Advanced Inverter Technologies for Storage, Solar and Wind Integration

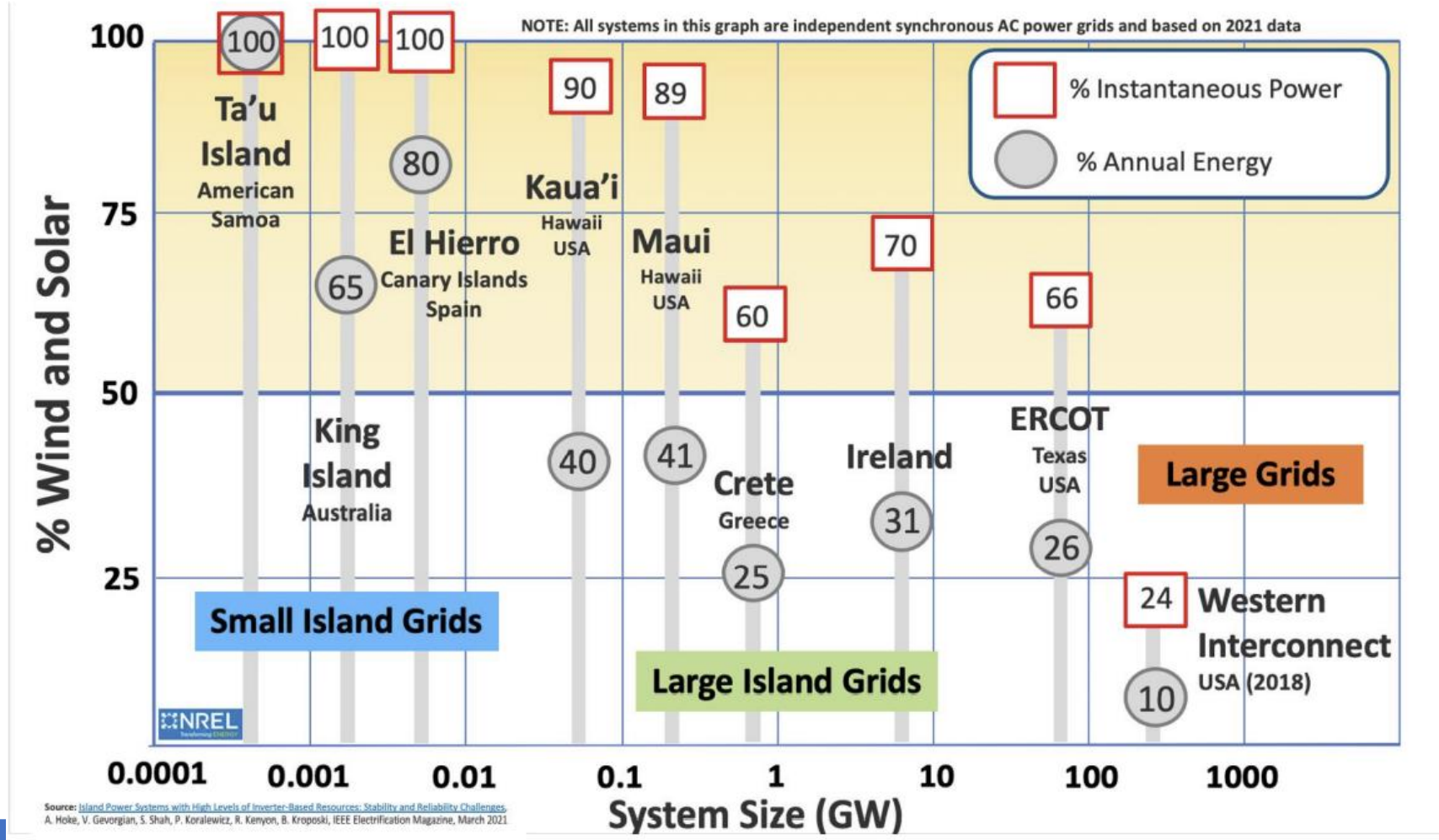
Julia Matevosyan, Chief Engineer, ESIG

March 1, 2022

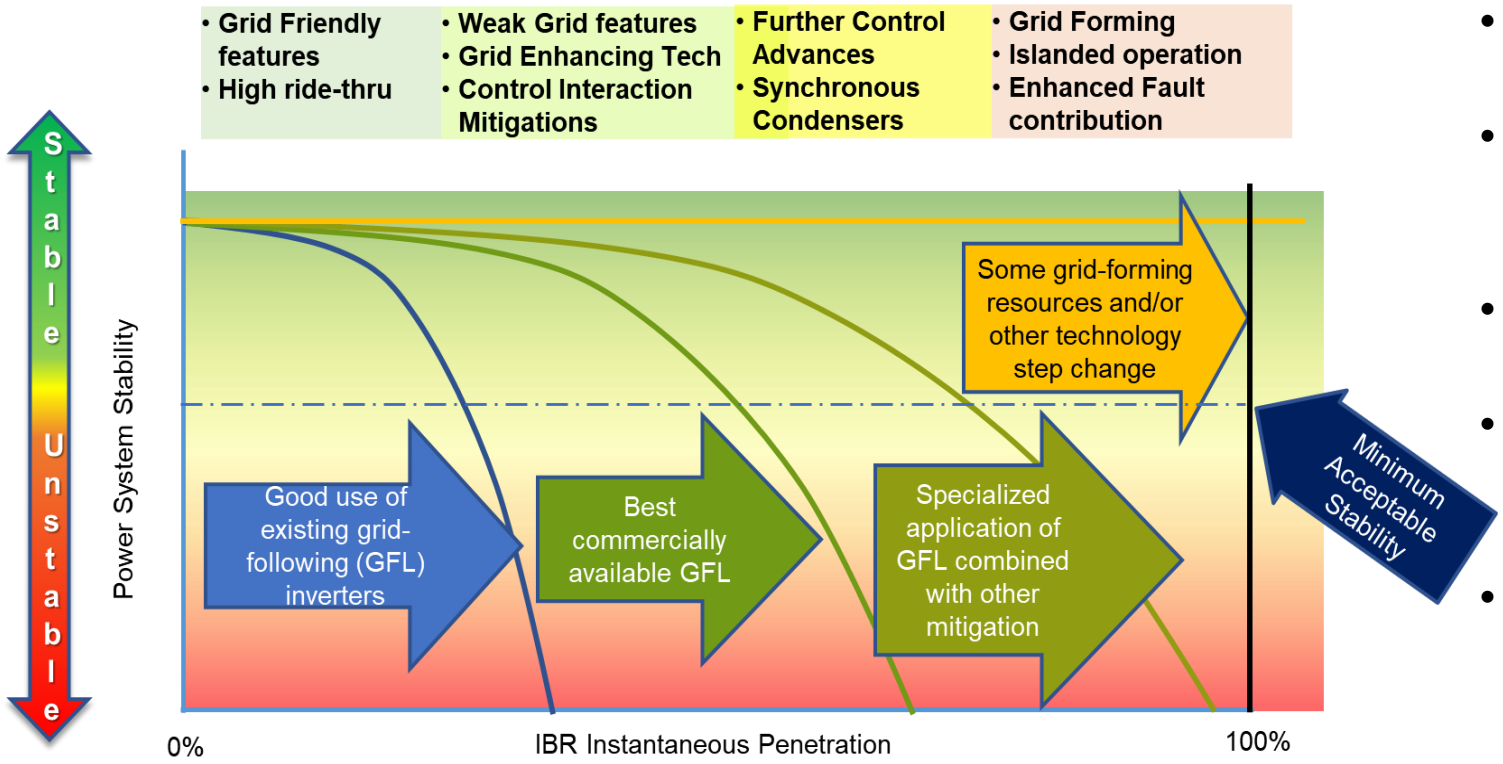
ESIG

ENERGY SYSTEMS INTEGRATION GROUP

Where Are We Today?



Technology Enablers to Promote the Shift to a Higher Renewable Future

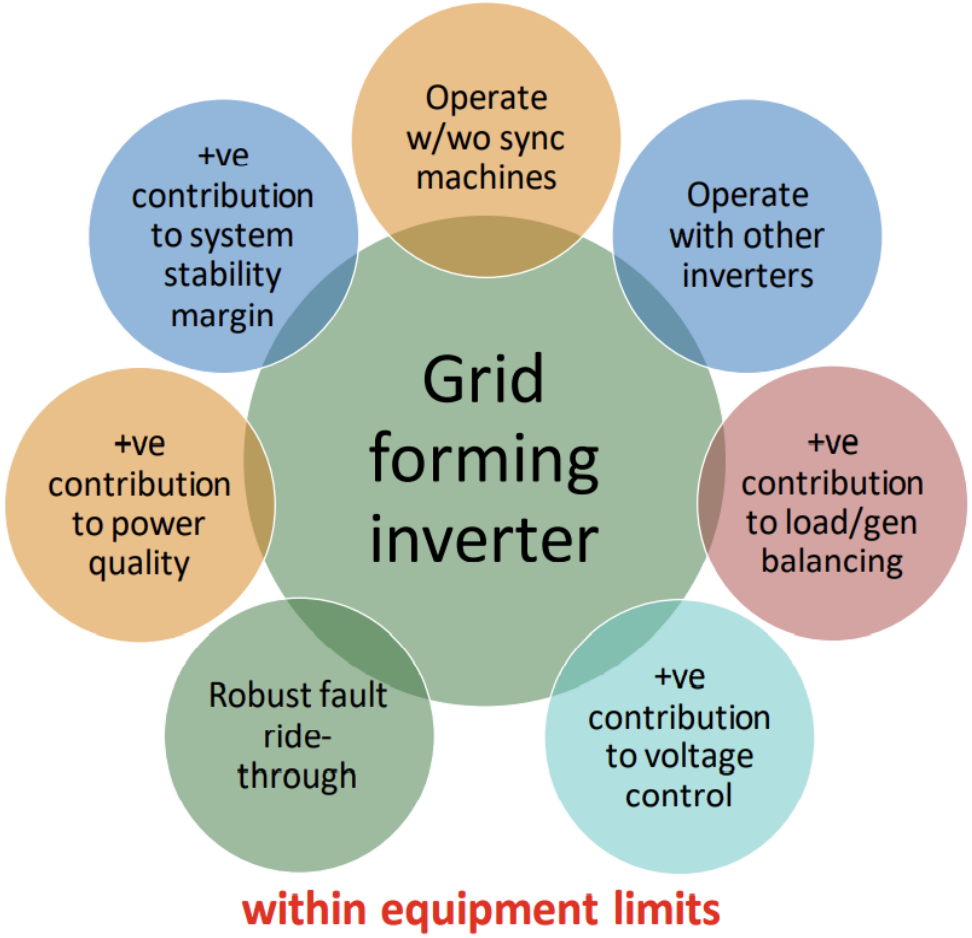


- Majority of the inverters today are “grid-following”
- They read the voltage and frequency of the grid, lock onto that, and inject power aligned with that signal.
- That signal comes from synchronous generators.
- The further wind and solar generation pockets are from synchronous generation, the “weaker” the grid.
- The signal is then easily perturbed by power injection from wind and solar resources, making it hard for inverters to lock onto it correctly.
- This may lead to local instability issues.

