Advancing the Application of Power Electronics to the Electric Power Infrastructure

Symposium Honoring Dr. Narain G. Hingorani
Franklin Institute
April 27, 2006

HVdc, FACTS and Custom Power

By

Stig Nilsson

Exponent

Alphabet Soup

- HVDC - High voltage direct current
- FACTS – Flexible AC transmission system
- Custom Power – mini-FACTS for distribution and industrial applications

Dr. Narain Hingorani

- **Adamson, C.and Hingorani, Narain, (1960) *High Voltage Direct Current Power Transmission*, Garraway, London.**
- **When I Started for ASEA in the HVdc Department in 1962, Dr. Hingorani was at UMIST (University of Manchester), Professor Adamson's and Dr. Hingorani's book the first treatise on HVdc Transmission**
  - **The "Who is Who" in HVdc has many members with roots at UMIST**
- **I met Dr. Hingorani in 1969 as a member of the ASEA-GE HVdc Joint Venture for building the Pacific HVdc Intertie system**
- **Worked for Dr. Hingorani for almost 20 years at EPRI**

Topics

- HVdc
- FACTS
- Custom Power

AC v. DC

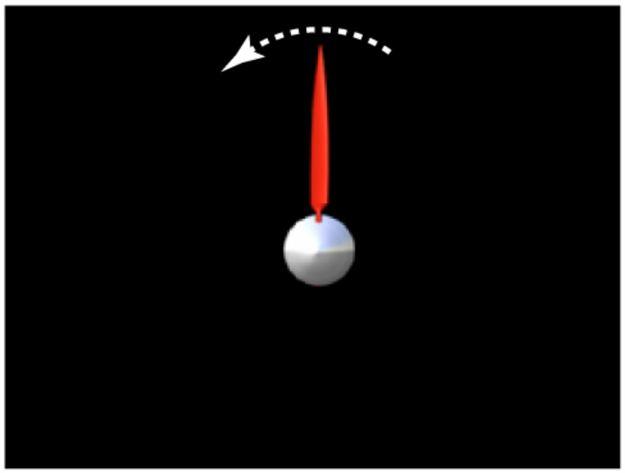
- Edison v. Westinghouse & Tesla
- AC won because AC can be transmitted with lower losses at high voltages
- DC is difficult to transform from a low voltage to a high voltage and back
  - In fact, it is not possible to do electrically
  - The coupling between ac and dc systems still uses transformers

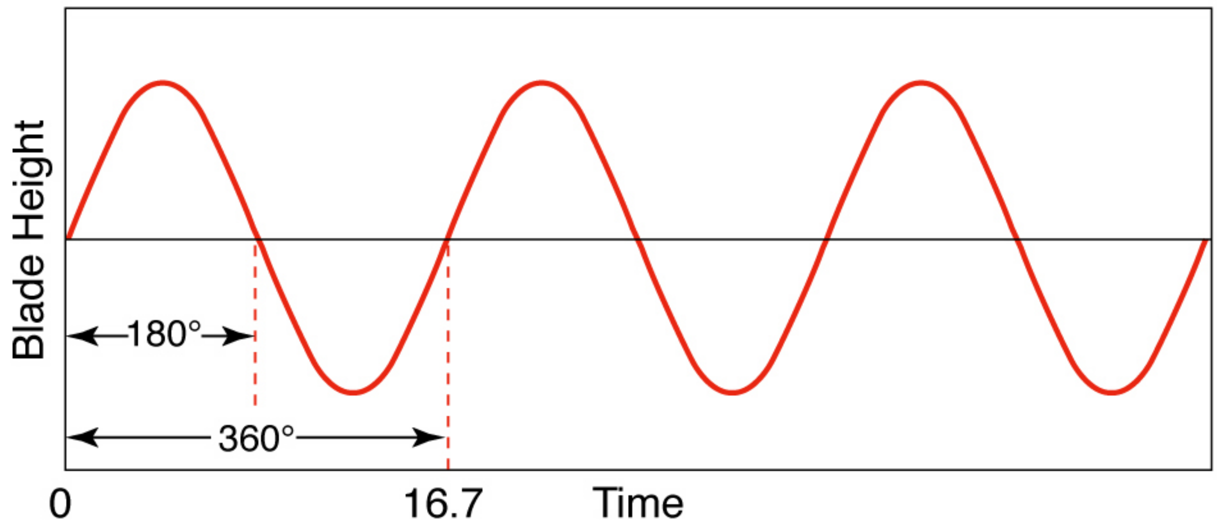
What is AC?

Single Phase

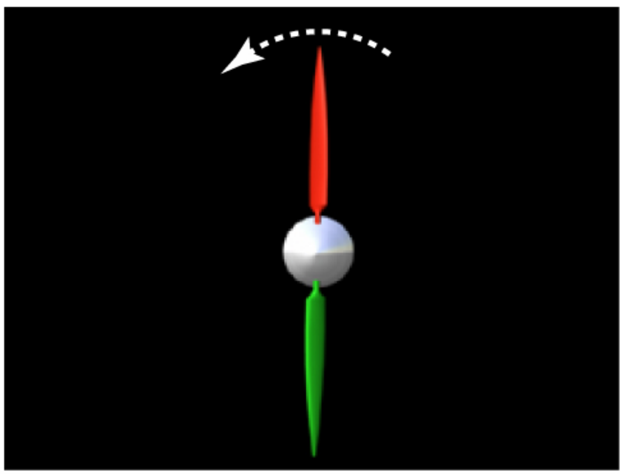
60 Hz = 60 cycles/sec

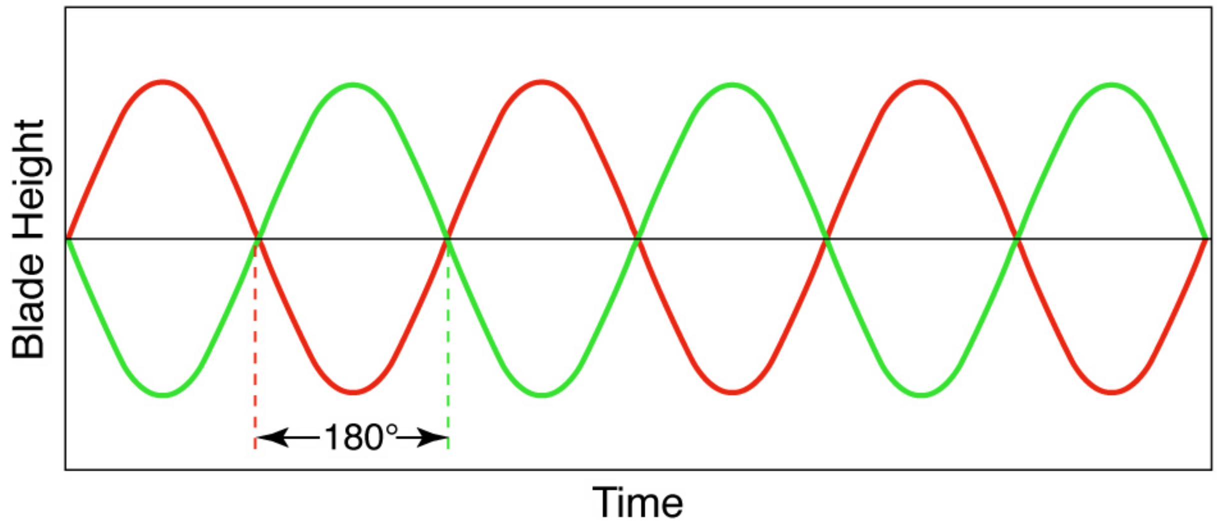
1/60 sec/cycle = 16.7/1000 sec = 360° (electrical degrees)



