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Power Devices for FACTS:
Current State of the Art and Opportunities for Advanced Materials

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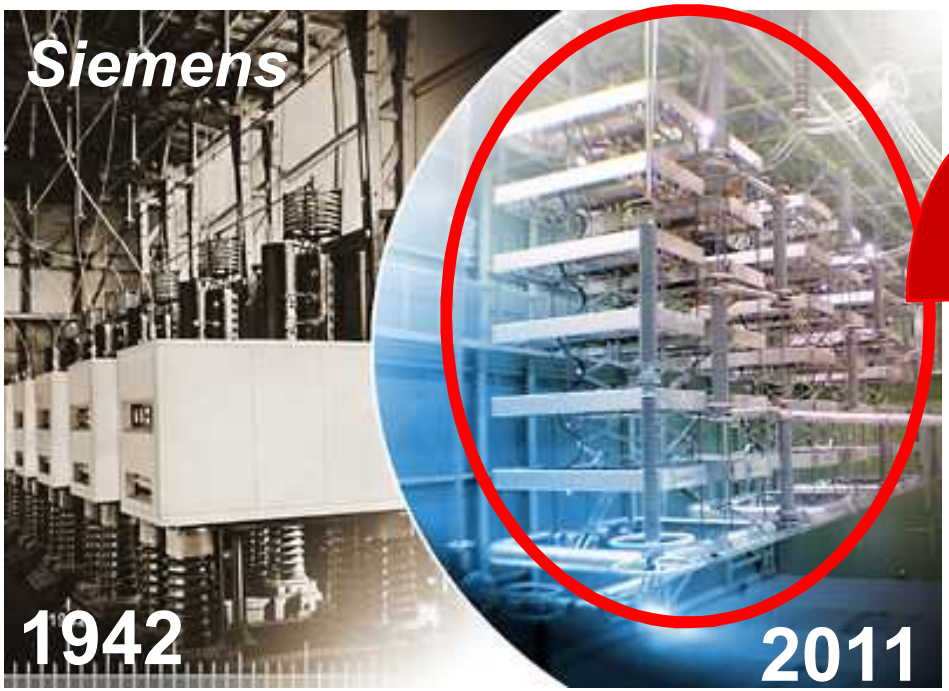
Power Conditioning



