Impact of Distributed Series Reactances on Power Networks

From Power Line to Pipe Line

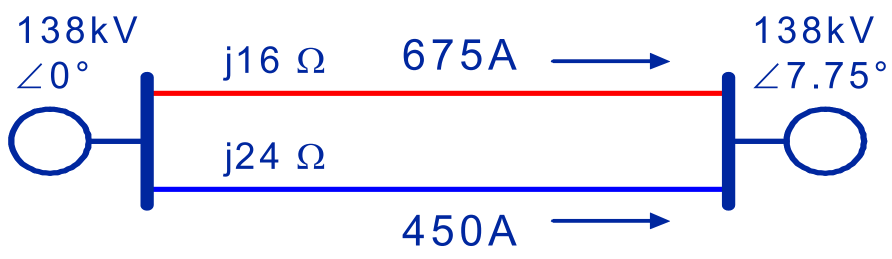
Deepak Divan **Harjeet Johal**
School of Electrical Engineering
Georgia Institute of Technology, Atlanta, GA, USA

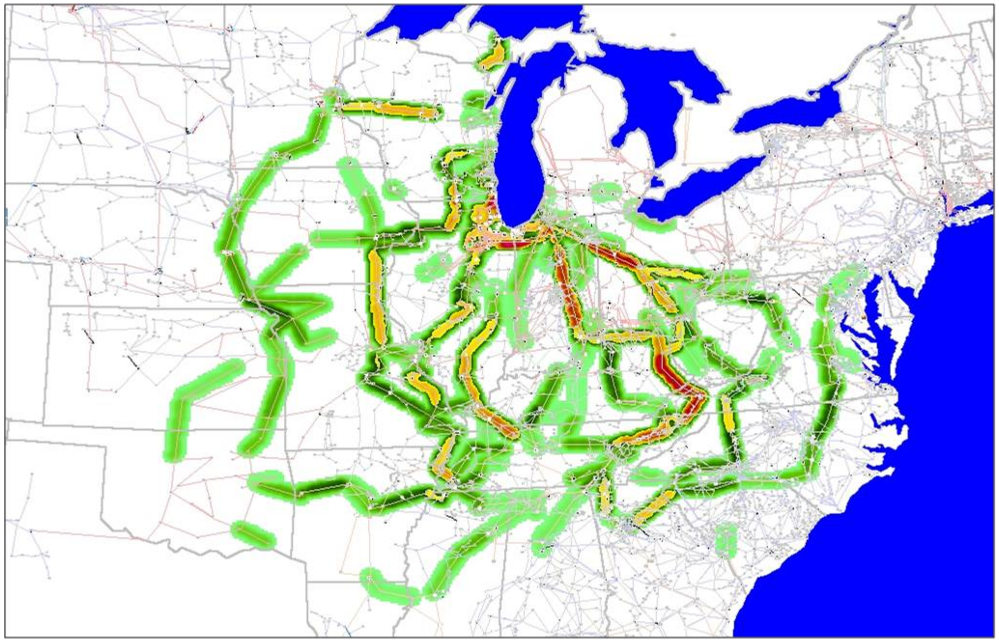
777 Atlantic Drive
Atlanta, GA

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, RPS standards and 'Smart Grid' initiatives under EISA 2007 will be major drivers for new investments





Power flow path from Wisconsin to TVA*

*Courtesy: Tom Overbye, UIUC

Unarticulated Market Need – Controlling Power Flows

- Reliability of meshed networks is substantially higher than for radial systems. However, utilization is poorer.
- Controlling network power flows along existing lines has not been considered feasible – either technically or economically.
- Benefits of controlling power flows includes:
  - Enhancement in system utilization and capacity without building new lines
  - Tool for managing load growth, congestion and contingency issues
  - Self-healing grid which responds to contingencies, improving system reliability
  - Routing of power along desired pathways, from ‘power-line’ to ‘pipe-line’. ‘Green’ electrons can be verifiably sent from renewable sources to specific loads.
  - Effective management of congestion and uncontrolled loop flows
  - Reduced level of generation reserves required to ensure system reliability
- Traditional approach has been through the use of phase-shifting transformers (too slow) or FACTS devices (too expensive).