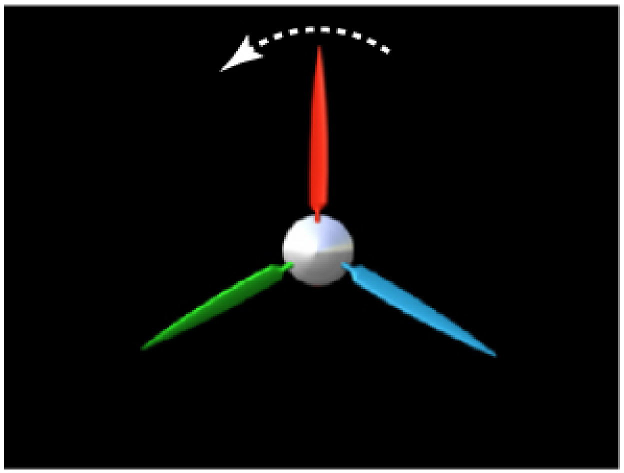


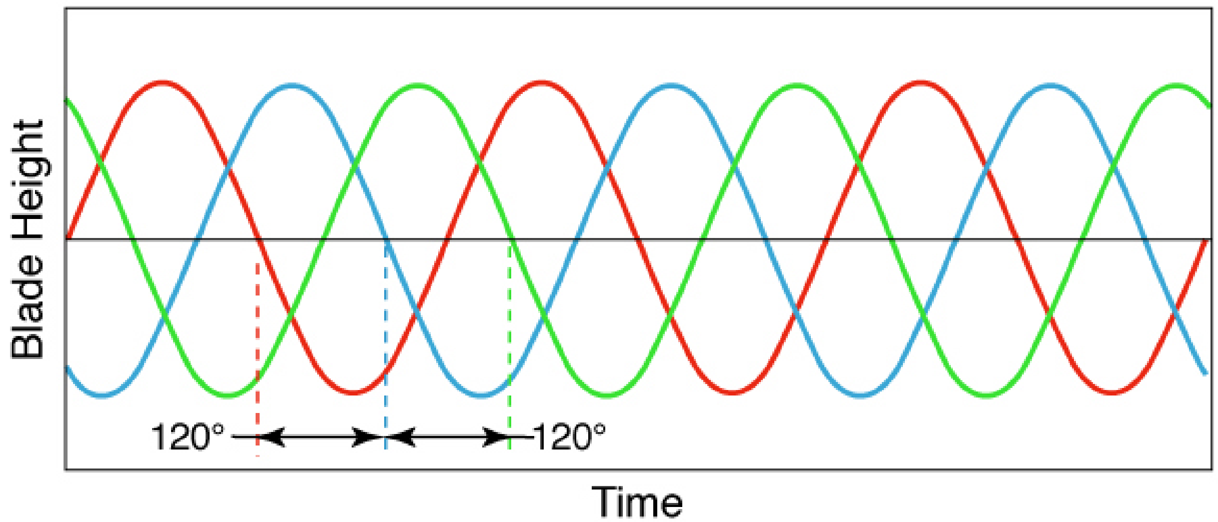
Two Phase
Blades are 180° Apart



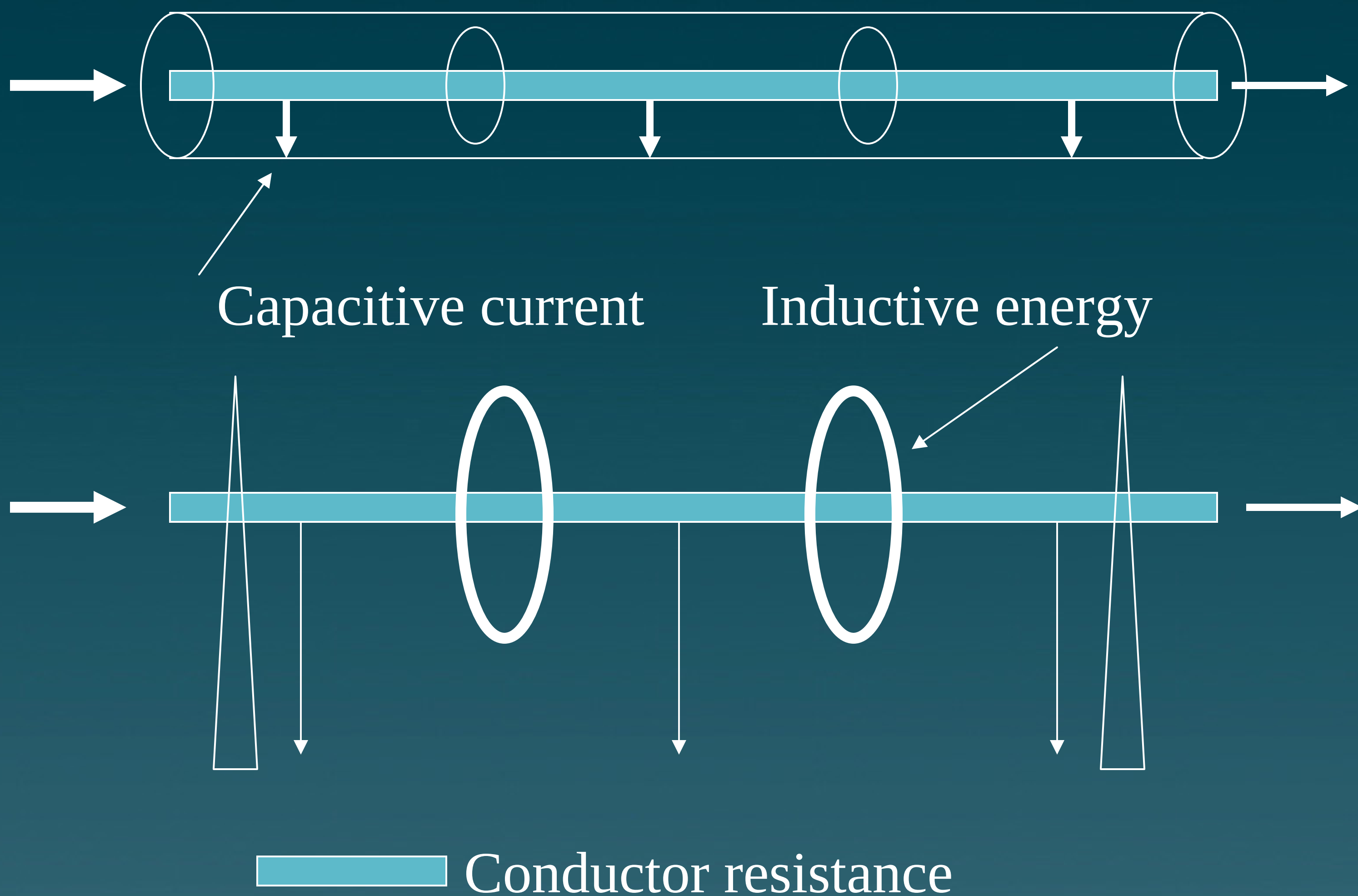


Three Phase
Blades are 120° Apart





Cables v. Lines



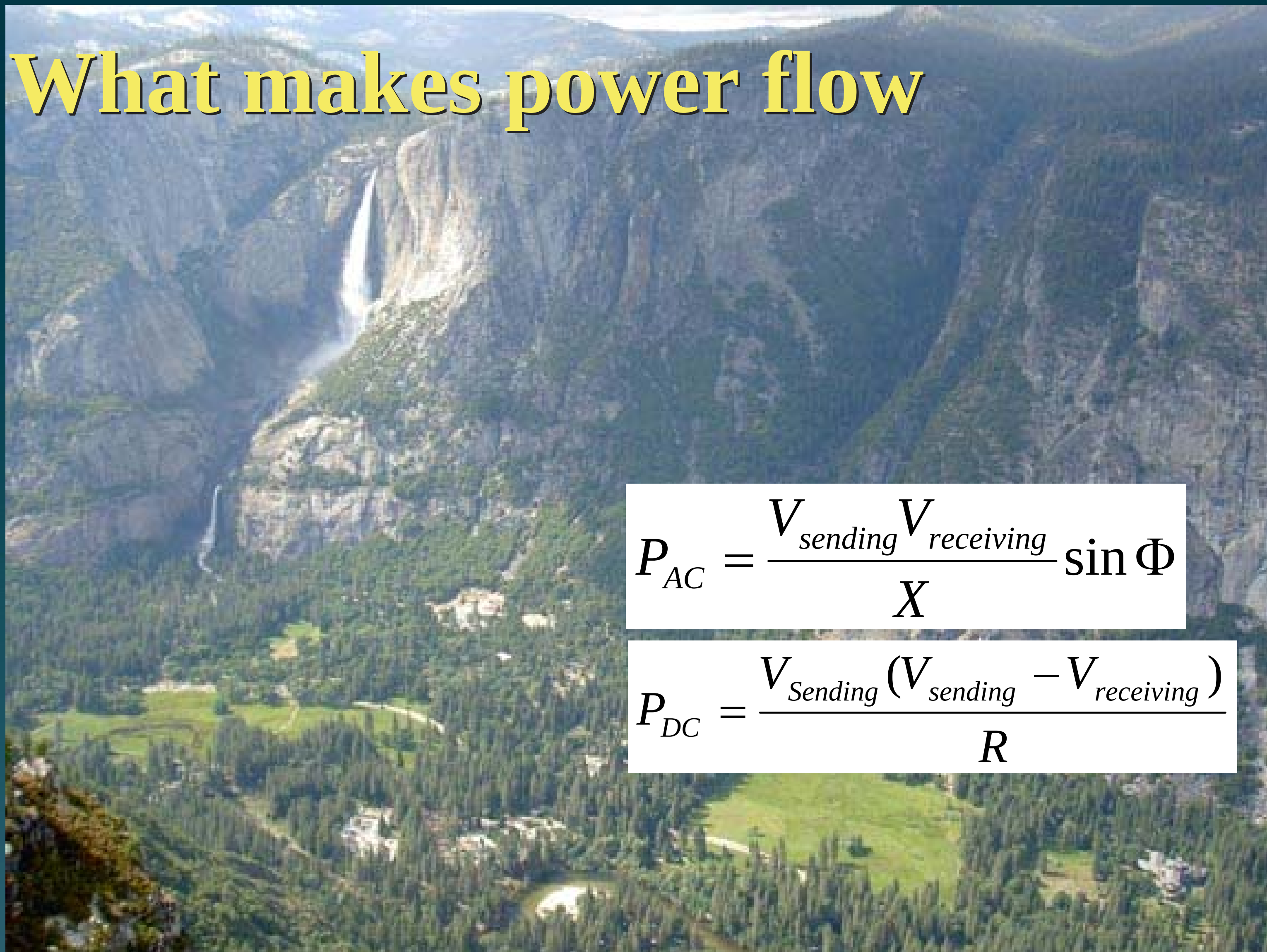
Mechanical Equivalent

v-speed =	current
F– force =	voltage
f – mechanical resistance =	Resistance
k – stiffness =	1/k - capacitance
m – mass =	inductance
F=fv -------------------------	V=RI

Power Transfer

- DC flows limited by voltage and resistance
- AC flows limited by resistance but also by the work needed to establish electric and magnetic fields
  - Electric fields charge and discharge the insulation media surrounding the electric conductor
    - Current “leaking” through cable insulation limits the useful length of cables for ac power transmission
  - Magnetic fields surround the electric conductors and can magnetize magnetic materials and induce currents into conductors
    - Energy required to build up the magnetic fields limits the useful length of overhead lines for power transmission

What makes power flow



$$P_{AC} = \frac{V_{sending} V_{receiving}}{X} \sin \Phi$$

$$P_{DC} = \frac{V_{Sending} (V_{sending} - V_{receiving})}{R}$$

Limitations on long distance power transmission

	English	Metric
Speed of light	186,000 miles per second	300,000 km per second
Cycles time = 1/frequency	16.7 ms for 60 Hz	20 ms for 50 Hz
Wavelength	3100 miles for 60 Hz	5000 km for 60 Hz
	3720 miles for 50 Hz	6000 km for 50 Hz
¼ wave antenna	775 miles for 60 Hz	1,250 km for 60 Hz
	930 miles for 50 Hz	1,500 km for 50 Hz

Image of Alphorn

Search on Alphorn Images for examples

At ¼ wave length the voltage goes to infinity and the current goes to zero

Solution: Detune antenna or use HVdc

Impetus for HVDC Power Transmission

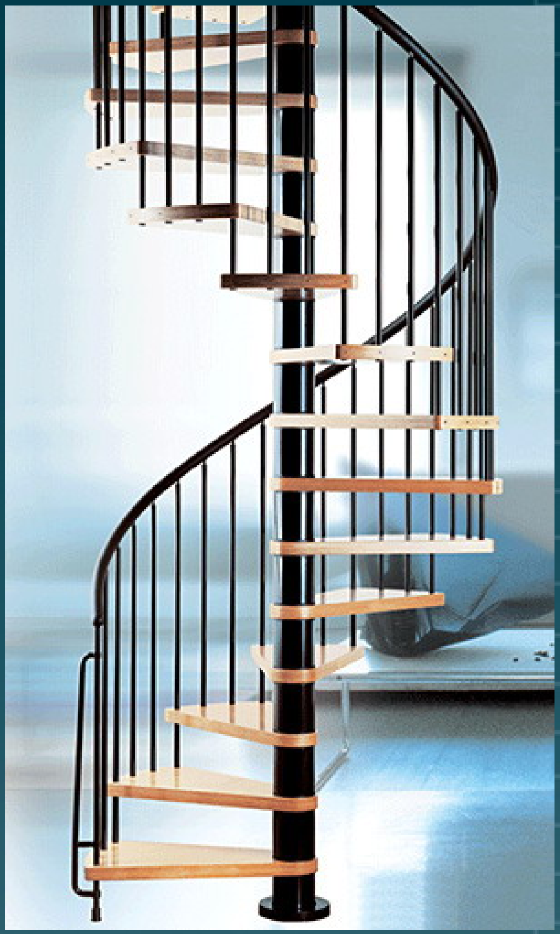
- Long distance undersea ac cable power transmission not feasible
  - Power supply to islands not feasible; ocean located wind farms to shore
- Water power resources far away from load centers
- AC systems operating asynchronously can not share ac power
- Long distance dc overhead lines saves one conductor (2 v. 3) that offsets the costs for the terminal equipment if the line is long enough
- DC links can help stabilize AC systems

High Voltage DC Transmission

- Early conversion of ac to dc used motor-generator sets
  - Limited voltage on the dc side because really high voltage generators can not be constructed
- Research on electric conversion in various parts of the world early
  - General Electric – Ignatron tube
  - AEG Germany – Test system in Berlin taken by the Russians in 1945
  - Uno Lamm at ASEA, Sweden made major invention in 1929
    - First test system built beginning in 1945 in Sweden

HVDC Converter Valves

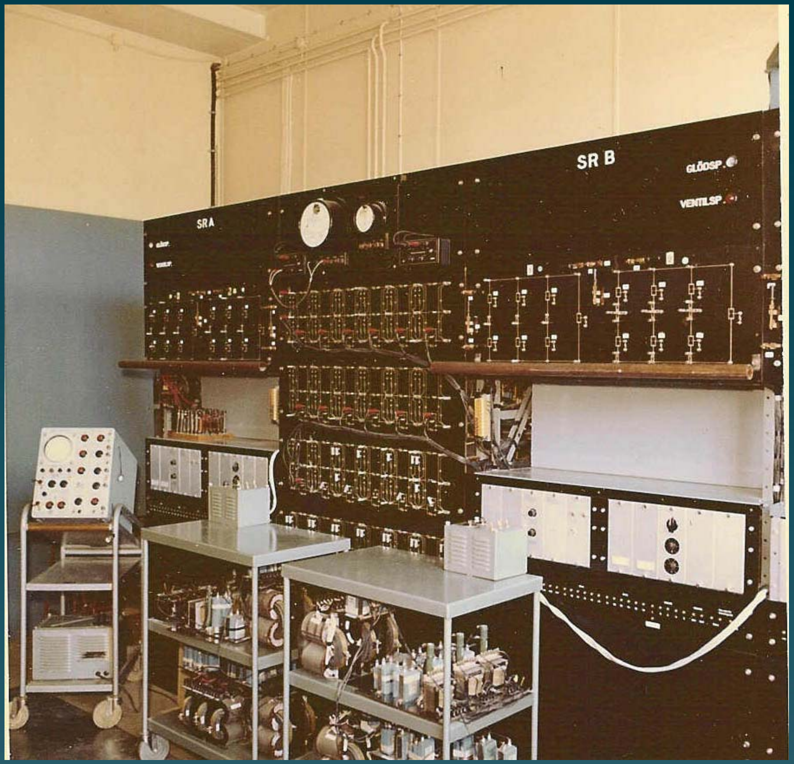
- Vacuum tubes have too high a voltage drop
- Low pressure gas tubes have voltage limitations
  - Solution: Divide the voltage stress in a low pressure gas gap by introducing grading electrodes
  - Invention by Uno Lamm in 1929



