Advanced Concepts for Fusion Power Supplies

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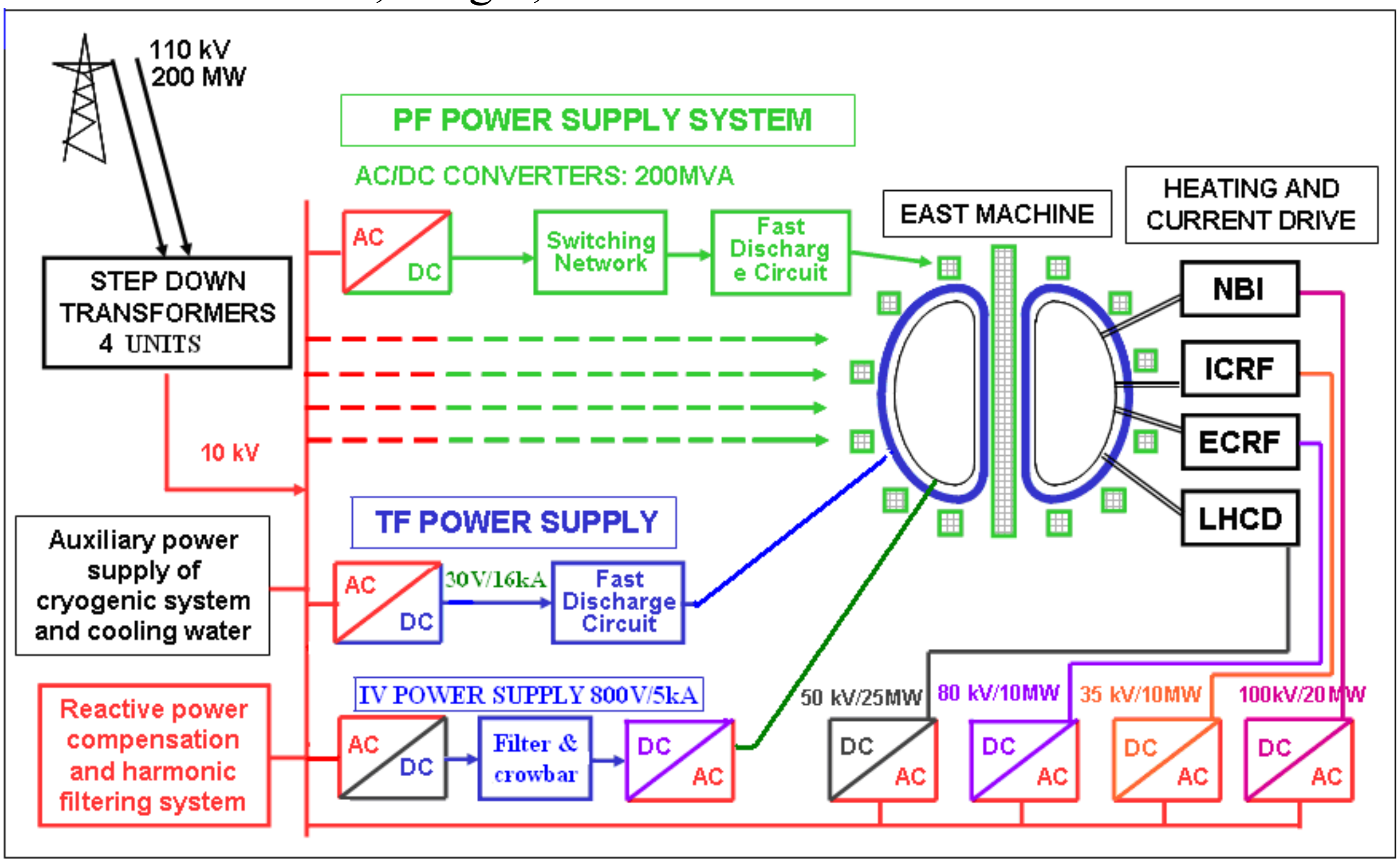
Challenges and Opportunities in Fusion Power Supplies

Extremely sophisticated high voltage power electronics network

- Large numbers of conversion units;
- Dynamic response required by new functions;
- Reactive power and harmonics issues;
- Size, weight, and cost.



System Diagram of the EAST Tokamak

Picture courtesy: Institute of Plasma Physics, China

Challenges and Opportunities in Fusion Power Supplies

Opportunity for optimizations overall power supply systems

- Universal modular circuits
- Control coordination between each function blocks

Newer and emerging technologies in power electronics

- IGBT and IGCT based switching circuits
- Multilevel inverters/converters
- Switched capacitor circuits
- Wide band gap devices, such as SiC and GaN

Suggested Approaches for Future Systems

Modular circuit structures

- Lower voltage/current stress for individual switching devices
- Lower costs
- Better power quality
- Fail safe

Adaptation of wide band gap devices

- Better efficiency
- Smaller footprint and weight
- Batter dynamic response

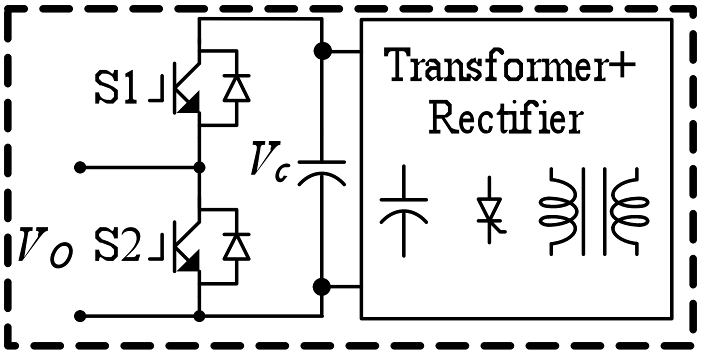
Distributed real time simulation

- Hardware-in-the-loop based algorithm development
- Platform for system level coordination and optimization