Mercury-arc rectifiers 100 kV, 140 A

Si thyristor tower 3000 MW, 500 kV

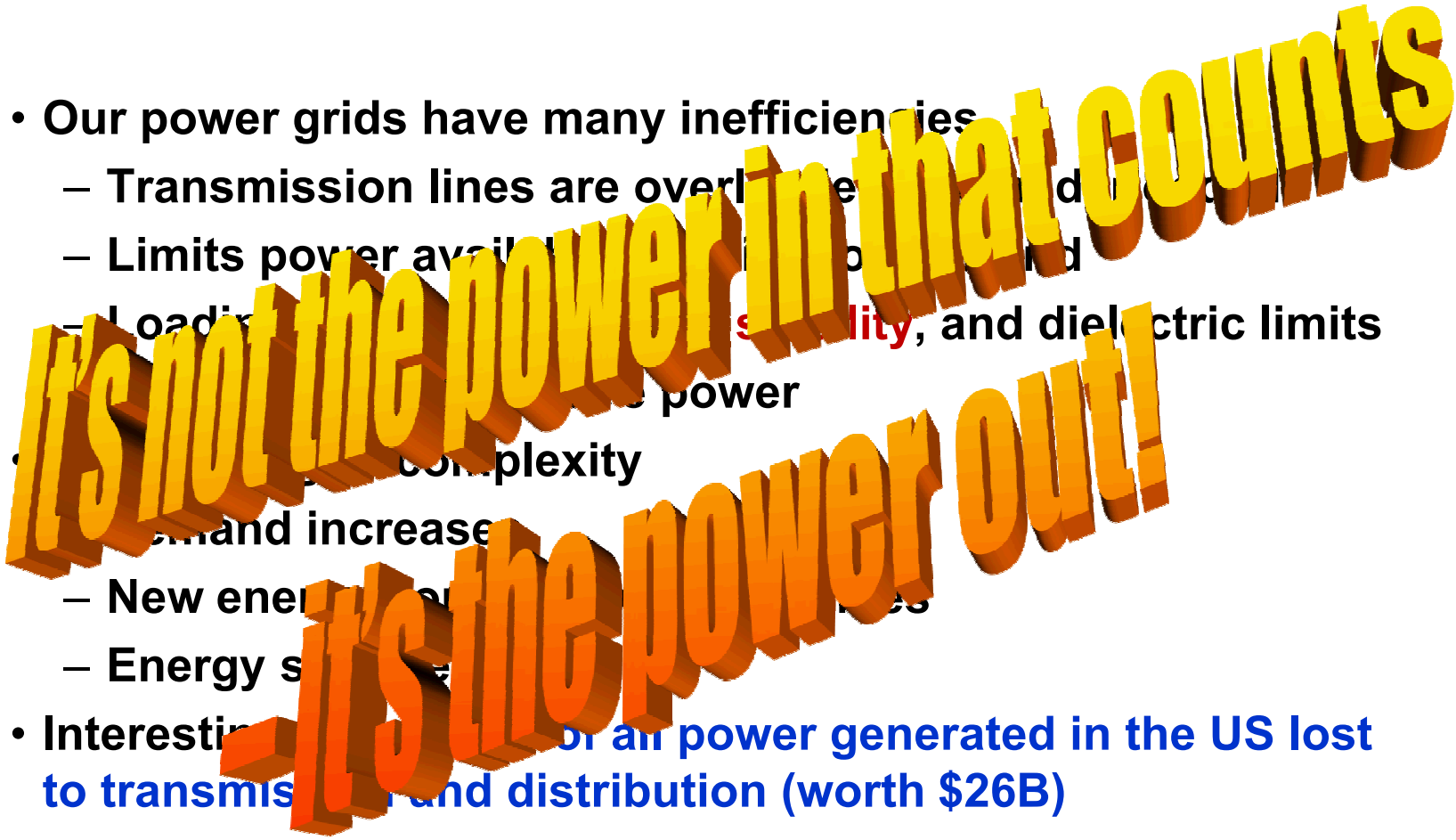
SiC version

Outline

- FACTS Overview
- Silicon Power Devices for FACTS
- Opportunities for WBG in FACTS
- WBG Power Device Work at Sandia

Introduction – The Power Grid

- Our power grids have many inefficiencies
  - Transmission lines are overl[illegible]
  - Limits power avail[illegible]
  - Loadi[illegible]s[illegible]lity, and dielectric limits
  - [illegible] power
  - [illegible]complexity
  - [illegible]and increase
  - New ener[illegible]
  - Energy s[illegible]
- Interesti[illegible] of all power generated in the US lost to transmis[illegible] and distribution (worth $26B)



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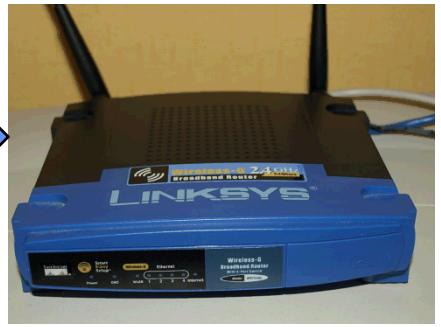
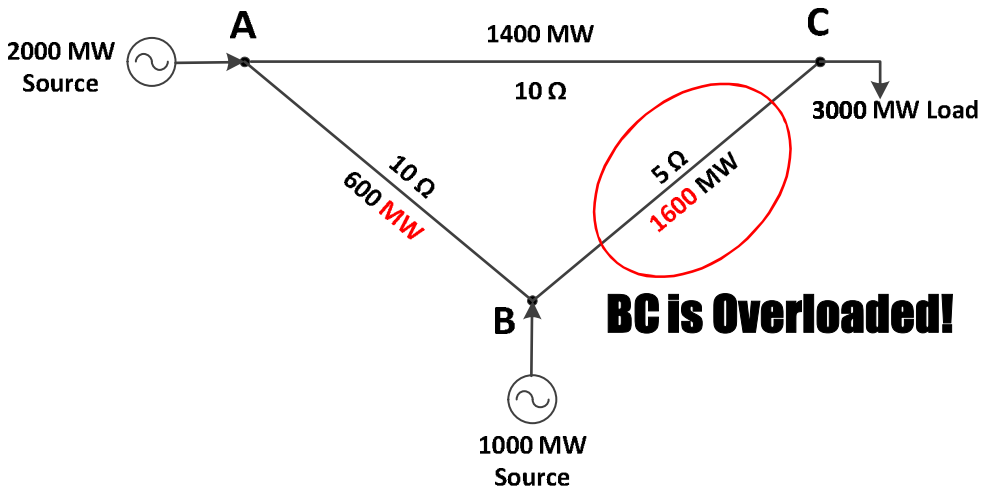
FACTS

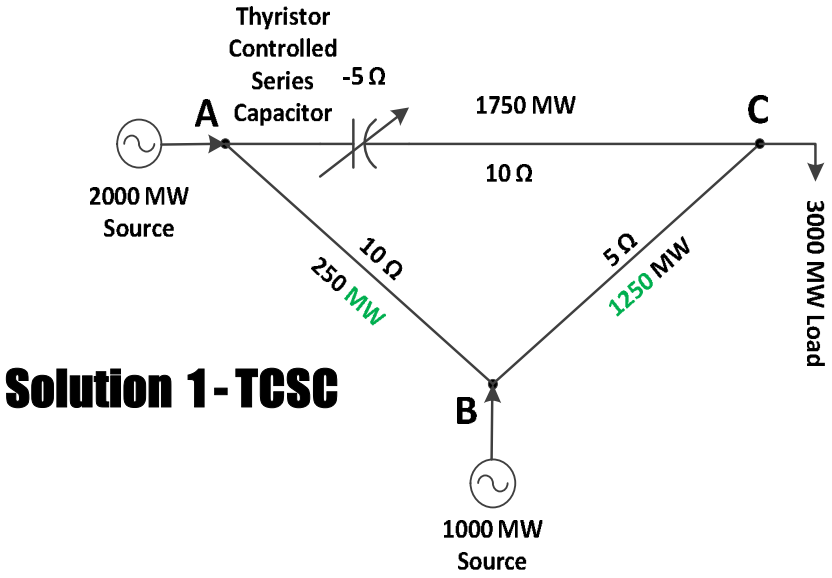
- **Flexible AC Transmission Systems (FACTS)**
  - **IEEE Official Definition: Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability**
  - **Practical Explanation: Facts can be thought of as a router for complex AC transmission networks**

