Intelligent Power Infrastructure Consortium

Smart Wires

Dynamically Controllable Grid Assets

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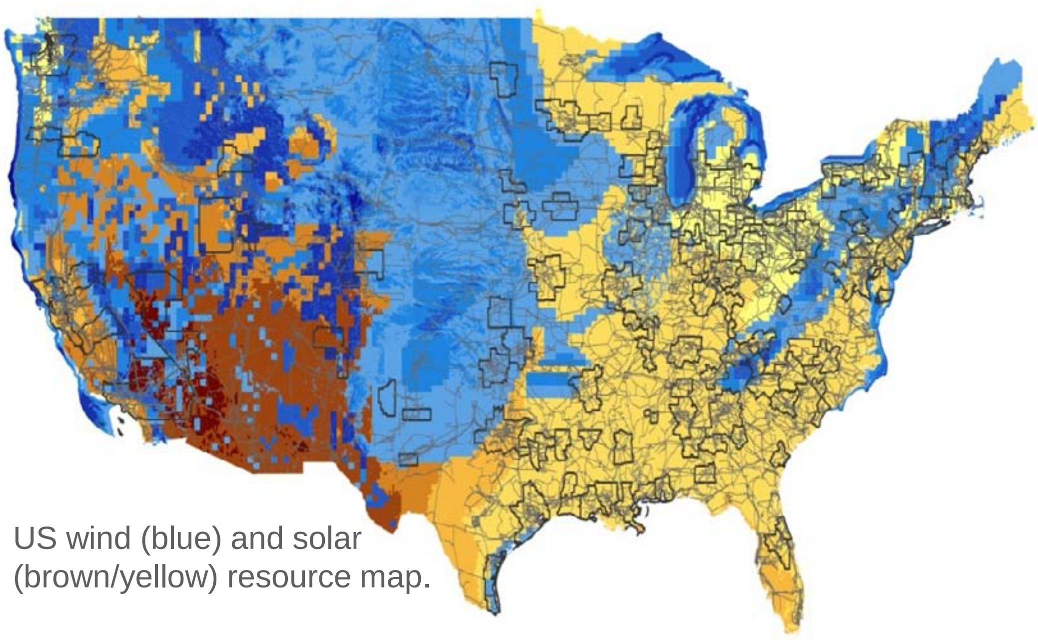
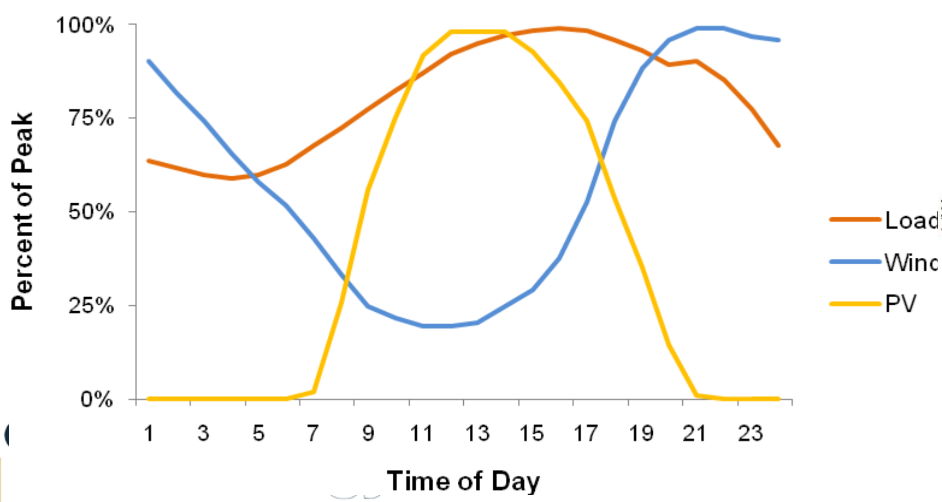
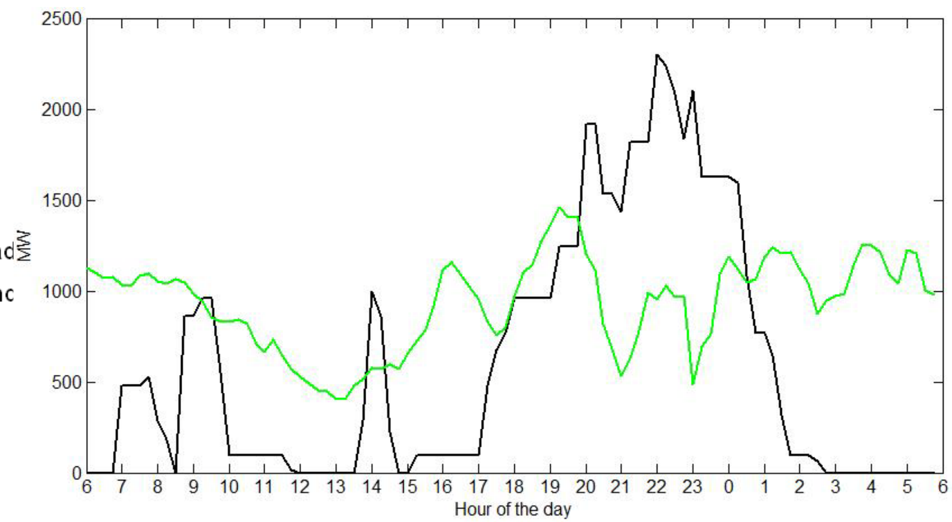
Power Delivery - Major Challenge for Sustainable Energy



US wind (blue) and solar (brown/yellow) resource map.

- Wind at price parity with natural gas, retail price parity imminent for solar PV. Binding RPS mandates of 10-40% in 27 states.
- To meet current reliability standards, new solar/wind plants need energy storage, back-up fossil plants & spinning reserve.
- EVs require spinning reserve and back-up generation.
- Excessive new T&D buildout with RPS and EVs to meet energy delivery requirements.

