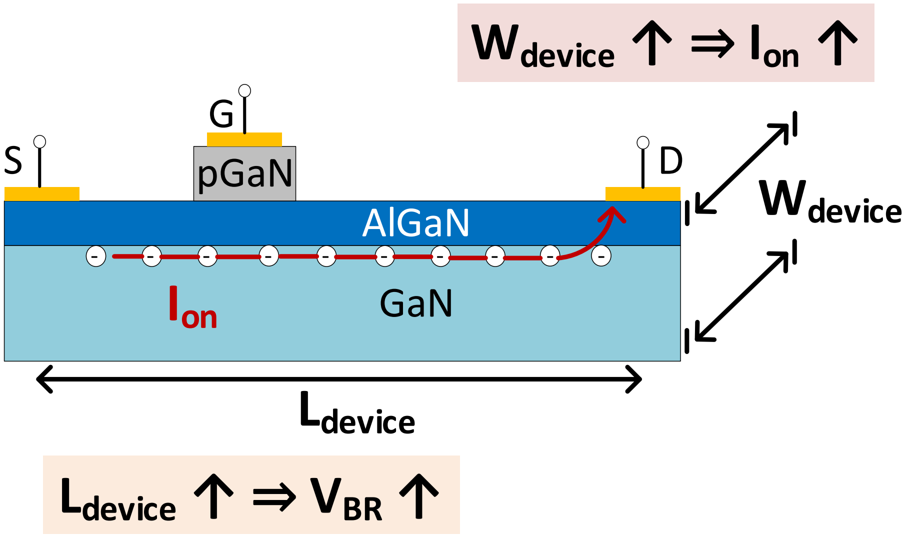
$R_{ON,U} = R_{CS} + R_{N+} + R_{CH} + R_D + R_{SUB} + R_{CD}$

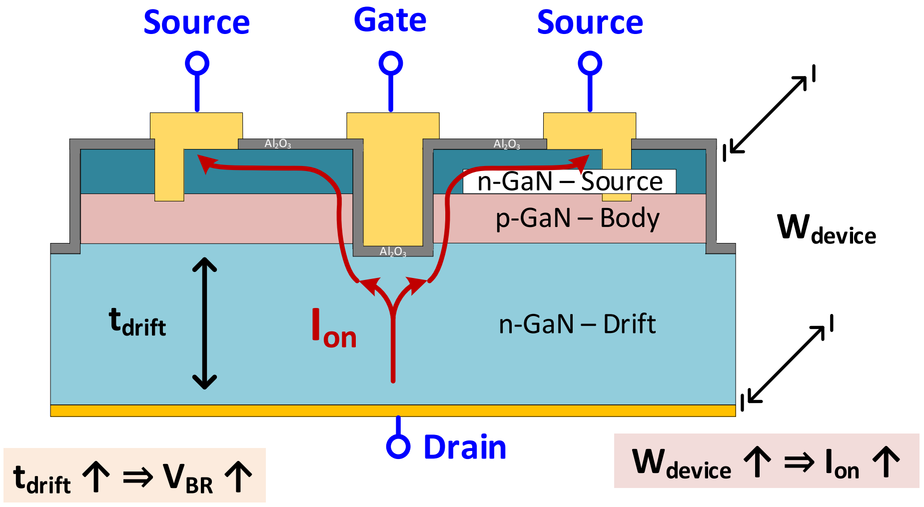
- 600-1700 V SiC MOSFETs commercially available from several vendors, inserted in systems (EV, PV, Fast chargers)
- Trench MOSFETs are capable of lower pitch and higher mobility but premature gate-oxide breakdown is an issue
- 3.3 kV, 6.5 kV, and 10 kV MOSFETs available as engineering samples; 15 kV IGBTs demonstrated
- SiC high-voltage modules and gate drives commercially available to 1.7 kV; demonstrated to 15 kV

GaN Device Architectures

Lower voltage (< 1 kV), more mature (e.g., HEMT)

Higher voltage (≥ 1.2 kV), in development (e.g., MOSFET) – similar to SiC device structure



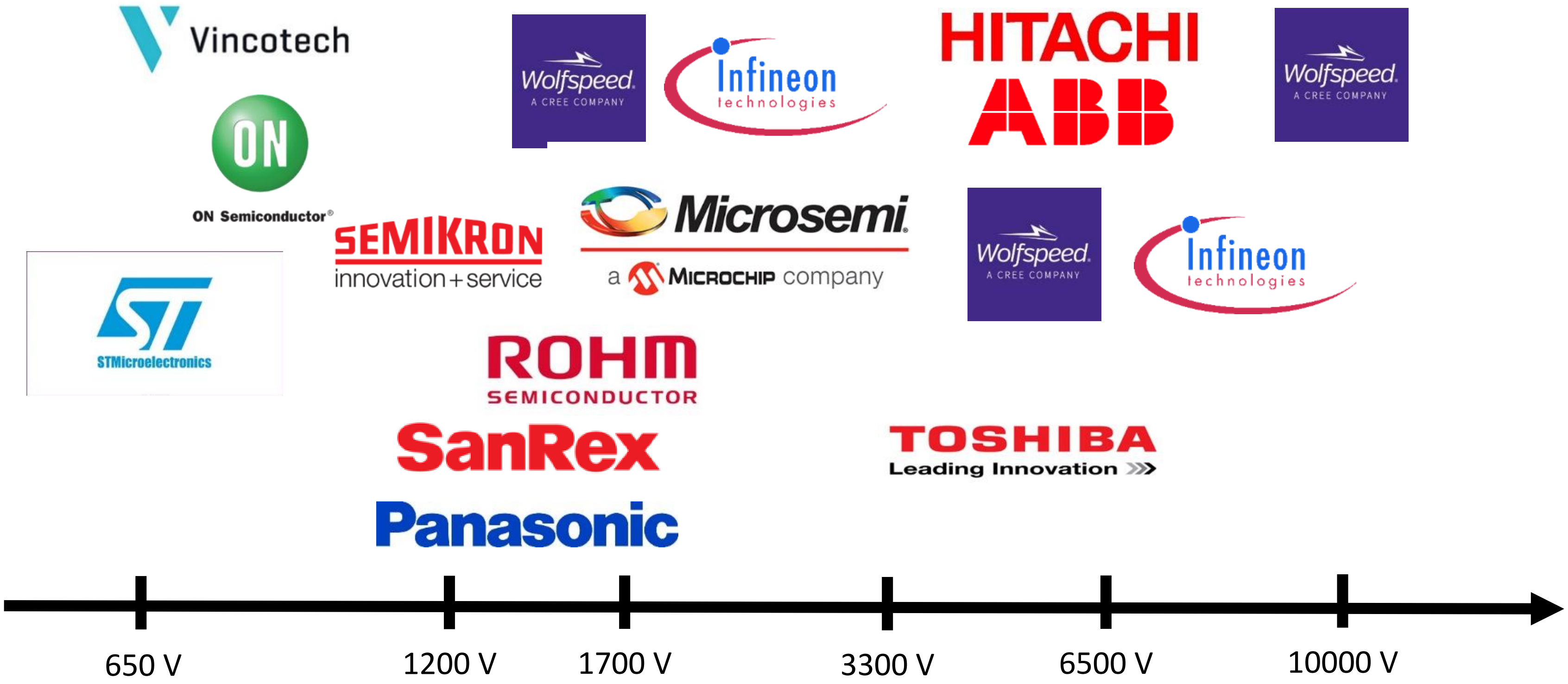


Lateral Scaling Rules

Vertical Scaling Rules

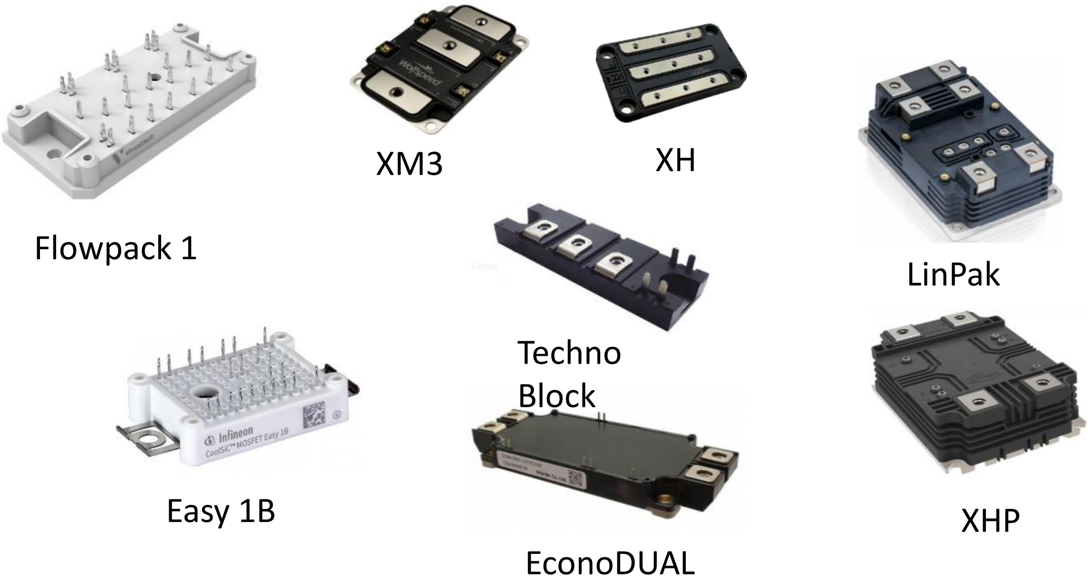
Power Modules for DER Conversion- Choices in the Market

Major SiC Module Players and Product Span



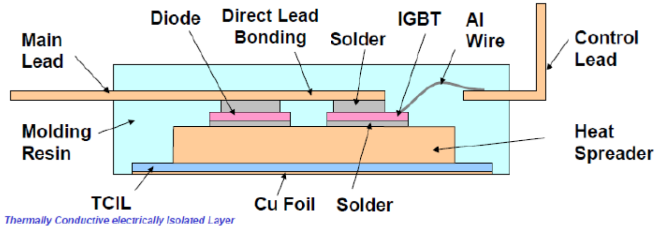
Power Modules for DER Conversion- Choices in the Market

Typical SiC Modules from the Market

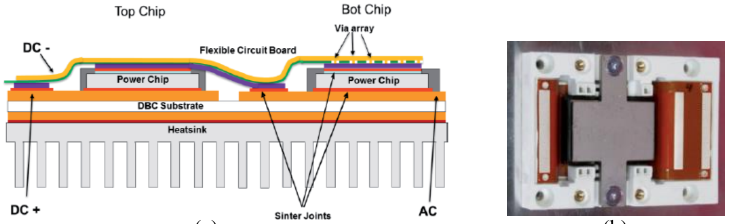


- Most of the modules are still based on wire-bonded structure
- Loop inductance varies from 9 nH – 20 nH
- Improved package structure with better parasitic control is needed for WBG operation

Power Modules for DER Conversion-Advanced Concepts

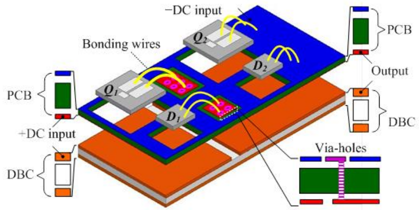


Direct-Lead-Bonding (DLB)

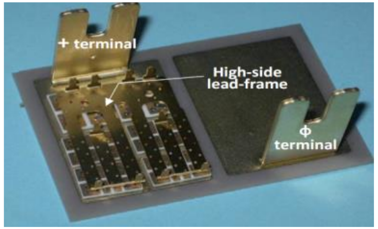


(a) (b)

SKiN technology used in SiC power module: (a) Modified SKiN structure, (b) 1200V/400A power module (1 nH loop inductance)-Semikron

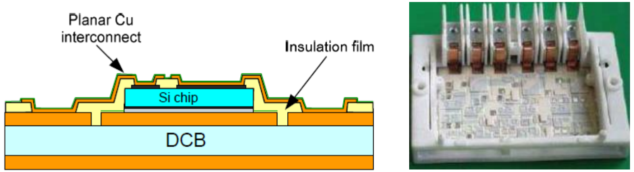


Hybrid Packaged SiC Module, C. Chen / F. Luo, HUST/Uark, 2017



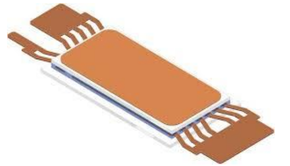
Full SiC DLB module by Silicon Power Corporation

STMicroelectronics SiC module for Tesla Model 3



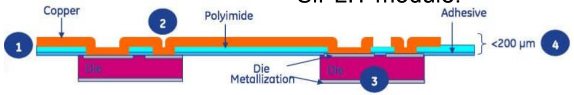
(a) (b)

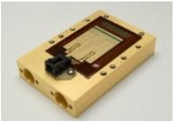
SiPLIT technology: (a) cross-section of power module, (b) SiPLIT module.



Delphi 3D packaged Viper module

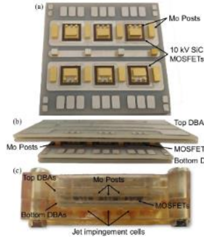
- Wireless package
- Significantly reduction of power loop inductance (1- 5 nH)
- Potential for double-side cooling



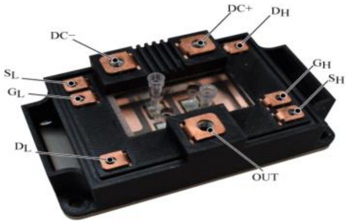


PWB like planar inter-connection

GE Power Overlay (POL)



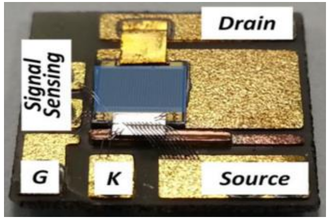
10 kV Wireless SiC Module from Virginia Tech.



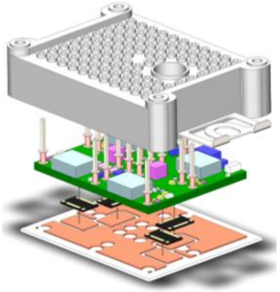
10 kV SiC Module from Aalborg Univ.