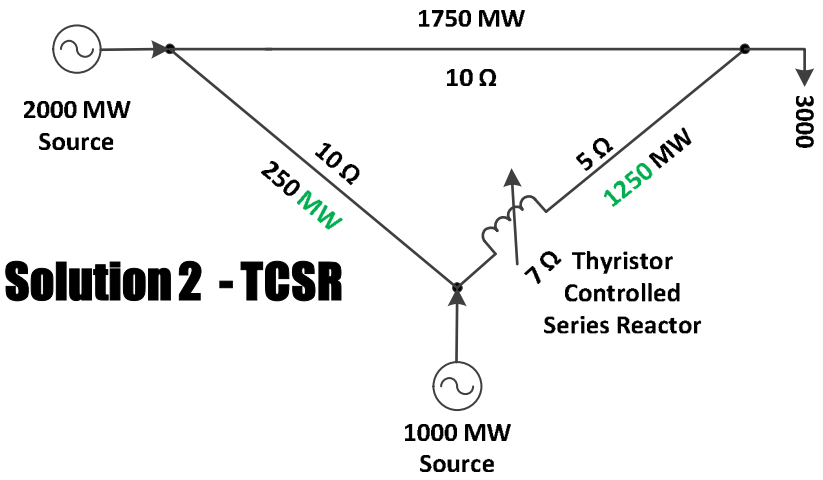


Basic Concept

- Simple Example[1]
- Line Ratings
  - AB = 1000 MW
  - BC = 1250 MW
  - AC = 2000 MW







[1]Adapted from Hingorani and Gyugyi

Evolution of Power Technology

- **Original Solution: Mechanical switches**
  - Mechanically switched capacitors (MSC)
  - Still in use today, often in conjunction with PE
  - Slow, limited switching cycles, poor reliability
- **Current Solution: Power electronics based FACTS**
  - Dominated by silicon thyristors and IGBTs

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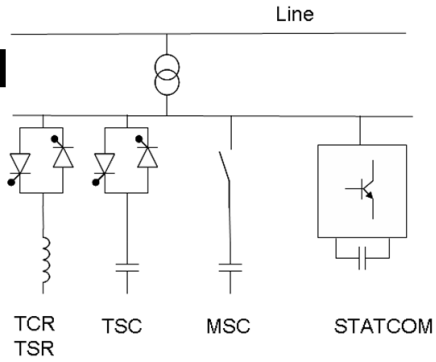
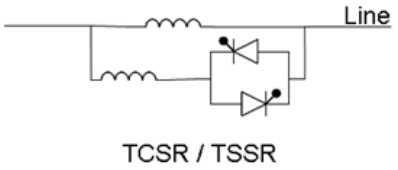
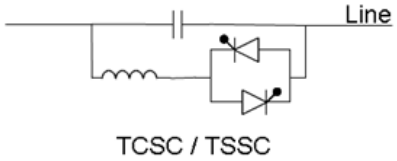
FACTS Controllers & Acronyms

- **Shunt Controllers**
  - Static Synchronous Compensator – STATCOM
  - Static VAR Compensator – SVC
    - Thyristor Controlled Reactor – TCR
    - Thyristor Switched Capacitor – TSC
- **Series Controllers**
  - Series STATCOM – SSSC
  - Thyristor Controlled Series Reactor – TCSR
  - Thyristor Switched Series Capacitor – TSSC
- **Combined Series-Shunt Controllers**
  - Unified Power Flow Controller – UPFC
- **High Voltage DC – HVDC** (not a FACTS controller)
  - HVDC is a power device technology related to FACTS







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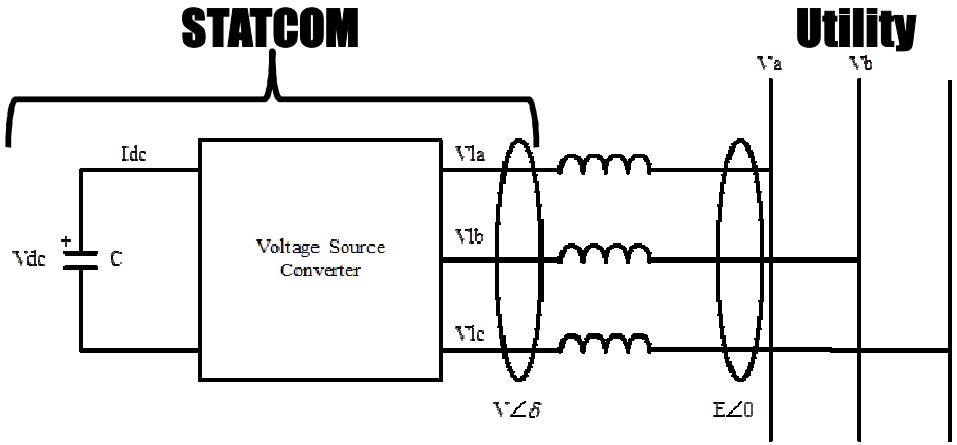
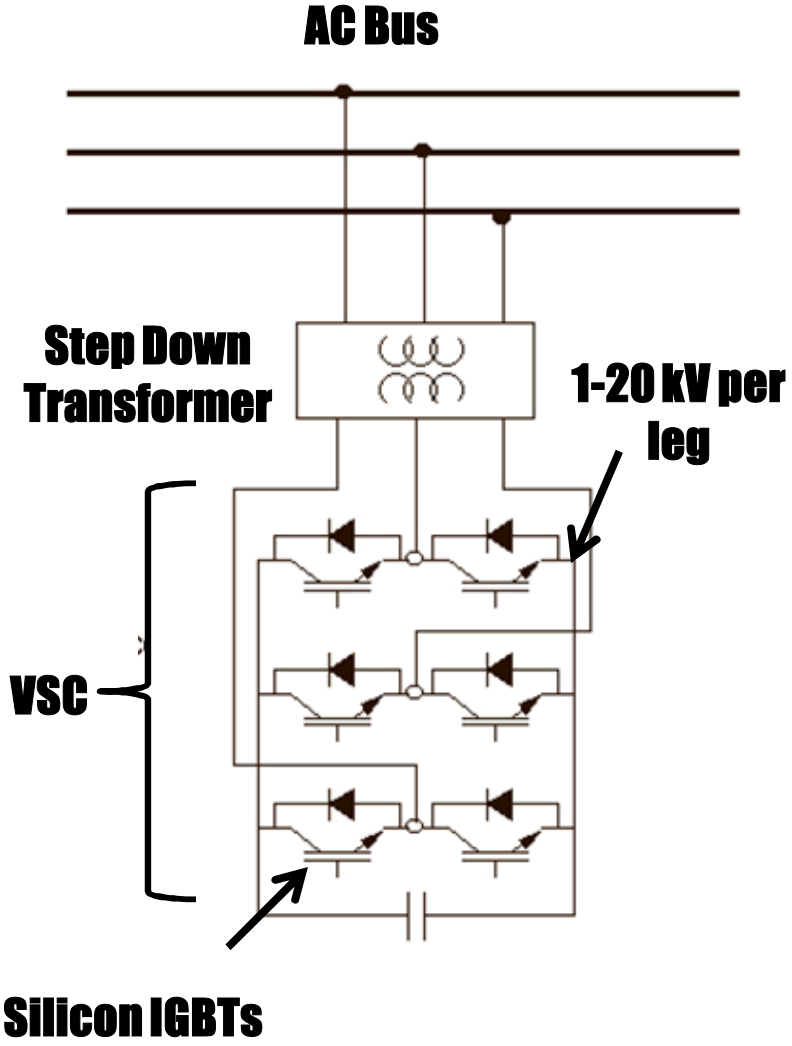
STATCOM

