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INTELLIGENT POWER INFRASTRUCTURE CONSORTIUM

Intelligent Power Infrastructure Consortium
DOE Peer Review Meeting
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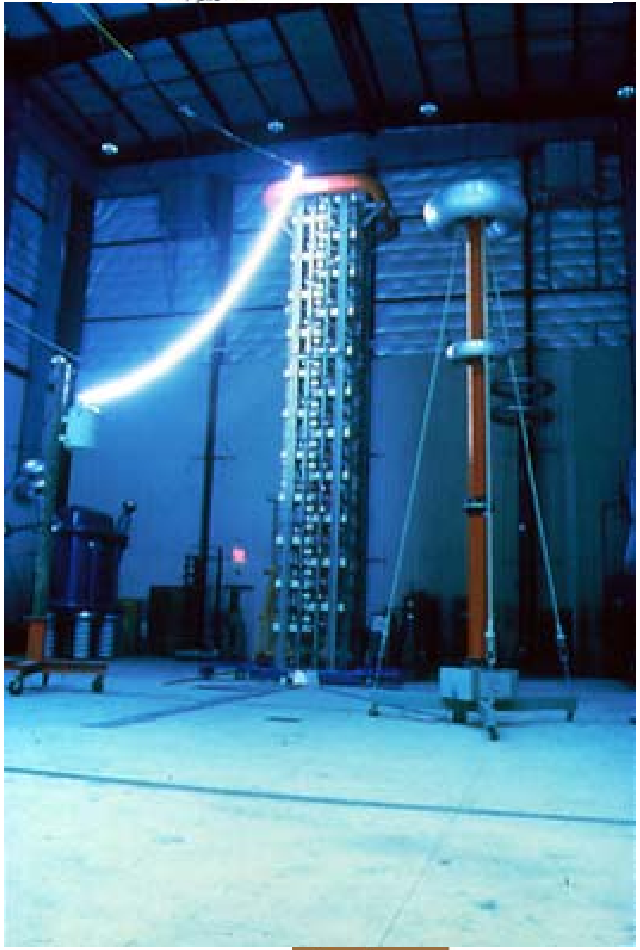
Georgia Institute of Technology

- Premier research university with focus on technology.
- Annual research budget >$349 million
- Ranked 5th in 2005 graduate engineering schools (US News & World report)
- Largest ECE Department in the US - 112 faculty, 1800 undergrad students, 800 grad students
- Strong presence in power, communications, nanotechnology, MEMS and microelectronics, embedded systems, computing, organic electronics, signal & image processing and bio-medical
- Faculty in the power area have competencies in power systems, power electronics, diagnostics, micropower, controls, communications, insulators, thermal design and high voltage engineering
- NEETRAC, IPIC and PSERC provide linked centers doing research in power related areas
- Located in Atlanta – fast growing high-tech center.



Intelligent Power Infrastructure Consortium

IPIC Mission

- Develop an integrated academic teaching and research program encompassing power electronics and drives; power systems engineering; and distributed sensing, diagnostics, control and communication.
- Provide a mechanism to foster and accelerate the development and adoption of early-stage pre-competitive high-risk and high-impact technologies in power applications
- Maintain close ties and interactions with industry and utility technology leaders to maximize relevance of research efforts and to facilitate technology transfer
- Target early-stage proof of concept demonstration projects, with quick transition to a funded project.
- Participants and supporters include TVA, Con Ed, Southern, ABB, Eaton and the Department of Energy

Intelligent Power Infrastructure Consortium – Research Thrusts

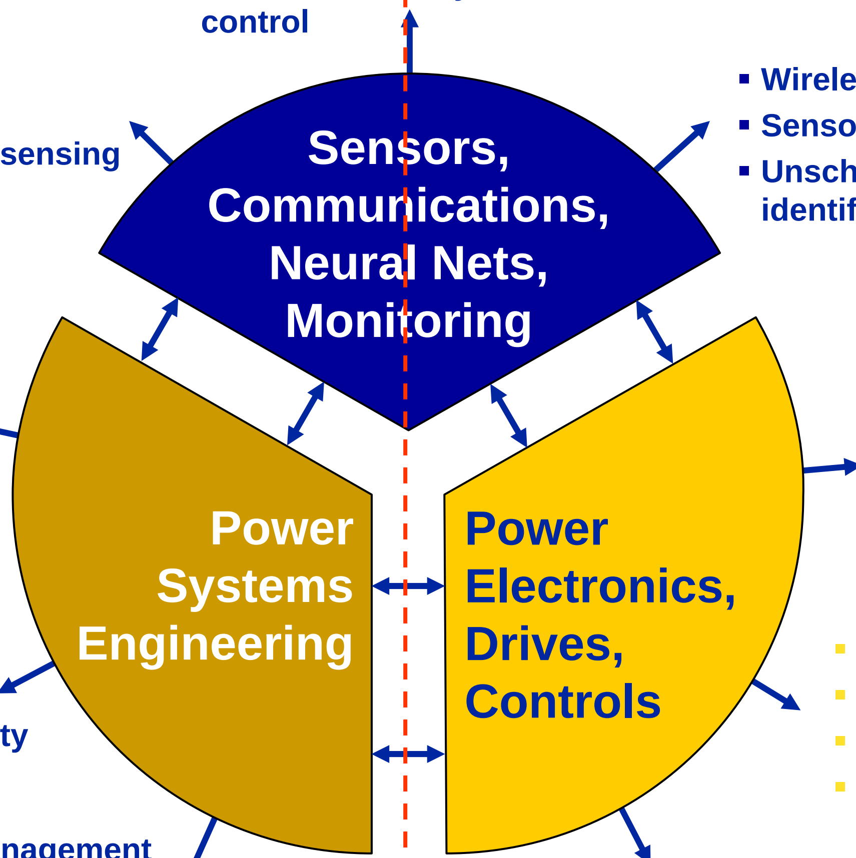
- Power line communications
- Neural nets for system I/D and control

UTILITY APPLNS

- Power line sensornets
- Wide area monitoring
- Distributed power line sensing

INDUSTRIAL APPLNS

- Wireless sensor networks
- Sensorless motor fault detection
- Unscheduled down-time identification



- Wide area control
- Wide area protection

- Neural network controls for PE
- Component failure prediction
- Power and analog ICs

- Power system operation and state estimation
- Protective relaying
- Bulk power system reliability

- Active filters
- Motor Drives
- Current surge limiters
- High power inverters & dc/dc converters

- Congestion management
- System control and stability with FACTS
- Distributed energy sources

- D-FACTS devices
- Current limiting conductors
- Fault current limiters
- Power quality and reliability

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INTELLIGENT POWER INFRASTRUCTURE CONSORTIUM

Major Challenges for Power Delivery

- Existing infrastructure is aging and underutilized
- New lines are expensive and difficult to get approved (ROW & NIMBY)
- As new generation and load is added, portions of the grid are getting overloaded
- Power flow in individual lines cannot be controlled, limiting ability of market to operate well.

