Smart Distributed Control of Power Systems

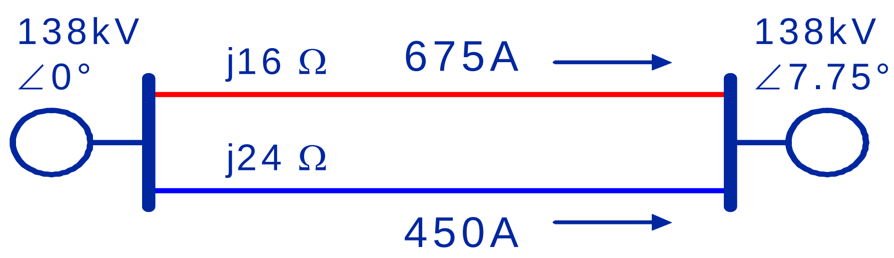
Deepak Divan **Ron Harley**
School of Electrical Engineering
Georgia Institute of Technology, Atlanta, GA, USA

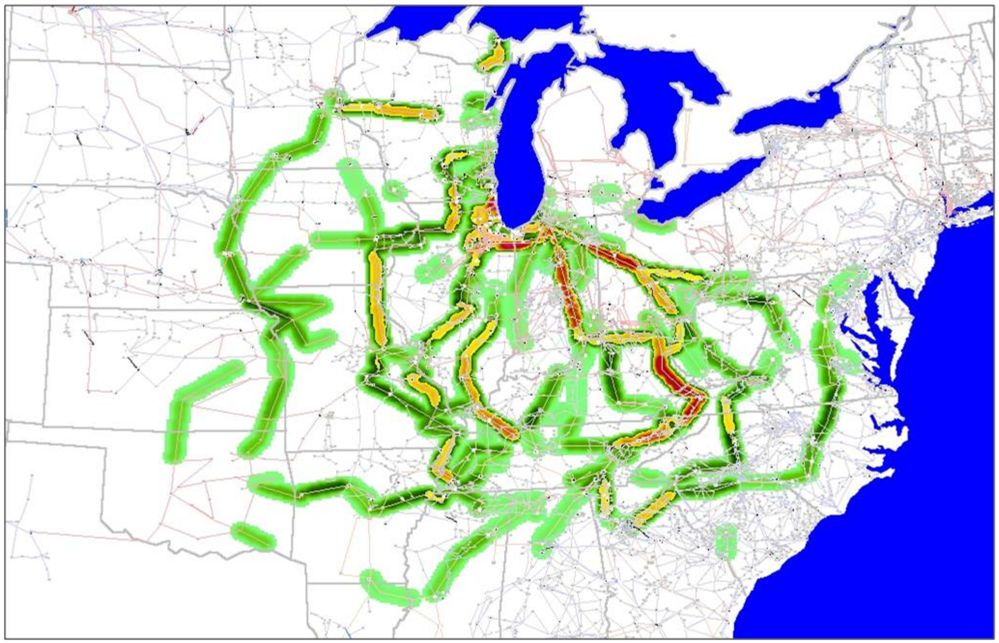
777 Atlantic Drive
Atlanta, GA

deepak.divan@ece.gatech.edu

US Power Grid: Problems (Opportunities)

- Grid is seeing increasing congestion and degraded reliability
- Uncontrolled power flow is a major issue for transmission & distribution
- Building new transmission/distribution lines is no longer a simple process
- First line to reach thermal rating limits system transfer capacity, even as neighboring lines are under-utilized
- Real situation is worse as reliability has to be ensured with (N-X) contingencies
- Lack of visibility and control leads to conservative operation resulting in significant under-utilization of assets
- Possible cascading failures under contingency conditions
- Reliability, load growth, will be major drivers for new investments





Power flow path from Wisconsin to TVA*

*Courtesy: Tom Overbye, UIUC

Proposed Vision for Electricity Infrastructure Research

The Vision:

