CHANGING WHAT'S POSSIBLE

Grid Power Flow Control and Optimization

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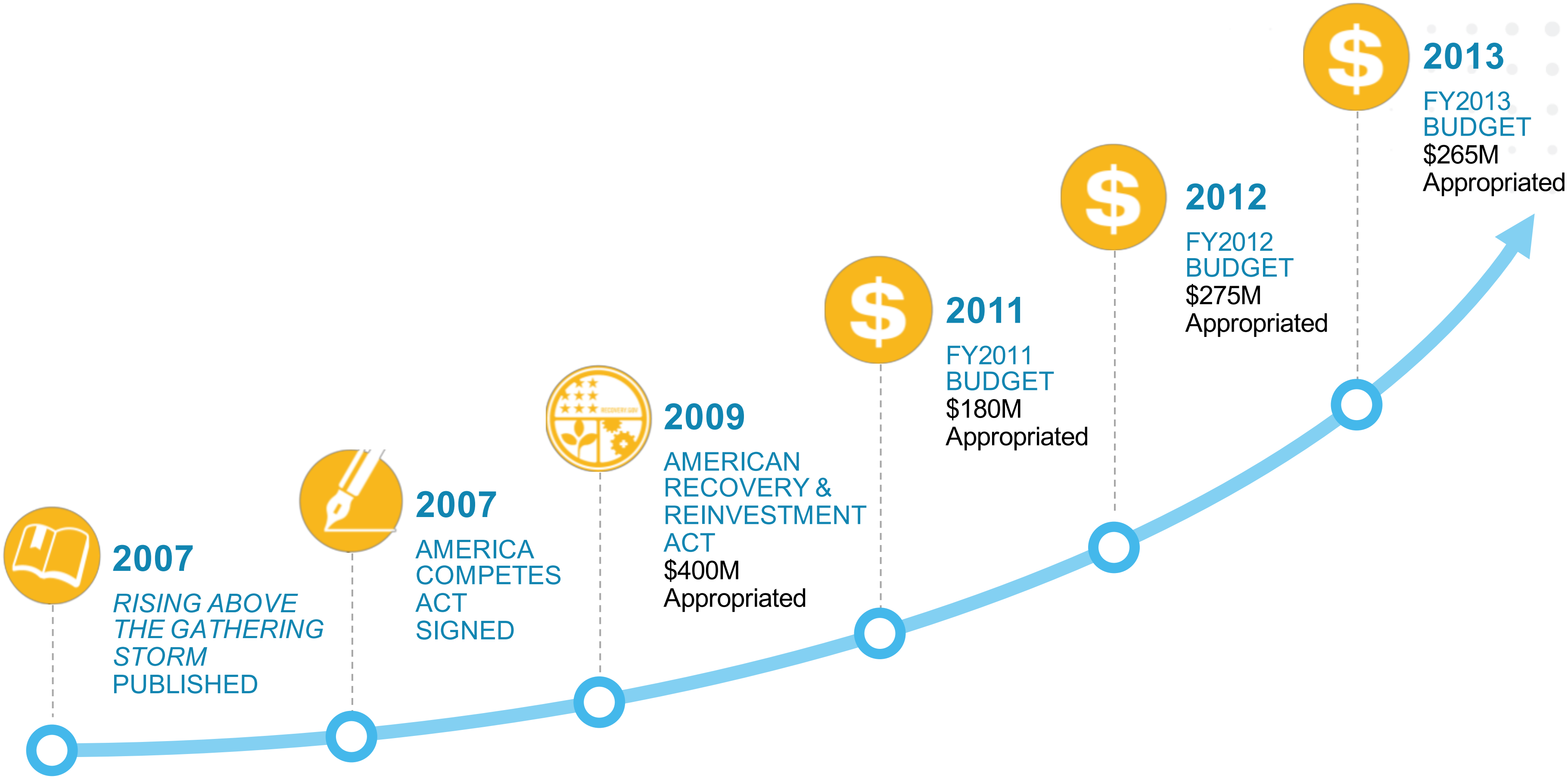
Advanced Research Projects Agency – Energy (ARPA-E)
U.S. Department of Energy

Carnegie Mellon Electricity Industry Center Seminar
Pittsburgh, PA, September 27, 2013

U.S. DEPARTMENT OF ENERGY

Evolution of ARPA-E



2007

RISING ABOVE THE GATHERING STORM
PUBLISHED

2007

AMERICA COMPETES ACT SIGNED

2009

AMERICAN RECOVERY & REINVESTMENT ACT
$400M Appropriated

2011

FY2011 BUDGET
$180M Appropriated

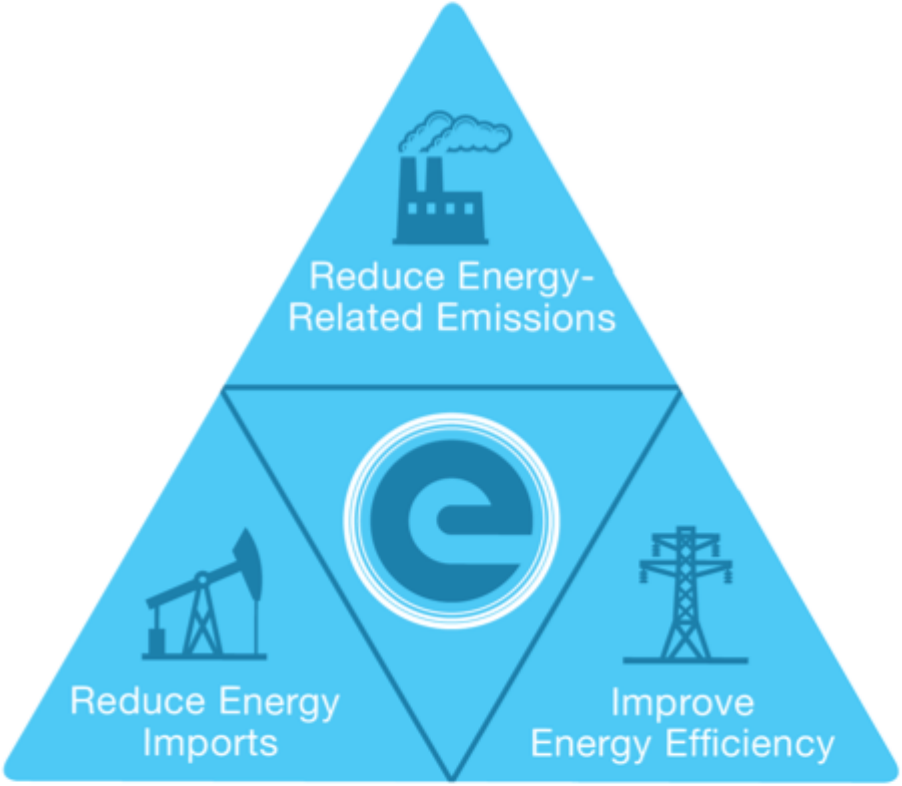
2012

FY2012 BUDGET
$275M Appropriated

2013

FY2013 BUDGET
$265M Appropriated

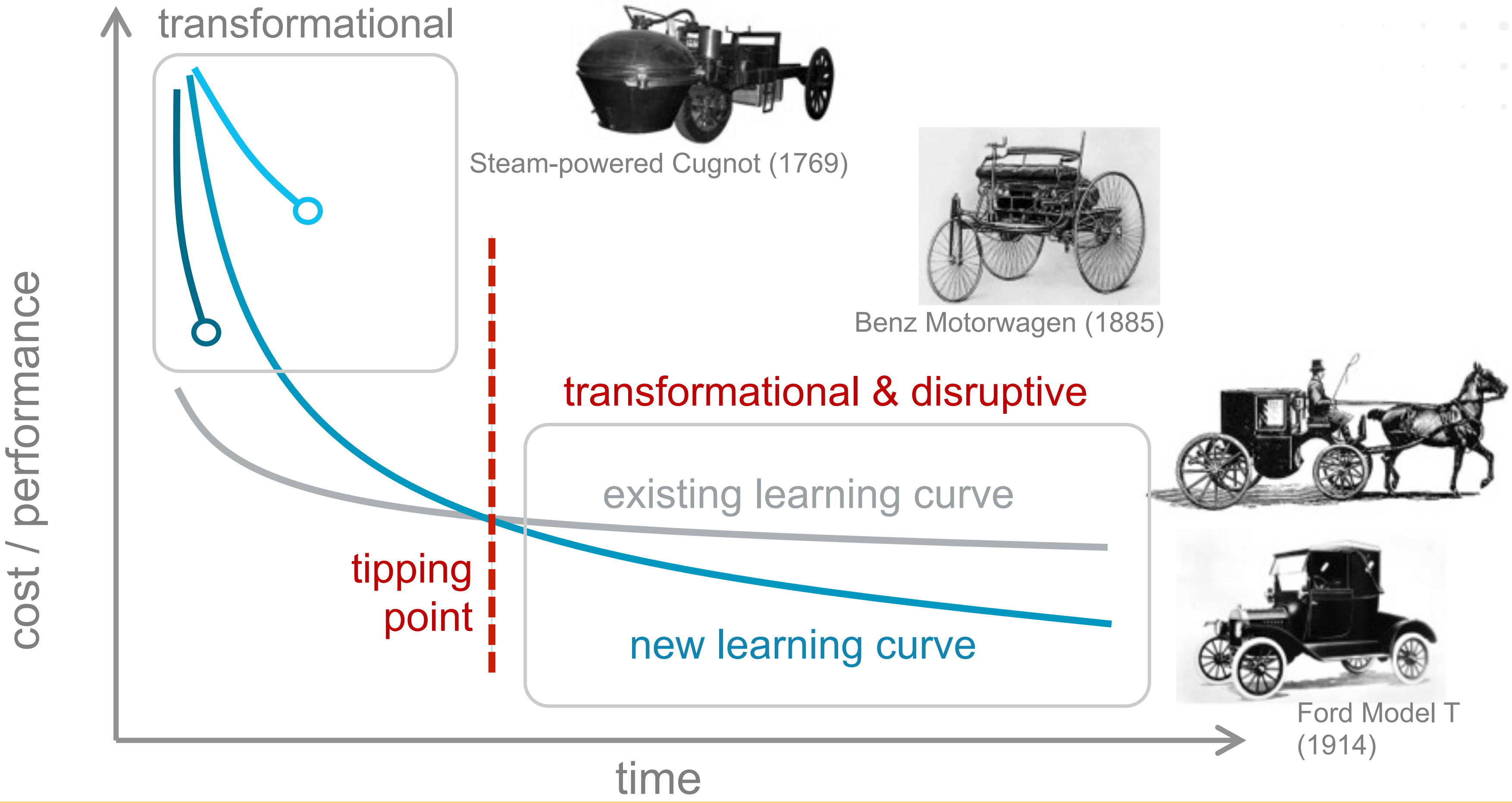
ARPA-E Mission



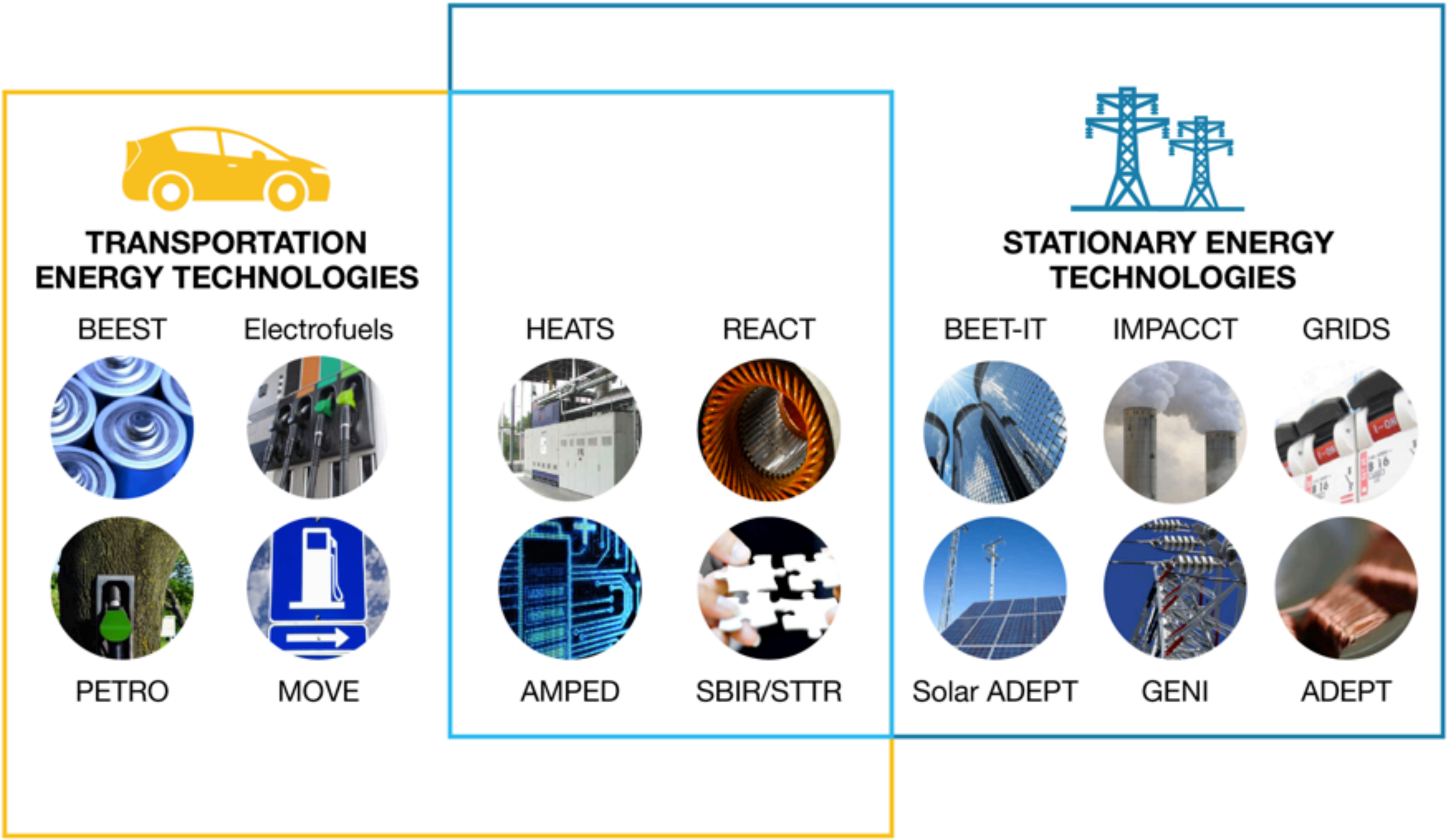
- Catalyze the development of transformational high-impact energy technologies.
- Ensure the U.S. maintains a lead in the development and deployment of advanced technologies.
- Enhance the economic and energy security of the United States.

