Flexible AC Transmission Systems (FACTS)

Presented By

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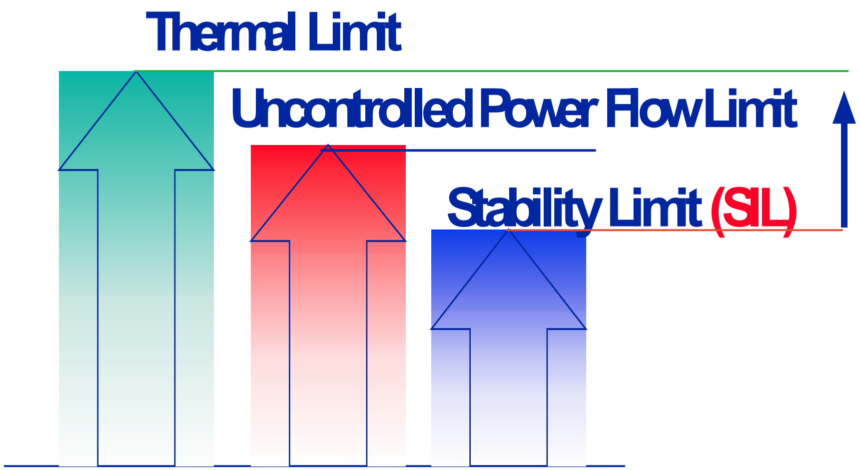
EPRI

Power Delivery Issues

- **Voltage regulation**
  - Maintaining desired transmission voltage profile
  - Prevention of voltage collapse
  - Limitation of overvoltage
- **Power flow control**
  - Increased power transmission
  - Elimination of bottlenecks
  - Minimization of loop flows
- **Stabilization of system dynamics**
  - Transient and dynamic stability
  - Voltage instability

The ultimate objective of transmission controllers are *Improving power delivery, Security, reliability, controllability and quality*

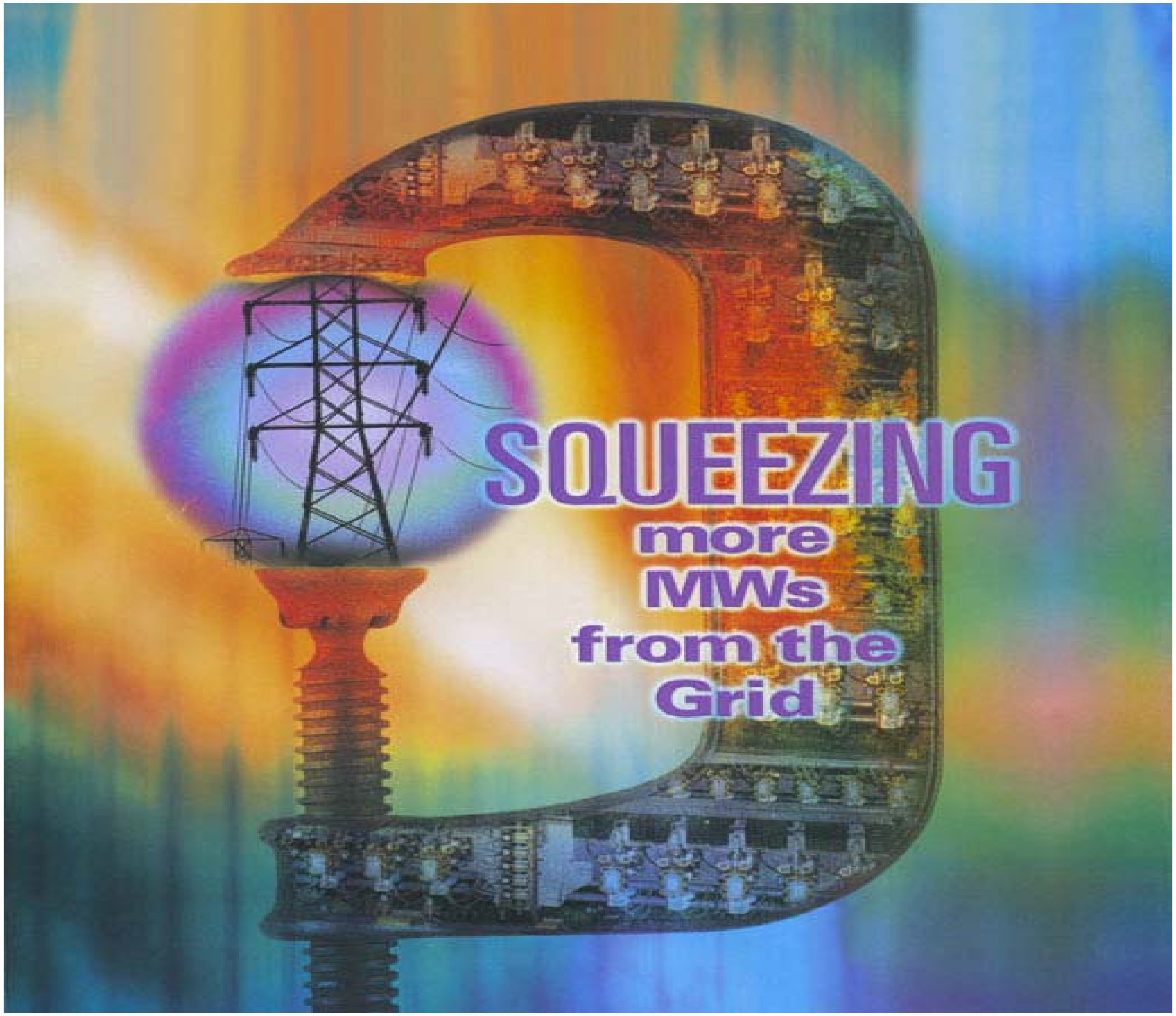
Transmission Capacity Challenges ??



Voltage (kV)	SIL (MW)	Typical Thermal Rating (MW)
230	150	400
345	400	→ 1200
500	900	→ 2600
765	2200	5400
1100	5200	24000

- Thermal Limits
- Uncontrolled Power Flows
- Stability Limits << Thermal Limits

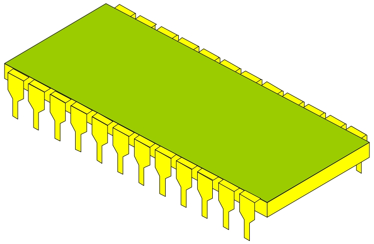
The Ever Challenge is



FACTS

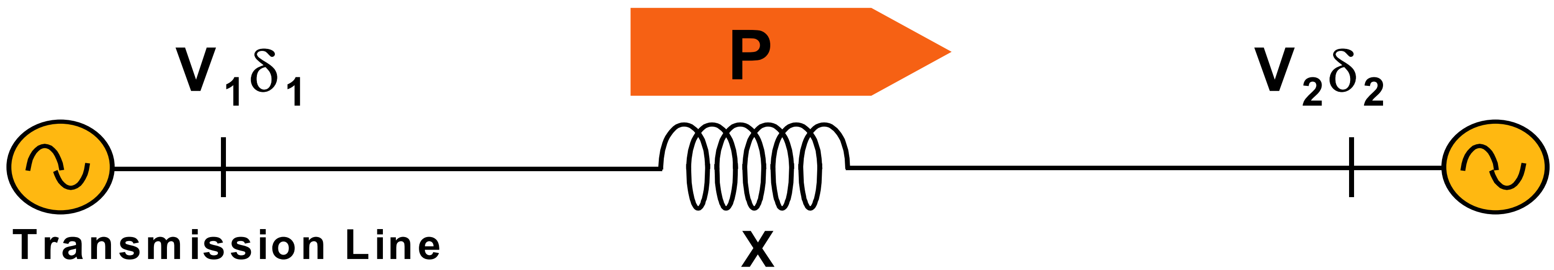
Flexible
Alternating
Current
Transmission
Systems

FACTS are a collection of power transmission control technologies based on very high power solid state electronic devices.



FACTS Technologies

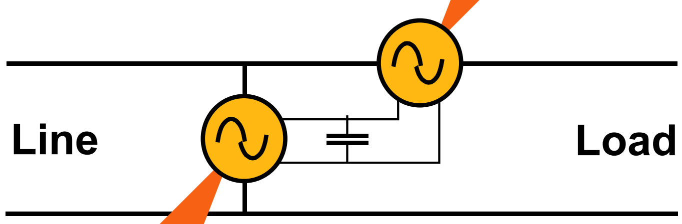
"Expands Laws of Physics"



$$P = V_1 V_2 \frac{1}{X} \sin(\delta_1 - \delta_2)$$

Electronic generator to provide reactive power and insert real power

Line Impedance & Angle Control



Electronic generator to provide reactive power and extract real power

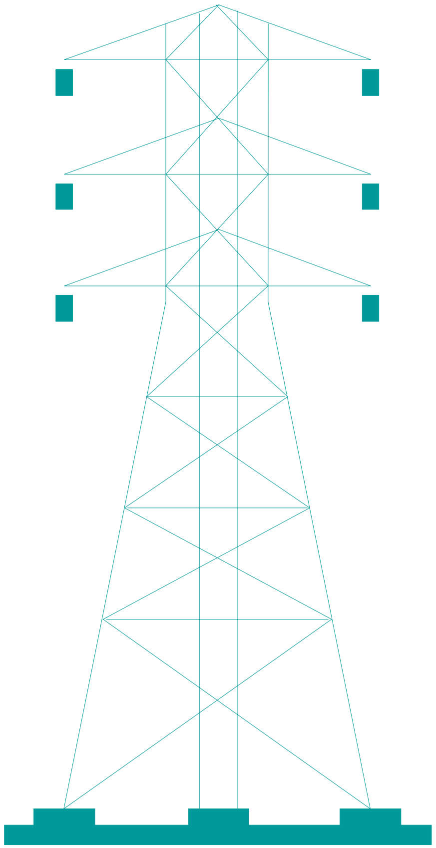
Voltage Control

FACTS

Q: What are these systems used for?

A: Fast and continuous active control of the transmission network

- Control of power flow
- Control of network instabilities
- Control of voltage



FACTS Hardware

Term covers transmission network systems employing:

- ***Traditional thyristors (SCR's, 25-30 year history)***
- ***Gate turn off thyristors (GTO's, 6 year history)***
- ***Other solid state high voltage switches (i.e., MCT's, IGBT's)***

FACTS Hardware

Traditional technologies include:

- ***Thyristor controlled reactors***
- ***Thyristor switched reactors***
- ***Thyristor switched capacitors***
- ***Static Var Compensators (SVC)***

“New” technologies include:

Thyristor Controlled Series Compensation (TCSC)

STATic synchronous COMpensator (STATCOM)

Static Synchronous Series Compensator (SSSC)

Unified Power Flow Controller (UPFC)

Interphase Power Flow Controller (IPFC)

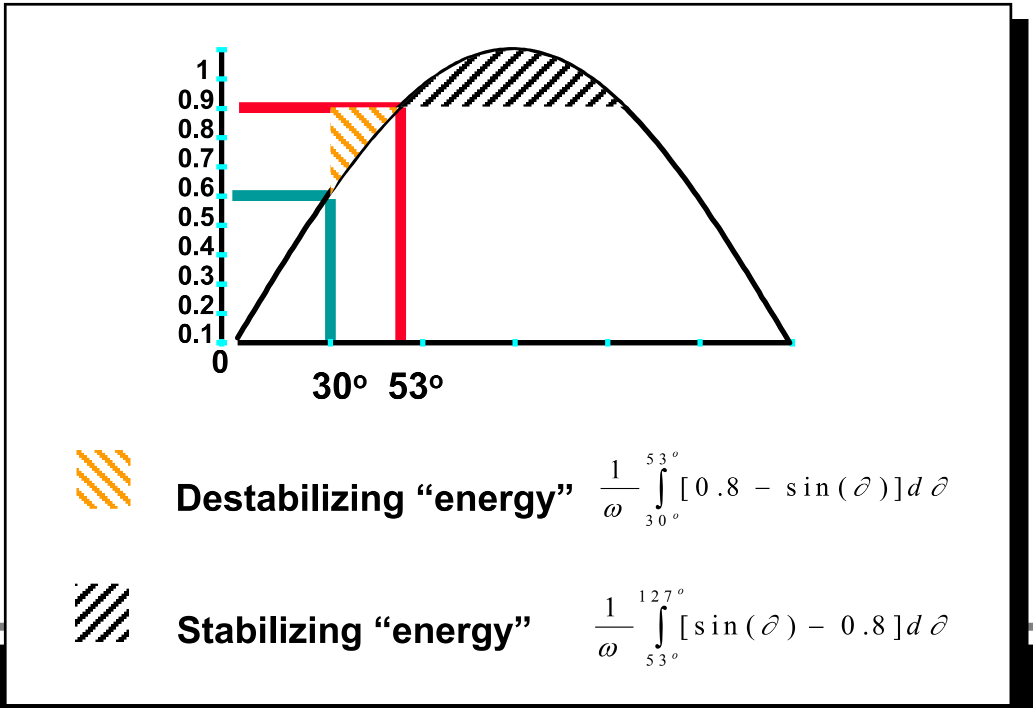
Taking Advantage of the Changes

All FACTS technologies can increase system stability

Where stability is a limit, this increases system capacity

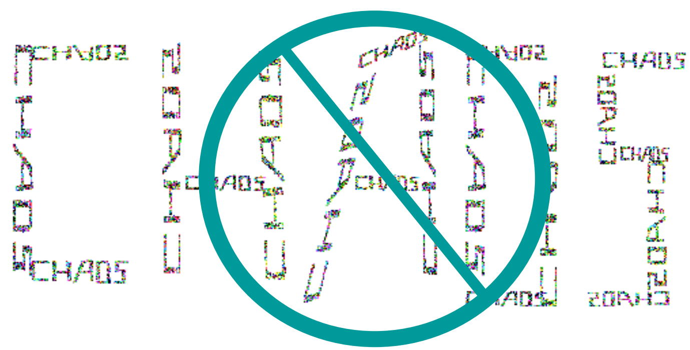
This removes
"bottlenecks"

Can accommodate
new demands
without new lines



Taking Advantage of the Changes

- *FACTS particularly UPFC, can be used to directly dispatch Watts and Vars*
- *FACTS can be used to restore control of the system*
- *FACTS can be used to provide improved power quality, both in transmission and distribution*



Taking Advantage of the Changes

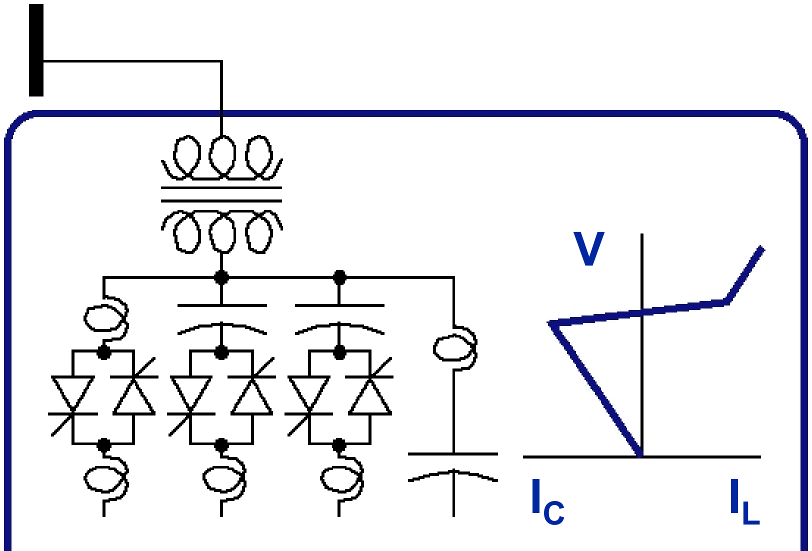
FACTS can be used to provide "new" services

Real Power	***Metering and Billing***	***Power Quality***
Reactive Supply*	***Load Management***	***Standby Capacity***
Voltage Support*	***Use Control***	***Dispatch***
Load Following	***Frequency Control***	***Brokering***
Capacity Increase	***System Stability***	***Load Forecasting***

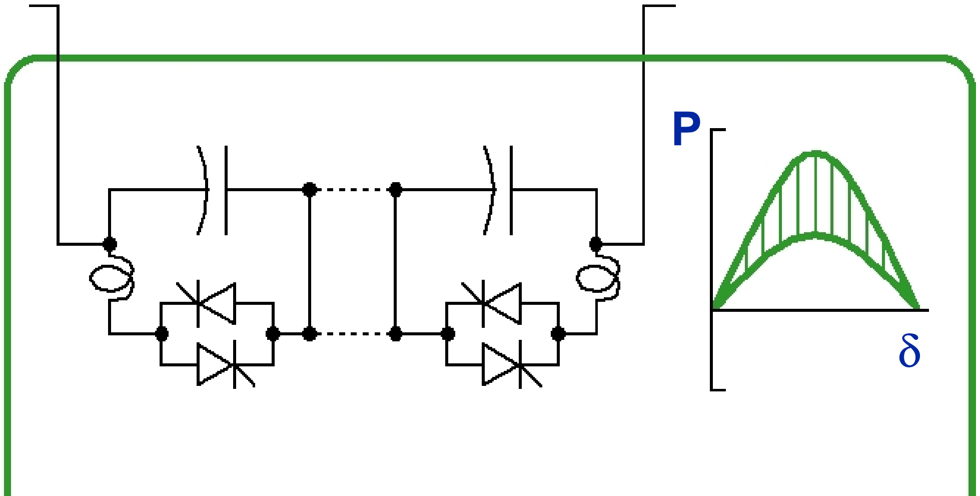
EPRI Technology Development

In the late 1970s, EPRI and number of US and foreign utilities introduced:

thyristor switched and/or controlled reactors and capacitor banks to provide the dynamic compensation.



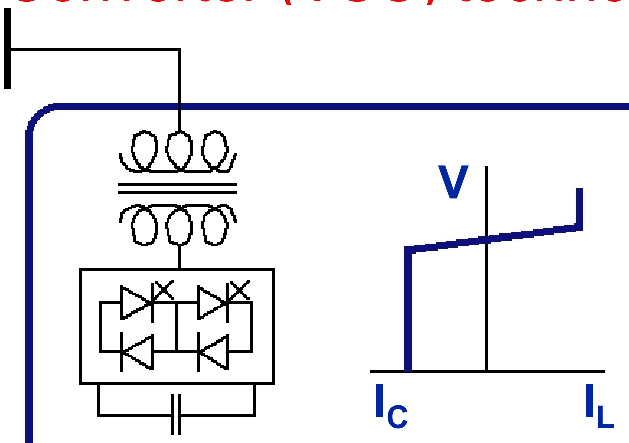
Static Var Compensator (SVC)



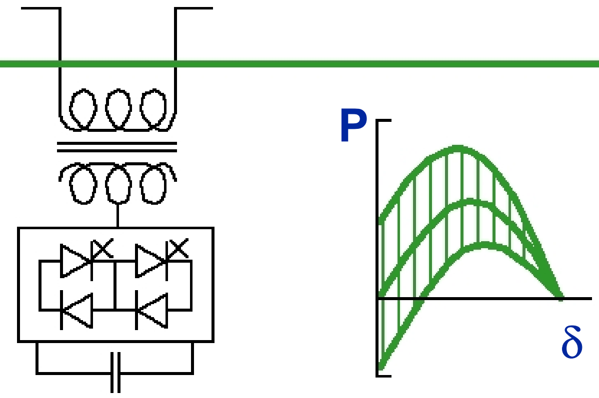
Thyristor-Controlled Series Capacitor (TCSC)

EPRI Technology Development

In the mid 1980s, EPRI led the technology development of Flexible AC Transmission System **(FACTS)**. A new group of synergetic transmission system controllers with names such as **STATCOM**; the Static Synchronous Compensator; **SSSC**, Static Synchronous Series Compensator; **UPFC**, Unified Power Flow Controller; and **IPFC**, Interline Power Flow Controller. These controllers are based on the use of Voltage Sourced Converter (VSC) technology.