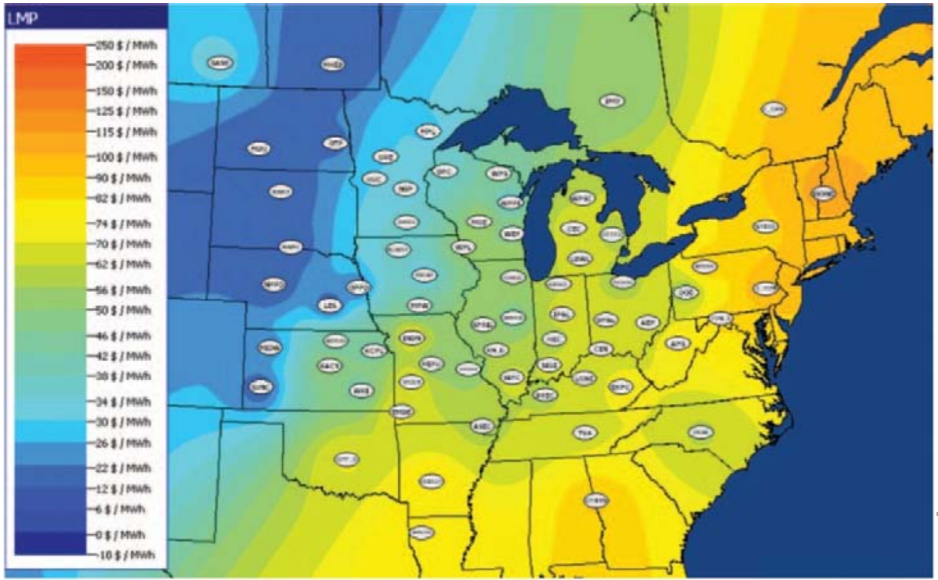




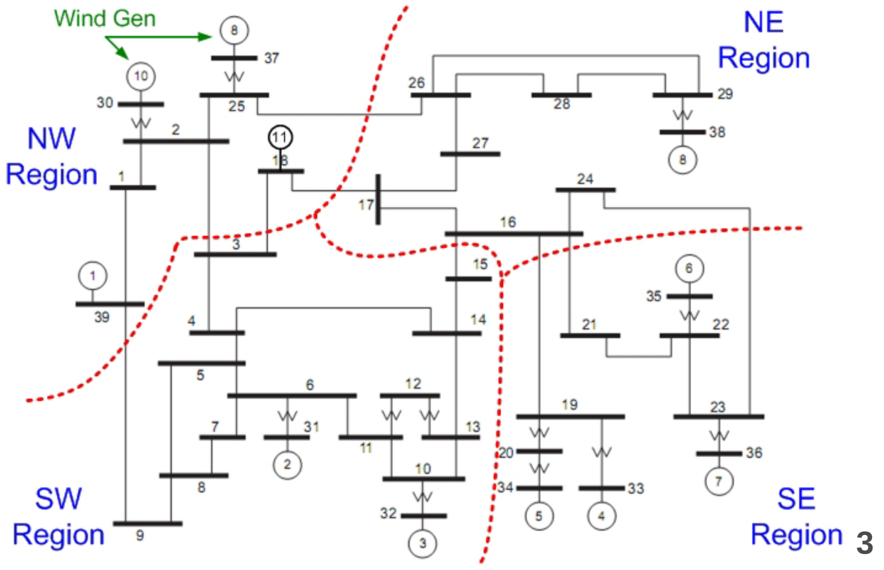
Impact of Renewable Generation on Transmission Grid

- DOE study shows LMP impact of 20% wind in eastern interconnect with existing transmission. 37.8% curtailment of wind generation; revenues unable to support wind generation without market-distorting make-whole payments, $33B/yr in congestion
- 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 (renewable generation lean, transmission heavy scenario)
- **BAU** case requires upgrade of 3 inter-regional paths, for a total of **186,000 MW-MILES.**
- **Smart Grid** case uses Controlled Energy Flows to route power along underutilized paths, **36,000 MW-miles** of new lines needed, only 20% of BAU.

Generation-weighted LMP for 20% Wind Scenario
(source DOE, Eastern Wind Integration and Transmission Study, 2010)