Power Modules for DER Conversion-GaN Modules

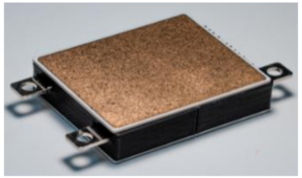
ViSIC 1.2 kV GaN module



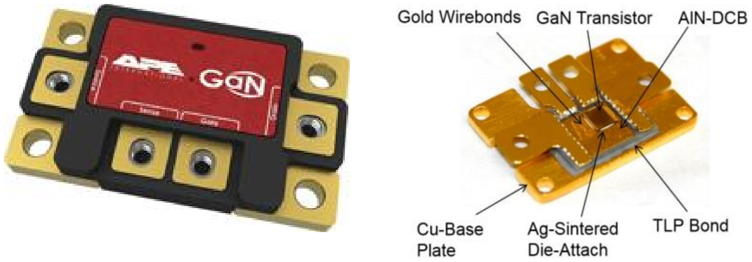
PQFN GaN package from Virginia Tech.



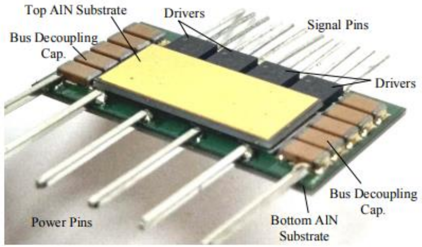
GaN module using Easy 1B from Aalborg Univ.



3D Integrated Double-Side-cooled GaN module from Univ. Arkansas (A. Emon)



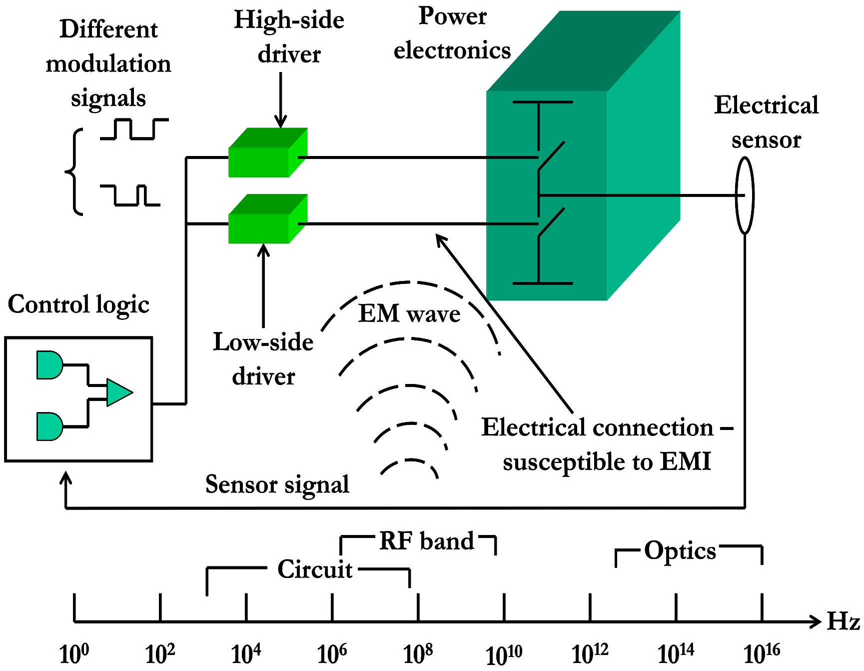
CREE high temperature GaN package

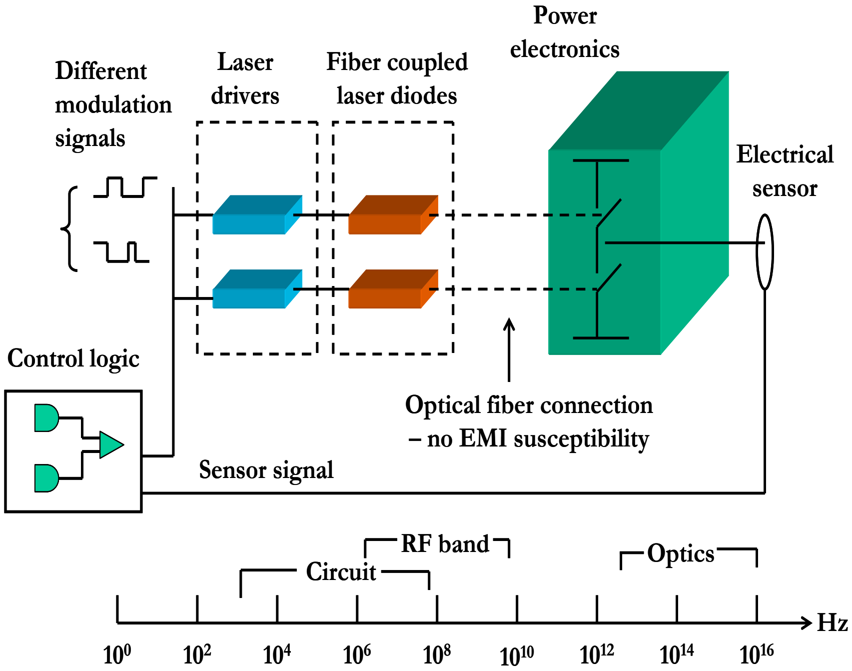


GaN Module with Integrated Gate drive from Xi'an Jiaotong Univ.

- GaN Devices offer even higher dV/dt and switching frequency
- Parasitic control is critical for GaN modules- wireless designs are promoted
- Loop inductance from existing literatures is reported to be sub-nano Henries (0.6nH -1 nH)

Optical Power Semiconductor Devices

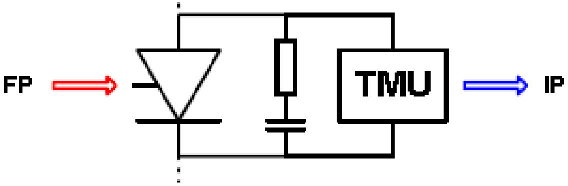


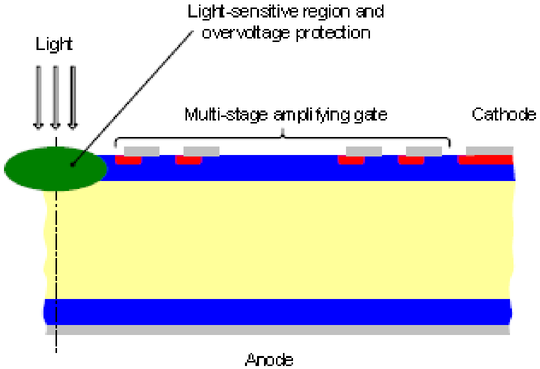


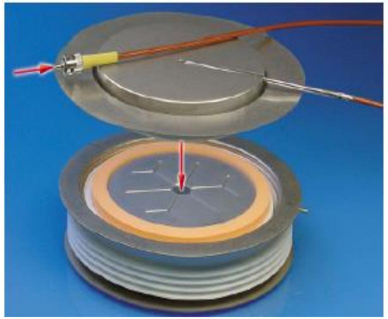
- Immunity from electromagnetic interference (EMI)
- Electrical isolation between power and control stages
- Reduced device triggering delay
- Reliable and reduced complexity medium/high voltage operation

S.K. Mazumder and T. Sarkar, “Optically-triggered power transistor (OTPT) for fly-by-light (FBL) and EMI-susceptible power electronics,” Plenary Paper, IEEE Power Electronics Specialists Conference, pp. 1-8, 2006.

Light Triggered Thyristor vs Optical ETO

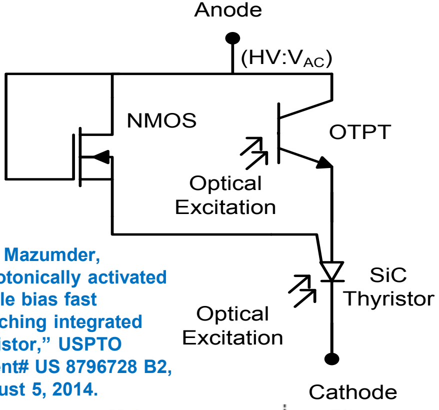




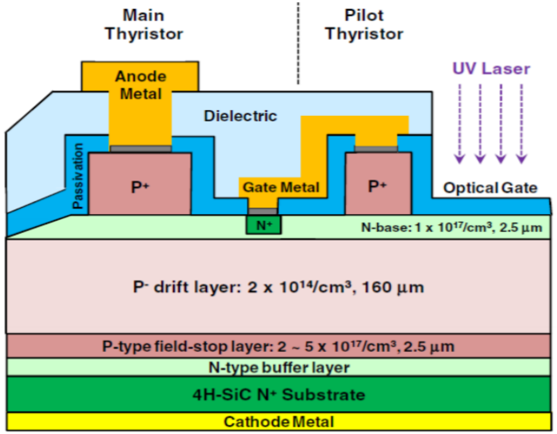


LTT:

- Smooth turn on
- High device gain
- Very low optical triggering power due to pilot thyristor
- Device real-time status available
- *Turn off is slow*
- *Gate drive is complex and lossy since it has to handle large turn-off current*
- *Integrated device structure complex*

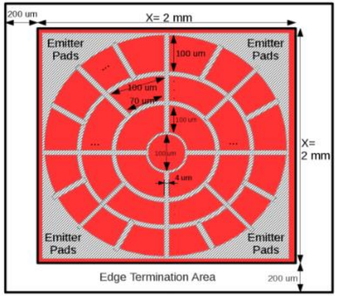


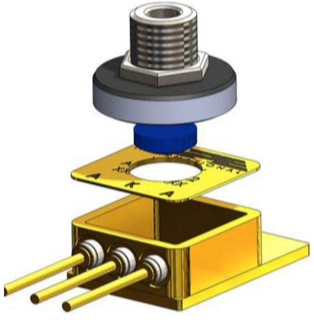
S.K. Mazumder, "Photonically activated single bias fast switching integrated thyristor," USPTO Patent# US 8796728 B2, August 5, 2014.



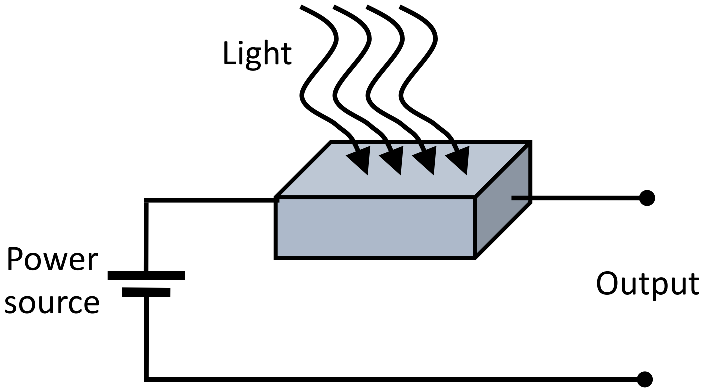
S.L. Rumayantsev, M.E. Levinshtein, M.S. Shur, L. Cheng, A.K. Agarwal, and J.W. Palmour, "Optical triggering of high-voltage 18-kVclass 4H-SiC thyristors," Semiconductor Science Technology, doi:10.1088/0268-1242/28/12/125017, vo. 28, pp. 1-4, 2013.

- Single-Bias Optical ETO
  - No control bias required
  - Additional low on-state drop
  - Medium frequency operation feasible
  - Simple control
  - Dynamic modulation possible
  - High reliability expected
  - Paralleling possible

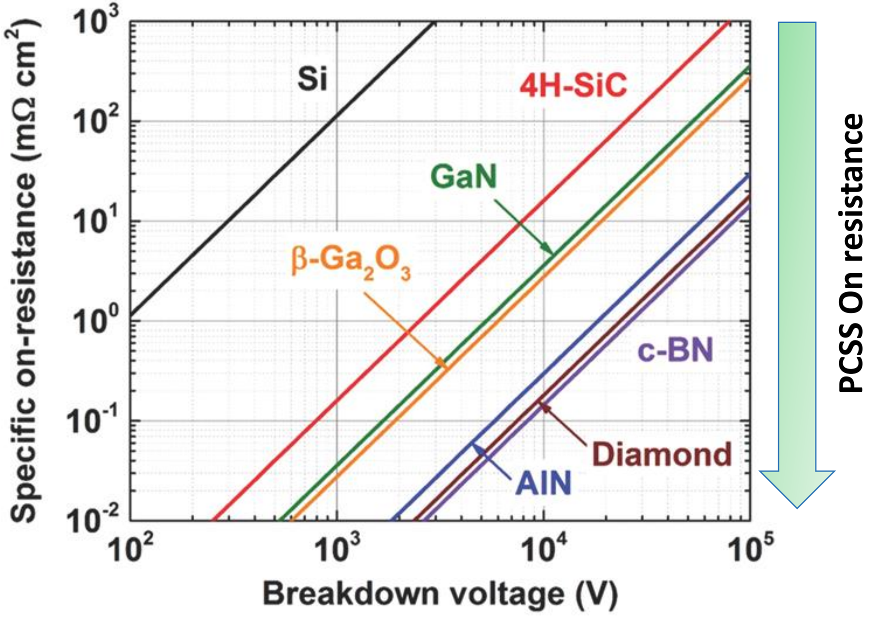




Photoconductive Semiconductor Switch (PCSS)

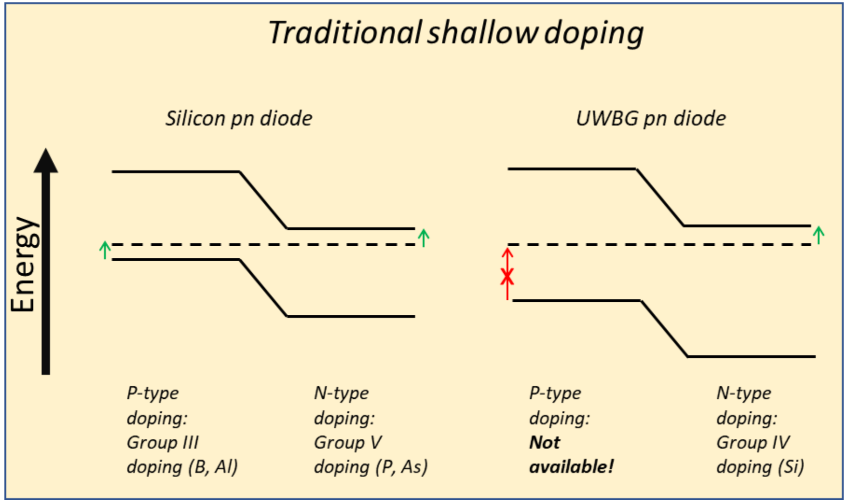


Arbitrarily low on-resistance can be reached by increasing laser power



Advanced Electronic Materials, Volume: 4, Issue: 1, First published: 04 December 2017, DOI: (10.1002/aelm.201600501)