This results in sub-optimal grid operation and poses significant operational challenges for utilities –

- Danger of load shedding and poor reliability under high-load and/or contingency conditions
- Fault currents that may exceed breaker ratings
- Lines that exceed thermal ratings, even as neighboring lines are under-utilized
- Conservative operation because of lack of visibility, leading to significant under-utilization of assets

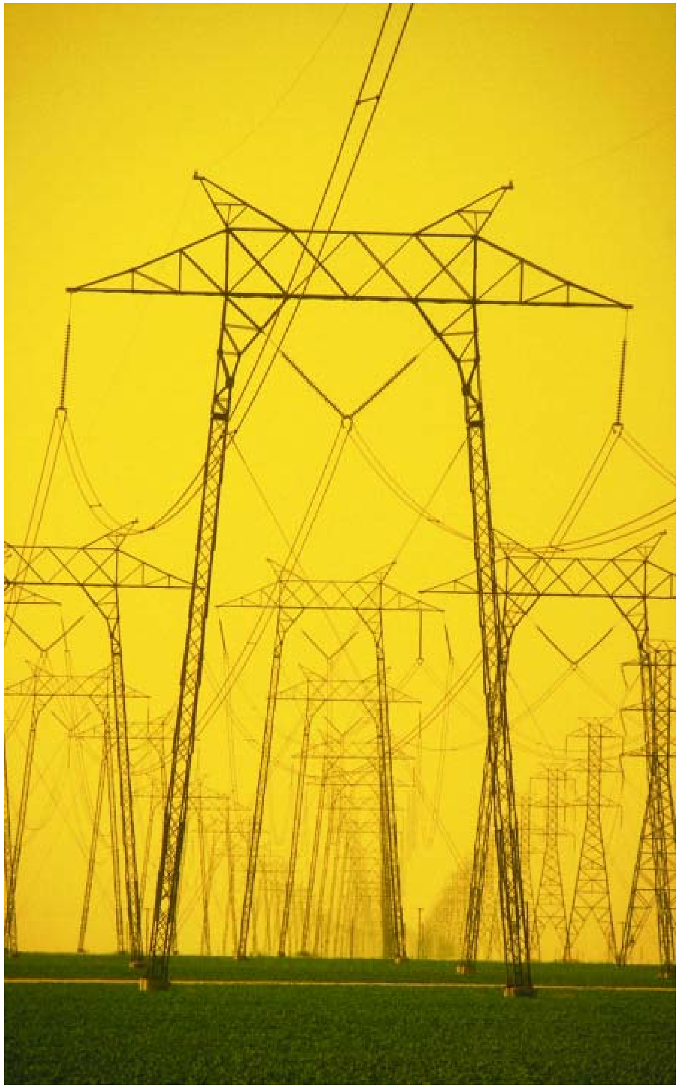
Solutions are needed for improving the controllability and utilization of the power grid

Axioms for Smart-Grid Design

- Unlike other modern networks, the power grid lacks distributed intelligence and automation, resulting in poor reliability and asset utilization
- A complete replacement of the electricity infrastructure seems unjustified as there is no performance metric, e.g. ‘bandwidth’, that promises orders of magnitude improvement

This leads to several fundamental tenets for Smart Grid design.

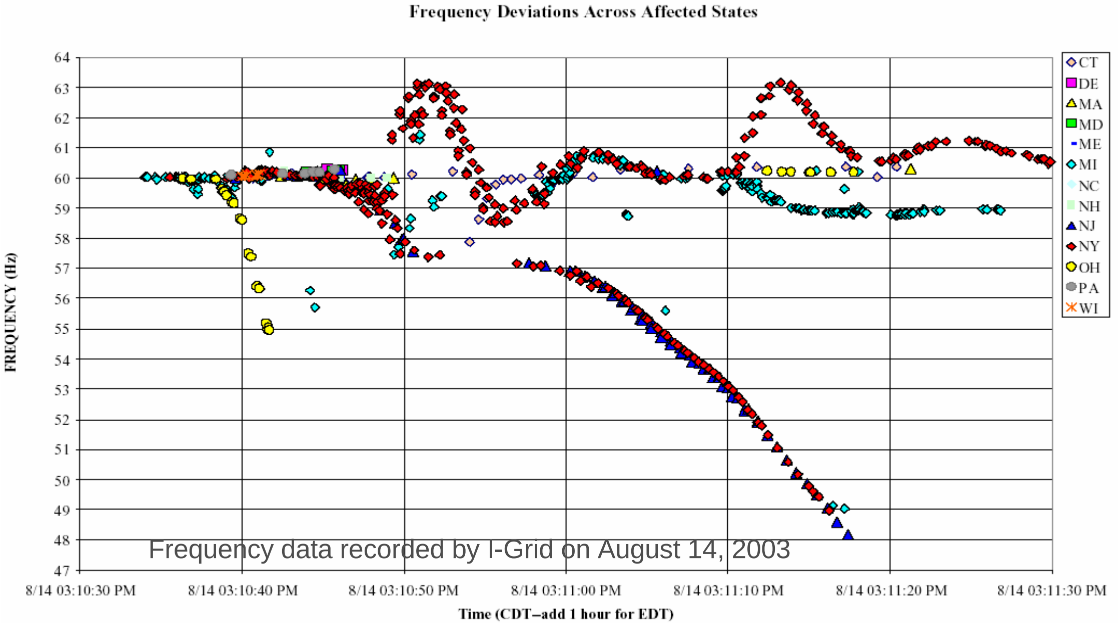
- Changes in infrastructure will have to be incrementally built to enhance and augment the legacy infrastructure
- Solutions cannot degrade the intrinsic reliability of the system – high system reliability through redundancy and fail-safe modes.
- Resulting grid needs to be self-healing, exhibiting graceful degradation as communications and vital elements are lost
- Capture additional value streams so that improved ROI can be obtained.

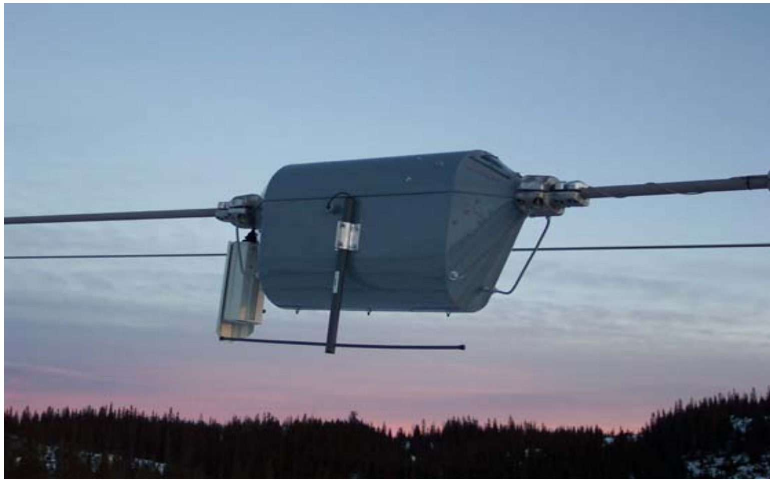


Selected IPIC Projects in Power Delivery

- Novel Cost-Effective Utility Transformers With Controllable Amplitude and Phase Angle
- Control of Wide Area Systems Using ANN's and FACTS devices
- Predicting Failure Rates of Widely Distributed Assets
- Particle Swarm Optimization for Locating STATCOMs on the System
- Fault-Tolerant Self-Healing Power System Architecture
- Off-Shore Wind Farms Using Large BLDC Machines and HVDC
- Plug-in Hybrid EV's as a Grid Connected Renewable Resource
- Power Line Sensornets – Distributed Monitoring
- Dual Mode Fault Current Limiter and Power Flow Controller for Networks
- Active Filters and Harmonic Compensators Without Inverters
- Controlling Harmonic Power Flow in MV Distribution Networks
- On-Line Monitoring and Diagnostics for Relays, Transformers, etc.