Modular Circuit Structure Example: M^2LC for Vertical Stabilization (VS) coils

Modular Circuit Structure Example: M²LC for Vertical Stabilization (VS) coils

Modular Multilevel Converter



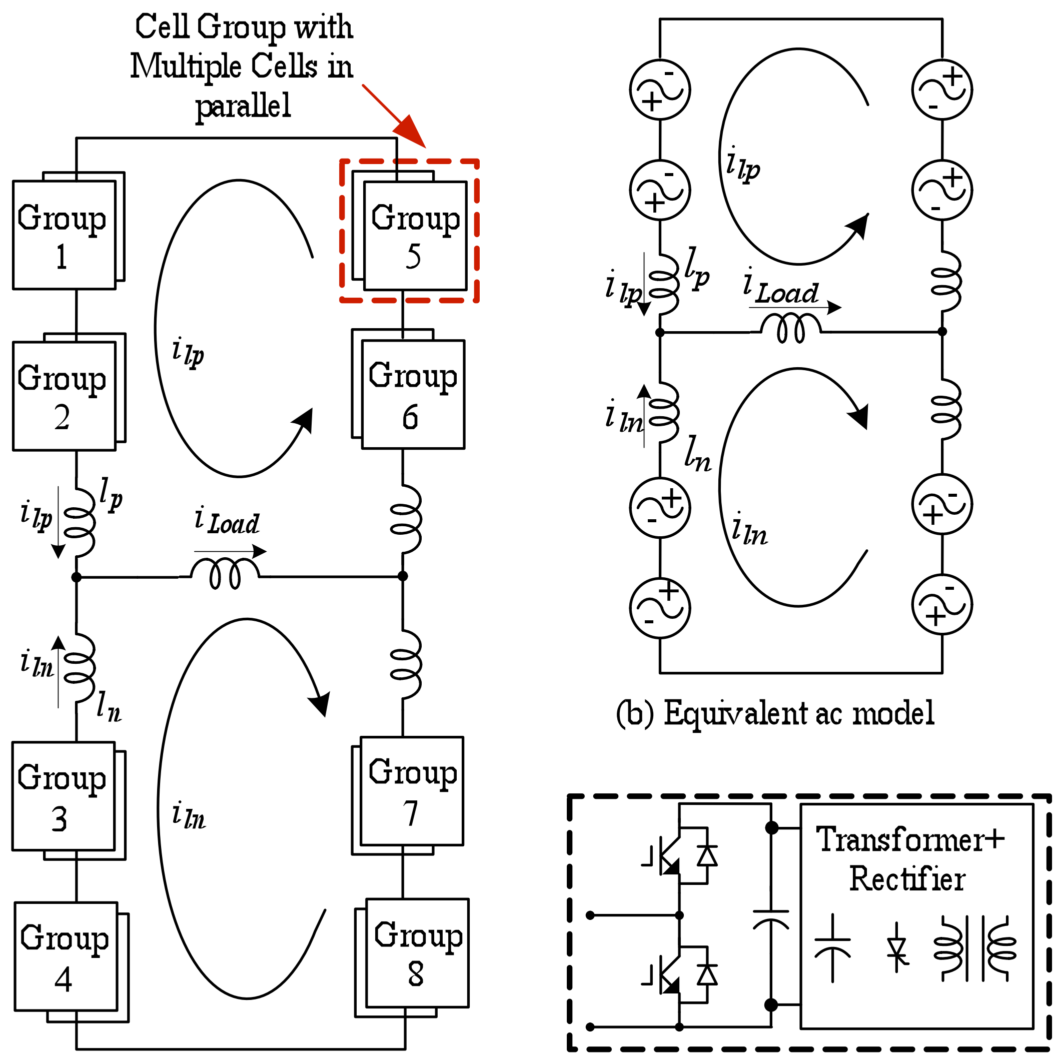
Basic switching module

Switching status	S1	S2	V_O
1	On	Off	Vc
2	Off	On	0

Active switching status

$$V_o = \frac{1}{2}V_C + \frac{1}{2}V_C \cdot M \cdot \sin(wt)$$

Equivalent output at pure sinusoidal Pulse Width Modulation



(a) Full circuit structure

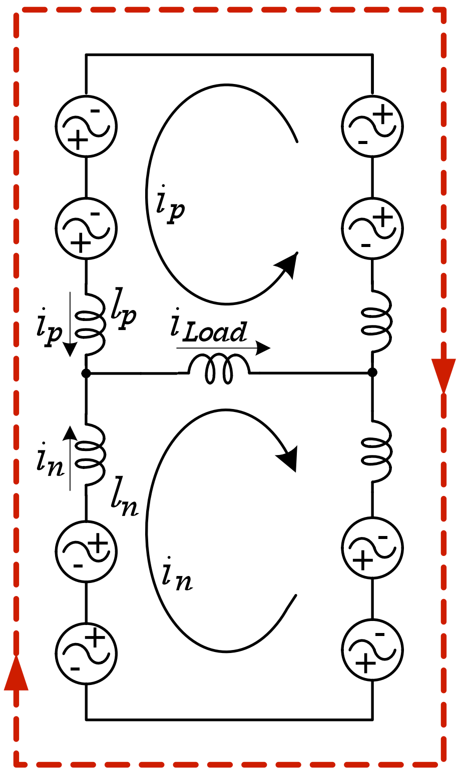
(b) Equivalent ac model

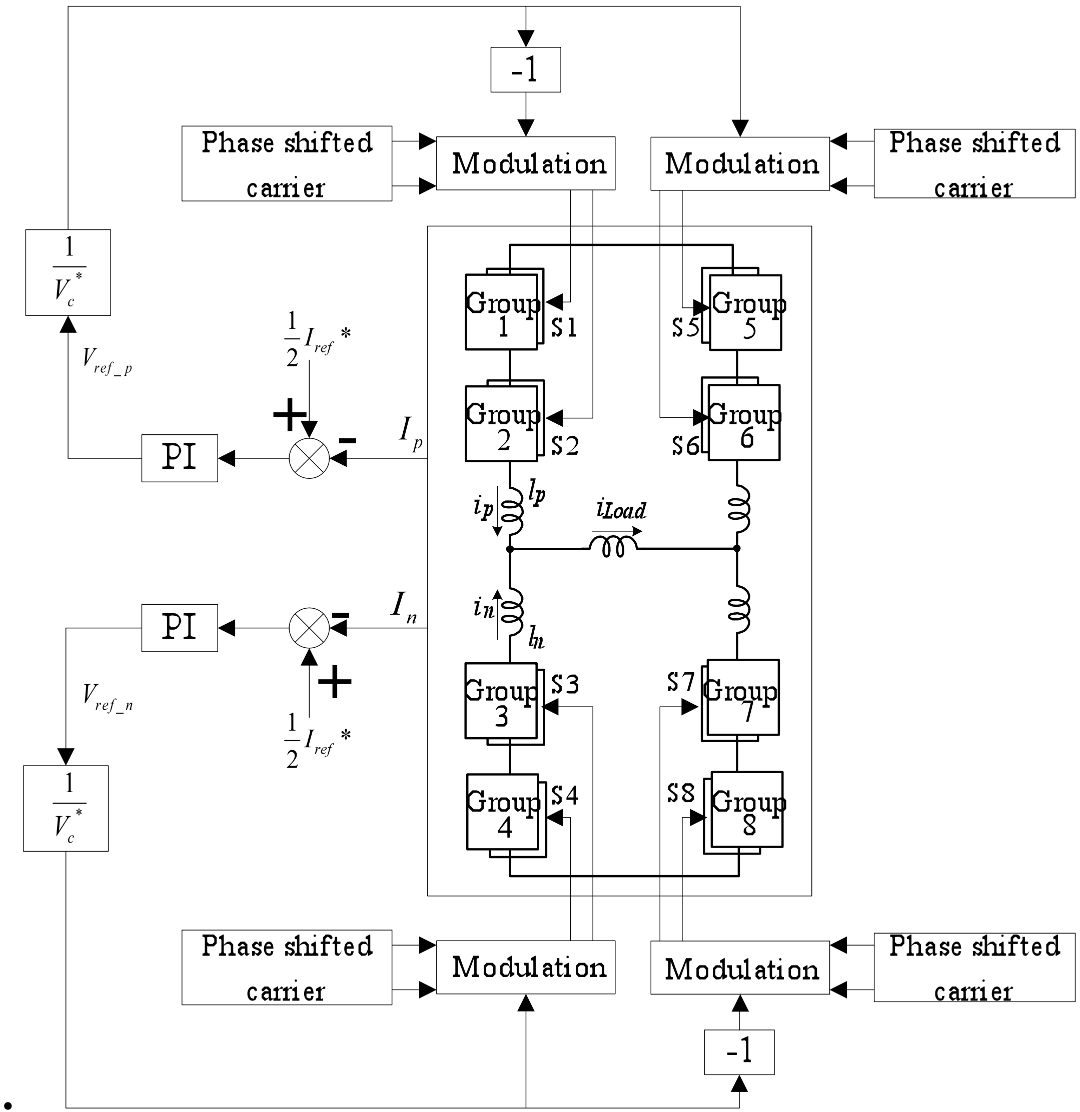
(c) Single cell structure

Control Strategy

Control Goal:

1. Regulate the VS coil current