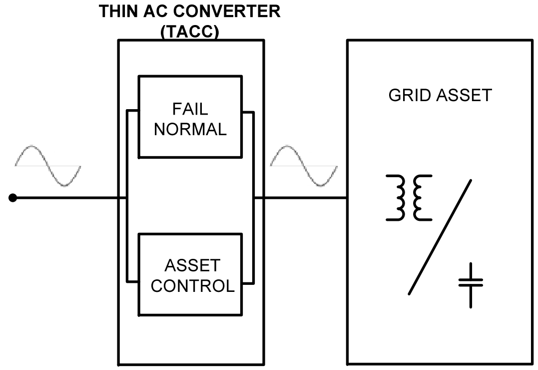
A fully controllable electricity delivery infrastructure that is cost-effective, provides flexible interconnection of sources and loads, is robust and reliable, is self-healing and degrades gracefully under contingencies, enables operation of market forces, never degrades system reliability to worse than current levels, and is scalable to meet societal requirements of growth and sustainability.

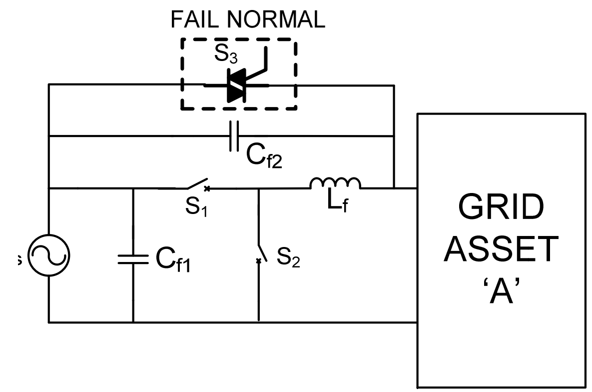
How Will This Be Implemented?

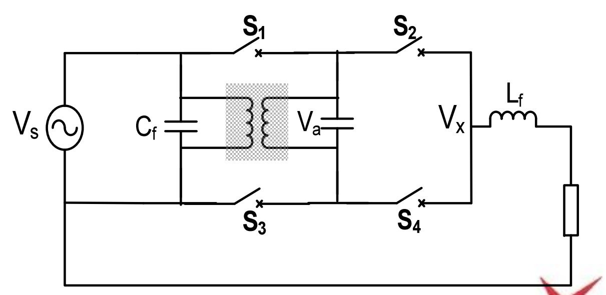
- Power delivery assets will have to be infused with intelligence, communications and control capability, using distributed mass-manufactured components for low-cost and high-reliability through redundancy.
- Power grid will be massively-networked for high-reliability, and will allow autonomous local control with local information while ensuring global system level optimization using feedback.
- New techniques for system level monitoring, visualization, protection and control in the presence of massive data streams from widely distributed assets will provide visibility and actionable information to allow operators to avert catastrophic events.
- This approach can dramatically reduce the cost and accelerate implementation of a Smart Grid, enabling system transforming applications such as PHEVs, demand side management, and support proliferation of distributed renewable resources that foster sustainability.

Thin AC Converters – Making Existing Grid Assets Controllable

- Proposed approach provides static and dynamic control of value of existing grid assets, such as shunt VAR capacitors and transformers
- Allows operation in ‘dispatch’ mode or under local control to regulate voltage or respond to faults
- Direct AC conversion using semiconductor switches, small LC filters, switchgear and minimal energy storage allowing compact size, low volume and low cost
- Imposes minimal additional stresses on the asset allowing use in retrofit applications.
- ‘Fail Normal’ mode of operation, where failure of the thin converter automatically restores normal function of the asset on the grid
- Multi-Level AC Converter allows transformer-less operation in medium voltage applications