Power Line Sensornets – Distributed Monitoring



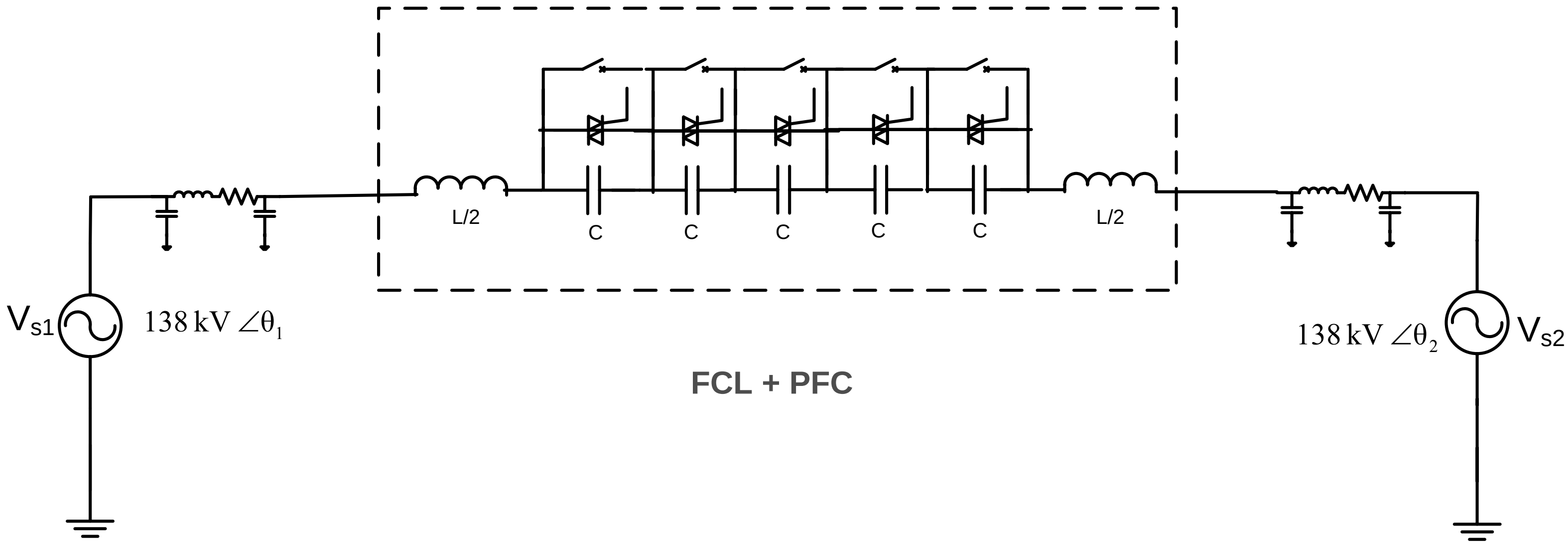


Courtesy: Protura

- Sensors that perform sensing, power scavenging and communications functions exist today – the cost is still too high
- Moving towards self-organizing sensor networks that perform distributed condition monitoring of the entire length of the power line
- Functions include sensing, on a span by span basis, of dynamic line capacity, imminent vegetation contact, failing insulators (voltage, current, temperature)
- Target cost is $250 per node.
- Objective: Improved system reliability and asset utilization

Dual Mode Fault Current Limiter + Power Flow Controller

Single device provides two value streams – power flow control in normal mode, fault current limiting in fault mode



Power Flow Mode

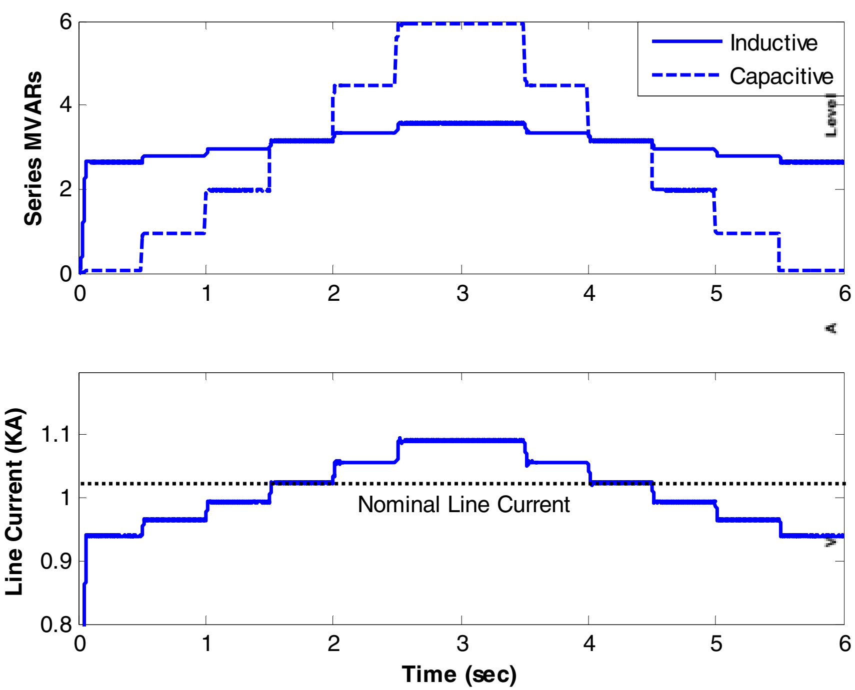
- Series VARs varied from max inductive to capacitive (say +15% to -15% in 5% steps)
- ½ cycle response to power flow changes
- No thyristor losses, compact, efficient
- Provides limited voltage regulation

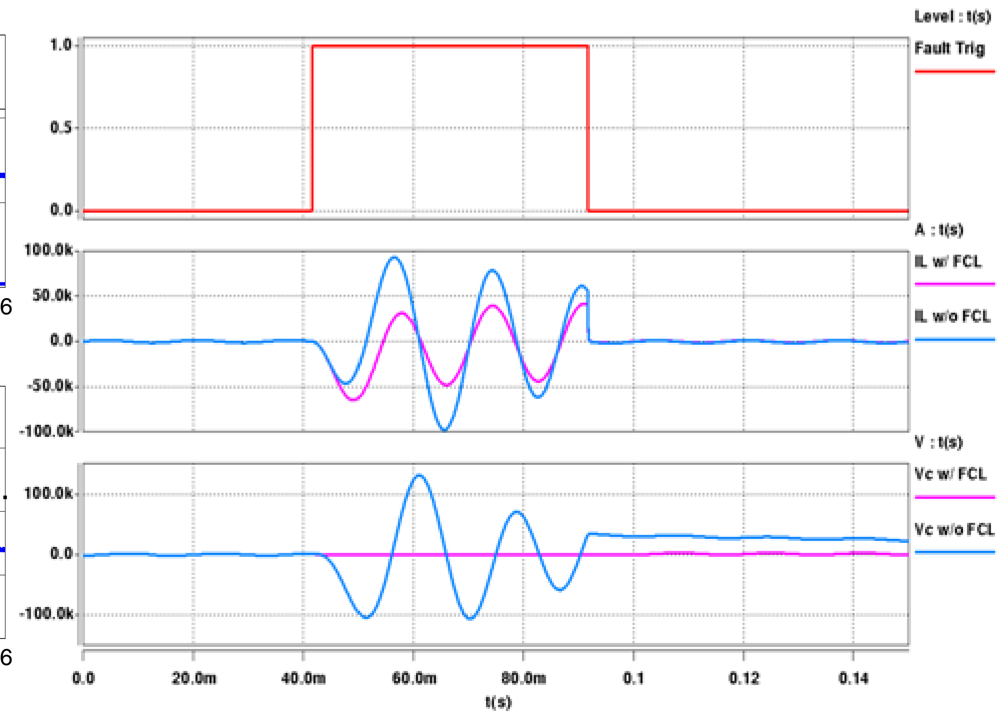
Fault Mode

- Capacitors bypassed within 10 μs of local fault detection, contactors limit thyristor losses
- Air core reactor limits current to desired level
- Fast recovery for subsequent fault protection
- Long duration fault handling possible