Uno Lamm @ ASEA

Anode Porcelains & Mercury Cathode Tank

Theory Development
Erich Uhlmann and HVDC Simulator @ ASEA



Gotland in 1954

- 90 km undersea cable
- 100 kV & 200 A
- 20 MW
- Asynchronous systems
- Black start capability
- Could supply island without local generation on the island

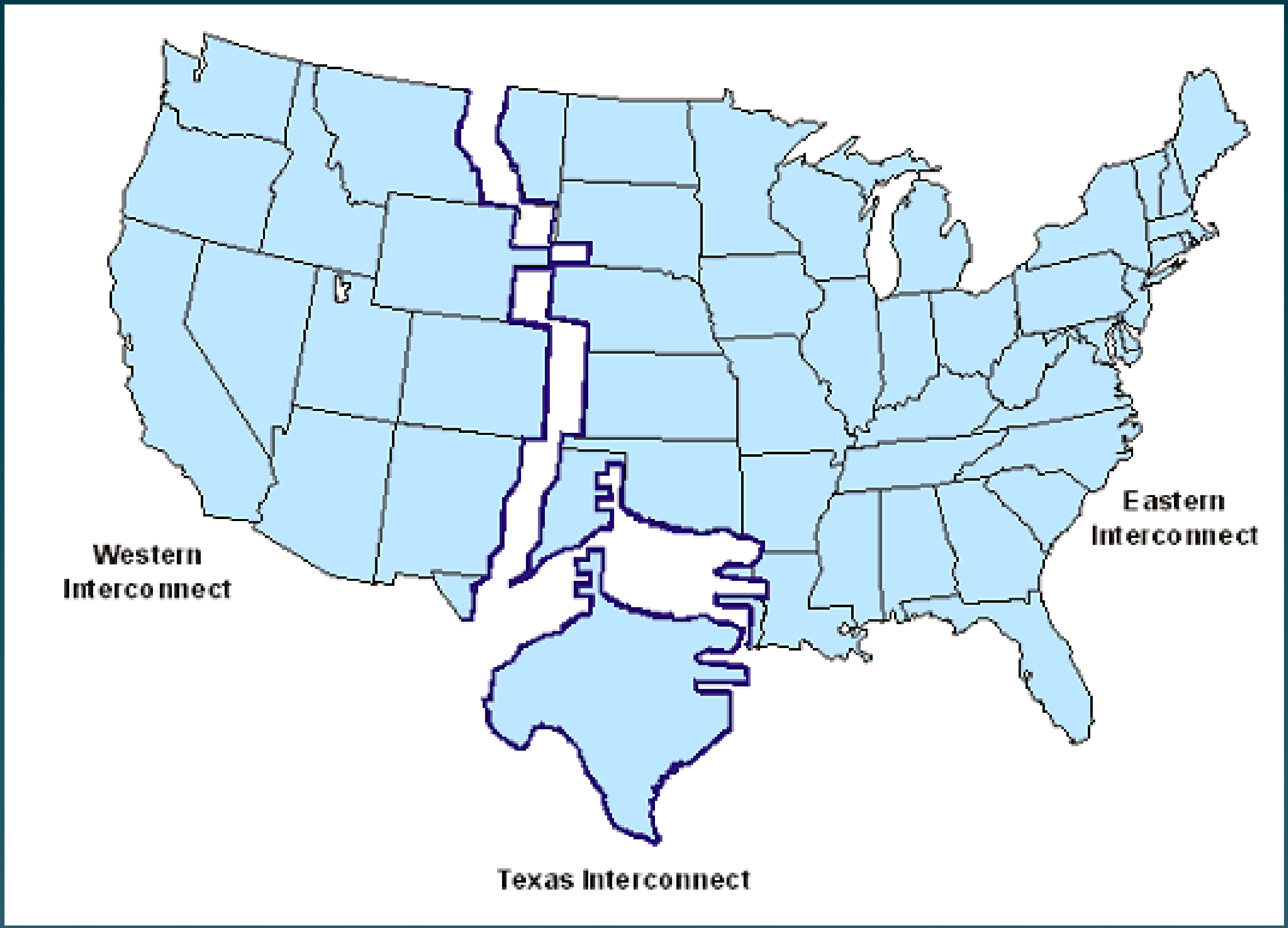
Not possible to sell what no one understands and competition needed!

- UMIST – Colin Adamson & Narain Hingorani
- Direct Current Magazine
- ASEA licensed competitors to achieve a competitive market
- Universities all over the world now participating by educating power electronics engineers
  - University of Wisconsin
  - University of Manitoba
  - University of Waterloo

Early HVdc systems

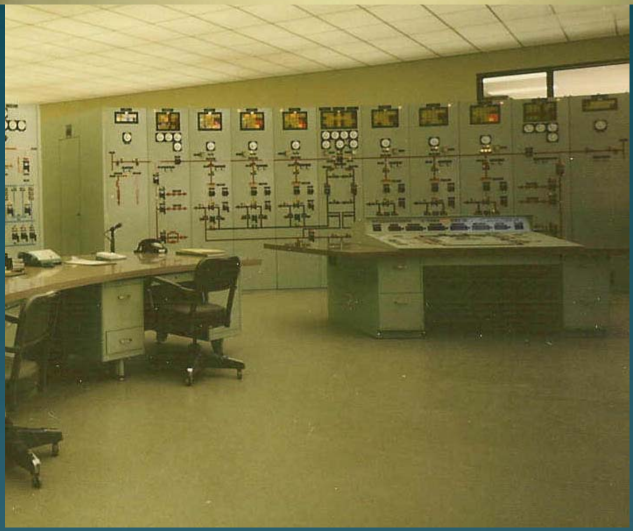
- Cross Channel -1961; 160 MW, 64 km cable between England and France (ASEA)
- Volgorod – Donbass - 1965; 720 MW, 470 km in Russia
- Sardinia; 1967; 200 MW, 413 km between Sardinia and Italian mainland (GEC England)
- New Zealand – 1965; 600 MW between the south and north islands (ASEA)
- Konti-Scan I – 1965; 250 MW, 180 km between Sweden and Denmark (ASEA)
- Sakuma - 1965; 300 MW frequency converter in Japan (ASEA)
- Vancouver I - 1968; 312 MW, 69 km between BC and Vancouver island (ASEA)
- Pacific HVDC Intertie – 1970; 1440 WM, 1362 km overhead line between Oregon and Los Angeles (JV between ASEA and GE)
- Gotland Extension – 1970; Adding 50kV and 10 MW to the Gotland scheme using thyristors (ASEA)
- Eel River – 1972; 320MW first all thyristor asynchronous link in Canada (GE)
- Cahora Bassa – started in the 1960s; 1920 MW, 1414 km overhead line with thyristor converters (JV between BBC, Siemens and AEG)

