# A Transmission UltraCAPacitor (TUCAP) utilizing Emitter Turn-Off thyristor (ETO) and UltraCAPacitor (UCAP)

## Development and Demonstration

**Chong Han[1], Alex Q. Huang[1], Stanley Atcitty[2*], Aty Edris[3], Mike Ingram[4], Haresh Kamath[5]**

**1: North Carolina State University**
**2: Sandia National Laboratories**
**3: Electric Power Research Institute**
**4: Tennessee Valley Authority**
**5: EPRI Solutions**

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# ACKNOWLEDGMENTS

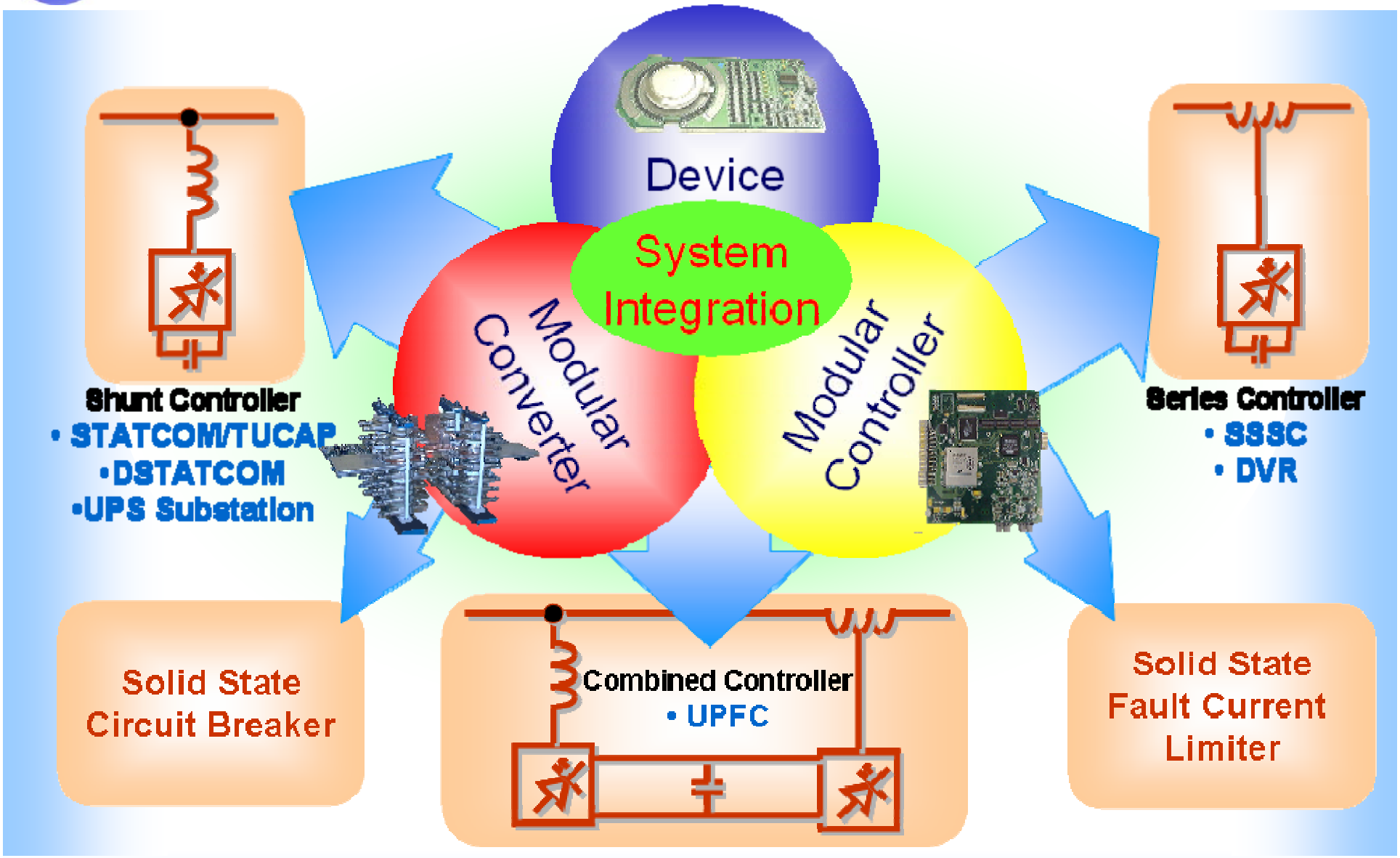

- Funded in part by the Energy Storage Systems Program of the U.S. Department Of Energy (DOE/ESS) through Sandia National Laboratories (SNL).