The ARPA-E Approach

Transformational & disruptive technologies that lead to new learning curves.



Focused Programs



TRANSPORTATION ENERGY TECHNOLOGIES

BEEST
Electrofuels
PETRO
MOVE

HEATS
REACT
AMPED
SBIR/STTR

STATIONARY ENERGY TECHNOLOGIES

BEET-IT
IMPACCT
GRIDS
Solar ADEPT
GENI
ADEPT

New Grid Challenges and Opportunities

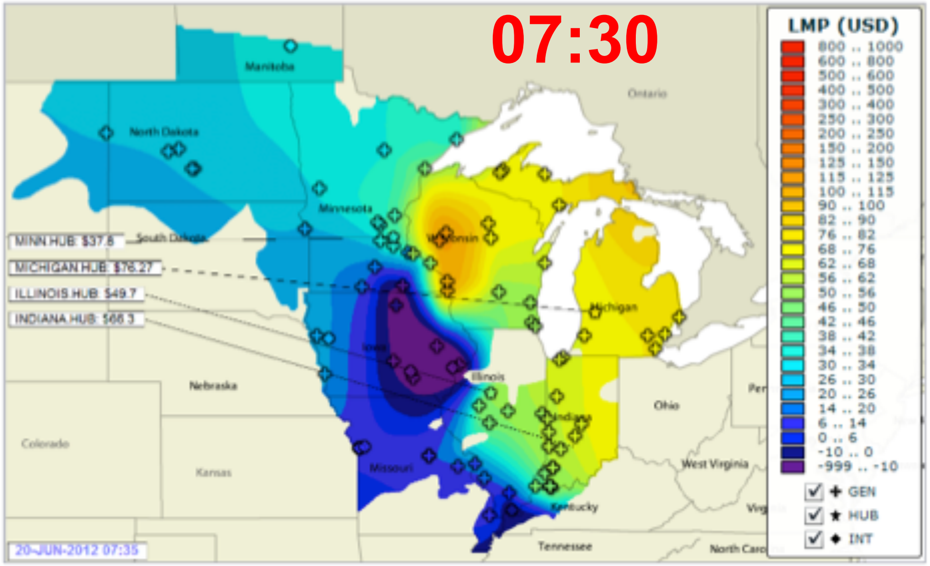
- **Many emerging grid challenges**
  - Aging infrastructure
  - Changing demand profiles
  - Increasing natural gas generation
  - Increasing wind and solar generation
  - Decentralization of generation

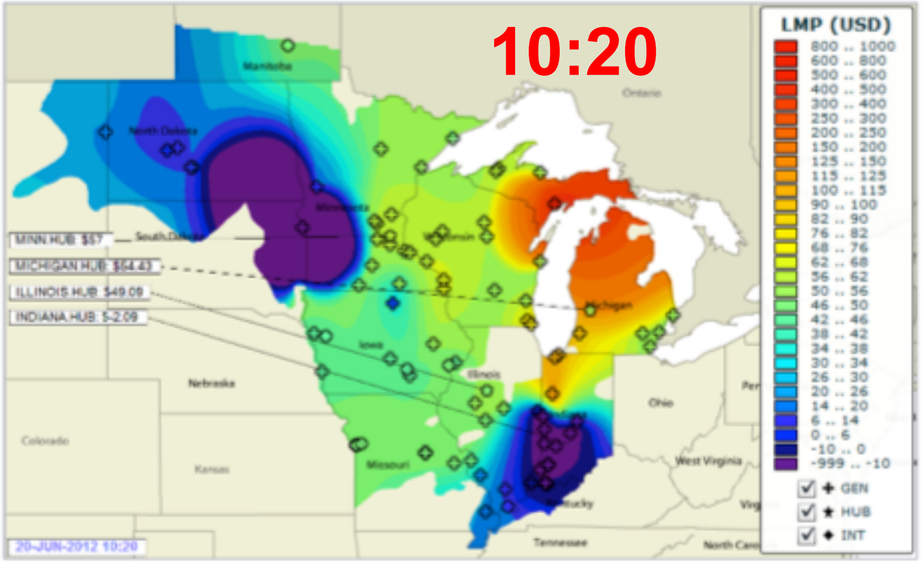
- **All of these challenges benefit from greater grid flexibility.**

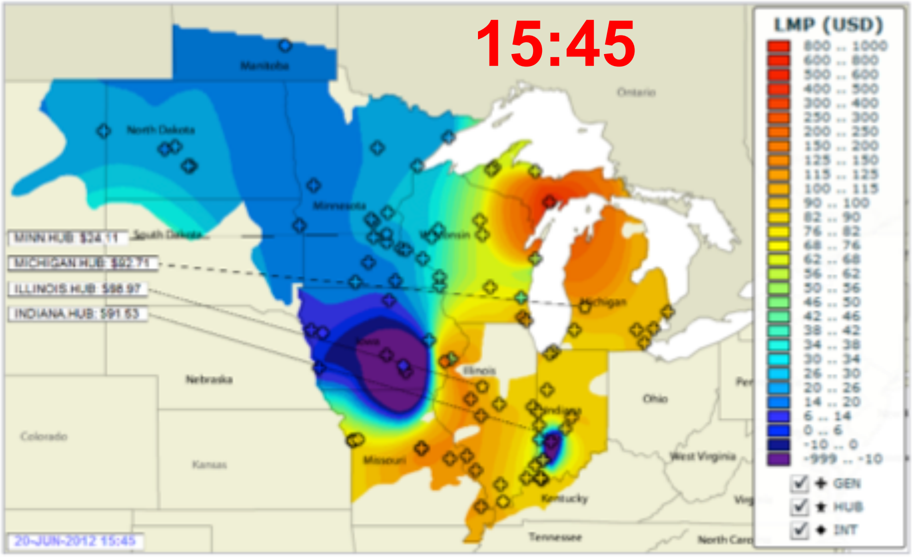
- **Today's grid is very dynamic. This will only increase in the future.**

Optimal Transmission Network: When?

Midwest ISO real time LMPs for June 20th, 2012



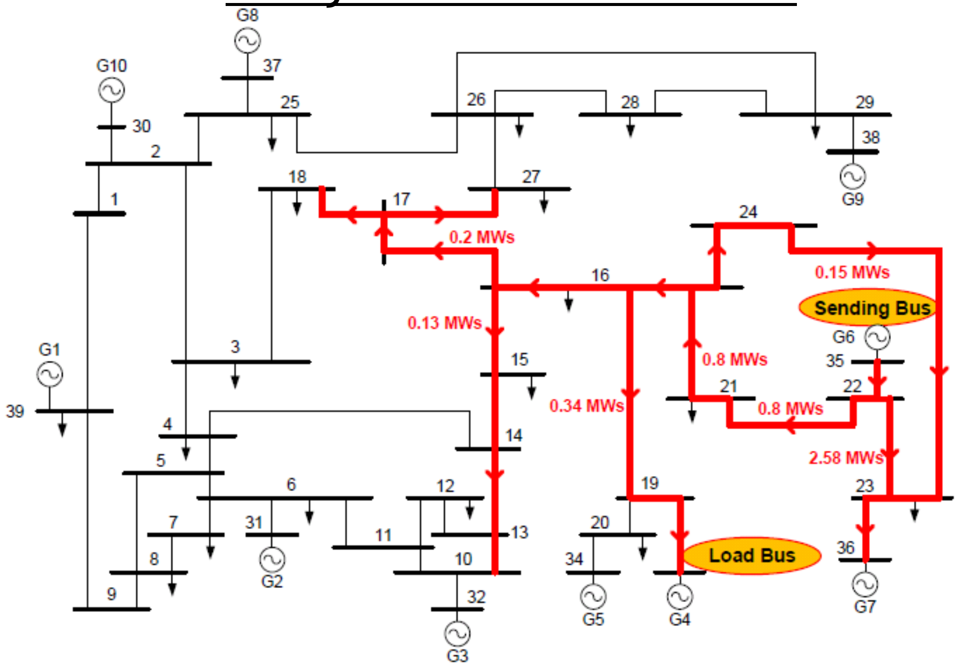




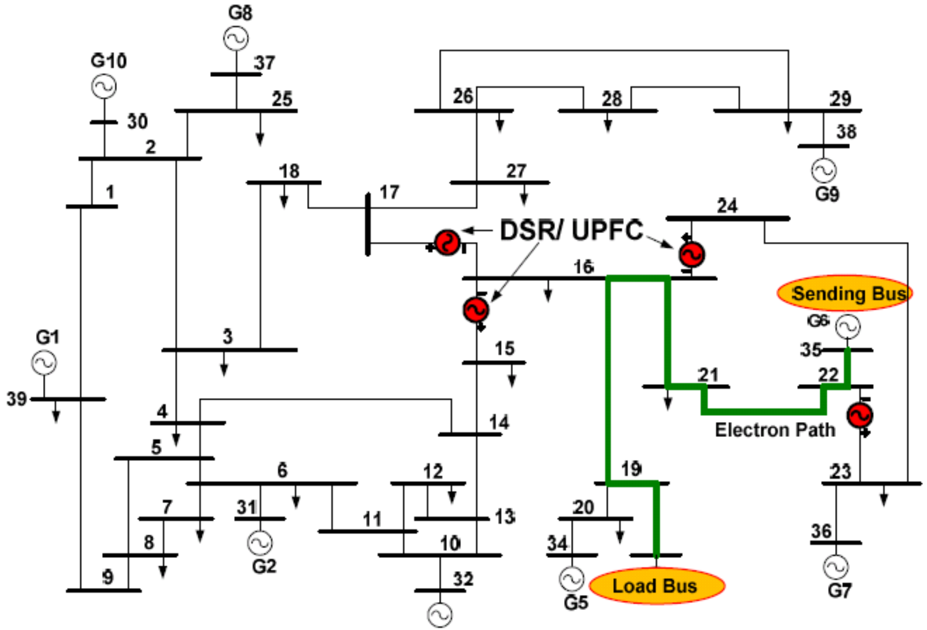
arpa·e
CHANGING WHAT'S POSSIBLE

Potential Benefits of Power Flow Control

Today: Uncontrolled Flows



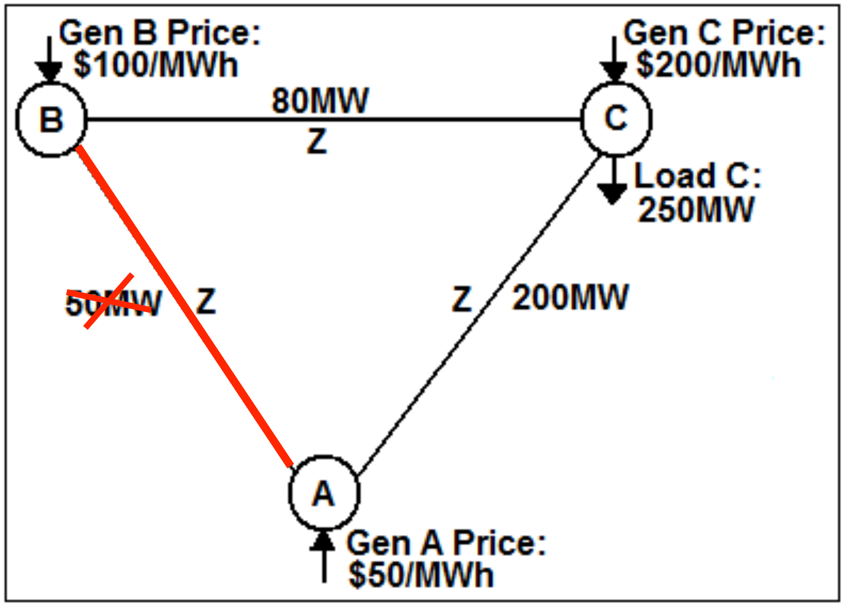
Future: Power Flow Control

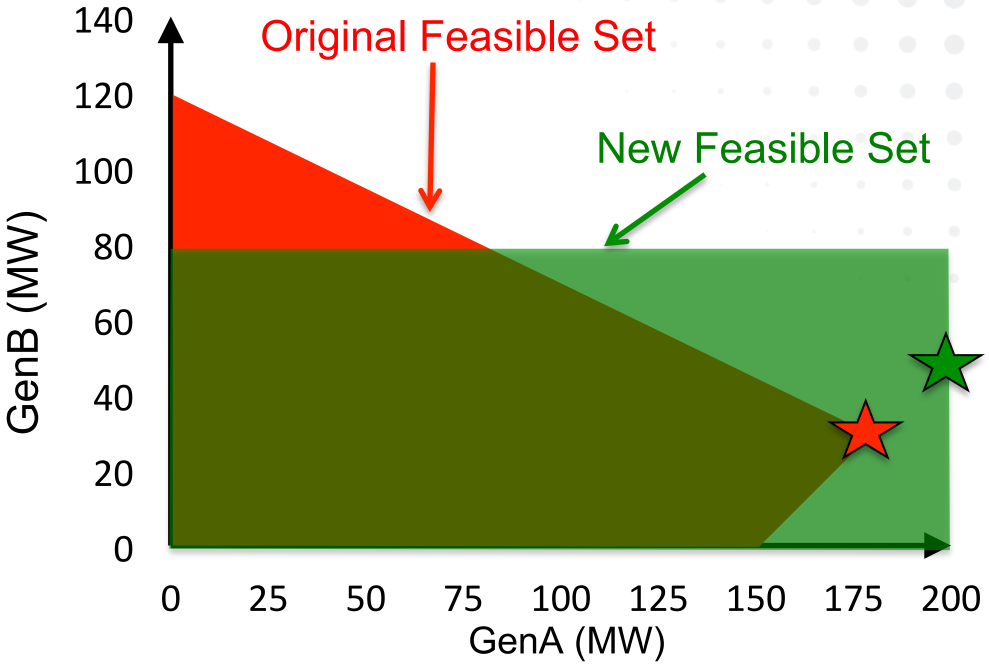


Potential Impact Example:

- GA Tech study of simplified IEEE 39 Bus system with 4 control areas.
- Operation simulated for 20 years, 20% RPS phased in over 20 years, sufficient transmission capacity added each year to eliminate curtailment of renewable generation.
- Power flow control to route power along underutilized paths → 80% less transmission infrastructure required.