United States
Interconnected Systems

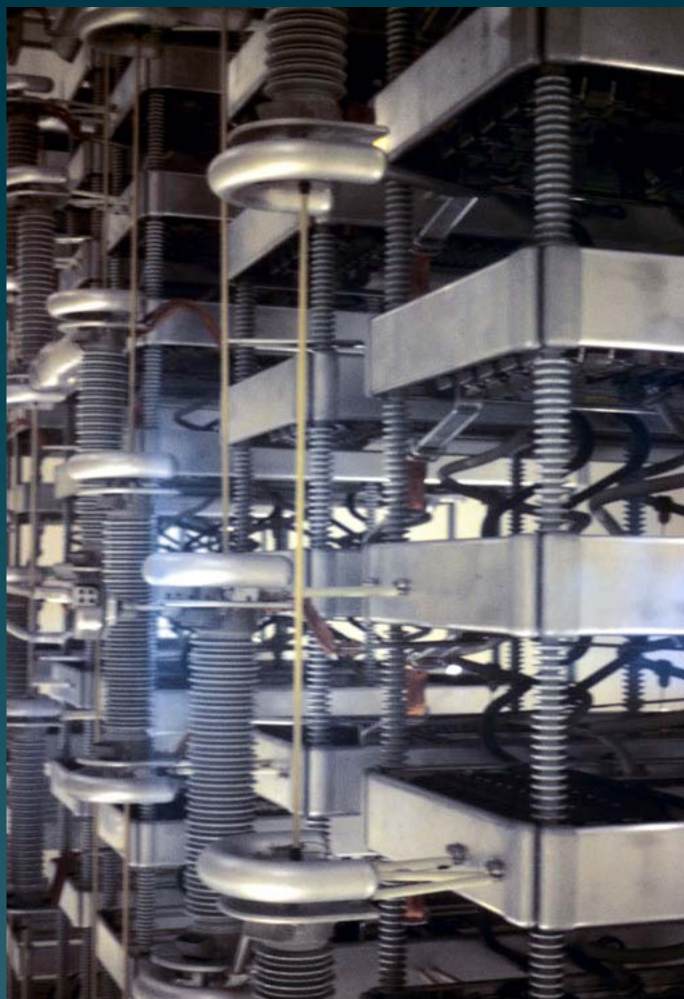


North America

Celilo



Thyristor Valves



Note: BBC and ASEA designs

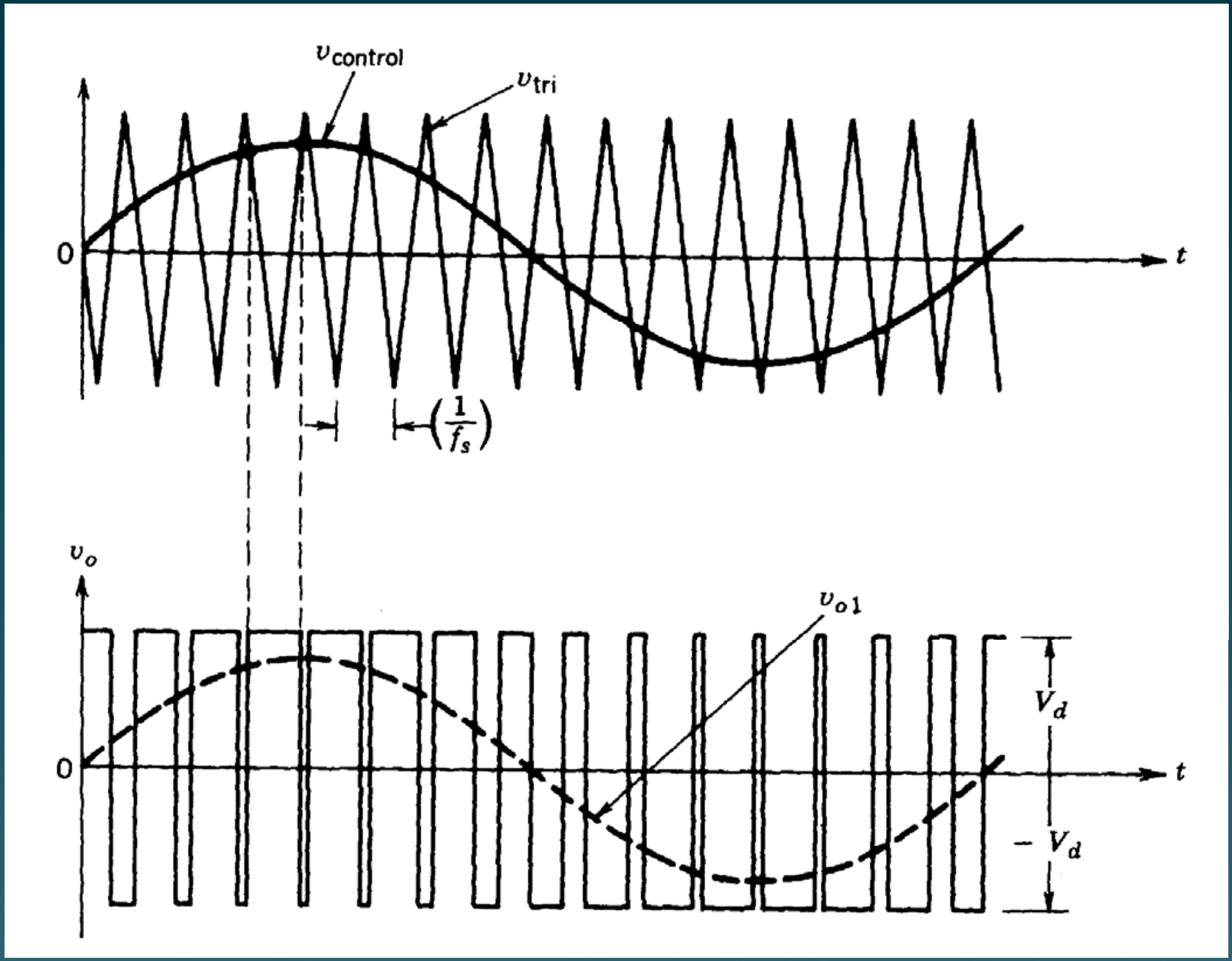
Foz do Iguacu
2 x 3000 MW @ +/- 600kV

Source: www.abb.com;

Shoreham; Long Island Sound
330MW HVDC Light

Source: www.abb.com

Pulse Width Modulation



HVDC & the Environment

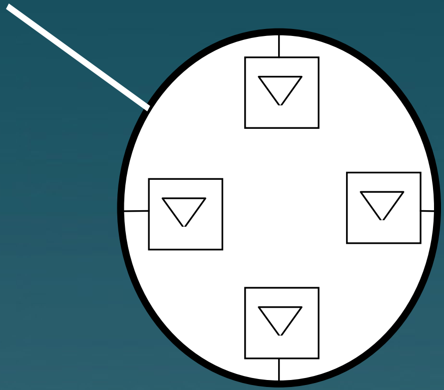
- Ground current – monopolar or bipolar systems
  - Undersea cables
    - Compass errors for shipping
    - Fish kills at electrodes
    - Corrosion
  - Overhead lines – bipolar systems
    - Corrosion
    - Ion effects
    - Radio interference
- Converter stations
  - Harmonics, radio and telephone system interference
- HVDC systems are difficult to tap to feed loads along the line and then need to be controlled

HVDC Worldwide

- Europe
- New Zealand
- Japan
- North America
- South Africa – Mozambique
- Zaire
- Brazil
- Australia
- India
- China

Super Conducting -HVDC Cable Systems

Link from Alberta Tar Fields to Southern California



FACTS

- Flexible AC Transmission System
  - Acronym firmly established through Dr. Hingorani's efforts
- Technology to squeeze more out of installed transmission system assets
- Stabilization of AC systems and control of power flows
- Technology enabling developing countries to build a transmission system with minimum of capital outlays

Macroeconomics Factors

- Oil Crisis in 74 and 79
  - 5% of US installed industrial capacity non-competitive
    - shift in manufacturing - new industrial facilities
    - More automation - robotics
  - Energy costs skyrockets
    - conservation - adjustable speed drives
    - again a factor in today's business environment

Market Drivers- Electric Utilities

- Utility market
  - Transmission Systems
    - PURPA - IPP/EWG emergence
    - NEPA ‘92 - Wholesale wheeling
      - No new lines
  - Distribution Systems
    - State Legislation - Retail wheeling
      - Power quality - reliability
      - Competition - blackmail
- Microelectronics everywhere
  - PC in every “home”

FACTS Precursors

- J.B. Tice, J.G. Anderson and G.D. Breuer: "New transmission concepts for long distance energy transfer for oil/gas displacement". American Power Conference, April 25, 1984.
- Comparison of costs and benefits for dc and ac transmission; ORL-6204, Oak Ridge National Laboratory, Oak Ridge, TN 37831 (February 1987) – Study led by the late Gene Starr

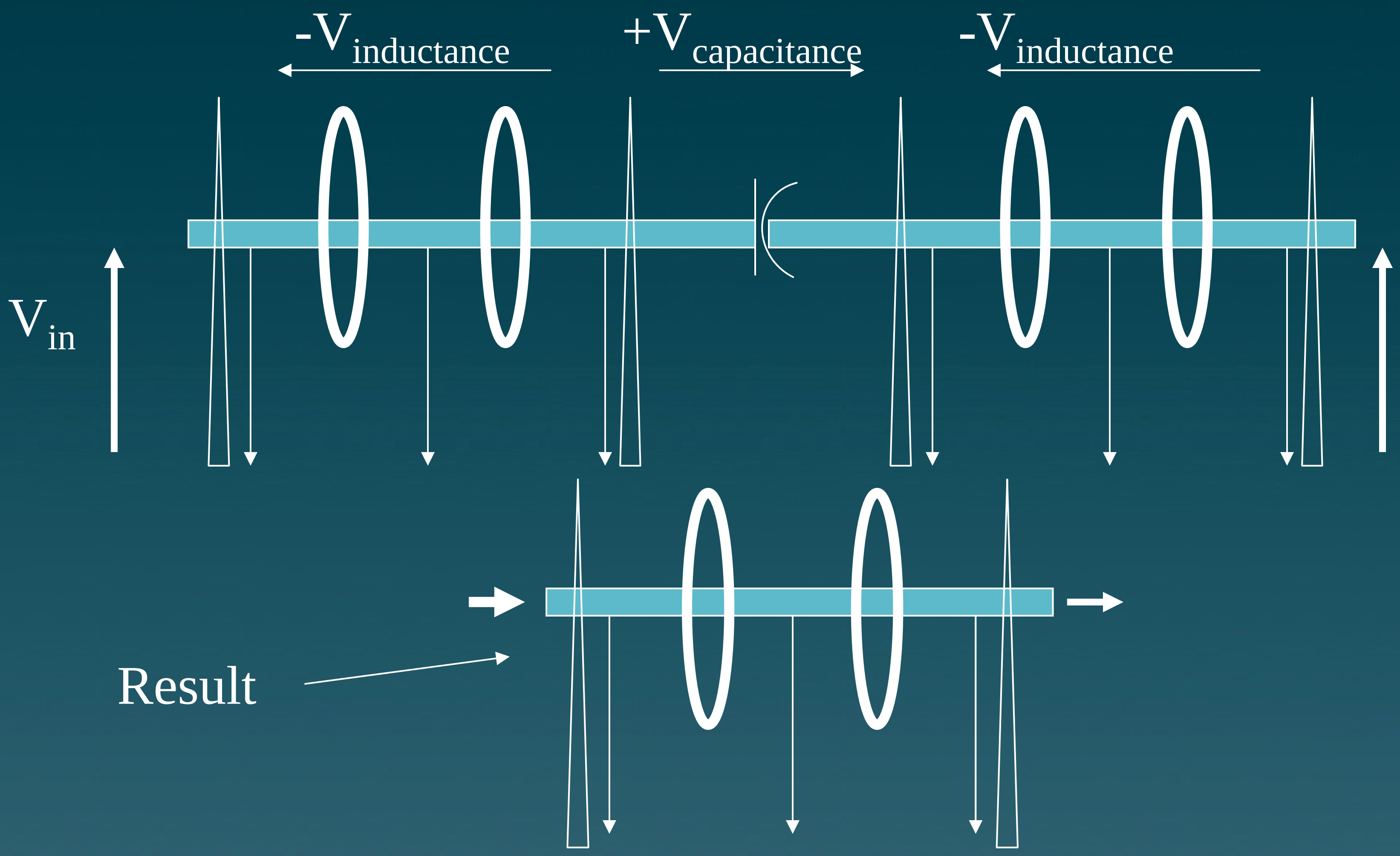
Electric Power System Growth

- 1960 grew at about 6%/year
- After the 1979 oil shock grown was close to zero
  - In some regions of the US it was negative
  - In the south growth was a bit positive
- In the late 80's low but positive growth
- Mid-1990's and continuing
  - Conversion to combined cycle gas turbines

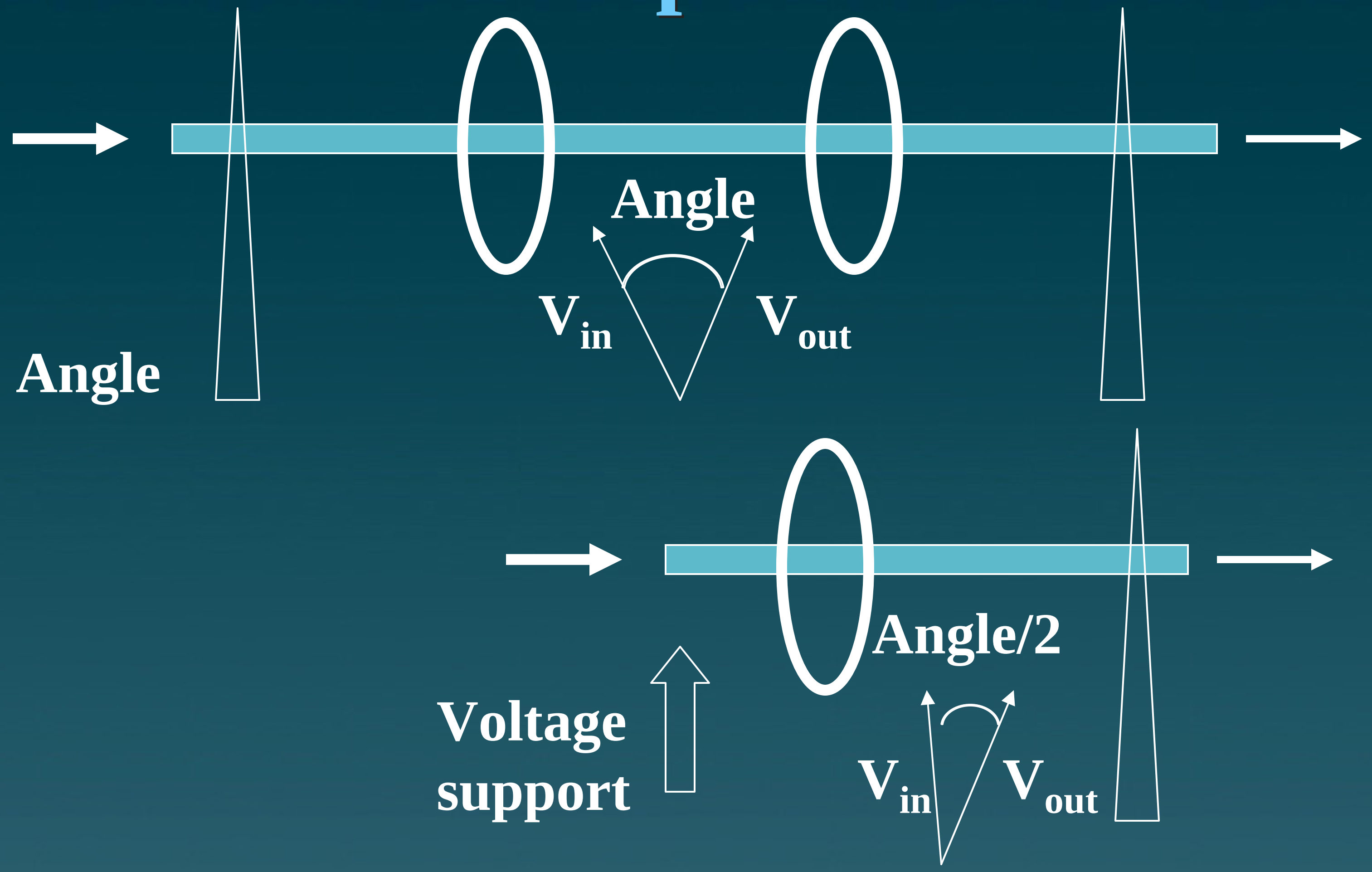
Matching Generation and Load

- Unexpected demands for load where lines are not optimum for transfer of power
  - Underutilization of lines capable of carrying significant load
  - Overloading of weak lines
- Control of the path where the power should flow is needed