Dual Mode Fault Current Limiter + Power Flow Controller

Simulation results for 4 bus system at 138 kV





Line current change with capacitance

Power Flow Control Mode

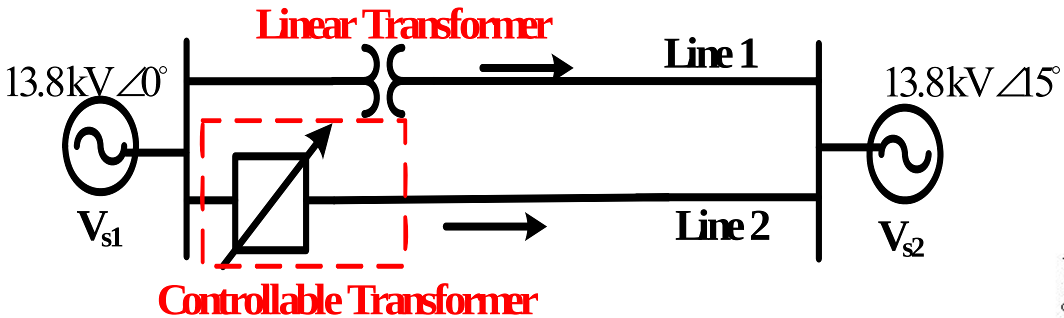
Fault current and capacitor voltage

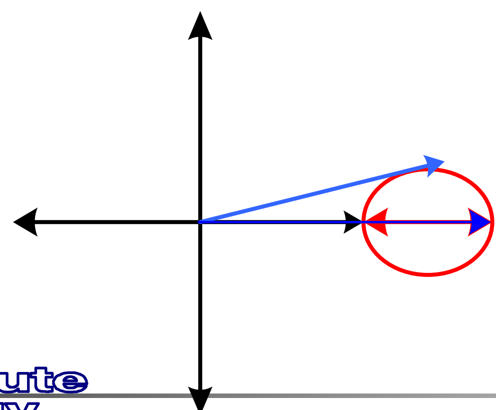
Fault Current Limit Mode

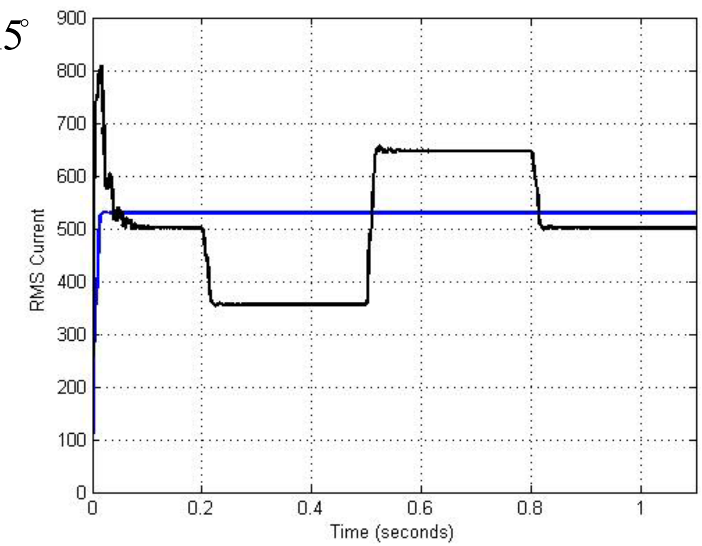
Utility Transformers with Phase Angle and Amplitude Control

➢Augmentation of existing transformers, especially tap changing transformers, using a small rated converter with no energy storage.

➢Novel approach provides simultaneous voltage regulation and phase-angle control, with graceful degradation as failures occur.



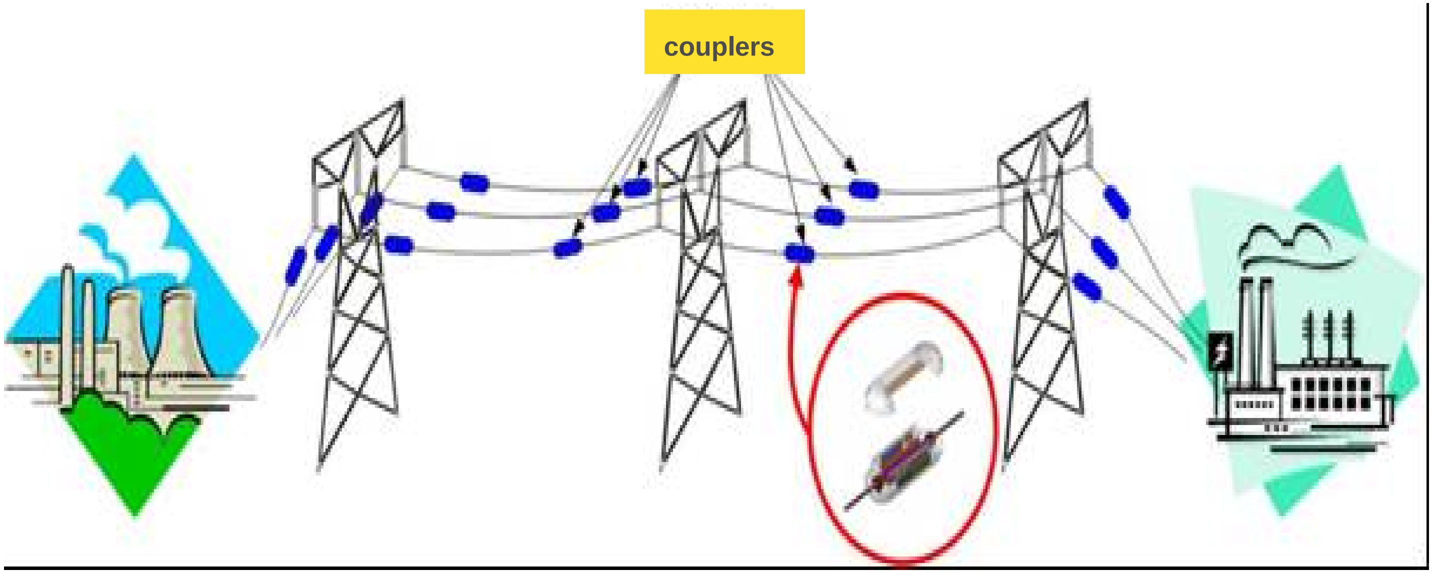




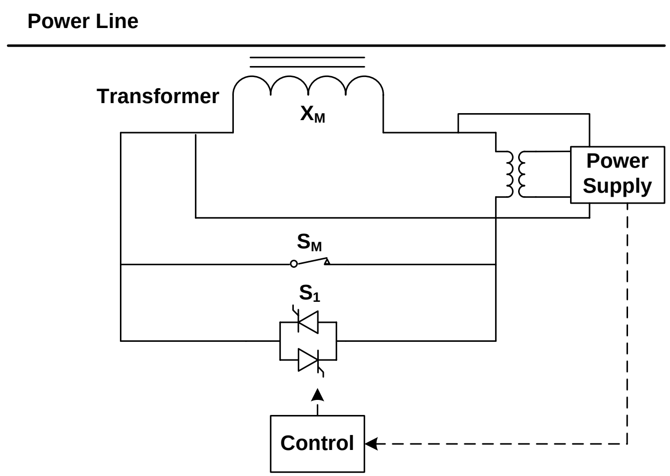
Control of line current using phase angle control capability