Grid Following vs Grid Forming

- A new class of inverters with advanced control that are gaining interest in industry - called “grid forming” inverters.
- These advanced inverter controls can be designed to have stabilizing effect in weak grid areas and improve stability for existing grid following inverter-based resources.
- They can also provide other grid services.
- The advantage of this solution is that it is provided by a generation resource itself and may not require additional transmission assets, such as e.g. synchronous condensers.
- Note that voltage-source HVDC technology if used in a transmission solutions can also have similar advantage for a weak grid area.

Grid Forming Inverter Capabilities



while *meeting standard acceptable metrics* associated with reliability, security, and stability of the power system

Source: EPRI Grid Forming Inverters EPRI Tutorial, September 1, 2020

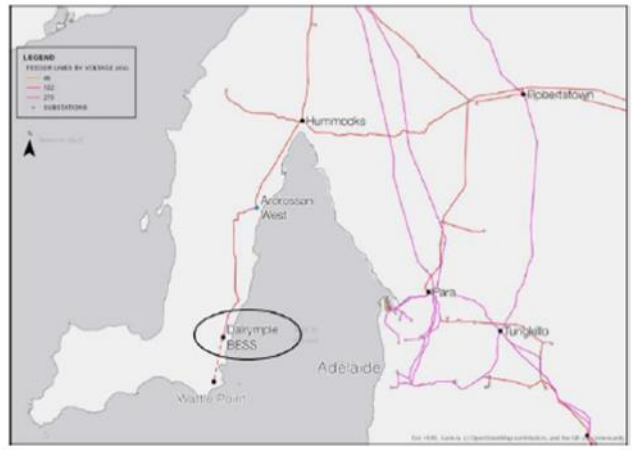
Pilot Projects and First Interconnection Requirements for Grid-Forming Capability

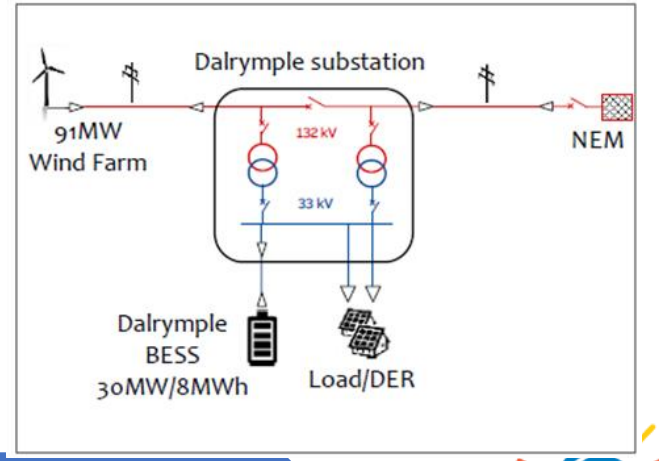
- Battery energy storage systems (BESS) for microgrids and black start of simple cycle gas turbines (GE)
- BESS on St Eustatius island (SMA)
- Dersalloch Wind Farm in Scotland (Siemens Gamesa)
- Mackinac back-to-back Voltage Source Converter HVDC Flow Control Project (Hitachi ABB)
- Dalrymple BESS in South Australia (Hitachi ABB)
- Hornsdale BESS in South Australia (Tesla)
- More Grid Forming BESS underway in Australia
- Stability Pathfinder in Great Britain (National Grid ESO)
- First Approved (non-mandatory) Grid Forming Interconnection Requirements in Great Britain

For further information: ESIG Survey of Grid Forming Inverter Applications

Hitachi ABB Energy Storage for Commercial Renewable Integration (ESCRI) in grid-forming mode

- Dalrymple BESS in South Australia is the largest grid-connected grid forming battery in the world, at 30 MVA and 8 MWh.
- Virtual Synchronous Machine control method is used
- Commissioned in 2018, near the end of a long 132 kV single-circuit radial feeder close to 91 MW wind farm, local load up to 8 MW and 2 MW of local rooftop PV
- In the first six months of operation, reduced the loss of supply in the area from ~8 hours to 30 minutes.





Source: “Grid Forming Energy Storage: Provides Virtual Inertia, Interconnects Renewables and Unlocks Revenue”, https://go.hitachi-powergrids.com/grid-forming-webinar-2020

Hitachi ABB Energy Storage for Commercial Renewable Integration (ESCRI) in GFM mode

The services provided by the project include:

- **Inertia** –can provide virtual inertial response with configurable magnitude, reducing impact on system frequency after sudden loss of load or generation.
- **System Strength** –can operate in very weak grids. It is also able to provide system strength support via short-term overload capability
- **Islanded operation** – regulates the frequency in the microgrid by utilizing virtual inertia and frequency control. Additionally, can adjust frequency of the island to invoke curtailment and avoid overgeneration conditions due to too much rooftop PVs.
- **Black start capability** – can black start the local distribution network with local demand.