2. Minimize looping current





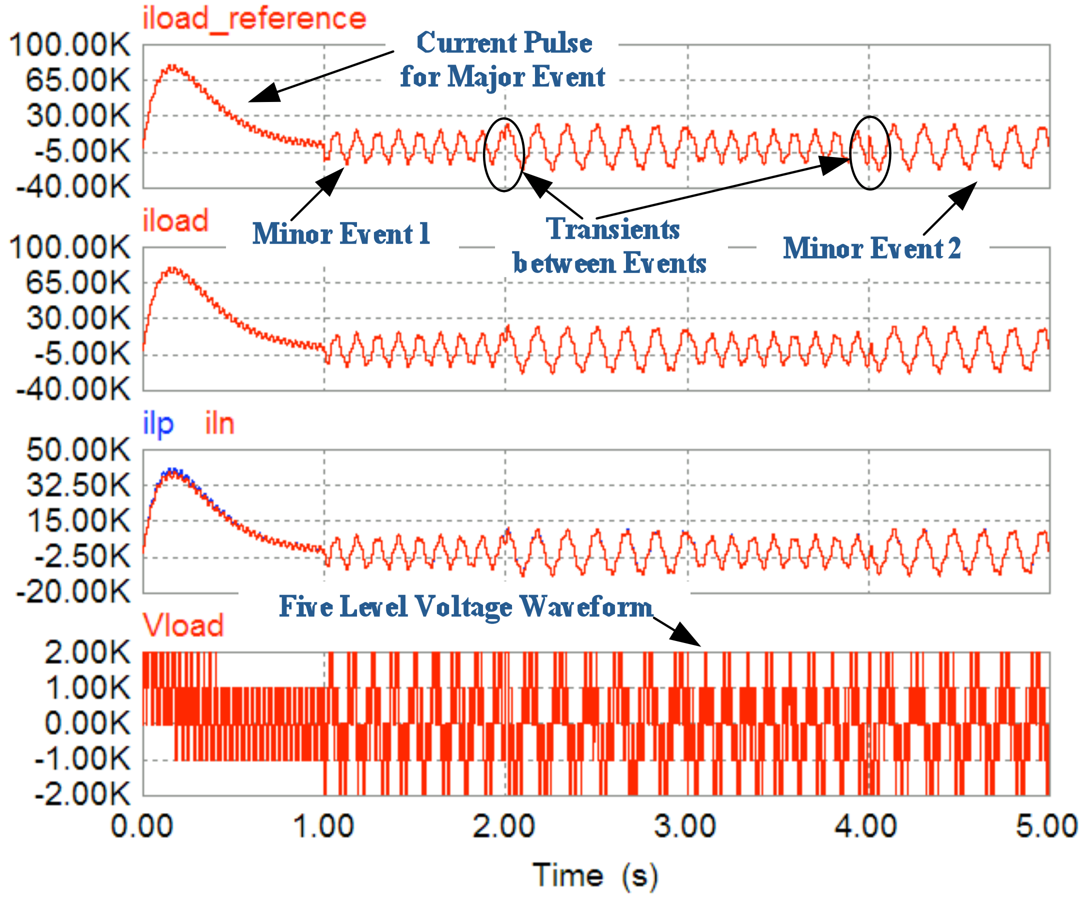
Control Strategies

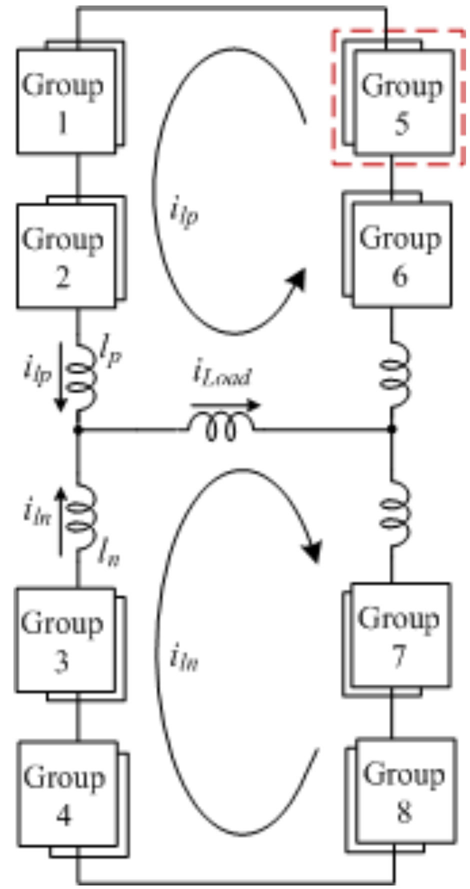
1. Independent control of i_p and i_n
2. Multi-carried phase-shifted Pulse Width Modulation

Simulation of the M^2LC for a VS coil

Load inductance L	1.4 mH
Load resistance R	10 m
Buffer inductance L_p,L_n	5 uH
Module capacitance	2 F
Capacitor voltage in cell groups 1&2 (V_{lu})	1185 V
Capacitor voltage in cell groups 3&4 (V_{ll})	1200 V
Capacitor voltage in cell groups 5&6 (V_{ru})	1230 V
Capacitor voltage in cell groups 7&8 (V_{rl})	1170 V
Carrier frequency	2 kHz
Proportional gain Kp	5 V/A
Integral gain Ki	10V/(A s)