Line Series Compensation



Line Shunt Compensation

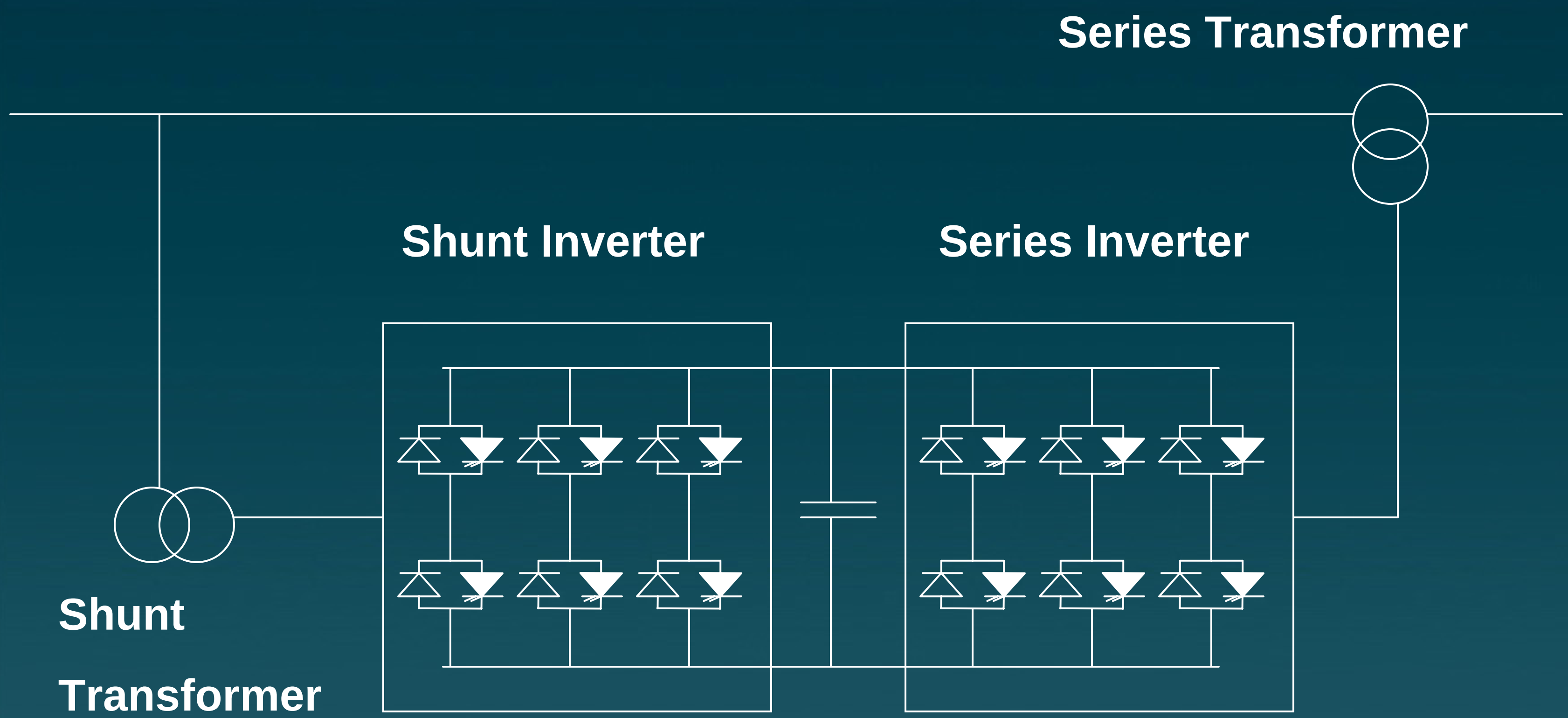


Series Compensation

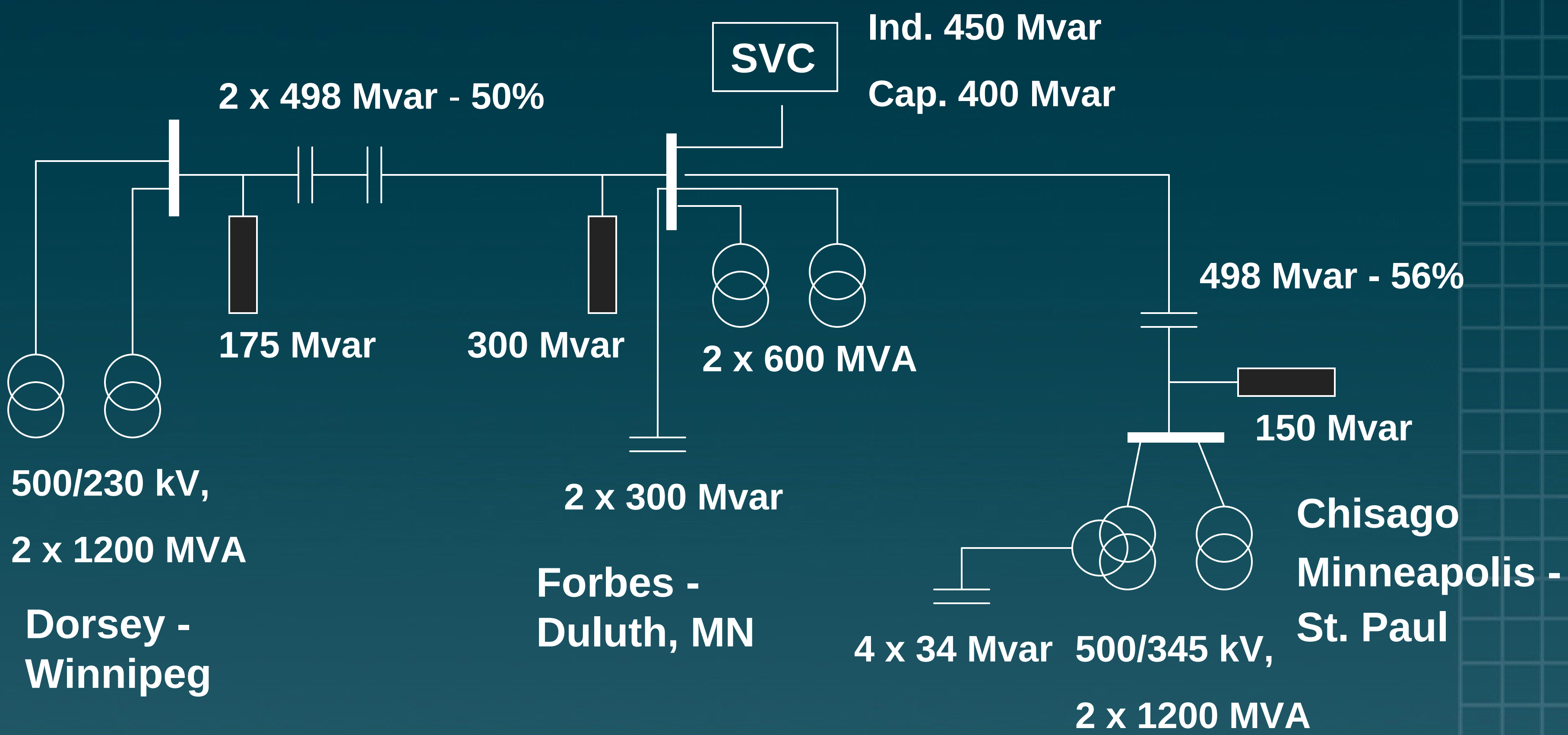
- Series capacitors
- Thyristor controlled series compensation systems
- Unified power flow controller

Shunt Compensation

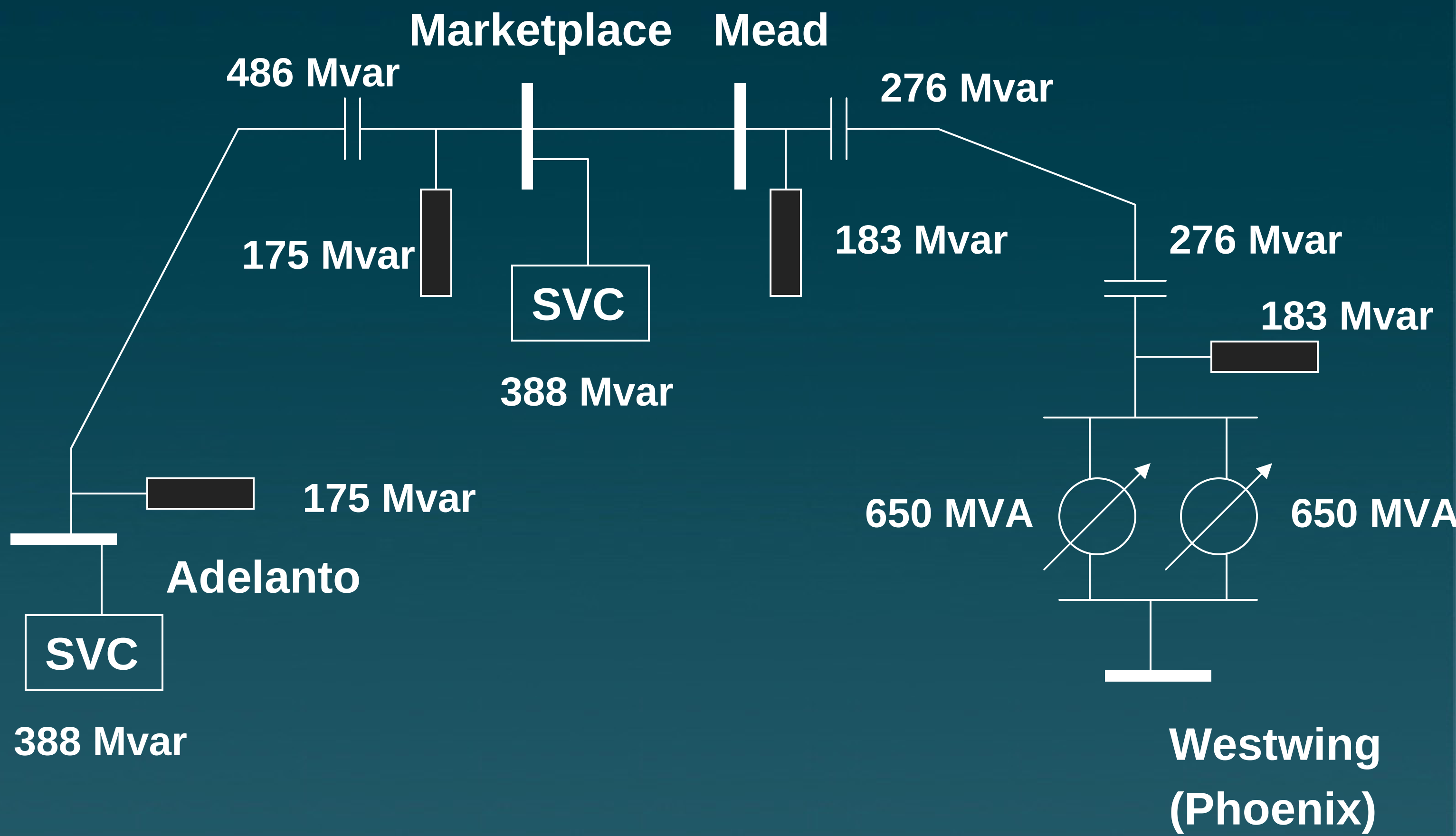
- Synchronous condenser (rotating machine)
- Shunt capacitors (lines)
- Shunt reactors (cables and lines)
- Static-var compensation system (combination of thyristor controlled reactors and thyristor switched capacitors)
- Static compensator (synthesizing a voltage using advanced semiconductor devices and small capacitors and reactors)