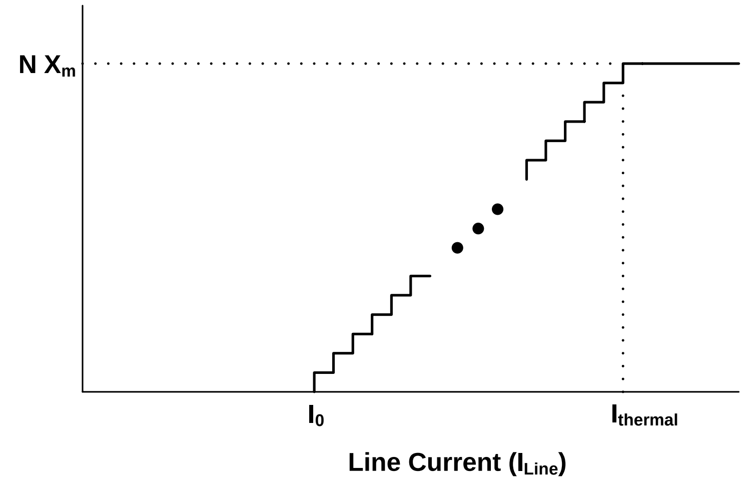
Distributed Solution for Power Flow Control – Smart Wires

- Distributed control of line impedances offers a new approach for controlling power flow in networked systems, allowing higher reliability & utilization
- Line impedance control is accomplished using a large number of 'clamp-on' 'couplers' (modules) that float on the line, electrically and mechanically.
- The modules use magnetic induction to increase or decrease line impedance, to 'push' current away from, or to 'pull' current into a line.
- Modules are 'standardized' and made in high volume using easily available low-cost components.
- Reliability is obtained through redundancy, where failure of individual modules has no impact on system operation.
- Smart Wires can be implemented using 'passive' or 'active' modules.



Distributed Series Reactance – Passive Smart Wires

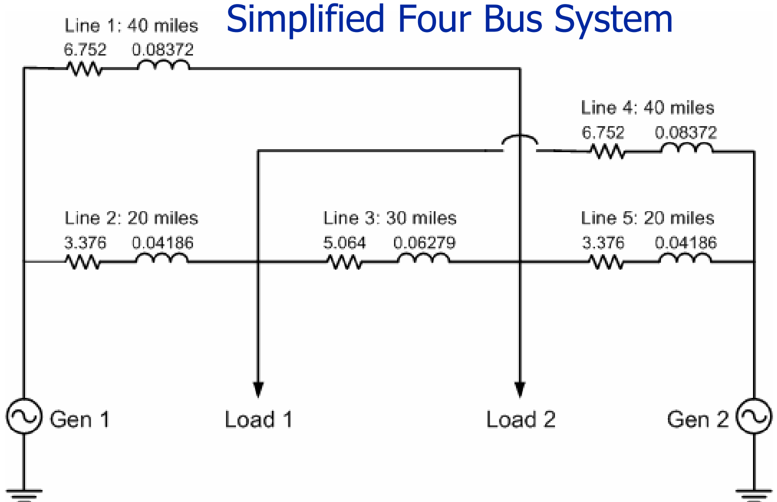




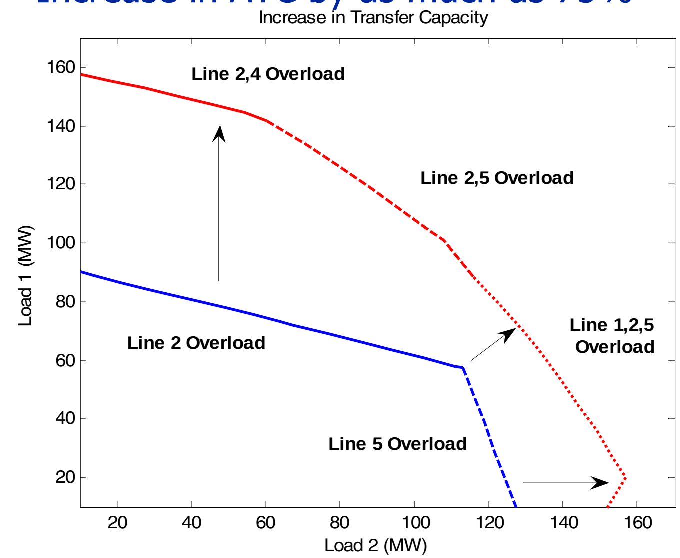
- Simplest implementation of DSI, with inductive impedance injection (Current Limiting Conductor or CLiC) – functions as a current limiting system
- As current in a line approaches the thermal limit, CLiC modules incrementally turn on, diverting current to other under-utilized lines
- Increase in line impedance can be realized by injecting a pre-tuned value of magnetizing inductance of the single turn transformer
- Each module is triggered at a predefined set point to reflect a gradual increase in line impedance
- No communication required and the devices can operate autonomously