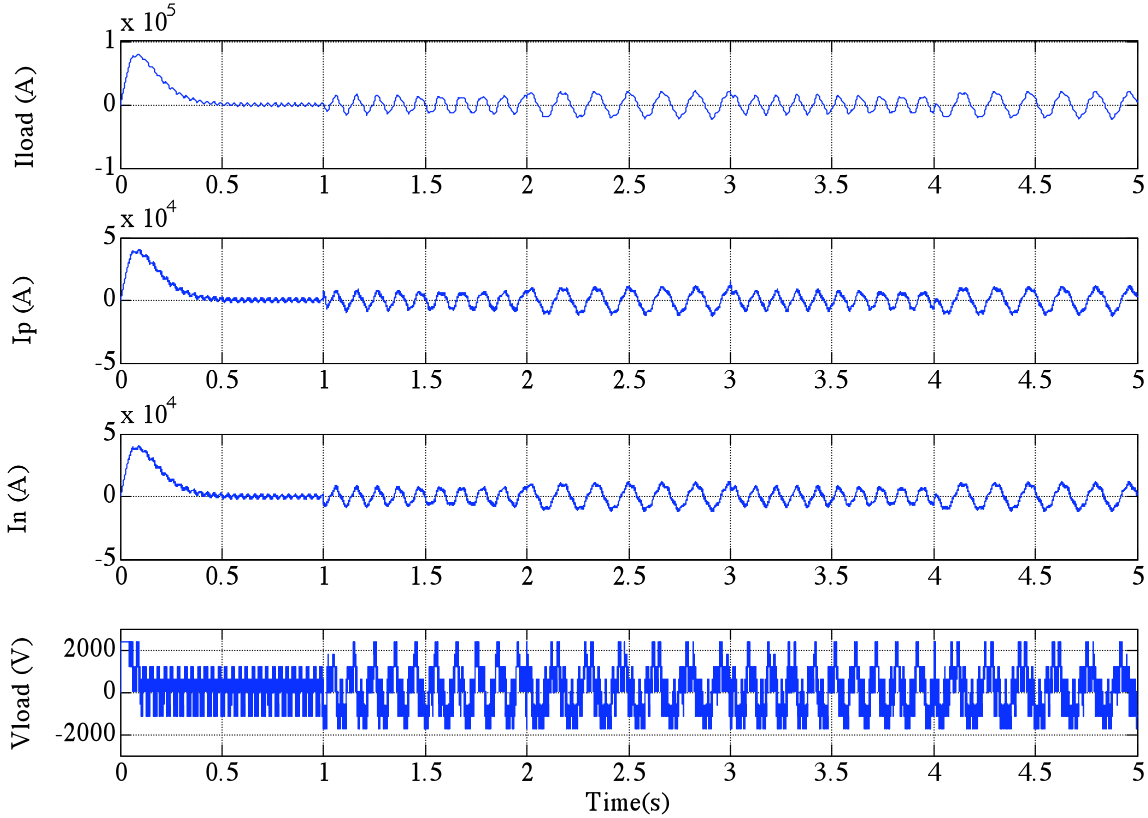
Simulation Results: M²LC for Vertical Stabilization (VS) coils

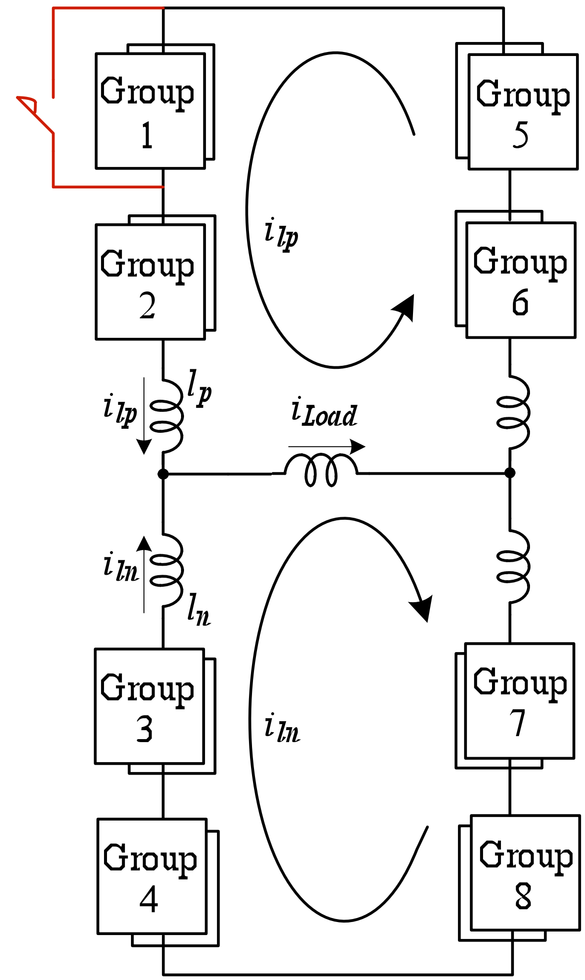




The current reference has one major event and two minor events. A continuous 30 Hz 3000 Ampere "noise" is added on top of all the events.

By-pass Operation of Faulty Modules, Case I





At 2.5 s, assuming there was a device failure, Group 1 was shorted out.

Because of the robust control strategy and redundant voltage for the two minor events, the load current is not affected.

Advantages of the Circuit

- **lower voltage stress on switching devices;** with lower voltage stresses, 1400 V to 1700 V rated IGBTs could be used; usually, IGBTs at this voltage range can be switched at a higher frequency than IGCTs; thus, superior dynamic response could be achieved;

- **lower current stresses**; since i_{load} is the summation of i_{ln} and i_{lp}, each cell (cell group) only needs to supply half of the load current;