Unified Power Flow Controller

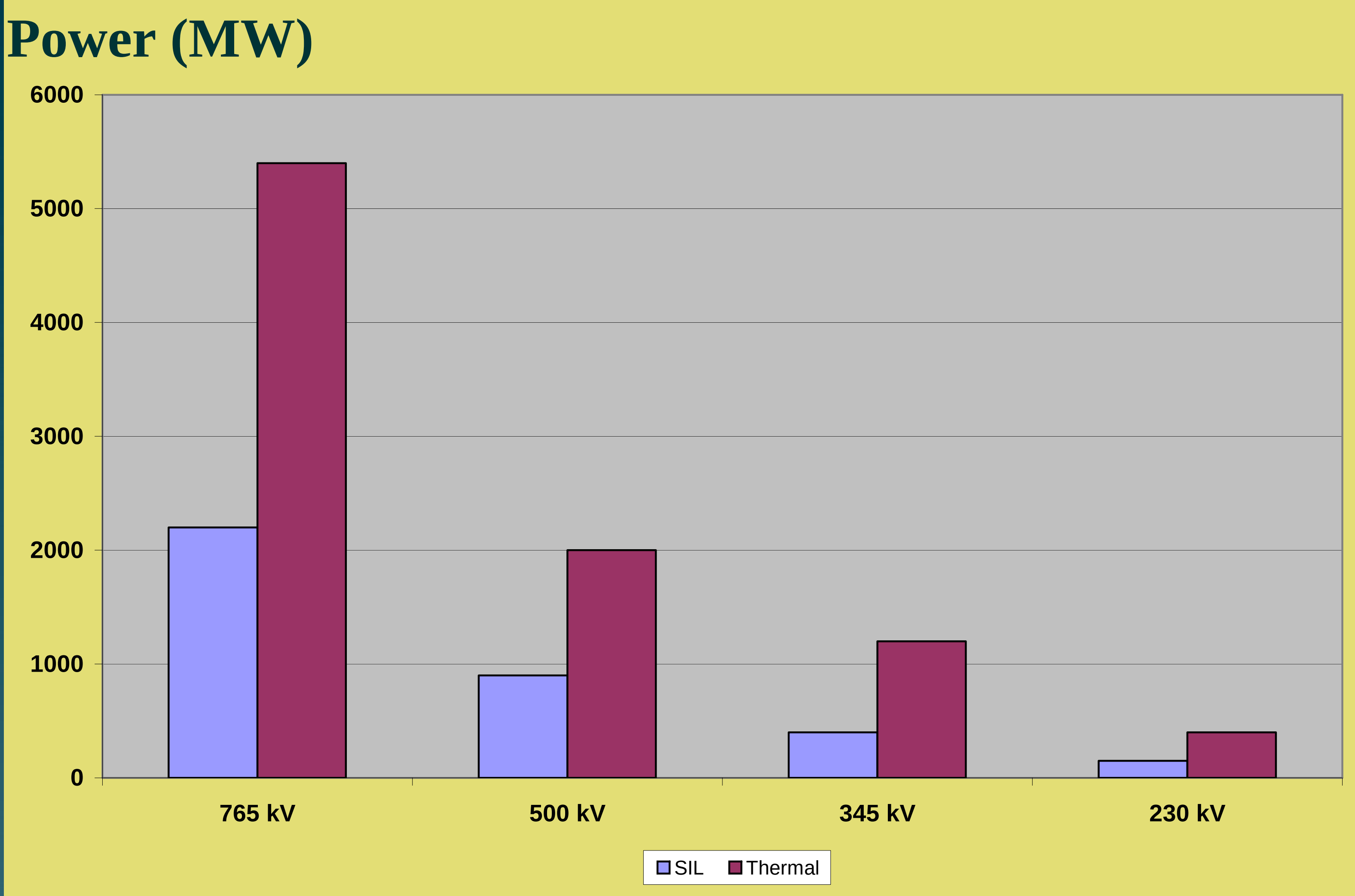


Winnipeg - Twin Cities FACTS Application



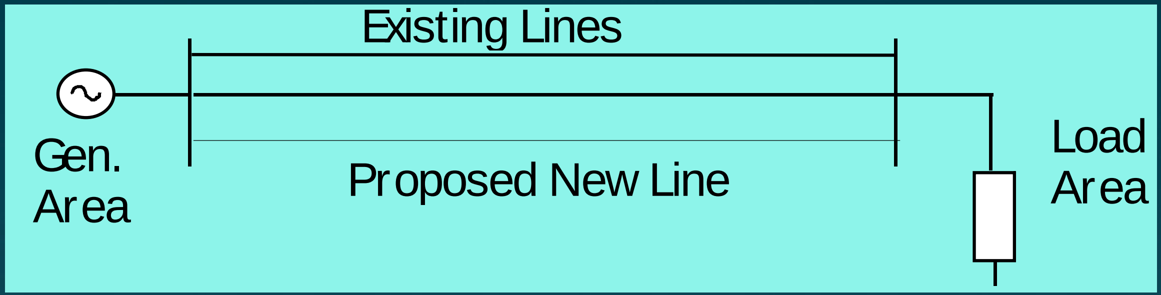
Phoenix-Mead-Adelanto FACTS Application

Long overhead line loading limits



Economics

Line Expansion Scenario

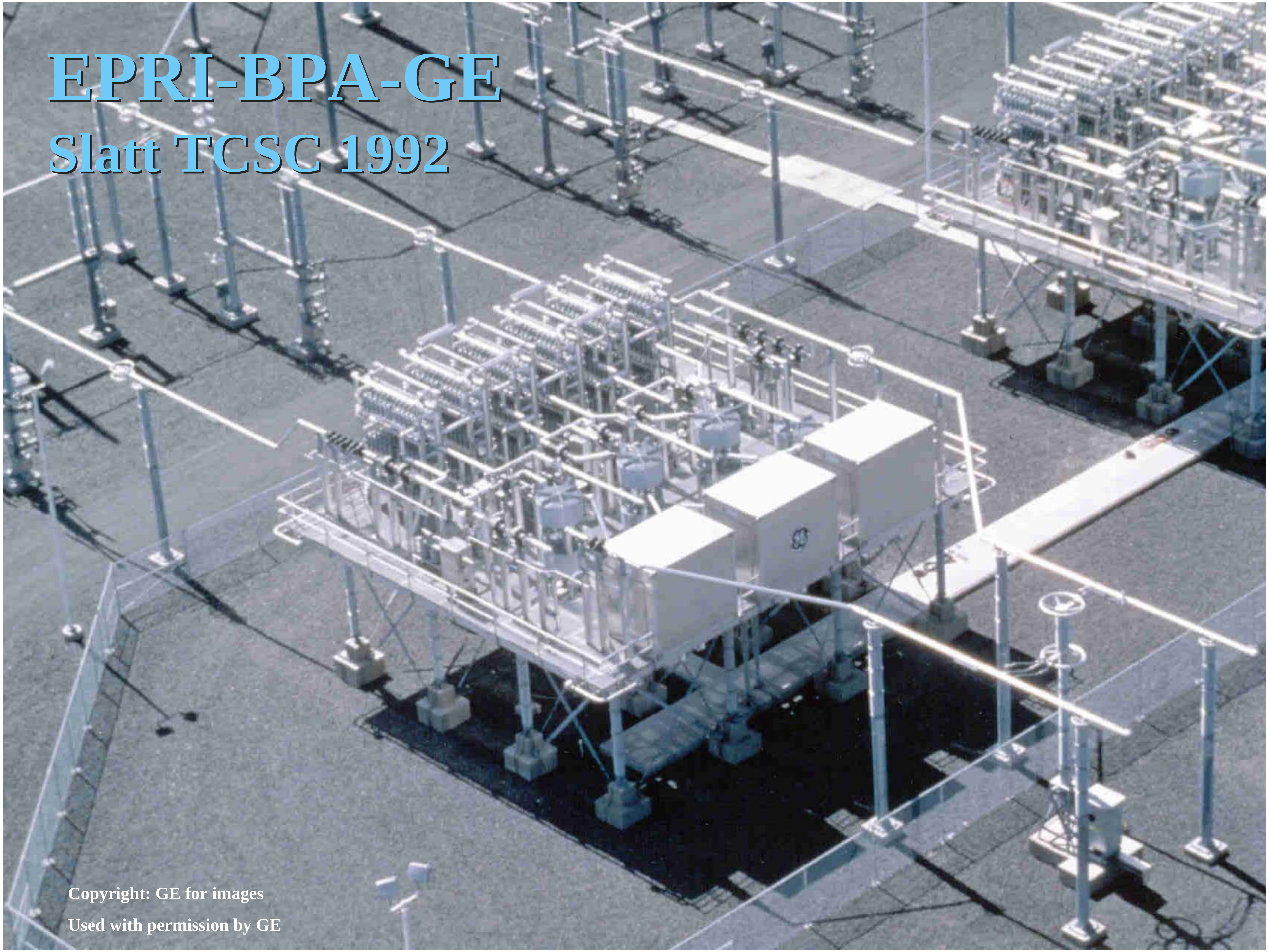


Impedance per mile: 0.55 Ω
X/R ratio: 25
Q/mile at SIL: 1.8 Mvar

The TCSC alternative:

Compensation level: 33%
(50% loading increase)
Cost/mile: $15 to 20% of new line

EPRI-BPA-GE
Slatt TCSC 1992



Necessity is the mother of invention

FACTS ideas emerging in many groups simultaneously

- AEP - ABB: Thyristor switched series capacitor
- WAPA - Siemens: Thyristor controlled series compensator (TCSC)
- EPRI - BPA - GE: SLATT TCSC

Worldwide Applications

Reducing capital outlays for AC transmission line construction

- First truly commercial application:
  - Brazil: Two long 500 kV lines with fixed and thyristor controlled series compensation systems
- China
- India
- Numerous applications possible in many other locations

Custom Power

- Distribution system FACTS
- Origin
  - Blinking VCR and digital clocks of the early 1980's
  - Variable speed drives and robotics in industrial applications
  - Widespread ownership and use of personal computers