Simulation Results – Passive Smart Wires

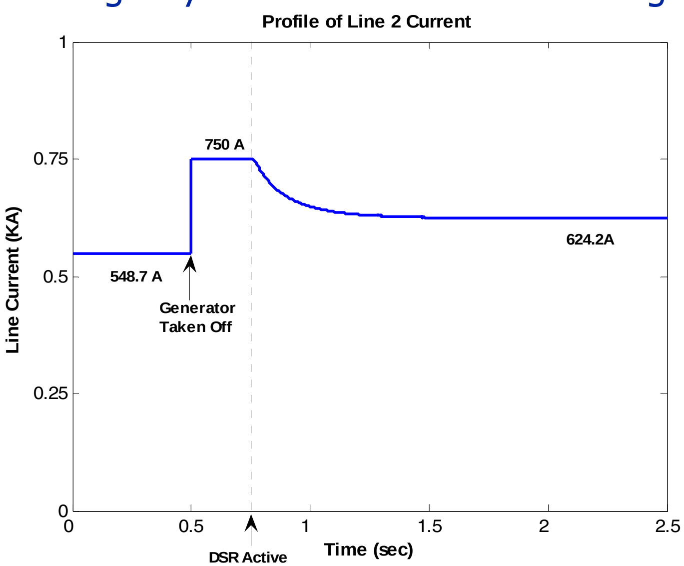
Simplified Four Bus System



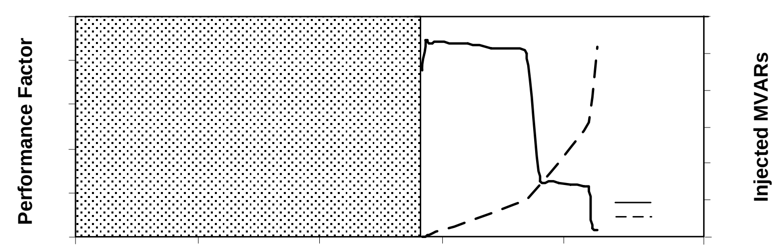
Increase in ATC by as much as 75%



Contingency Condition: Generator Outage

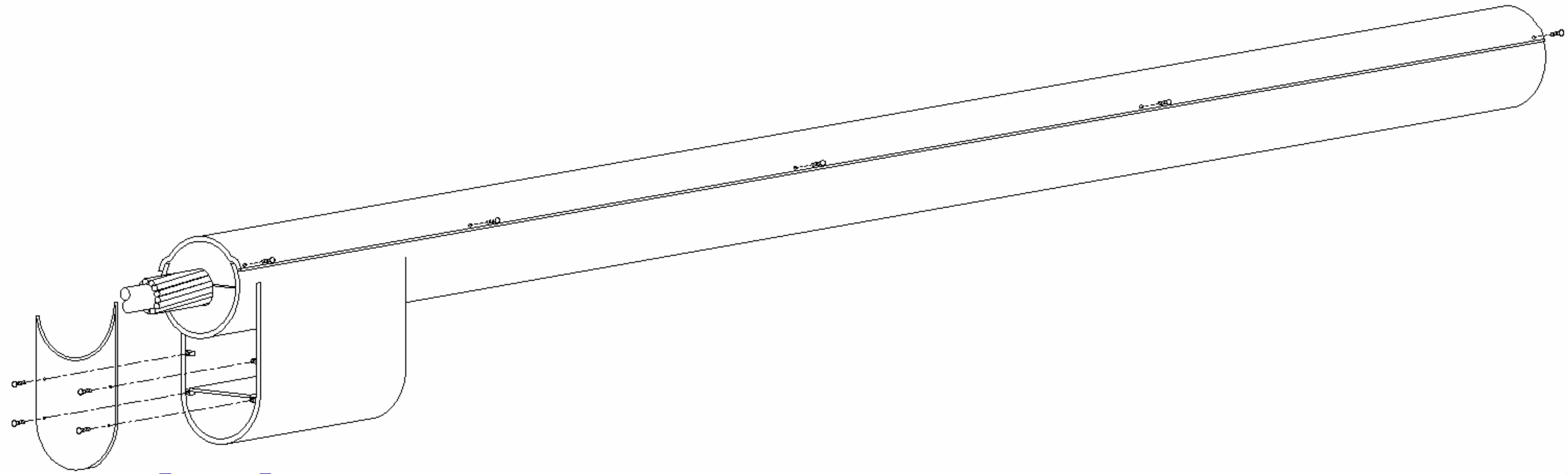


Network Performance Index: $PI = \dfrac{\Delta MW}{\Delta MVAR}$



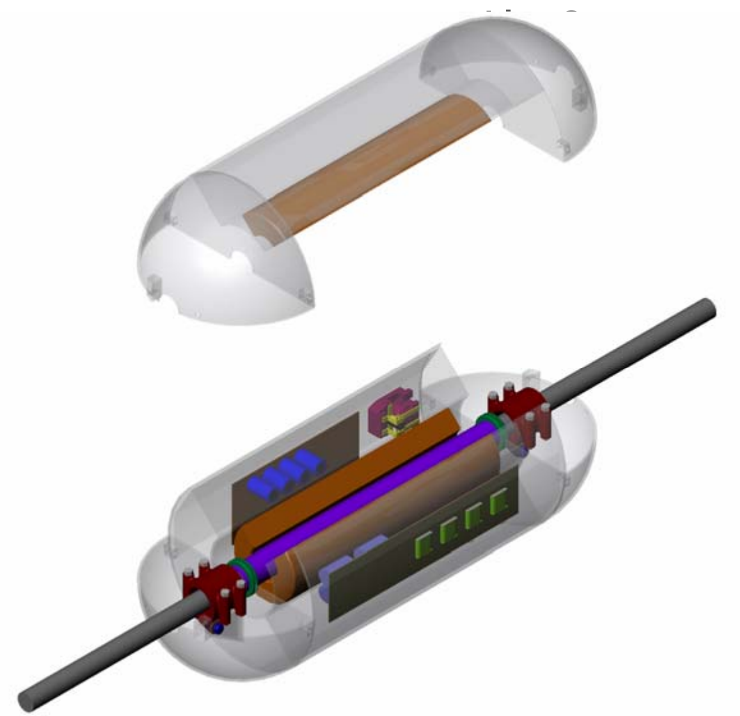
Prototype Passive Smart Wires Module Specifications

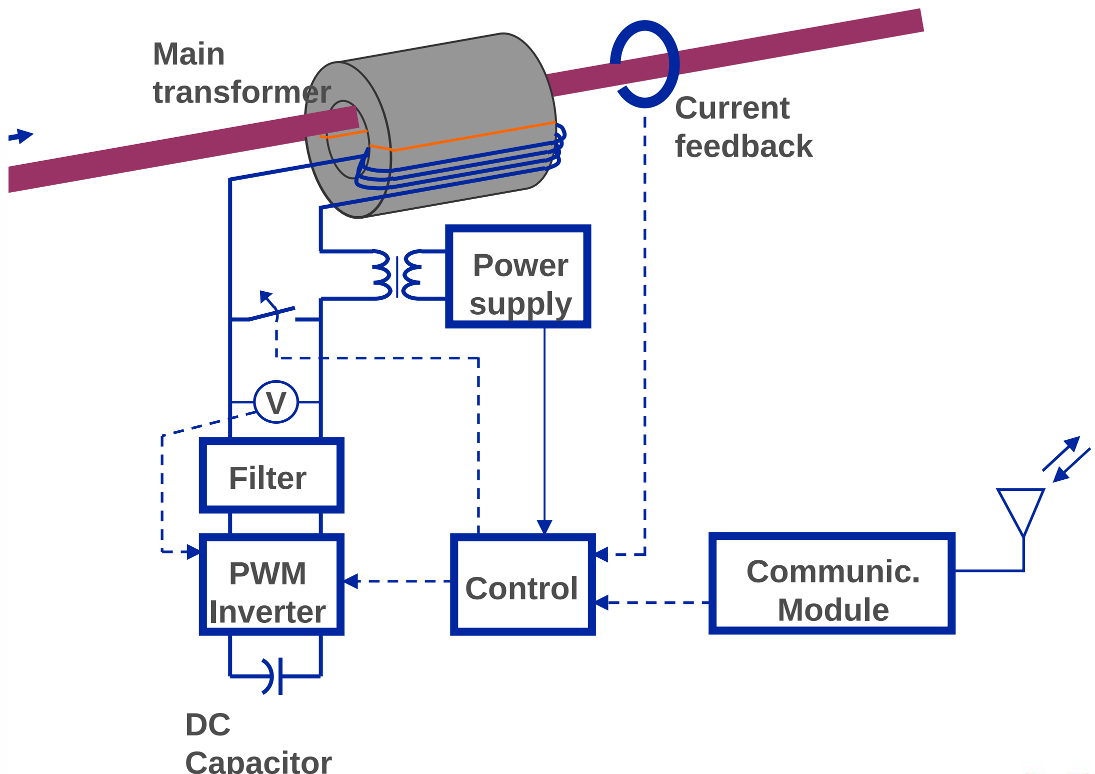
- **Electrical**
  - Operating : 161 KV / 1,000 A
  - Injected impedance= 10 mΩ per module
  - ACSR Conductor: Drake (795 Kcmil)
    - R= 0.128Ω, X= 0.4Ω per mile
  - Fault level: 50,000 A
- **Mechanical**
  - Target weight per module: 120 lb (critical design parameter)
  - Packaging to avoid corona discharge, and other mechanical, thermal and environmental issues



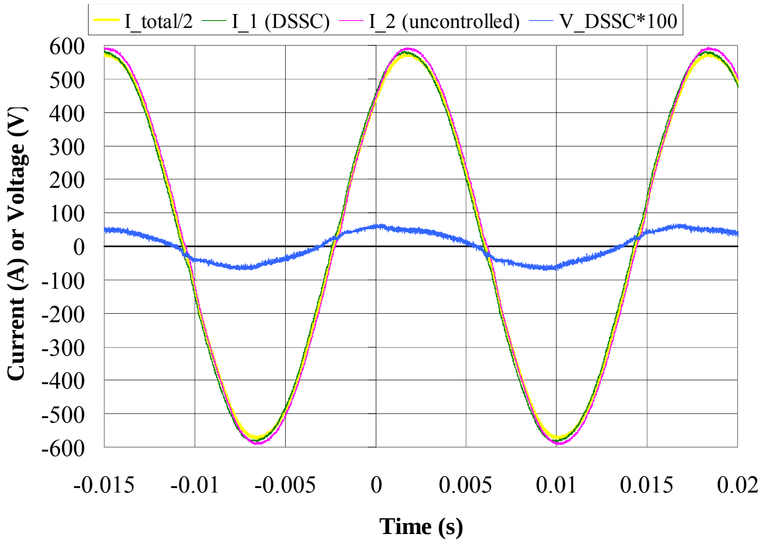
Active Smart Wires – Distributed FACTS (D-FACTS)