- Common facts controller
- Dynamically absorbs/provides reactive power
- Uses Voltage Sourced Conver
  - (aka Inverter)
- P(Watts) = VE sin(δ) / X
- Q(VAR) = [V^2 – VE cos(δ)] / X
- Pulse Width Modulation (PWM
  - 2-20 kHz with Si IGBTs





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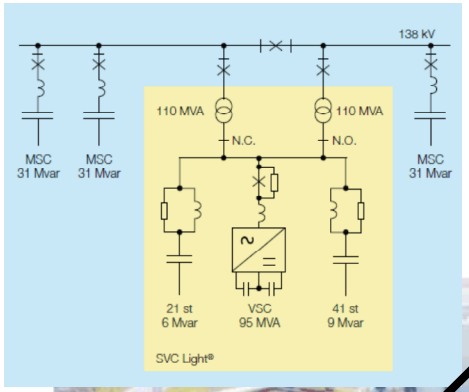
Real World STATCOM

- ***ABB Holly STATCOM near downtown Austin***



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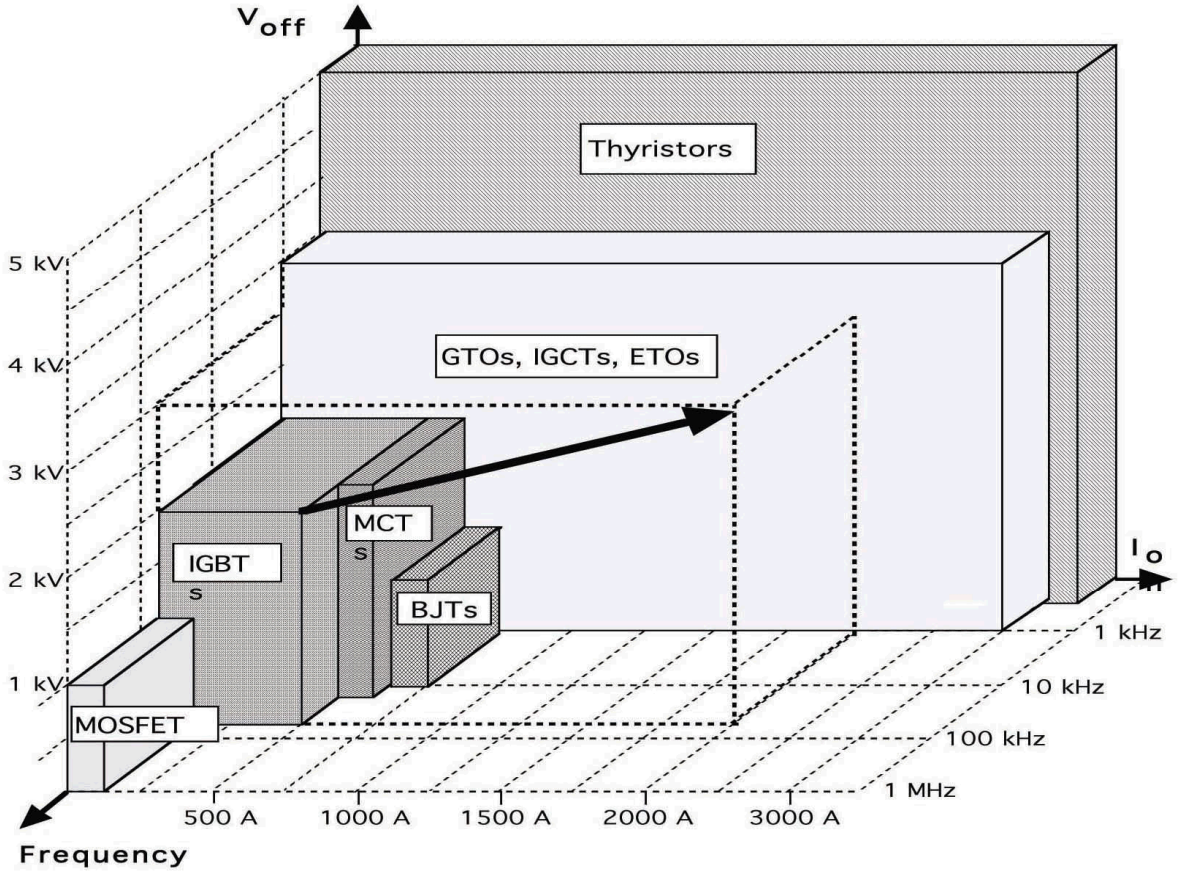
Power Devices used in FACTS