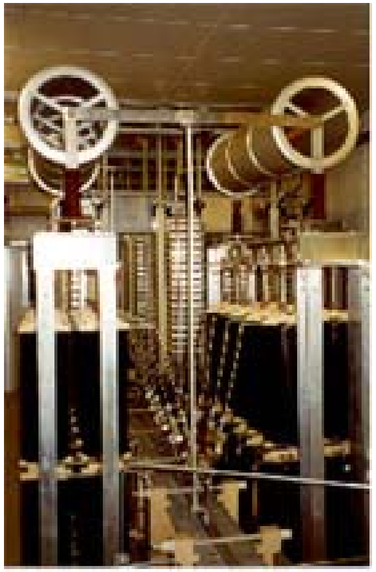


Static Synchronous Compensator (STATCOM)



Static Synchronous Series Compensator (SSSC)

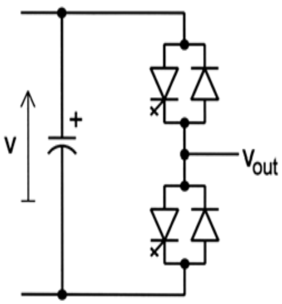
Voltage Source Converter

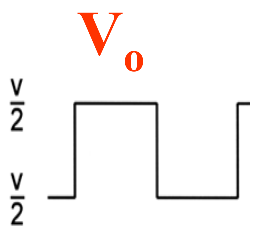


- Basic building block of FACTS devices
- Operates independently of strength of connected AC system
- Uses gate-turn-off solid state switches, e.g. GTO, GCT, IGBT

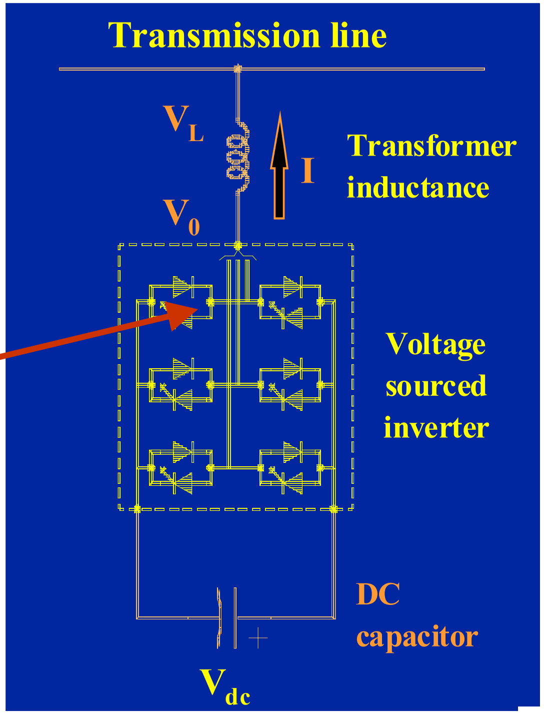
Voltage Source Converter

"A Building Block for New Transmission Controllers"



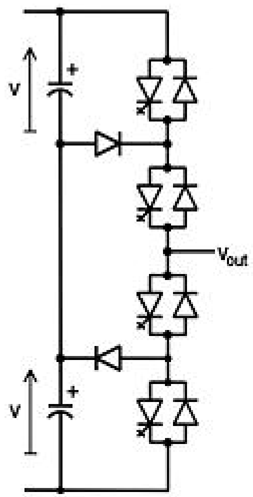


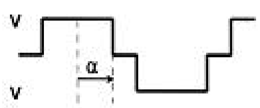
Gate Turn Off
GTO, GCT, IGBT



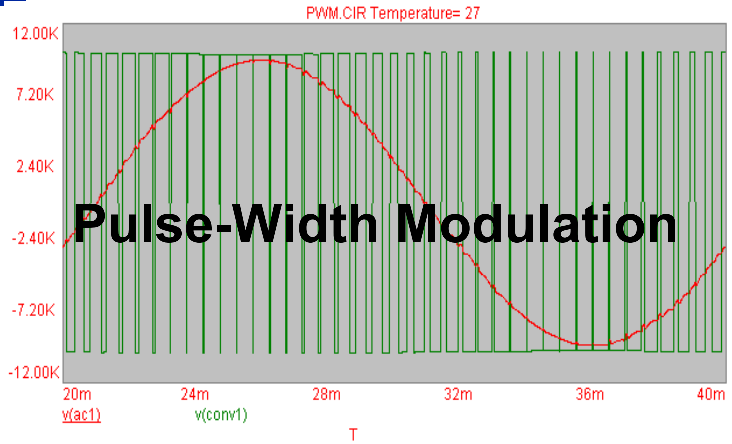
Voltage source converter with controlled output voltage

If $V_L = V_0$, I = 0
If $V_L < V_0$, I = capacitive
If $V_L > V_0$, I = inductive

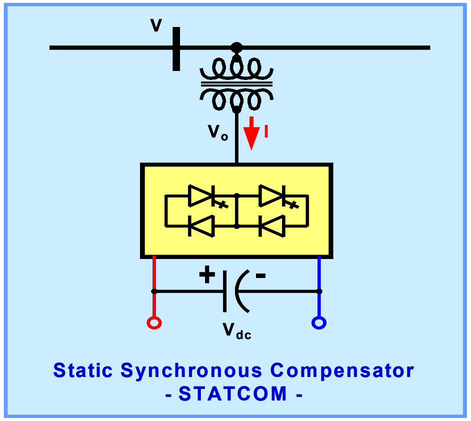




Three-Level Switching

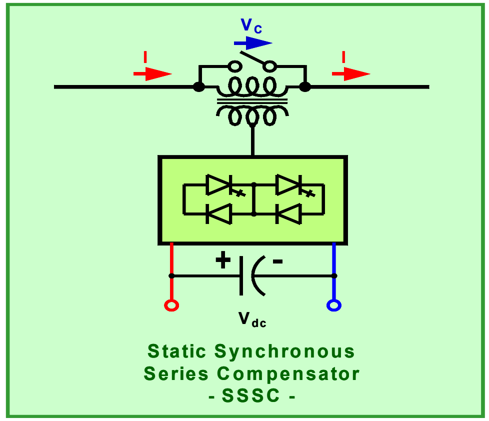


Transmission Applications of VSC



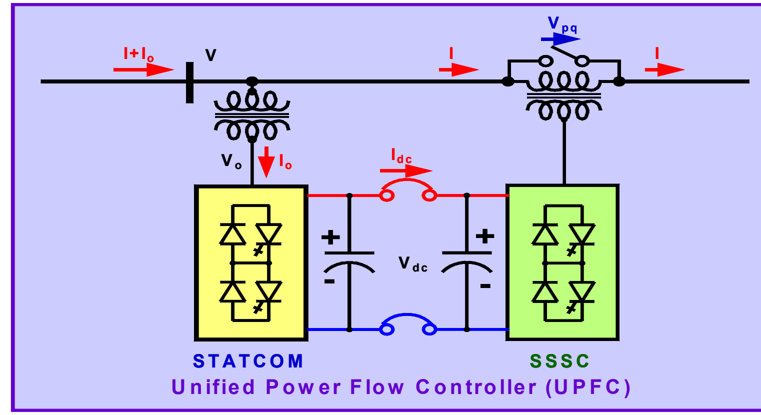
STATCOM

Voltage Control



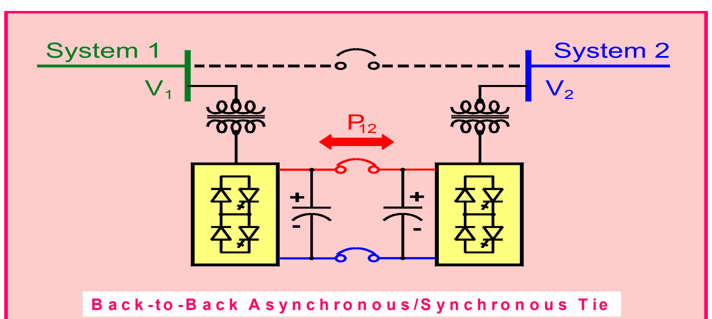
SSSC

Line impedance control



UPFC

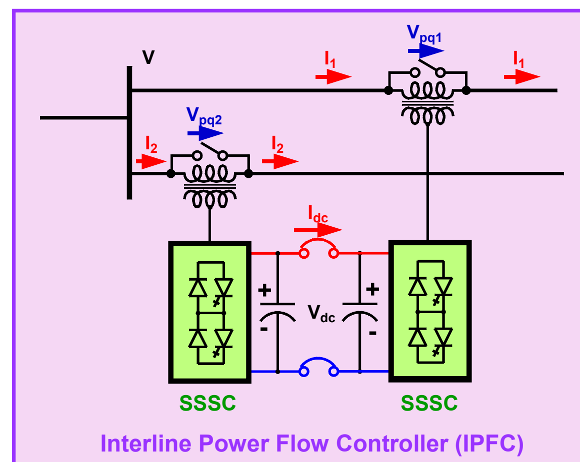
Voltage, line impedance, and phase angel control



Back-to-Back

Voltage and power transfer control

L. Gyugyi



IPFC

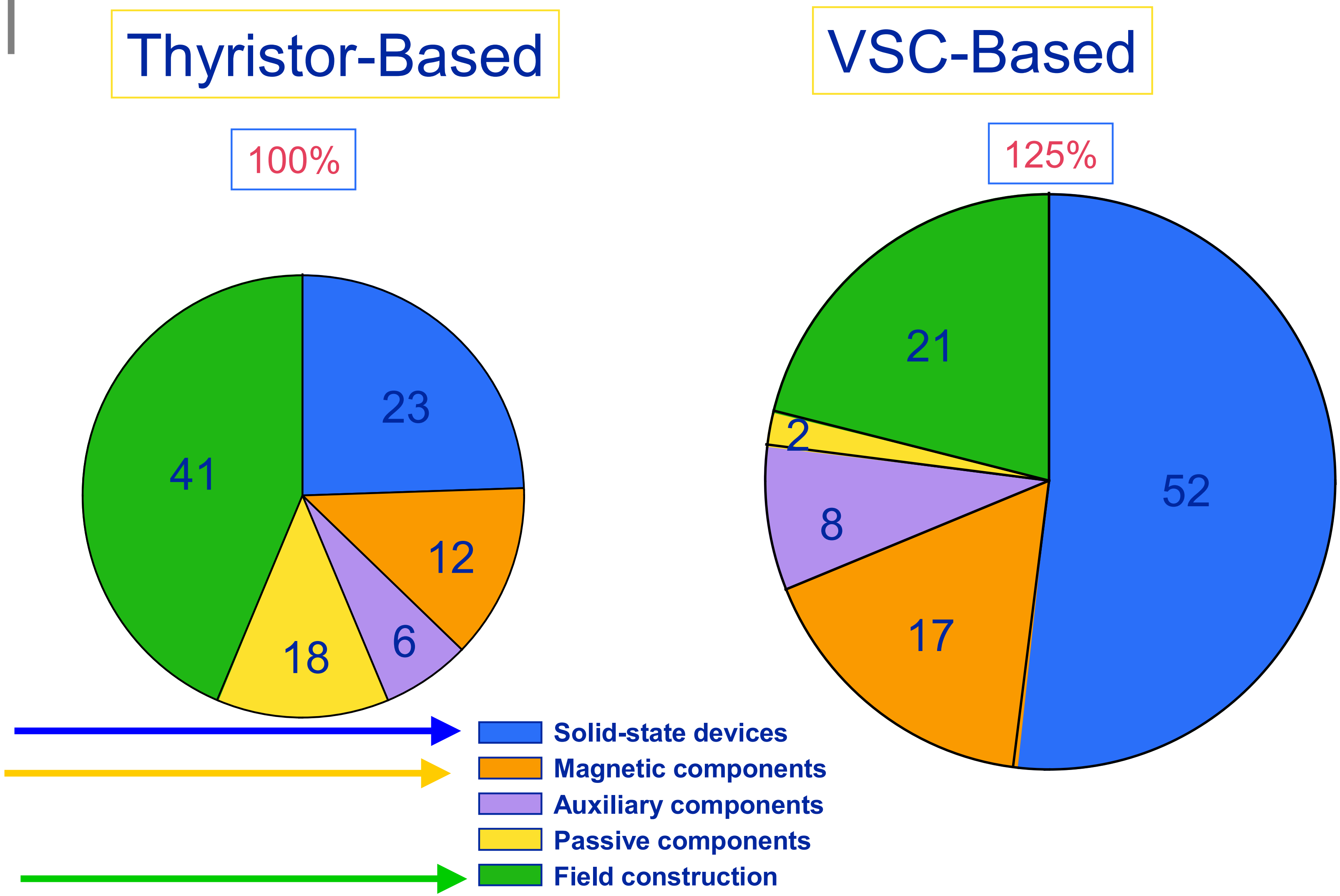
Interline power exchange

Rating - IPFC 01

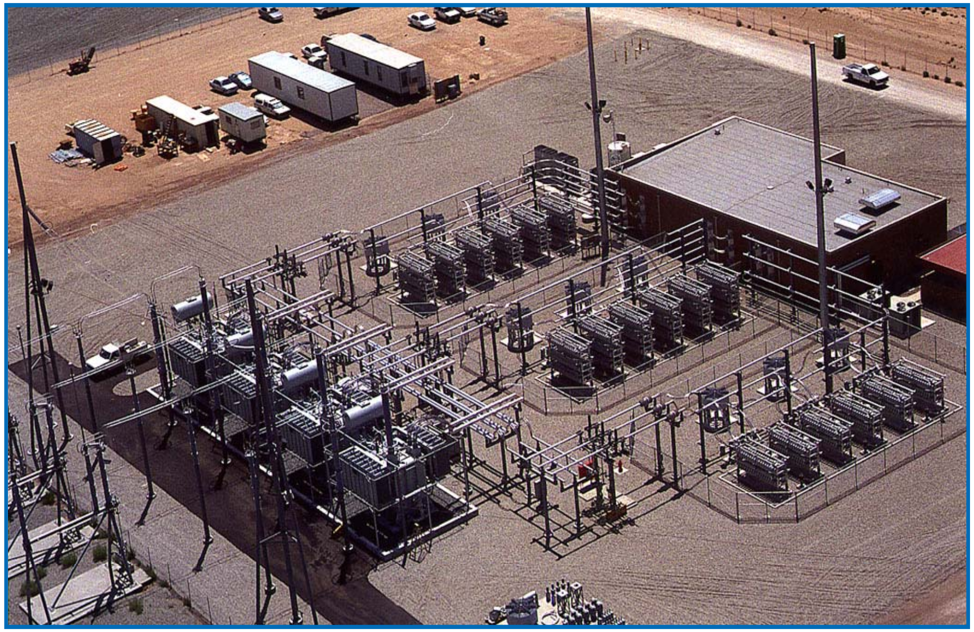
Power Electronic-Based Transmission Controllers

- **Thyristor-based**
  - Shunt- or series-connected switched/controlled reactor and capacitor banks for transmission voltage and power flow control.
  - Limited performance and response speed
- **Voltage Source Converter-based**
  - 100% Electronic control of transmission voltage and power flow, with no need to physical reactors or capacitor banks.
  - Versatility and functional capability are practically limitless

Cost Distribution



Installation and Real Estate



VSC-Based

Thyristor-Based

Power Electronic Controllers Development "Roadmap"

- **Reliability/Availability**
  - Robust Control
  - Redundancy
  - Quality Assurance
- **Cost Reduction**
  - Design Simplification- Transformer-less Controllers
  - Higher Ratings and Higher "Junction" Temperature Solid-state Switching Components
- **Expanded Functionality**
  - Power Circuit Development
  - Convertibility/Dual Functionality-Multimode Controllers
  - Relocatability

Power Electronic Controllers Development "Roadmap"

- New Switching Devices
- New Power Circuits Structural "Concepts"
- New "Integrated" Control

EPRI’s Post-Silicon Initiative

Double the voltage

Operate 100° C hotter

↓

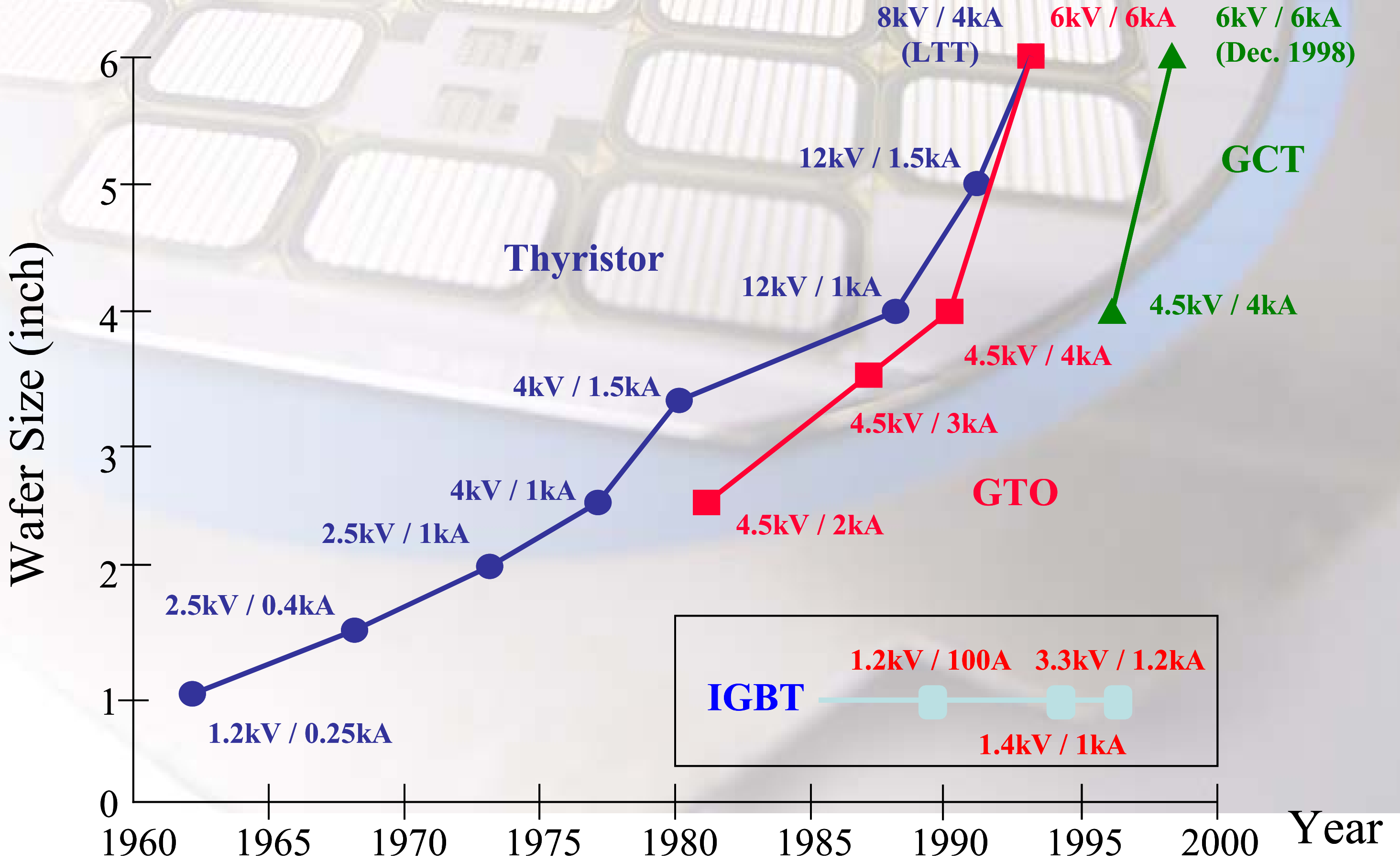
Much simpler cooling

Much smaller size (10x)

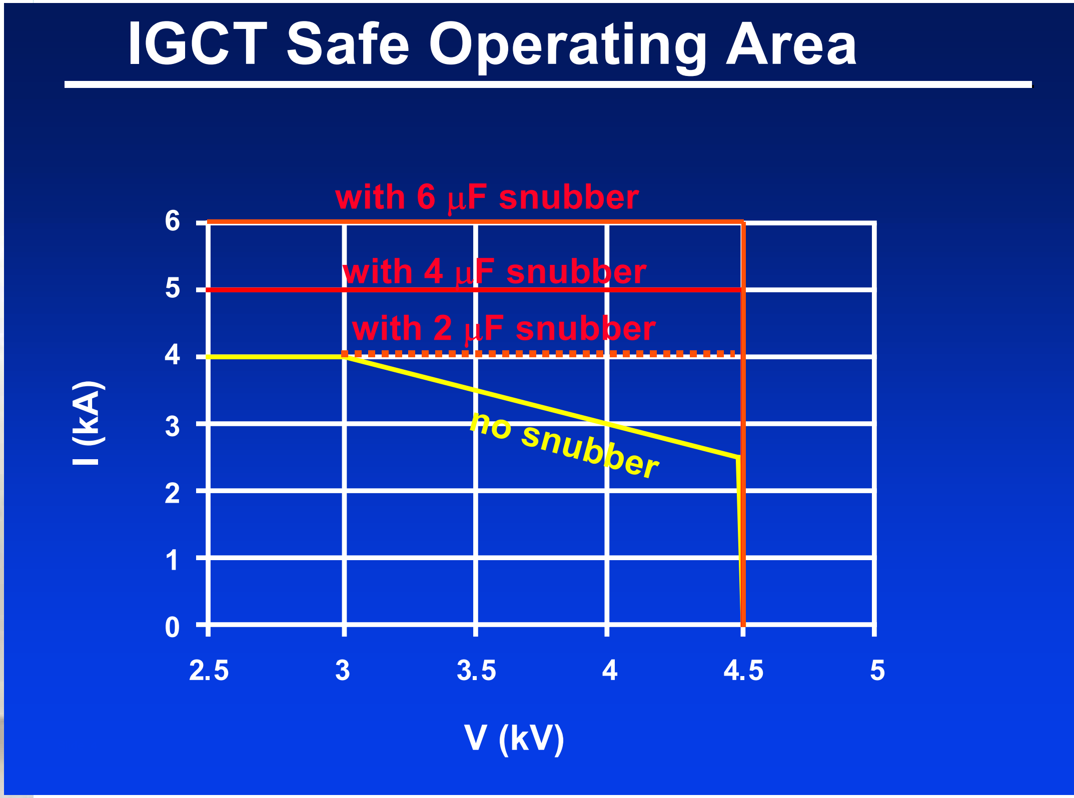
FACTS, motor drives, HVDC, electric automobiles