PCSS is Uniquely Suited for WBG and UWBG Switching



Semiconductor	P-type dopant (meV)	N-type dopant (meV)
Silicon	B (45), Al (67), Ga (72)	P (45), As (54)
SiC	Al (190)	N (100), P (100)
GaN	Mg (~200)	Si (20)
Diamond	**B (370)**	**P (600), N (1700)**
AlN	**Mg (500)**	Si (63)
Ga_2O_3	**N/A**	Si (30)

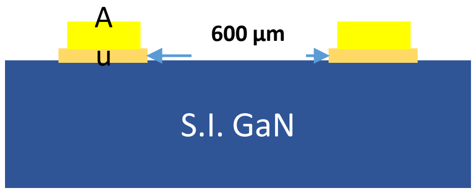
Wider bandgap

*Since the birth of semiconductors, **controlled shallow donor and acceptor doping has been the singular necessary step** that transforms a semiconductor material from scientific curiosity to technological relevance…. **not yet been achieved even for the most mature of the UWBG***

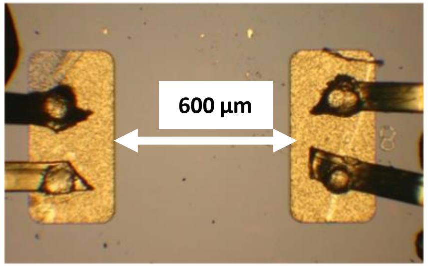
Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges. J. Y. Tsao et al., *Advanced Electronic Materials (2017)*

Lateral GaN PCSS

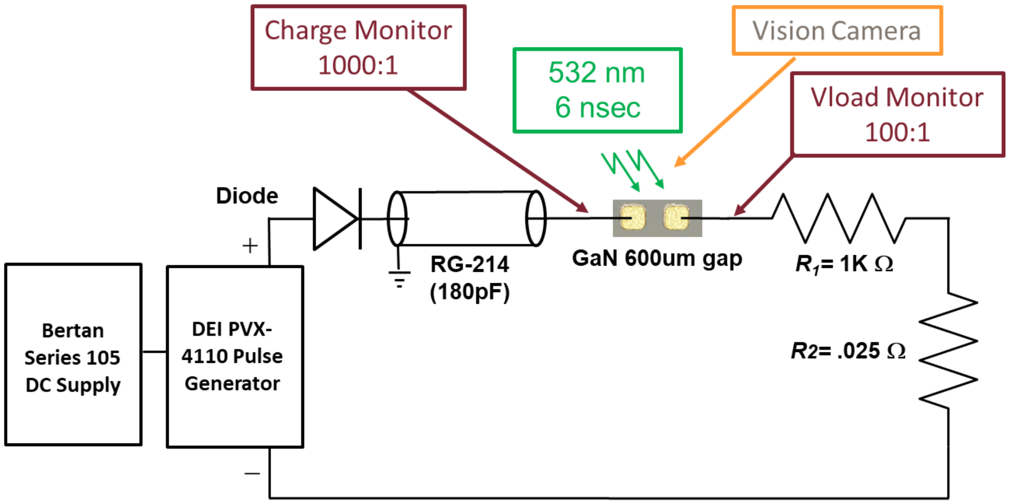
Cross-Section Diagram of GaN PCSS



Optical Image (top view) of GaN PCSS

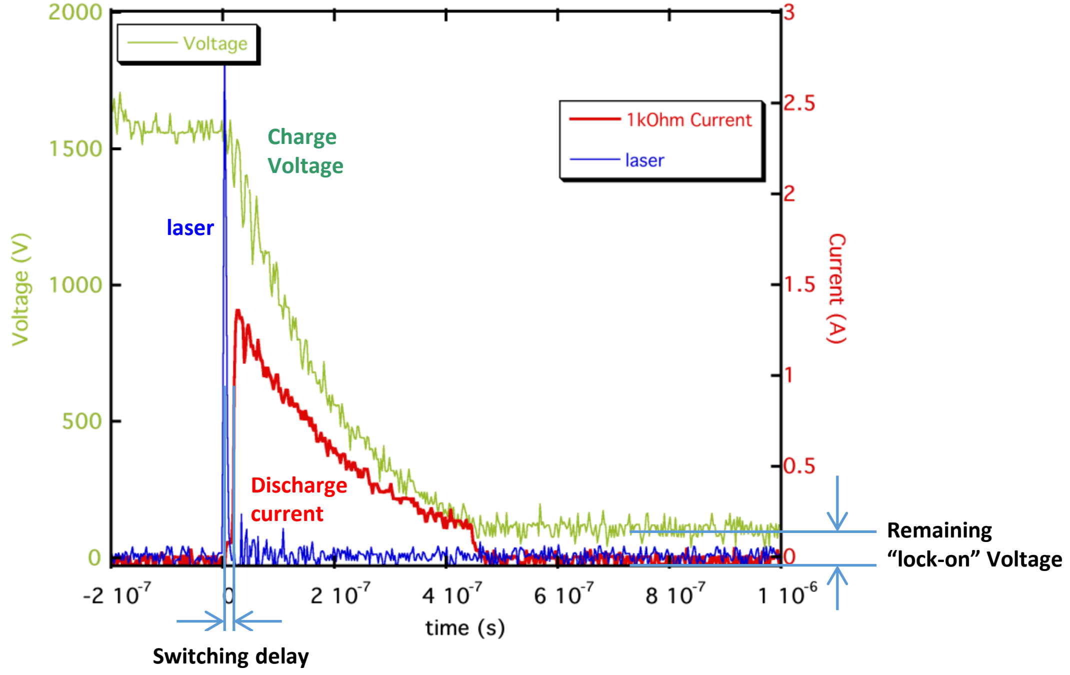


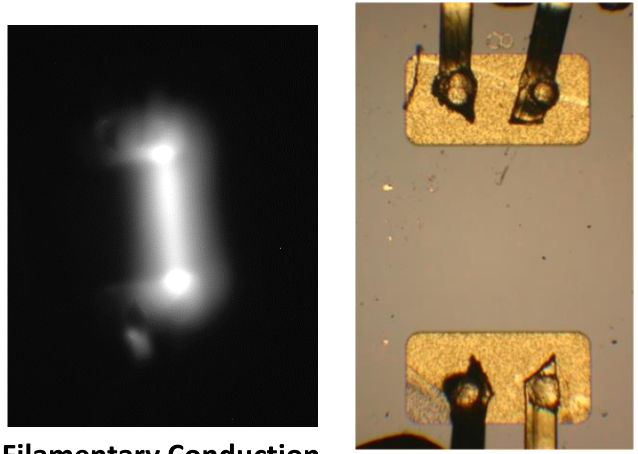
GaN PCSS Characterization Set Up



- GaN material properties for PCSS could be key enabler for high-voltage, high power applications
- 10x higher breakdown field than GaAs. > 3x thermal conductivity compared to GaAs
- Lateral devices fabricated on commercially available semi-insulating GaN substrates. Two top contacts spaced by 600 µm.
- Frequency doubled Nd:YAG (532 nm) Q-switched laser used as optical trigger (sub-bandgap triggering mechanism)
- 1.0 KΩ current limiting/sensing resistive load (~1.5A)
- Characterize devices for linear and high-gain (non-linear) operating mode (similar to GaAs)

GaN PCSS High-Gain Switching Characteristics





Filamentary Conduction
35 µJ trigger at 532 nm

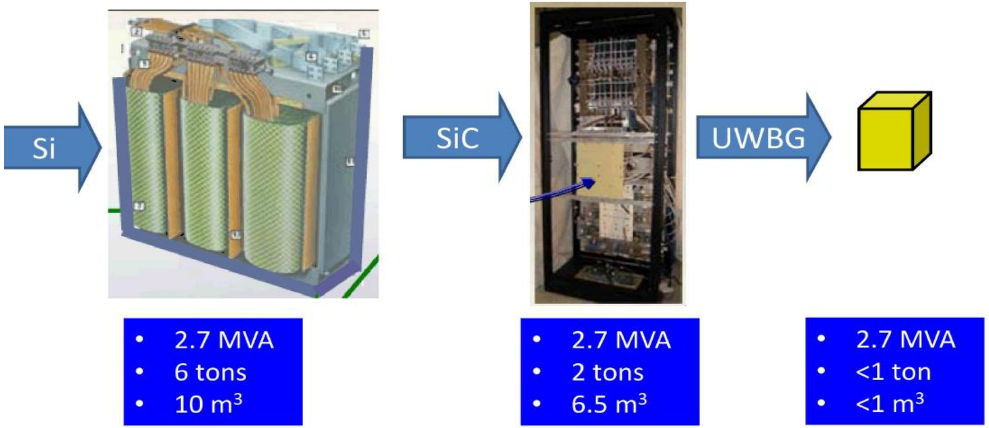
- Small laser energy (~30µJ, 6ns, gap overfilled) triggers PCSS into "on" state, well below breakdown field
- Highly repeatable on state persists well after laser pulse duration (high gain mechanism)
- On state maintained as long as minimum critical ("lock-on") field of ~3kV/cm maintained (200V/0.06 cm)
- Filaments evident in images during high-gain switching, non-damaging to GaN (at limited currents)

UWBG Advantages and Future Perspective

Properties	Si	4H-SiC	GaN	Ga_2O_3	AlN	Diamond
Bandgap (eV)	1.12	3.26	3.45	4.8	6.2	5.45
Mobility (e) (cm^2/Vs)	1500	1000	1250	200	500	2200
Mobility (h) (cm^2/Vs)	600	115	850	100	100	850
Breakdown Field (MV/cm)	0.3	2.2	2	**8**	**15**	**10**
Thermal Cond (W/m-K)	1.5	4.9	2.4	0.2	3	22

UWBG semiconductors (e.g., > 3.4 eV, e.g., AlGaN, Ga_2O_3, diamond)… are **substantially superior** to conventional (e.g., Si) and even SiC, GaN semiconductors. (pg. 52, Office of Science Basic Research Needs for Microelectronics, 2018)

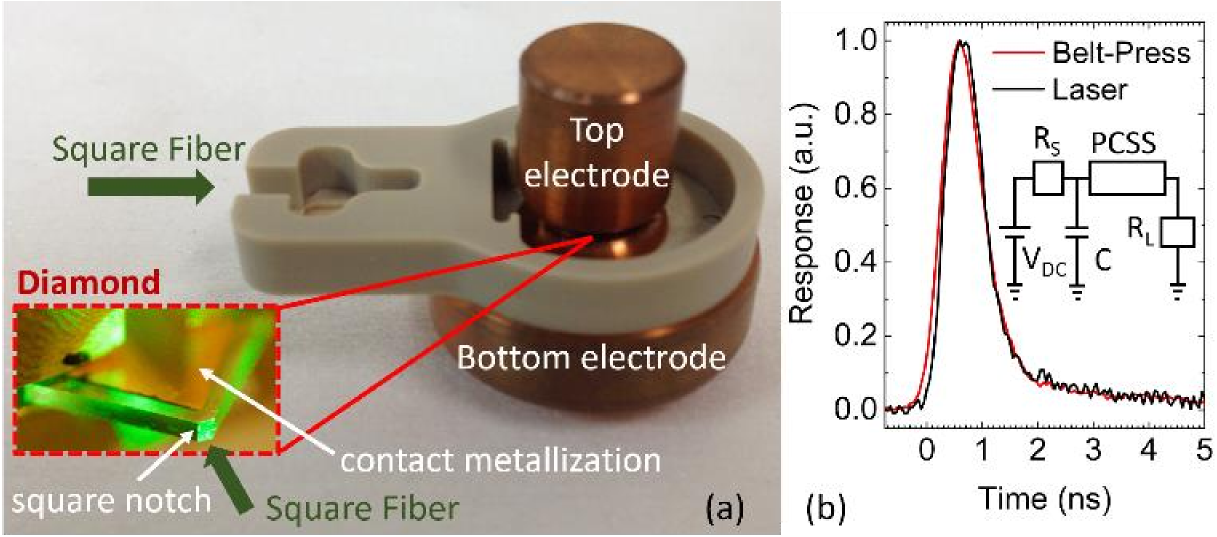
UWBG semiconductors have a theoretical advantage over SiC and GaN due to scaling of critical electric field (E_{crit}) and likely to yield > 10 kV class devices with lower on-resistance. Other benefits of UWBG technology: Extreme environment operation (e.g., high temperature), potential for new use-cases for active electronics in place of passive electronics.

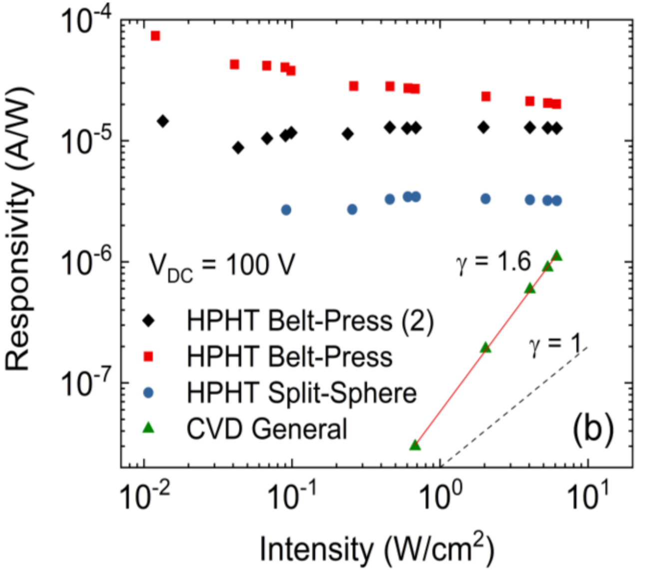


Relative immaturity of all UWBG platforms presents numerous challenges including:

- Availability of native substrates
- Efficacy of impurity doping (one or both dopant species are very deep in the bandgap; polarization doping may be used in some cases)
- Ohmic contact formation
- Low electronic and thermal conductivity (applicable to alloyed materials or materials with complex crystal structure)