IEEE 39 Bus System Partitioned into 4 Control Areas

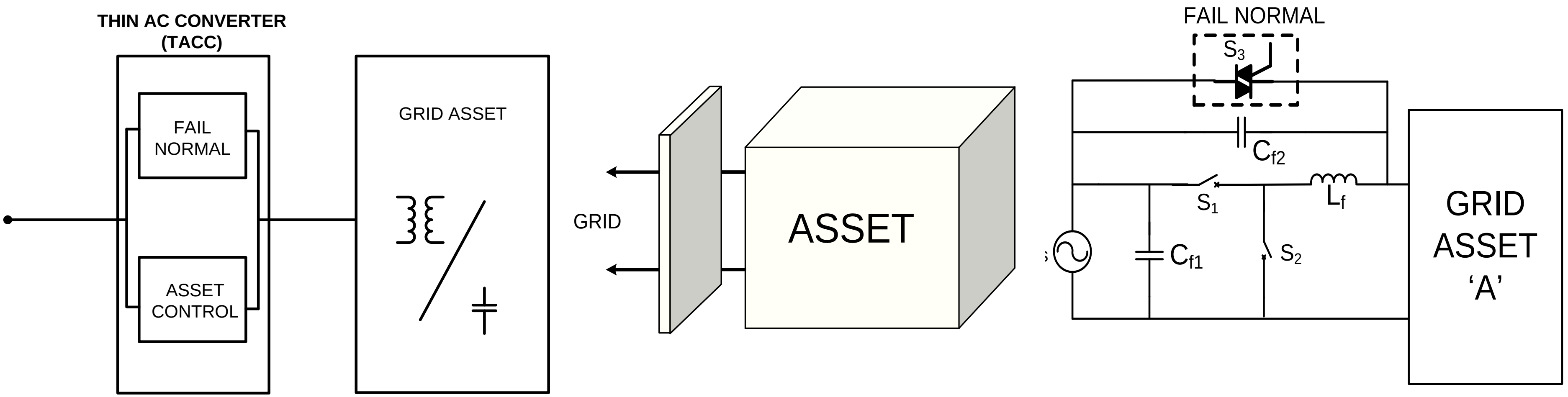


Smart and Dynamically Controllable Grid

- To achieve energy sustainability will require integration of renewable energy, electric vehicles, price based electricity demand, load-following generation, energy storage – results in tremendous spatial and temporal variability.
- This will need to be solved through increased smarts, communications, and control. Existing breaker based controls will be prohibitively costly, and will require dynamic controls that can enhance asset utilization without compromising system reliability.
- At a societal level, the Smart and Controllable Grid is the key to achieving cost-effective energy sustainability by using assets more effectively and minimizing the build of new transmission and distribution infrastructure.
- Utilities are wary of power electronics because of cost and reliability. Transmission and sub-transmission systems have 99.99% reliability, higher than most power conversion systems. Also, single point of failure can reduce system capability just at the time the capability is needed.
- Even though power electronics based FACTS devices have been available for 20 years, penetration has been poor (except in applications for point-to-point power delivery over distances – HVDC or HVDC Light).

Thin AC Converters – Dynamic Control of Grid Assets

•The concept of Thin AC Converters lies in utilizing existing grid assets to provide additional functionality, i.e. making the ‘dumb’ asset ‘smart’.



•Layer the existing asset with a direct ac converter – use the existing asset as the bulk energy storage element at the fundamental frequency

•Reflect the dynamically controlled asset value on the grid. No additional stresses.

•The converter has a ‘Fail Normal’ mode, where failure of the converter restores normal function of asset on the grid – maintains system reliability.

Thin AC Converters – Possible Applications

MULTI-LEVEL DIRECT AC CONVERTERS

INTELLIGENT POWER INFRASTRUCTURE CONSORTIUM

VIRTUAL QUADRATURE SOURCES

THIN AC CONVERTERS

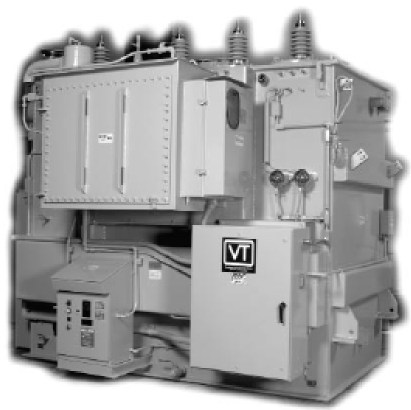
Smart Wires

Transmission Lines

Control power flows

Utility/DOE funded

Controllable Network Transformers



LTC Transformers

Dispatchable P/Q

ARPA-E Funded

Inverter-less STATCOMs

Shunt VAR Capacitors

STATCOM functionality

Industry Funded

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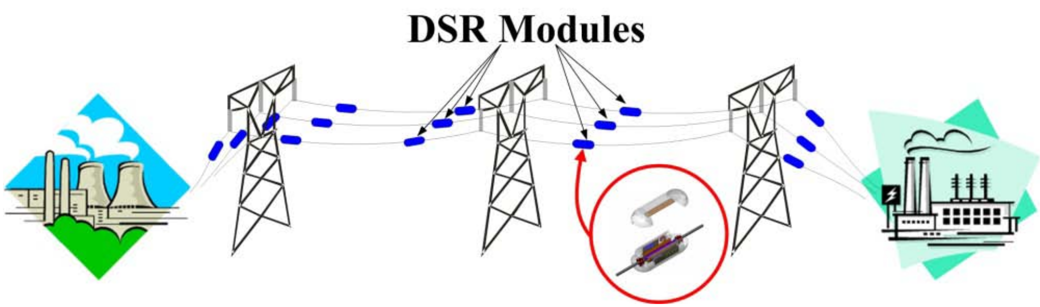
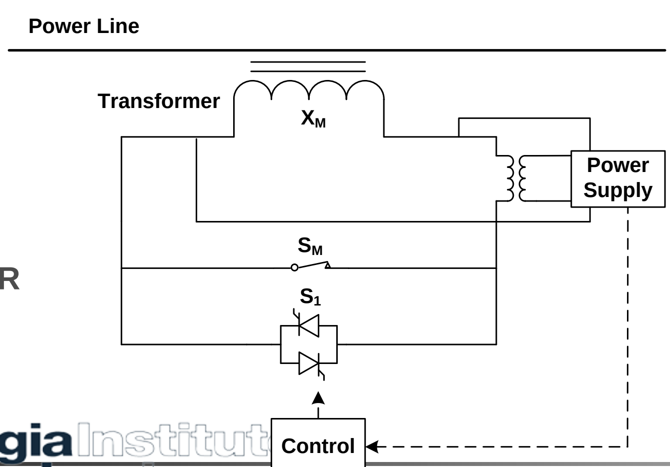
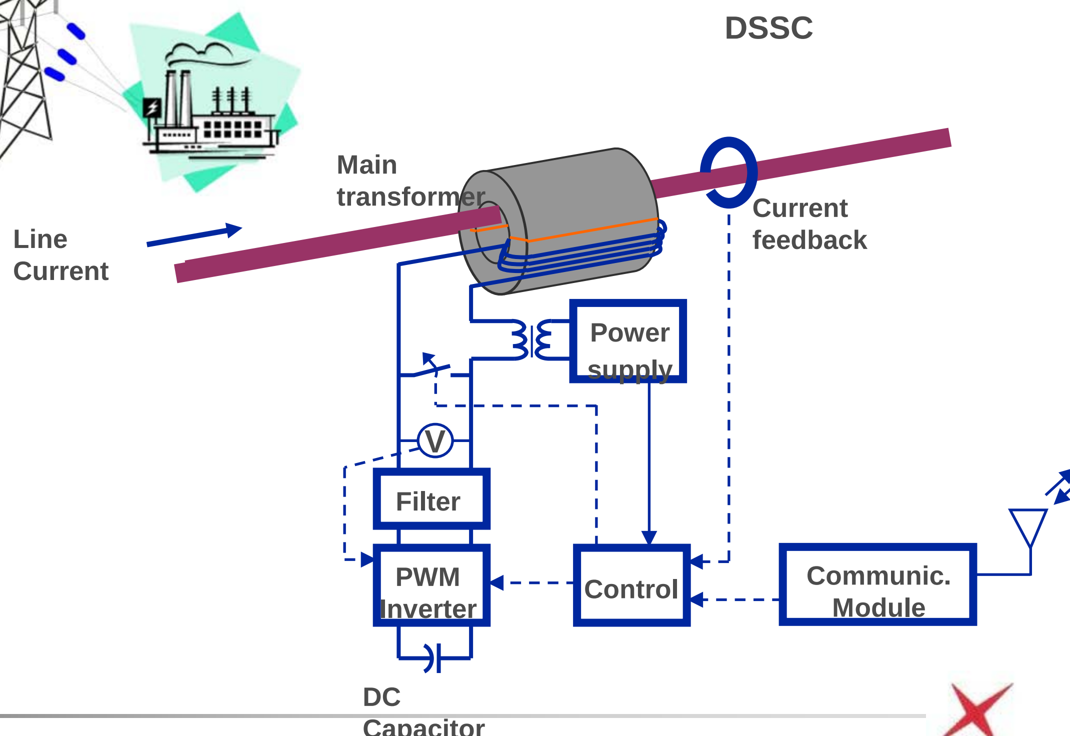
Smart Wires – Dynamic Control of Line Impedance