Post Silicon Development

- Higher voltage and current ratings
- Higher junction temperature = Much simpler cooling



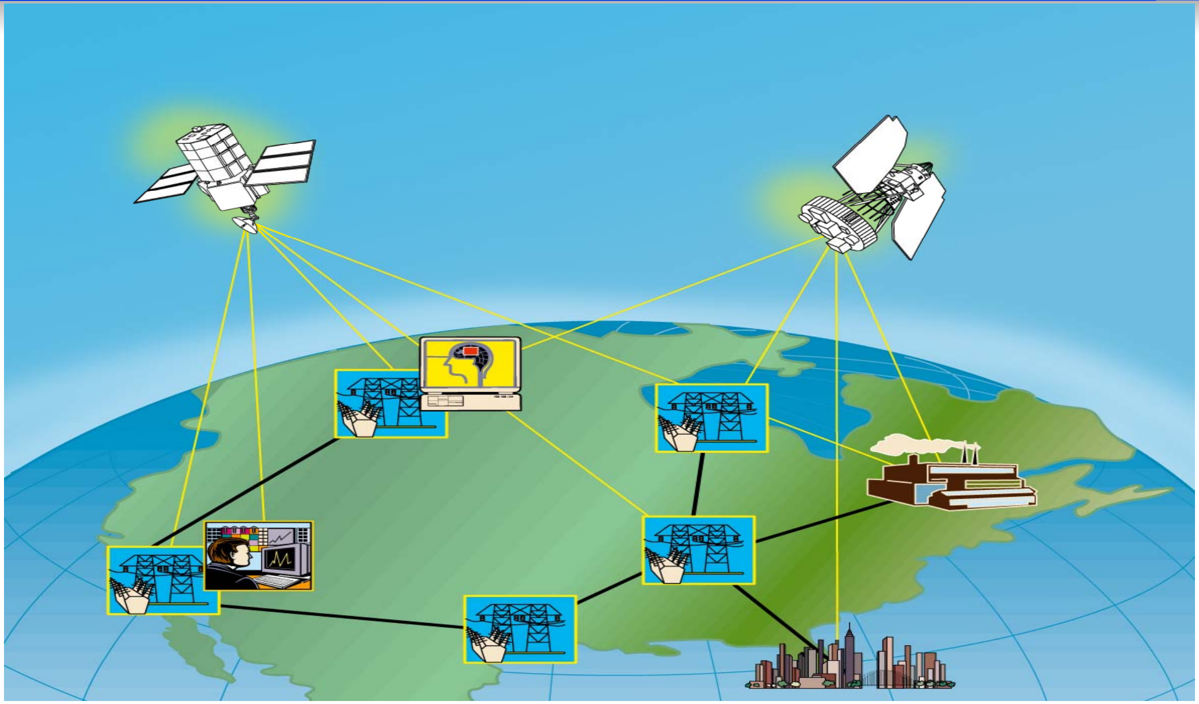
GTO Module Vs. IGCT



New Power Circuits Structural "Concepts"

- Simplification of the converter and the associated magnetic structure
- Directly interfaced with the controlled transmission, "transformer–less" controllers
- More flexible control and tighter protection
- **Compact and Re-locatable**

Integrated Network Control



- Intelligent Network Agents (INAs)
- Integrated Energy and Communication Systems Architecture
- Faster than real-time simulation

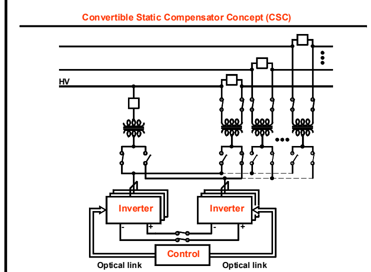
What Can Power Electronic-Based Controllers do for Transmission Grids ?

- Control Power Flows
- Increase Transmission Capacity
- Increase Transmission Security
- Reduce Reactive power Flows
- Provide Voltage support at Strategic Transmission Buses
- Provide Asynchronous/Synchronous Ties
- Increase Flexibility for Citing New Generators

EPRI Sponsored FACTS Installations

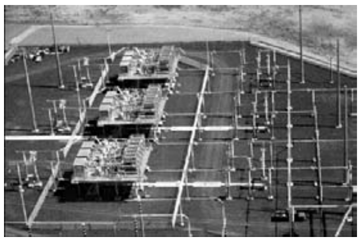
Unified Power Flow Controller (UPFC):
"All Transmission Parameters Controller"
± 160 MVA Shunt and ± 160 MVA Series at Inez Substation (AEP) 1998

UPFC



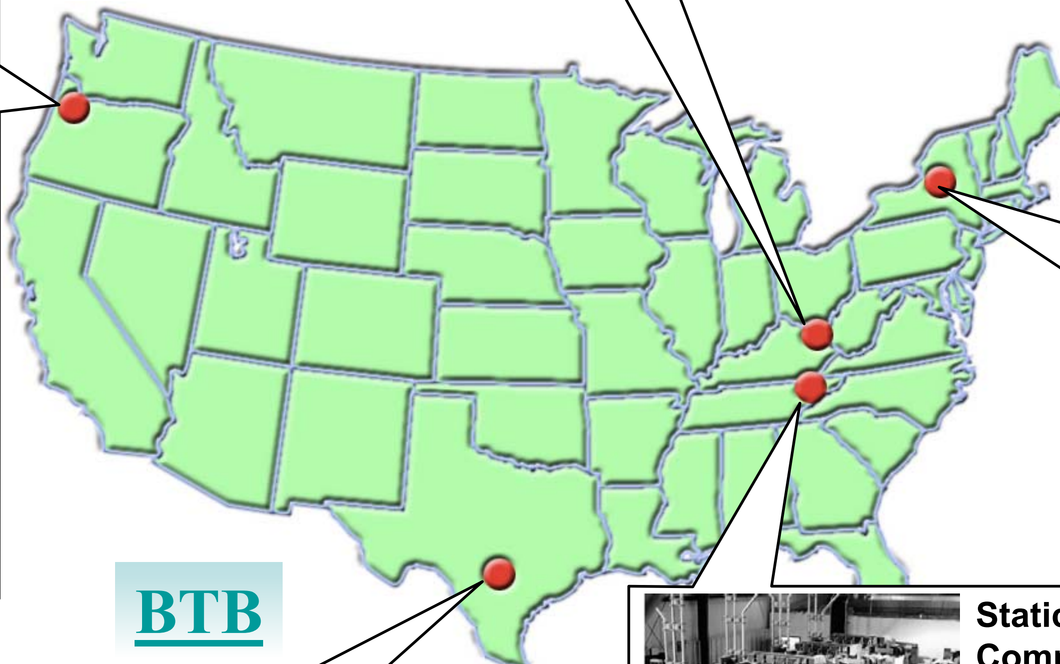
Convertible Static Compensator (CSC):
"Flexible Multi-functional Compensator"
± 200 MVA at Marcy Substation (NYPA)
2000 & 2002

CSC



Thyristor Controlled Series Capacitor (TCSC):
"Line Impedance Controller"
208 Mvar TCSC at Slatt Substation (BPA) 1993

TCSC



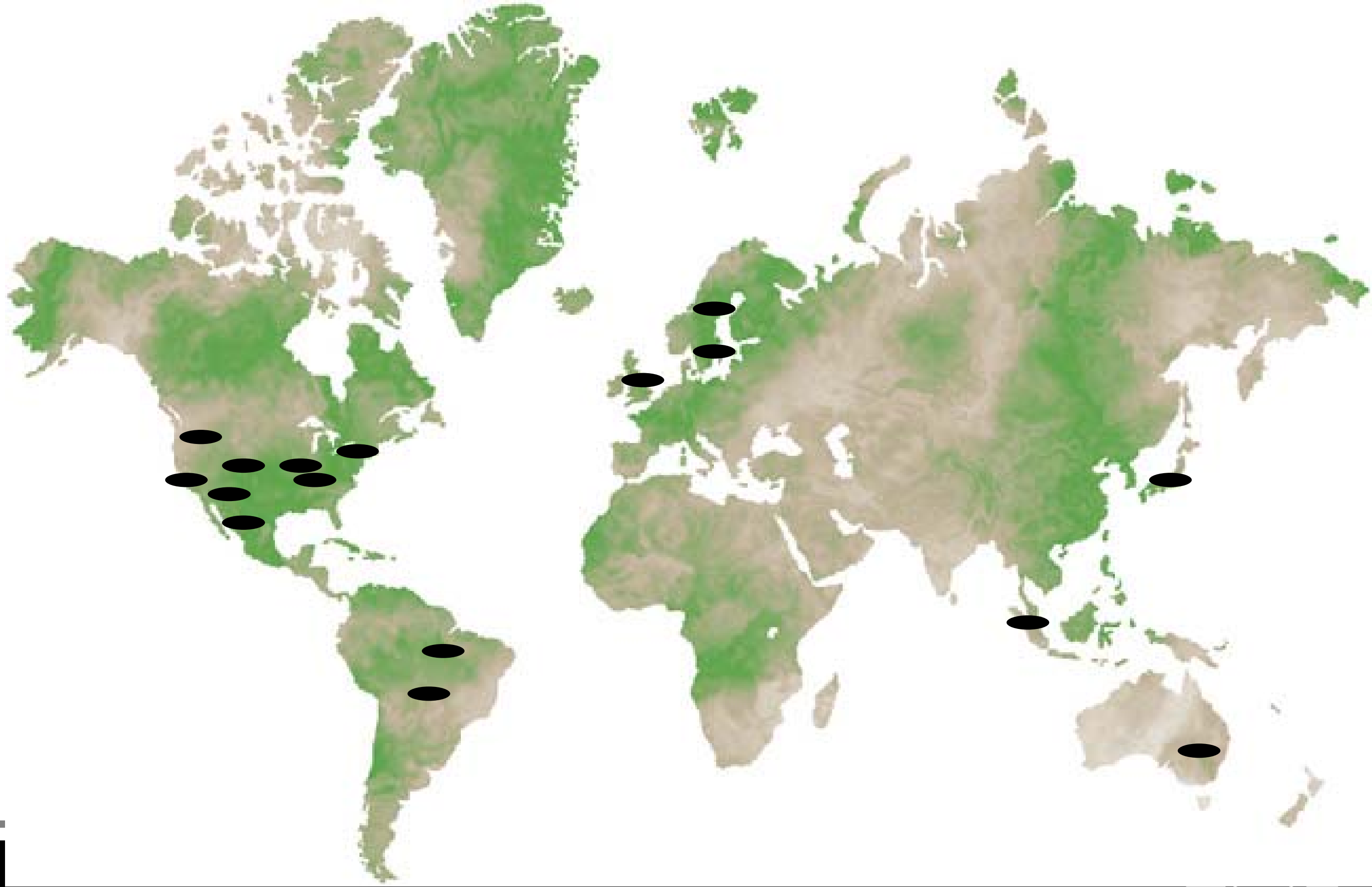
BTB

FACTS Controller
"Back-To-Back HVDC Tie"
36 MW at Eagle Pass (CSW)
2000

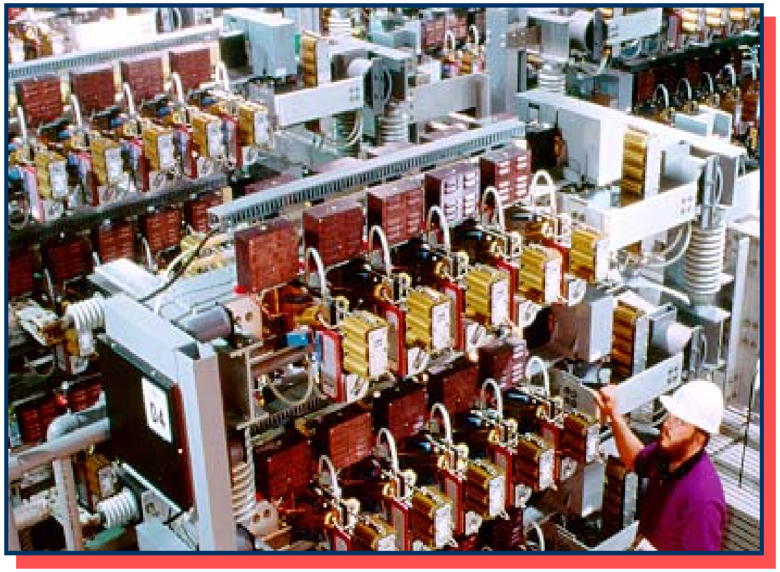
Static Synchronous Compensator (STATCOM) :
"Voltage Controller"
± 100 Mvar STATCOM at Sullivan Substation (TVA)
1995

STATCOM

FACTS Installations Worldwide



ullivan Static Compensator (STATCOM)

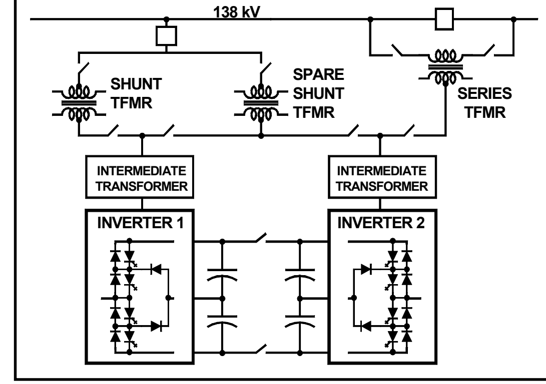


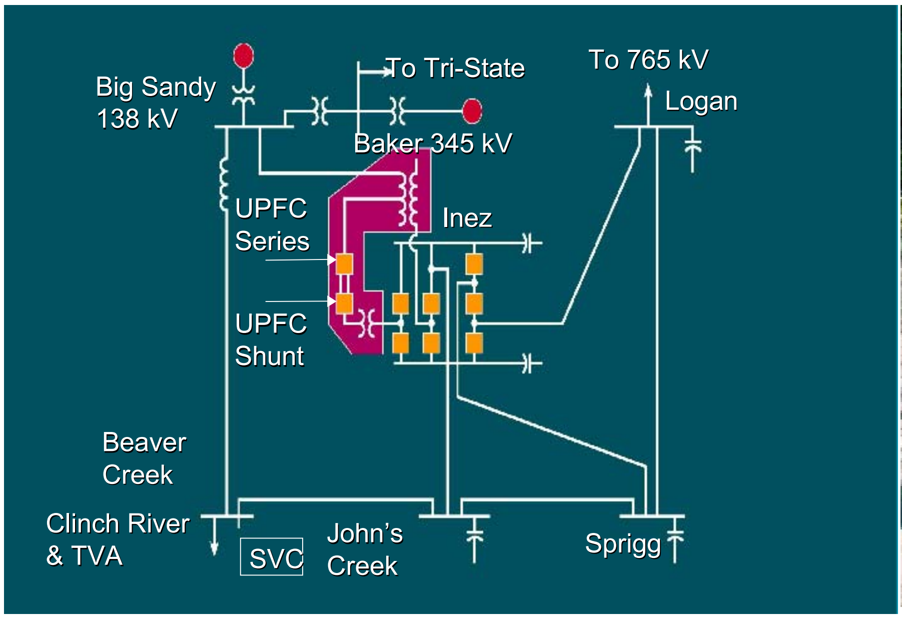
- TVA-EPRI-Westinghouse project
- Continuous voltage and reactive power control
- Enabled TVA to avoid building a new transmission line

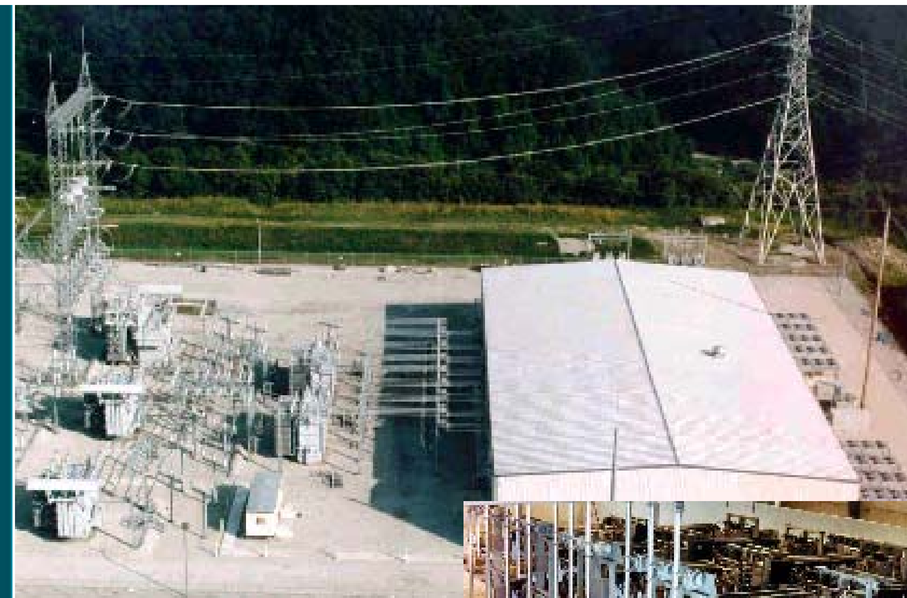
nez Unified Power Flow Controller (UPFC)

- AEP-EPRI-Siemens project
- Increased power transfer on 158 kV line from 600 MW to 700 MW
- Provides voltage support to improve system reliability