# Semiconductor Power Electronics Center Research Areas

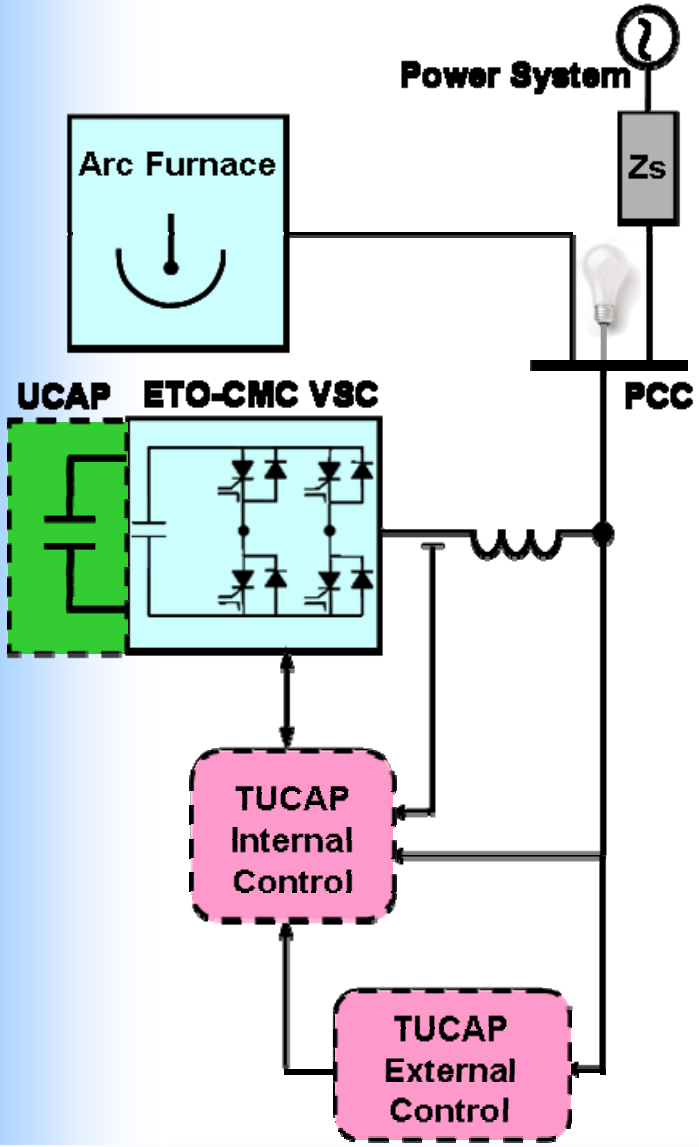
- Power Semiconductor Devices (PSD)
- Power Management Microsystems (PMM)
- Utility Power Electronics (UPE)
- Electric Power Systems (EPS)

- Director: Alex Q. Huang
- Nine faculty members
- 30+ graduate students
- 8000 sq. ft of lab space
- http://www.ece.ncsu.edu/spec/

# Key Technologies under Development at SPEC



# Transmission UltraCapacitor (TUCAP) Current Focus




**Objective:**

**4.5MVA/2MW Static Synchronous Compensator (STATCOM)/TUCAP Demonstration for Voltage Fluctuation Mitigation**

**Presentation Outline:**

- **Emitter Turn-Off thyristor (ETO)**
- **ETO-based PCS demonstration**
- **UCAP modeling and analysis**
- **TUCAP internal control design and verification**