- Distributed Static Series Compensator (DSSC) or Distributed Series Reactance (DSR) modules that clip on to existing conductors and change line impedance as needed
- Low-cost zero-footprint distributed solution that can change line impedance by 20%.
- Power flow control has substantial impact on system capacity and for enhancing system utilization, even under contingencies.
- Demonstrated at 161 kV level, with pilot demonstration underway.

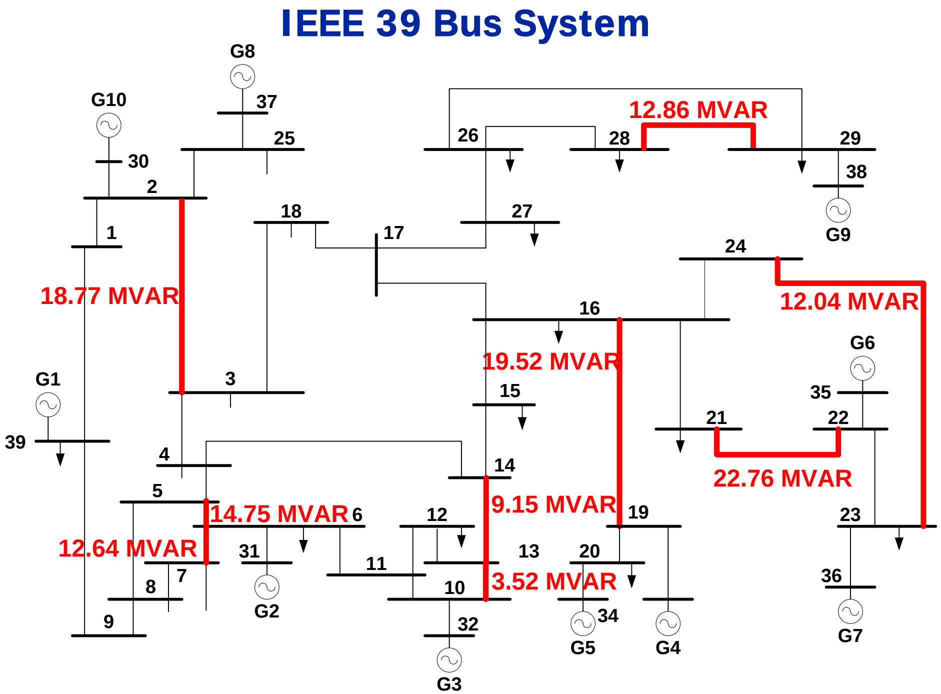


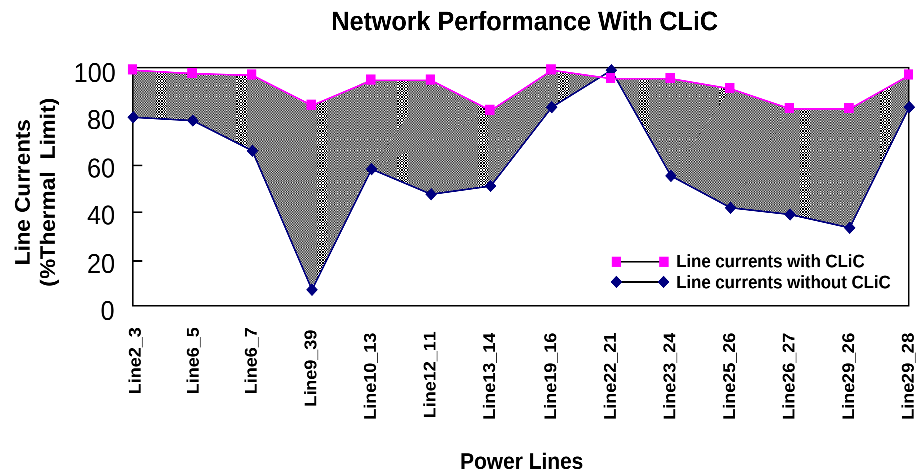
DSR

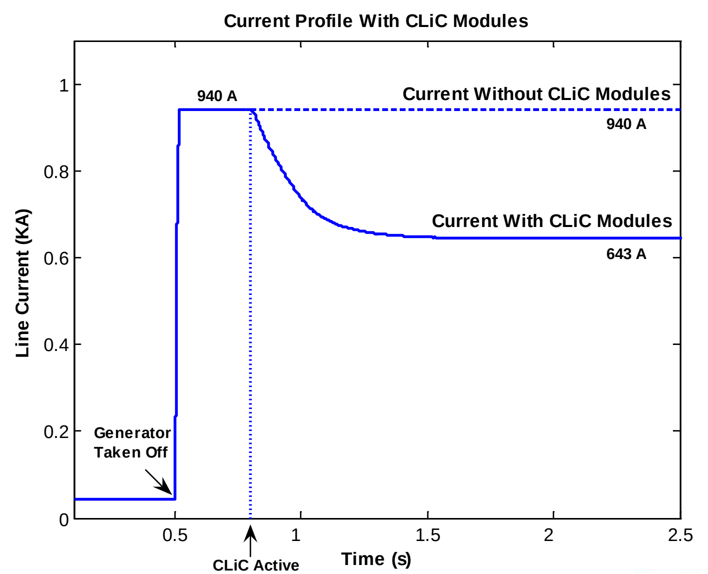




Increase in Network Utilization With DSR Modules



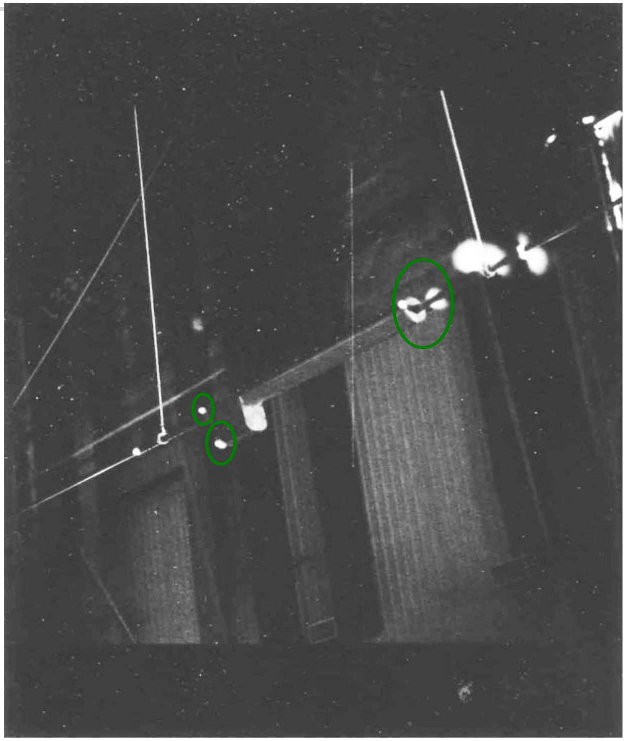




- Increase in Transfer Capacity from 1904 MWs (59%) to 2542 MWs (93.3%) - congested corridors are shown in red
- Would require 9 additional lines to realize capacity increase, capacity utilization stays at 63%
- With (N-1) contingency, capacity is decreased to 1469 MW (46%), and increased to 2300 MW with DSR modules without building additional lines. Self-healing grid!