Source: “Grid Forming Energy Storage: Provides Virtual Inertia, Interconnects Renewables and Unlocks Revenue”, https://go.hitachi-powergrids.com/grid-forming-webinar-2020

Conclusions

- As more wind, solar, battery storage are added to the power systems, essential reliability services that historically been provided by traditional thermal generators now need to be provided by wind, solar and battery resources as well.
- Existing inverter technology has already been enhanced over the years to enable provision of some of these services
- Currently new advanced inverter controls are being developed and deployed providing additional services that potentially will allow reaching even higher shares of renewable resources on the grid.
- Further steps are needed in incentivizing provision of grid services, standardizing performance requirements and performance validation of advanced inverter technologies.

Thank You!

ESIG
ENERGY SYSTEMS
INTEGRATION GROUP

Energy Systems Integration Group is a non-profit educational association that provides workshops, resources and education on the evolving electricity and energy systems.

ESIG supports engineers, researchers, technologists, policymakers and the public with the transformation of energy systems in a way that is economic, reliable, sustainable, thoughtful and collaborative.

www.ESIG.energy

Advanced Transmission Technologies
Operational Technologies to Enhance Transmission Capacity and Flexibility

CRITICAL CONSUMER ISSUES FORUM - SUMMIT 1 VIRTUAL EDUCATION SESSION

THE CUSTOMER-CENTERED CLEAN ENERGY TRANSITION:
BALANCING TECHNOLOGY, PEOPLE & THE PLANET



PRESENTED BY

T. Bruce Tsuchida (The Brattle Group)

MARCH 1, 2022

Brattle

Disclaimer

This presentation is intended to assist the discussion for the March 1, 2022 CCIF Webinar "The Customer-Centered Clean Energy Transition: Balancing Technology, People & the Planet." This presentation and associated discussion are not meant or permitted to be a substitute for the exercise of any business judgment. The contents of this presentation may involve the use of assumptions and projections with respect to conditions that may exist or events that may occur in the future. Although The Brattle Group has applied assumptions and projections that are believed to be reasonable, they are subjective and may differ from those that might be used by other economic or industry experts to perform similar analysis. In addition, and equally as important, actual future outcomes are dependent upon future events that are outside The Brattle Group's control. No one can give any assurance that the assumptions, projections, or judgments used will prove to be correct or that actual future outcomes will match the forecasts. The Brattle Group cannot, and does not, accept liability under any theory for losses suffered, whether direct or consequential, arising from any reliance on this presentation, and cannot be held responsible if any conclusions drawn from this presentation should prove to be inaccurate.

Agenda

- Transmission and Transfer Capabilities
- Advanced Transmission Technologies
- Potential Benefits



Slides are largely excerpted from the full report, available at https://watt-transmission.org/2021/02/22/unlocking-the-queue/

What Causes the Limit for the Wires?

Transfer capabilities are largely defined by two factors: the physical capacity of individual lines and network topology.*

Physical capacity of individual overhead lines are primarily defined by the maximum operating temperature to:

- Maintain minimum electrical clearances (line sagging, etc.).
- Limit annealing of conductor aluminum.
- Limit aging of connectors/hardware.

– Increased power flow warms the line (resistive heating).

– Ambient conditions also impact line temperature.

Network topology:

– Key factor defining the distribution of power flows—i.e., how much flows on each line.
  - Power flows on the path of least resistance.
  - That’s why touching a live wire is dangerous.



Grid Enhancing Technologies – Introduction

Traditional thinking treated transmission as if it is fixed and cannot be operated dynamically.

- Transmission has a fixed capacity, much like roads or railways do (e.g., the number of cars or trains that can go through at any given time).
- Advancements in maps and GPS technology have allowed for safer, easier and more efficient driving on the same roads and railways.
- Are there similar technologies that allow for such innovation in transmission **operations** (and planning)?

Grid Enhancing Technologies (GETs) enhance transmission operations and planning.

- Three GETs examples introduced today: Dynamic Line Ratings, Topology Optimization, and Advanced Power Flow Control.
- These technologies have matured over the past several decades, are commercially proven and **actively operating** on grids around the world.
- They **focus on operational improvements** and have a much lower cost and faster implementation than traditional transmission technologies.
  - Similar to the comparison between building a road to reduce congestion (long-term investment) and having a good map/GPS system to avoid congested roads (operational improvements).



Dynamic Line Ratings - 1/2

Historical practice was largely based on Static Line Ratings (SLR).



- Maximum operating temperature for a given line is pre-determined.
  - Uses conservative assumptions, such as low wind, high temperature, high solar irradiance, etc., to accommodate most conditions.
  - It is similar to setting highway speed limit based on snowy road conditions.
  - Recently more transmission operators have adopted ambient adjusted rating (AAR).

DLR enhances AAR further and utilize real-time data.