- **Diodes**
  - Most common device – usually a support device
- **Thyristors**
  - Main component of thyristor controlled capacitors/reactors
  - Original STATCOMs used thyristors, turn-off with zero crossing
- **Thyristor/transistor hybrids**
  - Gate, MOS, and Emitter turn-off (GTO, MTO, ETO)
  - Do not rely on zero crossing for turn off
- **IGBTs**
  - Major workhorse of modern STATCOMs
- **MOSFETs**
  - Do not exist in the voltages necessary!

ABB Si IGBT

I-V-f Ranges of Silicon Power Devices



Source: Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications and Design 3rd Edition (John Wiley & Sons, 2002)

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Power Device Requirements for FACTS

- **Reverse Blocking**
  - Transmissions voltages 60-100s of kV
  - Distribution voltages < 69 kV
  - Higher is better – reduc… p… element…
  - …rre…
  - …dern PE cooling syst… …eliable
  - Stable devic… …ry desirable
- **Frequenc…**
  - PWM (… …HVDC) operation at 2 kHz +
  - Switc… …important
  - Highe… …quencies desirable – gives greater control bandwidth and reduces passive filter requirements
- **RELIABILITY**

Thermal management systems are a major headache!

Thyristor Cooling Pipes

STATCOM Cooling System

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Silicon Power Devices

- *pin* diodes: $V_{BD} \approx 8000$ V commercially availa
- Thyristors: $V_{BD} \approx 8000$ V commer
- IGBTs: $V_{BD} \approx 6500$ V/75
- Sup
- All
- Ve uple chann gion

Silicon power devices are approaching their limits !