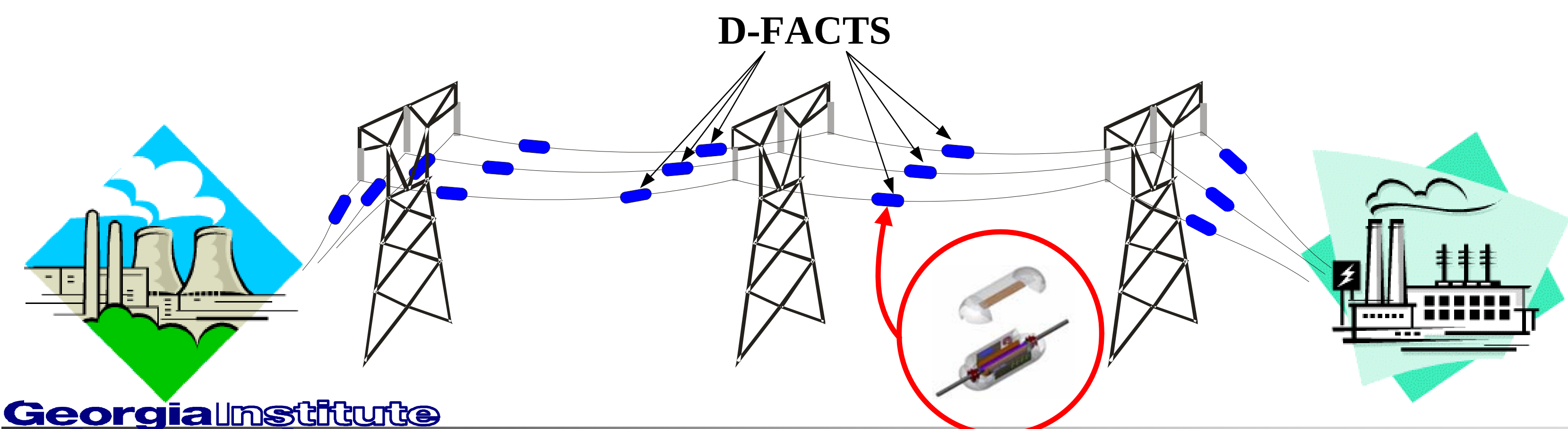
Distributed FACTS for Power Flow Control

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

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

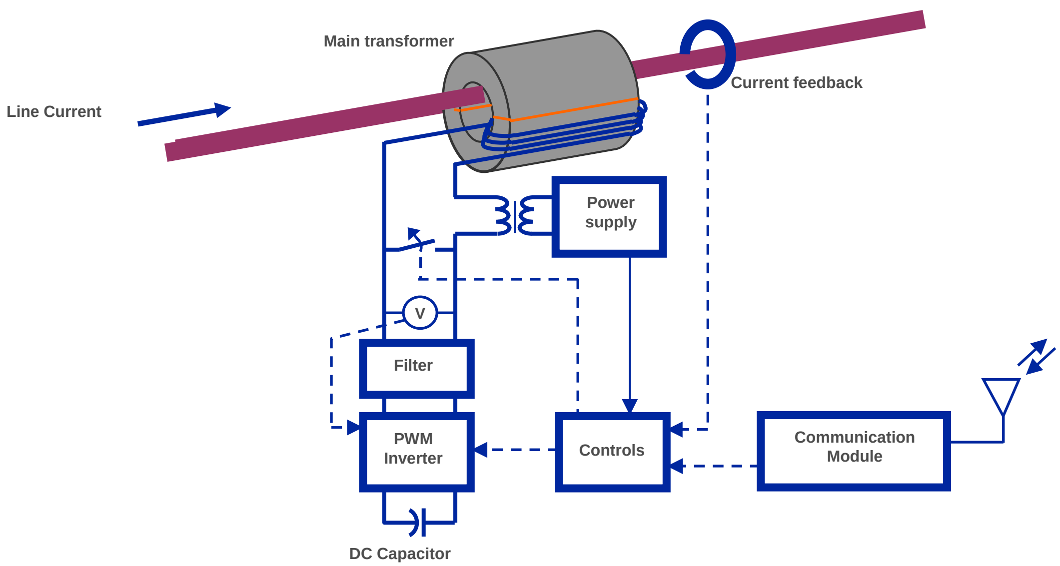
Control parameter

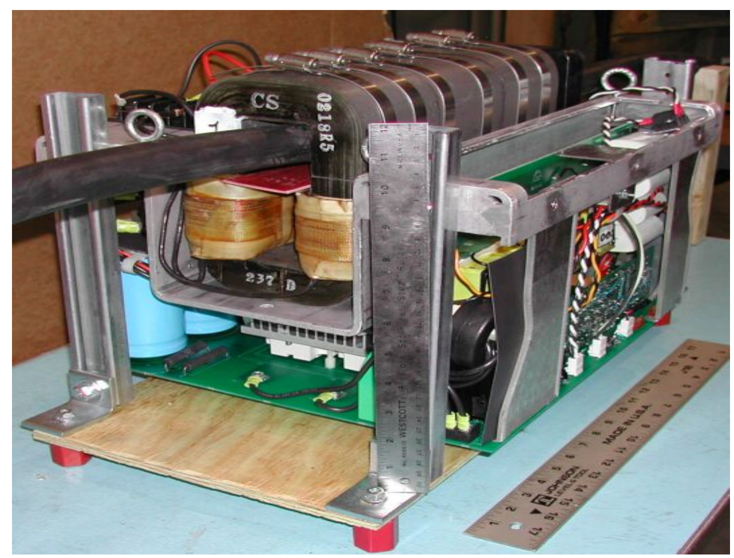
  - Series VAR injection controls effective line impedance & real power flow
  - Large number of modules float electrically and mechanically on the line
  - Can be incrementally deployed to provide controllable power flow
  - Standard low-cost mass-manufactured modules
  - Redundancy gives high reliability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