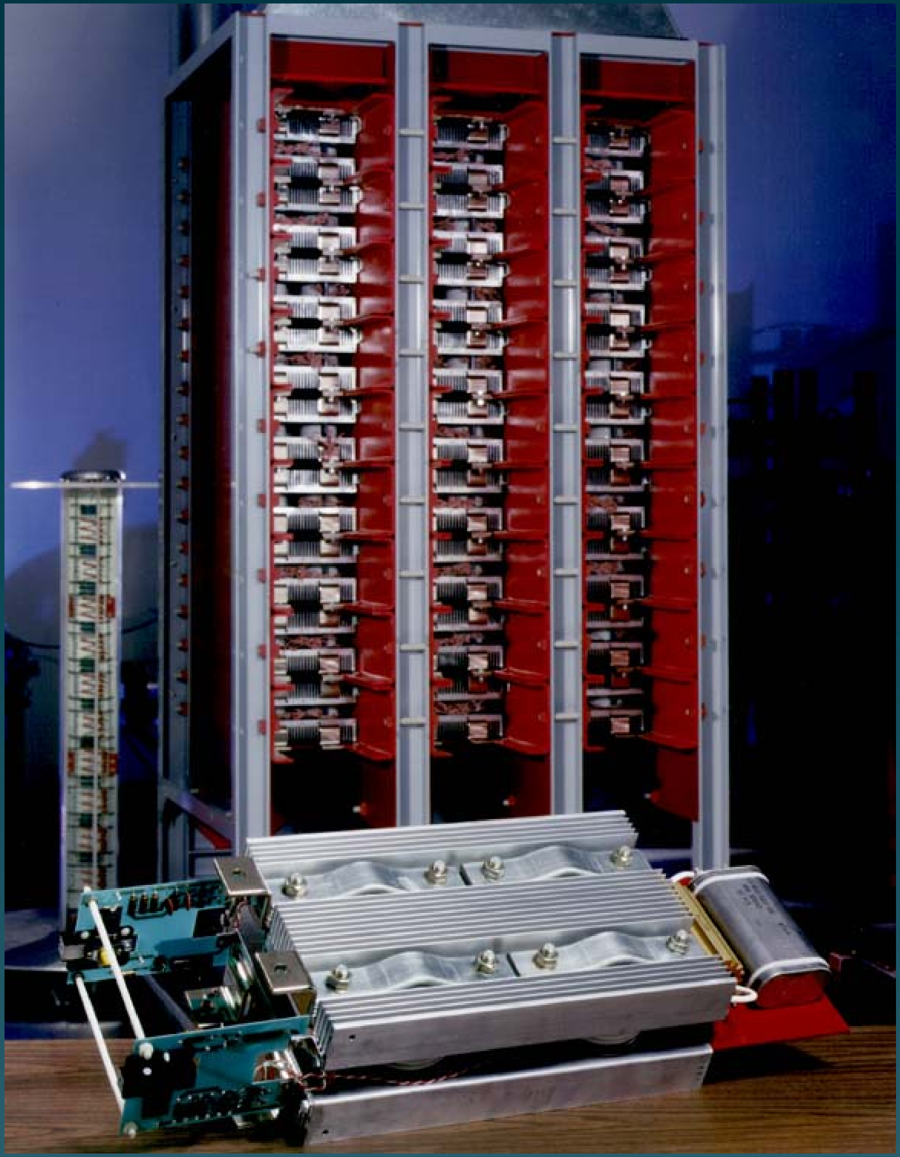
Power quality perceived as the problem and demands on the electric utilities to solve the problems arose

What is possible and what is not?

- Lightning can not be eliminated
- Frequency of ground faults, short circuits and equipment failures can be reduced but not eliminated
- The effect of utility system faults can be minimized but the faults within the customer premises can not be reduced to zero
- Sags and swells for utility system can be alleviated

Voltage flicker, sags and wells

- Arc furnaces causes voltage flicker affecting lighting systems
- AC system faults causes voltage sags on some phases but may be causing voltage swells on other phases because of ground potential rise
- Recovery from ac system faults may cause voltage rise
- Switching operations in the AC system will cause transient overvoltages (or undervoltages)

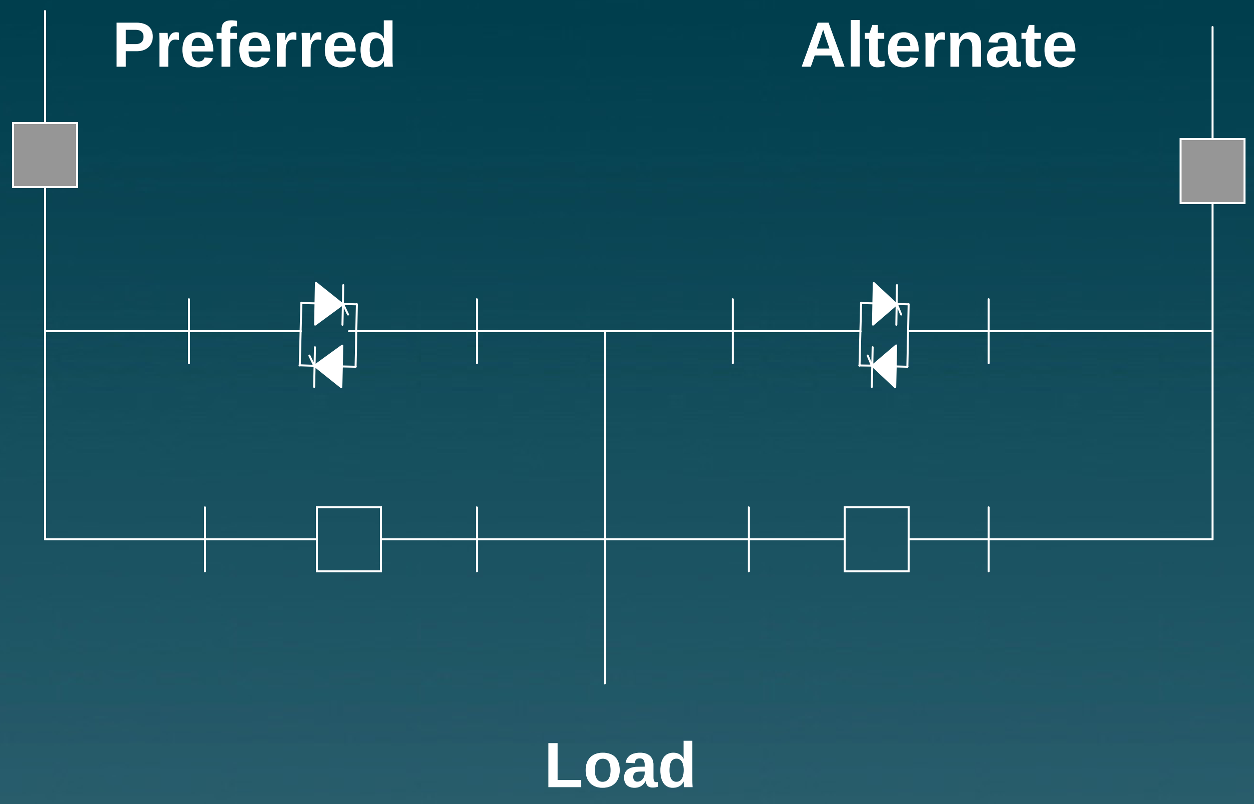


Redundancy on The Power System Supply
Solid State Transfer Switch

SPCO's 15 kV transfer switch

Transfer Switches

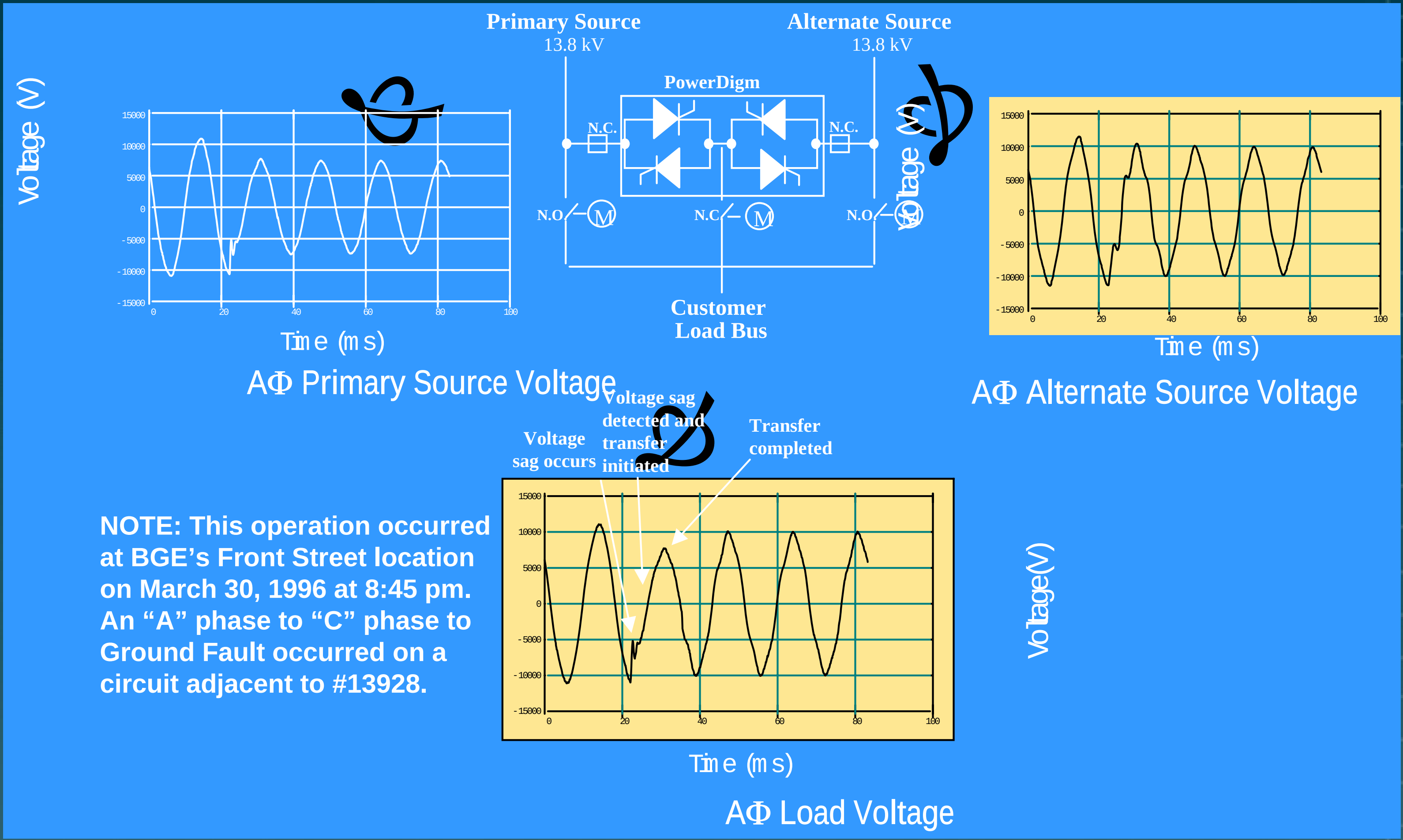
The Key Element in any Power Quality Enhancement



Alternate Source

- Second, unaffected AC supply line
  - Requires second feeder
- Backup power source
  - UPS (uninterrupted power supply) for all critical loads
  - UPS for utility
    - Energy storage can be batteries, fly wheels, superconducting magnetic energy storage, fly wheels etc.