Smart Wires Project Background

- Project initially supported by TVA, and has been supported by DOE over several years.
- Ongoing multi-year project under NEETRAC to prove concept at utility voltage/current level, and to move towards commercialization.
- Project funders include TVA, Southern Company, NRECA, BG&E, Consolidated Edison, Zenergy.
- Worked closely with utilities to develop a specification for the module – suitable for 69 – 230 kV class of lines in first design.
- First design targets DSR with communication only for maintenance. Utilities would like a design of Active Smart Wires with communication. Existing inverter based design is inadequate.



- **Electrical**
  - Operating Level : 161 KV, 1,000 A
  - ACSR Conductor: Drake (795 Kcmil)
  - Injection: 10 kVA, 750 A
- **Mechanical**
  - Target weight per module: 120 lb
  - Packaging to avoid corona discharge, and other mechanical, thermal and environmental issues

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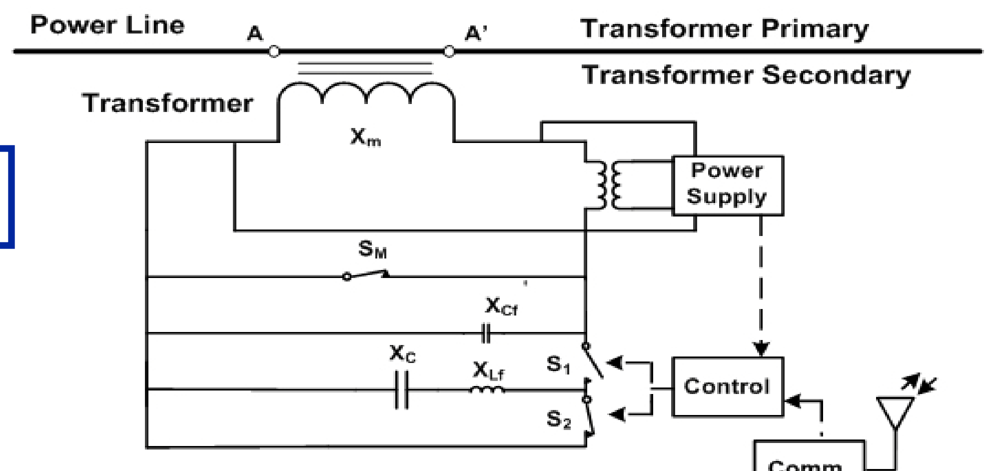
Active Smart Wires Design