Inez UPFC - AEP/EPRI/Siemens

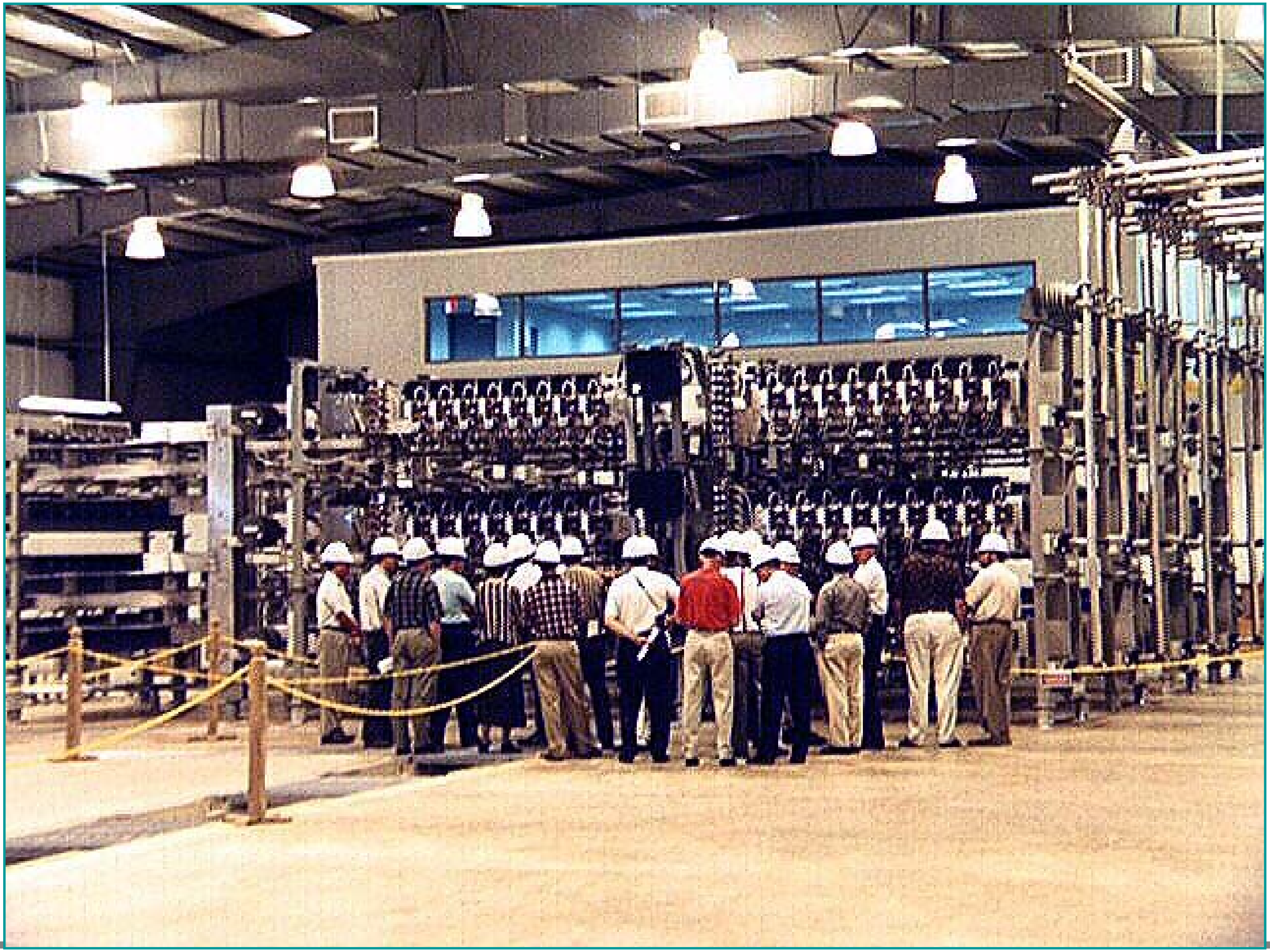




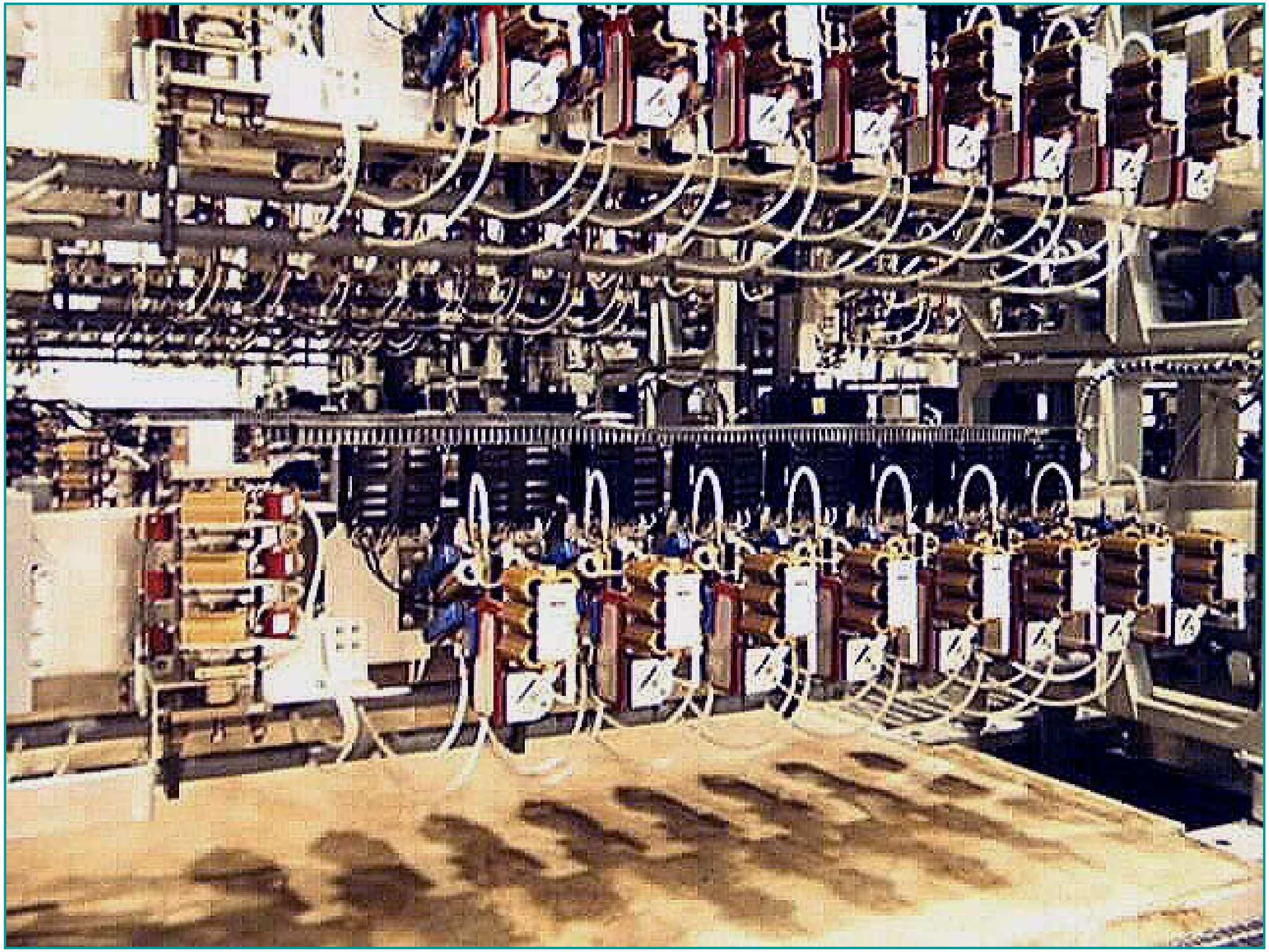


- **Reliable Power Delivery to the Inez**
- **Increase of Power Transfer (100 MW)**

UPFC Shunt Valve

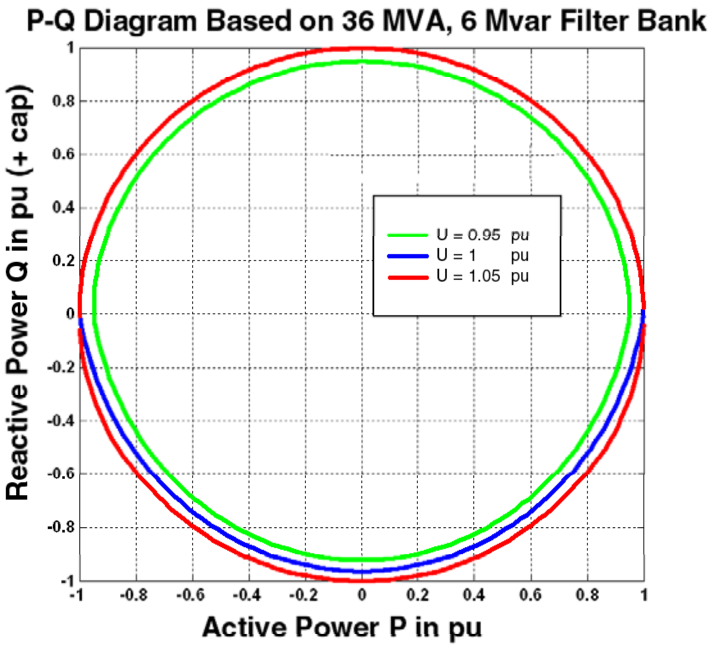


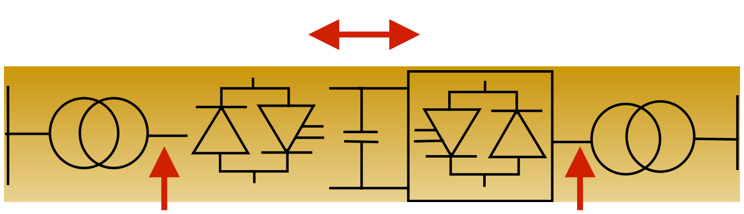
UPFC Valve Section



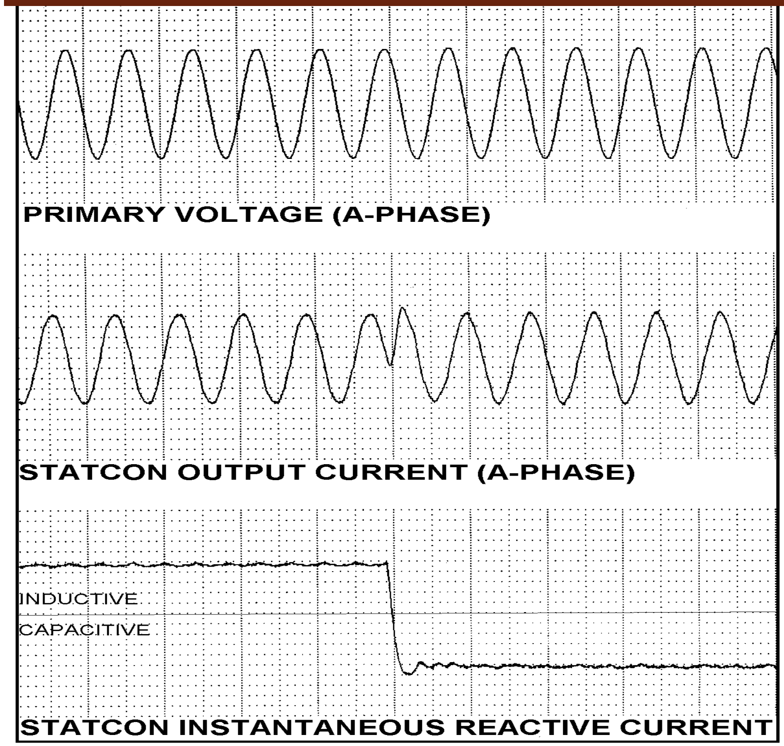
What FACTS Controllers can do ?

Bi directional Power Flow & Voltage Support



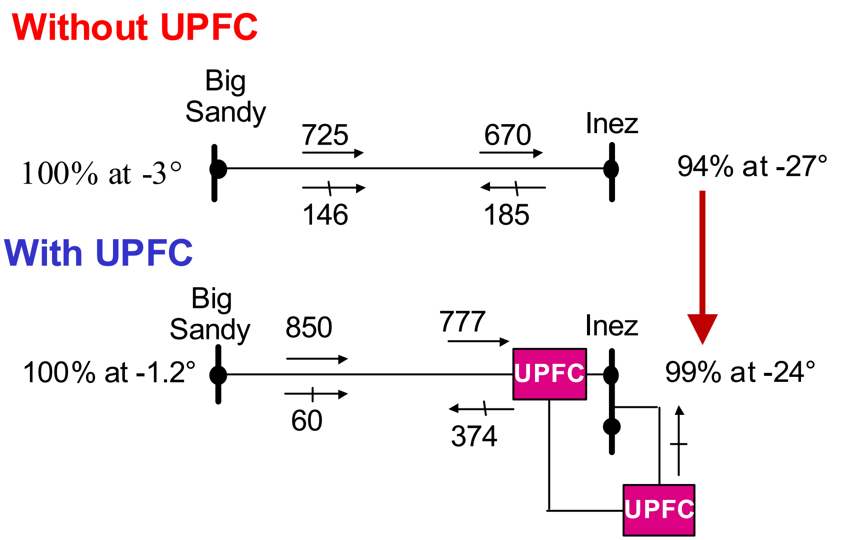


Fast and Transient Free V and Q Control

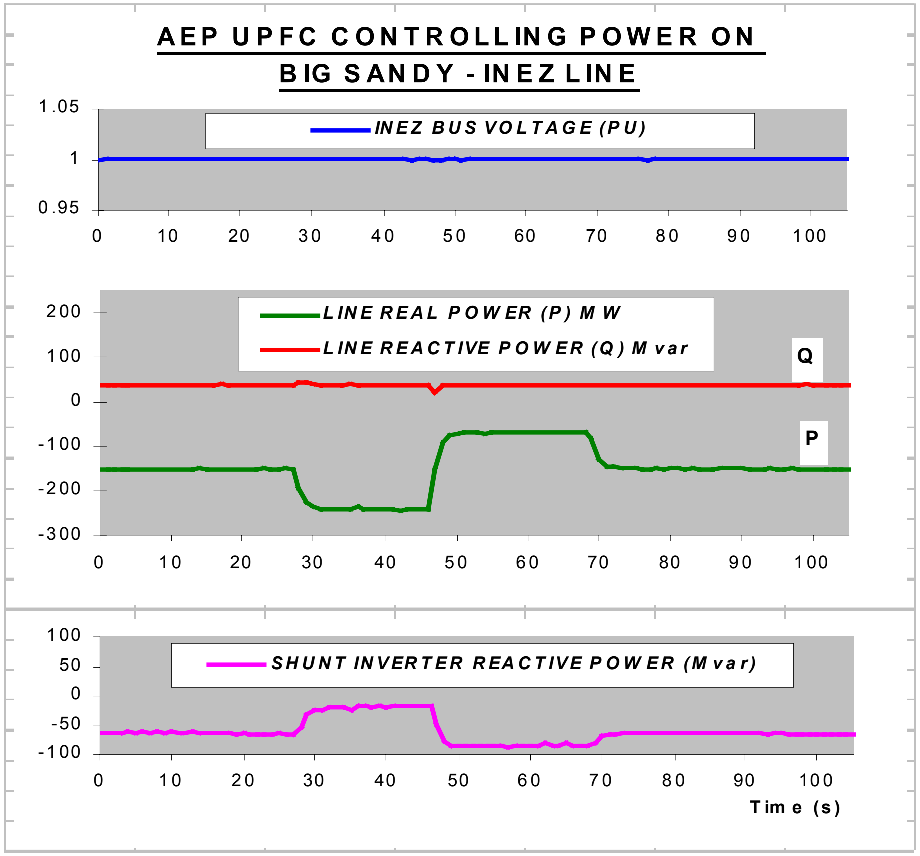


What FACTS Controllers can do ?

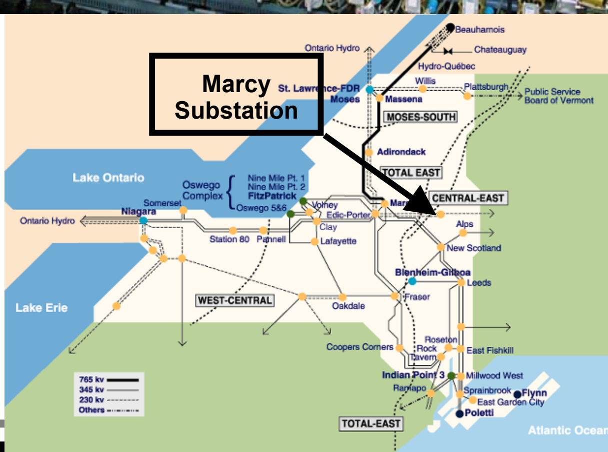
Increase of Power Transfer



Full Control of Power Transfer



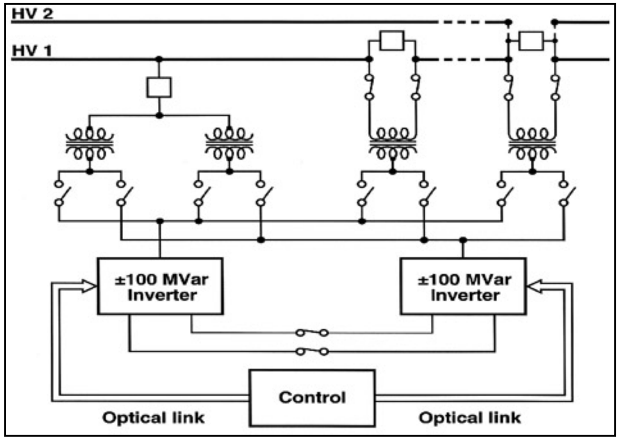
arcy Convertible Static Compensator (CSC)

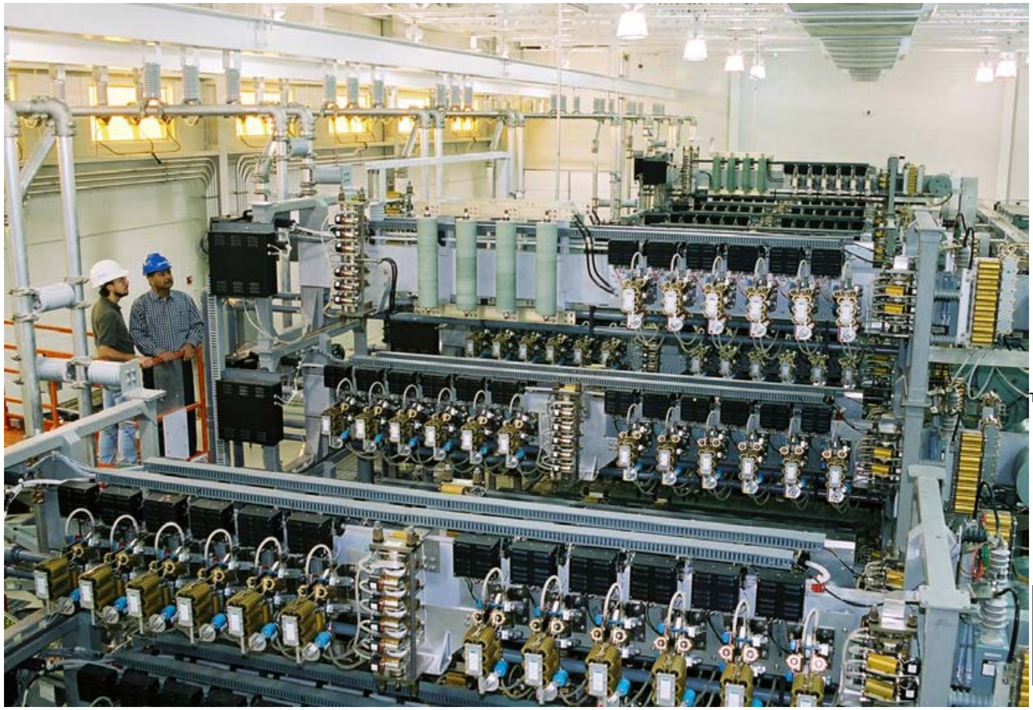


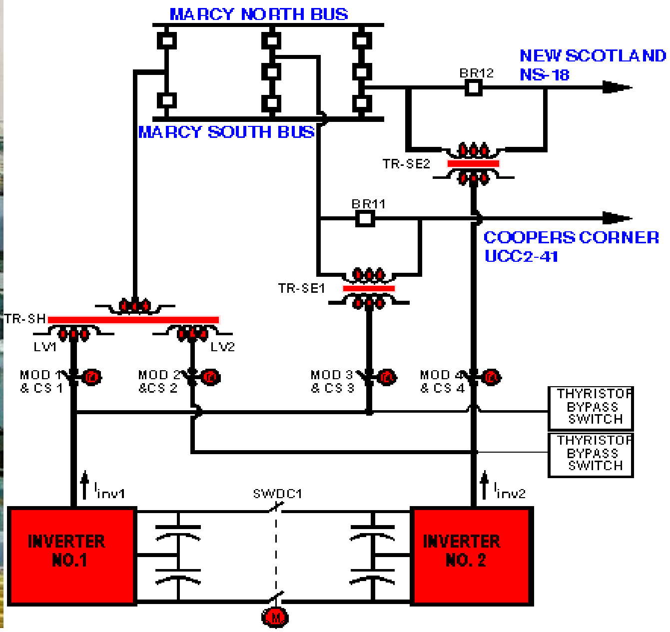
- NYPA-EPRI-Siemens project
- Increase upstate-to-downstate power transfer by 240 MW on 9000 MW corridor
- Can be reconfigured to serve different functions

Marcy Convertible Static Compensator (CSC)

NYPA/EPRI/Siemens





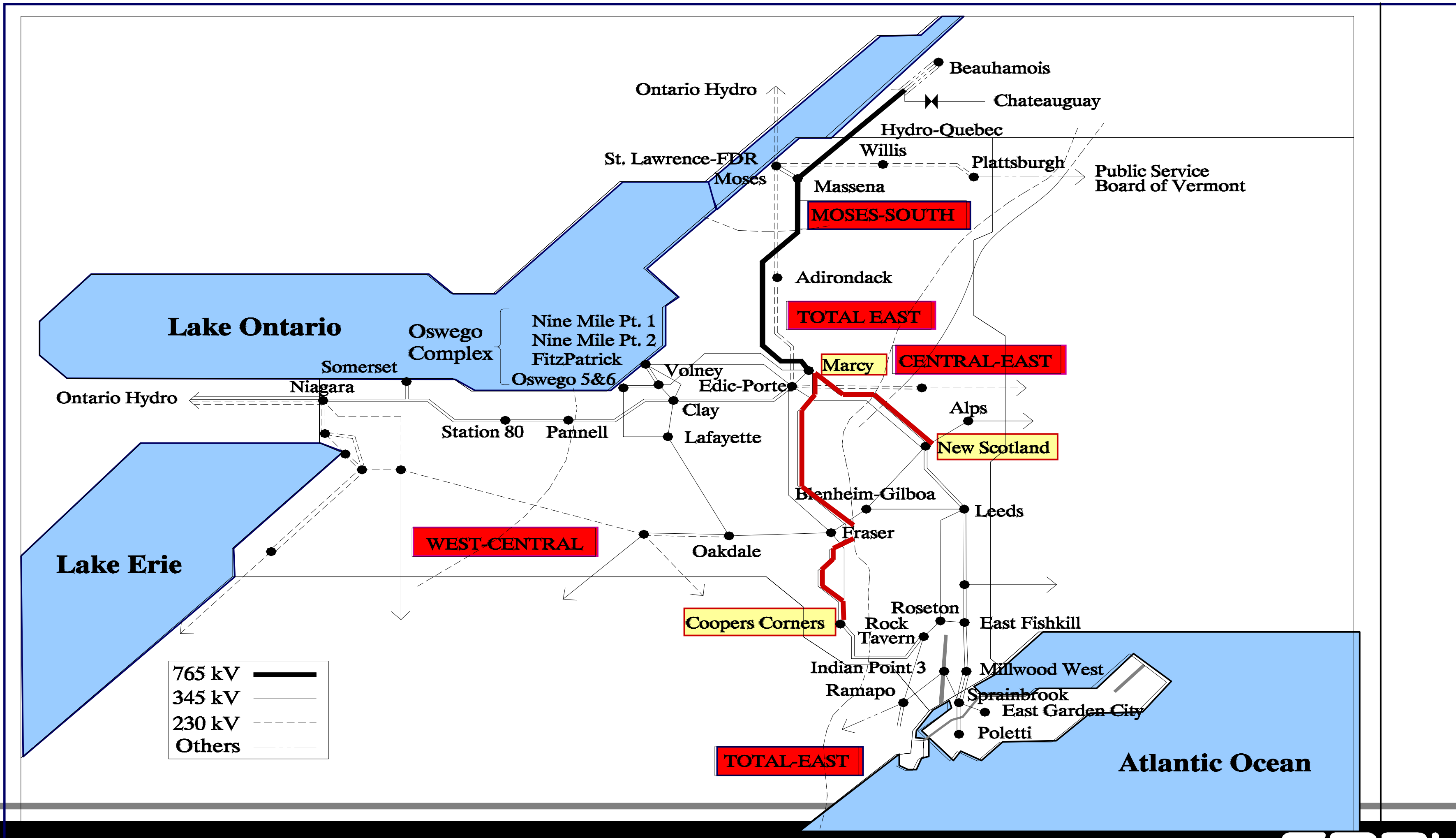


- **Increase upstate-to-downstate power transfer by 240 MW**
- **Relieve a major transmission bottleneck**
- **Improve voltage control**