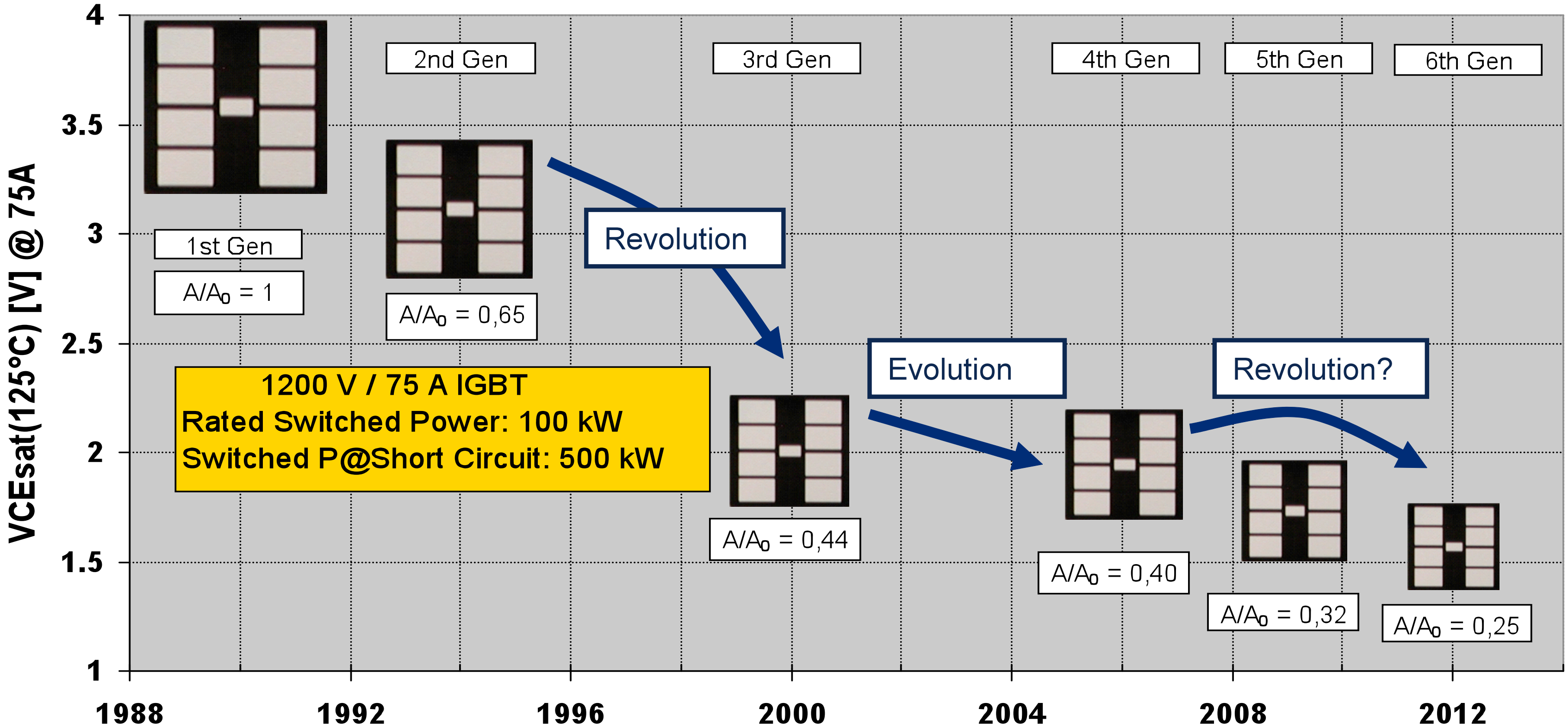
- **expandability;** if needed, more cell (cell groups) can be connected in series to achieve a higher voltage level;

- **multiple level output;** high resolution current control with low switching frequency and good efficiency;

- **fail safe**; failed module could be disconnected while the full system goes through safe shut down process.

Adaptation of Wide Band Gap Devices

Roadmap of major device manufactures

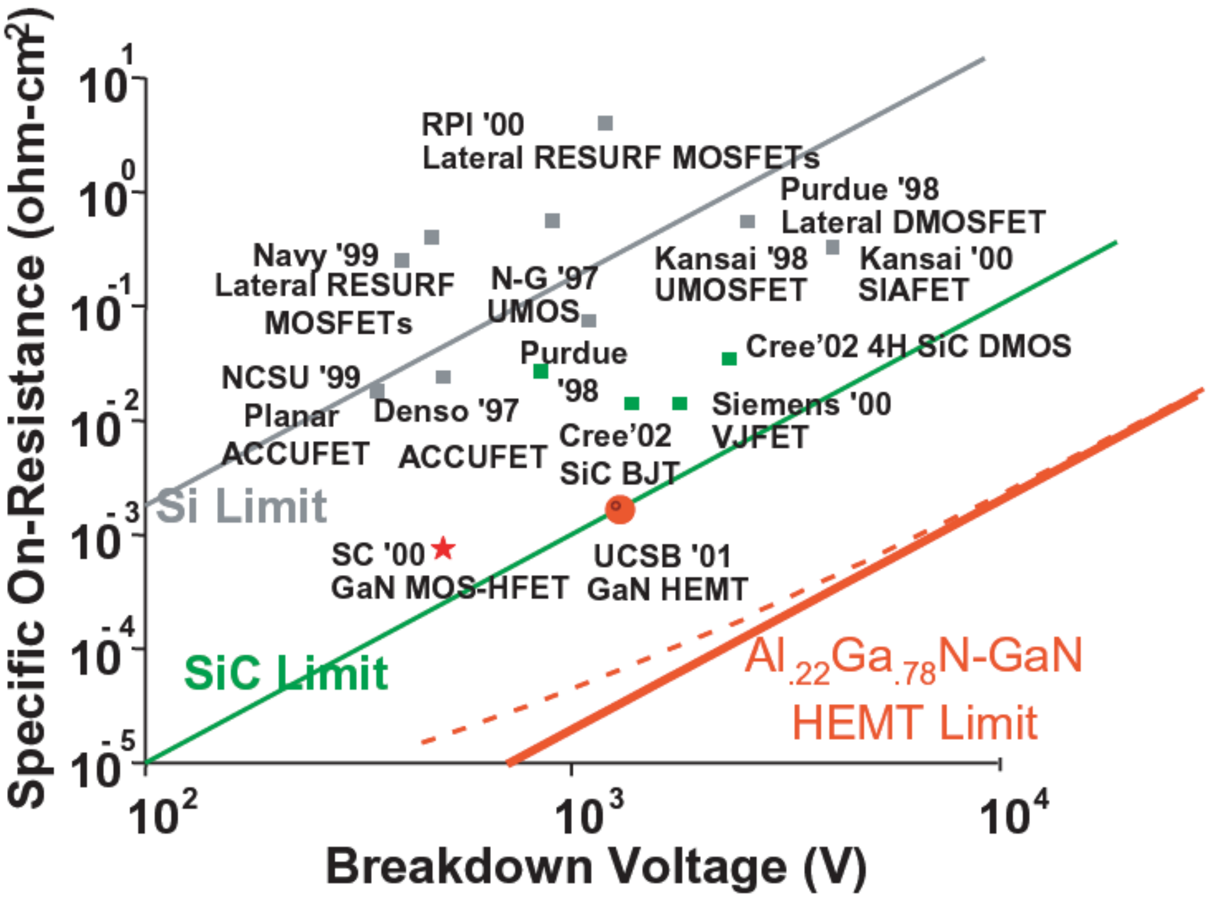


Infineon: High Temperature Power Electronic Devices and Packaging for HEV

- **Development of Si based chips for power switching has come to an end.**
- **The two development directions are: better cooling strategy and wide band gap devices.**

Adaptation of Wide Band Gap Devices

On Resistance vs. Breakdown Voltage



SiC have 10X lower total power dissipation than Si.