- Value in ability to increase or decrease line reactance
- Design specification meeting held 9/25/2009 for Smart Wires and Active Smart Wires, stakeholders require 20 year lifetime expectation with no maintenance
- 20 year life requires passive cooling and elimination of electrolytic caps:
  - Distributed - SSC: single phase solution leading to high cap ratings, difficult to replace electrolytic cap with a film cap, Unlytic capacitor is possible but costly
  - Distributed Series Impedance (DSI): capacitor and inductor in parallel with STT, impedance changed using thyristor pairs, unable to vary L/C continuously.
  - TACC Design: Smart Wires augmented with 2 AC switches, an AC capacitor, and communications → **Active Smart Wires**
  - Based on feedback from Sargent Electric line crew, stakeholders expressed interest in live-line and outaged installation. Design will accommodate both.

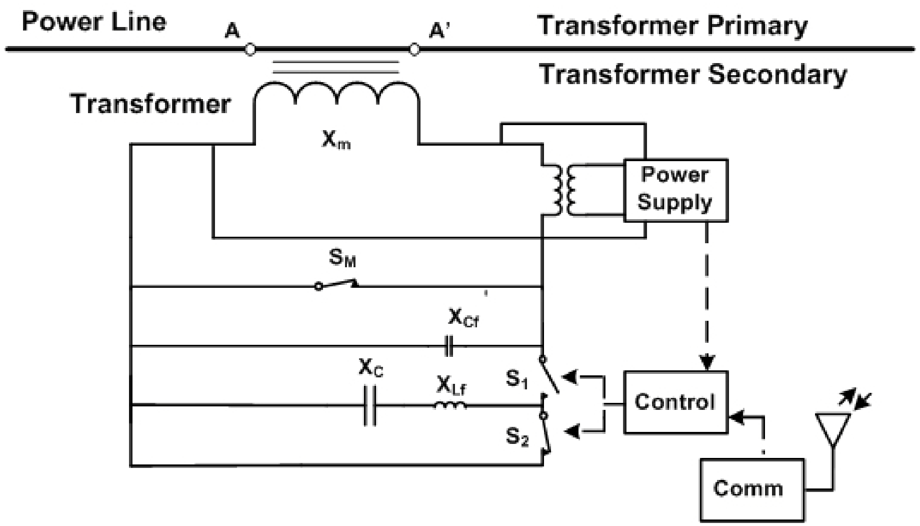
AC Chopper (TACC) + **CAP** = **Variable Cap (Modified Asset)**

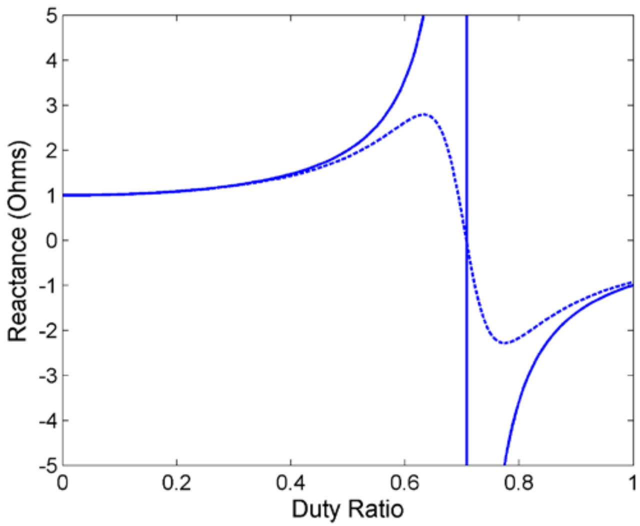


Active Smart Wires

Impedance vs. Duty Ratio for Active Smart Wires

- Developed concept of new ASW. Simplifies to fixed inductor (magnetizing inductance of STT) in parallel with variable capacitor
  - Effective value of C determined by duty ratio
  - Switches operate at high frequency with constant PWM control
  - No electrolytic capacitors, low losses

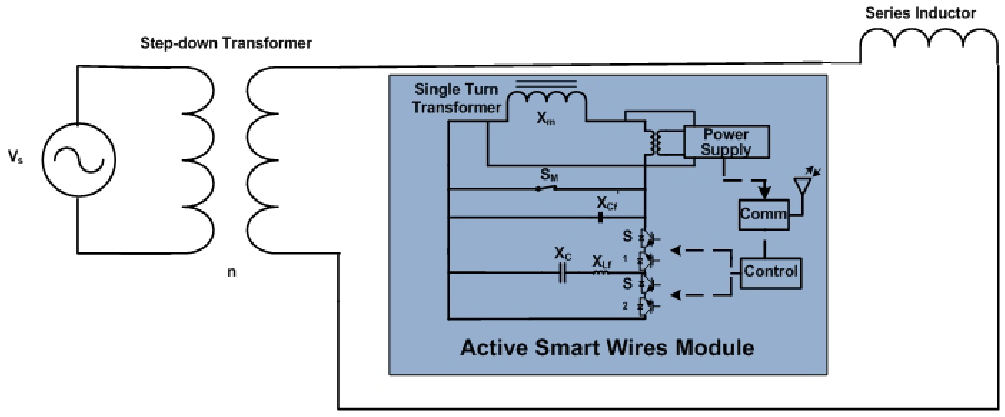




Reactance vs. Duty Ratio
(solid line w/o losses and dotted w/ losses)