Transmission Topology Optimization





Potential Impact Example:

- ISO-NE: 689 generators, 2209 loads, 4500 bus, 6600 binary variables
- Topology control (DC-OPF) to optimize state of only 4 transmission lines
- Solution Time: 82 hrs [CPLEX on dual-core 3.4GHz, 1GB RAM]
- Savings 5% for summer peak conditions/ 7% for a medium load summer condition.

Hedman, K. W., O'Neill, R. P., Fisher, E. B., and Oren, S. S. (2011), "Smart flexible just-in-time transmission and flowgate bidding," IEEE Transactions on Power Systems,Feb 2011.

Power flow control

Power flow control: the ability to change the way that power flows through the grid by actuating line switching hardware or by controlling high voltage devices connected in series or in shunt with transmission lines.

- Power flow control includes the ability to:
  - control the impedance on a major transmission line
  - inject a controlled voltage in series with a line
  - provide reactive voltage support for long lines so that they can be loaded to their thermal limits
  - switch line circuit breakers to redirect power to other lines.

Map: U.S. Department of Energy Office of Science and Technology osti.gov

Power Flow Control - Historical Background

- System operators historically had the ability to influence power flows by
  - Generation dispatch and curtailment
  - Tap changing on voltage phase angle regulating transformers
  - Switching transmission lines and interties
  - Switching capacitor banks
- Power electronically controlled hardware offering more granular and faster time scale power flow control have also been available for some time now:

Major Power Electronics-based Power Flow Controllers	
Thyristor-controlled Static Var Compensators (SVC)	Available since the 1970's. Provide voltage support allowing increased line loading.
Thyristor-controlled phase angle regulators and voltage regulators	Available for a long time. Transformer-based. Not as widely used as their mechanically switched counterparts.
Thyristor-controlled series capacitors (TCSC)	Available in different forms for decades. Widely used for compensation of long transmission lines.
Line-Commutated Converter (LCC) HVDC	Available for many decades. Best suited for bulk power transmission over great distances.
Static Synchronous Compensator (STATCOM)	Similar functionality to SVCs but utilizing voltage source converters.
Voltage Source Converter (VSC) HVDC	Increasingly used for cable transmission. Most powerful flow control capability. BTB VSC HVDC can solve many AC transmission flow problems, but at relatively high cost (two converters each rated for full transmitted power plus reactive generation).
Static Synchronous Series Compensator (SSSC)	Demonstrated in 3 UPFC installations starting in the 1990's. Fractional series voltage injection can control large swings in transmitted power. No known stand-alone SSSC installations (or UPFC's) built for transmission systems after the initial demonstrations.

Potential New Power Flow Controllers

- **Advances in power electronics, computer science, and mathematics have created new opportunities for optimizing grid power flows.**

Power Flow Controllers (Routing Power)

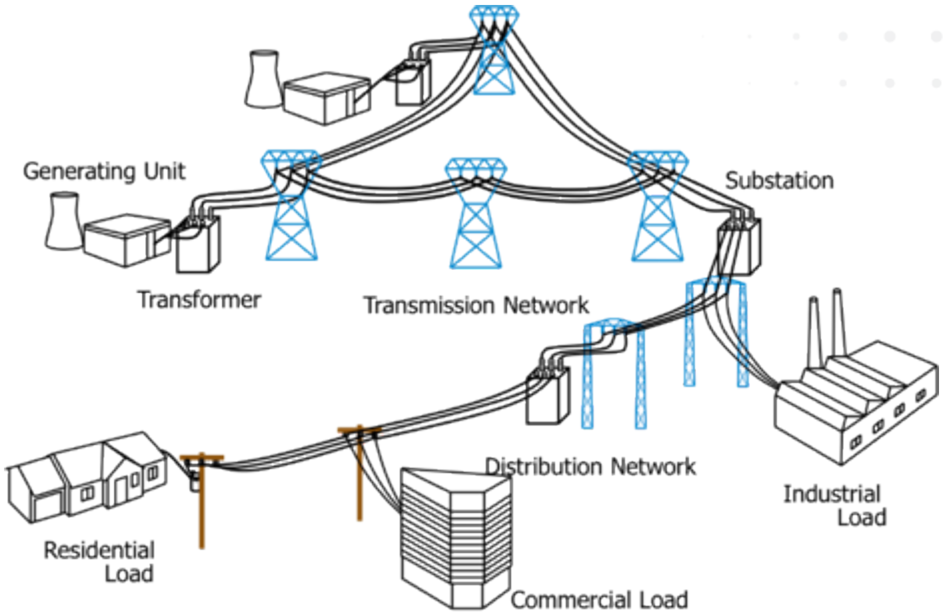
- AC Power Flow Controllers
- High Voltage DC Systems

Energy Storage Optimization

- Scheduling energy flows
- Coordination of diverse storage assets

Transmission Topology Optimization

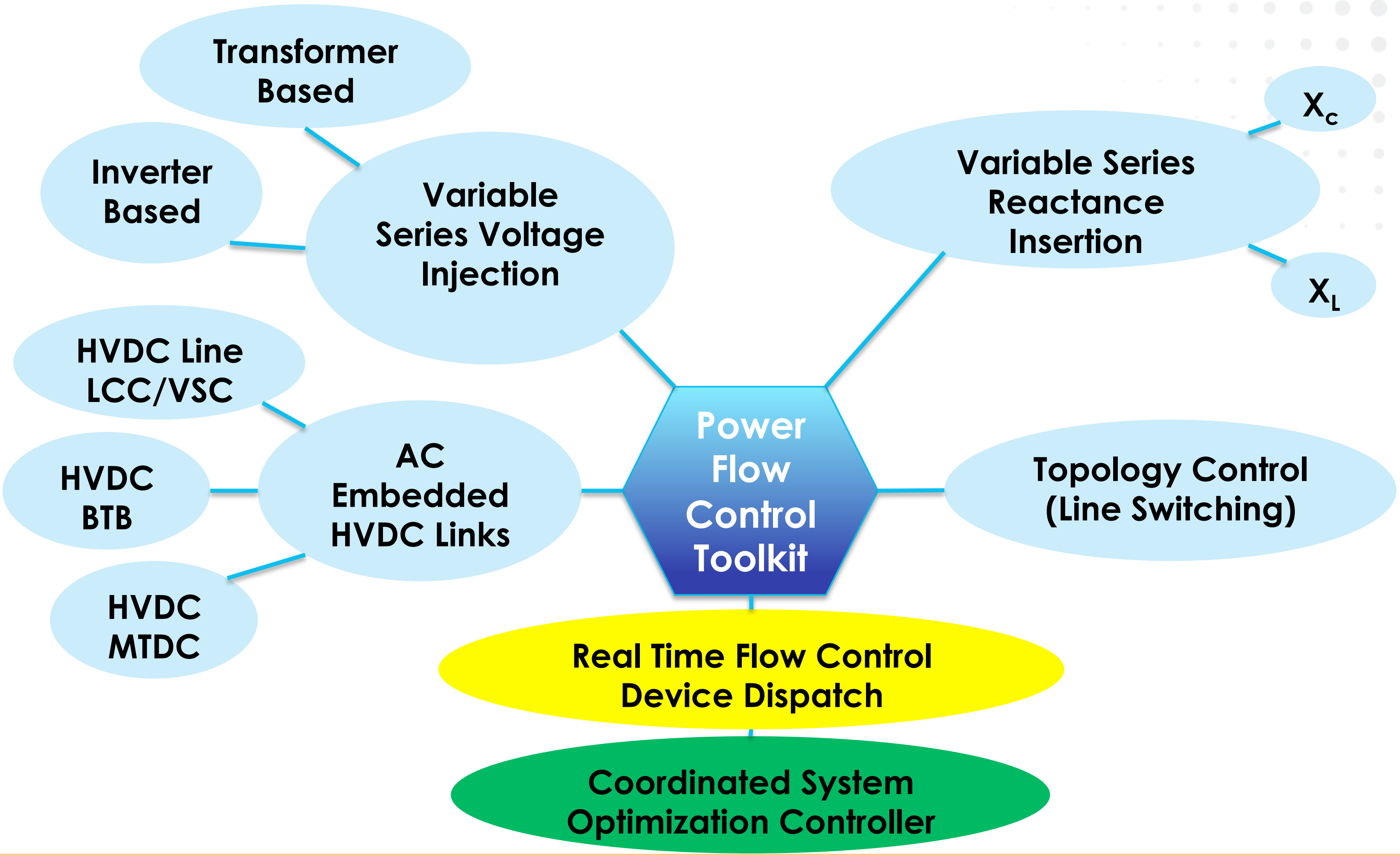
- Optimal line switching
- Corrective switching actions



Responsive Demands

- Scheduling large loads (eg. industrial loads)
- Mobilize large numbers of small assets

Power Flow Control Toolkit



Power Flow Control Toolkit

Variable Series Voltage Injection

Transformer Based

Inverter Based

Variable Series Reactance Insertion

X_C

X_L

AC Embedded HVDC Links

HVDC Line LCC/VSC

HVDC BTB

HVDC MTDC

Topology Control (Line Switching)

Real Time Flow Control Device Dispatch

Coordinated System Optimization Controller

Coordinated Real Time Flow Control

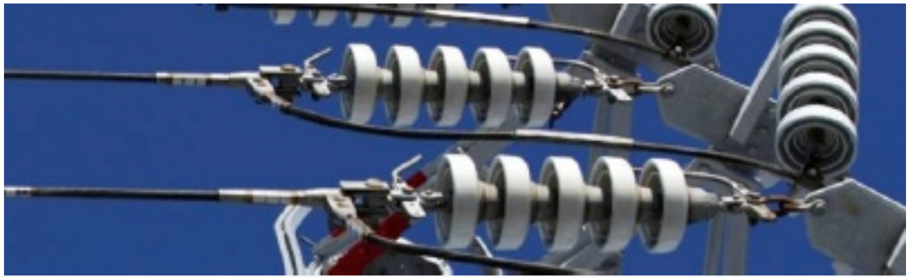
- Historically, power flow control devices have typically been manually dispatched to correct local problems.
- High costs and reliability problems are often cited against the widespread installation and use of power flow control devices.
- New approaches are needed to designing power flow control devices:
    - Fractionally rated converters (limited power device ratings).
    - Modular designs (increases manufacturability).
    - Series connected equipment with fail normal designs (gradual degradation).

- ***New hardware*** innovations that can substantially reduce the cost of power flow control devices are needed.
- ***New software*** advances that exploit new developments in optimization and computational technologies are needed to enable the real time coordinated, optimized dispatch of many power flow control devices.

GENI PROGRAM

(Green Electricity Network Integration)

INCREASING GRID FLEXIBILITY



Mission

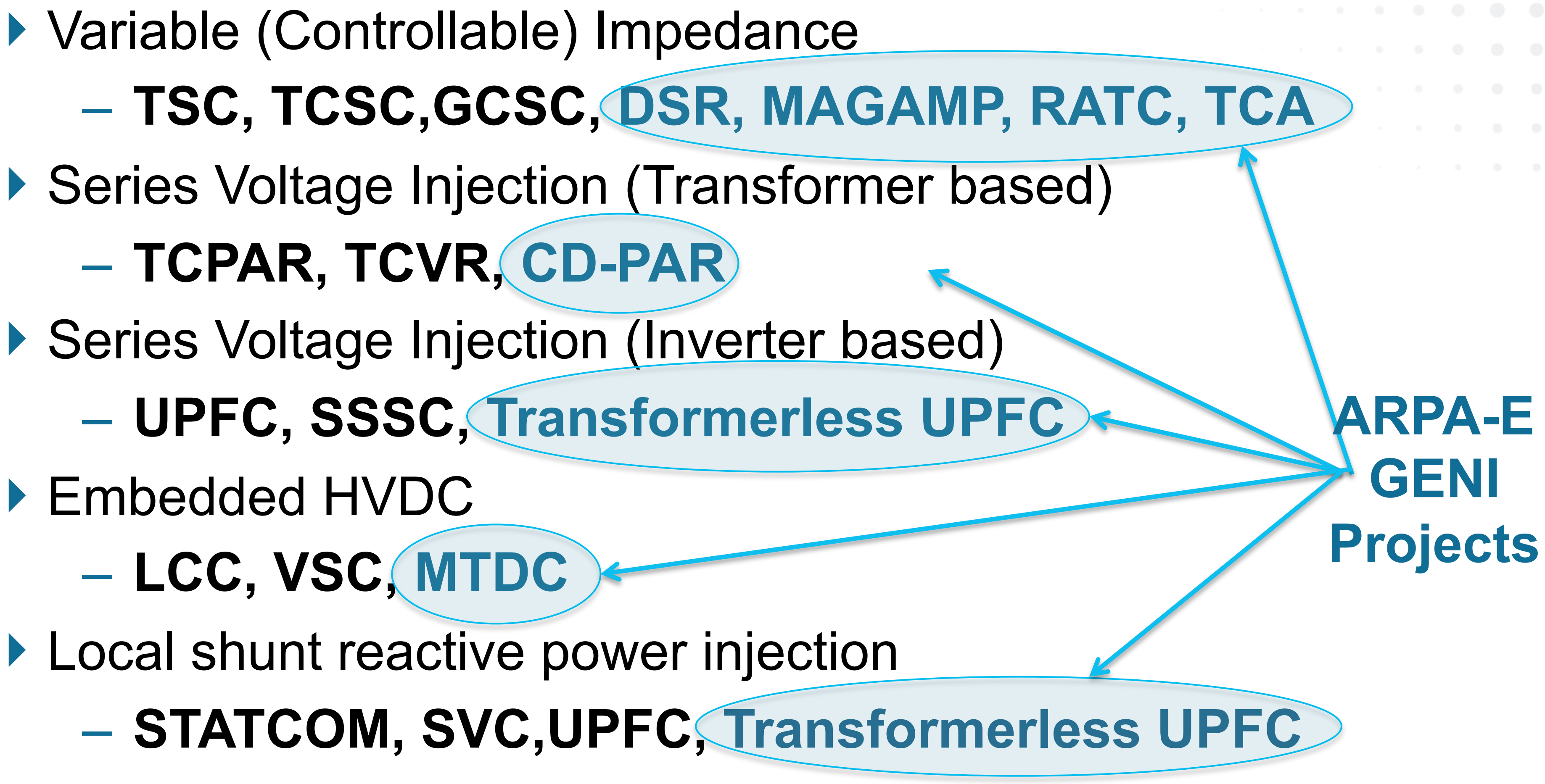
Improve the efficiency and reliability of electricity transmission, increase the amount of renewable energy the grid can utilize, and provide energy suppliers and consumers with greater control over power.