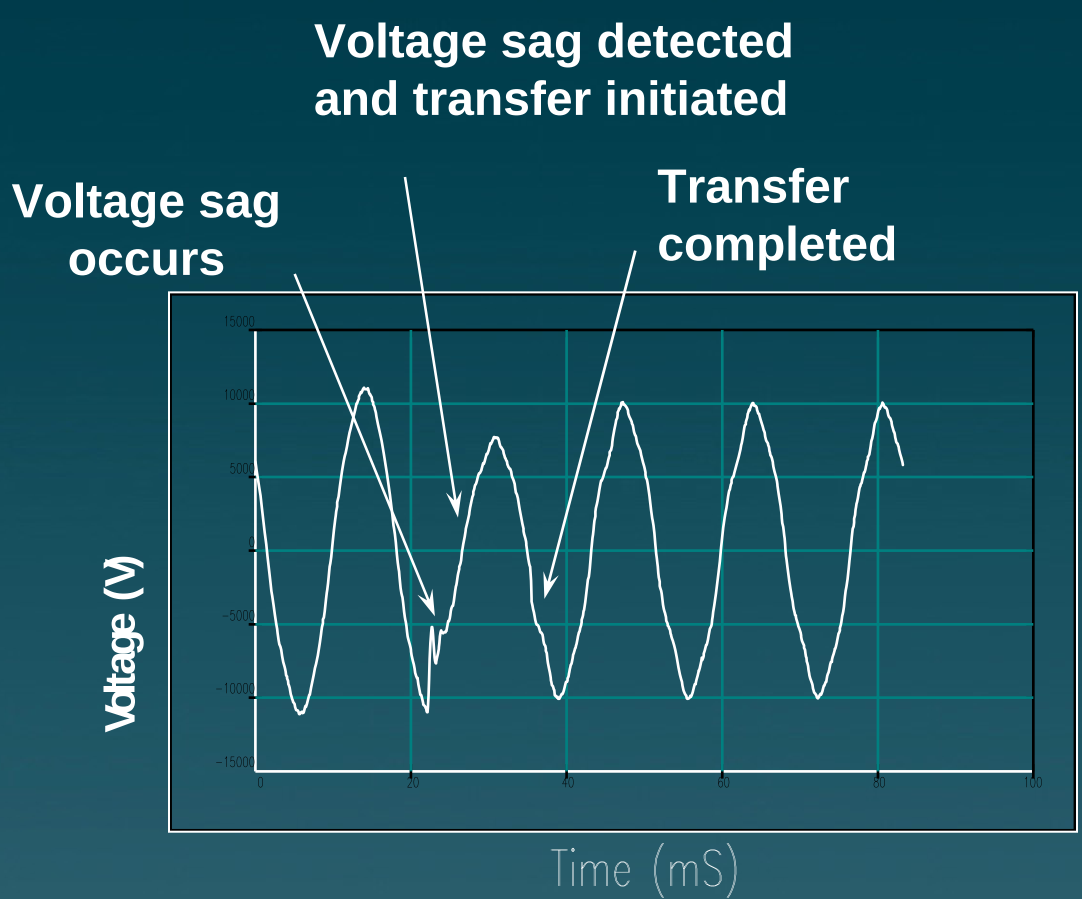
MVSTS Operation



NOTE: This operation occurred at BGE's Front Street location on March 30, 1996 at 8:45 pm. An "A" phase to "C" phase to Ground Fault occurred on a circuit adjacent to #13928.

Source: http://www.siliconpower.com

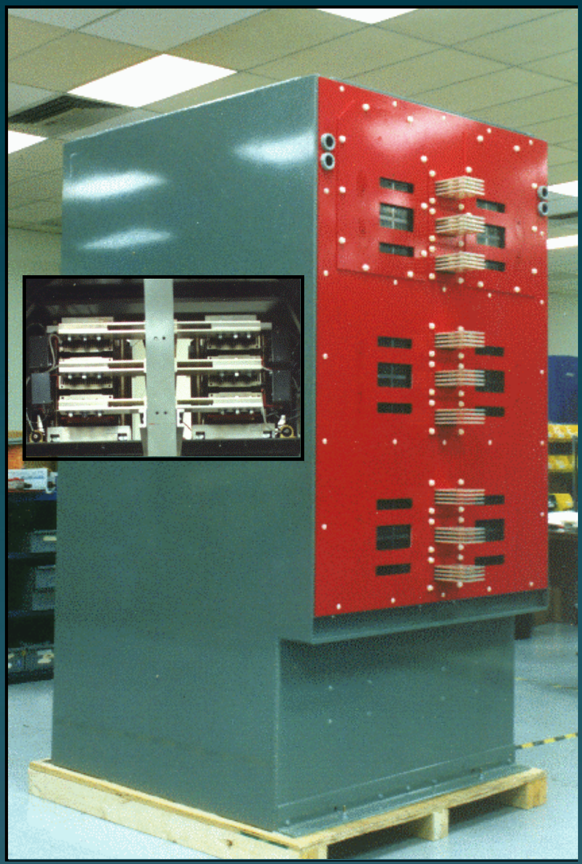
Transfer Switch Operation



AΦ Load Voltage

SPCO's Low Voltage Transfer Switch

- Used for protection of customers with loads under 3 MVA
- 600 V Class Unit with following current ratings and 4 cycle short circuit performance
  - 2000 A, 40 kA withstand
  - 3000 A, 65 kA withstand
  - 5000 A, 100 kA withstand



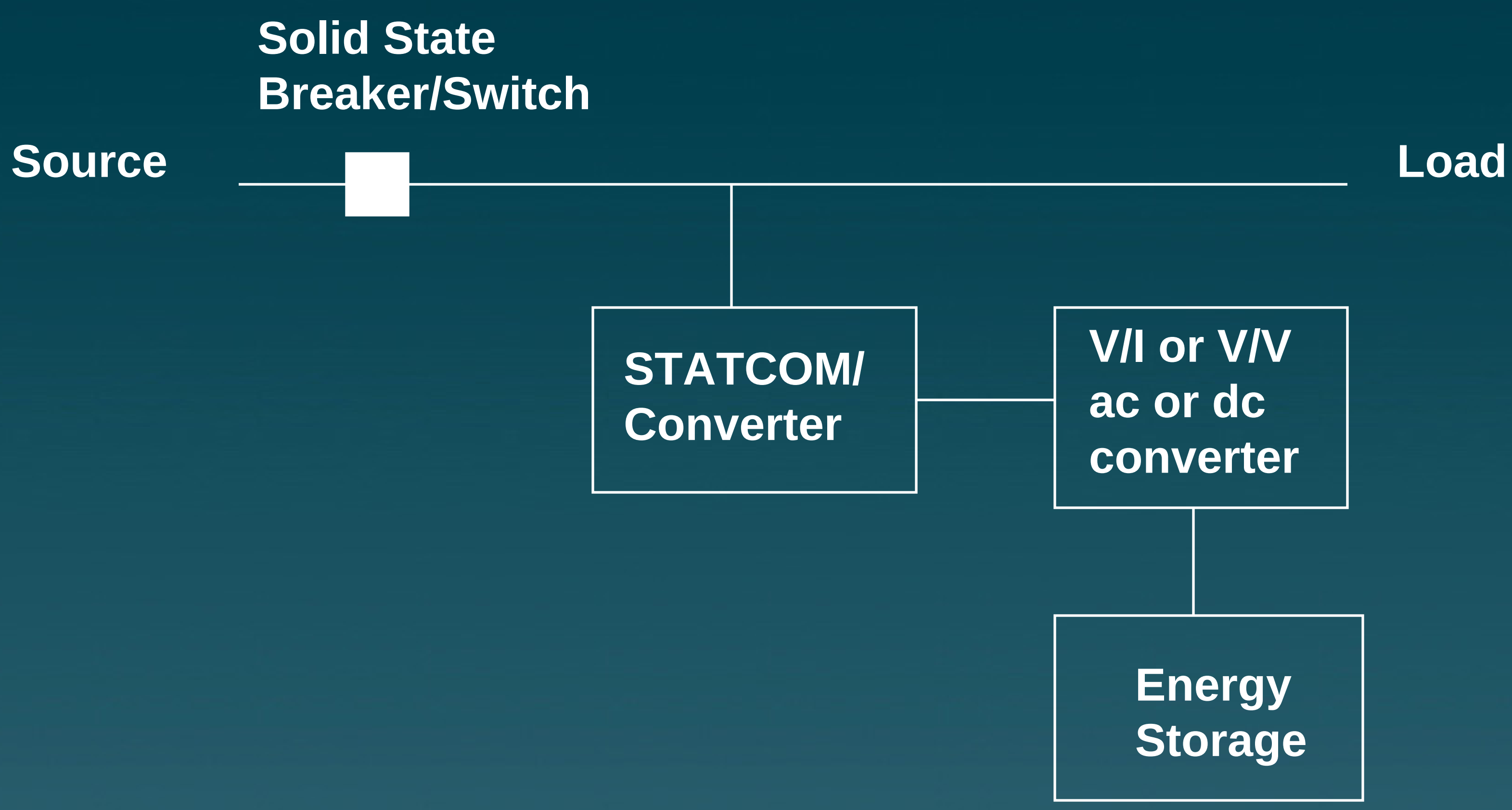
Source: http://www.siliconpower.com

125 mm Thyristor

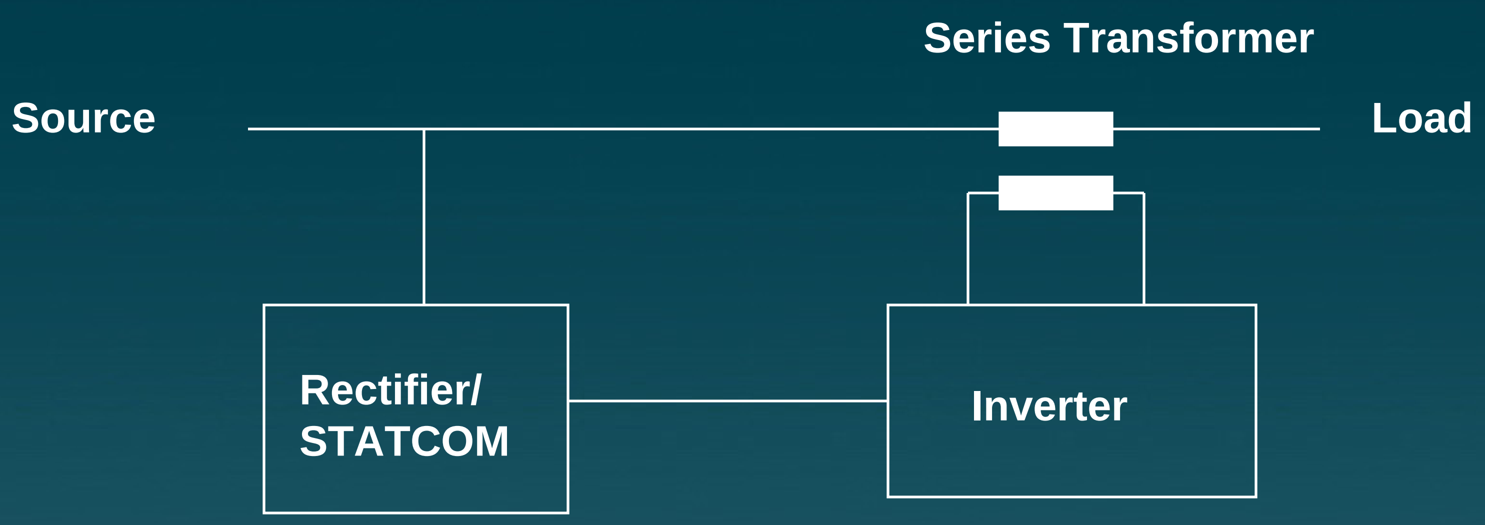
- 125 mm Thyristor for Utility Applications
- Available with Phase Control, Involute or Inter-digitated Gate Structure
- Industry First Light-weight, Thin, Plastic Package

Source: http://www.siliconpower.com

On Line UPS


Solid State
Breaker/Switch
Source
Load
STATCOM/
Converter
V/I or V/V
ac or dc
converter
Energy
Storage

Distribution UPFC



Custom Power

Barrier to Market Acceptance

- Utility not able to collect an increased charge for power
- Power user has insurance against losses caused by power supply disturbances
- Insurance companies not seeing a payback from investments in power quality enhancement technologies

Result is a tough market acceptance even if an outage of a modern automotive assembly plant could pay for the investment just by one avoided outage

Custom Power Applications

- Voltage flicker control where arc furnaces are used
- Reactive power compensation for voltage control

Summary

- Electric power transmission systems make use of both HVDC or AC
- Each system has its advantages as well as disadvantages
- FACTS is a viable technology that can under certain conditions be utilized to make the ac system perform in ways that it was not intended to work
- FACTS has been applied and most likely will continue to be applied in countries where the ac system is under development and less so in the US with an already installed transmission line base
- Custom power systems are also available but finding most use in voltage flicker control and less in reliability enhancements of the power supply