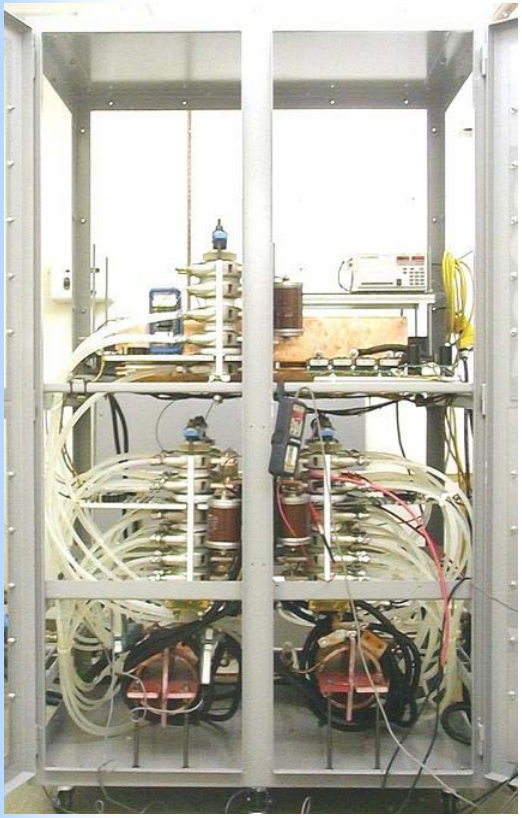
# ETO Characteristics and Advantages

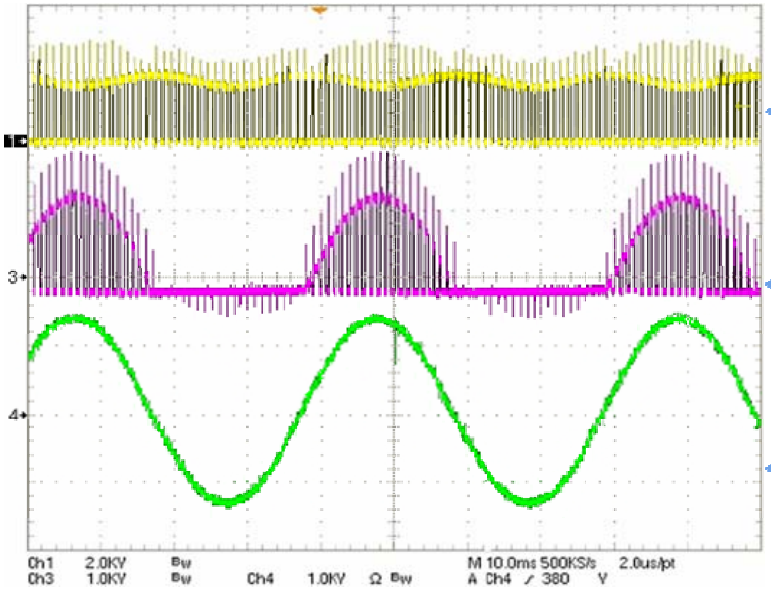
| Characteristic | ETO | IGCT | IGBT |
|---|---|---|---|
| **Conduction Losses** | Good | Good | Poor |
| **Positive Temperature Coefficient** | Best | Poor | Good |
| **Identical Switching Times** | Best | Best | Good |
| **Turn-Off Capability** | Best | Good | Good |
| **Built-In Current Sensing Capability** | Yes | No | No |
| **Control Power Needed** | Low | Very High | Low |
| **Cost per kW** | Lowest | Low | Higher |
| **Current Scalability** | Easy | Difficult | Moderate |
| **Technology Lifecycle Stage** | Introduction | Maturity | Saturation |

# ETO: 30% Capacity Improvement of GTO

| | ETO4045TA03 | GTO 5SFG 40L4502 |
|---|---|---|
| Voltage/Current | 4500V/4000A | 4500V/4000A |
| Thermal resistance ( double sides water cooling, Tj=120° C, Tw=55° C) | 21.6K/kW | 19.5K/kW |