Rajan: GaN Device in OSU

Adaptation of Wide Band Gap Devices

SiC Power Devices

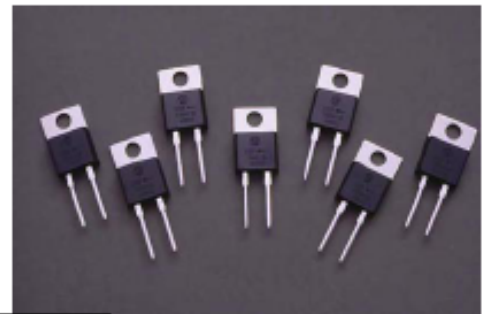
Commercial Availability

- Silicon Carbide Schottky rectifiers commercially available from 3 sources:
  - CREE, Inc (NC), SiCED (Siemens/Infineon-Germany), SemiSouth Laboratories (MS)

Product links to U.S. Manufacturers Diode Products

http://www.semisouth.com/products/powersemi.html

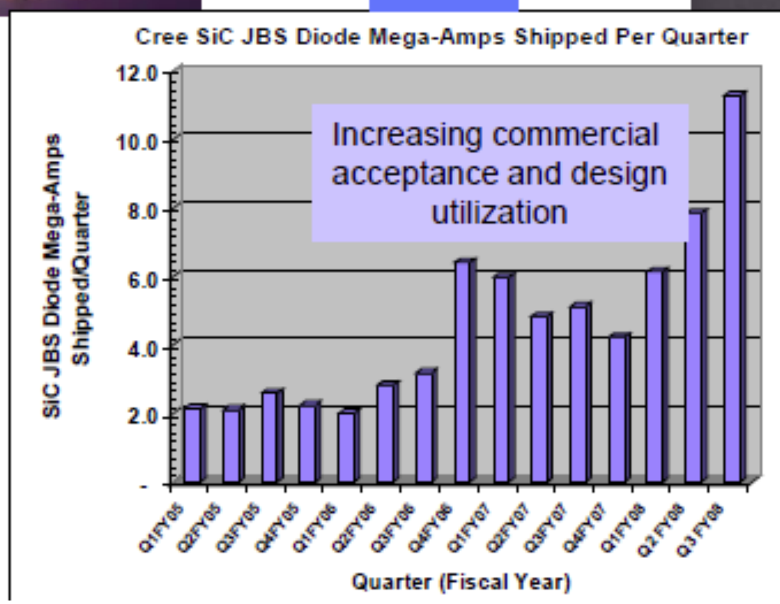
http://www.cree.com/products/power_docs2.asp



TRL 9

11 x 10^6 Amps Delivered in 3Q 2008 Commercial viability an implied requirement for DoD availability.

COST
RELIABILITY
PERFORMANCE



- Over 2x Price Reduction

1. Higher Quality SiC Material
2. Larger Production Volumes
3. Increase SiC Wafer Size from 3 inch to 100 mm

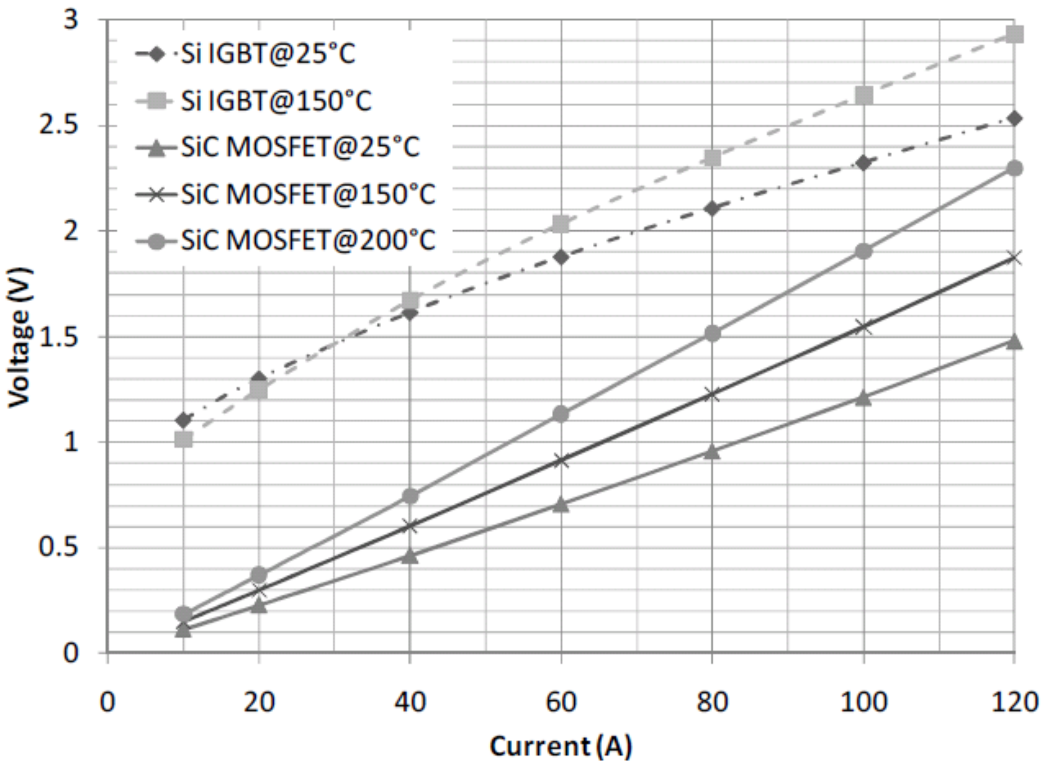
Lack of a switching product slowed large scale adoption

Picture courtesy: Wright Patteron Air Force Base

Adaptation of Wide Band Gap Devices

Megawatt scale applications

External view of 1.2kV/100A, all-SiC Half H-Bridge power module



Comparison of on-state voltage between the 1.2kV/100A SiC module and the equivalently rated Si IGBT module (CM100DY-24NF)

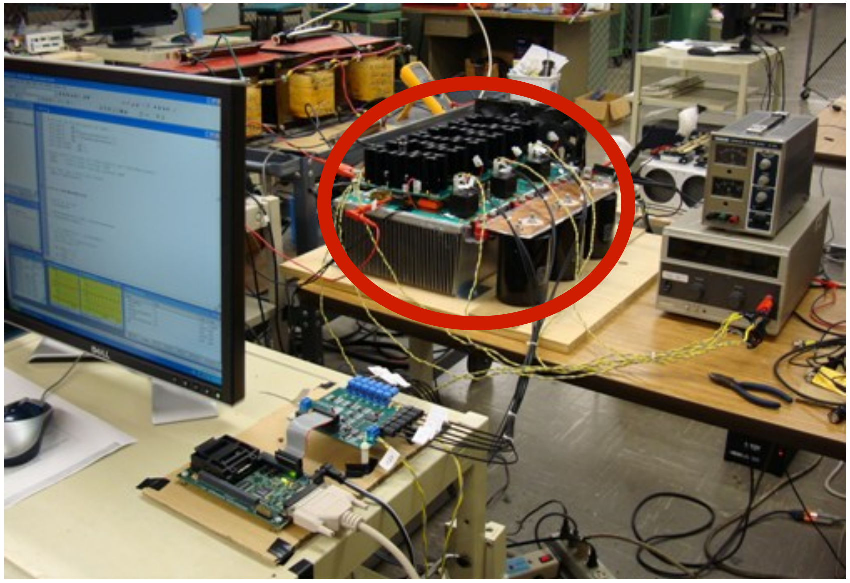
Jim Richmond, Scott Leslie, etc. "Roadmap for Megawatt Class Power Switch Modules Utilizing Large Area Silicon Carbide MOSFETs and JBS Diodes"