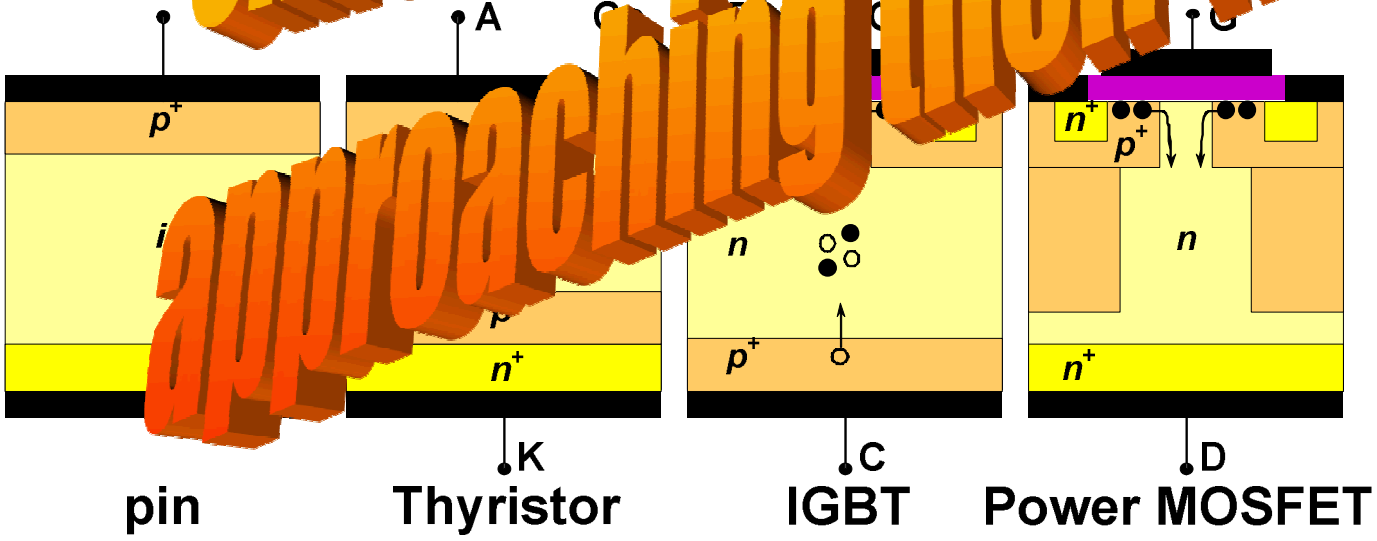

ABB Thyristor

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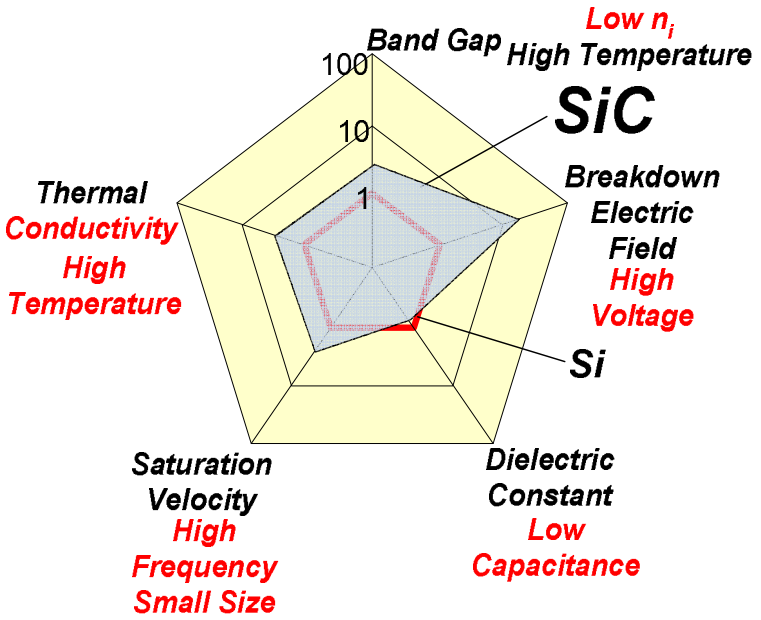
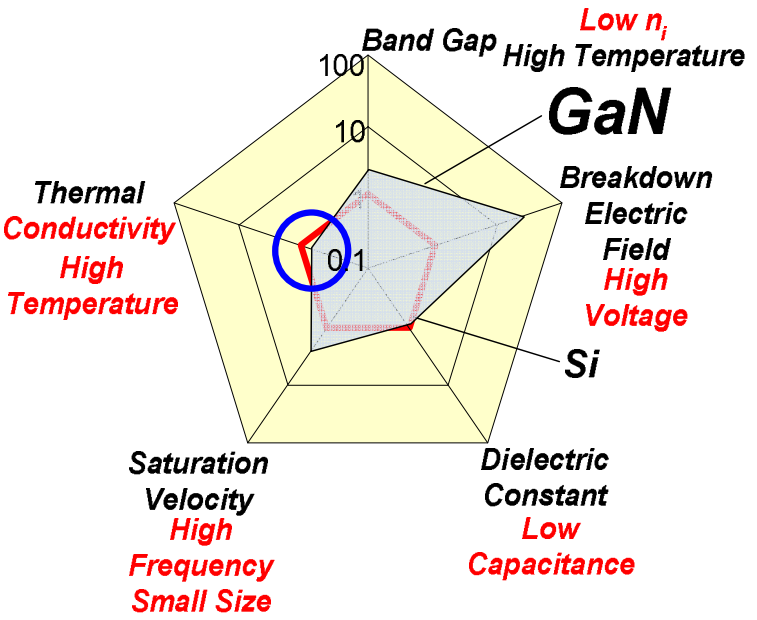
Why Wide Bandgap?





… Plus SiO_2 and Substrates

p

… Plus Heterojunctions

Both outperform silicon !

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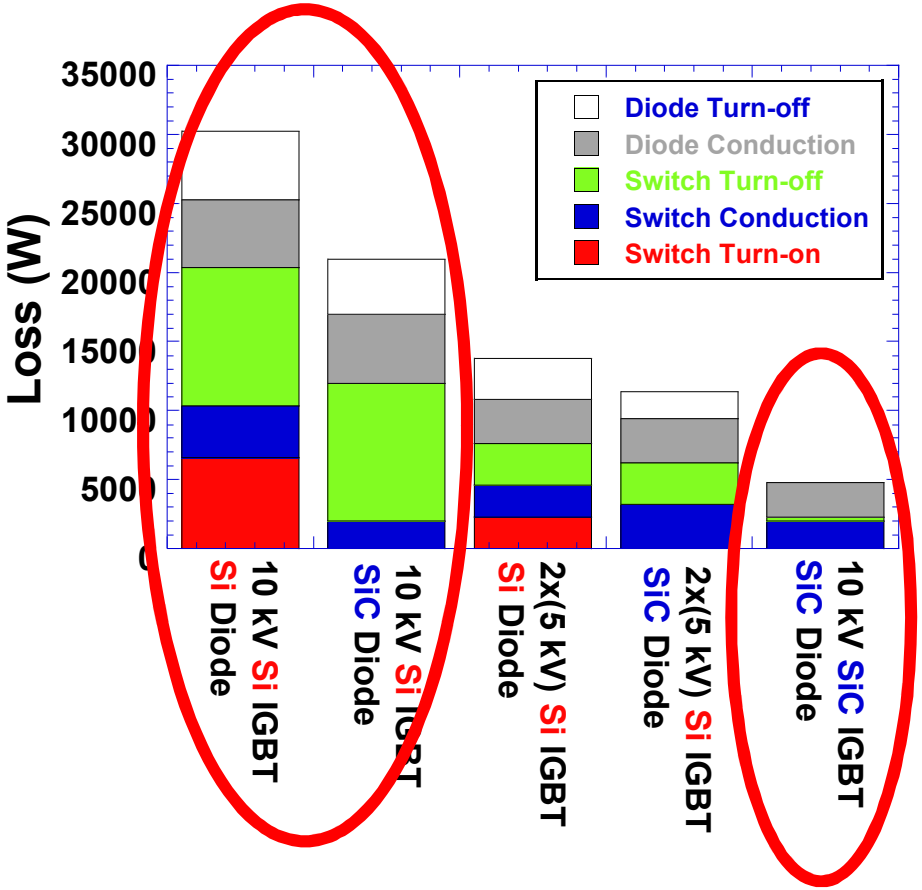
Why Wide Bandgap?

- **Example: 10 kV, 1000 A Switch**



SiC IGBT/SiC diode are best
……but SiC IGBT not available!