| RMS Current due to thermal limit | 2426A | 2440A |
| Turn off snubber | Snubberless, RCD Voltage Clamp, C=1.5 μ F, R=0.5 Ω | RCD Snubbers C=6 μ F,R=5 Ω |
| Typical turn-on di/dt snubber | L= 4 μ H | L=6 μ H |
| Turn-off storage time | 2 μs | 25 μs |
| Maximum trip current level assuming fault current rising @ 40A/μs | 3800 | 3000 |
| RMS current @ 1.22 pu | 2500 | 1920 |
| RMS current @ 1.0 pu | 2050 | 1574 |
| **Output power capacity** | **130%** | **100%** |
| Voltage Clamp/Snubber loss | 180 W | 720 W for each GTO |
| Short through protection capability | Yes (RMS current=1574A) | No |
| Operation in series | Very good<br>Less voltage de-rating | Need timing adjustment by control<br>Large voltage de-rating |
| Driver circuit | Simple | Complex |

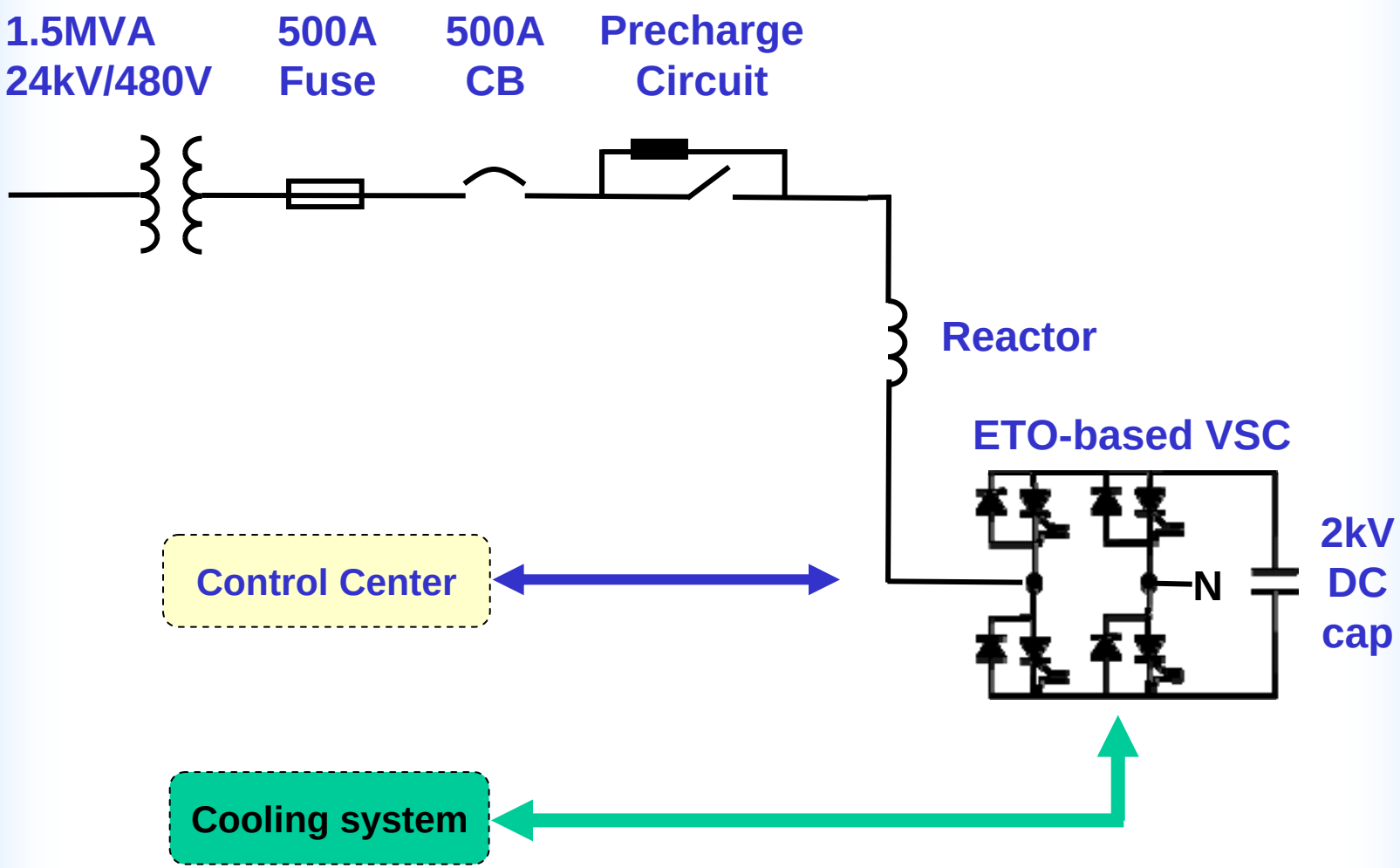
# ETO-Based 1.5MVA Modular H-Bridge Voltage Source Converter