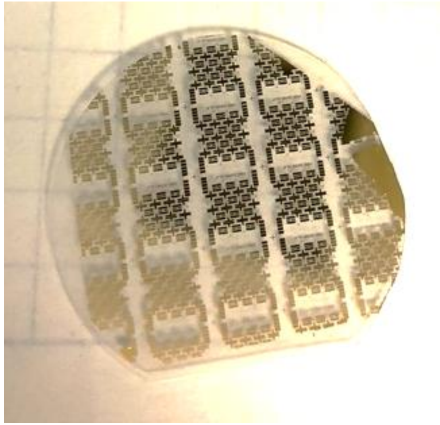
UWBG (Diamond) PCSS



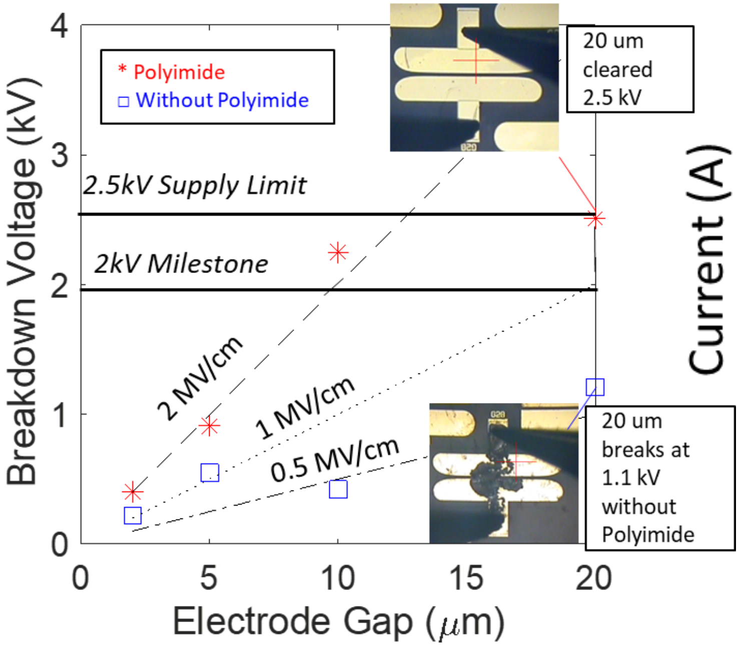


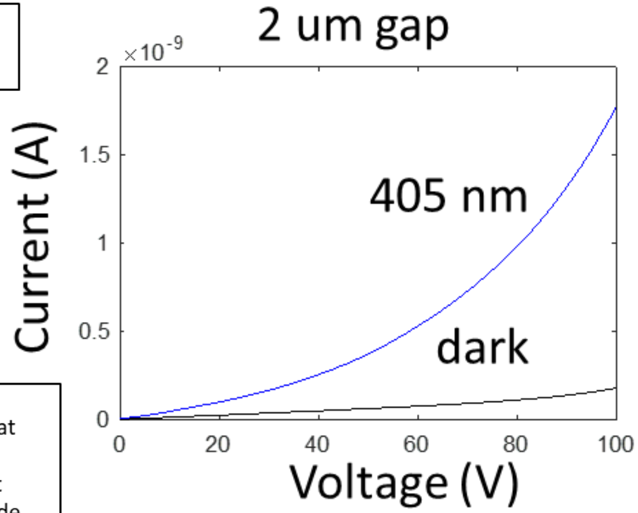
Demonstrated voltages up to 5 kV at with GHz switching capability

Initial Results for Bulk Ga_2O_3 Show Promise for Very High Voltage and Sub-Band Gap Excitation



Recently fabricated and tested Ga_2O_3 lateral PCSS (May 2021)





Suggests that 100 kV bulk devices possible with < 500 micron thick wafers

Power System Support Functions of Power Converter-Based DERs

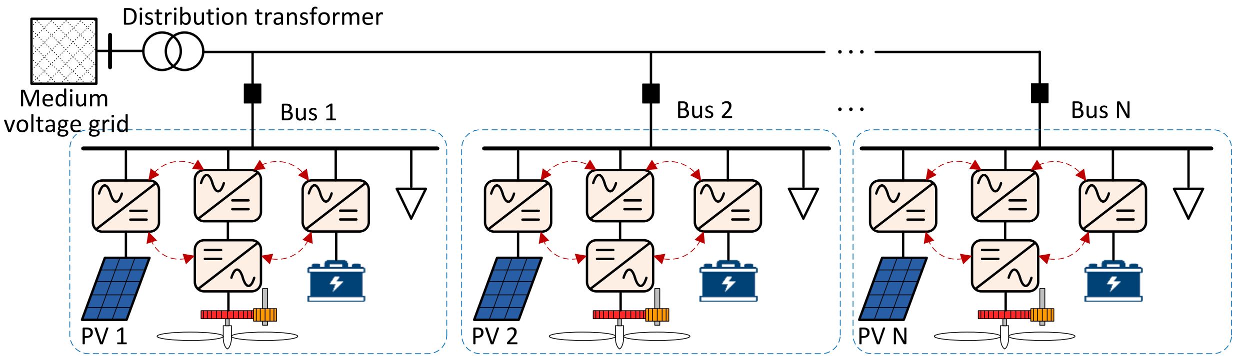
Voltage Regulation

Frequency Regulation

Voltage Ride-through

Frequency Ride-through

Voltage Regulation: Why?



- Radial distribution network
- With high penetration of distributed energy resources, there could be a reverse power flow when the PVs generate more power than local loads.
- Reverse power flow can cause voltage rise, leading to overvoltage problems.

Traditional solutions:

- Capacitor banks and inductors
- Tap changing transformers

☹ **Investment cost. Limited life span. Slow in action to compensate the voltage fluctuation caused by transient events such as a gust of wind or a cloud passing over PV panels.**

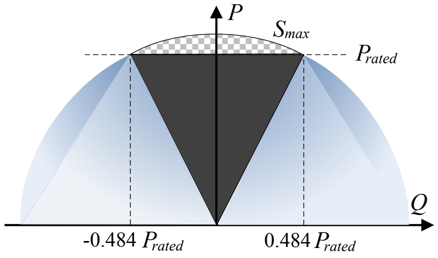
Additional solution:

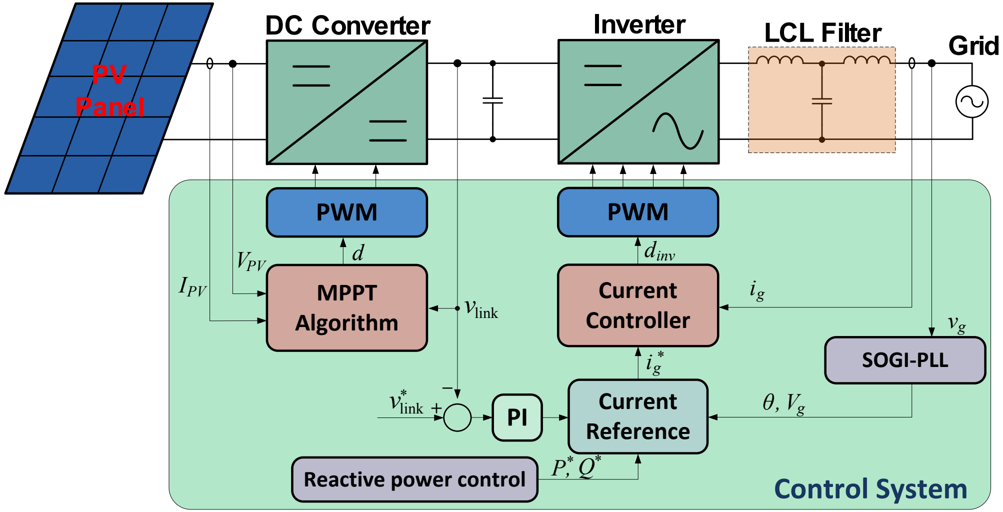
» **Reactive power control for DER inverters.**

☺ **Faster and more precise regulation, with longer life span.**

Voltage Regulation via Reactive Power Control

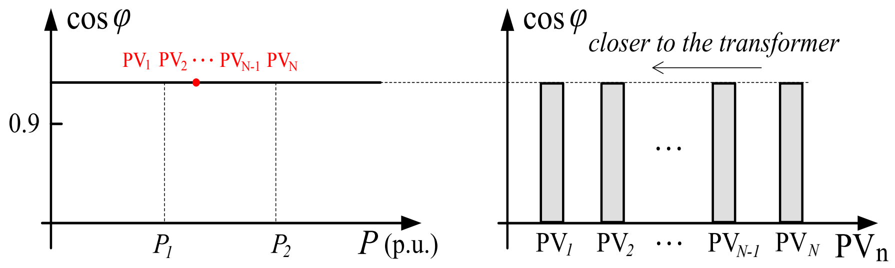
- Reactive power control based on DER power converters





Reactive Power Control – Fixed Power Factor (PF)

- **Without location variance**

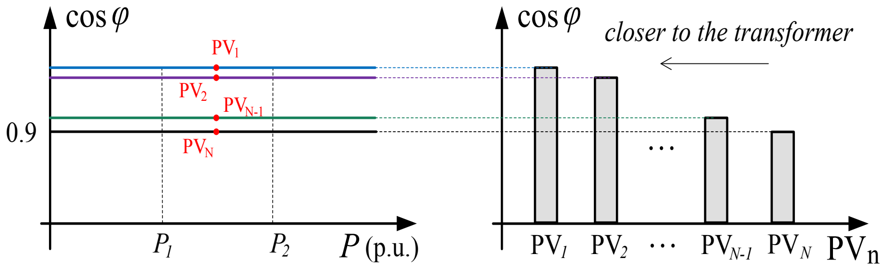


❑ **When $\cos\varphi \geq 0.9$, $\tan\varphi$ is almost equal to $\sin\varphi$:**

$$\frac{Q}{P} = \tan\varphi \approx \sin\varphi = \sqrt{1-\cos^2\varphi} = \text{constant}$$

Advantages	Disadvantages
• Easily implemented because only a constant value is set in the controller.	○ Distributing the reactive power evenly does not effectively utilize Q.

- **With location variance**



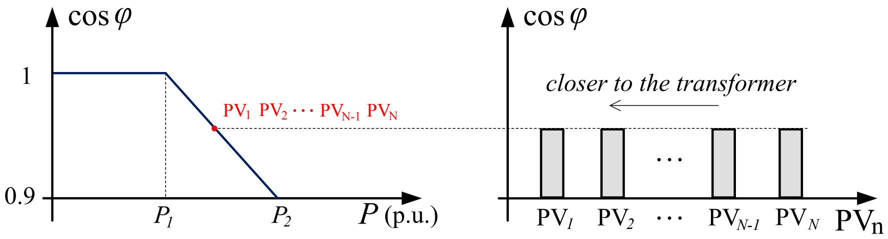
❑ **Each inverter's PF value decreases with the increase of distance away from the transformer.**

❑ **According to voltage sensitivity analysis, the voltage is more sensitive to reactive power absorbed by inverters farther away from the transformer.**

Advantages	Disadvantages
• The same voltage regulation effect can be achieved by less total amount of reactive power.	○ There is reactive power flow even if there is no overvoltage problem, which increases converter currents.

Reactive Power Control - cosφ(P) Method

- **Without location variance**

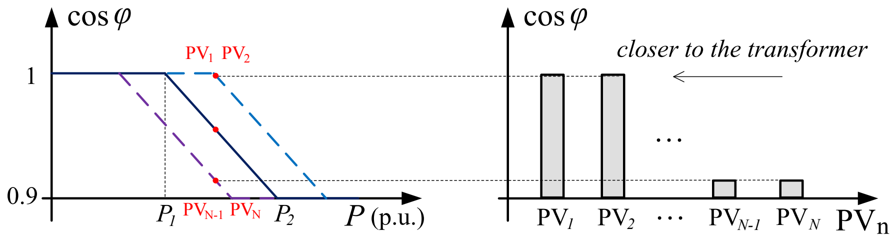


$$\cos\varphi = \begin{cases} 1, & P < P1 \\ \frac{0.1}{P_1 - P_2}(P - P_1) + 1, & P_1 \leq P \leq P_2 \\ 0.9, & P > P_2 \end{cases}$$

❑ **Power factor decreases linearly with the increase of active power generation.**

Advantages	Disadvantages
• Inverters operate at 1.0 PF at nominal voltage • Inverters provide more voltage support when the possibility of overvoltage is high.	○ Distributing the reactive power evenly does not effectively utilize Q.

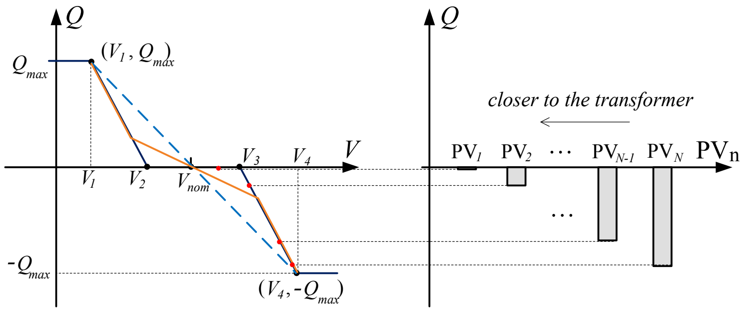
- **With location variance**



❑ **DER inverters farther away from the transformer are operated following a lower PF curve, and DER inverters closer to the transformer are operated following a higher PF curve.**

Advantages	Disadvantages
• The same voltage regulation effect can be achieved by less total amount of reactive power.	○ When high active power generation coincides with high local load demand, there is no overvoltage problem but the inverters still absorb Q.

Reactive Power Control - Q(V) method



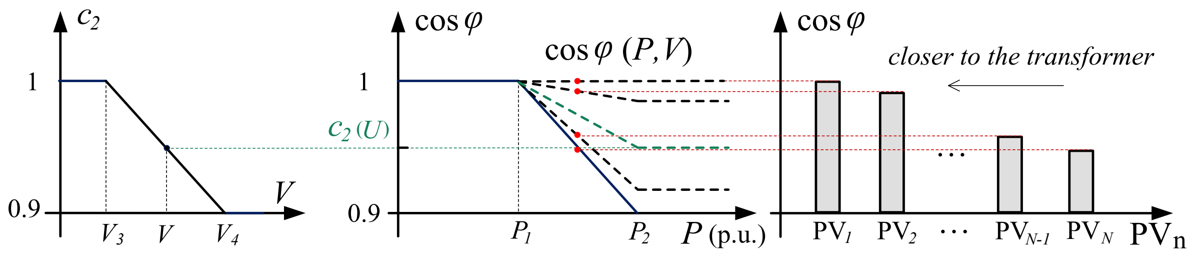
$$
Q = \begin{cases} Q_{\max}, & V < V_1 \\ \dfrac{Q_{\max}}{V_1 - V_2}(V - V_1) + Q_{max}, & V_1 \le V \le V_2 \\ 0, & V_2 < V \le V_3 \\ \dfrac{Q_{\max}}{V_3 - V_4}(V + V_3), & V_3 < V \le V_4 \\ -Q_{\max}, & V > V_4 \end{cases}
$$

- **Voltage levels increase with the distance away from the transformer, and DER inverters absorb more reactive power with the increase of voltage levels.**

Advantages	Disadvantages
• The inverters absorb reactive power only when there is an overvoltage at corresponding connection point. • Reactive power absorption is in accordance with voltage sensitivity.	○ The inverters near the transformer may not help absorb Q even though the voltage level at critical bus is out of limit.