Problem Description & Recommended Solution

- The Central-East (C-E) interface power transfers are voltage-limited to 2850 MW
- The above limit is further reduced during system outage conditions
- Heavy utilization of The C-E interface is anticipated in the future
- A hybrid solution of FACTS and conventional equipment is found to address the short-term needs and provide flexibility for the future

One-Line Diagram of NYS EHV Transmission System



CSC PROJECT

- **Two ±100 MVA GTO-based, three-level inverters at Marcy 345 kV Substation**
- **One 135 MVAR capacitor bank at Oakdale, One 200 MVAR capacitor bank at Edic**
- **Multiple (11 utilized) configurations each with multiple control modes**
- **Steady-state and dynamic voltage and power flow control capability**
- **Control voltage at the Marcy bus and flows on the Marcy-New Scotland and Marcy-Coopers Corners lines**

CSC Benefits

- Increase Total-East interface power transfer Capability by 240 MW and Central-East by 120 MW
- Increase system dynamic resiliency
- Improve voltage control
- Reduce transmission congestion
- Provide flexibility for system operation, and maintenance

Short-Term Reinforcements

- +/- 200 MVAR dynamic voltage support and control at Marcy 345 kV substation
- 135 MVAR capacitor bank at Oakdale substation
- 200 MVAR capacitor bank at EDIC substation

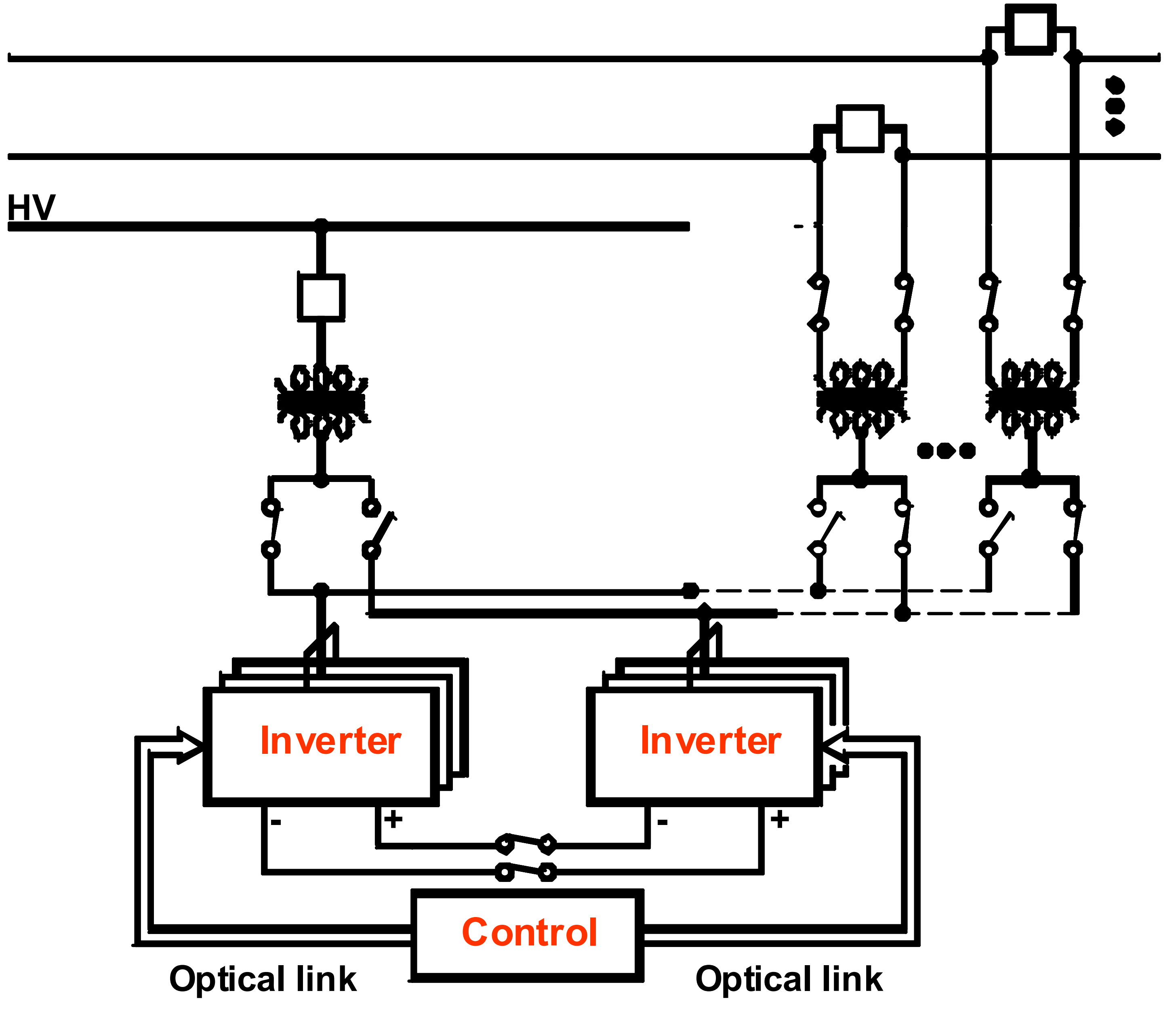
- The CSC in its shunt configuration will provide dynamic voltage support and control

Long-Term Reinforcements

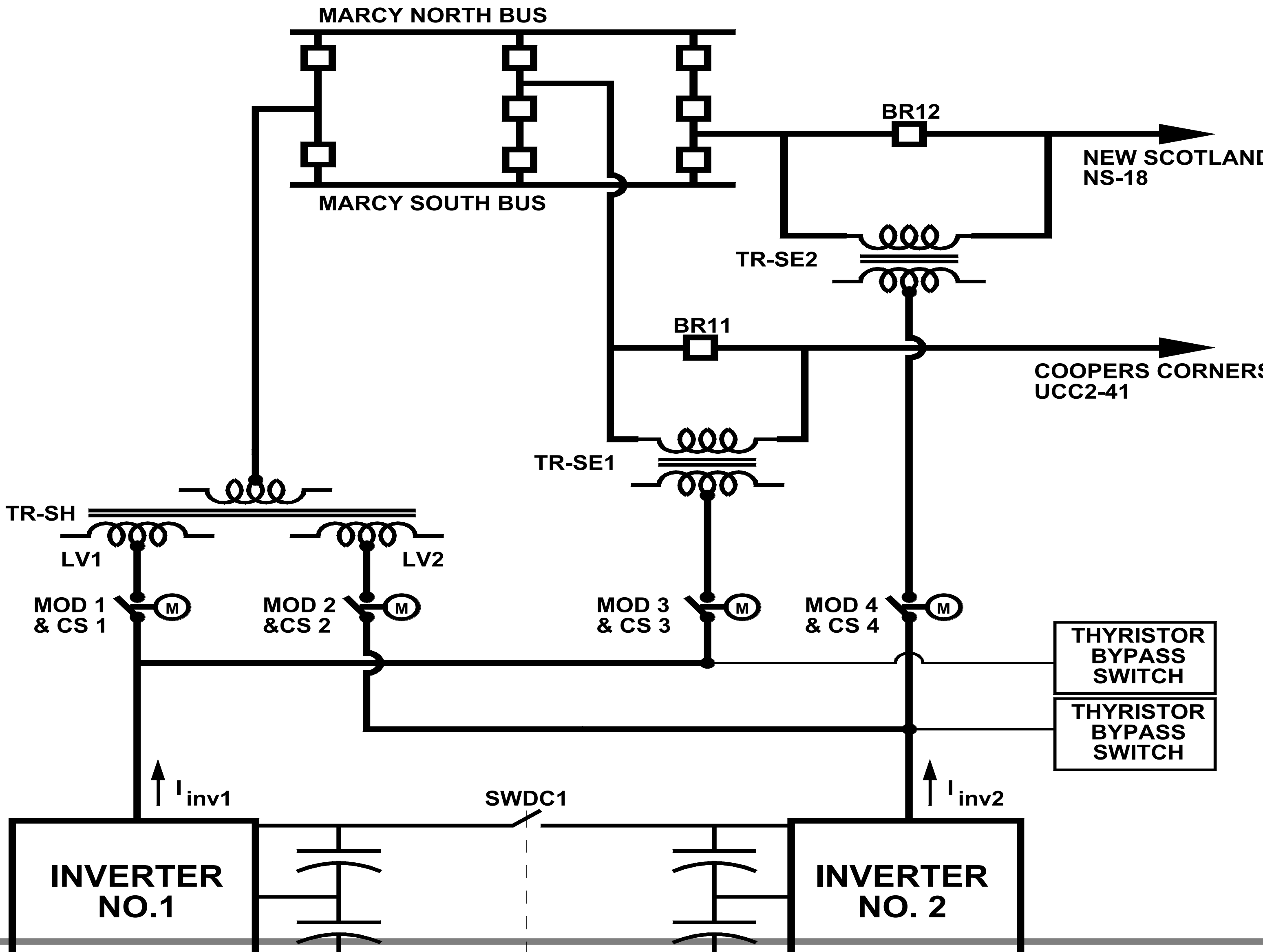
- Series Configurations

- The CSC in its series configurations will provide power flow control capability on one or two lines as well as voltage support

Convertible Static Compensator Concept (CSC)



CSC One-Line Diagram



Marcy CSC's Four basic Devices

- +/- 200 MVAR shunt compensation for voltage control: Static Compensator (STATCOM)
- Series compensation for power flow control: Static Series Synchronous Compensator (SSSC)
- Coupled shunt/series compensation, Unified Power Flow Controller (UPFC)
- Coupled series/series compensation, Interline Power Flow Controller (IPFC)

CSC Configurations

1	STATCOM100-1	7	STATCOM100-1 SSSC100-UNS
2	STATCOM100-2	8	STATCOM100-2 SSSC100-UCC
3	STATCOM200	9	UPFC100/100-UCC
4	SSSC100-UCC	10	UPFC100/100-UNS
5	SSSC100-UNS	11	IPFC100-UCC/100-UNS
6	SSSC100-UCC SSSC100-UNS		

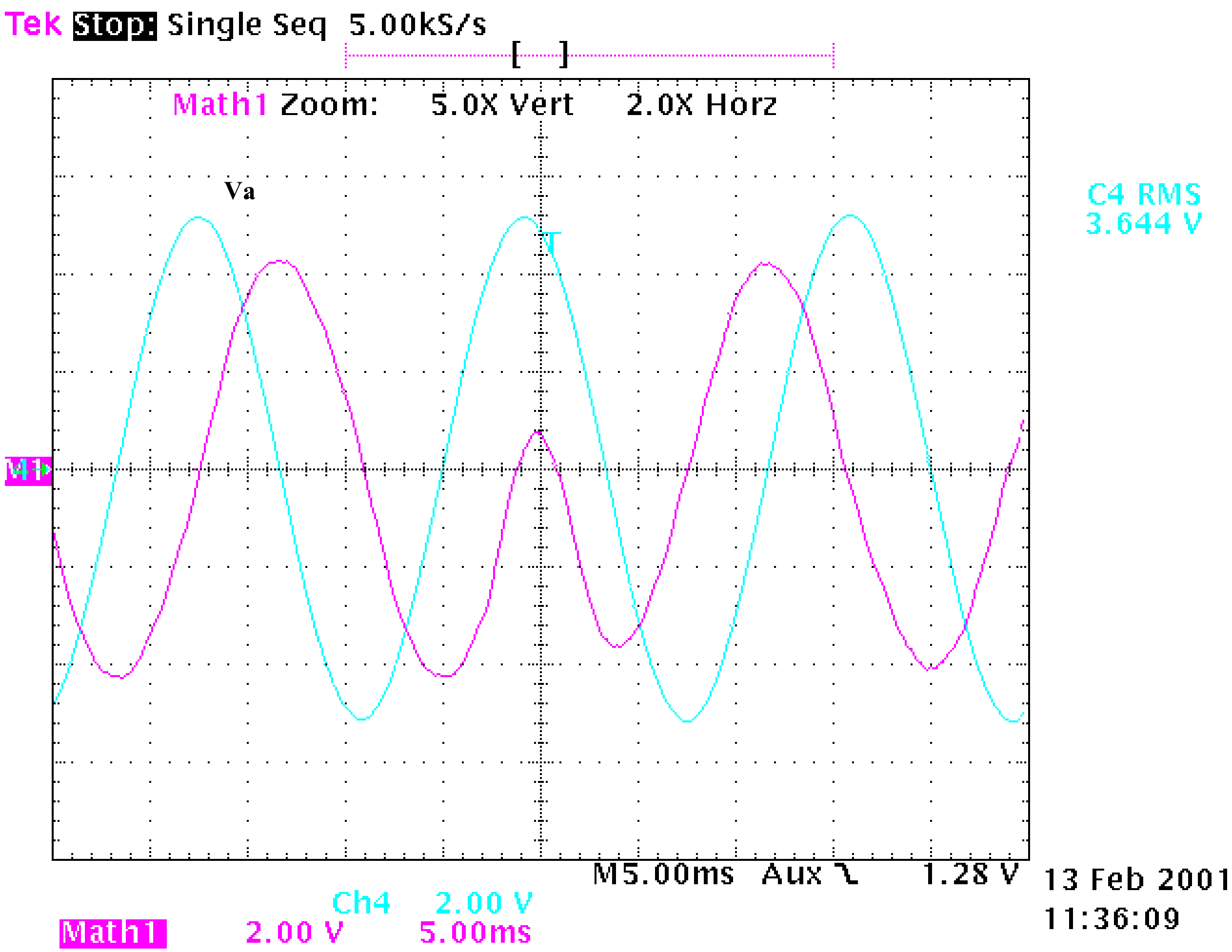
Note: 100 and 200 denote MVA rating;
1 and 2 denote inverter in service;
UCC and UNS are lines compensated.

CSC Project Cost & Schedule

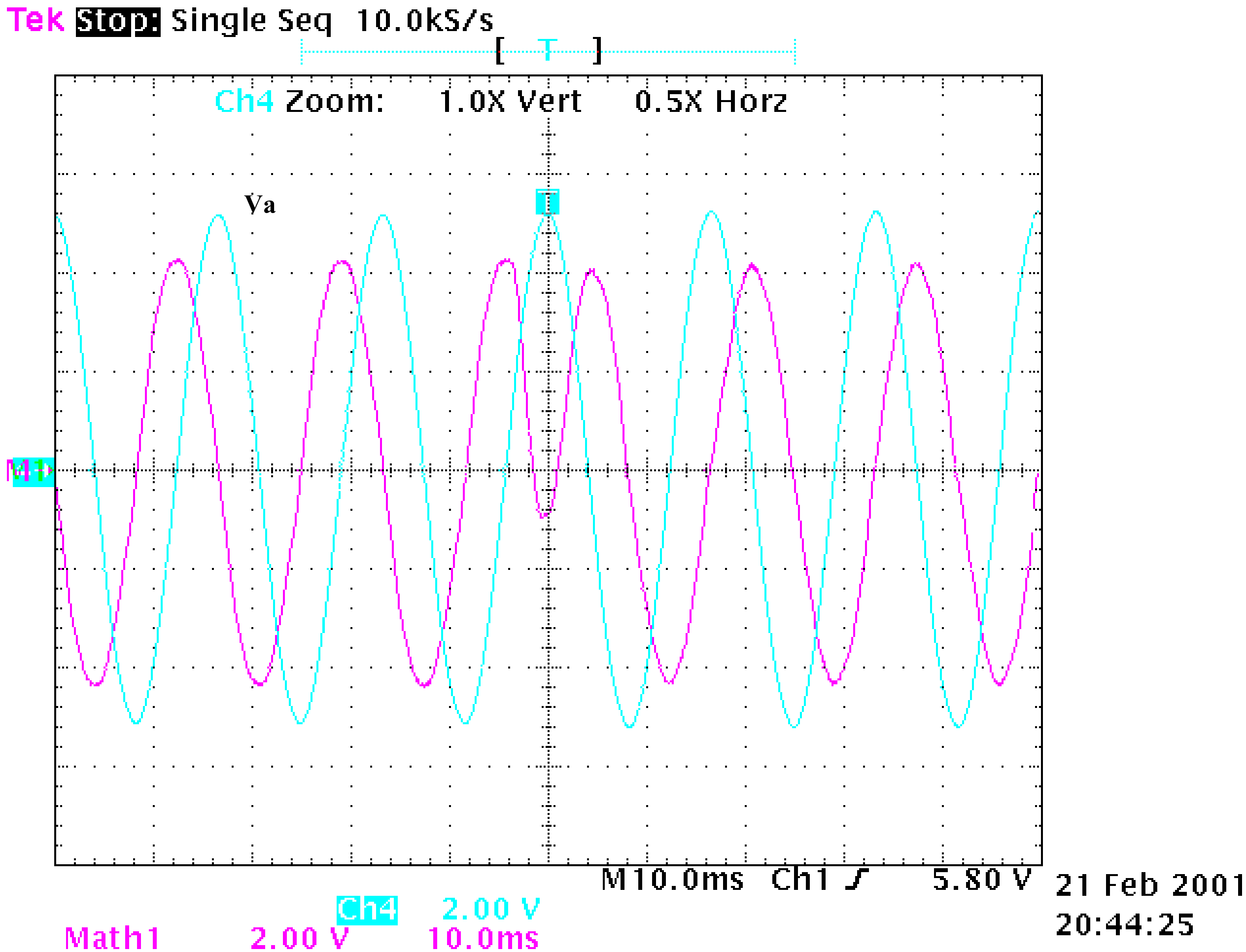
- **Estimated NYPA Project Cost: $41.2 M**
- **Industry Contribution: $13.0 M**
- **Construction Start Date: April 1999**
- **On-Line Testing - STATCOM: February 2001**
- **STATCOM NYISO Operation: April 2001**
- **Series On-Line Testing: September 2003**

CSC (STATCOM) On-Line Commissioning Tests

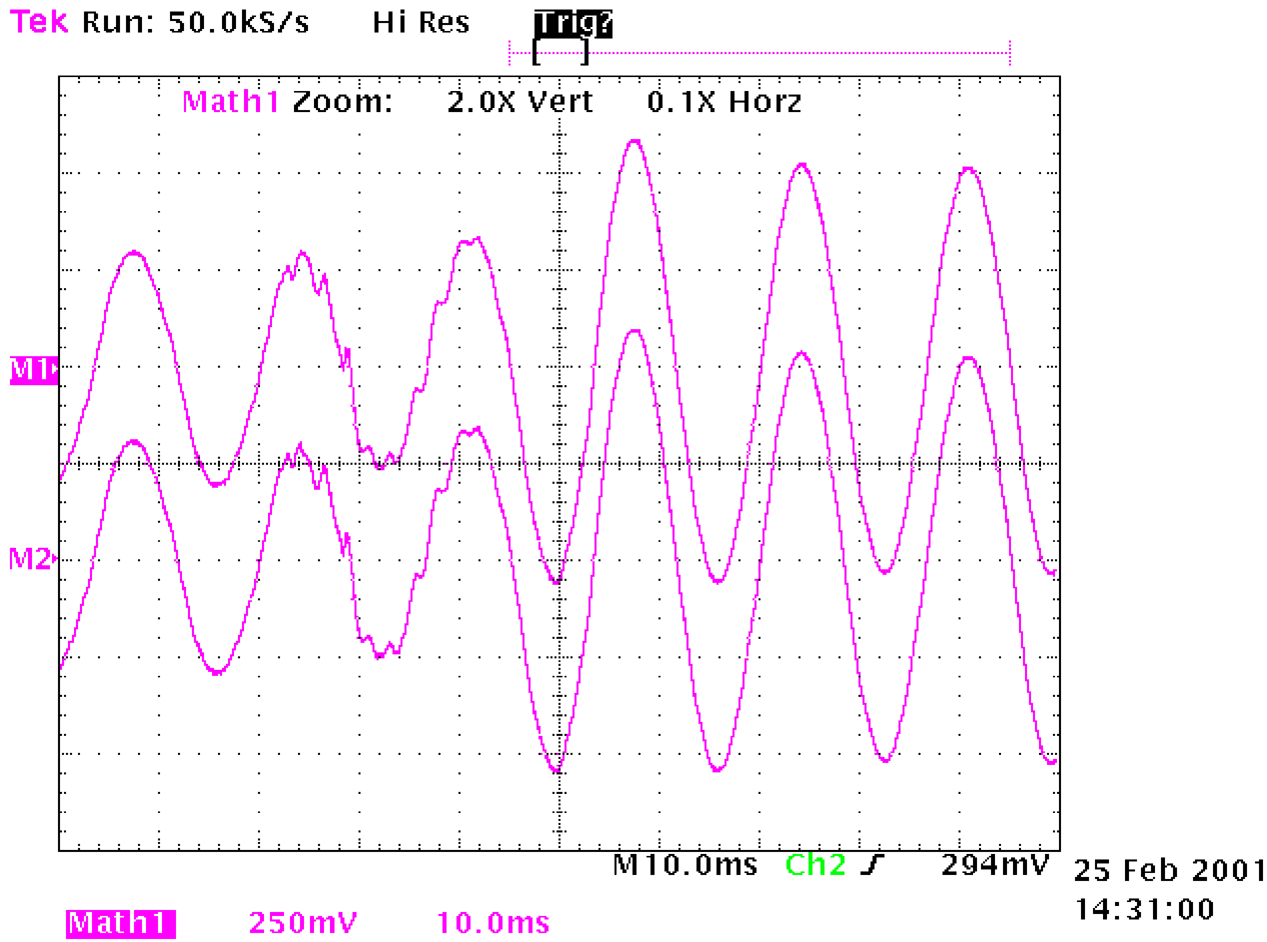
- Start up/Shut down
- MVAR (Current) control mode
- Voltage control mode
- Step response
- Capacitor/Reactor bank switching
- Droop verification
- VAR-Reserve function