Simulation Setup

- Objective: Simulate ASW operation within the Georgia Tech High Current Test Rig to inform fabrication of a Proof of Concept ASW
  - Simulation conducted in Sabre
  - Parasitic values derived from survey of commercial components
  - ASW rated 10 kVA (at D=0 or D=1)
  - STT parameters derived from existing Smart Wires Proof of Concept
  - STT saturation neglected
  - Test-Rig rated 1200A

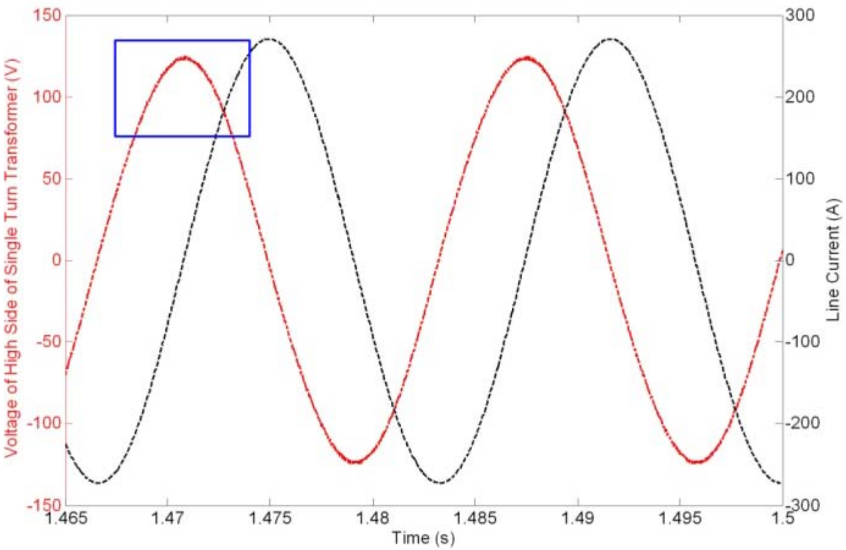


ASW Embedded in Georgia Tech High Current Test Rig

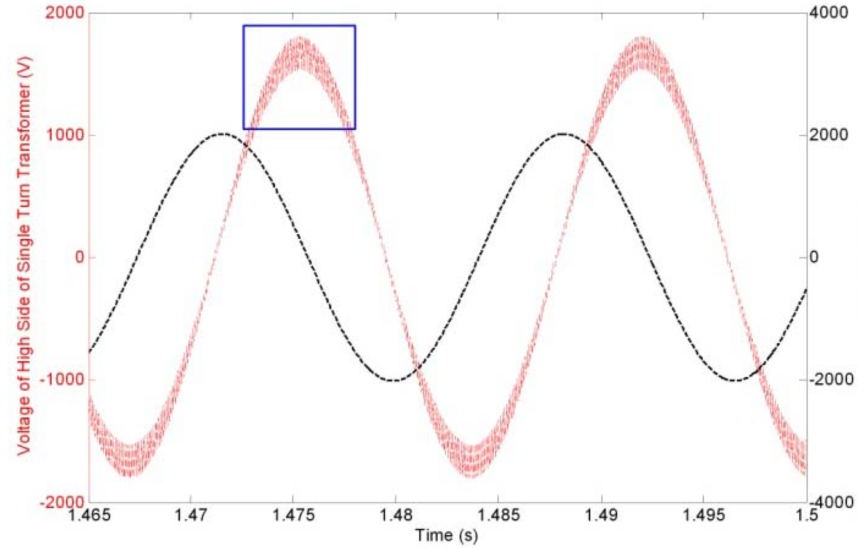
Parameter	Value
Source voltage (Vs)	377 V
Step down transformer duty ratio (n)	10:1
Inductance of transmission line series inductor	90 μH
Switching frequency	10 kHz
L_m (line side)	41.6 μH
C	450 μF
C_f	30 μF
L_f	20 μH
ESR of L_f	50 mΩ
Turns ratio of STT	1:25
Winding resistance of high side of STT	164 Ω
R_{on}	1 mΩ
t_{on}, t_{off}	1 μs

Simulation Parameters

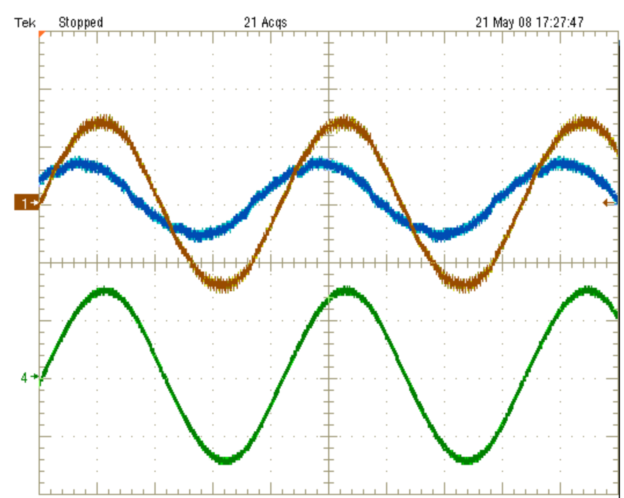
Simulation and Preliminary Experimental Results



Voltage and Current Waveforms for D=0.1



Voltage and Current Waveforms for D=0.9



Upper traces: Simulations showing inductive and capacitive injection.

Right trace: Experimental results showing effective capacitor using ac chopper switching.