Thin AC Converters

MULTI-LEVEL DIRECT AC CONVERTERS

VIRTUAL QUADRATURE SOURCES

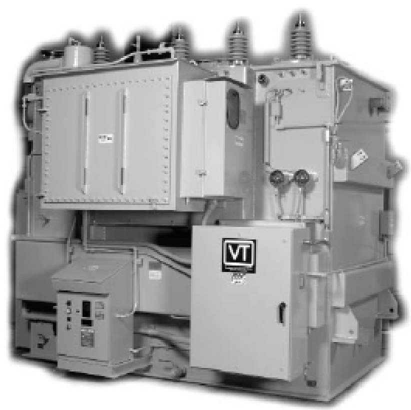
THIN AC CONVERTERS

Possible Applications

Inverter-less STATCOMs

Shunt VAR Capacitors

Controllable Network Transformers



LTC Transformers

http://www.vatransformer.com

Smart Wires

Transmission Lines

http://www.tradesurinc.com/products

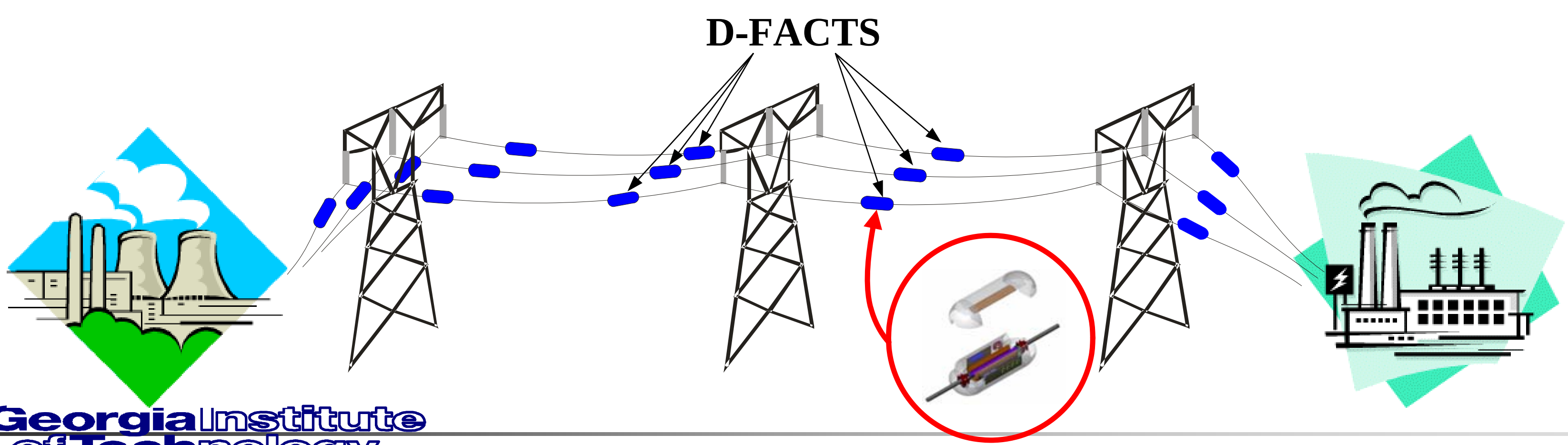
Distributed FACTS for Power Flow Control

- Distributed FACTS suggested by Divan – Smart Wires
  - Provide the functionality of FACTS at lower cost and high reliability