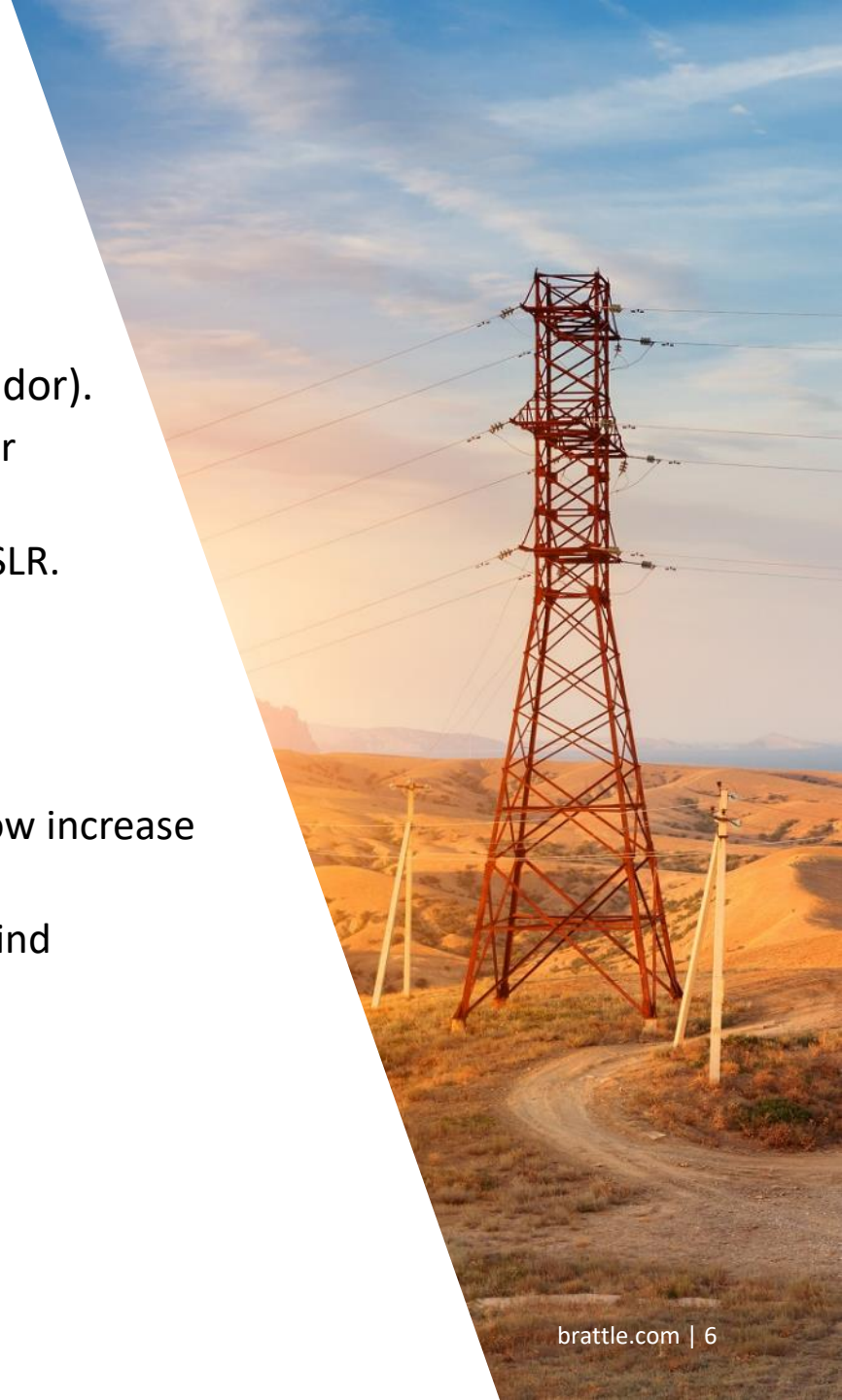
- Commonalities between SLR, AAR, and DLR.
  - Minimum allowable electrical clearance is the same.
- Differences between SLR, AAR, and DLR.
  - SLR applies uniform weather conditions to all lines and is generally lower than AAR and DLR that applies line-specific conditions.
  - AAR requires line-specific data and ambient temperature, but has a ≥ 15% risk of exceeding electrical clearance limitations (as commonly implemented in the U.S.)*
  - DLR requires line-specific data in conjunction with real-time monitoring of ambient temperature, wind and conductor position, and can provide forecasts for operations planning.*

* Post-Technical Conference Comments of the WATT Coalition, November 2019, available at: https://watttransmission.files.wordpress.com/2019/11/post-technical-conference-of-the-watt-coalition.pdf, pp 2-5.

Dynamic Line Ratings - 2/2

DLR adjust limits based on ambient conditions.

- Thermal ratings use real-time measurements the line location (along line corridor).
  - Line temperature, line sagging, ambient conditions (temperature, humidity, solar irradiance, wind, precipitation etc.).
  - DOE/ONCOR study indicates DLR transfer capability to be 5 to 25% higher than SLR.
- Accumulation of real-time data can be used for future calibration.
  - DLR is variable and requires a forecast for operations planning.
- High wind leads to higher cooling and allows for increased flow.
  - High degree of overlap between wind production and DLR-induced allowable flow increase has been observed.
  - European studies indicate DLR contributes to approximately 15% reduction in wind curtailments in some areas.



Advanced Power Flow Control - 1/2

Phase Shifting Transformers (PSTs)* and Flexible Alternating Current Transmission Systems (FACTS) devices help the operator control flow through a given path.