C.M. Johnson, *Int. J. Electron.* ***90,*** 667, 2003
Marinella et al

Opportunities: Silicon is Approaching Limits

- HV power electronics is a major opp tunity f WG
- Fact: 6.5% of all power rated in t los transmission an is
- R uire abi w ctro

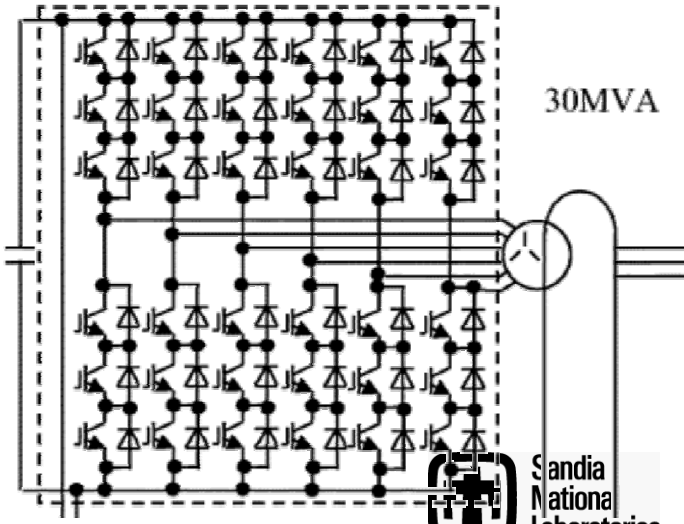
C

- ver ectronics

C

cy operation (>20 kHz)

Reliability is key!



FUJII K., et al., IEEE Trans. Power Electron., 2005, 20, (5), pp. 1125–1132

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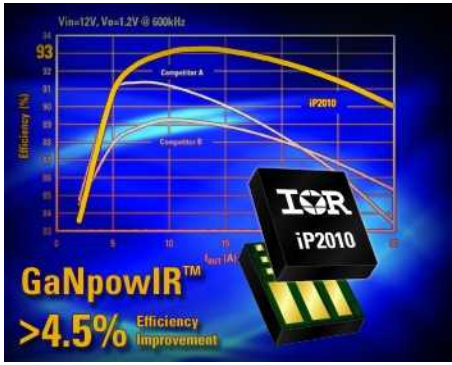
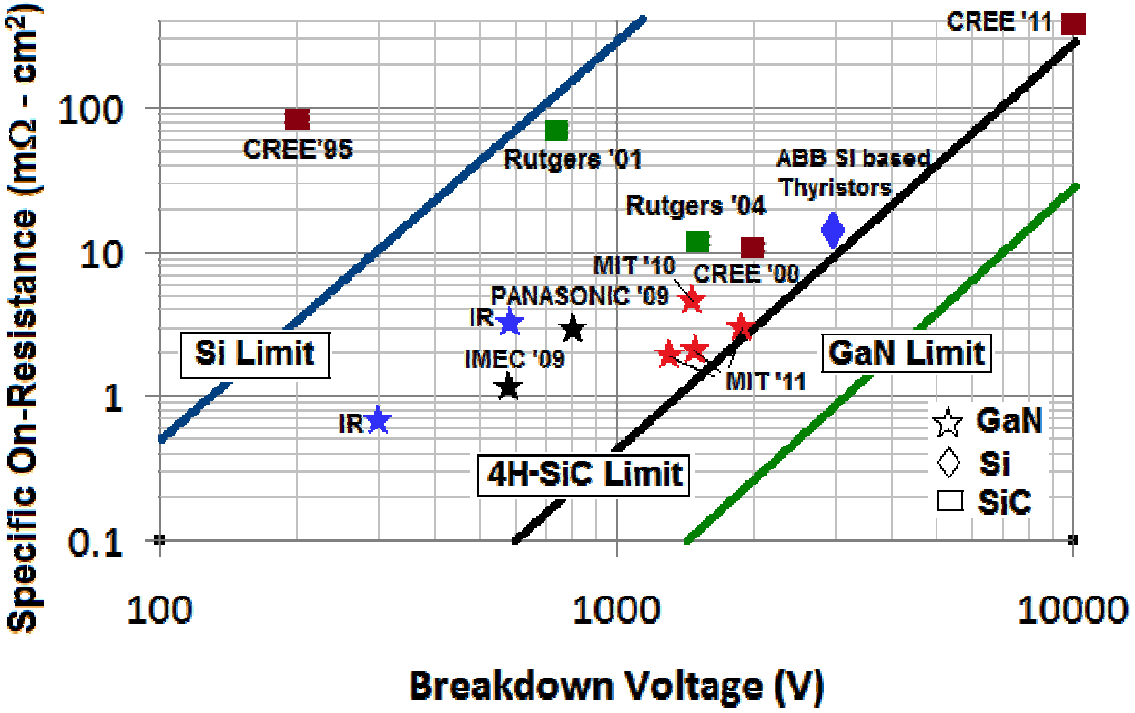
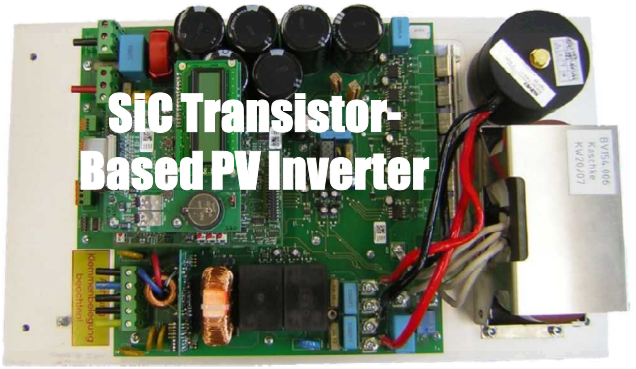
Status of WBG Power Devices?