$$P_{12} = \frac{V_1 V_2}{X_s} \sin(\delta)$$

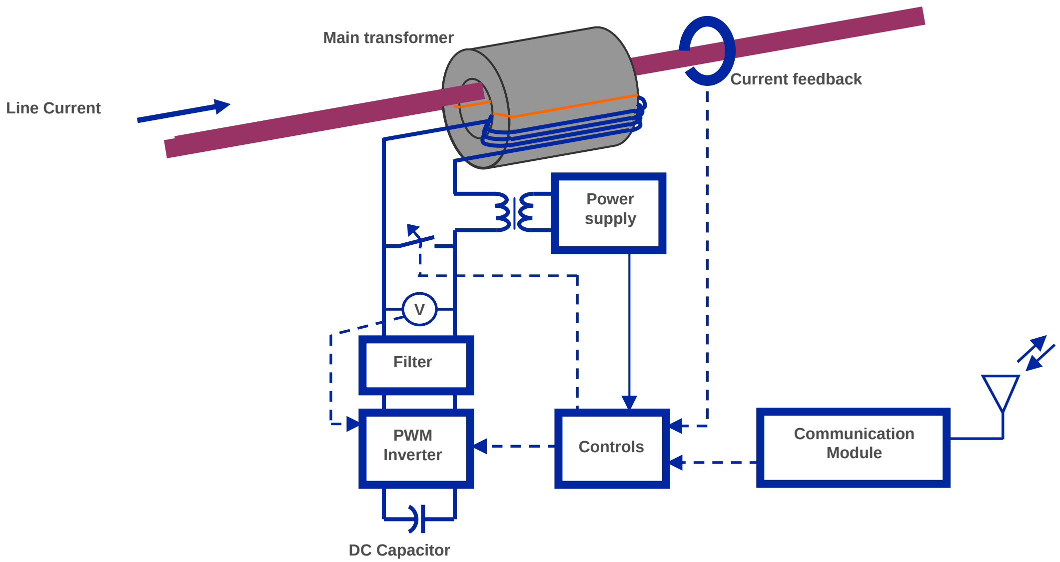
Control parameter

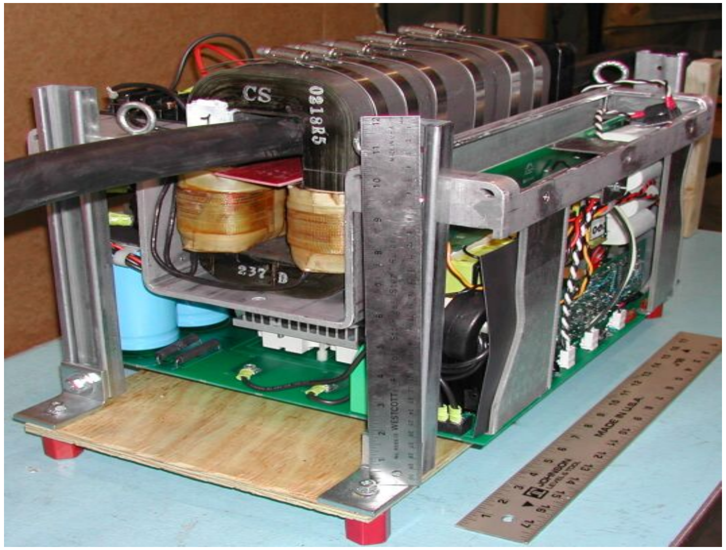
  - Series VAR injection controls effective line impedance & real power flow
  - Large number of modules float electrically and mechanically on the line
  - Can be incrementally deployed to provide controllable power flow
  - Standard low-cost mass-manufactured modules
  - Redundancy gives high reliability and availability
  - Phase I supported by TVA, Con Ed, DOE and others