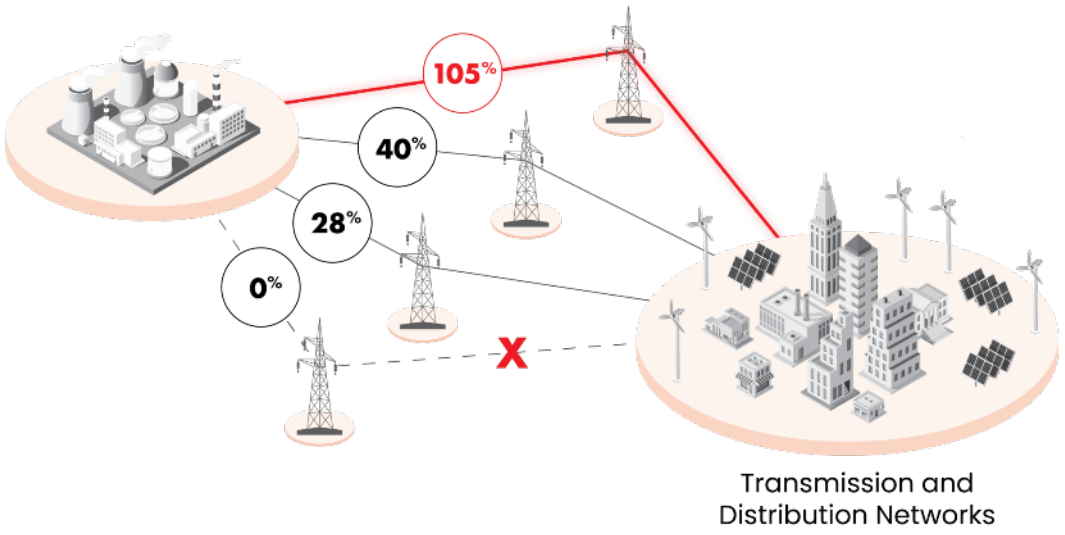
- These devices are widely accepted in the industry.
  - The largest drawback is the cost—for example, a recently-installed PAR* between Michigan and Ontario has an annual carrying cost of over $10 million.
- FACTS devices are power-electronic-based static devices that allow for flexible and dynamic control of flow on transmission lines or the voltage of the system.
  - Some FACTS devices alter the reactance of a line to control the flow (i.e., increasing the reactance will push away flows while decreasing the reactance will pull in more flow to the line).
  - FACTs devices typically cost less than PARs, can be manufactured and installed in a shorter time, are scalable, and in many cases, are available in mobile form that can be easily deployed (or redeployed, as needed) while providing flexible layout options.



* Phase Shifting Transformers are also called Phase Angle Regulators (PARs).

Advanced Power Flow Control - 2/2

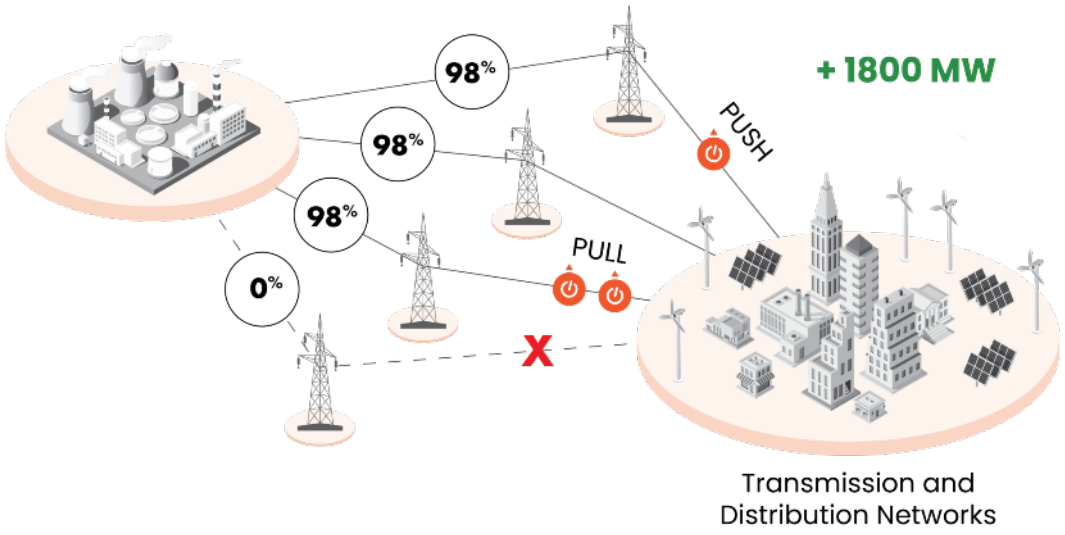
Before FACTS Device*



Traditional solutions include:

1. Redispatch generation
2. Reconductor constraining element
3. Install PSTs/Series Capacitor/Series Reactor
4. Construct a new parallel circuit

After FACTS Device



Power can be **PUSHED** and **PULLED** to alternate lines with spare capacity—leading to maximum utilization (typically obtained by a number of small applications on more than one circuit.)