High Voltage Devices

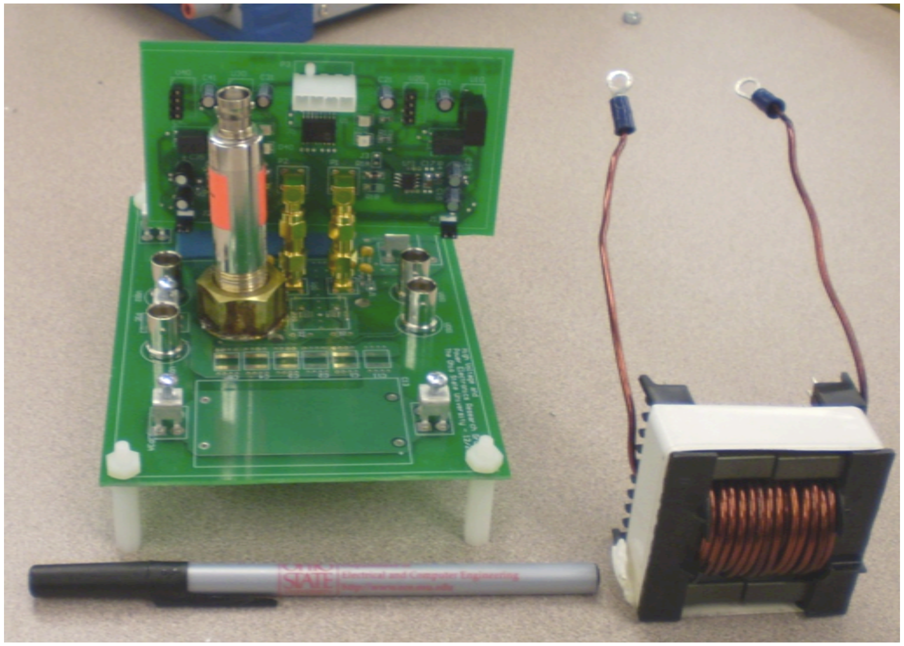
9% Weight and 12% Volume vs IGBT module

High Voltage Silicon Carbide Power Devices. [Online]. Available: http://arpae.energy.gov/LinkClick.aspx?fileticket=RaTsvSs0acE%3D&tabid=116

OSU 30 kW SiC JFET Inverter and GaN Tests



30 kW SiC JFET Inverter



GaN Test Board

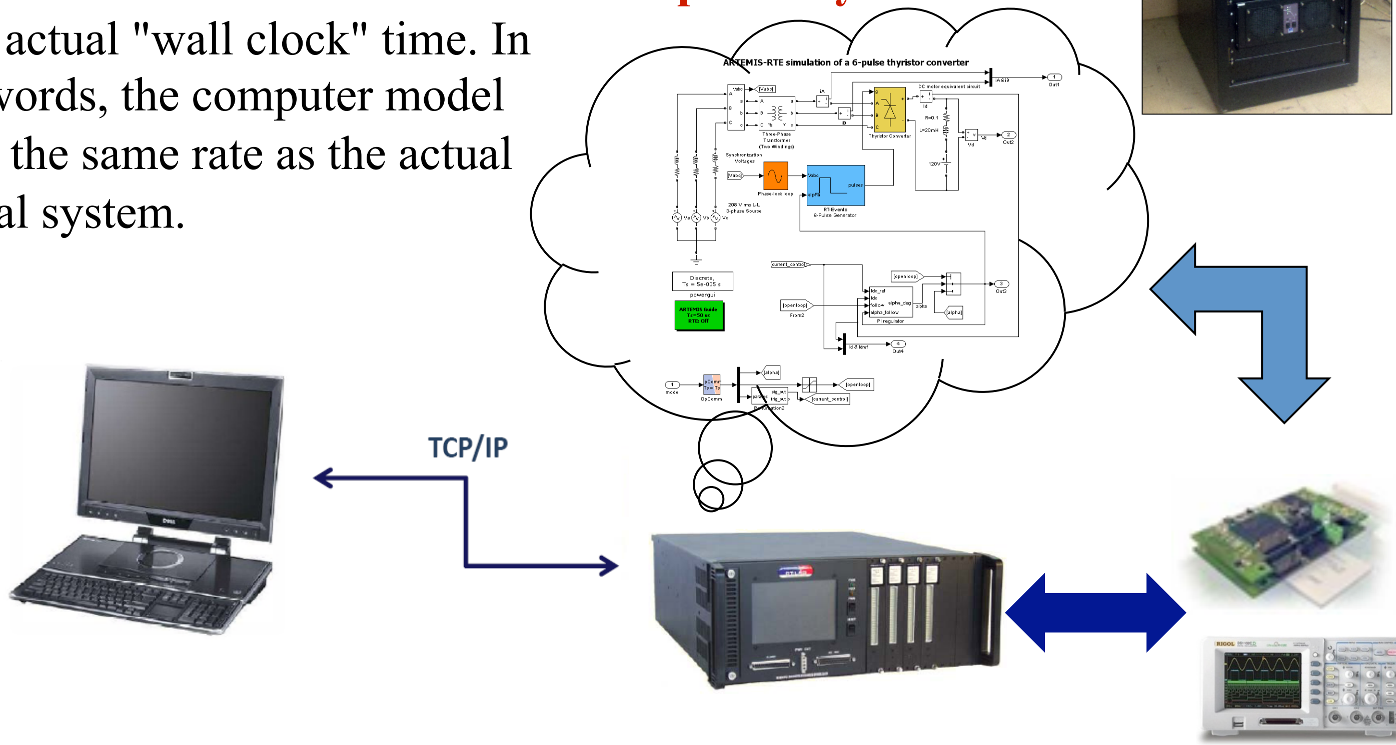
Distributed Real-time Simulation

Advanced Real Time Simulation System

Real-time simulation for Electric Power Systems

Real-time Simulation refers to a computer model of a physical system that can execute at the same rate as actual "wall clock" time. In other words, the computer model runs at the same rate as the actual physical system.