- **Commercial SiC:**
  - 1200 V, 24A MOSFET (Cree), 1700 V Schottky diodes (up to ~25A), 1700V, 4A JFET (Semisouth)
- **Commercial GaN:**
  - 10V, 30A FET (IR announced 600V by end of 2011)







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Cree/Powerex/GE 10 kV 120 A H-Bridge

Device	Brkdwn Voltage	$P_{switching}$ 500 Hz	$P_{switching}$ 5 kHz	$P_{switching}$ 20 kHz	$P_{conduction}$ 100°C
Cree SiC MOSFET	12 kV	4 W/cm^2	40 W/cm^2	160 W/cm^2	100 W/cm^2
ABB Si IGBT	2x6.5 kV	72.5 W/cm^2	725 W/cm^2	2900 W/cm^2	182 W/cm^2

Si IGBT Module 13.5 kV, 100amps

SiC MOSFET Module 10 kV, 120amps

SiC 10 kV Modules are 9% Weight and 12% Volume of IGBT 13.5 kV Module

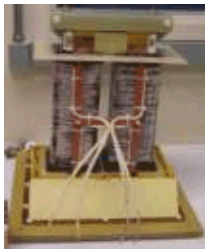
Funded by DARPA/ONR HPE Program

Cree/Powerex/GE 10 kV 120 A H-Bridge

OTS Transformer for SiC System

330 kVA 60 Hz transformer
55” high
2700 lb

LANL Transformer

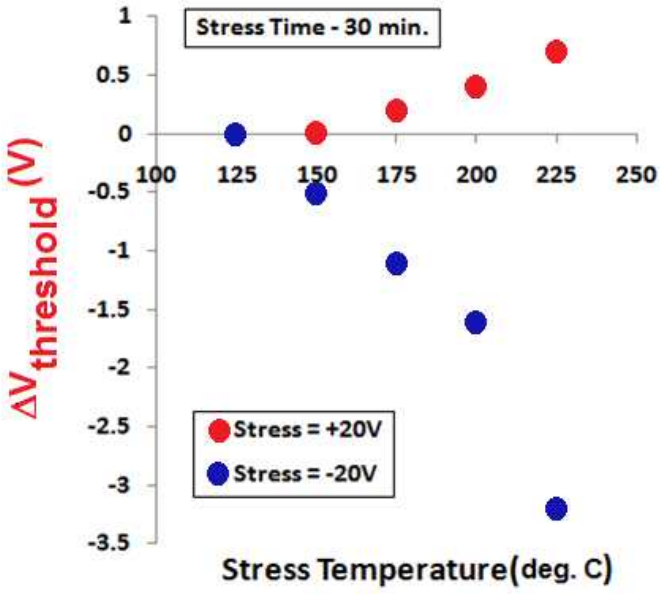


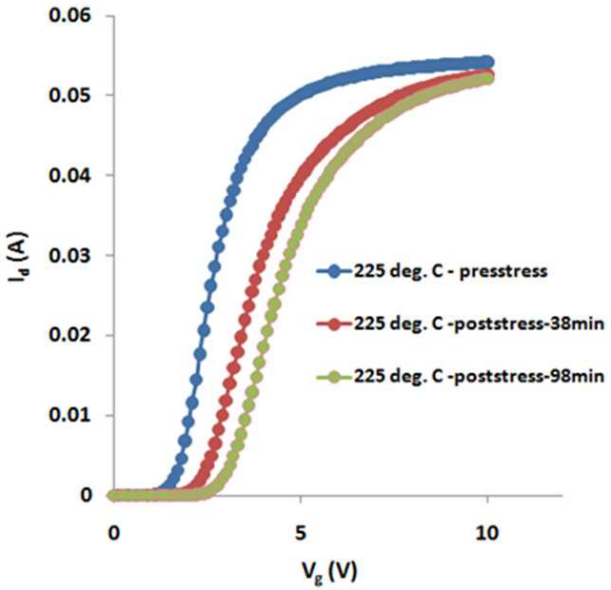
250 kVA 20 kHz transformer
16” high
75 lbs

Funded by DARPA/ONR HPE Program

Reliability is Key

- Power grid engineers will not even consider new components without a proven track record of reliability
  - Possible energy/cost savings does not compare with the fear of a blackout!
  - Must prove reliability is ≥ Si power devices
- Sandia has launched a program to study WBG reliability





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Summary

- FACTS controllers are like routers for the power grid
- FACTS controllers route the flow of power on transmission and distribution networks to avoid overloading
- Most common controllers are STATCOMs, SSSCs and SVCs
- HV SiC and GaN devices have a major opportunity to improve the world's power grids
  - Save energy, reduce component size, increased op temp
- Performance improvements are on track
  - HV SiC MOSFETs, IGBTs, and GaN HEMTs under dev
- Need focus on creating devices with impeccable reliability
  - Must prove reliability is ≥ Si power devices

References & Acknowledgements

- **References:**
  - Hingorani and Gyugyi, *Understanding Facts*, IEEE Press, 2000
  - Siemens FACTS Website (www.siemens.com/energy/facts)
  - ABB FACTS Website (http://www.abb.com/facts)
- **Acknowledgements**

  - Work at Sandia funded by the DOE Energy Storage Program managed by Dr. Imre Gyuk and x Program managed by Mike Soberoff of the DOE Office of Electricity.
  - D.K. Schroder (ASU) for several WBG device figures
  - Mrinal Das (Cree) for 10 kV SiC transformer pictures