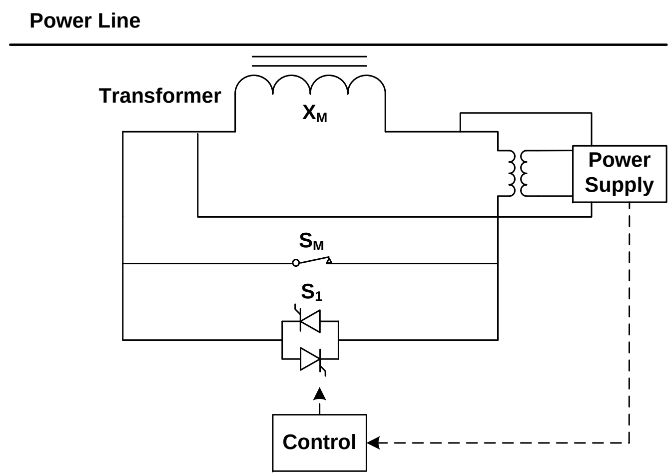
Active Smart Wires

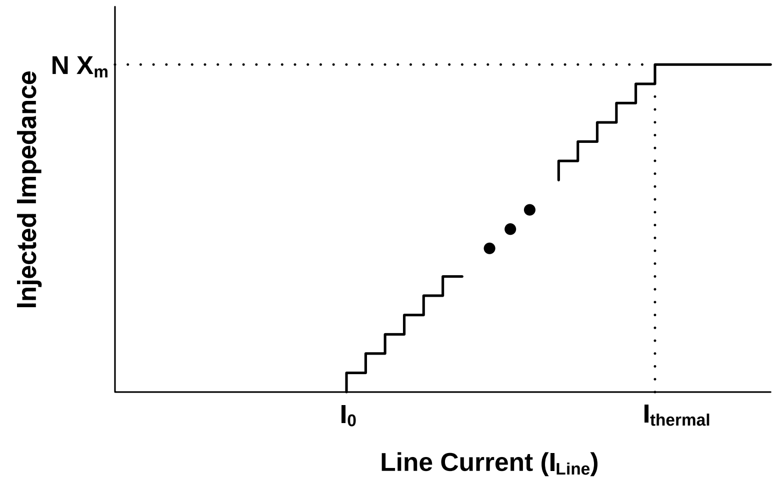
- Distributed Static Series Compensator (DSSC)
  - Active solution employing a synchronous voltage source inverter
  - Each module rated for 5 KVA (capable of injecting ± 4.6 V @ 1000 A)
  - Communication interface is required to realize the bi-directional control
  - Can be made larger for distribution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