Projects	Total Investment
15	$39.4 million

Kickoff: December 2011

- **Power Transmission Controllers**
  - Devices enabling power flow control within mesh AC grids.
  - Devices enabling resilient multi-terminal HVDC networks.
- **Grid Control Architectures**
  - Optimization of power grid operation; incorporation of uncertainty into operations; distributed control and increasing customer control.

Categories of Power Flow Control Devices



- Variable (Controllable) Impedance
  - **TSC, TCSC,GCSC, DSR, MAGAMP, RATC, TCA**
- Series Voltage Injection (Transformer based)
  - **TCPAR, TCVR, CD-PAR**
- Series Voltage Injection (Inverter based)
  - **UPFC, SSSC, Transformerless UPFC**
- Embedded HVDC
  - **LCC, VSC, MTDC**
- Local shunt reactive power injection
  - **STATCOM, SVC,UPFC, Transformerless UPFC**

ARPA-E GENI Projects

CHANGING WHAT'S POSSIBLE

Who might adopt power flow control tech?

- Vertically integrated utilities
  - Optimize generation and/or transmission upgrades
  - Improve economic dispatch of generation
  - Assist with integration of renewable generation
  - Reduce congestion on AC lines
  - Reliability
- Investor/Shareholder owned utilities
  - Deferral or prioritization of transmission upgrades
  - Assist with integration of renewable generation
  - Reduce congestion
  - Reliability
- Merchant transmission owners (private ownership of transmission)
  - Increase efficiency of planned transmission lines
  - Dispatch of transmission lines

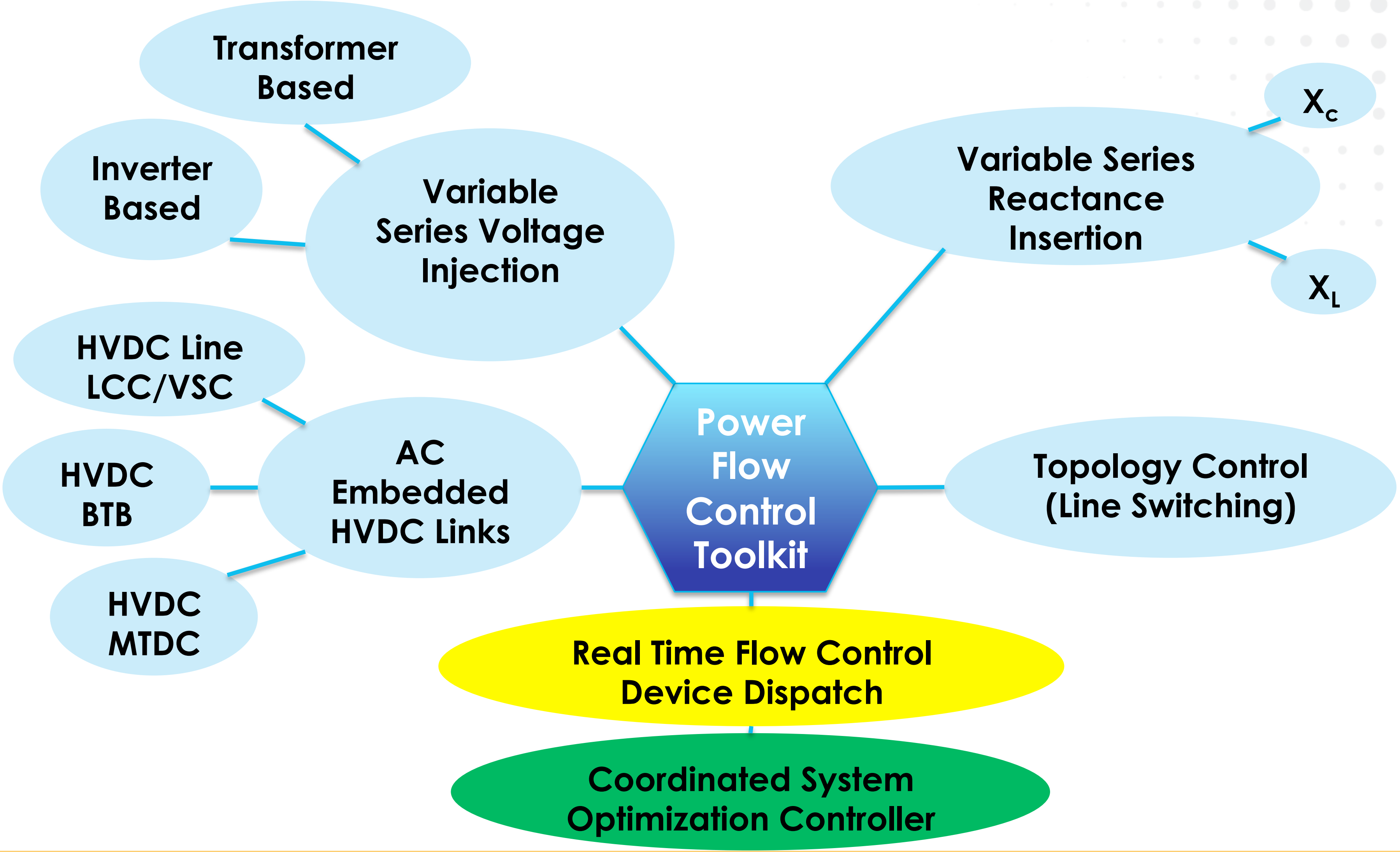
System Level Effects

- In many cases, a given stakeholder will gain value in some categories but lose in others
  - Magnitude of win/loss is highly context dependent
- Qualitative assessments can indicate stakeholder impacts:
  - Generalized Winner/Loser Analysis
  - Theoretical scenario examples where gains/losses occur
  - Data from case study attempts to represent system effects
- **However, the system dynamics are complex and need to be modeled in detail for better quantitative estimates of value gain/loss.**

PFC Technology Winners and Losers

Stakeholders	Asset Management		Renewable Integration		Congestion Relief		Economic Efficiency		Reliability & Security	
Problem	Under Utilization	End of Life	Inter Connection	Curtailment	Dispatch & planning	Real Time	Energy	Ancillary	Contingency	Black start
Transmission Owner	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟨 ?	🟩	🟩
ISO/RTO	🟩		🟩	🟩	🟩	🟩	🟩		🟩	🟩
Renewable Generator	🟩		🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩
Base Load Generator	🟩		🟩		🟩	🟨	🟨	🟨	🟩	🟩
Reserve Generator	🟨		🟥		🟩	🟨	🟨	🟥	🟩	🟩
FERC							🟩	🟩	🟩	🟩
PUC		🟩	🟩				🟩	🟩	🟩	🟩

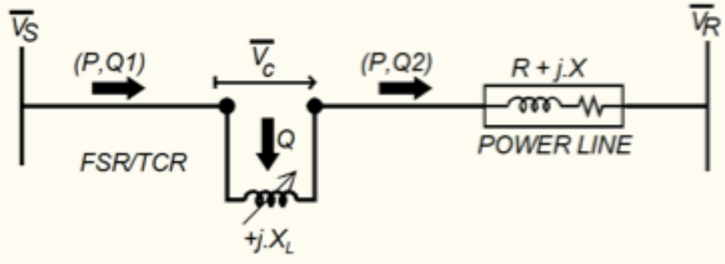
Power Flow Control Toolkit



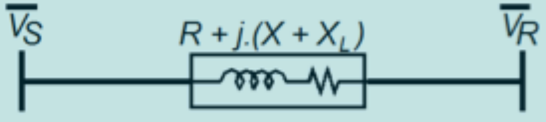
CHANGING WHAT'S POSSIBLE

Variable Series Reactance Injection

FSR / TCR / TSR



Equivalent cct.



- Max X_L (~ between X and 2X) gives fractional (~ 20-30%) reduction in line current (depending on voltage, system SC capacity, etc)
- Max X_L value limited by voltage drop (~5%) and steady state stability (~ $\delta = 44°$)
- Single phase control allows phase balancing
- Device absorbs reactive power Q

Distributed Series Reactors

Power flow control for the Grid
SWG

- Functions as a current limiter to divert current from the overloaded lines to underutilized ones
- Increases line impedance on demand by injecting the magnetizing inductance of the Single-Turn Transformer
- Two modes of operation:
  - Autonomous (set point) operation
  - Two way communications enabled for greater control and line monitoring

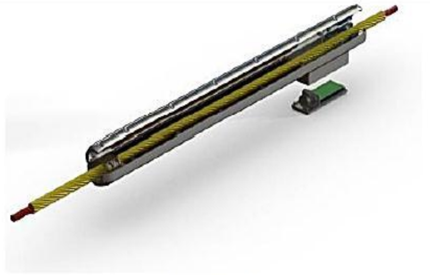


Figure 1

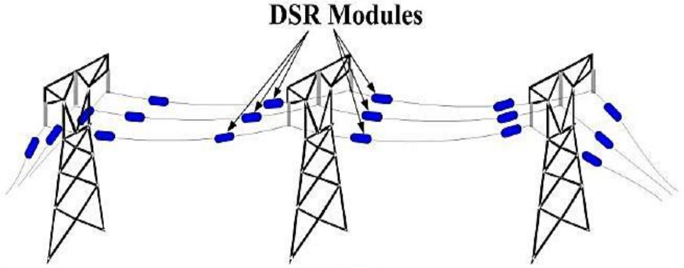


Figure 2

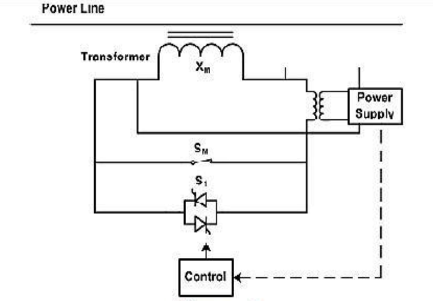


Figure 3

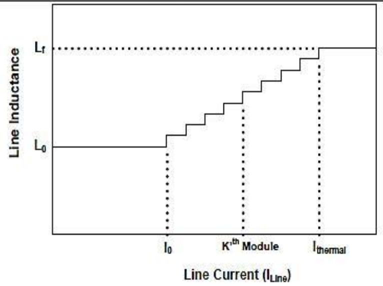


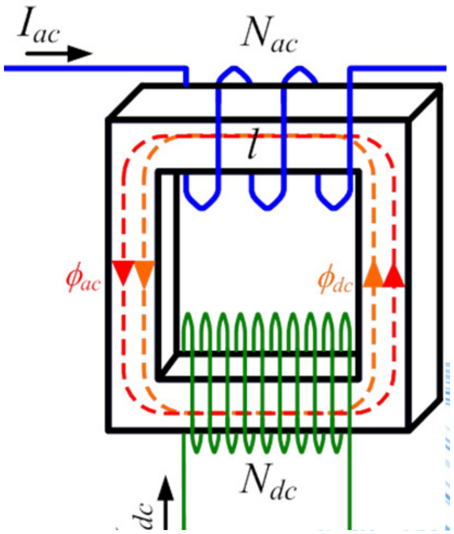
Figure 4

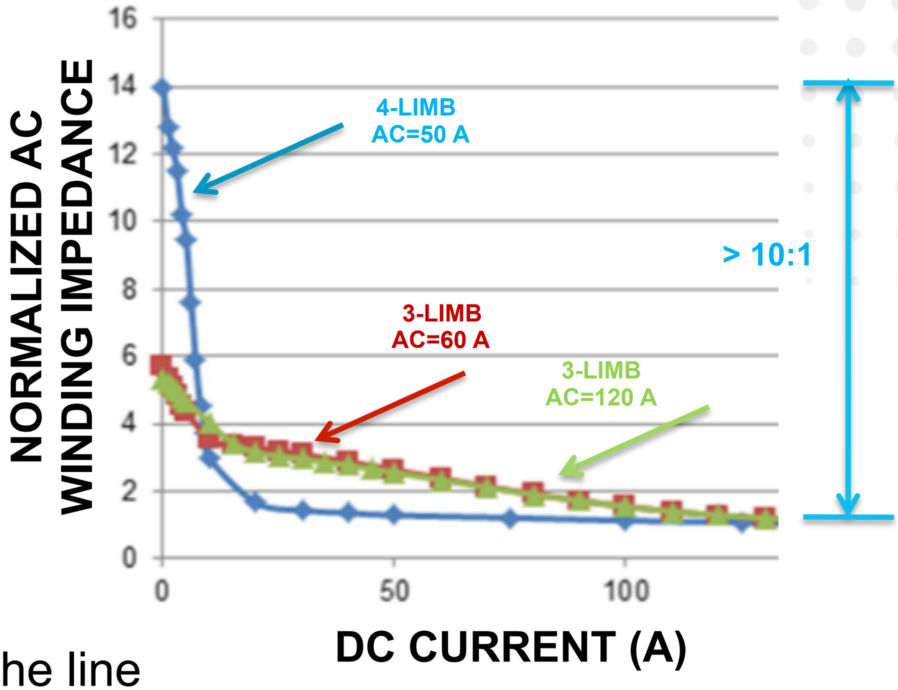
INNOVENTOR® "The Original Idea People"® · edd · Carnegie Mellon University · newpotato TECHNOLOGIES · Georgia Tech NEETRAC National Electric Energy Testing, Research and Applications Center · PowerWorld Corporation The Visual Approach to Analyzing Power Systems

Distributed Series Reactors Test Array

TVA DSR Array Installation: October 15-20, 2012 99 Units
Field Testing Ongoing Throughout 2013

Magnetic Amplifier for Power Flow Control





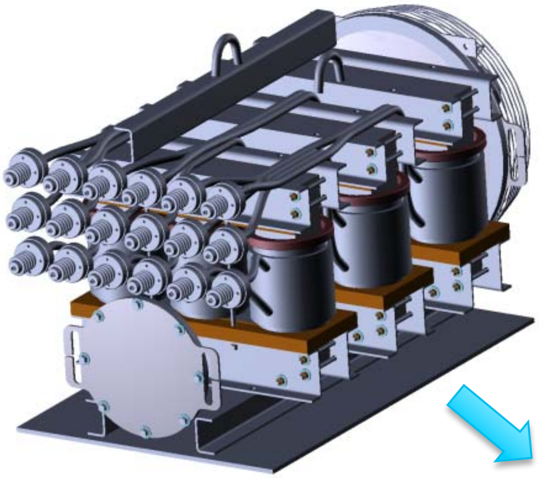
- Inserts a controlled variable inductance in the line
- Power electronics isolated from the HV line
- Low power dc source controls the high voltage ac inductance
- Smooth reactance regulation, acceptable harmonics
- 161 kV, 2000 A prototype under construction
- Uses standard transformer manufacturing methods