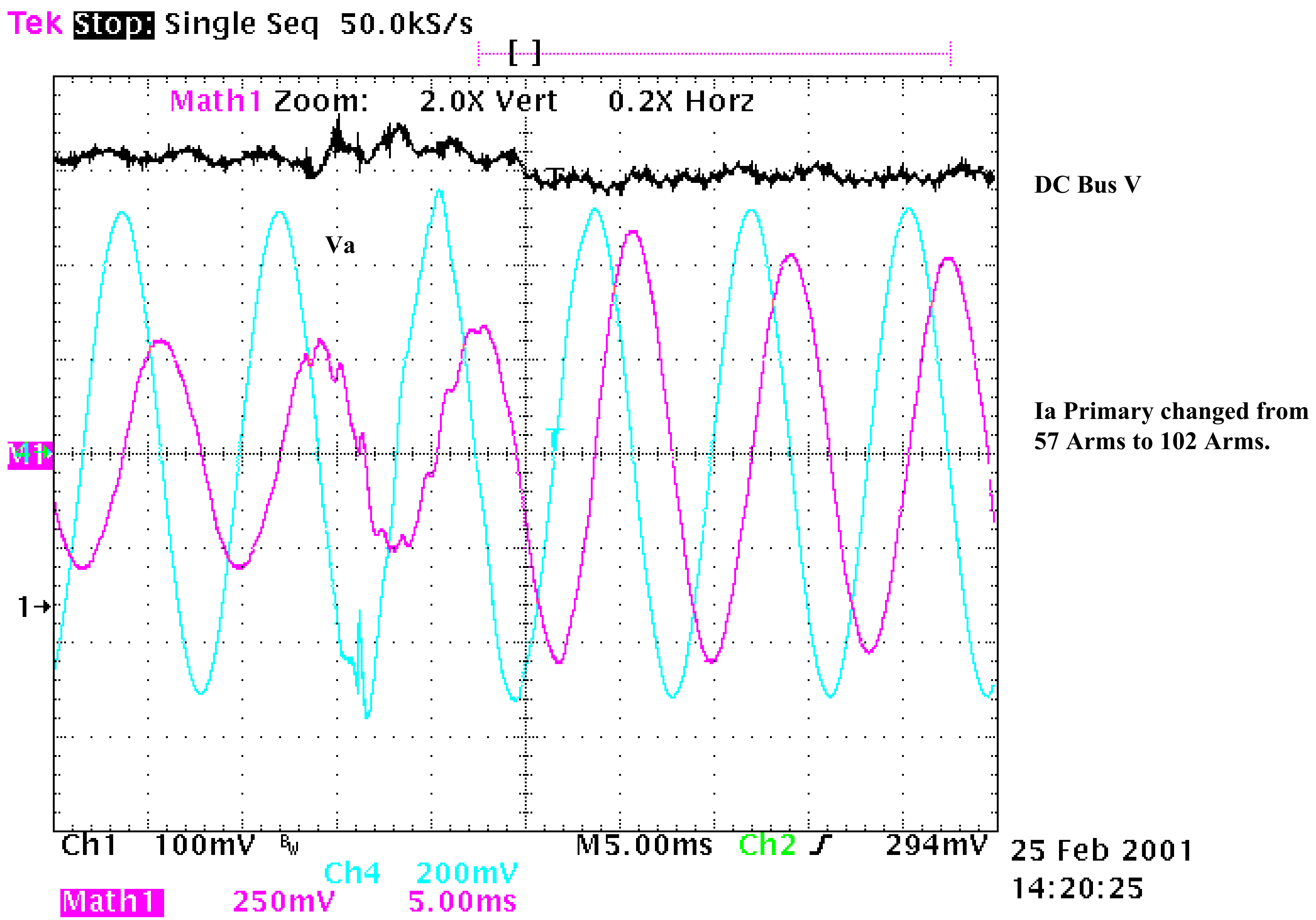
Inverter 1 (100 MVAR STATCOM) Current step response
+50 MVAR (inductive) to -50MVAR (capacitive)
(VAR control mode)



200 MVAR STATCOM in VAR Control Mode; Step Response +100MVAR (capacitive) to -100MVAR (inductive)

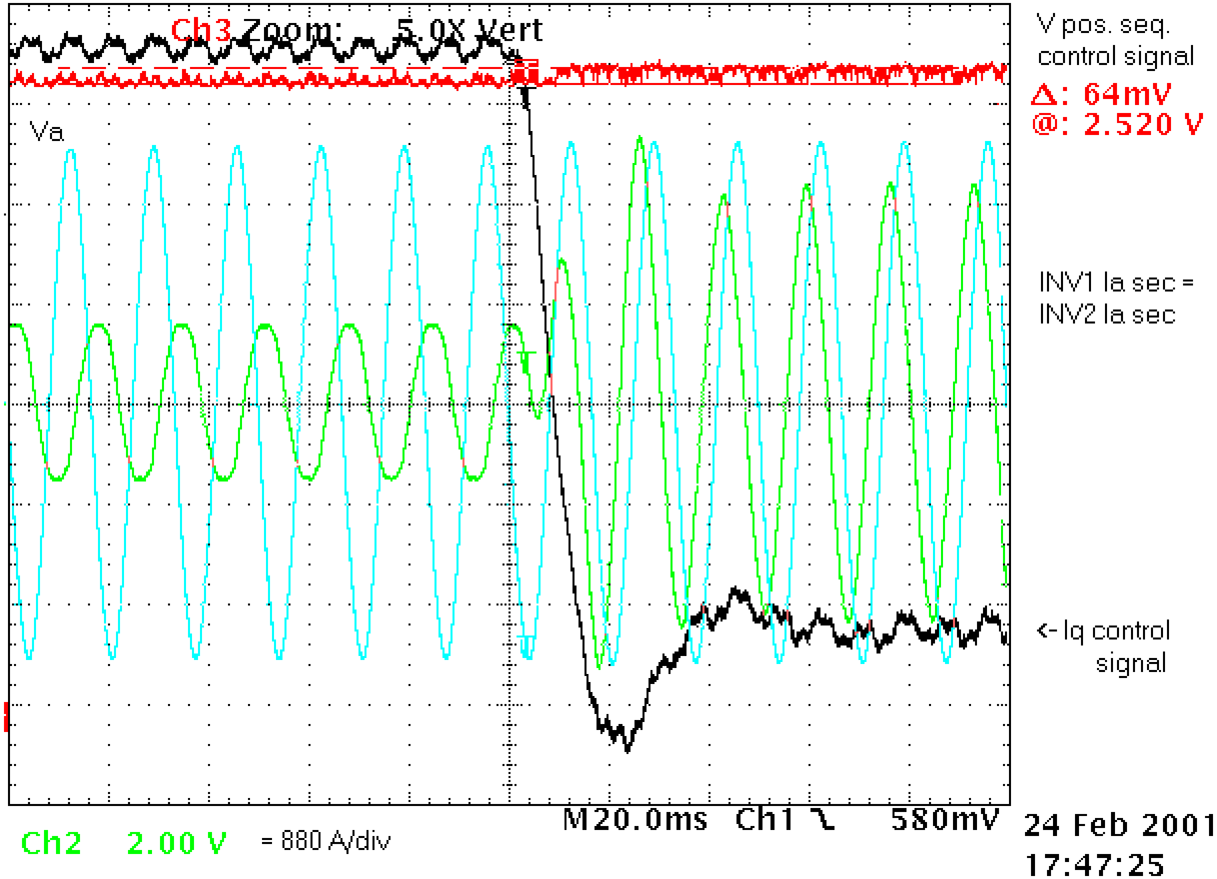


200 MVA STATCOM in Voltage Control Mode - Inverter 1 and 2 Primary Currents During 200 MVAR Capacitor Switching indicating Dynamic Sharing by the Inverters

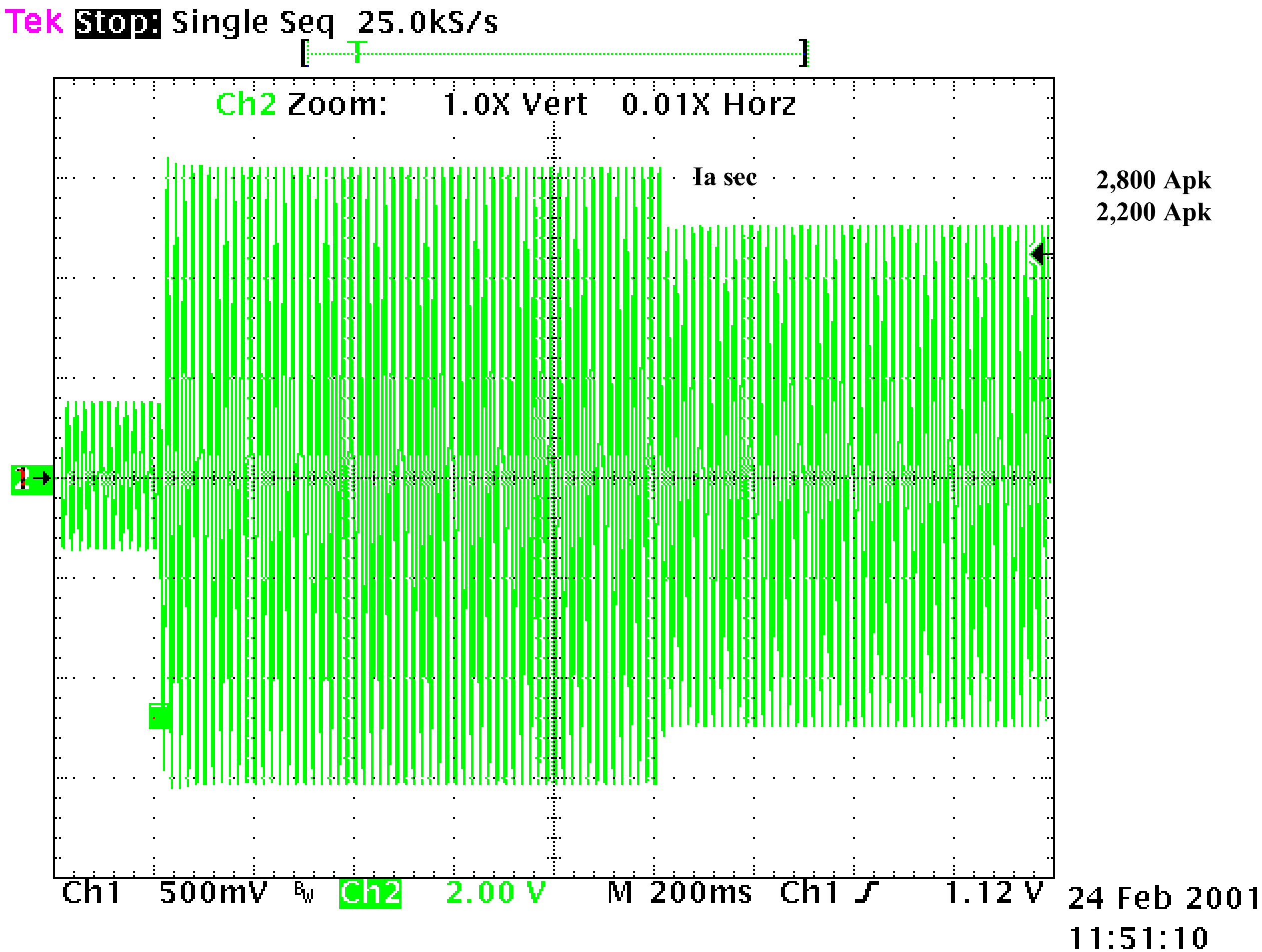


200 MVAR STATCOM Response to 200MVAR Capacitor Bank Switching IN

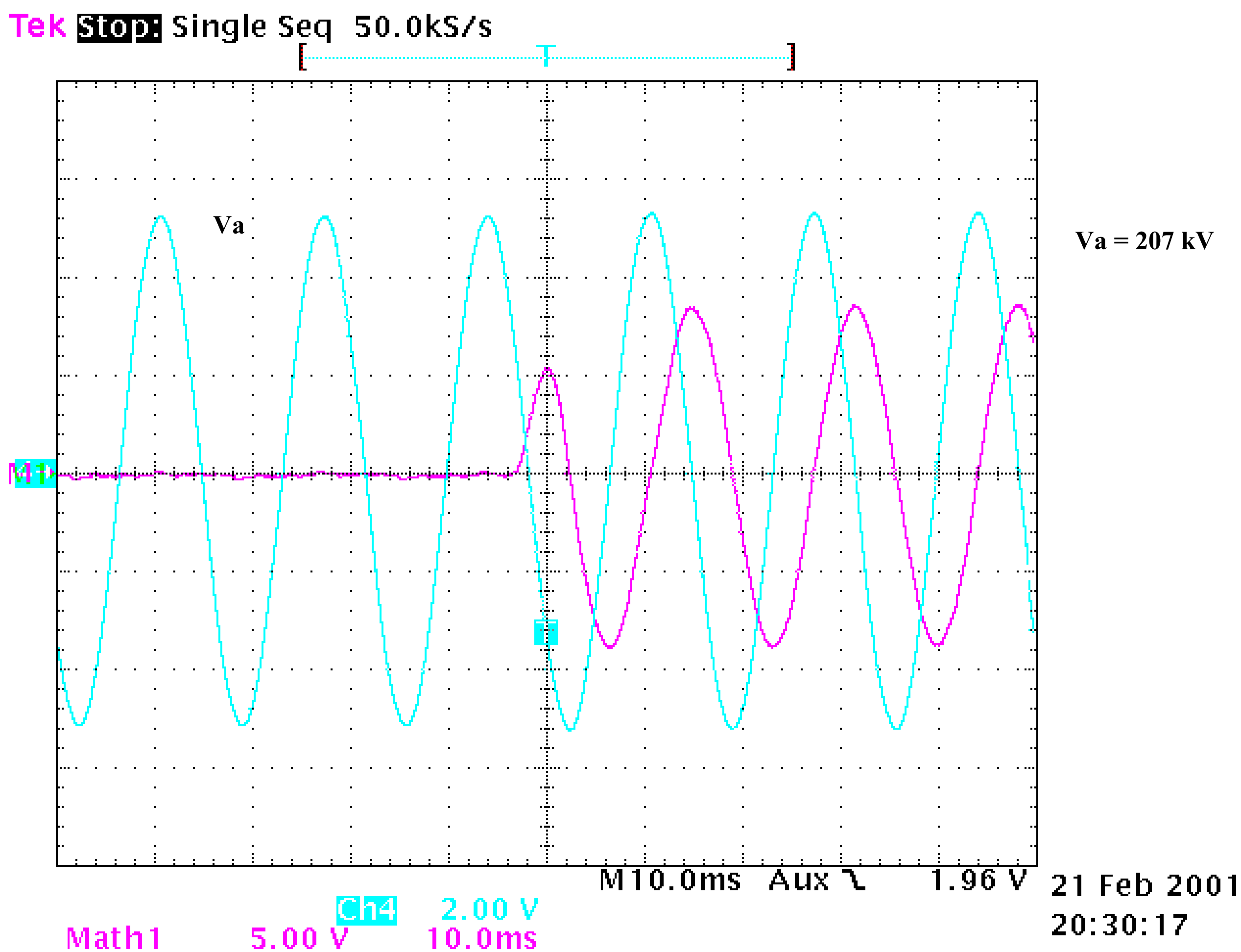
(Inverter output changed from 70 to 120MVAR inductive)



200 MVAR STATCOM Step Response; -70 MVAR to +180 MVAR (Voltage Control)
Voltage increase of 345*(.064/2.52)=8.7 kV (orange trace)
Inv. 1 and Inv. 2 currents are identical and overlap
Iq is quadrature component of the inverter(s) current



Inverter 2 (100 MVAR) Overload Response
Change from 25MVAR to 126MVAR (Inductive)