Distributed Series Reactance – Passive Smart Wires

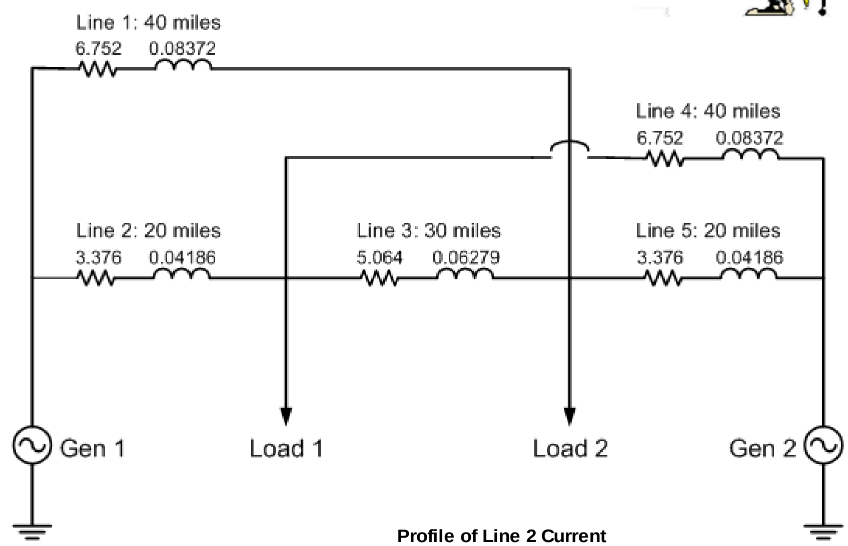


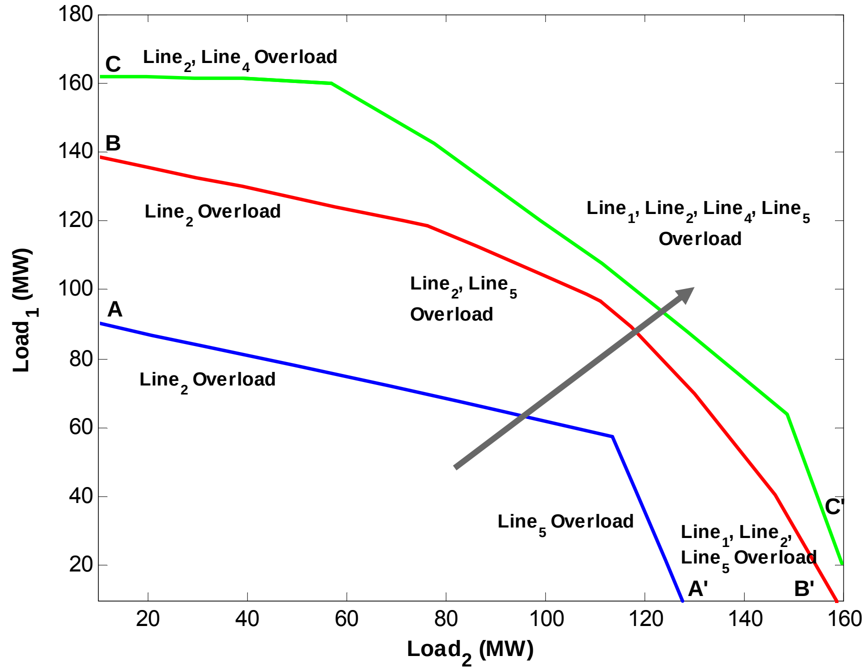


- Simplest implementation of DSI, with inductive impedance injection (Current Limiting Conductor or CLiC) – functions as a current limiting system
- As current in a line approaches the thermal limit, CLiC modules incrementally turn on, diverting current to other under-utilized lines
- Increase in line impedance can be realized by injecting a pre-tuned value of magnetizing inductance of the STT
- 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