OAK RIDGE National Laboratory

SPX WAUKESHA

THE UNIVERSITY of TENNESSEE UT KNOXVILLE

Magnetic Amplifier Development Timeline



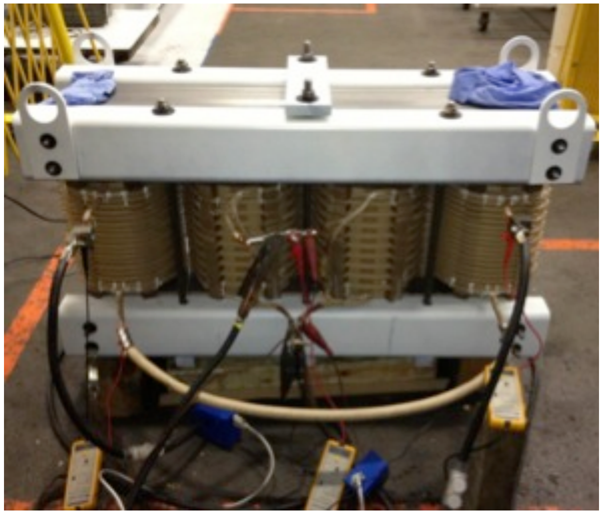
(2012)
480 V 200 A
3-phase
Laboratory Prototype
- Proof of Concept

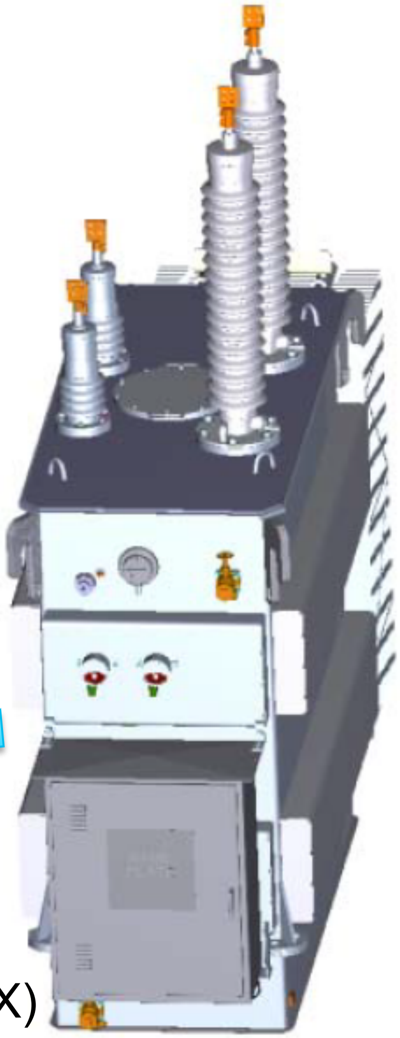
OAK RIDGE
National Laboratory

SPX
WAUKESHA

THE UNIVERSITY of TENNESSEE UT
KNOXVILLE

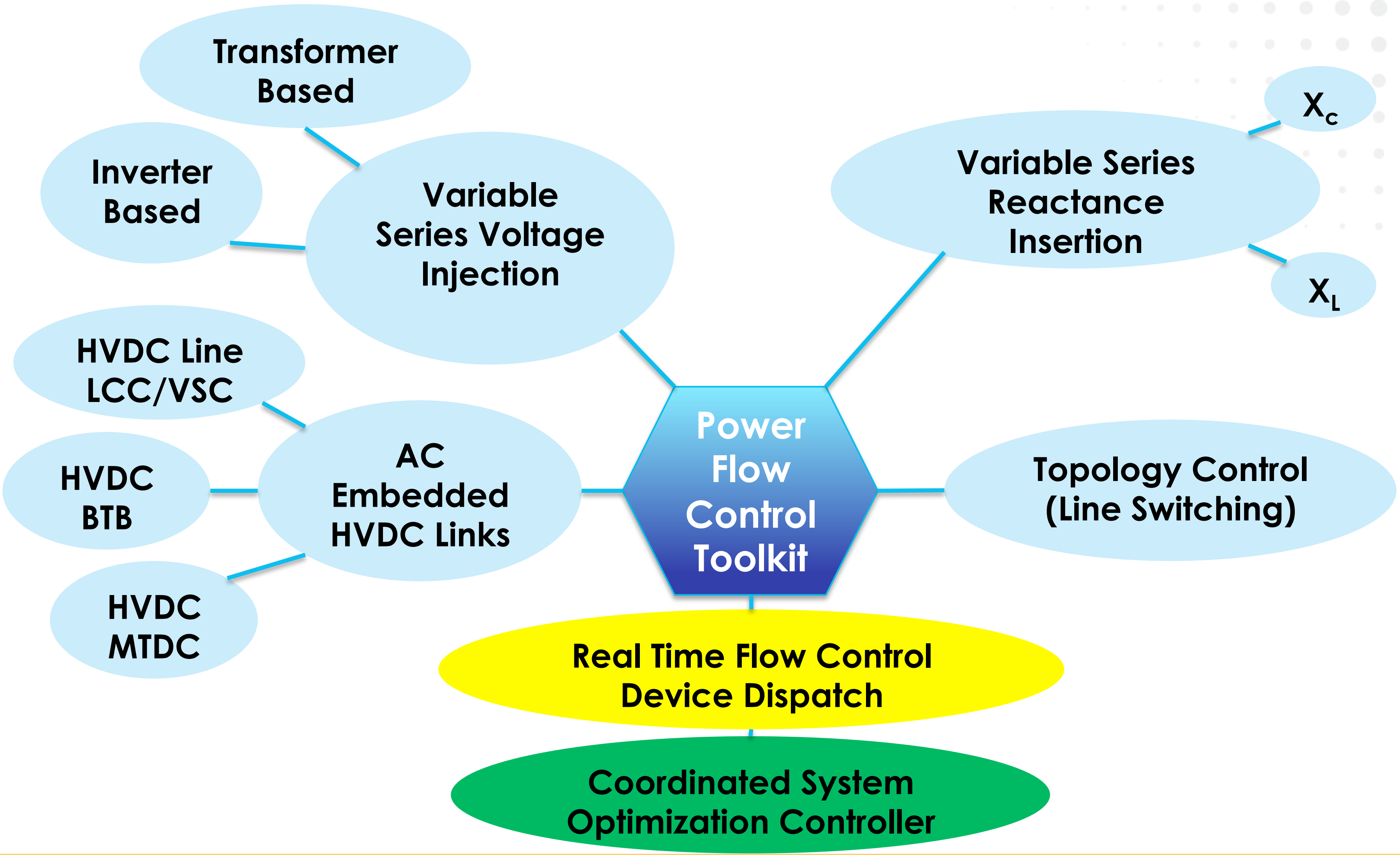
(2013)
480 V Improved Design
With 4-Limb Core





(2014 →)
161 kV 2 kA
Field Prototype
(manufactured by SPX)

Power Flow Control Toolkit



Transformer Based

Inverter Based

Variable Series Voltage Injection

HVDC Line LCC/VSC

HVDC BTB

HVDC MTDC

AC Embedded HVDC Links

Power Flow Control Toolkit

Variable Series Reactance Insertion

X_C

X_L

Topology Control (Line Switching)

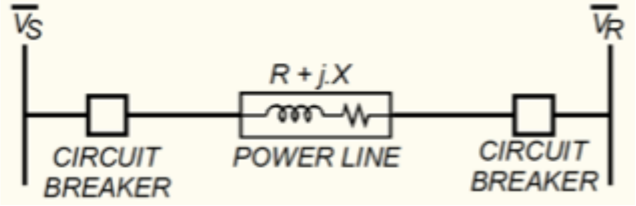
Real Time Flow Control Device Dispatch

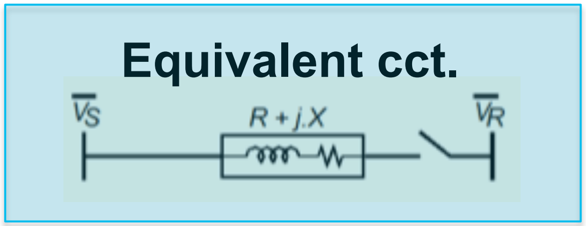
Coordinated System Optimization Controller

CHANGING WHAT'S POSSIBLE

Transmission Line Switching

TOPOLOGY CONTROL
(Line Switching)




Equivalent cct.

- Line current drops to zero when CB's open
- Line power rerouted on other lines
- Line CB's incur additional operating cycles
- Transmission switching is done routinely today by many utilities and ISOs on an ad hoc basis.

Transmission Topology Optimization

Objectives:

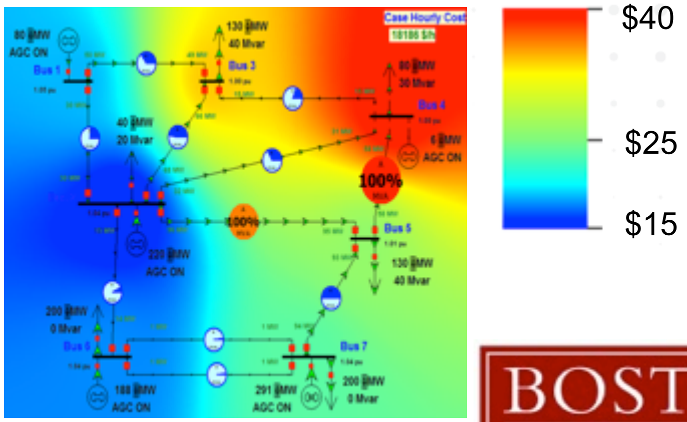
- Significantly lower generation costs.
- Provide additional controls to manage congestion.
- Enable higher levels of variable renewable penetration.
- Extract more value out of existing transmission capacity.

Evaluation:

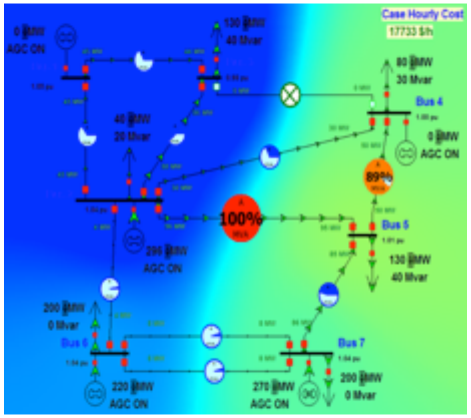
- Simulations on detailed operational models of the PJM real-time and day-ahead markets.

Approach:

- Focus on tractability, aiming at providing good topologies in short times.
- Exploring multiple solution algorithm approaches.
- Smart use of sensitivity information, such as LMPs and LODFs.
- Dynamic state estimator technology and efficient techniques for stability evaluation are the basis for ensuring reliable and secure topology and dispatch solutions.



Before ($18186/hr)



After ($17733/hr)

BOSTON UNIVERSITY

The Brattle Group

Tufts University

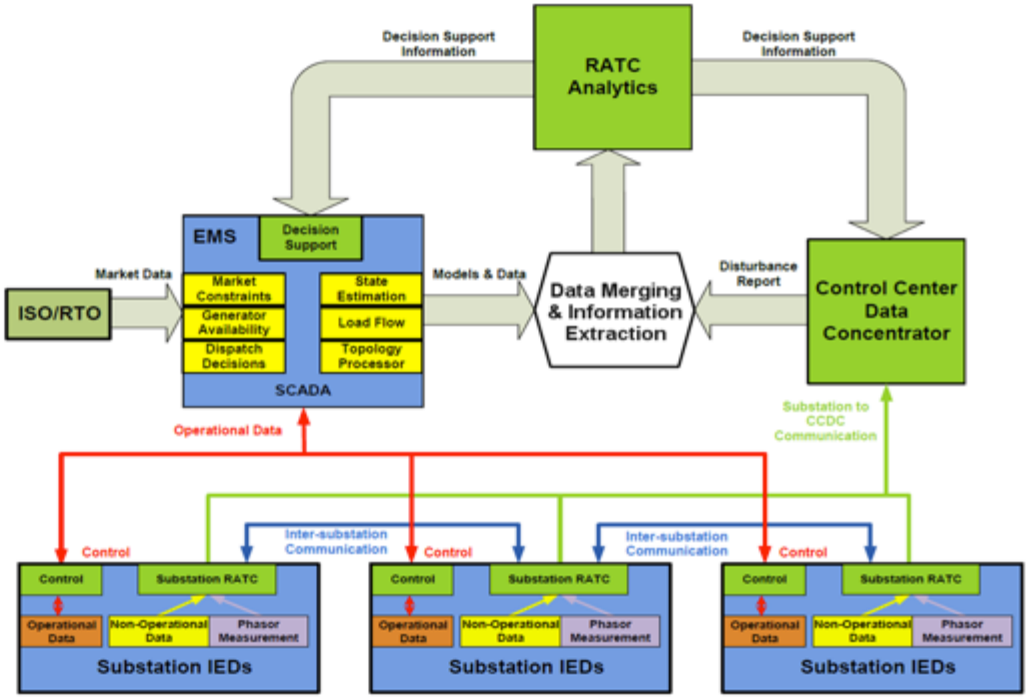
Northeastern University Research

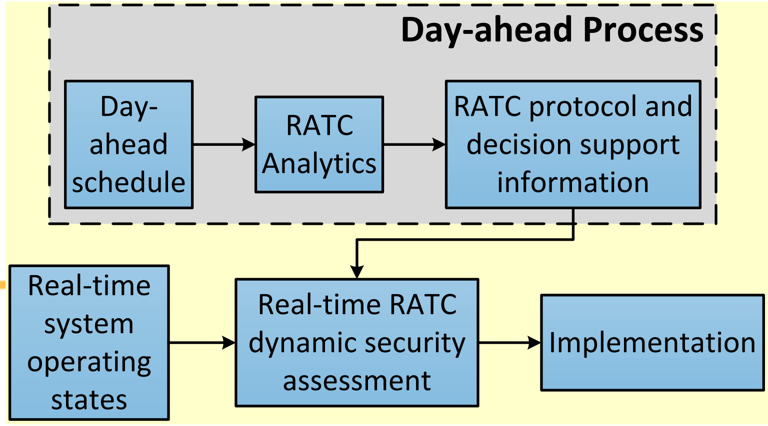
Polaris Systems Optimization

pjm

Robust Adaptive Topology Control

- Decision support tool to enable network topology optimization (both pre- and post-contingency).
- Selected system components:
    - Real-time security assessment
    - Detection of transmission lines tripped erroneously during cascade events
    - Adaptation of protection system settings
    - Breaker reliability and risk monitoring
- Demonstration of value using large scale TVA system data model.