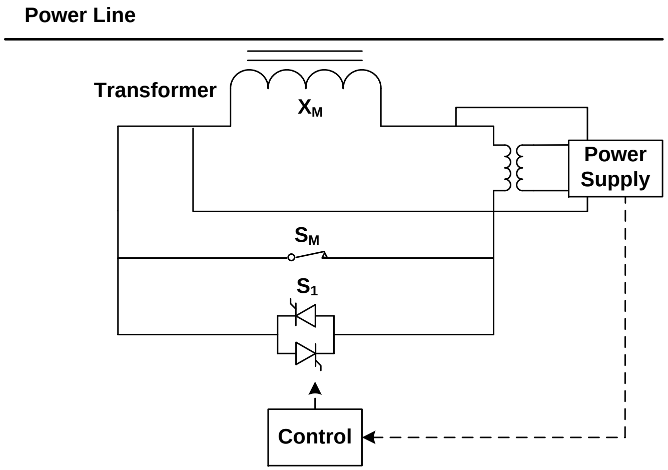
Active Smart Wires

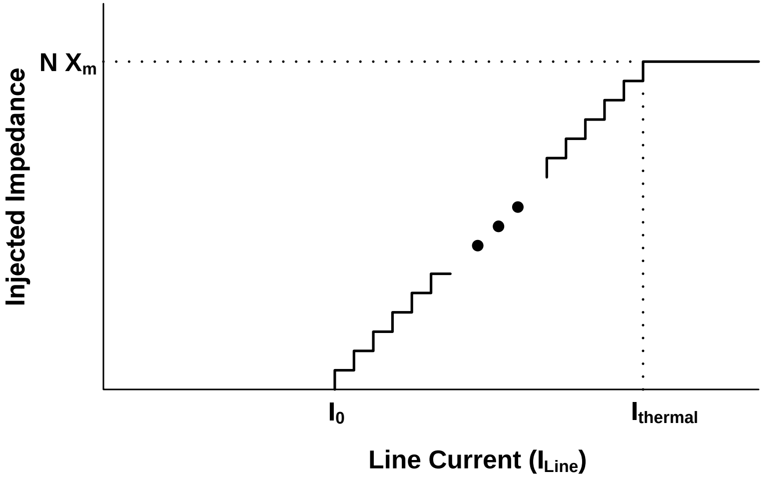
- Distributed Static Series Compensator (DSSC)
  - Active solution employing a synchronous voltage source inverter
  - Each module rated for 5 KVA (capable of injecting ± 4.6 V @ 1000 A)
  - Communication interface is required to realize the bi-directional control
  - Can be made larger for distribution applications (one per line)