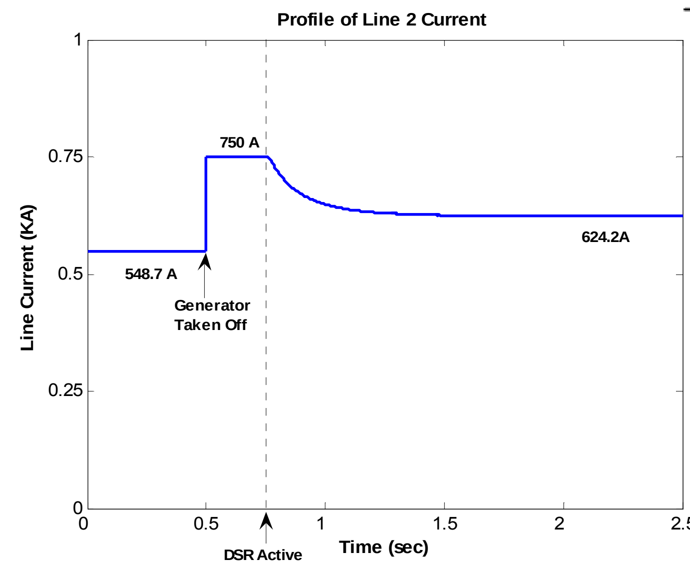
Simplified Four Bus System





System Capacity with DSI/DSR Modules

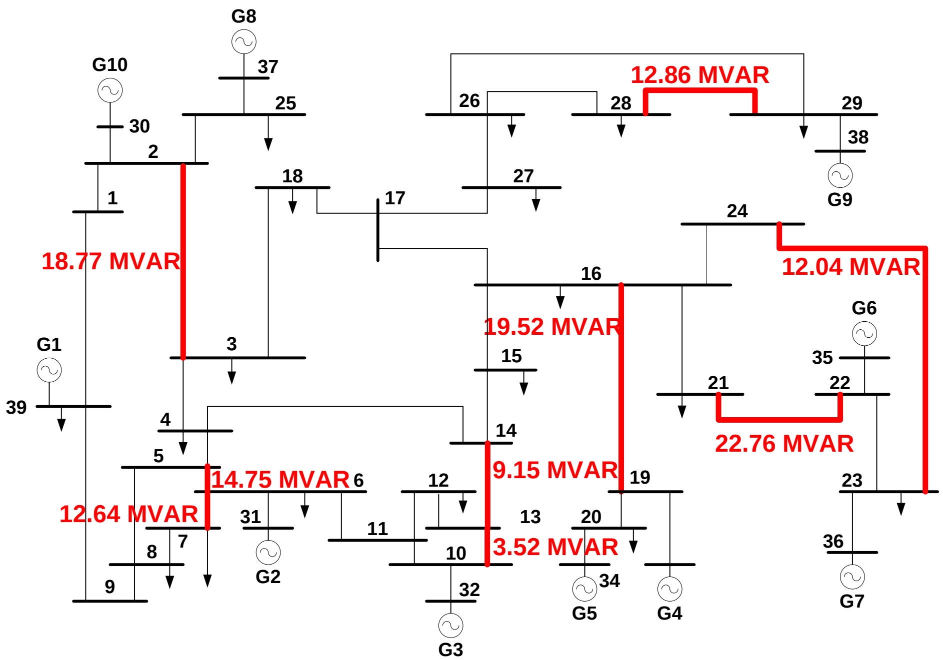
Blue: Normal, Red: DSR, Green:DSI



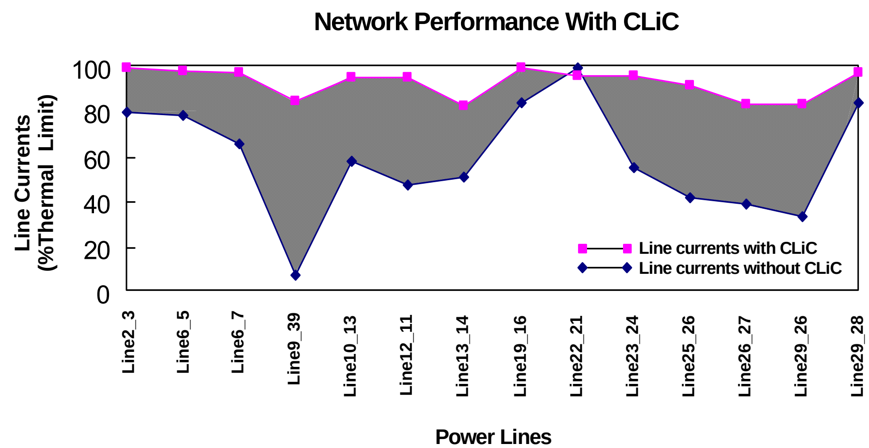
Contingency Condition: Generator Outage

Increase in Network Utilization

IEEE 39 Bus System