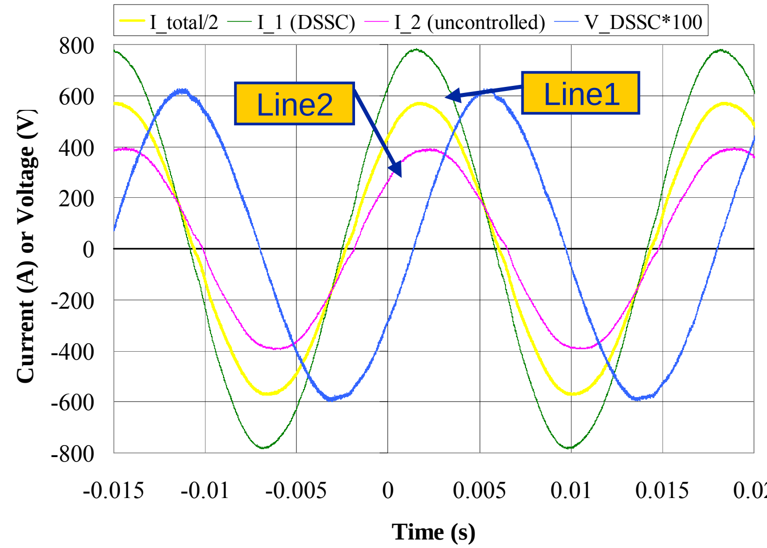
- Distributed Static Series Compensator (DSSC) modules that clip on to existing conductors and use inverters to inject positive or negative impedance into line
- Multiple DSSC modules that float on the line and are self-powered. The modules use mass-produced power electronics and communications methods

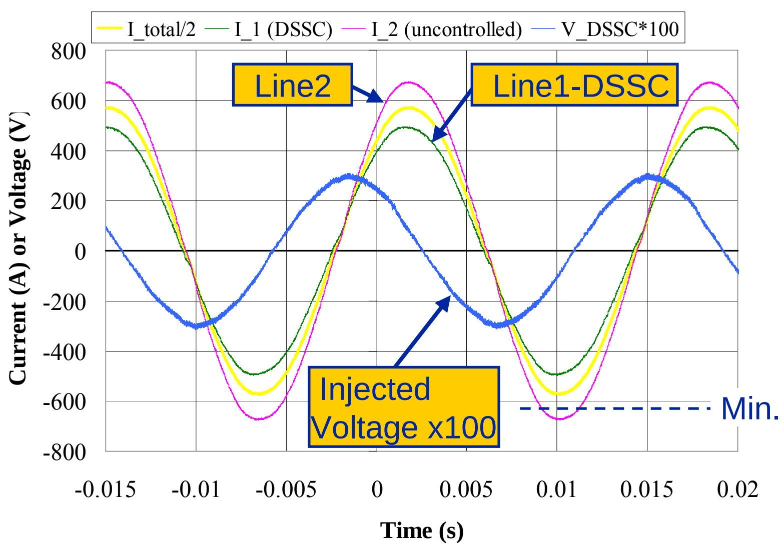


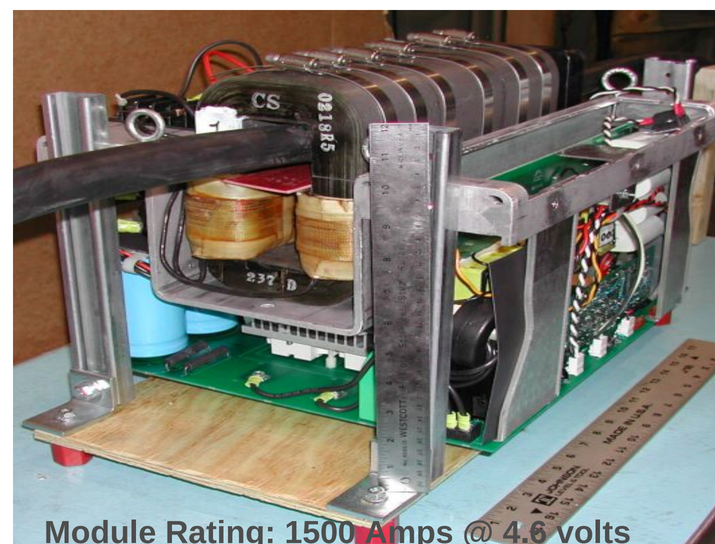


Active Smart Wires Prototype – Experimental Waveforms









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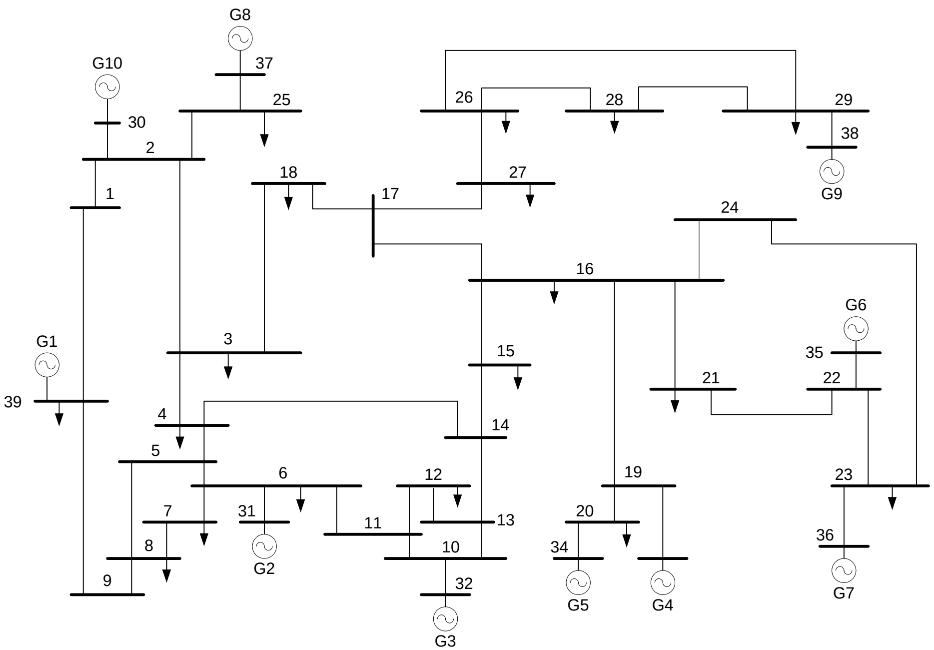
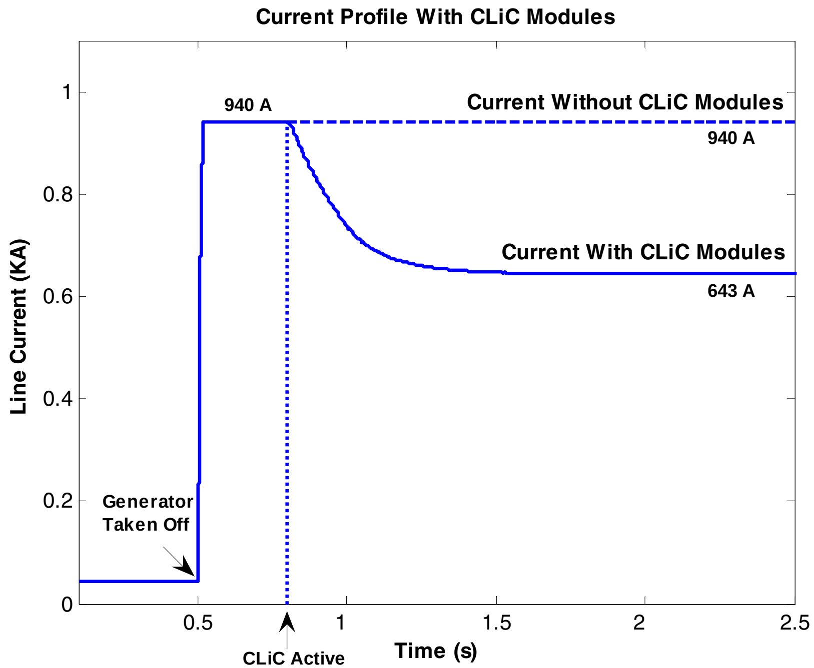
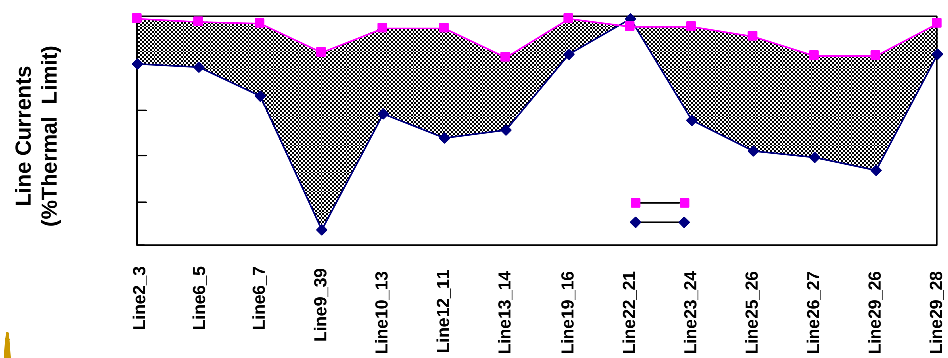
IEEE 39 Bus System – Impact of Smart Wires