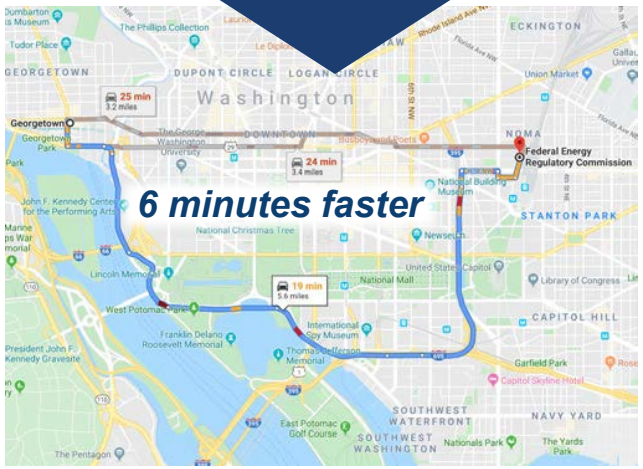
* Illustrative example from Smart Wires, https://www.smartwires.com/smartvalve/

Topology Optimization - 1/2

Topology Optimization is analogous to Waze: "Arrive to destination reliably, with minimum delay even when there are events on the road" by re-routing.

- Re-routing is achieved by grid reconfigurations: switching circuit breakers open or close.
  - Analogous to temporarily diverting traffic away from congested roads to make traffic smoother.
  - Similar effect as advanced flow control devices, using existing equipment.
- Reconfiguring the grid in operations is feasible today.
  - Circuit breakers are capable of high duty cycles and extremely reliable—some breakers are switched very frequently today, e.g., those connecting generating units with daily start and stop operations.
  - Switching infrastructure is already in place—most breakers are controlled remotely over SCADA by the TO.
  - Low cost: usually $10-$100 per switching cycle.





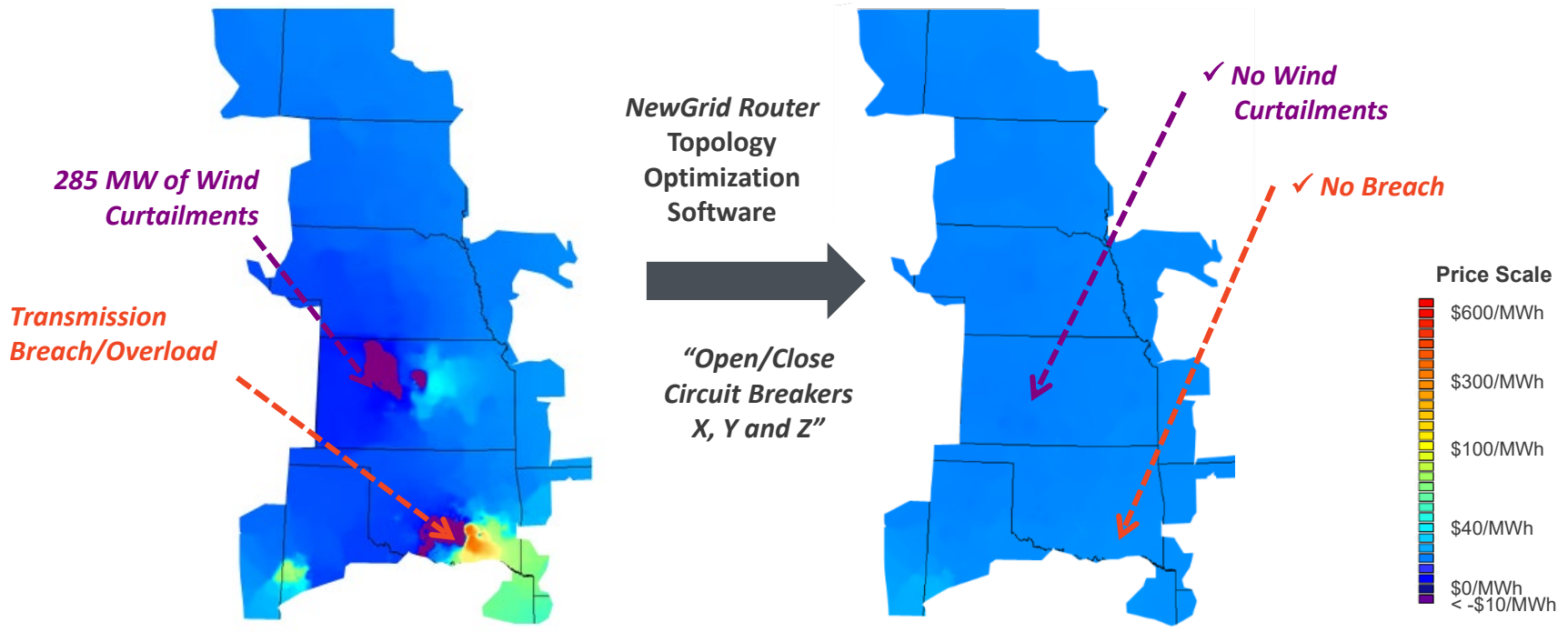
Road closure picture from https://www.islandecho.co.uk/plea-motorists-heed-road

Topology Optimization - 2/2

Topology Optimization software technology automatically finds reconfigurations to route flow around congested elements ("Waze for the transmission grid").

SPP Historical Case
(March 10, 2018 20:10 CST, 38% Wind Penetration)

With Reconfigurations
(3 actions, 1 per constraint in Historical Case)





Potential Benefits of GETs

Various studies indicate significant benefit potential at relatively low cost.