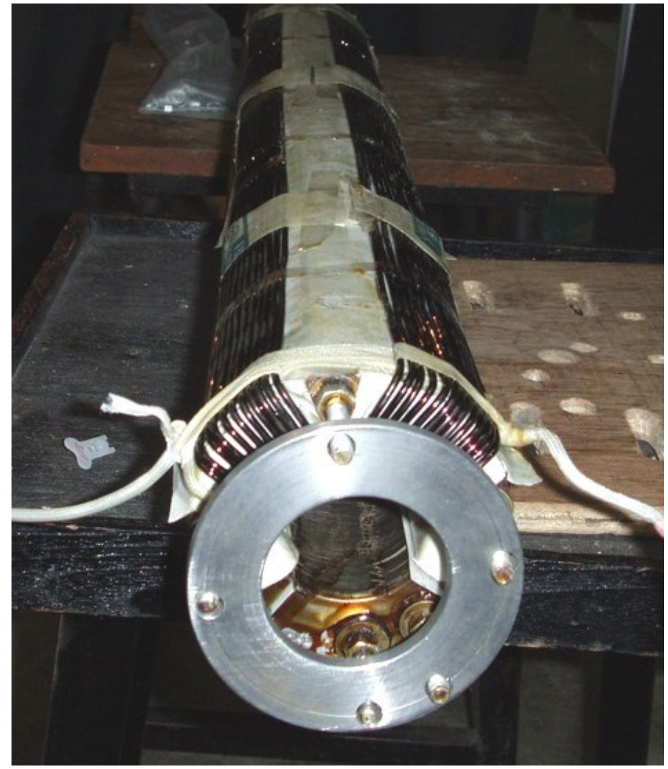
Increase in utilization from 59% to 93.3% for 14 lines



- **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



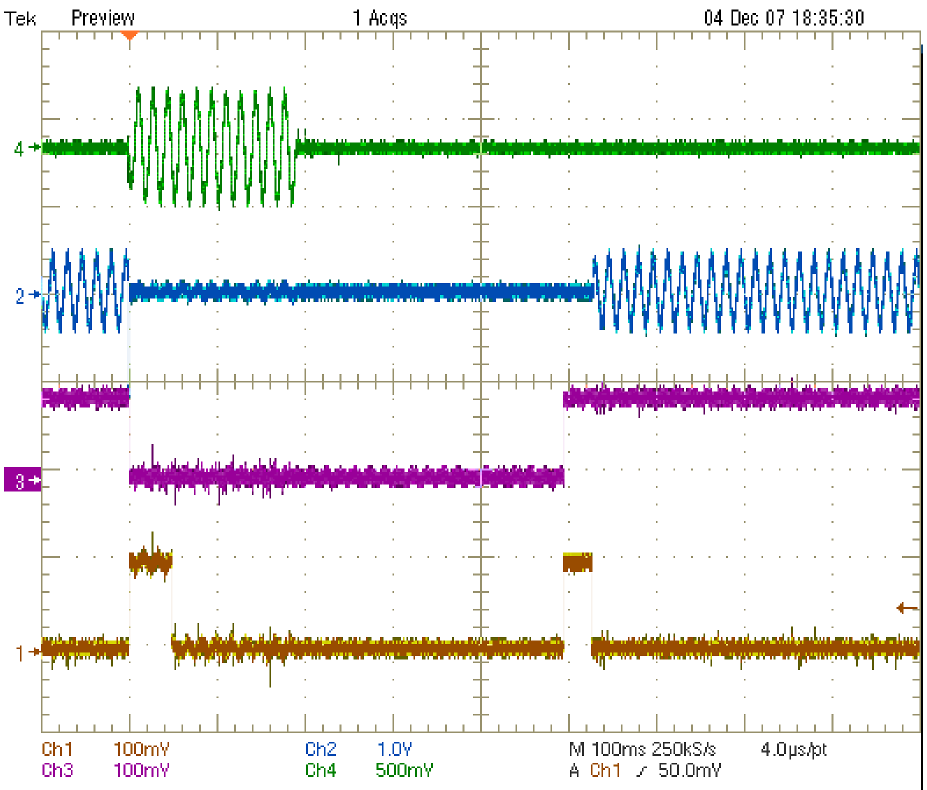
- **Simple low-cost design suitable for mass manufacturing**
- **Suitable for distribution and transmission applications**