200 MVAR STATCOM Step Response 0 to -100MVAR (VAR Control) resulting in 2.5 kV bus voltage reduction

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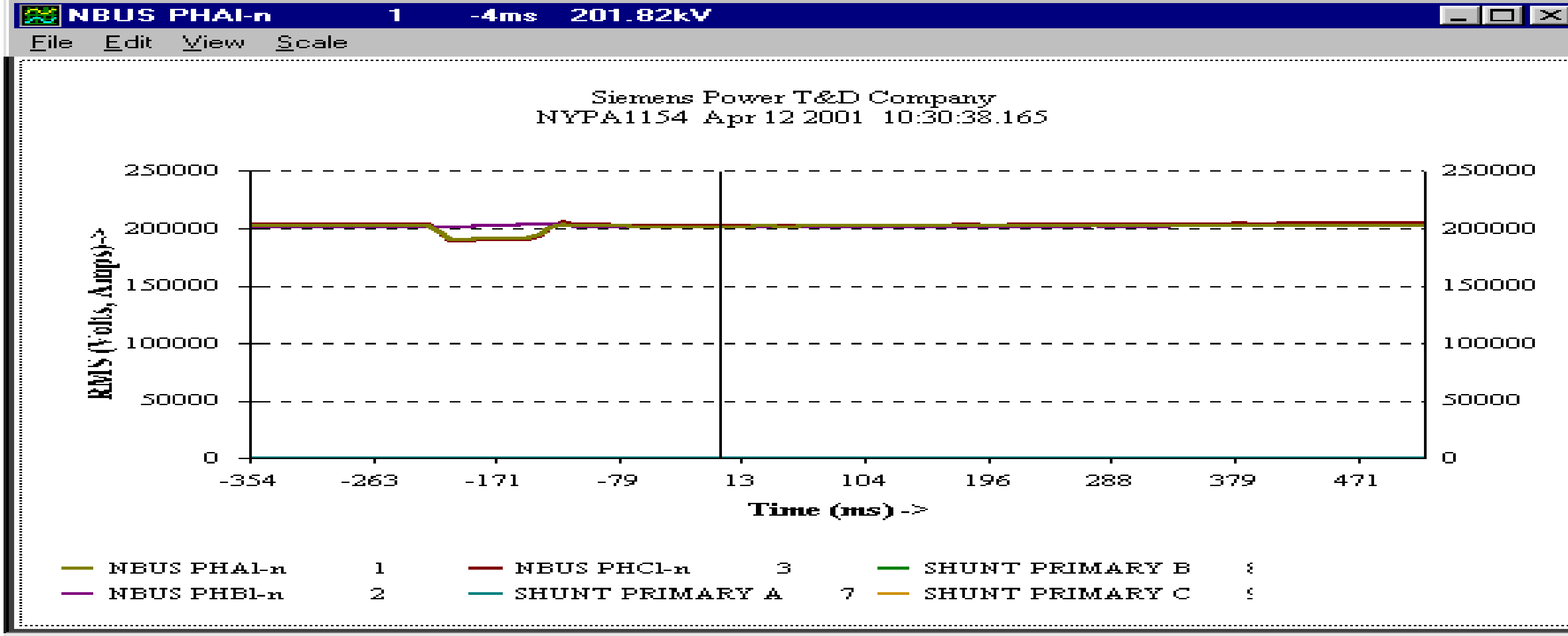
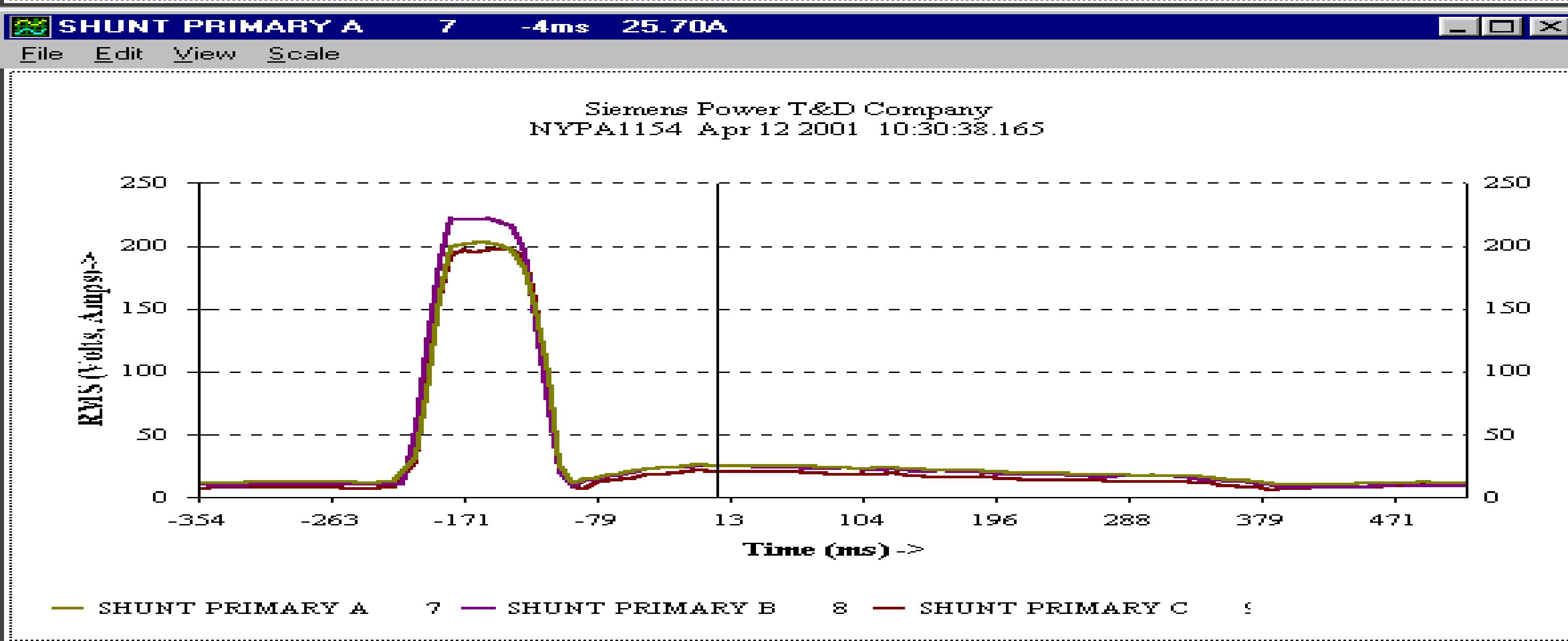
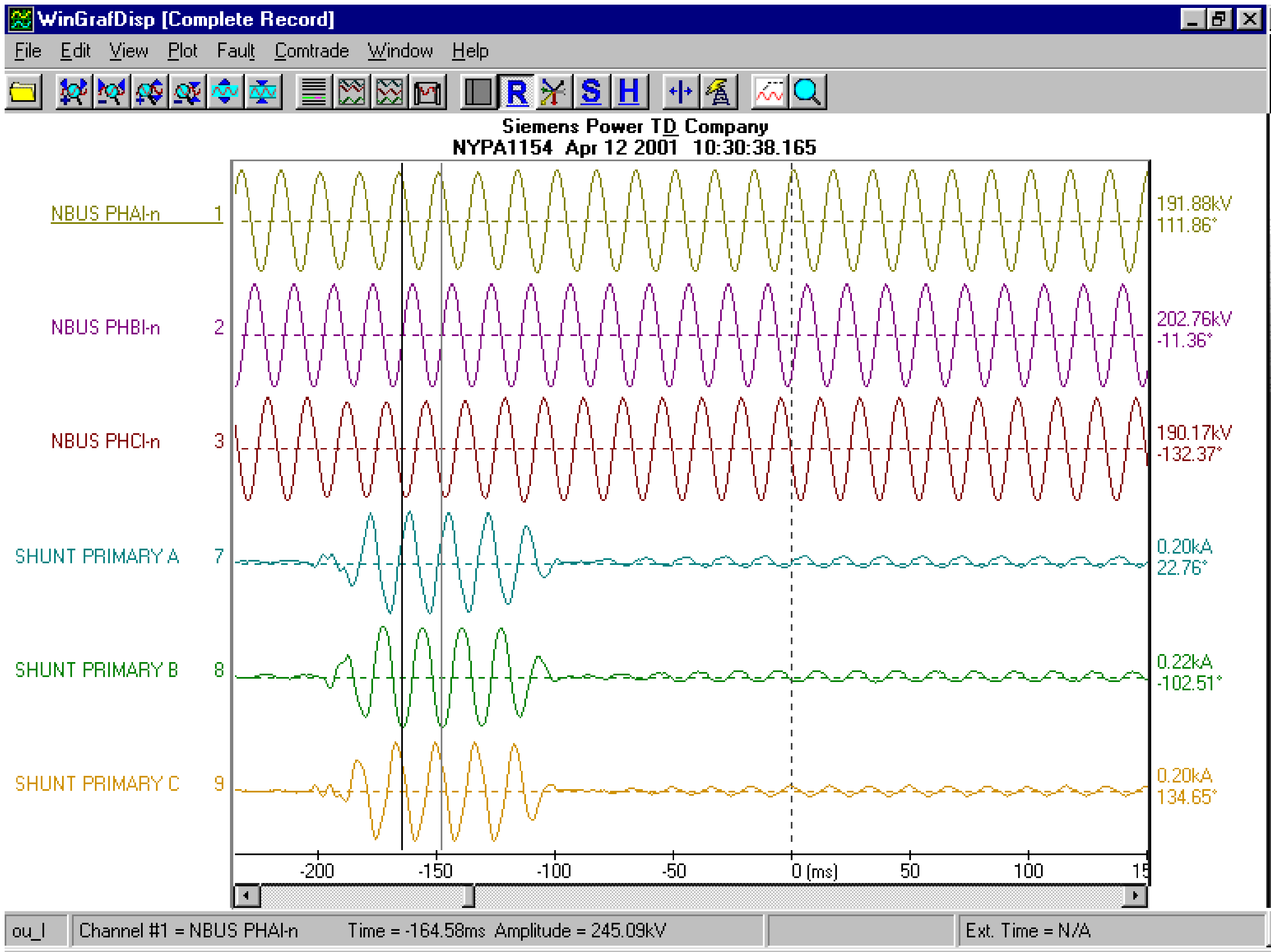

NBUS PHAI-n 1 -4ms 201.82kV
File Edit View Scale
Siemens Power T&D Company
NYPA1154 Apr 12 2001 10:30:38.165
RMS (Volts, Amps)->
250000
200000
150000
100000
50000
0
-354 -263 -171 -79 13 104 196 288 379 471
Time (ms) ->
NBUS PHAI-n 1
NBUS PHBI-n 2
NBUS PHCI-n 3
SHUNT PRIMARY A 7
SHUNT PRIMARY B
SHUNT PRIMARY C


SHUNT PRIMARY A 7 -4ms 25.70A
File Edit View Scale
Siemens Power T&D Company
NYPA1154 Apr 12 2001 10:30:38.165
RMS (Volts, Amps)->
250
200
150
100
50
0
-354 -263 -171 -79 13 104 196 288 379 471
Time (ms) ->
SHUNT PRIMARY A 7
SHUNT PRIMARY B 8
SHUNT PRIMARY C



WinGrafDisp [Complete Record]
File Edit View Plot Fault Comtrade Window Help
Siemens Power TD Company
NYPA1154 Apr 12 2001 10:30:38.165
NBUS PHAl-n 1
NBUS PHBl-n 2
NBUS PHCl-n 3
SHUNT PRIMARY A 7
SHUNT PRIMARY B 8
SHUNT PRIMARY C 9
191.88kV
111.86°
202.76kV
-11.36°
190.17kV
-132.37°
0.20kA
22.76°
0.22kA
-102.51°
0.20kA
134.65°
-200 -150 -100 -50 0 (ms) 50 100
ou_l
Channel #1 = NBUS PHAl-n Time = -164.58ms Amplitude = 245.09kV
Ext. Time = N/A

NYS Transmission System Benefits Realized from STATCOM

- **Increased Transfer Capability Across Critical Central-East Interface by 60MW**
- **Increased Overall New York State West-to-East Power Transfers by 114 MW**
- **Both Voltage and Stability Limits Raised**

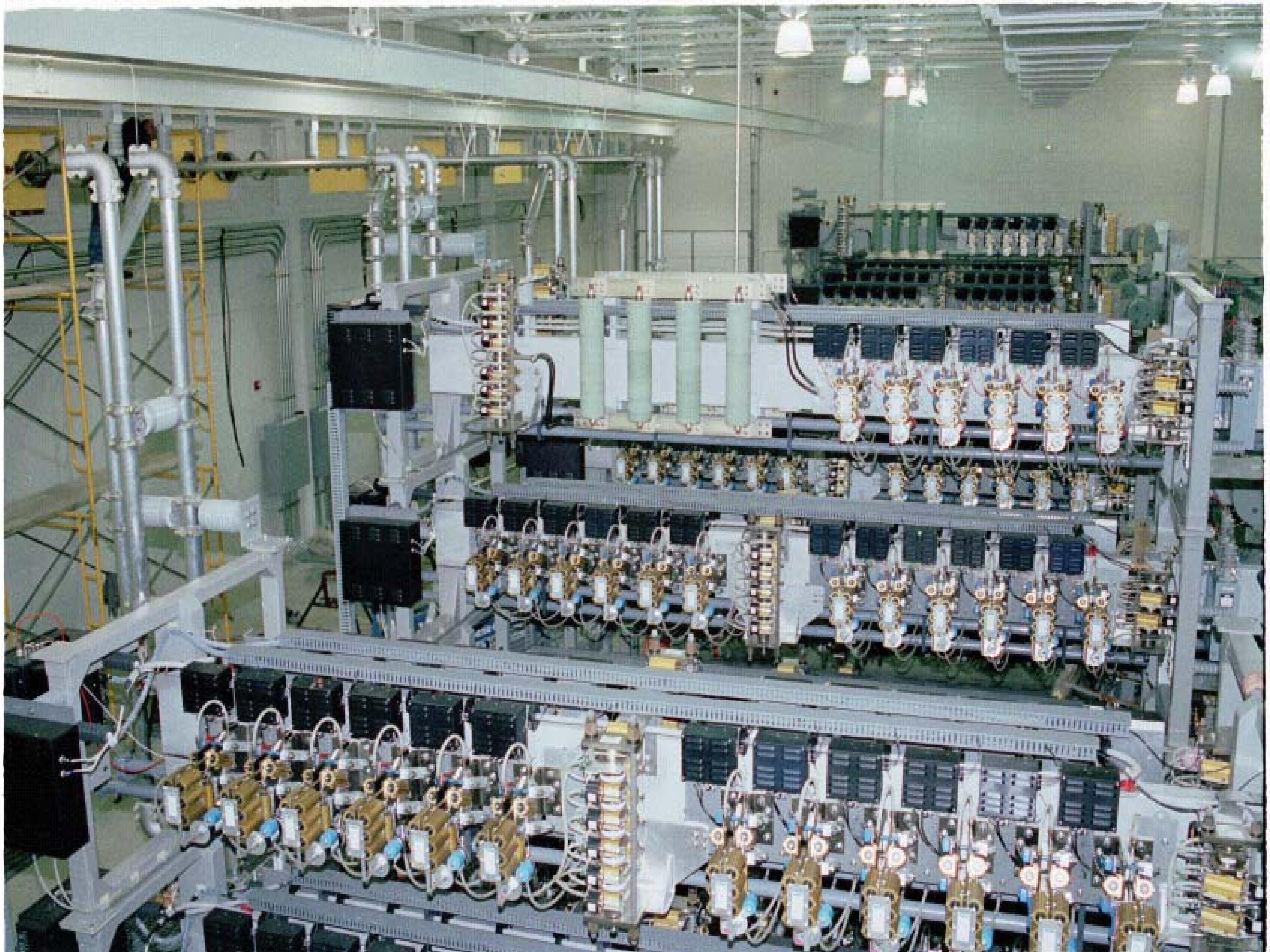
Operating Experience to-Date

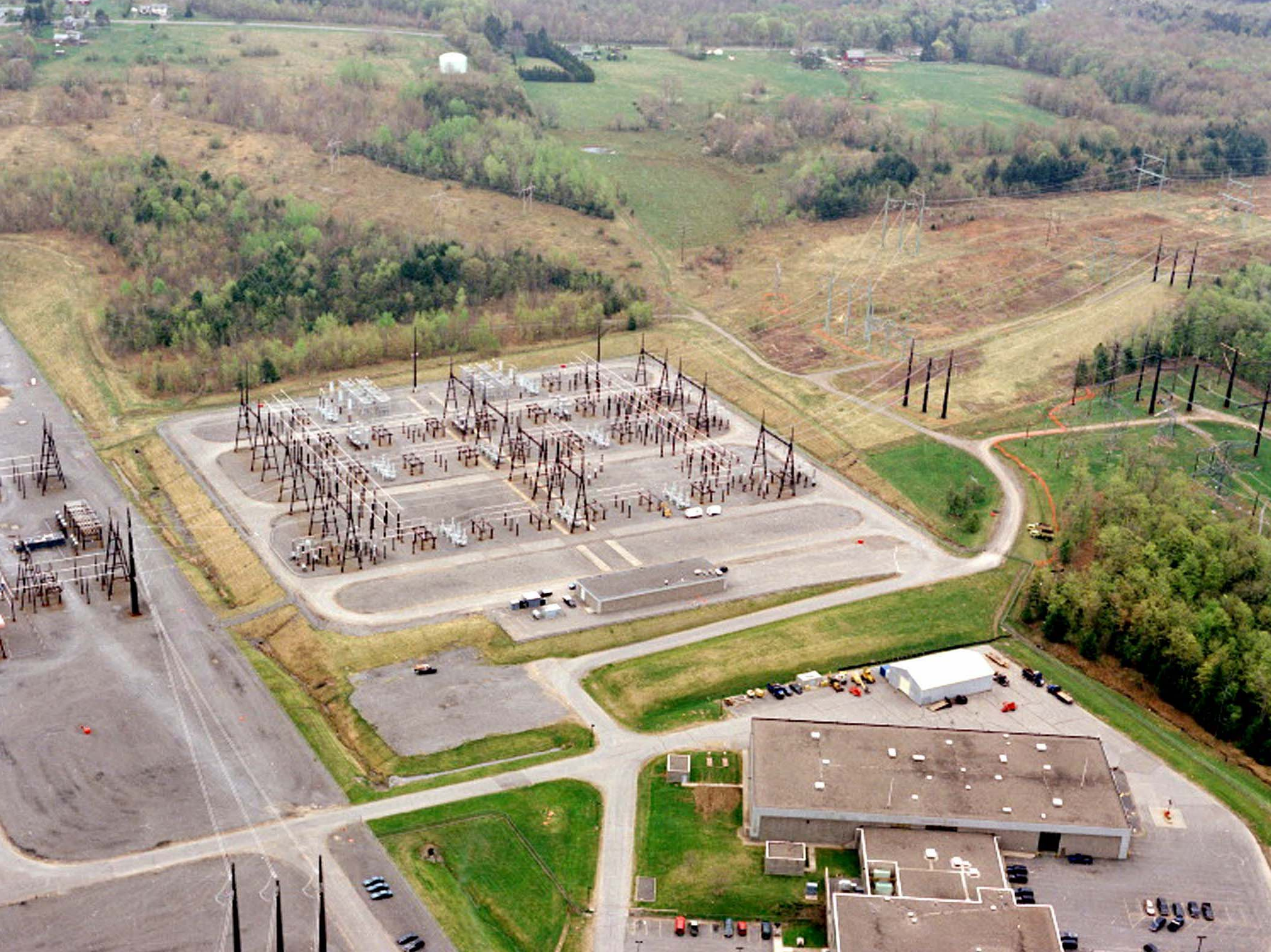
- **Primary Configuration: STATCOM 200**
- **Has Allowed System Operators to "Fine-Tune" local 345kV Voltage Lessening the Need for Switching Larger Shunt Devices (200 MVAR Cap and Reactor Banks)**
- **Operated in Inductive Mode to help Lower Voltages During Extreme Light Load Periods**

MARCY CONVERTIBLE STATIC COMPENSATOR

Industry Participation

- Allegheny Power System
- Alliant
- American Electric Power
- Baltimore Gas and Electric
- BC Hydro (Canada)
- Bonneville Power Administration
- Boston Edison
- California ISO
- Central Hudson Gas and Electric
- Central and Southwest
- Consolidated Edison
- Duke Energy
- First Energy Corp.
- Georgia Transmission Corp.
- Genesis (New Zealand)
- GPU Energy Corp.
- Great River Energy
- Illinois Power
- Montana Power
- National Grid USA (NEES)
- Nebraska Public Power District
- New England ISO
- Northern Indiana Public Service
- Ontario Hydro (Canada)
- Pennsylvania Power & Light
- Public Service Electric & Gas
- Salt River Project
- Southern California Edison
- Tennessee Valley Authority
- Tri-State G&T Association
- United Illuminating



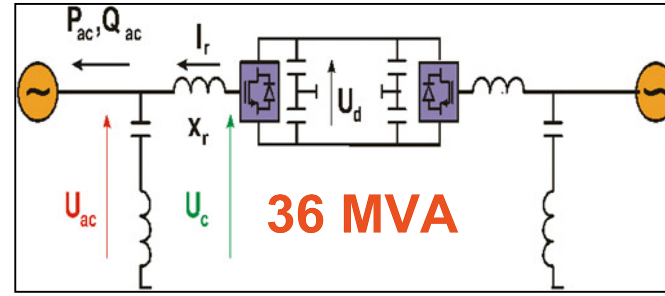


Eagle Pass/Piedras Negras Tie

- Back-to-Back (BTB) FACTS/Light concept
- Replaces mechanical tie
- Enables uninterrupted power exchange between Mexico and U.S.
- Will improve stability of both systems