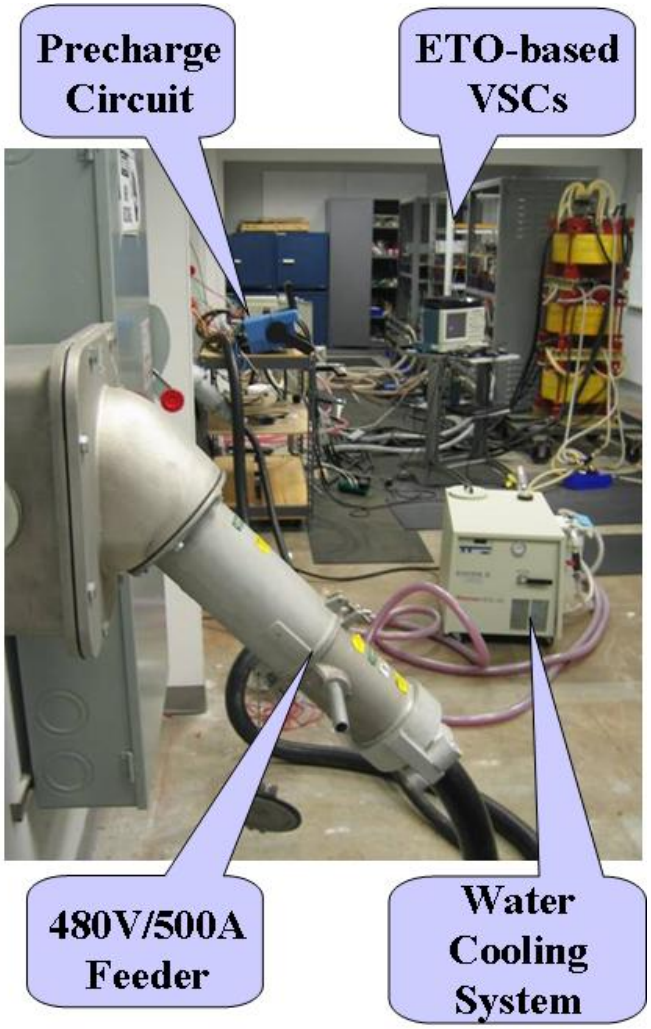



**Testing condition: Power capacity: 1.5MVA**
**Line frequency: 25 Hz, Switching frequency: 1 kHz**
**DC bus voltage: 2 kV, Output RMS current: 1.0kA**

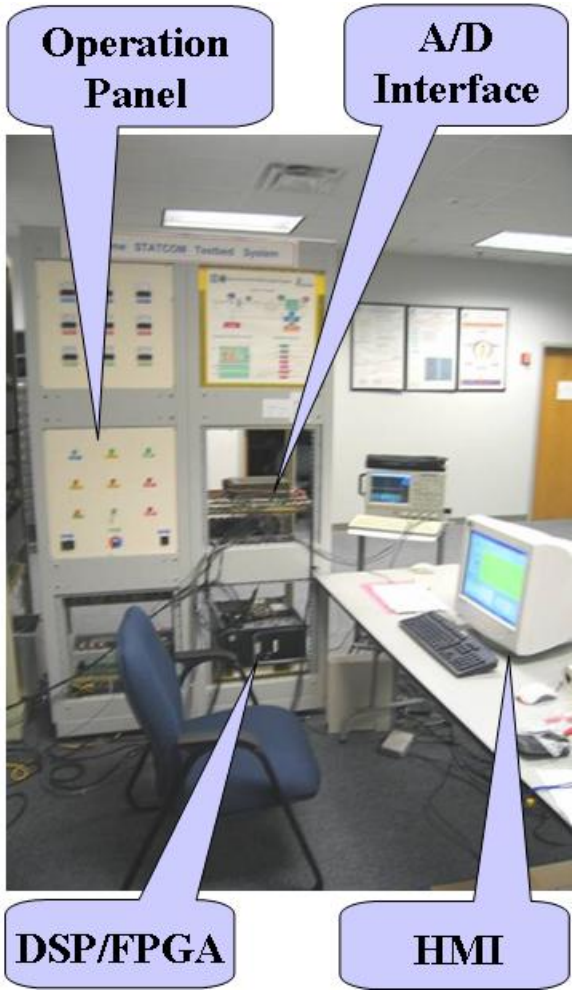
# 480V/500A Demonstration One-line Diagram of a 4.5 MVA ETO-Based STATCOM