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

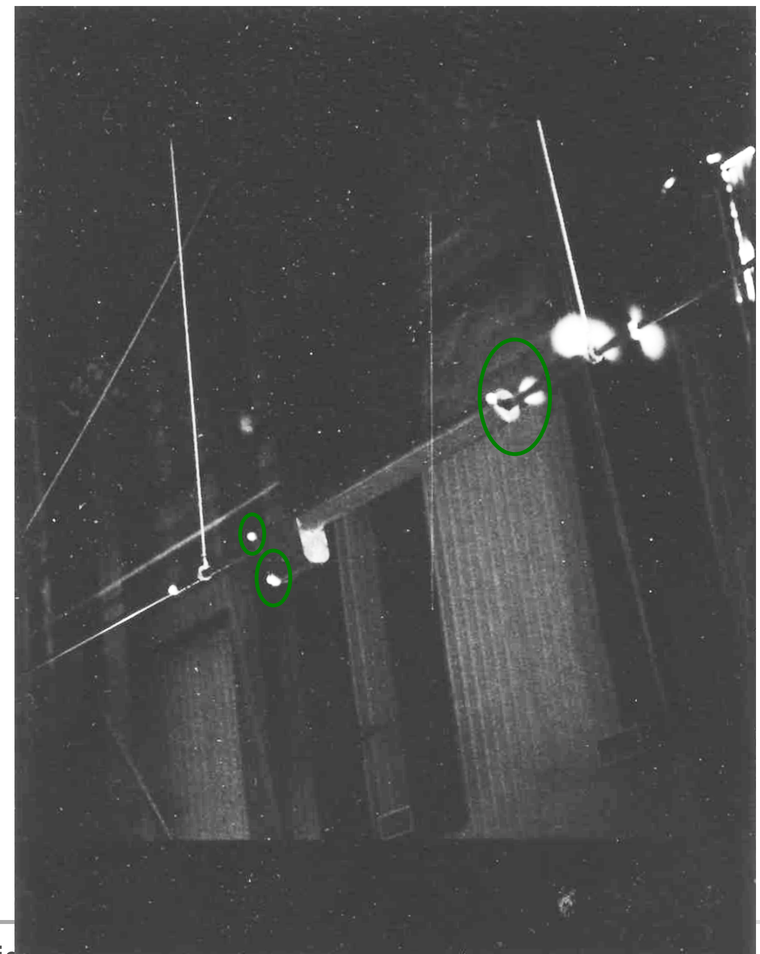
Validation at High Voltage and Current

Corona inception: 125 kV   Extinction: 123 kV

Operation Under Fault Currents

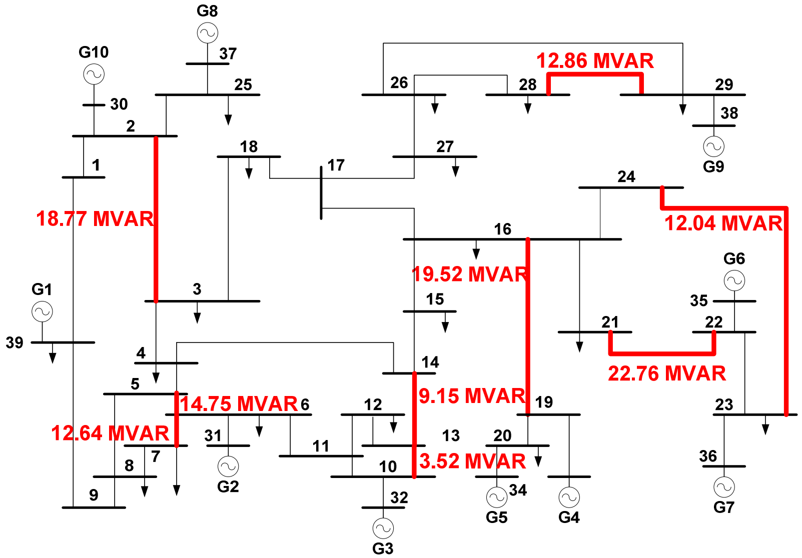


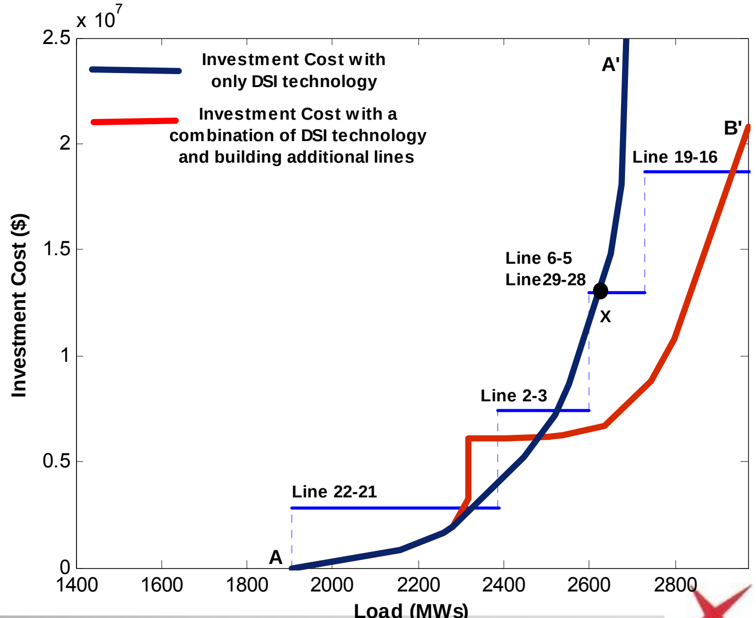
Photographs correspond to 166 kV



Investment Cost for IEEE 39 Bus System

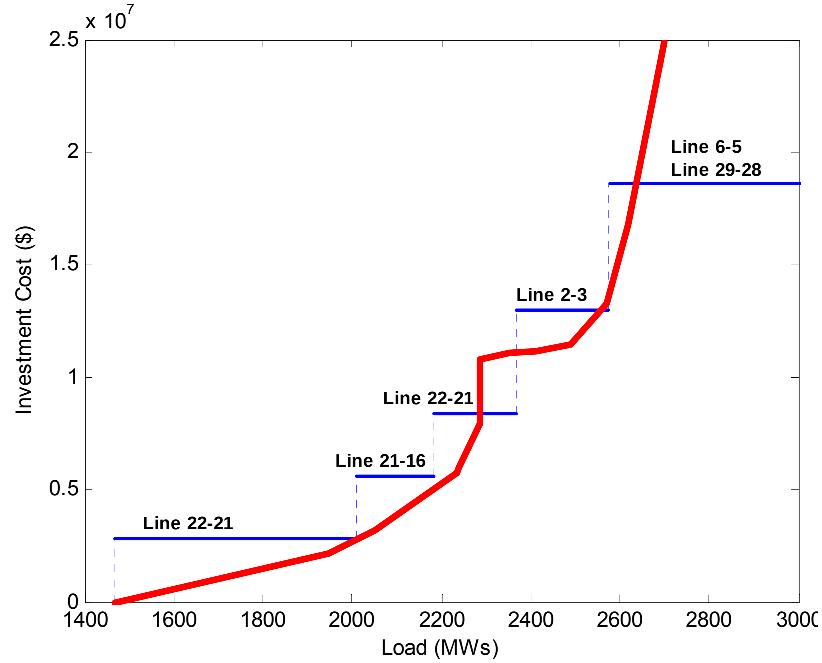
- Cost of laying additional lines: $500,000/mile
- Target cost of DSR unit: $100/KVA, cost of redeployment: $30/KVA
- ATC of the system is limited to 1904 MWs
- DSR modules can relieve network congestion at a lower cost for the first 400 MWs
- DSR continues to be attractive for next 300 MWs
  - Building additional lines can be suspended for the first 700 MWs
- A combination of the two schemes can provide a much lower investment cost
- Allows incremental investment decisions with rapid implementation.





Solution Cost Under Contingencies

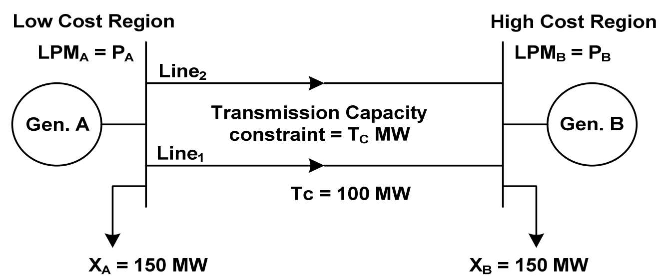
- Network congestion occurs at a load of 1470 MW with one contingency, as opposed to 1900 MW with no contingencies
- DSR modules are attractive until 2000 MW, i.e. for the first 530 MW of load growth.
- DSR modules can maintain optimal congestion levels from a pricing perspective
- If 2.5% load growth is assumed, the investment in the new line can be deferred for 13-15 years. Reduces uncertainty and risk, improves ROI.
- Interest on deferred cost of new line may pay for DSR modules!