Day-ahead Process

Day-ahead schedule

RATC Analytics

RATC protocol and decision support information

Real-time system operating states

Real-time RATC dynamic security assessment

Implementation

ASU

TEES

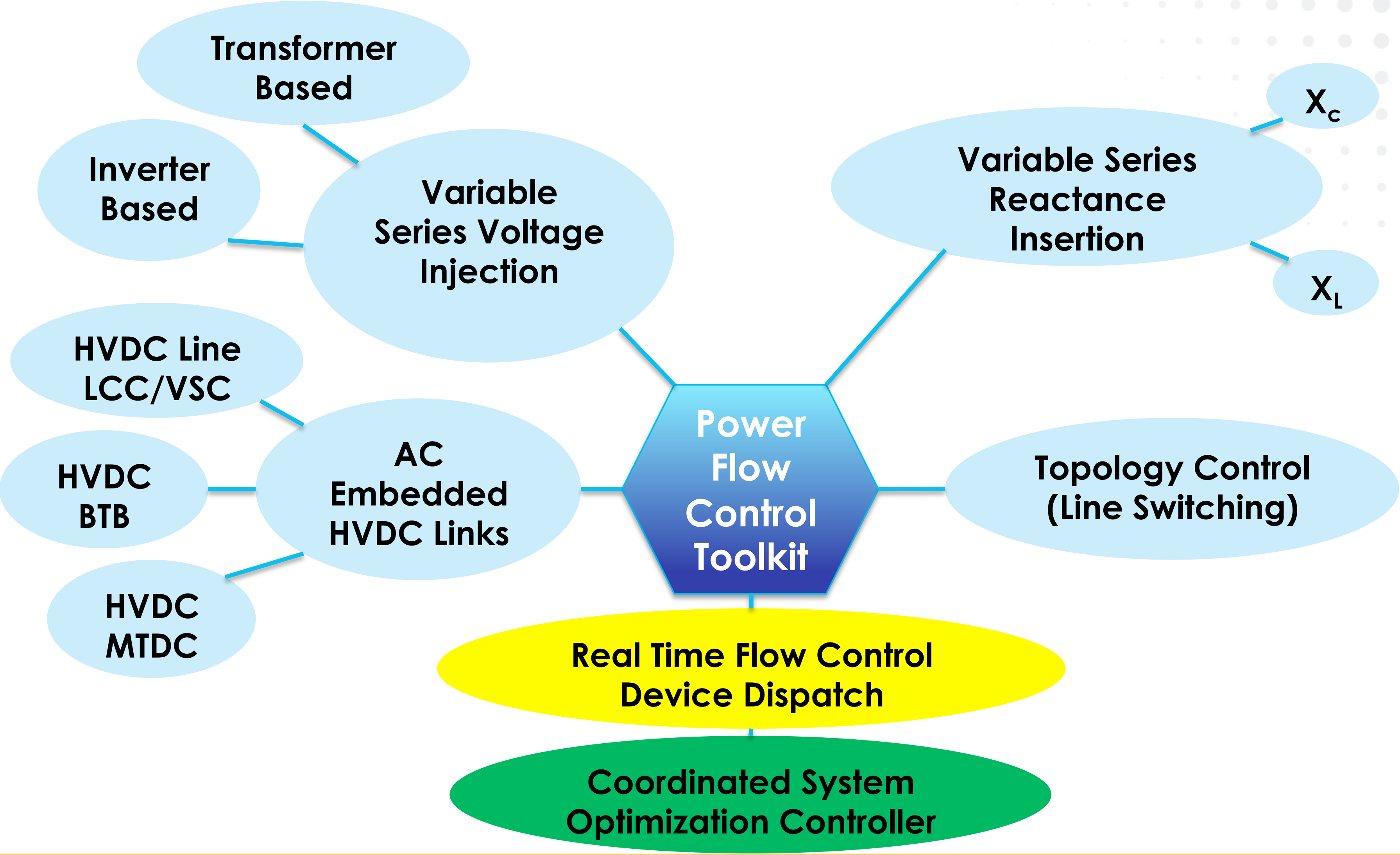
TEXAS A&M ENGINEERING EXPERIMENT STATION

TVA

OAK RIDGE National Laboratory

APPLIED COMMUNICATION SCIENCES

Power Flow Control Toolkit



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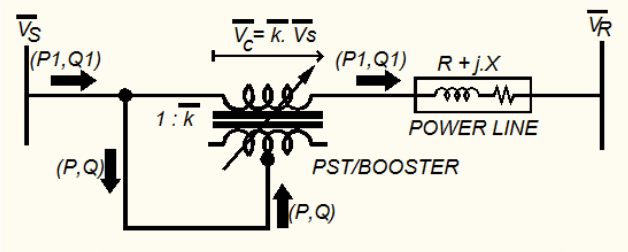
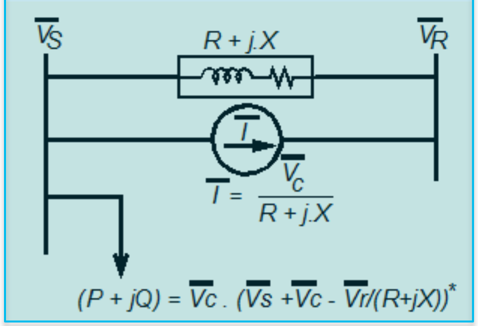
TCPAR / TCVR (Transformer Based)

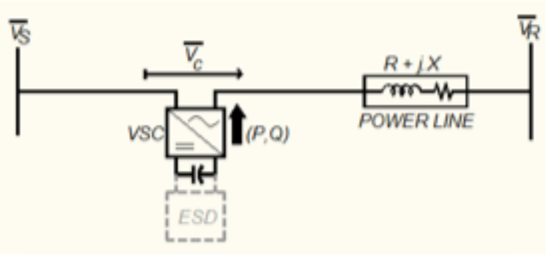


Equivalent cct.

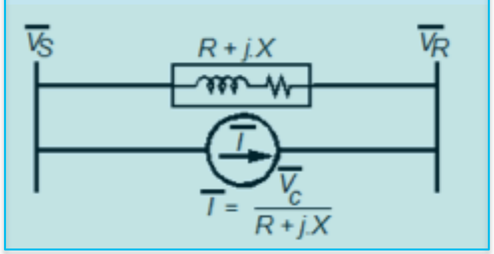


- Fractional MVA rating (10-20%) for >1p.u. (raise/lower/reverse) power swing on a typical line
- All series injected power (P and Q) is reflected as local shunt load
- Fast response with power electronic controls

SSSC (Inverter Based)

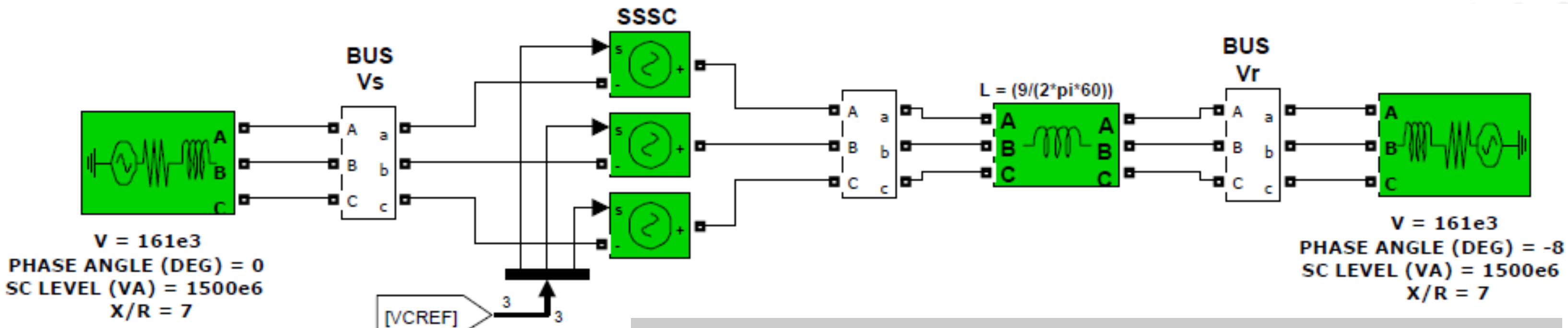


Equivalent cct.



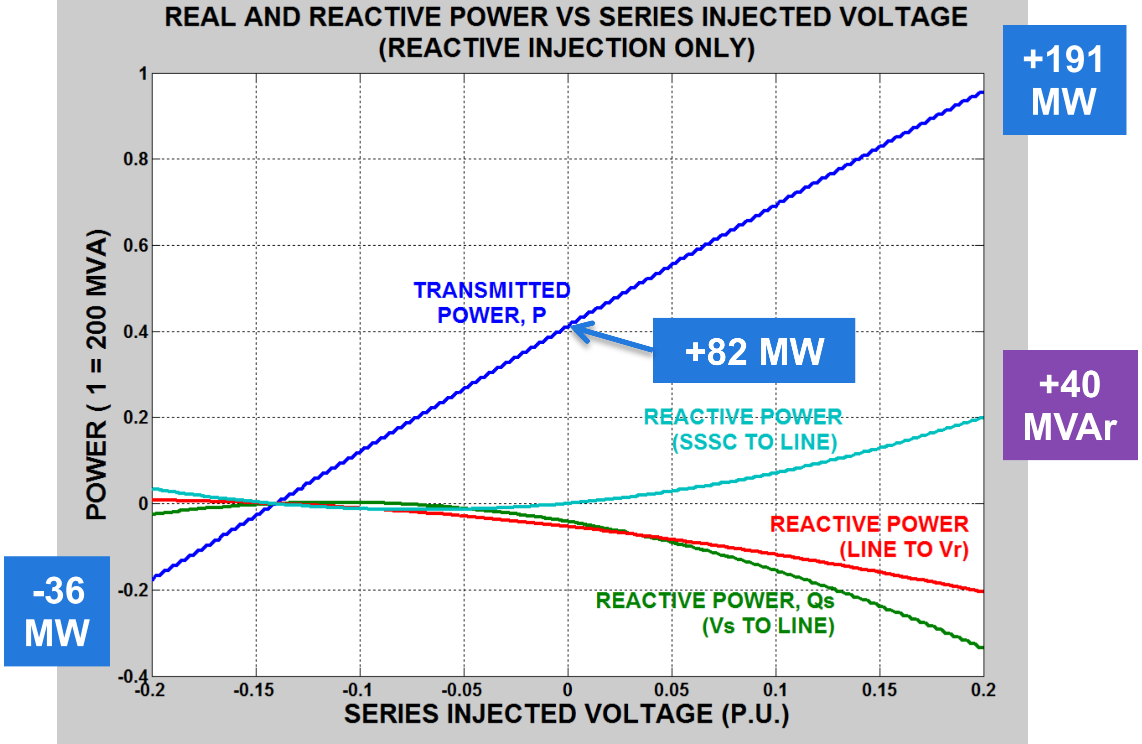
- Fractional MVA rating (10-20%) for >1p.u. (raise/ lower/reverse) power swing on typical line
- VSC electronically generates injected reactive power Q
- Injected real power P can be
  - ➢ Zero (classic SSSC with reactive output)
  - ➢ Drawn from optional dc-connected ESD
  - ➢ Drawn from the line as local shunt load (classic UPFC)

REACTIVE SERIES POWER INJECTION CAN RAISE, LOWER, OR REVERSE TRANSMITTED POWER

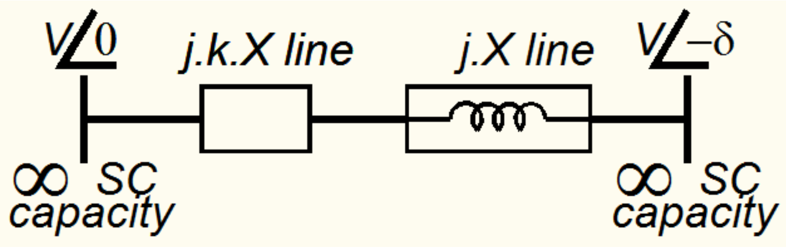


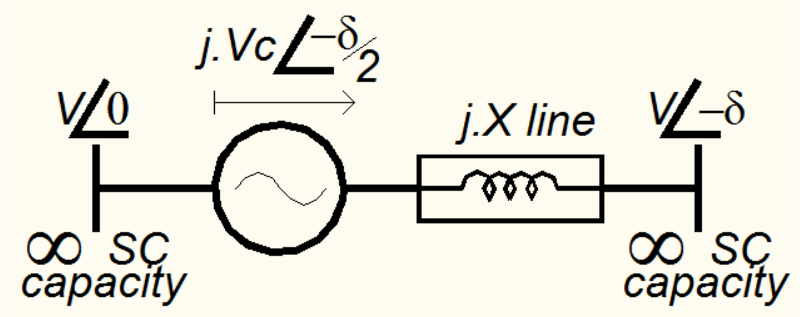
161 kV TRANSMISSION LINE EXAMPLE:

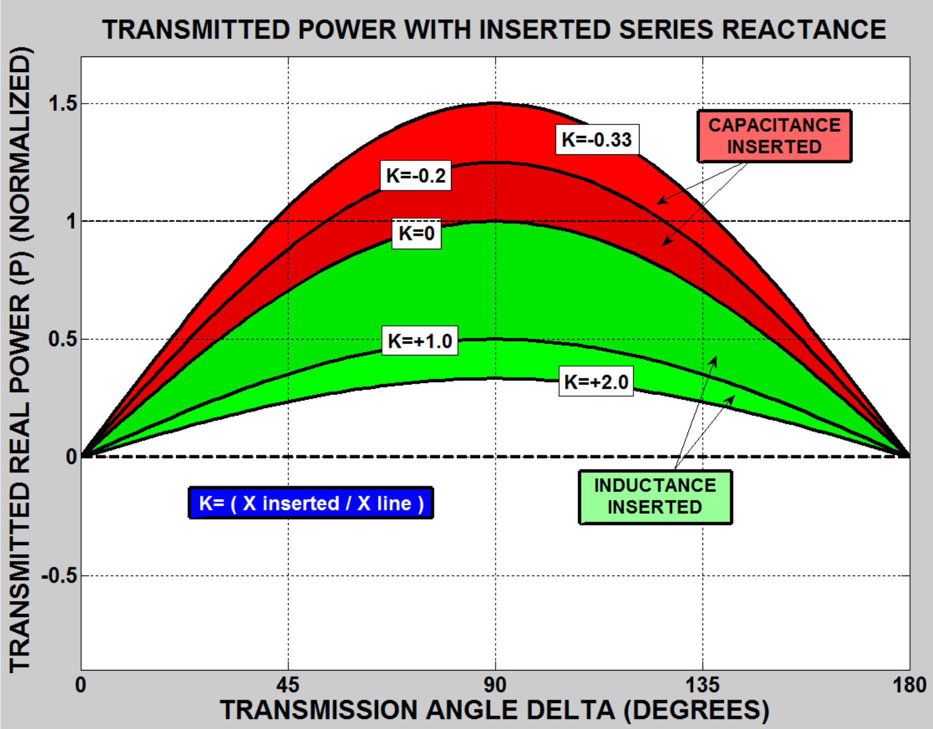
- *P = 82 MW WITH NO INJECTED VOLTAGE*
- *P = +191 MW WITH +0.2 P.U. VOLTAGE INJECTION (SSSC OUTPUT = +40 MVAr)*
- *P = -36 MW WITH -0.2 P.U. VOLTAGE INJECTION (SSSC OUTPUT = +7 MVAr)*