Distributed Series Reactance – Passive Smart Wires

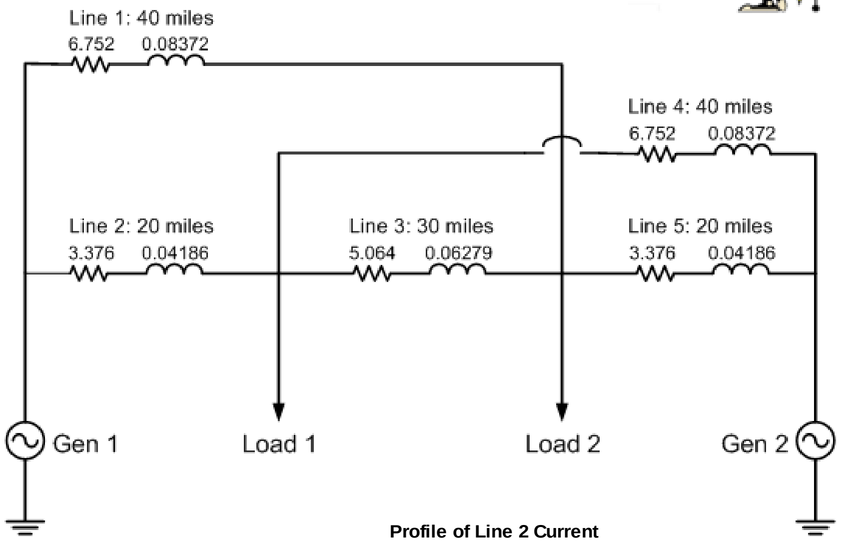


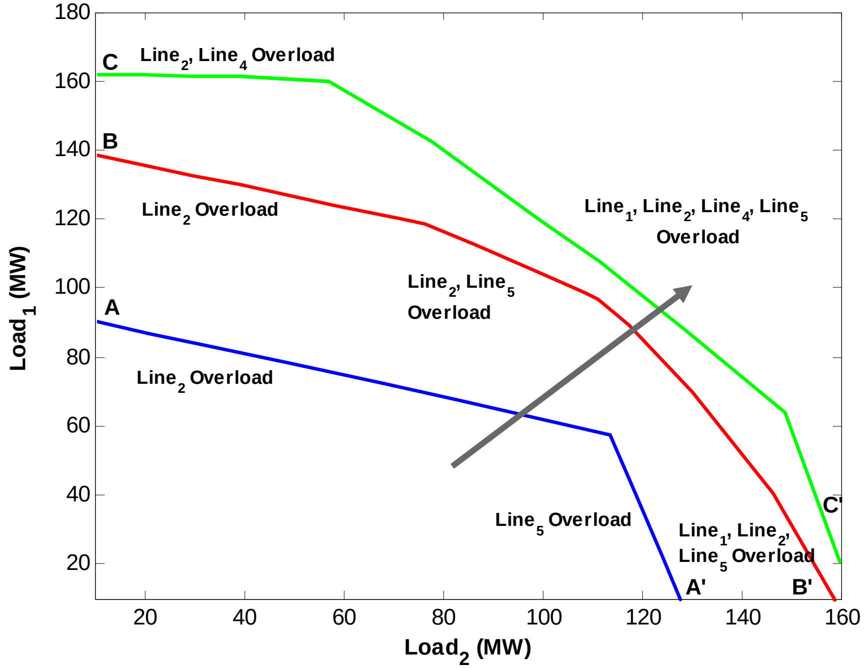


- Simplest implementation of DSI, with **inductive** impedance injection (Current Limiting Conductor or CLiC) – functions as a current limiting system
- As current in a line approaches the thermal limit, CLiC modules incrementally turn on, diverting current to other under-utilized lines
- Each module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