Reactive Power Control - cosϕ(P,V) Method

- **cosφ(P,V) method without location variance**

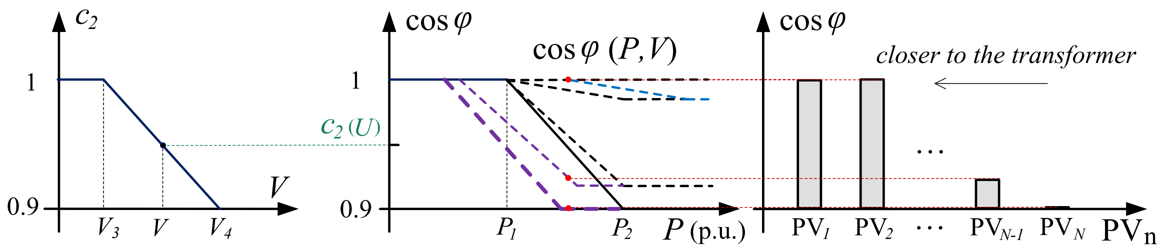


❑ **A PF limit is produced first according to the droop function of Q(V); then the PF reference is assigned on each inverter according to cosφ(P) .**

Advantages	Disadvantages
• All inverters are operated with the relationship of cosφ(P) while the inverters farther away from the transformer undertake more Q.	○ The inverters close to the transformer provide less help than without location variance, thus stressing out the critical bus inverters.

Reactive Power Control - cosϕ(P,V) Method

- **cosφ(P,V) method with with location variance**

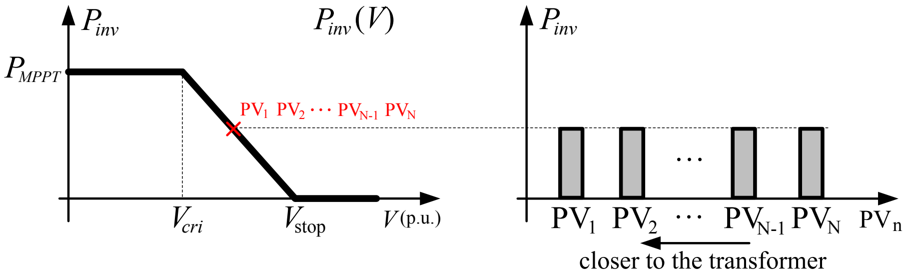


❑ **The inverters are operated according to cosφ(P,V), but the inverters farther away from the transformer are operating according to lower cosφ(P) curve, and the inverters close to the transformer are operating according to higher cosφ(P) curve.**

Advantages	Disadvantages
• Same voltage regulation effect can be achieved by lower total reactive power when assigning lower PF curve to inverters farther away from the transformer.	○ According to voltage sensitivity analysis, the utilization of reactive power can be further improved. ○ More complex controls

Active Power Control - Droop-Based Control

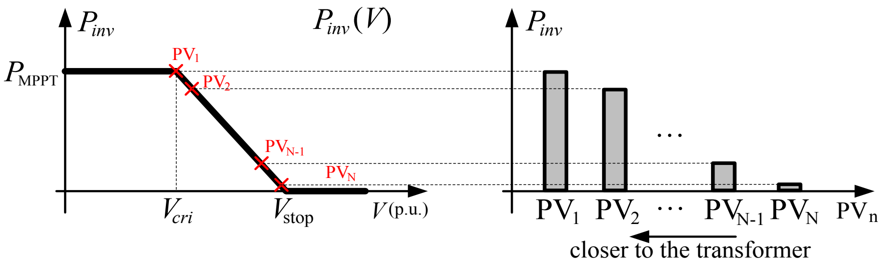
With average voltage



- The active power decreases linearly with the increase of voltage level at point of common coupling.

Advantages	Disadvantages
• Easily implemented because only one active power curve is used to decide all active power reference.	○ Distributing the active power curtailment according to the average bus voltage is not effective.

With location variance

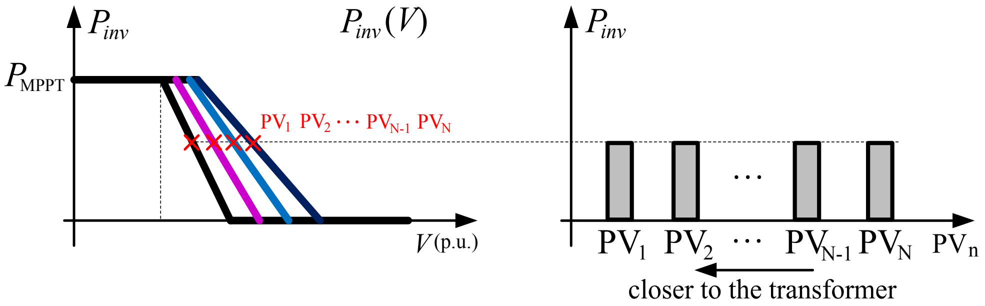


- Same as Q(V) method, the P(V) curve determines the active power reference of each inverter.
- The voltage levels increase with the distance away from the transformer, and DER inverters curtail more active power with the increase of voltage levels.

Advantages	Disadvantages
• Active power curtailment is in accordance with voltage sensitivity analysis, leading to more effective utilizing the active power.	○ The PV generation revenue for downstream customers are lower than those for upstream customers.

Active Power Control - Droop-Based Control

- **Droop-based control with equal losses**

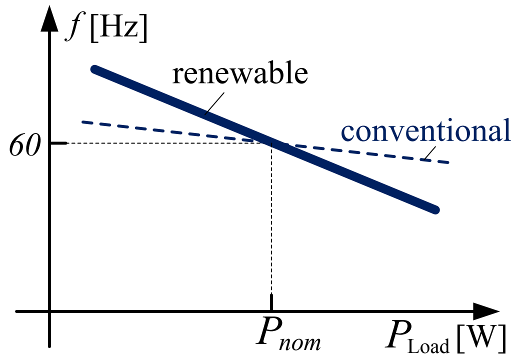


❑ **The droop curves for inverters close to the transformer are steeper than those away from the transformer.**

Advantages	Disadvantages
• The inverter close to the transformer can provide more help with fair active power curtailment.	○ The same voltage regulation effect needs to be achieved by larger total amount of active power curtailment.

Frequency Droop Control

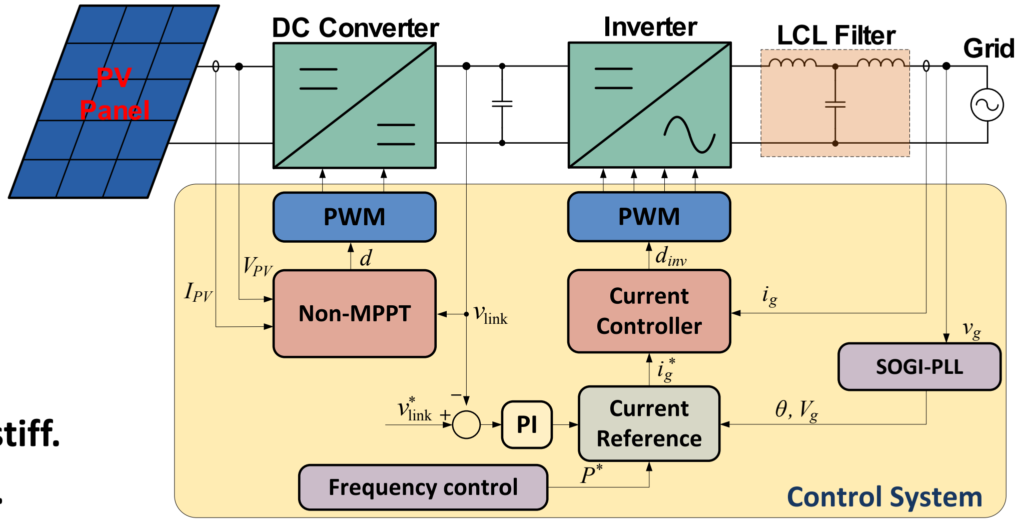
- **Droop curves of generators**



- **Conventional plants (thermal, hydro): more stiff.**
- **Renewable energy sources (wind, PV): softer.**

- **A conventional generator is usually driven by a prime mover to generate AC power at a specific frequency.**
- **As the power drawn from the prime mover increases, the speed at which it rotates will decrease.**

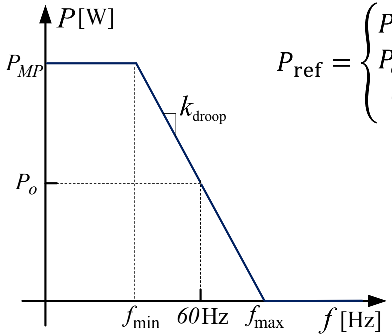
- **Frequency control strategy**



- **DER inverters are expected to provide frequency regulation through active power control.**
- **Instead of working at MPPT, DERs with frequency regulation need to be curtailed to have active power reserve in case of frequency contingency.**

Frequency Droop Control – Basic Droop Curves

- **Basic frequency droop control**

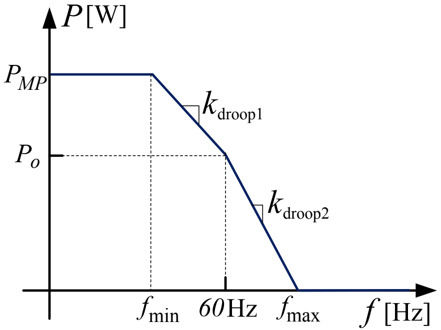


$$P_{\mathrm{ref}} = \begin{cases} P_{MP}, & f < f_{\min} \\ P_o - k_{\mathrm{droop}}(f - f_{\mathrm{nom}}), & f_{\min} \le f \le f_{\max} \\ 0, & f > f_{\max} \end{cases}$$

- ❑ **DER output power is set at 50% maximum power.**
- ❑ **DERs supply more power when the system frequency is below the nominal value, and supply less power when the system frequency is above the nominal value.**

Advantages	Disadvantages
• Easily implemented because only one droop coefficient is applied to decide all active power reference.	○ The generated power is lower (and the DER is under-utilized).

- **Asymmetrical frequency droop control**

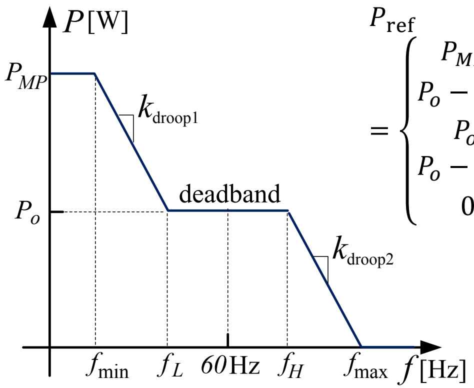


- ❑ **DER output power is more than 50% of Pmax**
- ❑ **The droop coefficient below the nominal frequency is smaller than the droop coefficient above the nominal frequency.**

Advantages	Disadvantages
• Better utilization of the available PV energy as compared to the basic frequency droop control.	○ Small frequency deviation due to errors and noise may frequently activate the droop control.

Frequency Droop Control – Segmented Droop Curves

- **Frequency droop control with dead-band**

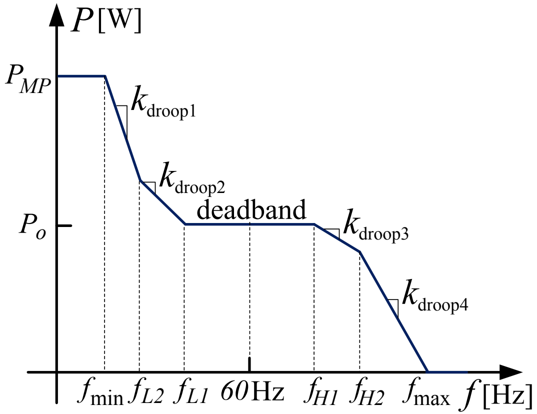


$$P_{\text{ref}} = \begin{cases} P_{MP}, & f < f_{\min} \\ P_o - k_{\text{droop1}}(f - f_L), & f_{\min} \le f \le f_L \\ P_o, & f_L < f < f_H \\ P_o - k_{\text{droop2}}(f - f_H), & f_H \le f \le f_{\max} \\ 0, & f > f_{\max} \end{cases}$$

❑ **The dead-band is centered on nominal frequency, within which the droop control is not activated.**

Advantages	Disadvantages
• Prevent the frequency adjustment of the droop control in response to small frequency fluctuations.	○ Under-utilization of the rapid and flexible control of DER inverters since it adjusts the active power reference with the same slope.

- **Segmented frequency droop control**

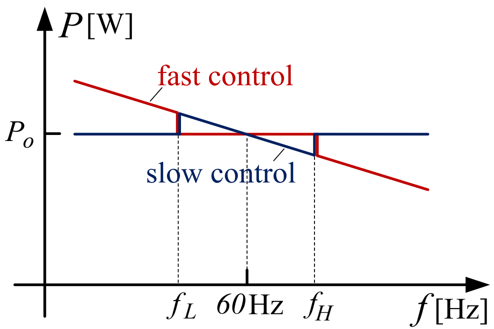


❑ **The droop coefficient is smaller when the frequency deviation is small, and is larger when the frequency deviation is greater.**

Advantages	Disadvantages
• Restore the frequency faster when the frequency deviation is greater.	○ The system may result in a dynamic equilibrium at the edge of the dead-band, and causes frequent activation of droop control.

Frequency Droop Control – Variable Rates of Regulation

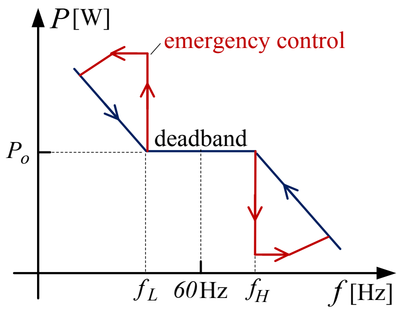
- **Frequency droop with fast and slow control**



- ❑ **The slow frequency control is applied when the frequency deviation is small (every 400 grid cycles), and the fast frequency control is applied when the frequency deviation is large (every 20 grid cycles).**

Advantages	Disadvantages
• Restore the frequency quickly when the frequency deviation is out of the dead-band.	○ The large regulation in fast control can cause a big disturbance.