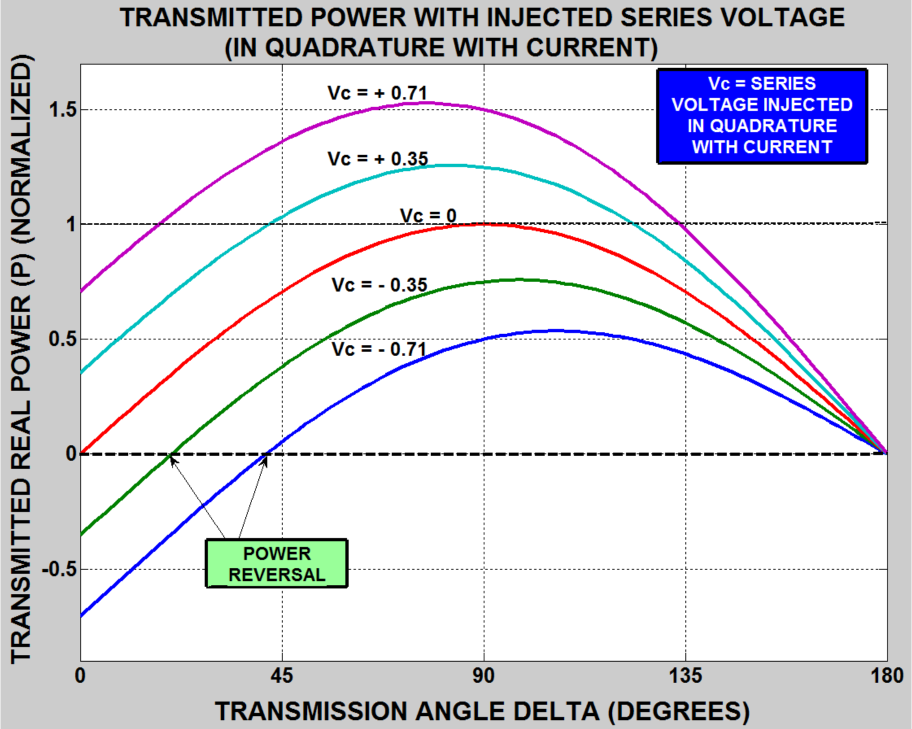


Reactance Insertion and Voltage Injection Comparison

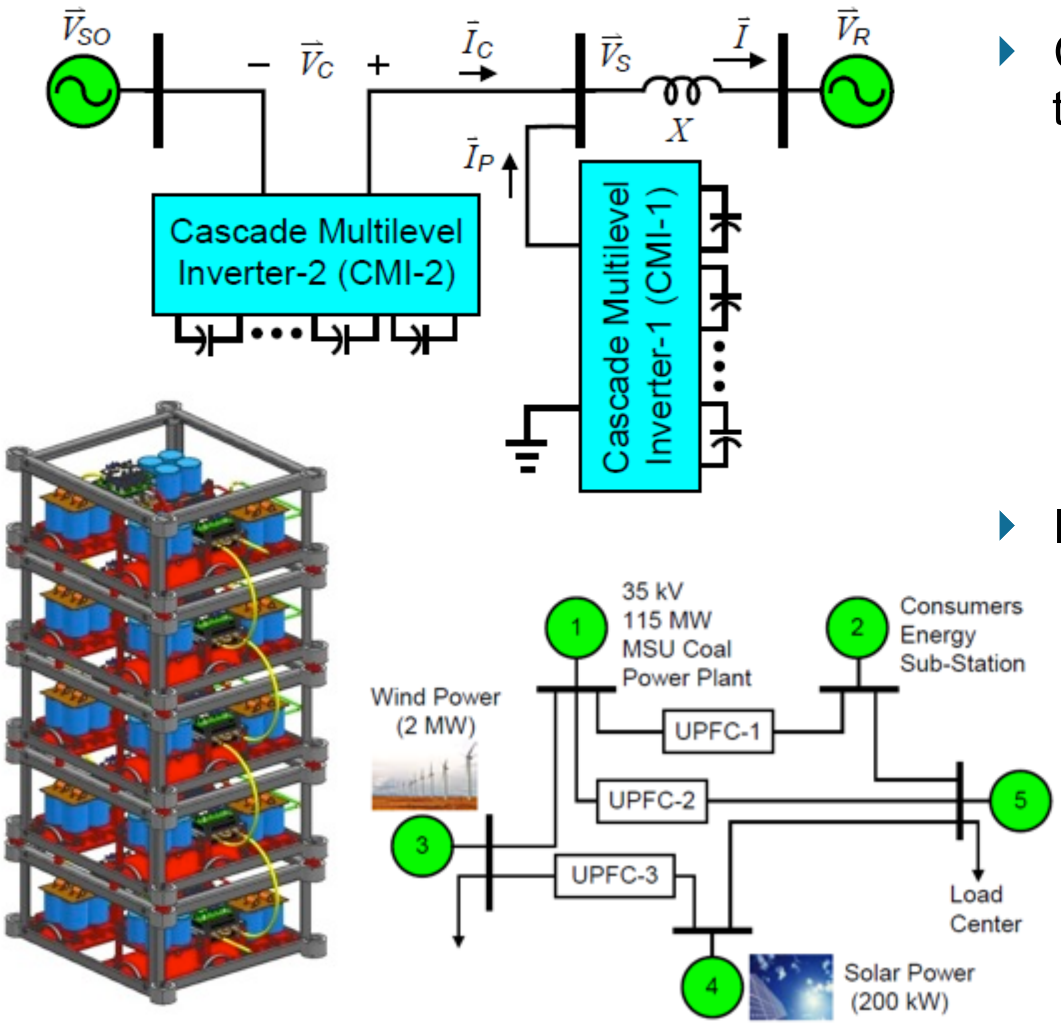





TRANSMITTED POWER WITH INSERTED SERIES REACTANCE


TRANSMITTED POWER WITH INJECTED SERIES VOLTAGE (IN QUADRATURE WITH CURRENT)

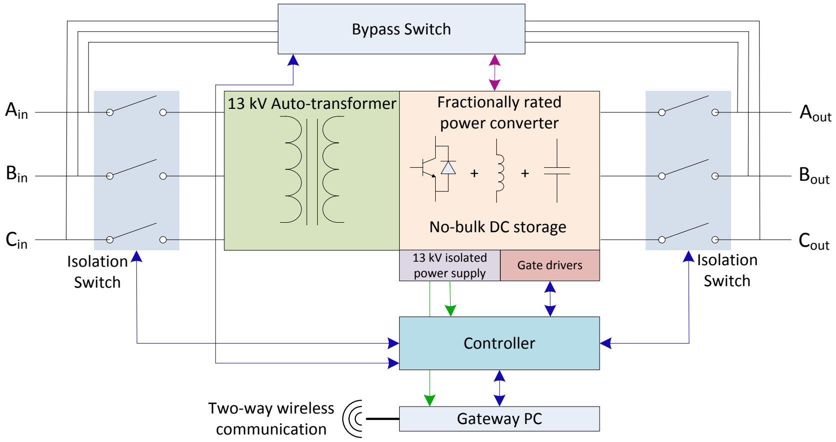
Transformer-less Unified Power Flow Controller



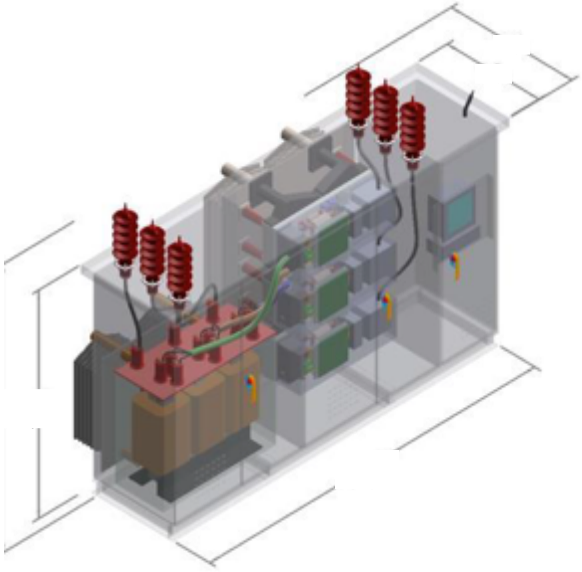
- Cascaded multi-level inverters (CMIs) to eliminate transformers
  - Modular, scalable design
  - Low cost ($0.04/VA)
  - Lightweight (1000 lbs/MVA)
  - High efficiency (>99%)
  - Fast dynamic response (<5 ms)
- Project goals:
  - Assemble and test 100 CMI sub-modules
  - Prototype a 2-MVA CMI UPFC
  - Pilot test/demonstration of the proposed UPFC on MSU's campus.

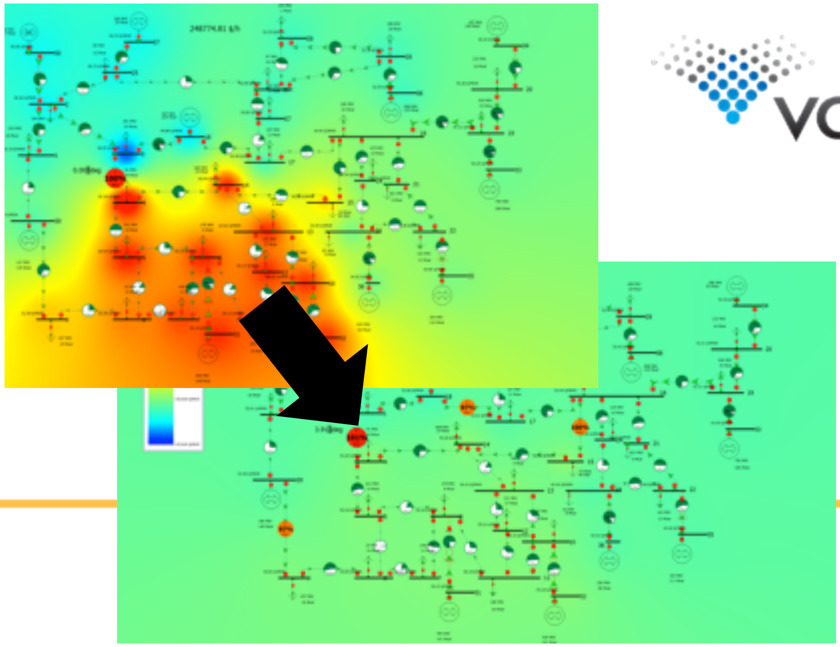
MICHIGAN STATE UNIVERSITY

Compact Dynamic Phase Angle Regulators



- Static, fractionally rated series voltage injection (transformer based).
- 1 MW circulating power demonstrated at 12kV
- Next Step: Testing and demonstration in a 12 kV AC meshed network at NEETRAC
- Field test at Southern Company next year
- Target: $20-30/kVA of power controlled
- Modeling dynamic and steady-state impact of CD-PAR at both distribution and transmission