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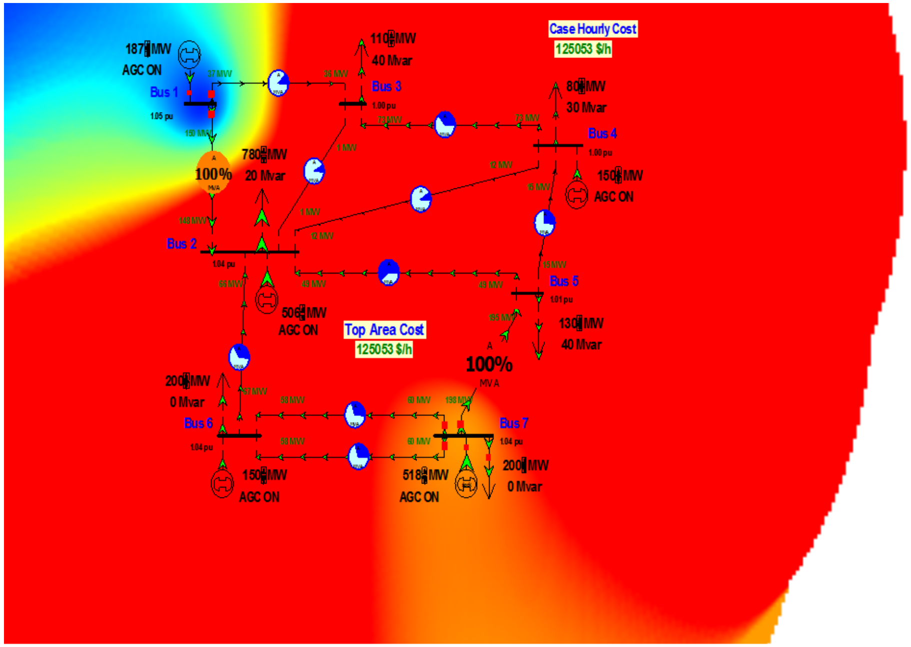
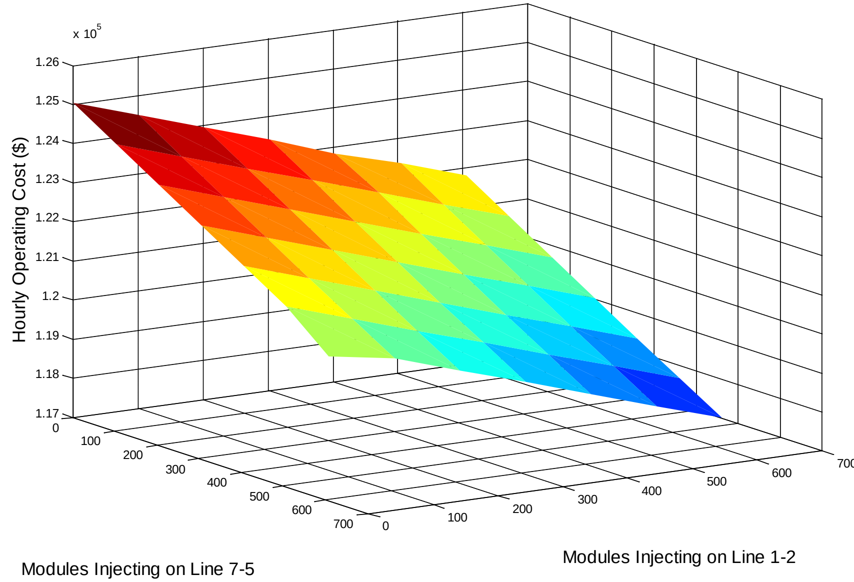
Impact of Smart Wires on Power System Economics



Test System



Impact of Module Additions on system Operating Cost

- **Objective**: Simulate impact of Smart Wires on congestion costs during periods of high network loading
- Test system: 7 bus system with 3 gas generators (G2-G4), 1 coal (G5), 1 wind (G1). Smart Wires installed on Line 1-2 and Line 7-5
- PowerWorld Simulator used to optimize total system operation, able to vary generator setpoints and amounts of installed Smart Wires capacity
- Result: Smart Wires reduces total system operating costs by 6%, payback achieved in ~140 hours of operation under test conditions

Commercialization, Technology Transfer & Publications

- While preliminary capacitor control was experimentally observed, fabrication of proof of concept ASW was not finished due to the abbreviated project period (3 months rather than the scheduled 12) and change in commercialization partner. Project is restarting with completion of commercialization negotiations. ASW will be in the 2nd wave of products.
- Five invited presentations and three peer-review papers presented at conferences in 2010 (PES 2010 Conference on Innovative Smart Grid Technologies , PES 2010 T&D Conference and Exposition, PELS/IAS 2010 Energy Conversion Congress and Expo)
- Coalition of stakeholders formed to inform design and fund development – Georgia Power, TVA, BG&E, and NRECA – project under NEETRAC umbrella. Over $1.2Million in funds.
- New venture capital backed firm is being established to carry the technology forward
- New firm is moving towards a 2011 full scale pilot demonstration
  - Independent design firm has completed an initial design for manufacturing
  - More than 15 STT cores were fabricated and tested to identify a low-cost core with appropriate performance
- Coalition of stakeholders have nominated candidate lines for the pilot project, leading to prioritization of a line in the Georgia Power footprint and another in the TVA footprint

Conclusions

- Concept of Dynamically Controlled Grid Assets using Thin AC Converters (TACC), developed at the IPIC lab at Georgia Tech, offers a new approach for achieving cost-effective control of the grid.
- DOE has provided partial support towards completion of major project objectives aimed at commercializing the Smart Wires technology as the first product based on TACCs.
- The basic design approach for Smart Wires and the value proposition have been shown. Smart Wires can help to defer transmission investments, improve system reliability and utilization, and reduce the cost of integrating significant level of renewable energy into the grid.
- The DSR provides only one way control, while the Active Smart Wires developed here, can realize increase and decrease in line impedance. ASW however, requires communication.
- The impact of Smart Wires at a system level, and in terms of economic impact, has also been presented, and is seen to be very promising.
- Smart Wires technology is moving towards commercialization with strong utility and vendor support.