# 480V/500A Grid-Tie Demonstration Setup

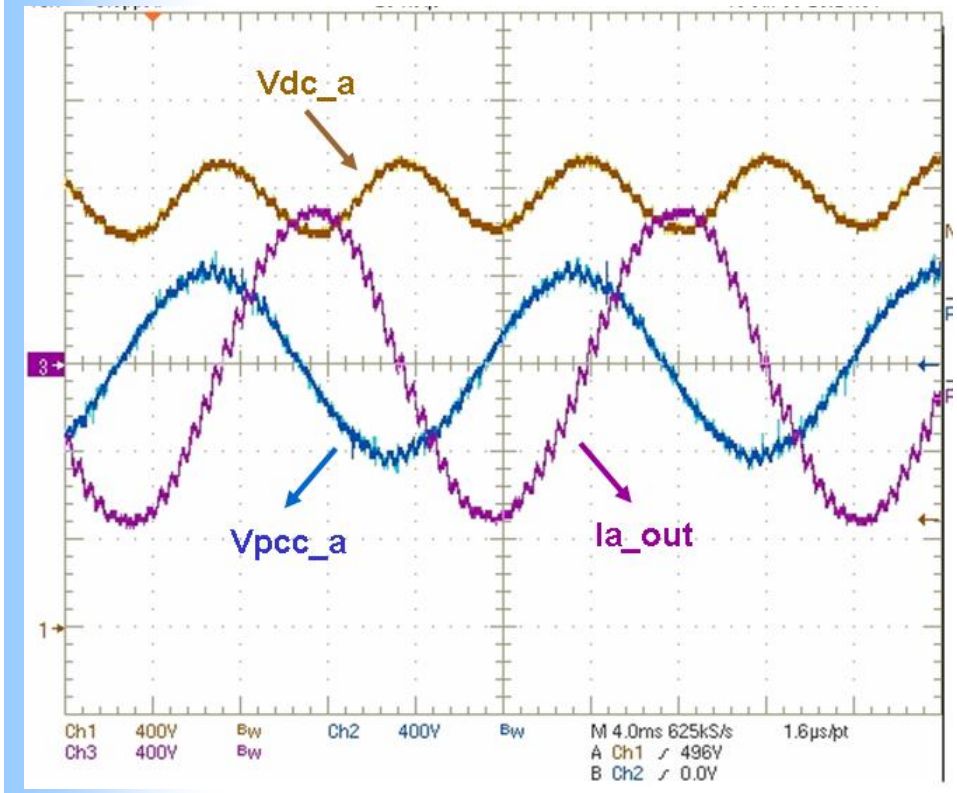



Power stage setup

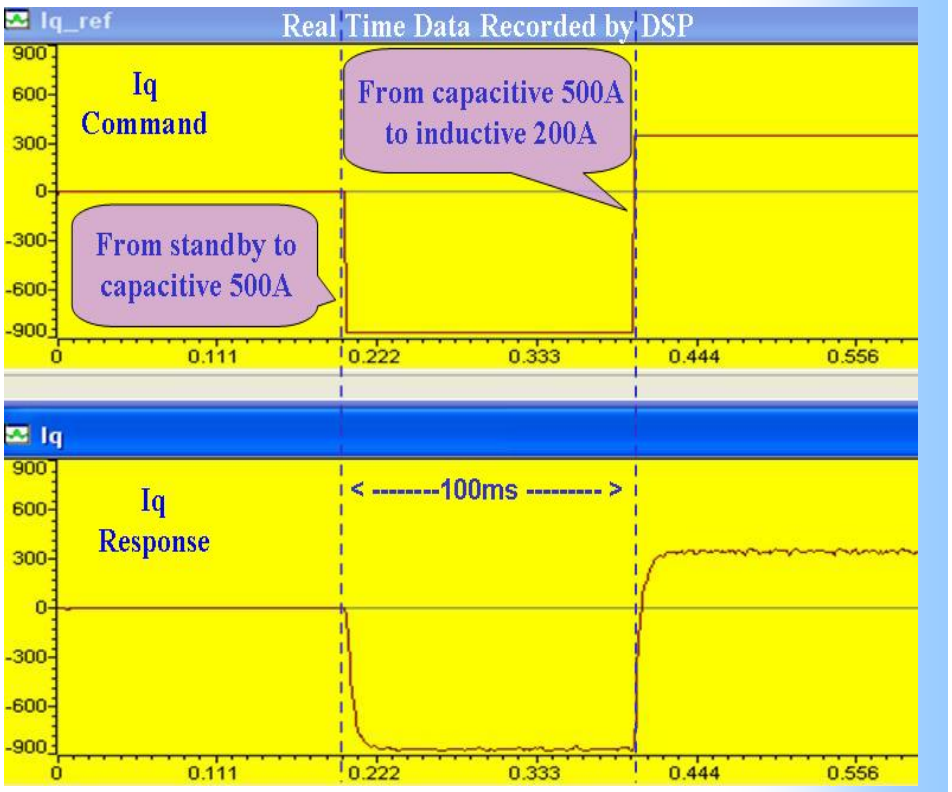



Central controller setup

# 480V/500A Grid-Tie Demonstration Results




500A Capacitive Current



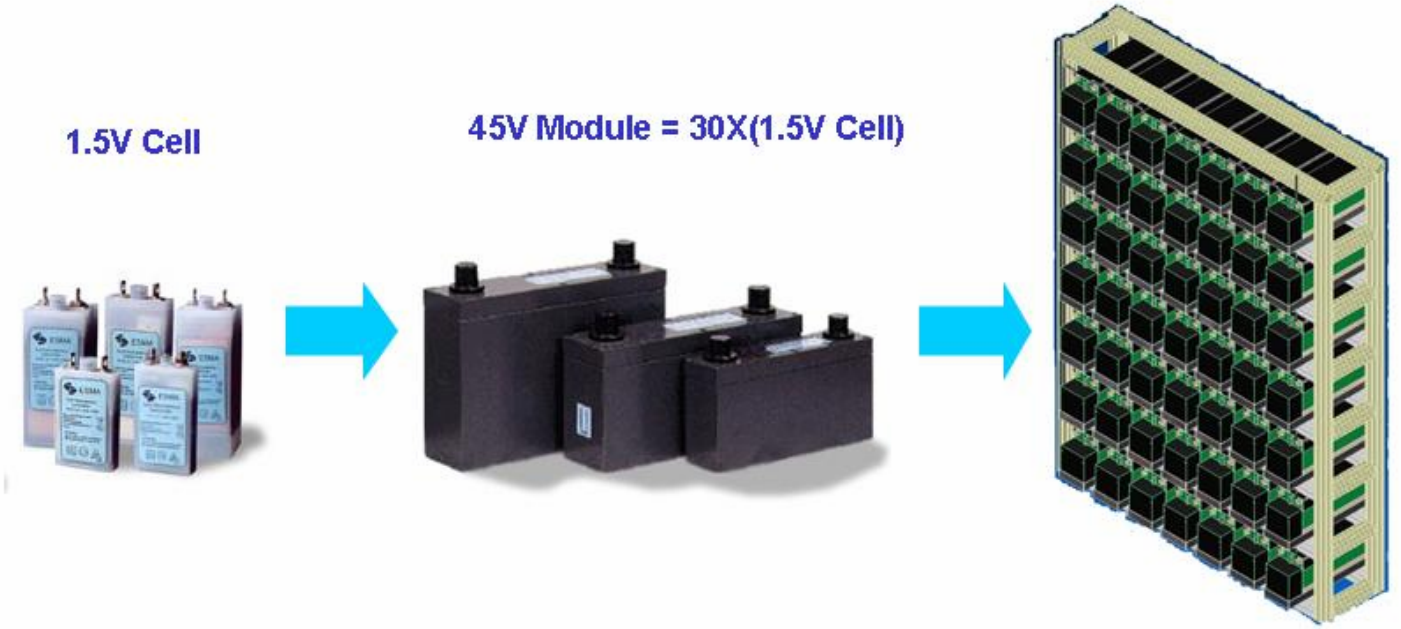

Fast Step Transient Response(subcycle)

# Configuration of a UCAP String

2KV String = 45X(45V Module)

1.5V Cell

45V Module = 30X(1.5V Cell)