- Regional benefits of GETs are in the tens to hundreds of million dollars.
  - PJM study indicates over $100 million in production cost savings a year in real-time markets.
  - Pacific Gas and Electric Company's (PG&E's) review of Distributed Series Reactors (DSRs) indicated installing approximately 2,000 DSR to mitigate thermal overloading of a 230 kV line at an estimated cost of approximately $33 million would lead to almost a 75% cost savings compared to reconductoring.
- GETs reduce congestion and help integrate renewables.
  - European studies indicate DLR's contribution to reduced wind curtailment (~15%).
  - Quick implementation helps with the fast clean energy transition pace.
- Other benefits
  - Increased operational awareness, while providing redundancy and helping with resiliency.
  - Relatively lower cost investments help cash-stranded utilities that need to invest to accommodate load growth (which could be triggered further by electrification, etc.).

For more examples, see:



Available at: https://elibrary.ferc.gov/eLibrary/filedownload?fileid=15283553

Other Benefits – Renewable Integration



Study Outline

- The SPP Generation Interconnection Queue shows over 9 GW of renewables with signed Interconnection Agreements (IA) awaiting in the Kansas/Oklahoma region.
- Can GETs help integrate these projects?
- GETs analyzed include the three introduced in this presentation. Analysis looks at the combined benefits of the 3 GETs.
- Analysis performed for test year of 2025 (not enough time to build new transmission).
- Case study demonstrates how GETs (including their advanced software) can help in system planning.

The full report is available at: https://watt-transmission.org/2021/02/22/unlocking-the-queue/

Unlocking the Queue Study Results

Key benefits of GETs for Kansas and Oklahoma

- Enables more than **twice** the amount of additional new renewables to be integrated.
  - 2,600 MW without GETs vs 5,300 MW with GETs. This difference of 2,700 MW is 1.5x the amount of wind SPP integrated in 2019.
- Estimated annual production cost savings: $175 million (assuming $20/MWh).
  - Payback for GETs investment is about 0.5 years.
- Estimated carbon emissions reduction: Over 3 million tons per year.
- Over 11,300 direct short-term and 650 direct long-term jobs.
- Over $32 million annual tax revenues and $15 million land lease revenues.

Potential Nation-Wide Benefits

Extrapolating these results to a nation-wide level* indicate GETs to provide **annual benefits** in the range of:

- Over **$5 billion** (~$5.3 billion) in production cost savings.
- **$90 million tons** of reduced carbon emission (more than enough to offset **ALL NEW** automobiles sold in the U.S. a year).
- About **$1.5 billion** in local benefits (local taxes and land lease revenues).
- More than 330,000 short-term (only for first year) and nearly 20,000 long-term jobs.
- Investment cost is $2.7 billion (only for first year). Ongoing costs would be around $300 million per year.

* EIA shows 2019 generation in Kansas and Oklahoma combined (136 TWh) was about 1/30 of the nationwide generation from utility-scale resources (4,100 TWh). EIA data, available at: https://www.eia.gov/electricity/state/kansas/, https://www.eia.gov/electricity/state/oklahoma/, and https://www.eia.gov/electricity/annual/html/epa_01_01.html

About Brattle

About Brattle

The Brattle Group answers complex economic, finance, and regulatory questions for corporations, law firms, and governments around the world. We are distinguished by the clarity of our insights and the credibility of our experts, which include leading international academics and industry specialists. Brattle has over 400 talented professionals across three continents. For more information, please visit **brattle.com**.

Our Services	Our People	Our Insights
Research and Consulting	Renowned Experts	Thoughtful Analysis
Litigation and Support	Global Teams	Exceptional Quality
Expert Testimony	Intellectual Rigor	Clear Communication

This Report may be redistributed. If only a portion of Report is redistributed, the redistributed portion(s) must be accompanied by a citation to the full Report.

Our Practices and Industries

ENERGY & UTILITIES

- Competition & Market Manipulation
- Distributed Energy Resources
- Electric Transmission
- Electricity Market Modeling & Resource Planning
- Electrification & Growth Opportunities
- Energy Litigation
- Energy Storage
- Environmental Policy, Planning & Compliance
- Finance and Ratemaking
- Gas/Electric Coordination
- Market Design
- Natural Gas & Petroleum
- Nuclear
- Renewable & Alternative Energy

LITIGATION

- Accounting
- Alternative Investments
- Analysis of Market Manipulation
- Antitrust/Competition
- Bankruptcy & Restructuring
- Big Data & Document Analytics
- Commercial Damages
- Consumer Protection & False Advertising Disputes
- Cryptocurrency and Digital Assets
- Environmental Litigation & Regulation
- Intellectual Property
- International Arbitration
- International Trade
- Mergers & Acquisitions Litigation
- Product Liability
- Regulatory Investigations & Enforcement
- Securities Class Actions
- Tax Controversy & Transfer Pricing
- Valuation
- White Collar Investigations & Litigation

INDUSTRIES

- Electric Power
- Financial Institutions
- Infrastructure
- Natural Gas & Petroleum
- Pharmaceuticals & Medical Devices
- Telecommunications, Internet & Media
- Transportation
- Water

This Report may be redistributed. If only a portion of Report is redistributed, the redistributed portion(s) must be accompanied by a citation to the full Report.

Our Offices



























Brattle

Clarity in the face of complexity

Brattle



Copyright © 2021 The Brattle Group, Inc.