Increase in System Capacity With DSR Modules

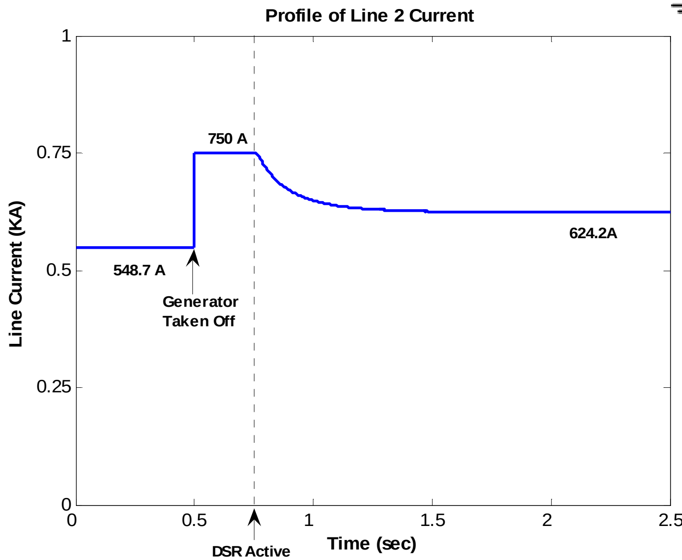
Simplified Four Bus System





System Capacity with DSI/DSR Modules

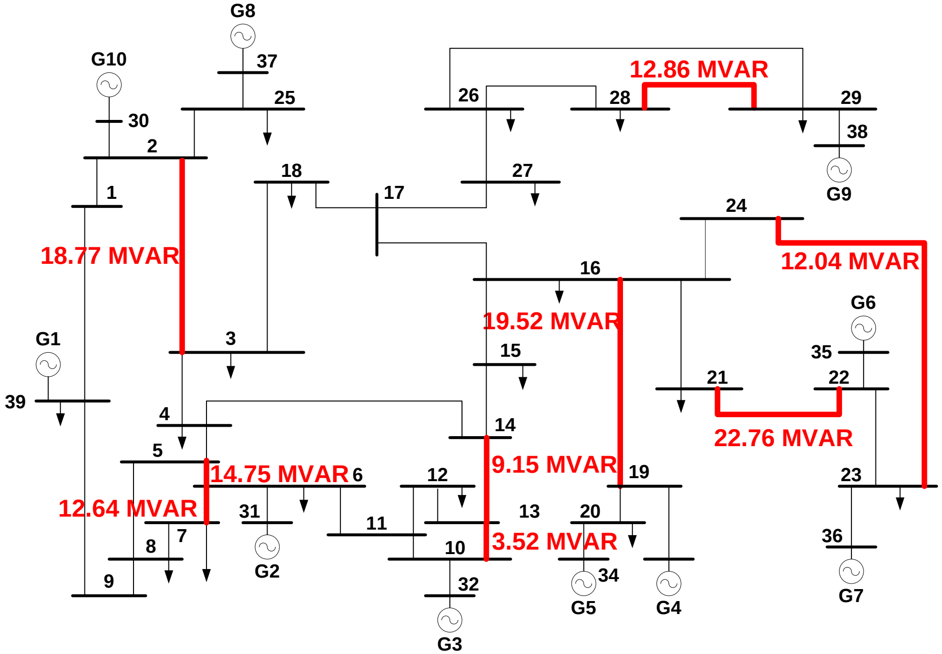
Blue: Normal, Red: DSR, Green:DSI



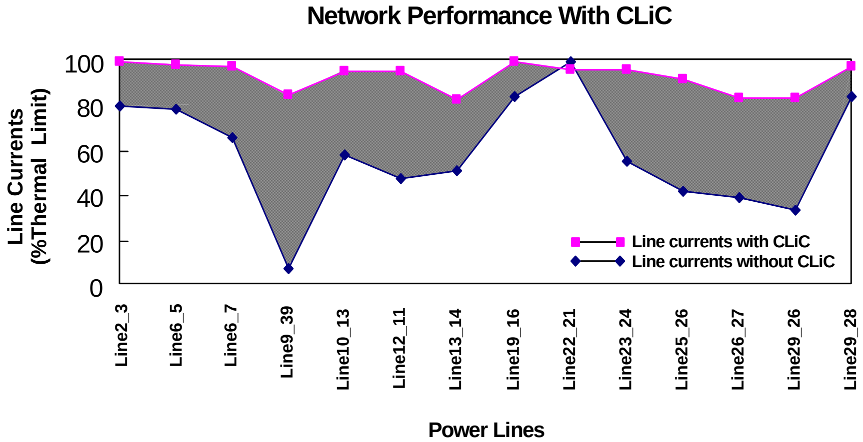
Contingency Condition: Generator Outage

Increase in Network Utilization

IEEE 39 Bus System

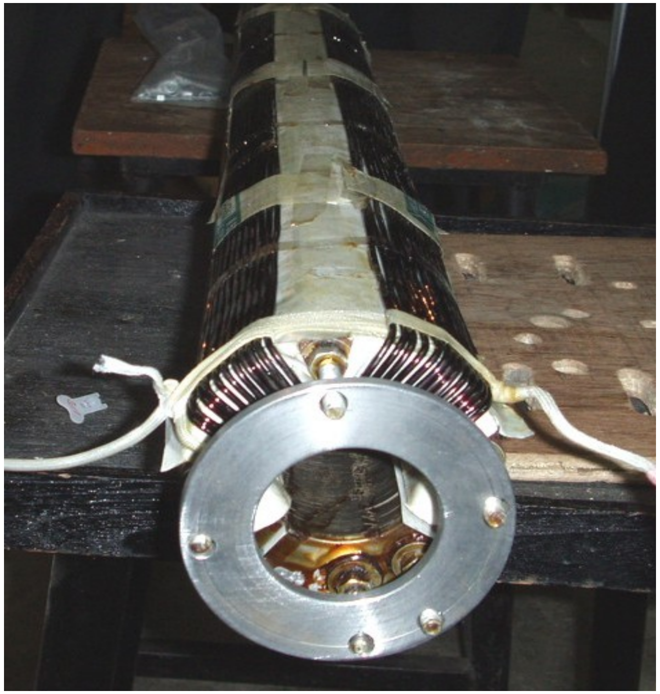


Increase in utilization from 59% to 93.3% for 14 lines



- Increase in Transfer Capacity from 1904 MWs to 2542 MWs (congested corridors and the required MVARs are shown by red lines)
- With (N-1) contingency, capacity is increased from 1469 MW to 2300 MW without building additional lines
- Would require 9 additional lines to realize capacity increase