varentec

SPX

Georgia Tech

EPRI ELECTRIC POWER RESEARCH INSTITUTE

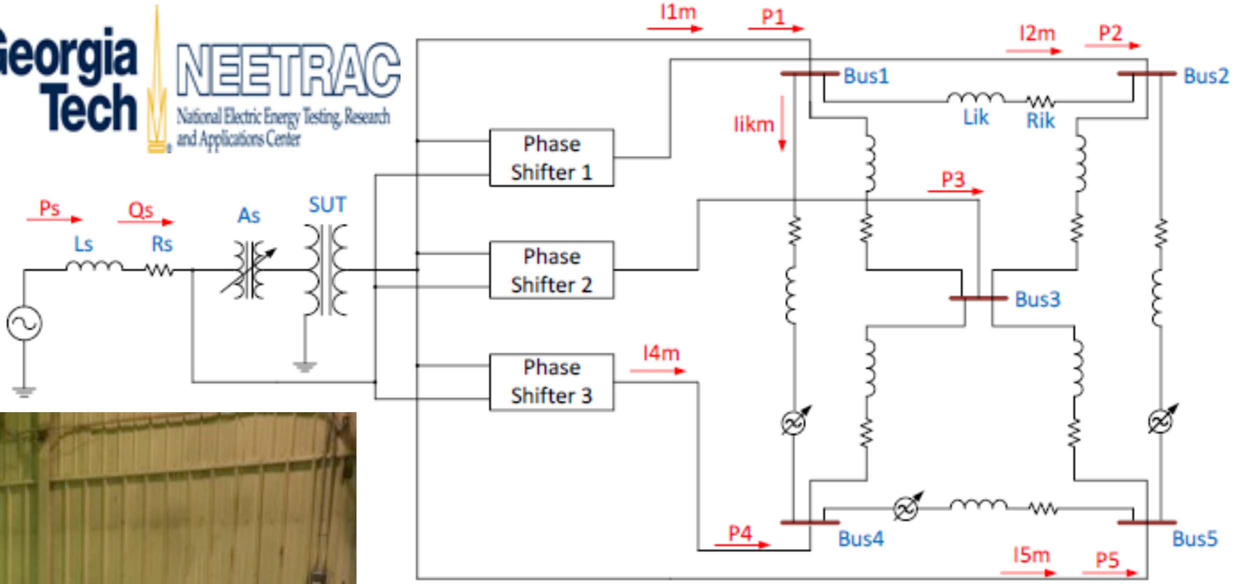
SOUTHERN COMPANY

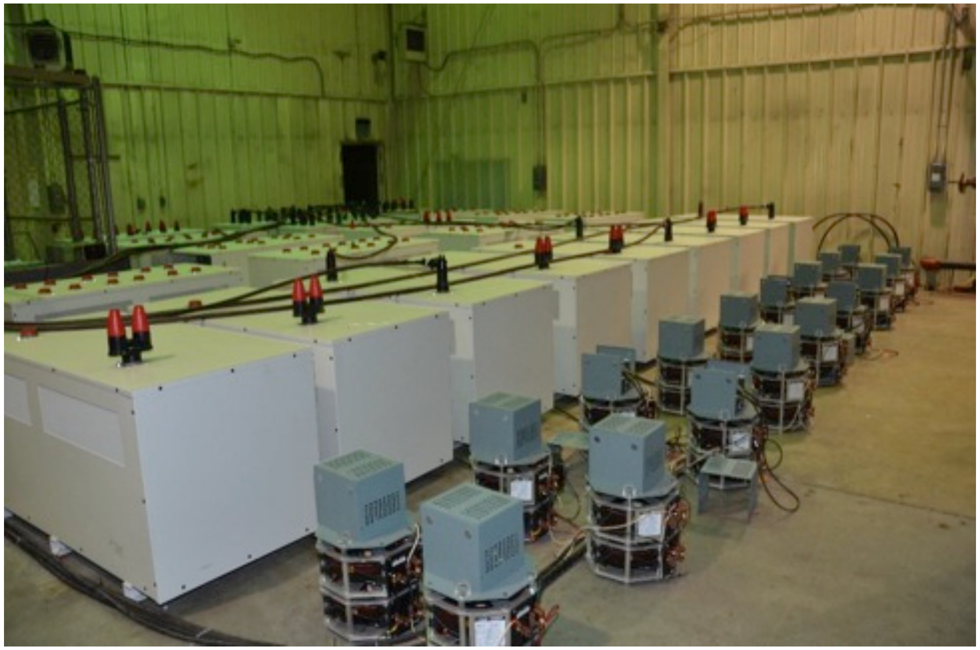
arpa·e CHANGING WHAT'S POSSIBLE

Medium Voltage Mesh Power Flow Test Bed

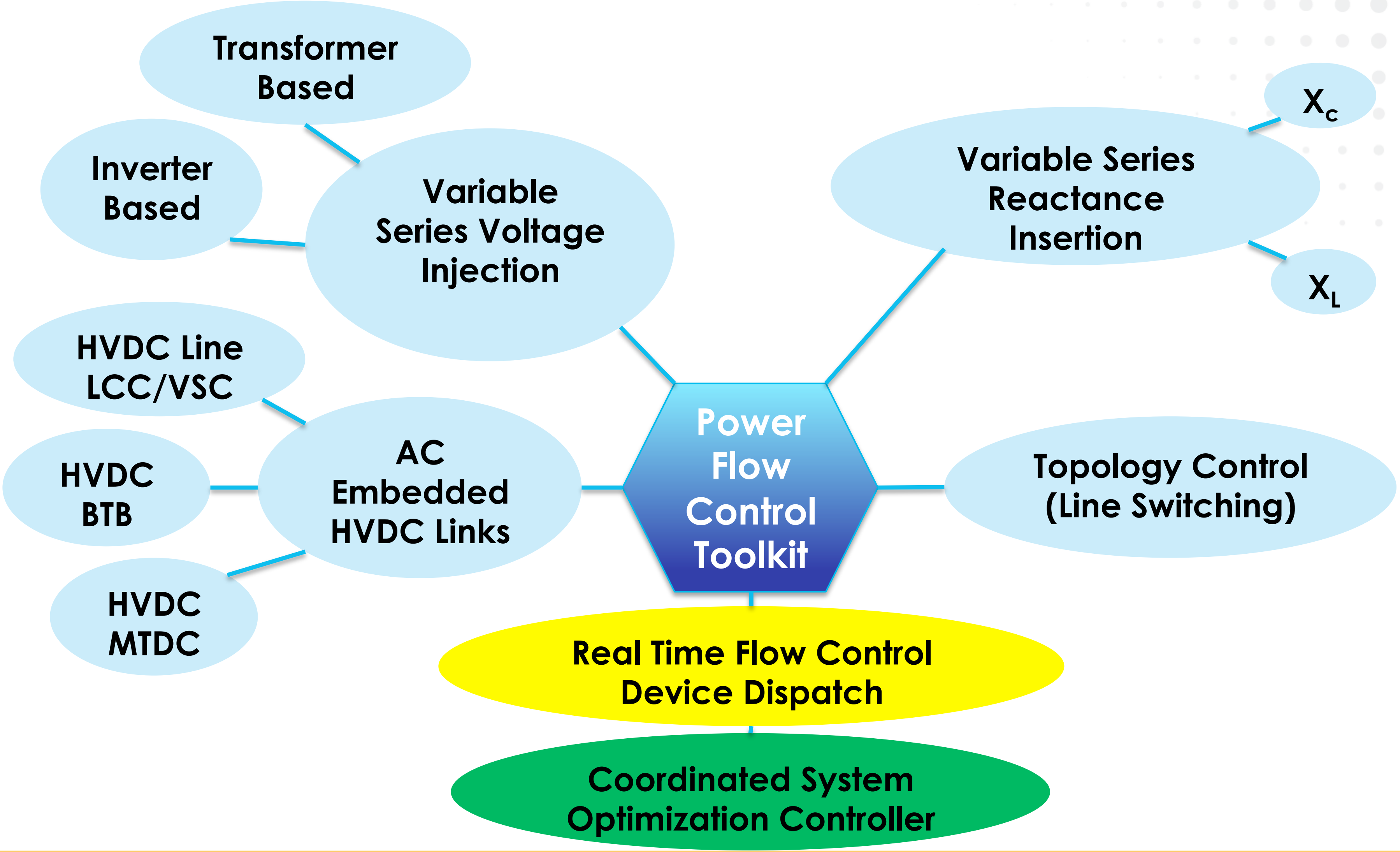
Georgia Tech NEETRAC

National Electric Energy Testing, Research and Applications Center





Power Flow Control Toolkit



Transformer Based

Inverter Based

Variable Series Voltage Injection

HVDC Line LCC/VSC

HVDC BTB

AC Embedded HVDC Links

HVDC MTDC

Power Flow Control Toolkit

Variable Series Reactance Insertion

X_c

X_L

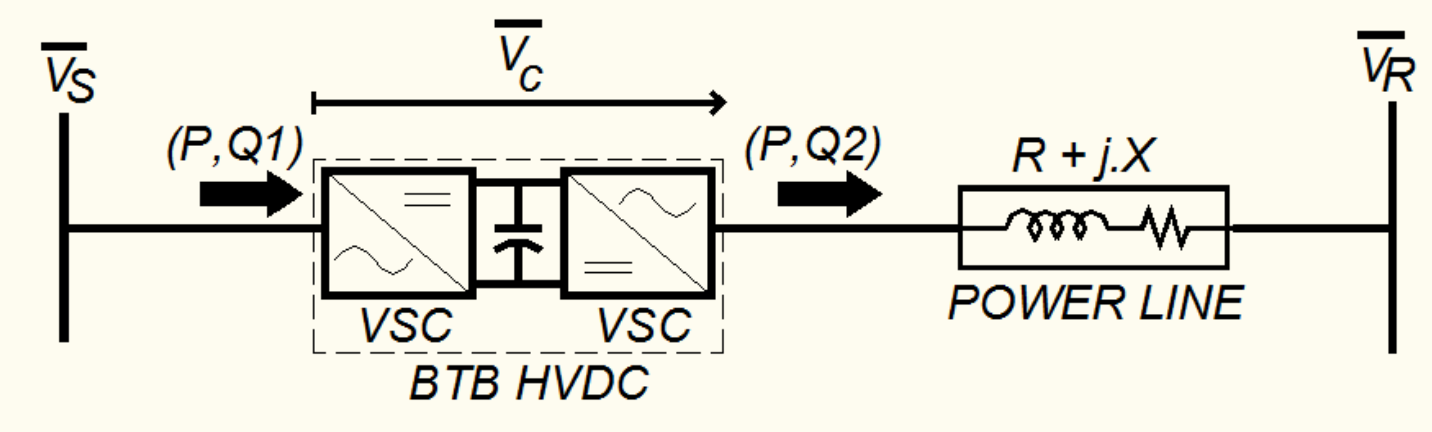
Topology Control (Line Switching)

Real Time Flow Control Device Dispatch

Coordinated System Optimization Controller

CHANGING WHAT'S POSSIBLE

AC Power Flow Control Using HVDC Links



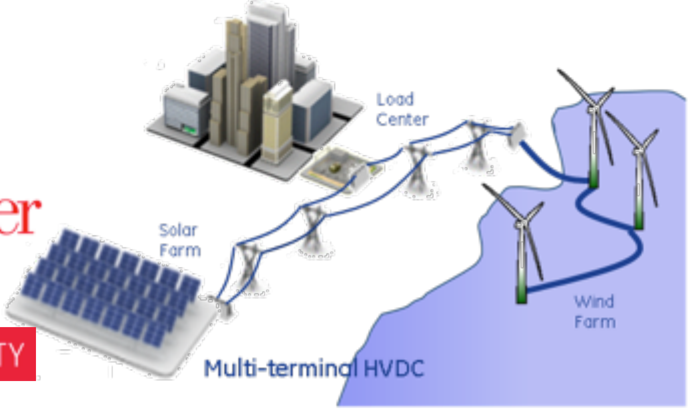
- Potentially the most powerful flow control device
- Arbitrary control of P (either direction)
- Independent control of Q1 and Q2 (generating or absorbing VARs)
- High VSC equipment MVA rating relative to power flow controlled
- Each terminal rated for full real power transmitted plus reactive power generated
- Each terminal controlled to act as current source (i.e. infinite impedance seen from the ac grid)

High Voltage Direct Current Transmission

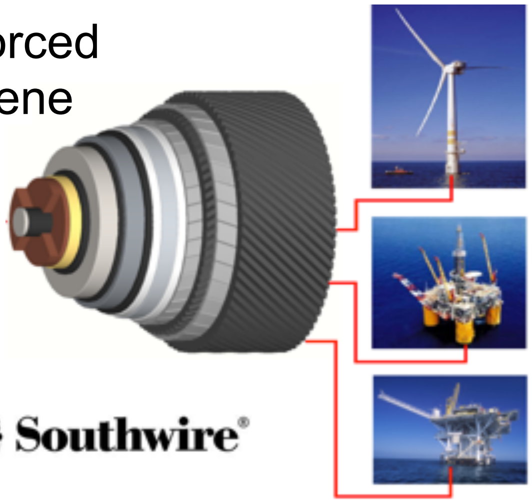
Resilient Multi-terminal HVDC Networks with High Voltage High Frequency Electronics

Rensselaer

NC STATE UNIVERSITY

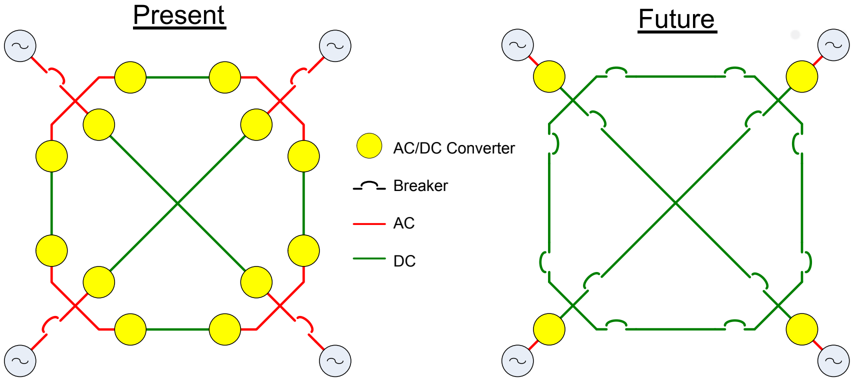


Nanoclay Reinforced Ethylene-Propylene Rubber for Low-Cost HVDC Cabling

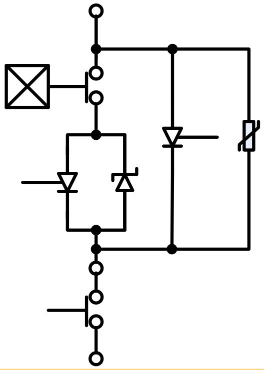


Southwire®

Magnetically Pulsed Hybrid Breaker for High-voltage Direct Current (HVDC) Power Distribution Protection

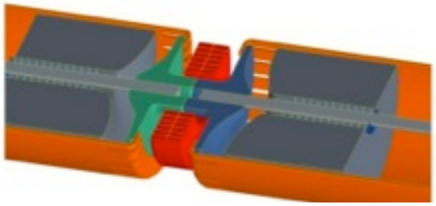


IGCT commutation for fast, arc-less opening



GENERAL ATOMICS

MISSISSIPPI STATE UNIVERSITY



Coil-driven mechanical interrupter for low insertion loss and fast opening

Open Questions: Cost & Effectiveness Metrics

- Historically, for shunt-connected transmission compensators, the rule of thumb for the acceptable total power loss limit has been 1% based on terminal MVA rating of equipment.
- Traditionally, capital cost has been calculated as $/MVA based on the equipment
- "Apples with apples" comparison metrics for series-connected PFC devices are needed that account for the ***effectiveness*** of the device (not apparent simply from MVA rating). For example, should the efficiency and cost be expressed relative to:
  - The maximum achievable ***change*** in power through the transmission line?
  - The maximum magnitude of the ***voltage drop injected*** into the line?
  - A basis calculated for the device in a standard hypothetical ***benchmark system*** so it is more absolute?
- Standard methodologies are needed for comparing different types of power flow control solutions.

Conclusion

- Widespread deployment of power flow control devices could offer many benefits. (Though, these benefits have not yet been quantified sufficiently.)

- AC power flow control can be accomplished by:
    - controlling the impedance on a major transmission line
    - injecting a controlled voltage in series with a line
    - providing reactive voltage support for long lines so that they can be loaded to their thermal limits
    - switching line circuit breakers to redirect power to other lines.

- Fast, automatic, electronically-controlled, low cost, series-connected ac power flow control devices appear very promising for enabling ubiquitous ac power flow control.

- ARPA-E's GENI program is focused on early stage development, validation and demonstration of a portfolio of new power flow control technologies.

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ENERGY

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