Model of electric power systems

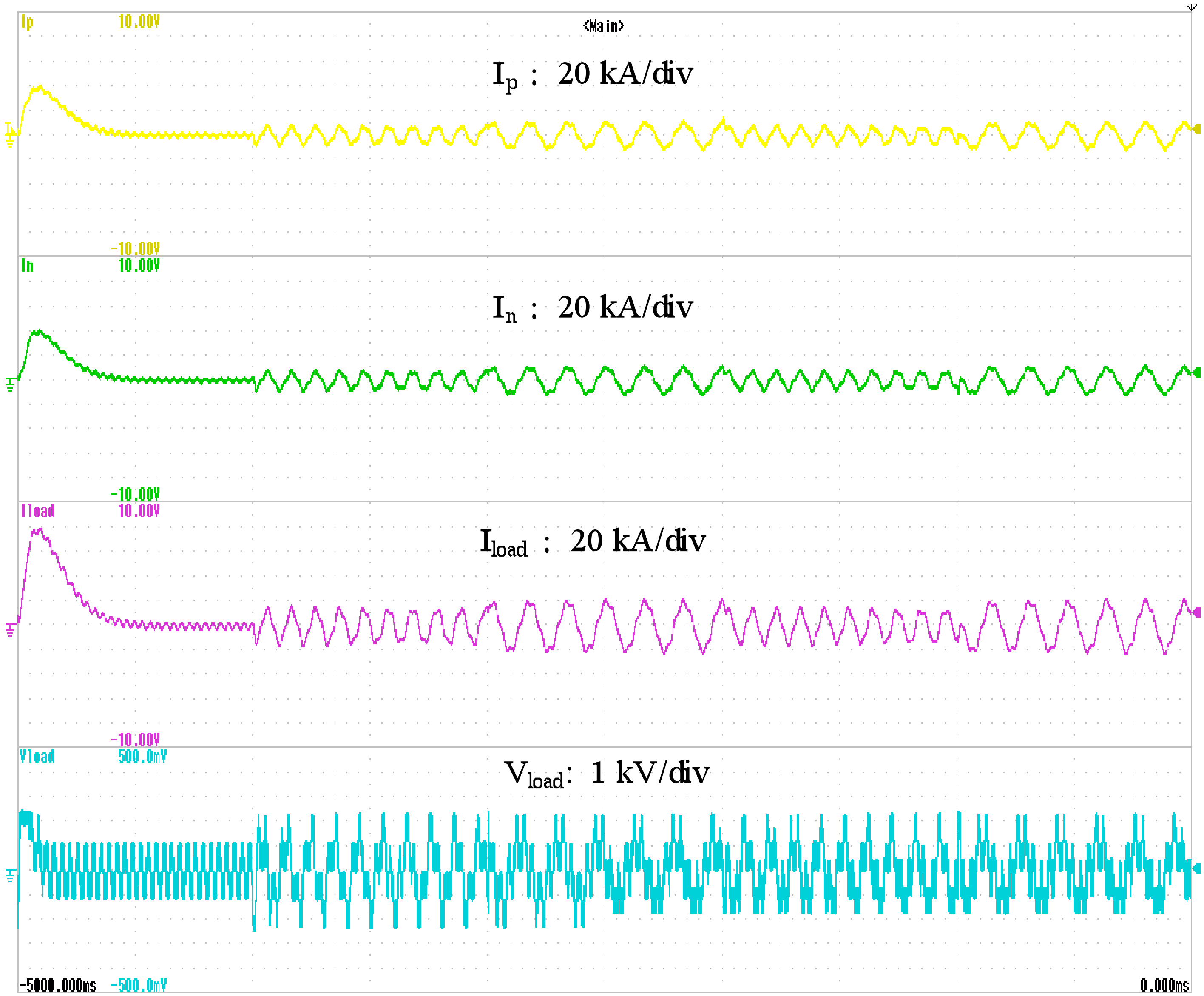


- 4 real-time target machines;
- 10 CPUs;
- PCI links between targets;
- 512 Digital I/O;
- 4 Xilinx FPGAs
- 282 Analogue I/O.

I/O and real-time model execution

External monitoring and control units

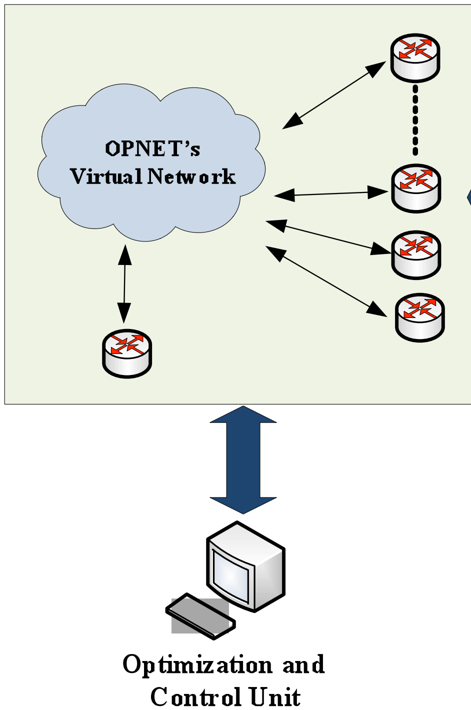
Real Time Simulation Results of the M^2LC for a VS coil

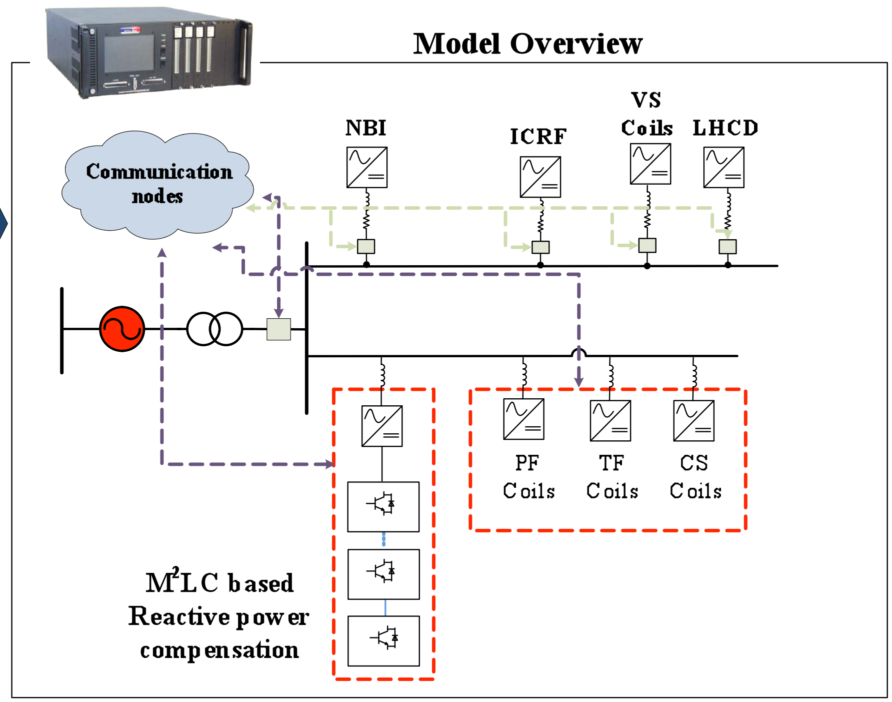


Simulation Results Observed with Digital Oscilloscope (Yokogawa DL480V)

Next Step: System-in-the-loop based Real Time Simulation and Analysis

Real time simulation of Communication Network





Real time simulation of Electric Power System

- Combine real time simulations of electric power system and real time simulation simulations of communication (system-in-the-loop) network;
- Analysis the impact from communication network failure and latency;
- Pave the road for system level coordination/optimization.

Thanks for your attention.

Questions?