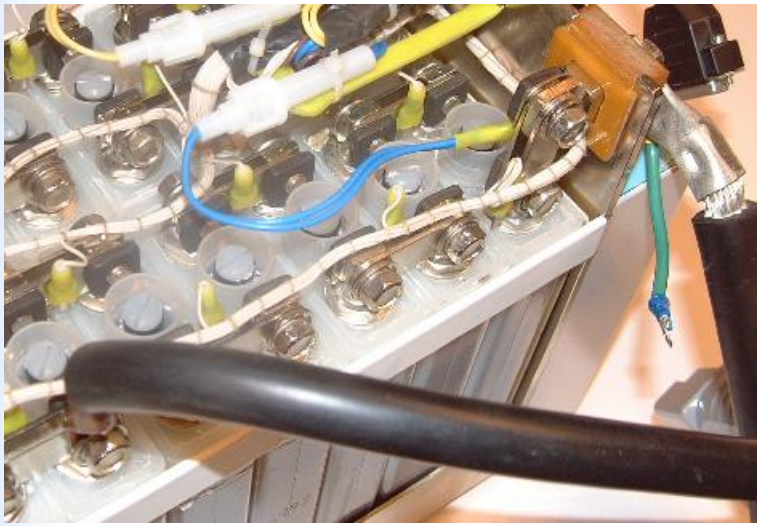


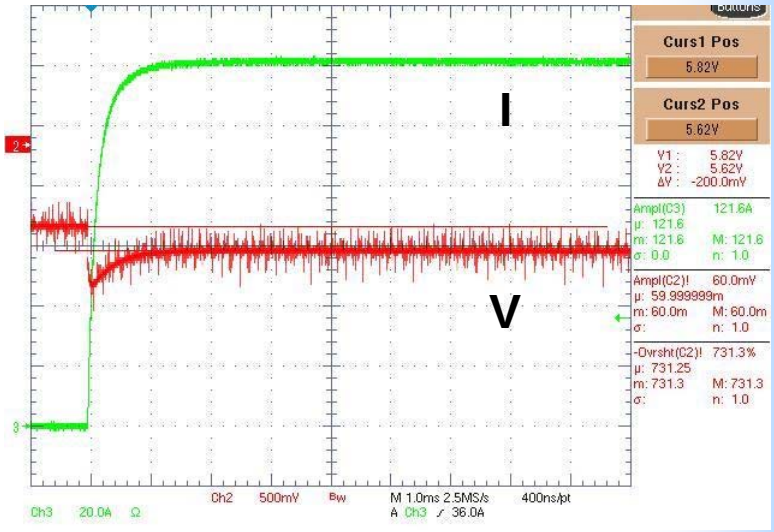
UCAP Cell

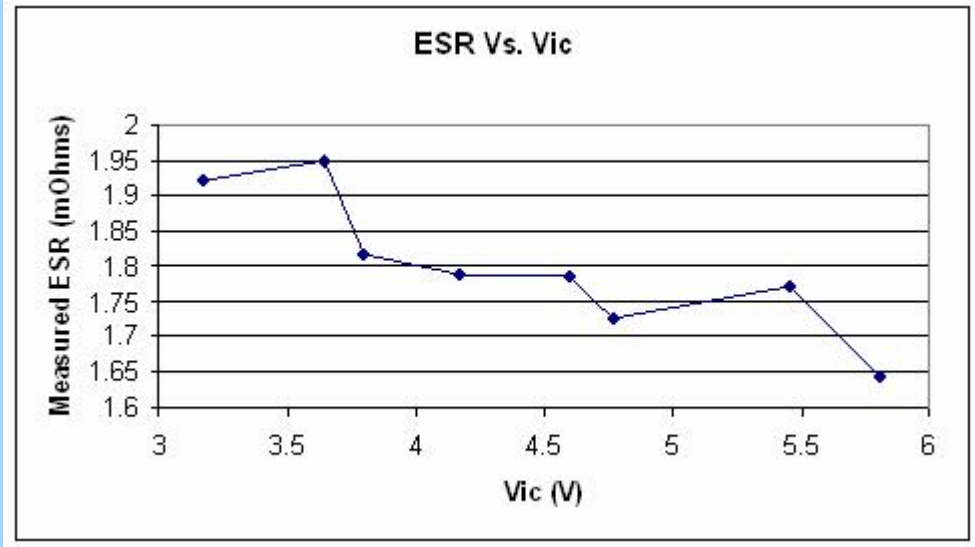
UCAP Module

2KV UCAP String

# Equivalent Series Resistance Measurement of EC402 Cells






- **Constant current (I) discharge**
- **As I is constant, $V_L$=L*di/dt =0.**
- **Measure the voltage drop (∆V)**
- **ESR= ∆V/I**

**Measured average ESR / Cell = 0.3mOhms**
**From datasheet: ESR / Cell = 0.3mOhms**

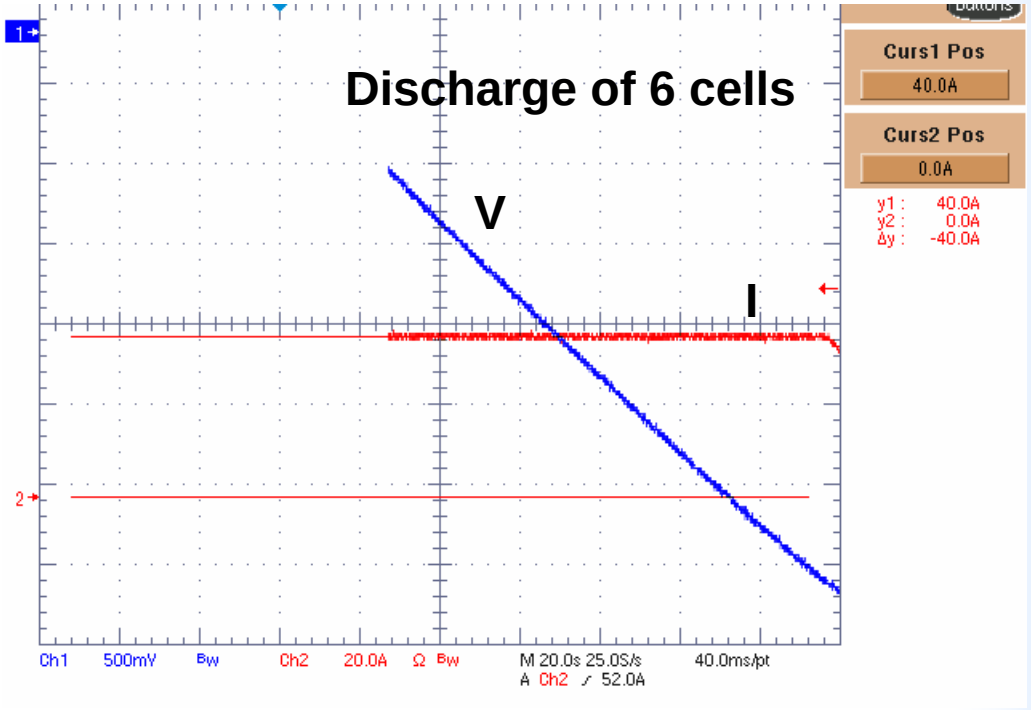
# Capacitance Measurement of EC402 Cells