Drivers for Transmission Capacity Investments

- In a free market, price differentials should provide incentives for investments to increase transmission capacity
  - Lower cost generator's opportunity for windfall profits should incent him to invest in incremental transmission capacity
  - Congestion costs provide the opportunity of arbitrage
  - Price differentials help to finance investments

	With Congestion	With Complete Congestion Relief
LMP_A ($/MW)	25	25
LMP_B ($/MW)	50	49
Consumers costs in region A ($)	3750	3750
Consumers costs in region B ($)	7500	7350
Gen. A revenue ($)	6250	11100
Gen, B revenue ($)	2500	0
Available revenue for transmission Inv. ($)	0	4850

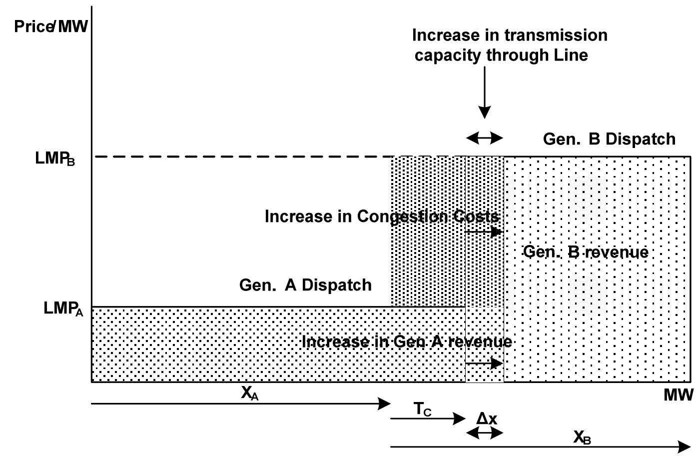


- In a regulated market, increase in societal welfare is <u>supposed to</u> form the basis of any policy initiative
  - Reliability improvements are easily supported by PSC's and can support capacity increases
- Increased societal benefits can be realized from congestion relief, but it is not clear how such investments may be funded.

Impact of Incremental Transmission Capacity

•Incremental increase in transmission capacity affects market participants differently

Participants	Change in Welfare
Congestion costs	(LMPB-LMPA) Δx
Producers	- (LMPB-LMPA) Δx
Consumers	$(LMP_B - LMP_A)\ \Delta x$



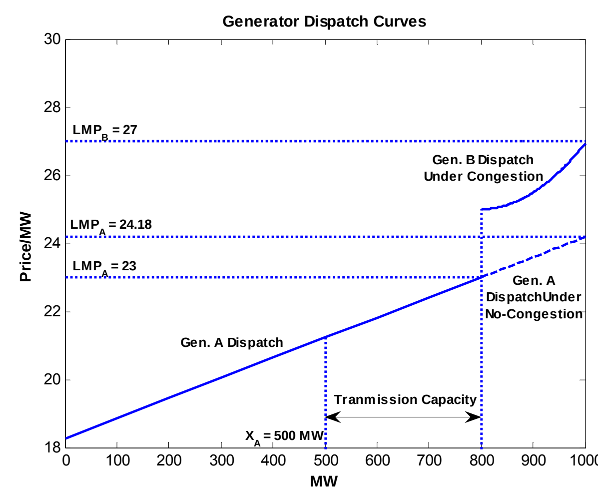
•The congestion revenue collected by ISO increases

•Gen. B loses revenue, while Gen. A gains revenue. Net change in generator revenue is negative.

•Consumer welfare increases; ISO's allocate congestion costs back to market participants (FTR)

•Consumers may not benefit uniformly with increase in transmission capacity (marginal costs can cause consumers in Region A to pay more)

•Market operates under the assumption that infrastructure changes happen too slowly, and so congestion costs are redistributed to participants.



Business Models for Smart Wires

Reliability

- Works well with the traditional utility approach of maintaining system reliability
- In line with EISA, “Creation of smart grid to improve reliability and performance.”

Economics/Congestion

- Investor model: A profit sharing mechanism between investor and consumer

Congestion relief through outside investment can provide break-even in 2 years

Congestion Costs	Congested Hours/year	Increase in welfare	DSR Cost PI=8	Profit-Sharing Formula
$25/ MWHr	500 hours	$12,500/ year/MW	$13000 /MW (cost for 13 modules)	50% consumers, 50% investors till desired ROI is reached

Time	Investment Costs	Investor profit	Consumer welfare
12 months	$ 13000	- $ 6250	$ 6250
24 months	-	- $ 500	$ 12500
36 months	-	$ 6250	$ 18750

Directed Power Flow

- ‘Green’ electrons can be directed along a designated network path (pipeline)
- Carbon cap & trade may generate opportunities for investment

Title XIII of the Energy Independence & Security Act of 2007

Places great emphasis on Smart Grid – Electricity delivery network modernization using latest technologies to meet key defining functions:

- Optimizing asset utilization and operating efficiently
- Self healing and resilient operation
- Greater control of the grid to enable new business models and functionality

Financial Incentives

- $100M/year for 2008-12, 50% cost share for utilities on demonstration projects, 20% reimbursement for expenditures on Smart Grid
- Rate recovery and accelerated depreciation allowed

Renewable Portfolio Standards and Real-Time Pricing.

- Results in significant level of dynamics on the grid, with significant challenges
- Increased adoption of Advanced Meters to serve as pricing gateways will result in greater volatility of loads

Key Technologies Targeted:

- Controls to improve reliability, dynamic optimization of grid operations, smart appliances, to facilitate integration of advanced technologies in electric networks to improve performance, power flow control and reliability.

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.
- Project is supported by IPIC, TVA, ConEd, Southern, NRECA, and others. Target full-scale pilot demonstrations in 18-24 months.