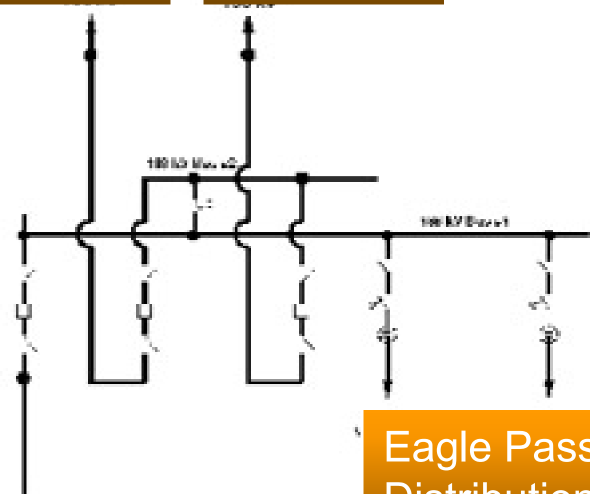
Eagle Pass/Piedras Negras Tie

AEP CFE EPRI ABB



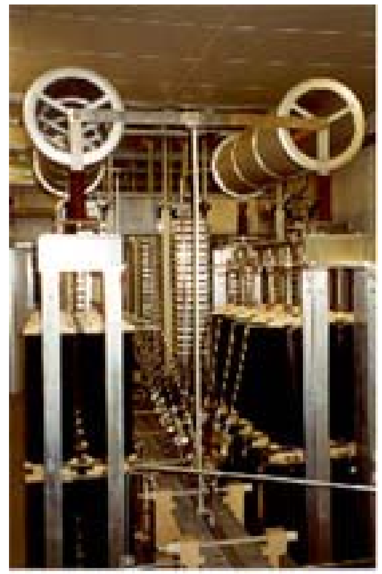
Hamilton Road

Asherton 138 kV

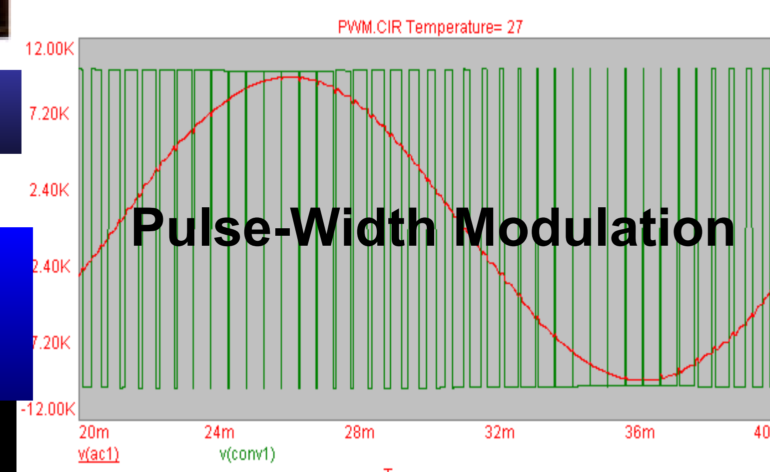


To Mexico

Eagle Pass Distribution Network

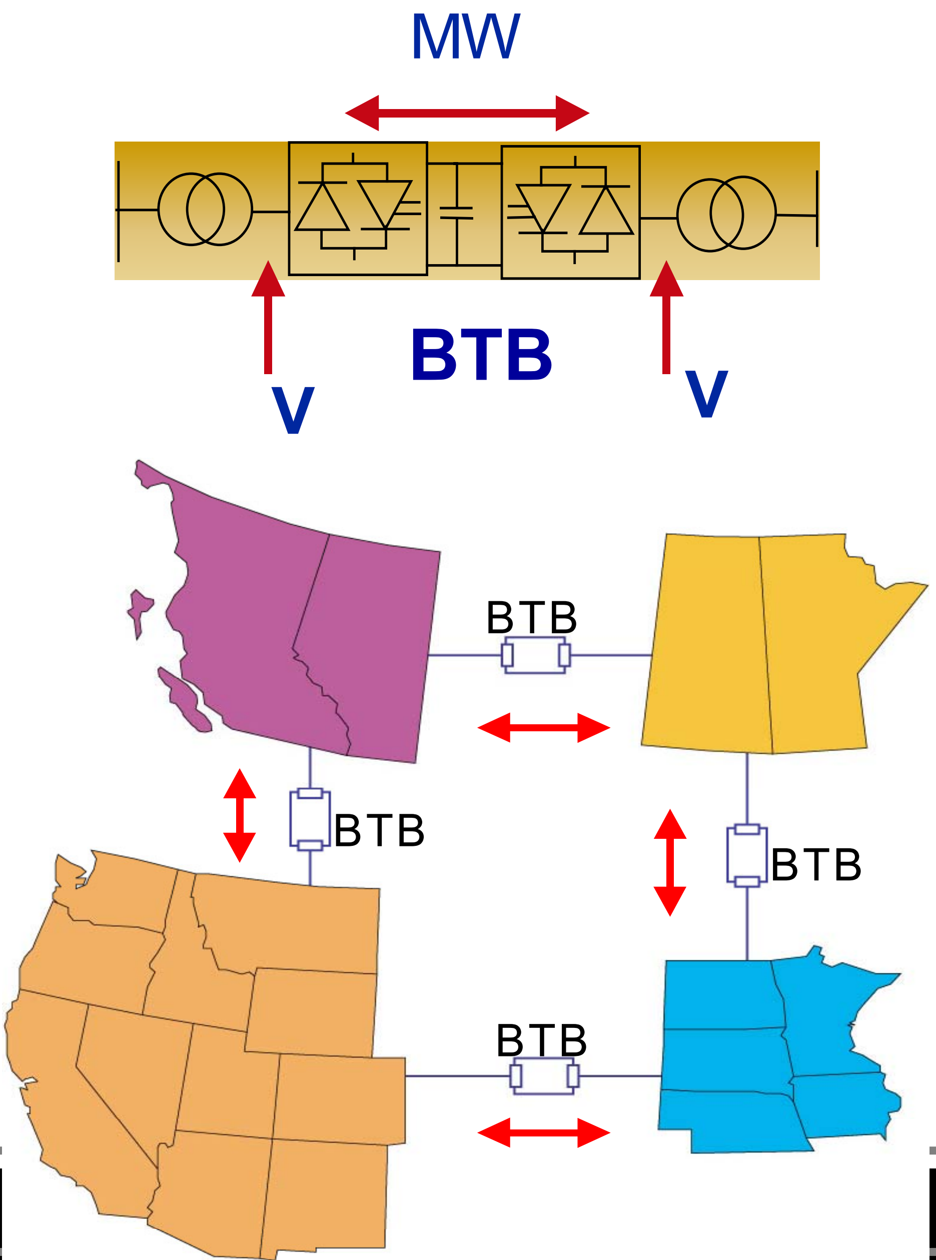


IGBTs Valve



- **Improves Reliability and Quality of Power Delivery**

Wide Use of VSC-based BTB



FACTS systems are revolutionizing the way electric power is transmitted

EXAMPLES:

Transmission line in the Southwestern US:

- **Boost power flow from 300 MW to 400 MW (+33%)**

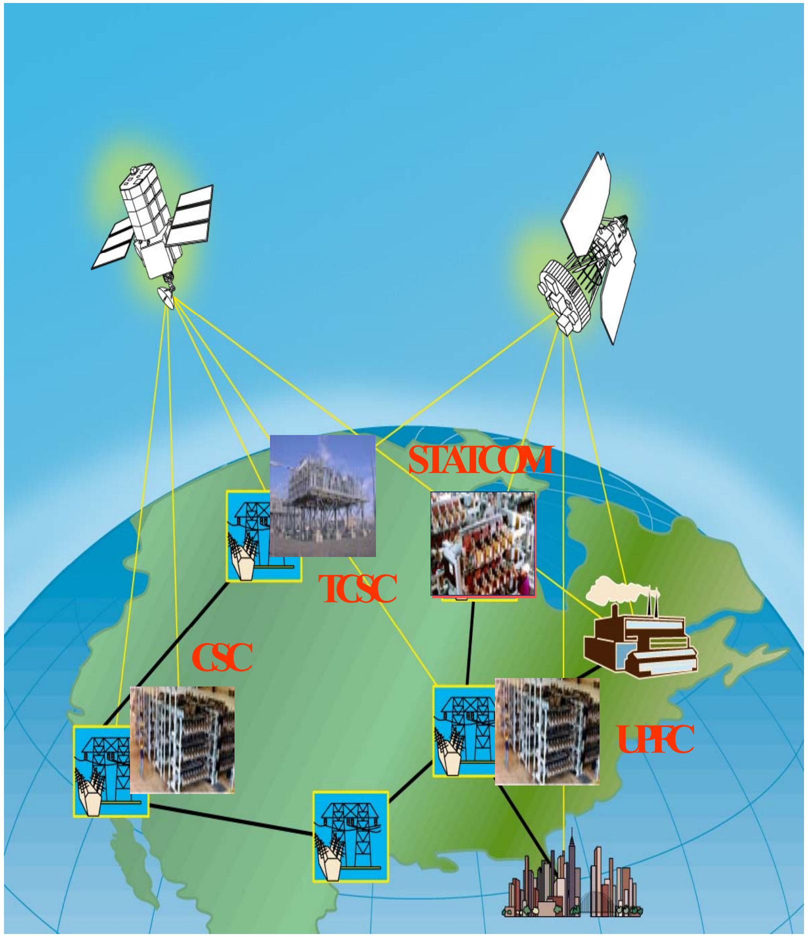
Ties between Southern US and Florida:

- **Boost power flow from 3400 MW to 4100 MW (+21%)**

Ties between upstate New York to New York City:

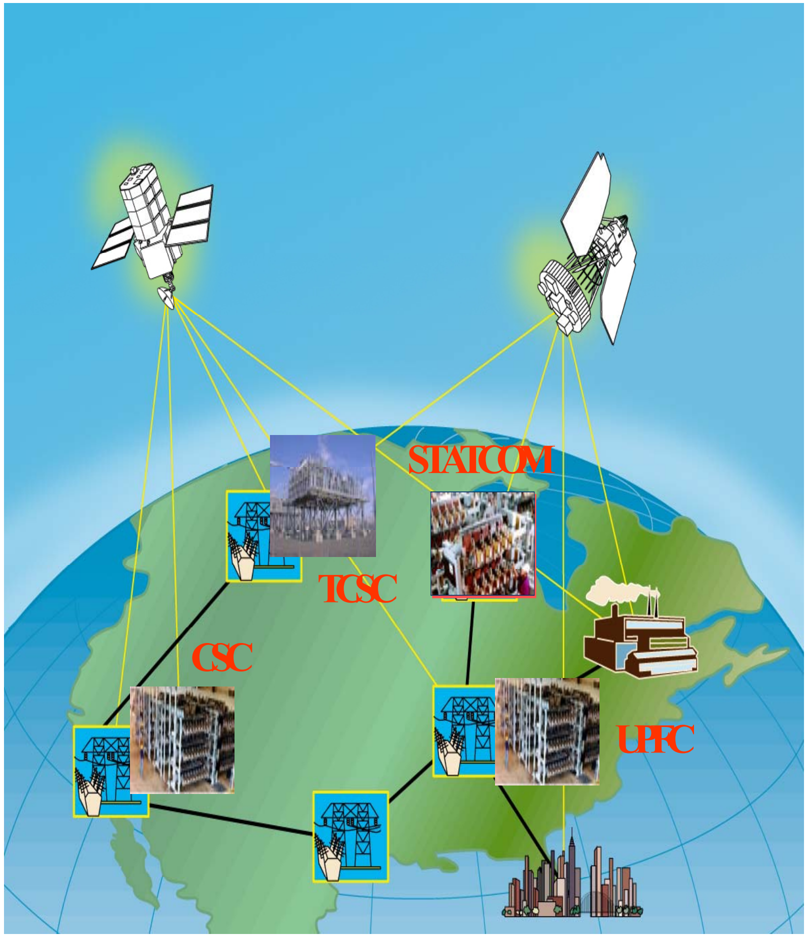
- **Boost power flow from 2600 MW to 3200 MW (+23%)**

Hierarchical Control of FACTS Controllers



- Issues
- FACTS Controllers
- Directions
- Deliverables

Conceptualization of Hierarchical Control



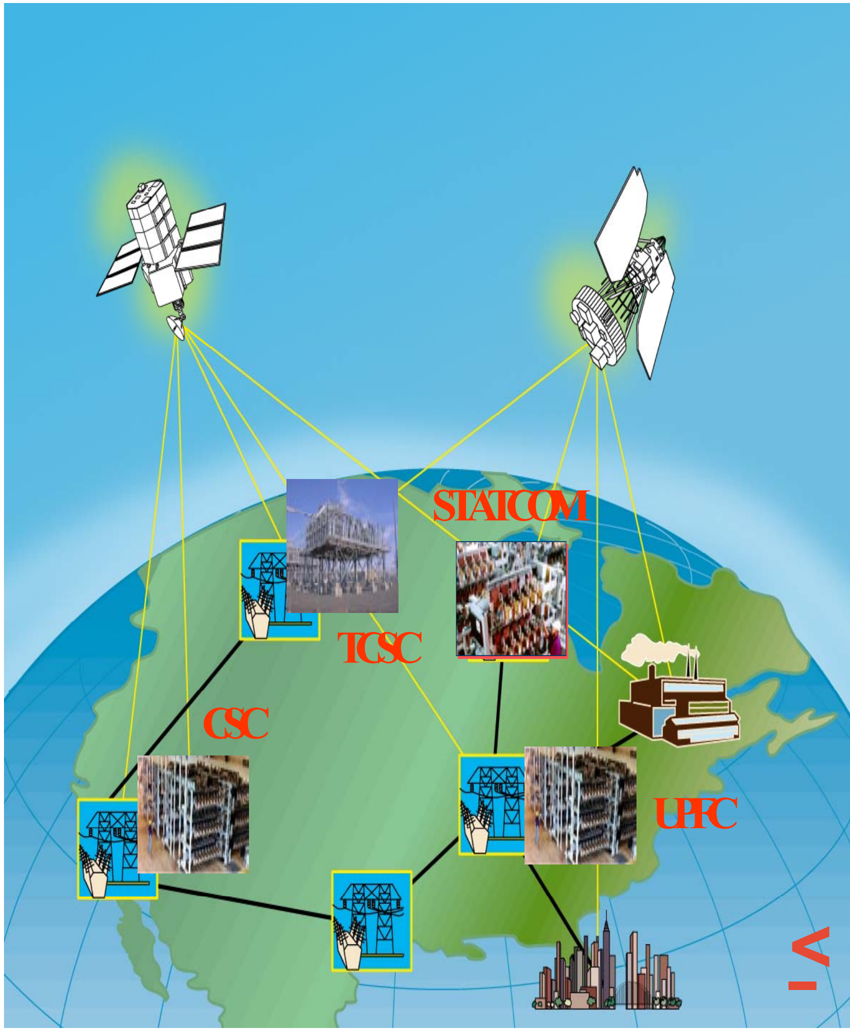
- Identification of a "Benchmark" Network
- Conceptualization of the Control
- Software Algorithm Design "Master Control Algorithm"
- Technical Progress Report

Hierarchical Control of Multiple FACTS Controllers

- Optimal power flow for congestion management

- Dispatch Available Transfer Capabilities (ATCs) between areas in an interconnected system

- Expands Total Transfer Capability (TTC) and ATC



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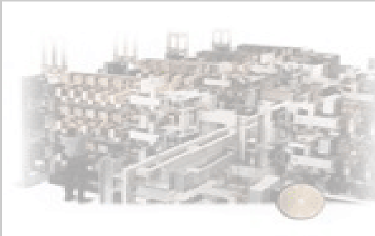

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- AEP BTB

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- Previous Meetings
- Upcoming Meetings
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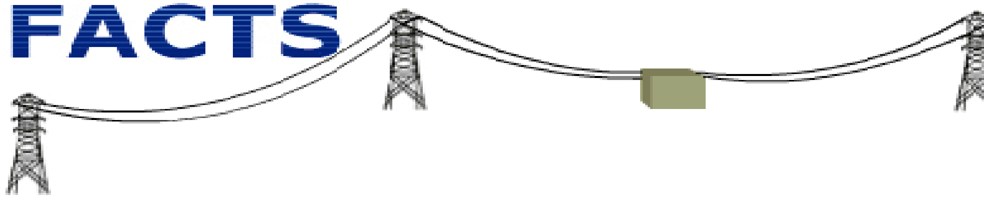
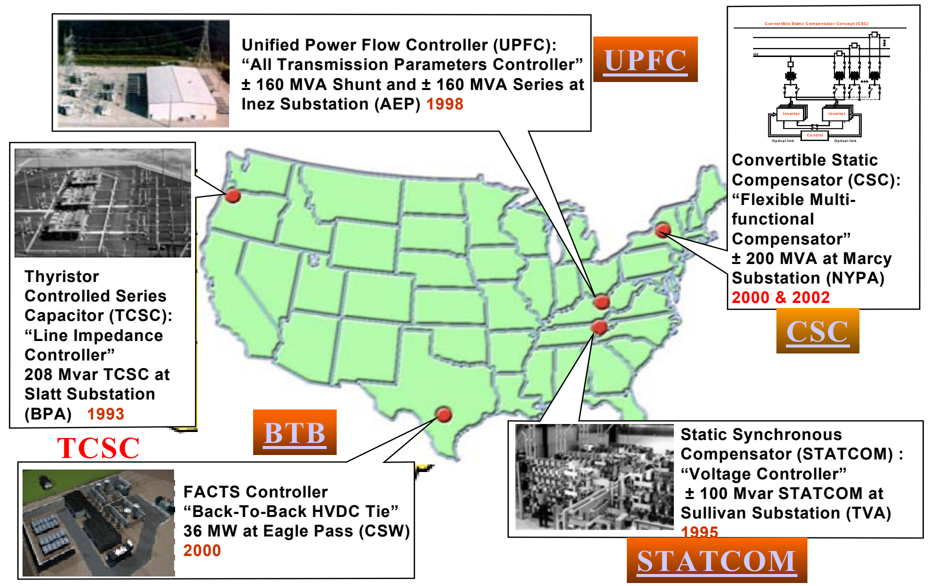
FACTS





News & Updates

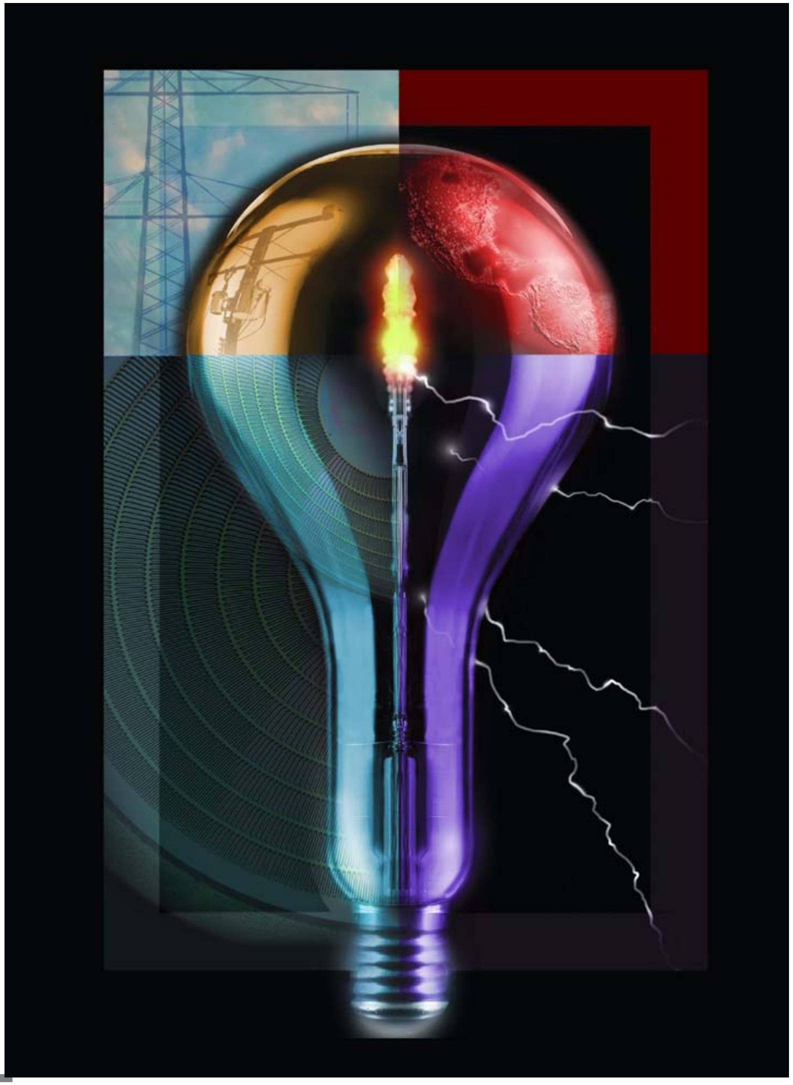
This section is currently unavailable. Please check back at a later date. Thank you.

FACTS and EPRI

EPRI pioneered the development and deployment of these technologies

EPRI and EPRI's partners have been the first to make these technologies commercially available

EPRI continuously pushes the leading edge of these and other technologies, the energy industry's needs, both today and tomorrow



Summarizing ...

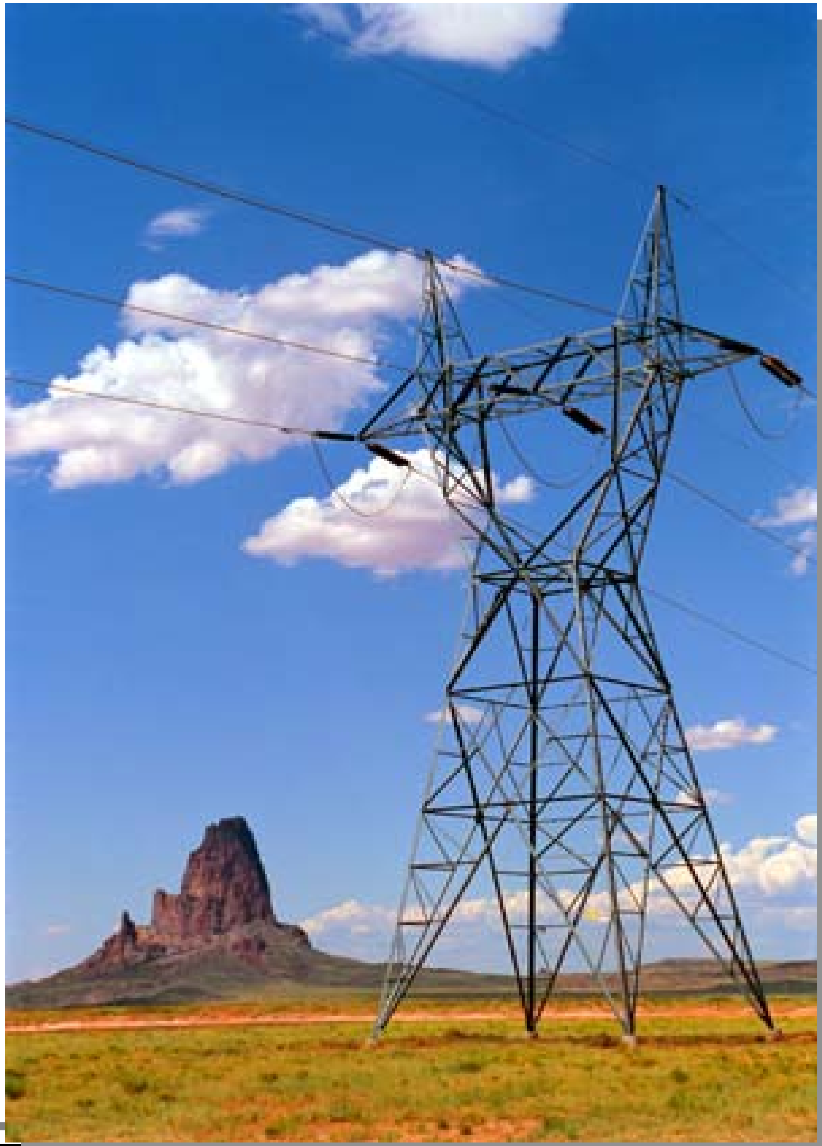
Changes in the rules and changes in the players

New demands on the transmission system

Need new services

Need new software

Need new technologies



THANKS FOR YOUR ATTENTION

FACTS is the solution