DSR Prototype

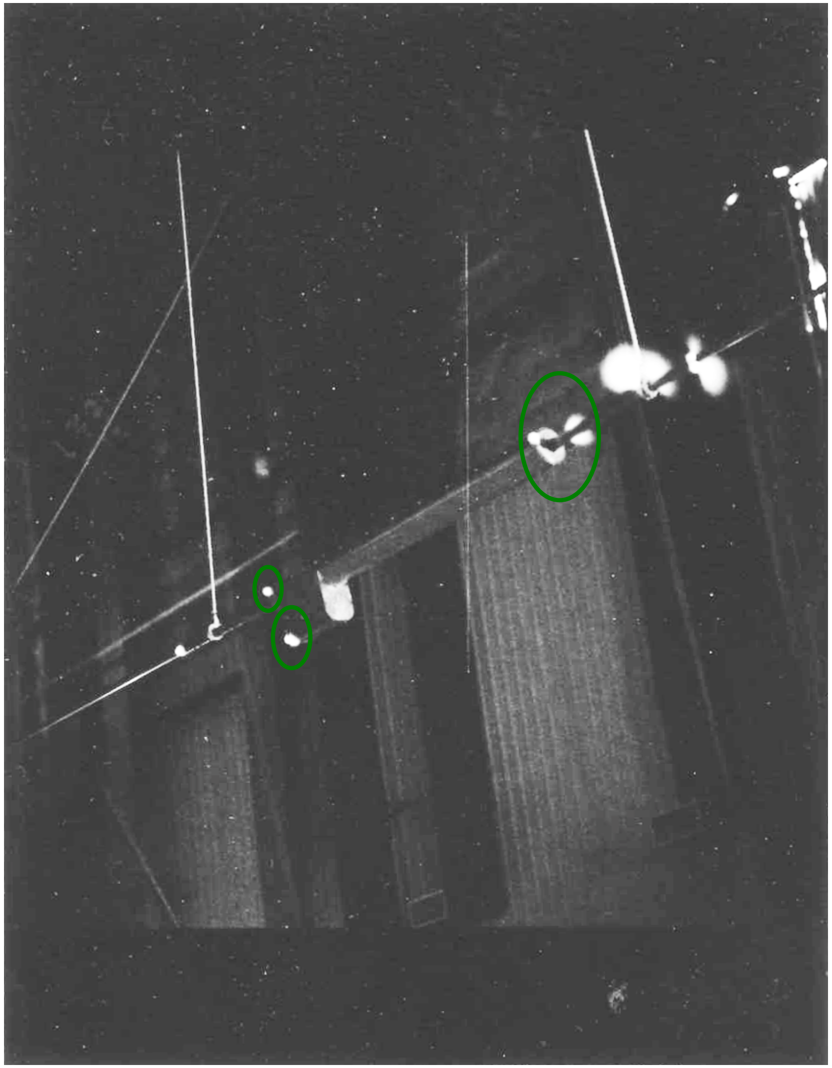


Complete module with the casing

- **Simple low-cost design suitable for mass manufacturing**
- **Suitable for distribution and transmission applications**

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

Validation at High Voltage and Current



Photograph correspond to 166 kV

Corona inception: 125 kV
Extinction: 123 kV

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 dynamically controllable meshed grids, significantly enhancing grid reliability, capacity and utilization. This can enable:
    - Improved reliability without having to build new lines
    - Improved dynamic coordination between regions
    - Reduction in dynamic capacity reserve for generators
    - Possibility of moving power along a predetermined contract path
- Can be applied at the transmission, sub-transmission and distribution levels.
- Can be layered incrementally onto the existing infrastructure as desired, and will not degrade the inherent reliability of the existing system.
- Makes the grid self-healing, automatically maintaining safe operating levels even in the face of contingencies.
- Funding such investments on the basis of congestion relief is problematic in regulated environments, new mechanisms may have to be found.