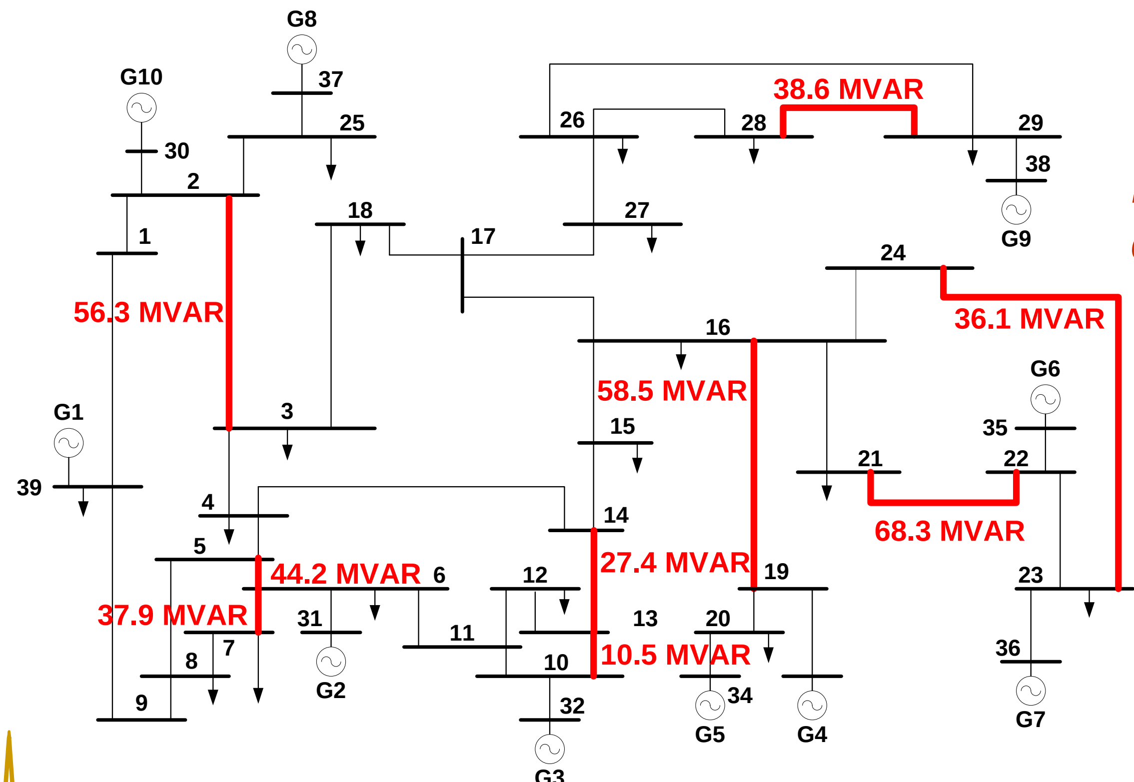




- Current in Line 22-23 drops from 940A to 643 A with CLiCs following outage of generator 7
- System utilization increases from 59% (1904 MW) to over 93.3% (2542 MW) with CLiC modules
- 80 MVARs (10K modules) of series VARs yields 420 MW, relieving congestion along six corridors

Control Effort Versus Realized Capacity

- Baseline MWs: 1904 MW
- Increase in ATC possible: 638 MW (New system capacity: 2542 MWs)
- Number of modules required: 10,000 modules for 420 MW, 45,000 modules for 600 MW
- Total control effort: 378 MVARs (equivalent to 8.4 KVAR per module)
- Target installed price of under $1,000/module



Increase in ATC of up to 638 MW on the nine highlighted lines

(IEEE 39 Bus System)

Reliability/Economic Benefits of Smart Wires

- System is resilient and operates as a self-organizing and self-healing power grid even in the face of unplanned contingencies
- Enhance network reliability and operation under (N-X) contingencies by automatically routing current from overloaded lines to lines with available capacity – reduces possibility of cascading failures
- Distributed scalable solution allows strategic, targeted and incremental deployment of modules for maximum budget flexibility.
- Relieve network congestion at specific points as required.
- Defer investments in new power lines while enhancing system capacity
- Enable energy contracts between low-cost generators and interested end-users using existing lines that have available capacity (merchant transmission)
- Zero footprint solution. Reduce or defer access to new ROW.
- Mass produced modules. High system reliability and availability. Rapid and incremental deployment. Reprogrammable to meet changing needs

Smart Wires in a Smart Grid

- It is proposed that the use of distributed solutions based on low-power power electronics can allow utilities to move towards fully controllable meshed grids, significantly enhancing grid reliability, capacity and utilization.
  - Current status of grid nodes and lines using distributed sensing
  - Node voltage control using distributed shunt VARs
  - Line current control using distributed series VARs
- Can be applied at the transmission, sub-transmission and distribution levels.
- Can be layered onto the existing infrastructure as desired, and will not degrade the inherent reliability of the existing system.
- Makes the grid self-healing, showing graceful degradation, automatically maintaining safe operating levels even in the face of contingencies.
- Can significantly enhance grid capacity and utilization without building new lines.
- Redundancy and ability to operate with local data provide high system reliability and availability
- Provides solutions that are low-cost and can be implemented in a gradual manner as resources and budgets permit