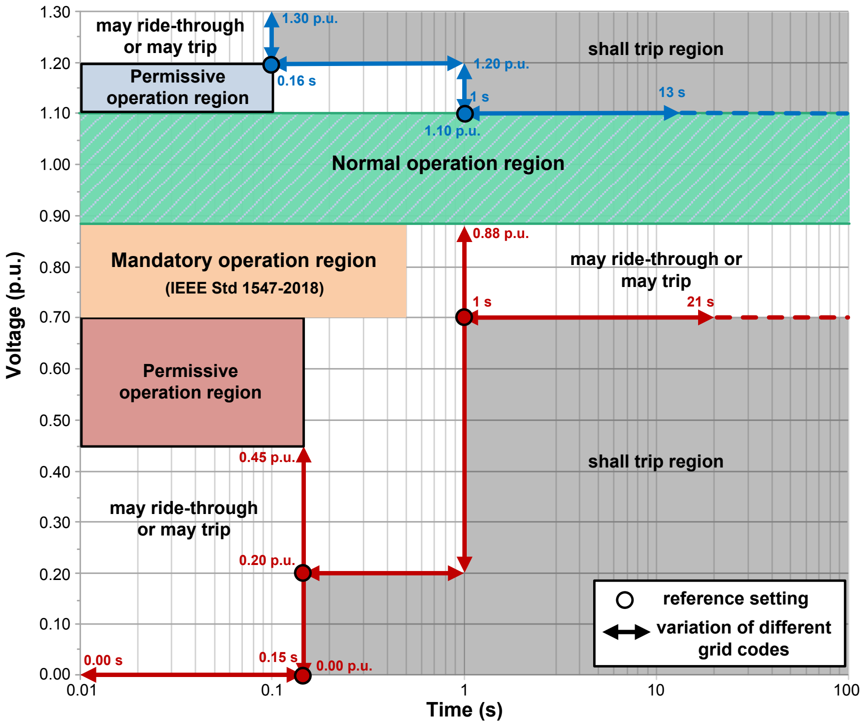
- **Frequency droop with emergency control**



- ❑ **The active power reference changes sharply according to the emergency control when the frequency deviation is out of dead-band.**
- ❑ **The rate of frequency change is used as an additional trigger for the emergency control.**

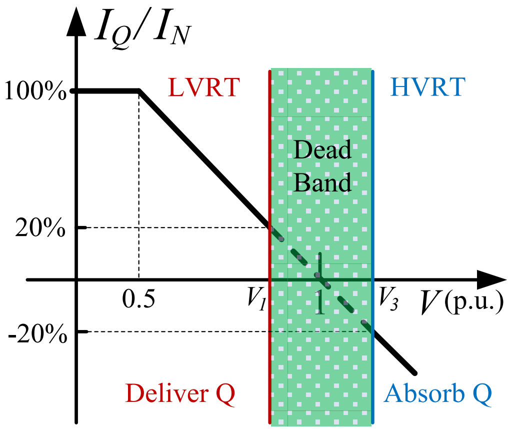
Advantages	Disadvantages
• Restore the frequency quickly when the frequency deviation is out of the dead-band.	○ More signal detection and computational burden due to complex control algorithm.

Voltage Ride-Through (VRT) Requirement – Standards (Codes)



- With increase of DER penetration, anti-islanding protection alone is insufficient for power system operation anymore during grid voltage faults.
- DERs are required to remain connected for a certain period of time before the fault is cleared.

Voltage Ride-Through Capability



- **Wind power generation systems**
  - AC power generation through a rotational generator
  - Output power cannot be changed rapidly
  - Auxiliary devices for voltage and current limitation
- **Solar power generation systems**
  - DC power generation through PV array
  - Output power can be changed rapidly
  - Inherent voltage and current limitation according to I-V curve

❑ The basic principle is the same as the voltage regulation by reactive power control: the inverters absorb Q when the voltage is swelling, and deliver Q when the voltage is sagging.

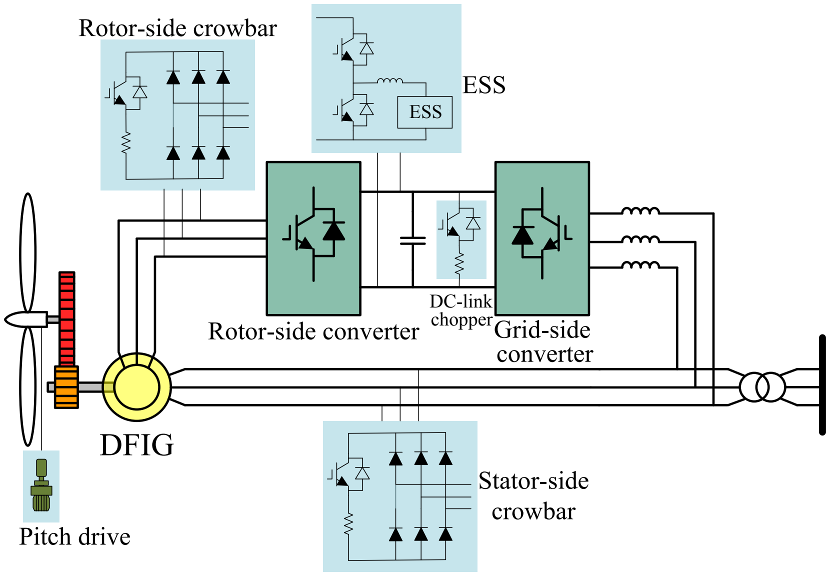
❑ The majority of transmission system operators (TSO) have similar grid codes for wind and solar power systems.

❑ The operation under voltage faults is different from the normal operation because there exist overvoltage and over-modulation problems under voltage swells, and there is an overcurrent problem under voltage sags.

Voltage Ride-Through Controls - Wind & PV Systems

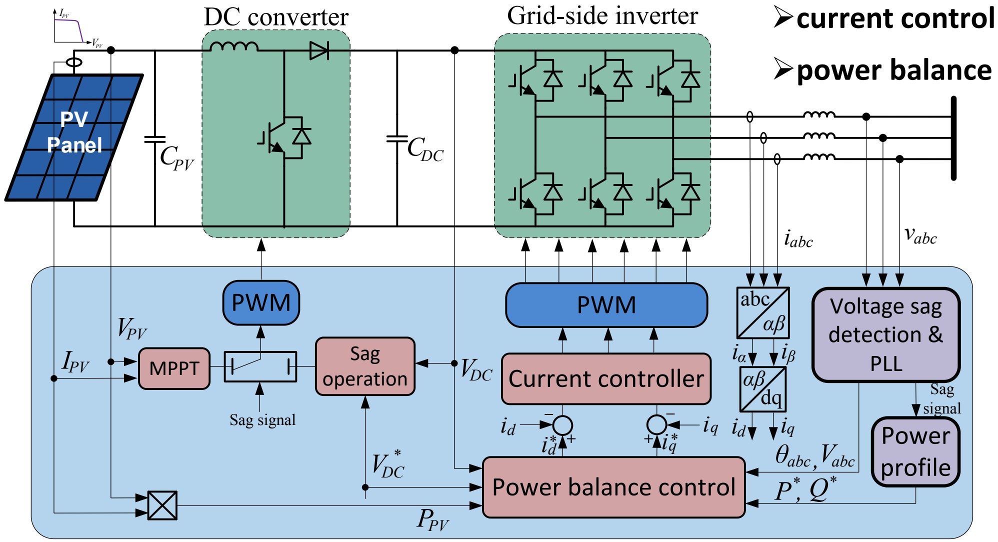
- grid voltage detection
- synchronization
- current control
- power balance

- **Passive methods using auxiliary devices**



- Pitch drive for blade pitch angle control
- Crowbar for limiting rotor voltage and current
- Energy storage system and static VAR compensator

- **Block diagram of PV system**

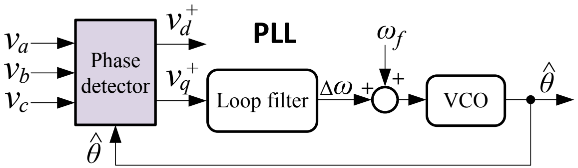


- Control strategies are applied to detect voltage sags or swells, assign active and reactive power references when a voltage fault is detected, switch the first stage to sag operation from MPPT, synchronize with faulty grid voltage through PLL, and inject proper current to the grid.

Voltage Ride-Through for PV Systems - Detection

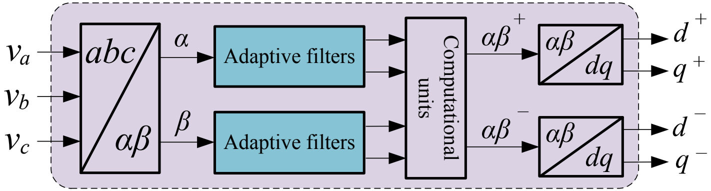
- **Gird voltage detection and synchronization**
  - **The voltage detection methods are usually integrated with SSM into PLLs.**

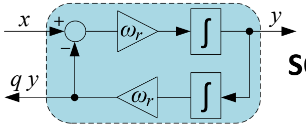
PLL method	DDSRF-PLL	DSOGI-PLL	EPLL	VSPF-PLL	MAF-PLL
Detection time	12ms	11ms	80ms	25ms	20ms
PLL method	LSRF-PLL	MRF-PLL	MCCF-PLL	FASRF-PLL	
Detection time	60ms	40ms	20ms	10ms	



- Phase detector
- Loop filter
- Voltage controlled oscillator

Sequence Separation Method (SSM)





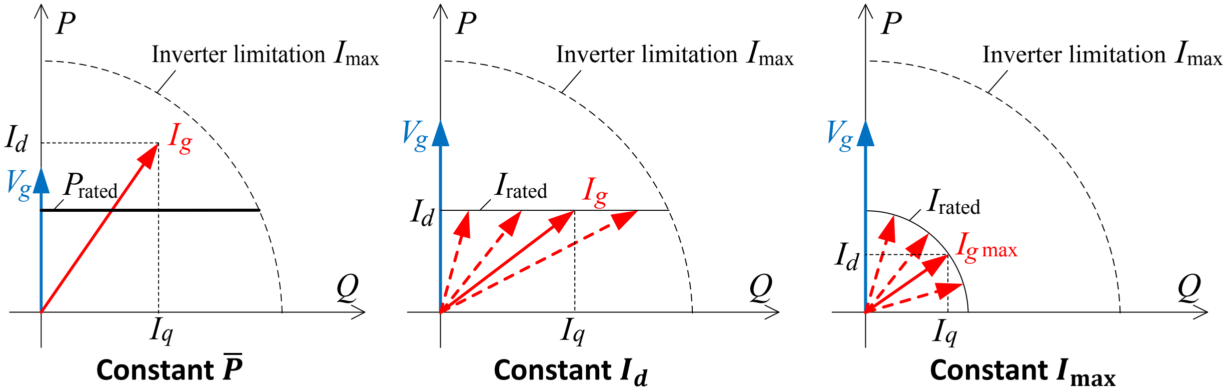
SOGI

- **Since the occurrence of symmetrical faults is extremely rare as compared with asymmetrical faults, SSMs are used in PLL to obtain more accurate amplitude and phase angle for synchronization.**

- Notch, band-stop, Low pass filters
- Delayed signal cancellation (T/4 delay)
- Differentiation method
- Second-order-generalized-integrator (SOGI)

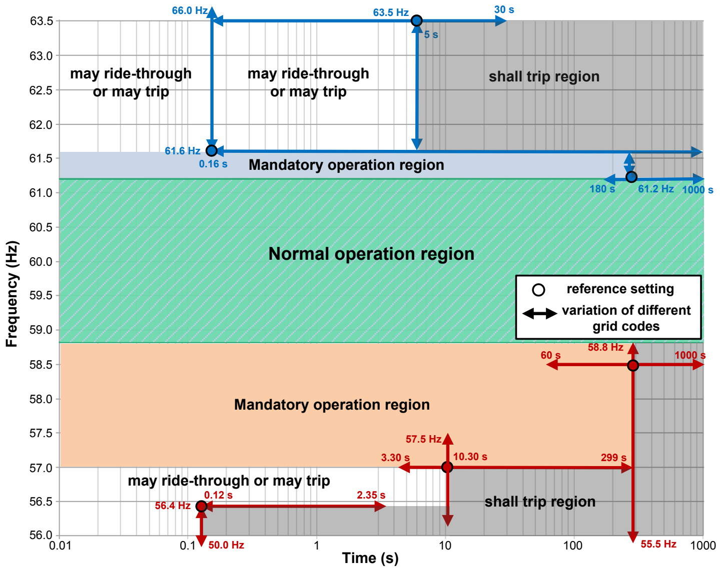
Voltage Ride-Through for PV Systems – Single-Phase

- **Single-phase VRT techniques**
  - **An orthogonal signal generator is used to decompose active and reactive components and control them respectively.**



- ❑ **Constant average active power control has the overcurrent problem when the voltage sags.**
- ❑ **Constant active current control has the overcurrent problem when DER inverter needs to provide high reactive current support.**
- ❑ **Constant peak current control limits the current by compromising active power.**

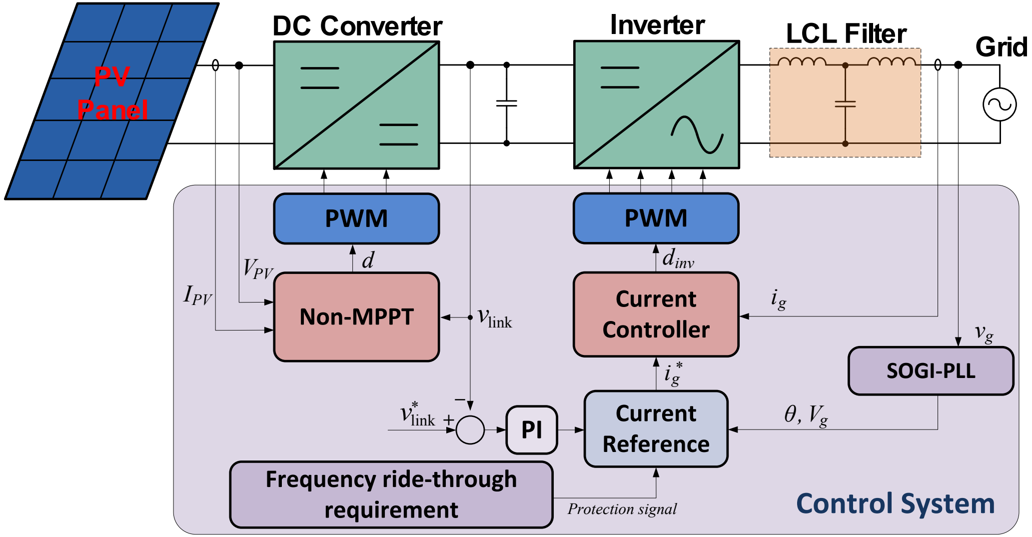
Frequency Ride-Through Requirements - Standards



- ❑ **DER inverters are required to remain connected during frequency excursions to limit the amount of load shedding and to prevent system collapse.**
- ❑ **Unlike voltage ride-through, frequency ride-through usually does not have overvoltage or overcurrent problem that makes DERs susceptible to damage.**

Frequency Ride-Through - Controls

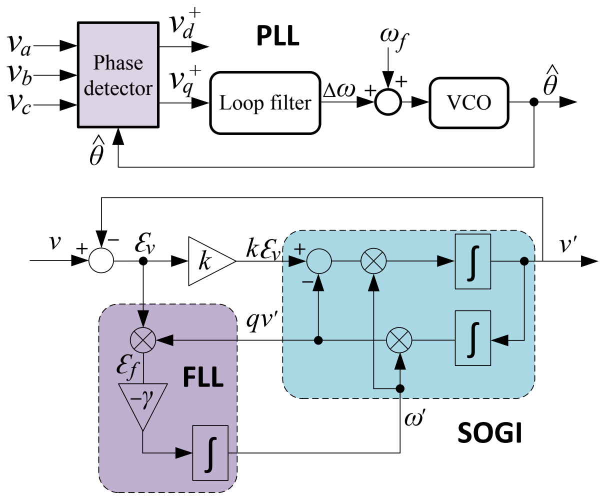
- **Control block diagram**



- ❑ **Frequency deviation does not cause overvoltage or overcurrent problems, so the operation under frequency faults is almost the same as that under the normal operation.**
- ❑ **Frequency ride-through requirements are used to update the protection scheme in DER inverters.**

Frequency Ride-Through – Frequency Detection

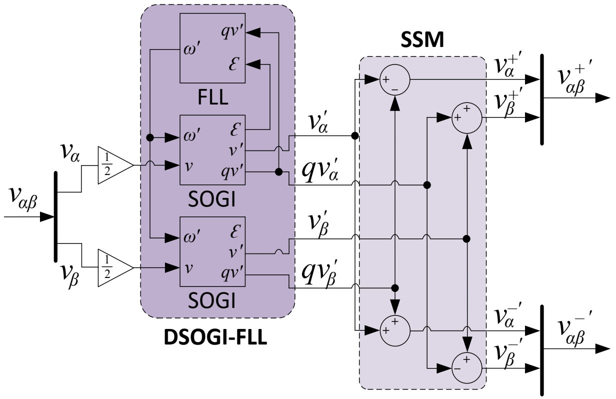
- The frequency detection methods are usually integrated into phase-locked-loops (PLLs) or frequency-locked-loops (FLLs).

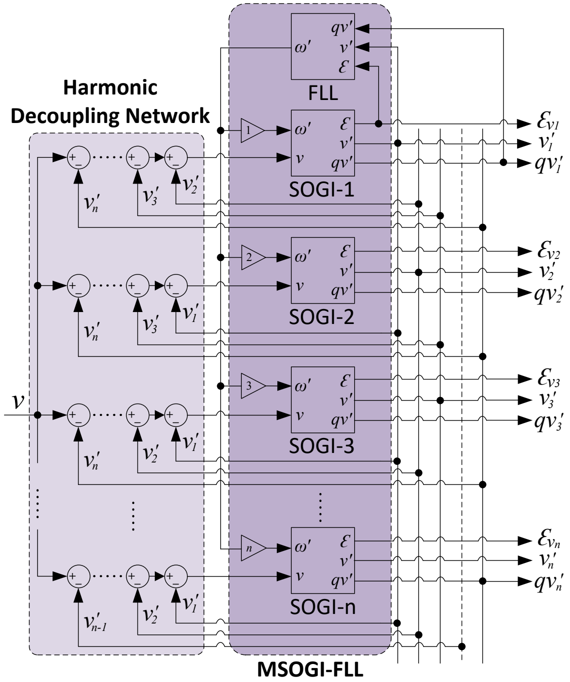


- Since synchronous reference frame (SRF)-PLL has deficient response under unbalanced grid fault, various PLLs are presented:
  - Decouple double SRF-PLL
  - Dual SOGI-PLL
  - Enhanced PLL
  - Variable sampling period filter (VSPF)-PLL
  - Moving average filter (MAF)-PLL
  - Low-pass-filter SRF-PLL
  - Multiple reference frame (MRF)-PLL
  - Multiple complex coefficient filter (MCCF)-PLL
  - SRF-PLL with fast and accurate detection
  - SOGI-FLL
  - Multiple SOGI-FLL

- ❑ PLLs synchronize with the phase of the input signal so that the accuracy is highly influenced by phase angle jumps.
- ❑ FLLs estimates the frequency of the input signal regardless of phase angle jump.

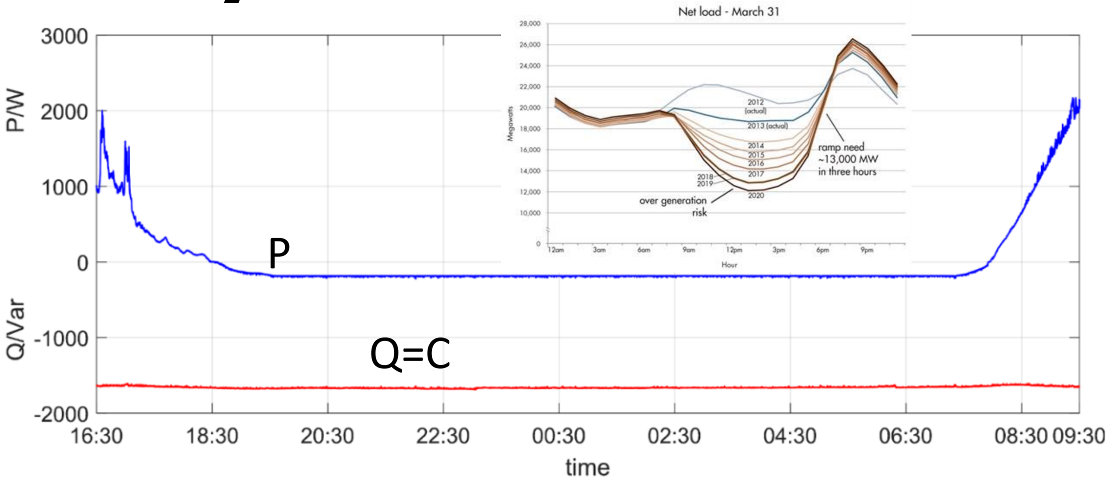
Frequency Ride-Through – Synchronization Methods

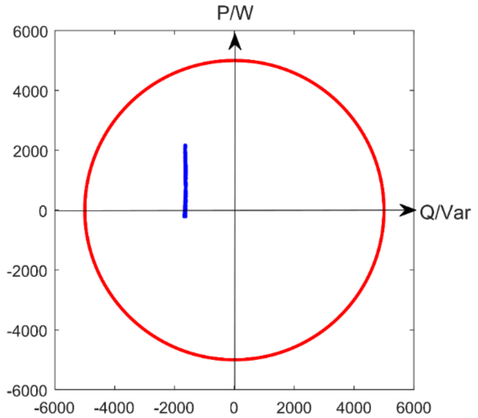


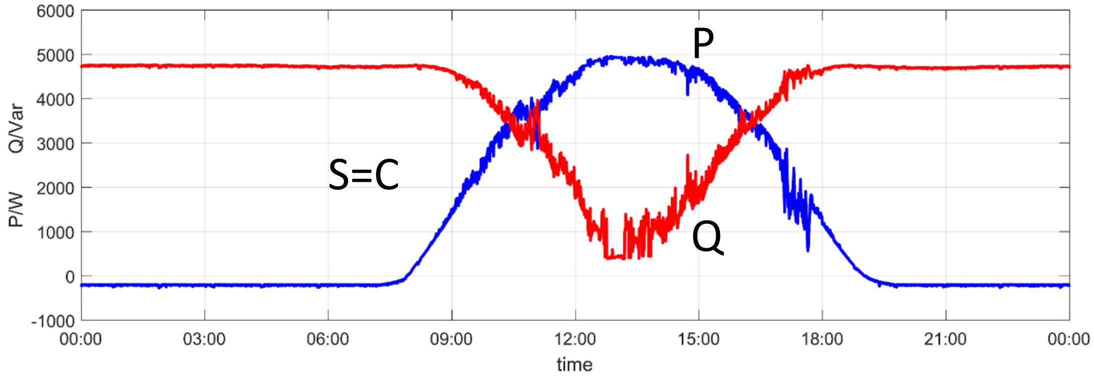


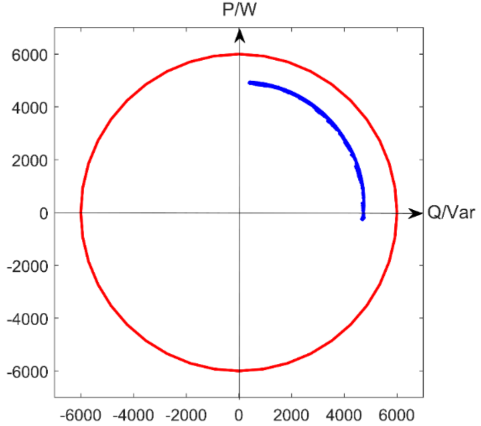
- ❑ **Other synchronization methods such as self-synchronized controllers can achieve synchronization without PLL or FLL, e.g. PLL-less hysteresis current control.**

PV Systems as Grid Resources – P & Q

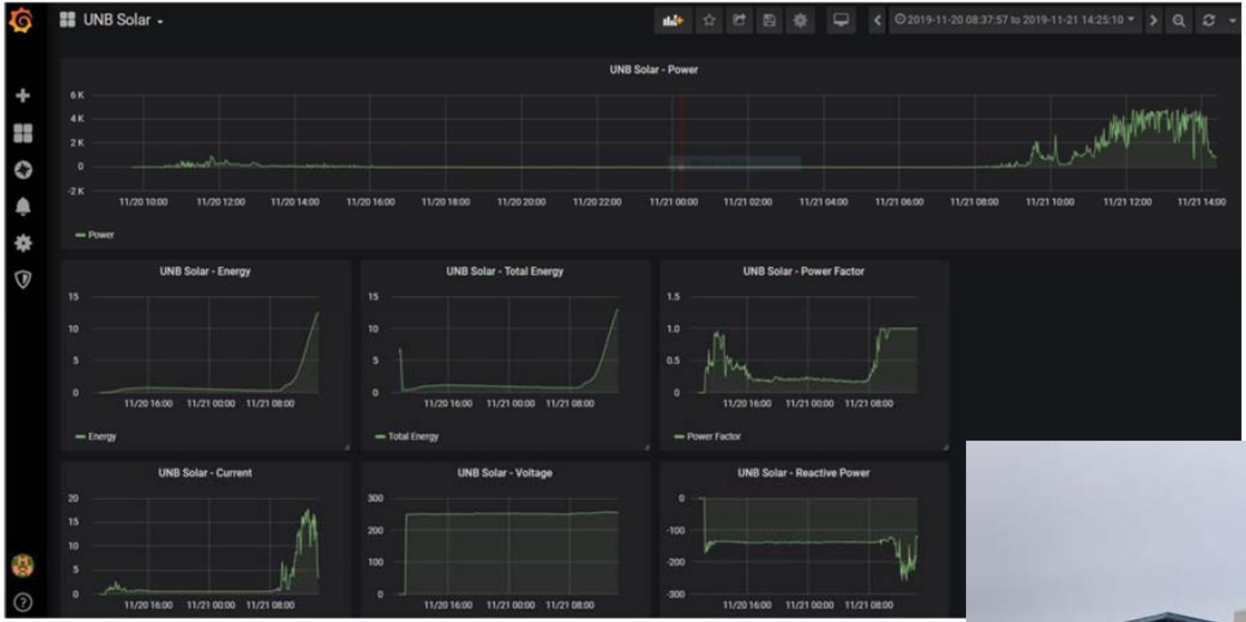


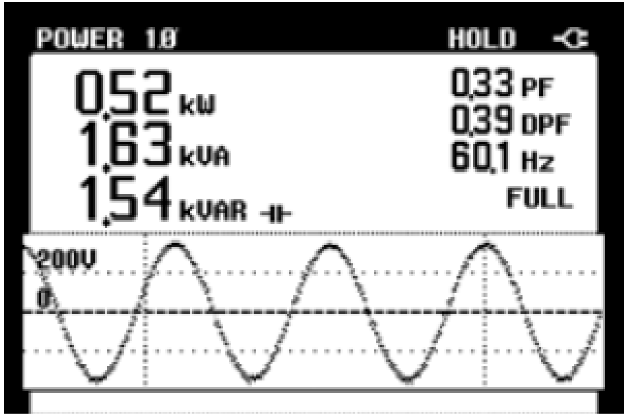






A Baby Step in an Actual Utility System





Pilot DERs in the Energy Control Centre: PVs, EVs, heat pumps, ETS, water heaters, battery systems, backup diesels & DERMS

pels IEEE POWER ELECTRONICS SOCIETY Powering a Sustainable Future

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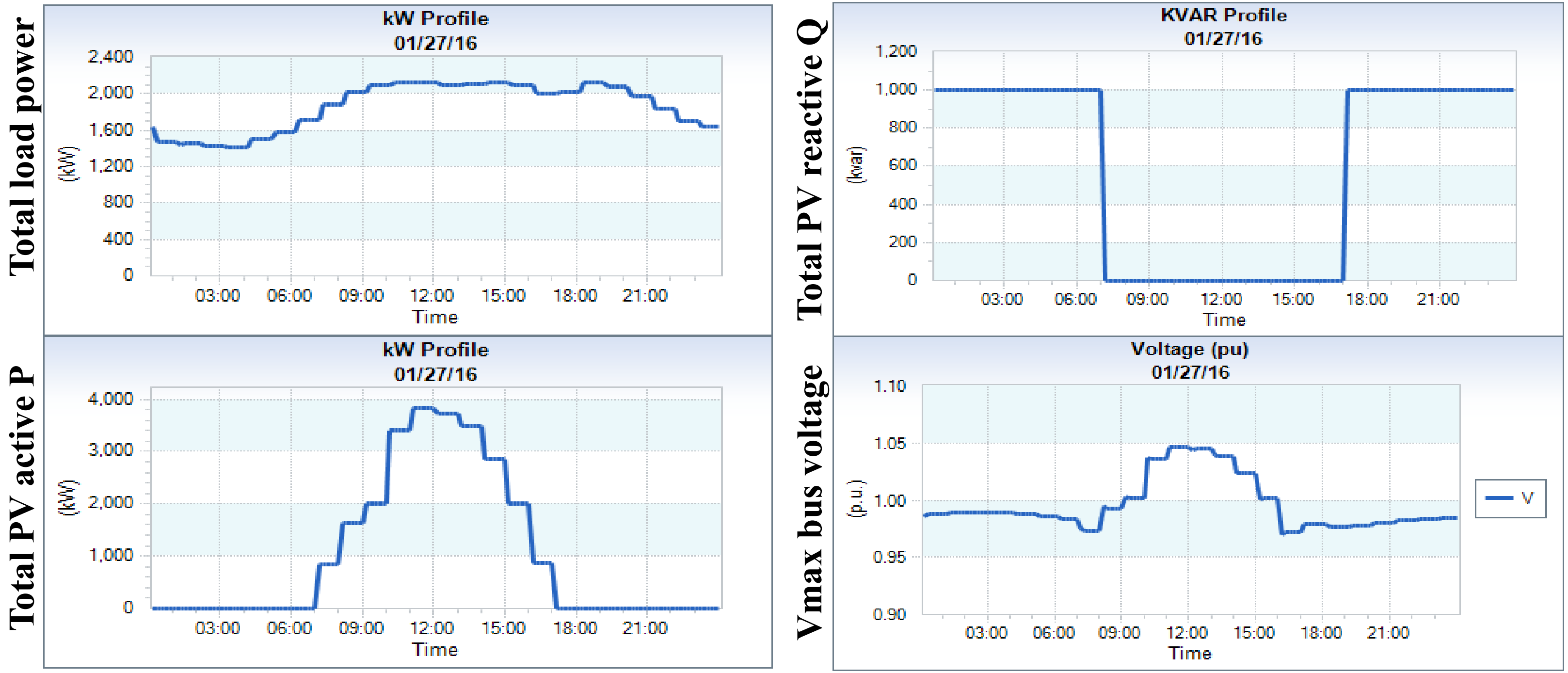
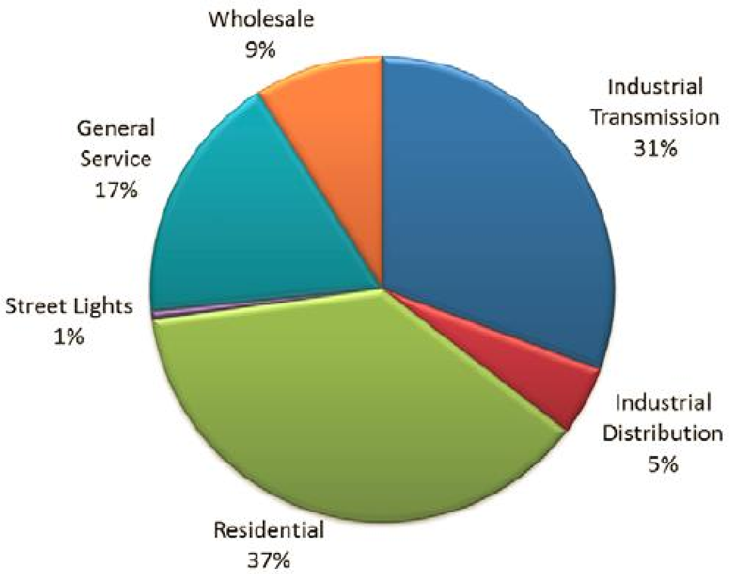
Voltage Regulation Solution for a Utility

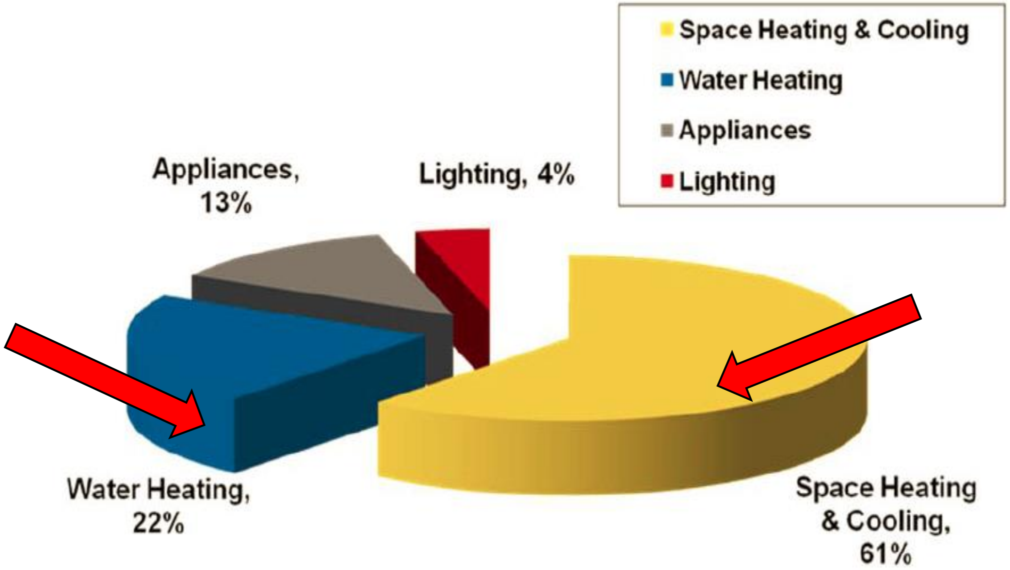
CYME Simulation for recommended solution for keeping the bus voltage at the end of the feeder within the normal range (5%): Transformer tap (primary): 102%, PV-Q=1 MVar (Location: EH_Junction, Operation time: from 5pm to 7am)



Keep an Open Mind: Load as Storage?

Load Control

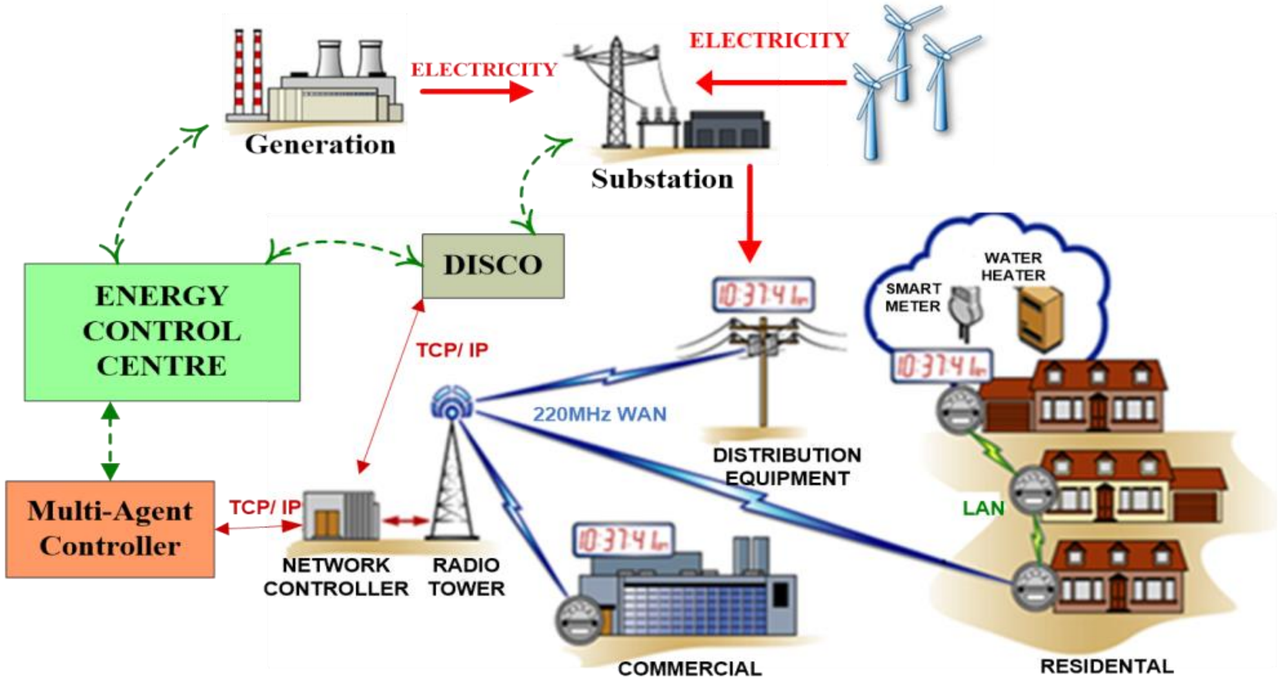




Typical household electricity usage in NB, Canada

- 83% has energy storage capacity

Direct Load Control – Evolution



- AMI infrastructure
- Continuous demand response
- No impact to end use
- Frequency regulation
- Synchronous reserve
- Load following
- Peak shaving

Controllable Loads as System Resources

Verified ancillary services by loads - temporally decouple the end use and electricity consumption – PowerShift Atlantic (PSA), $32 M, 5 years

PSA End Uses					
Electrical Storage Heater (ETS)	Electrical Storage Furnace	Refrigeration	Water Storage	Domestic Electric Water Heater	Commercial HVAC
					

POWER SHIFT ATLANTIC ATLANTIQUE
An energy research project • Un projet de recherche sur l'énergie

Énergie NB Power

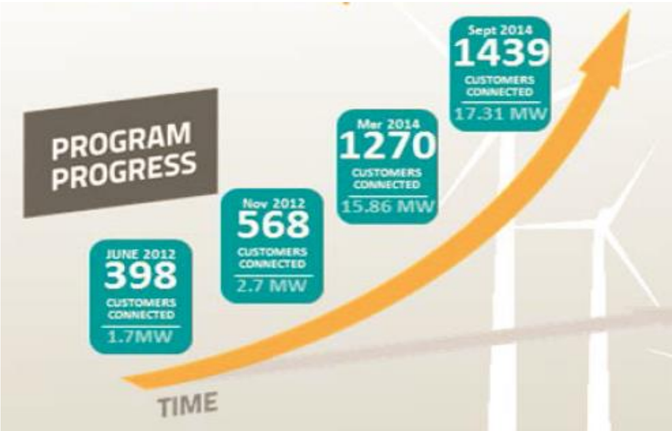
NOVA SCOTIA POWER
An Emera Company

NBSO ERNB

MARITIME ELECTRIC
A FORTIS COMPANY

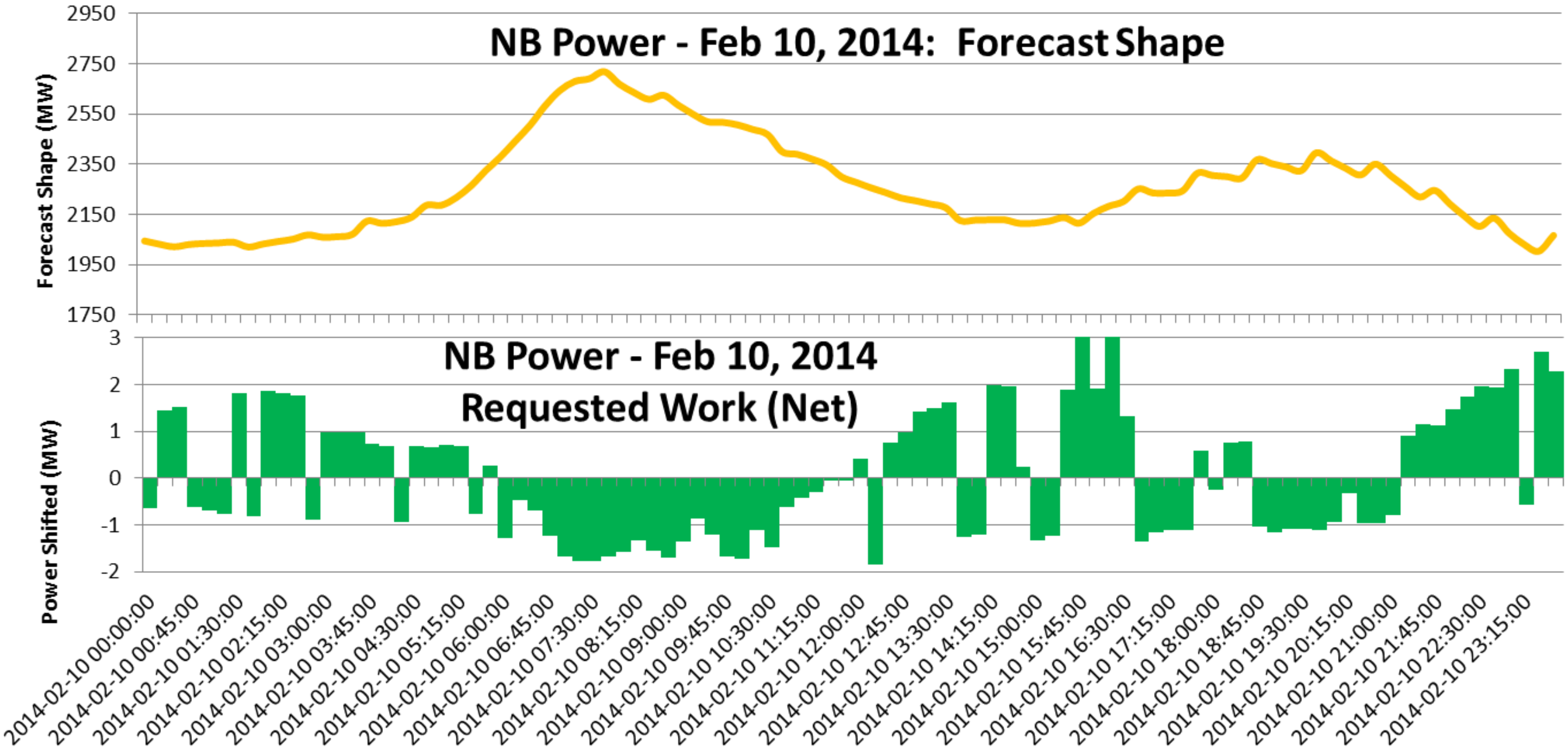
Saint John Energy

UNB



Virtual Power Plant (VPP) - Functions

- Optimize load profile based on system resource requirements
- Shift load power (energy dispatch) without impact to normal end use
- Real-time power system operation - Ancillary services (e.g. 10-minute reserve)



Conclusions

- Distributed Energy Resource (DER) market is growing, fast and steady.
- Power converters are critical apparatuses for DERs in power systems, to provide conversion, interface, control and integration.
- WBG devices may be the natural choice for the next-generation DER power converters (over a long-term horizon).
- The algorithms and applications of power system support functions (voltage regulation, frequency regulation, voltage ride-through and frequency ride-through) are evolving.
- There are tremendous benefits to power systems and opportunities for DER technologies, helping the transition of our electrical grids.

Thank You Very Much!