- Constant current discharge
- C=I*Δt/ ΔV

**C=36.8A*132.4s/2.68V**
**=1818F**

**Estimated C / Cell:**
**1818*6 = 10.9 kF**

**From datasheet:**
**C / Cell =10 kF**



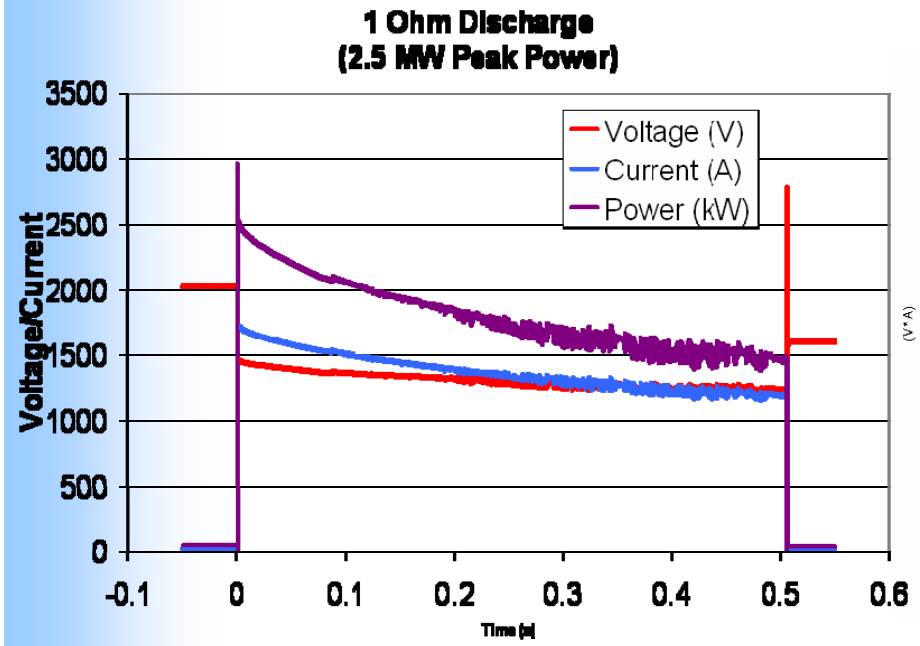
# High-Voltage Testing at EPRI Solutions

- Previously, test equipment for 2000 Vdc strings was limited
  - Mechanical switches to break current: Switches deteriorate over time
  - Limited discharge control
  - Fewer testing trials

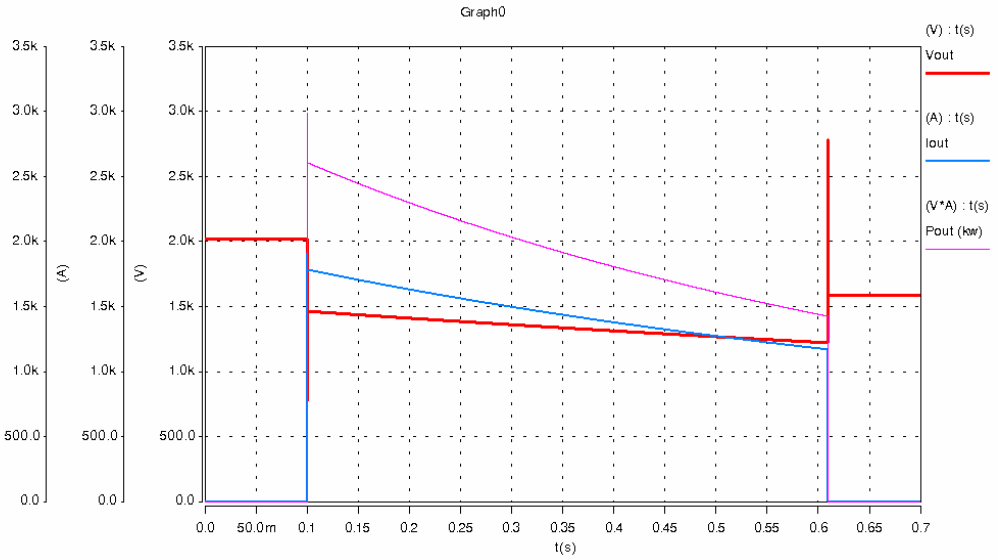
- New test equipment uses Gen-3 ETO switch
  - Allows fast switching at high DC voltage and current

# UCAP String Testing Result and Model

## Discharge test at EPRI solutions

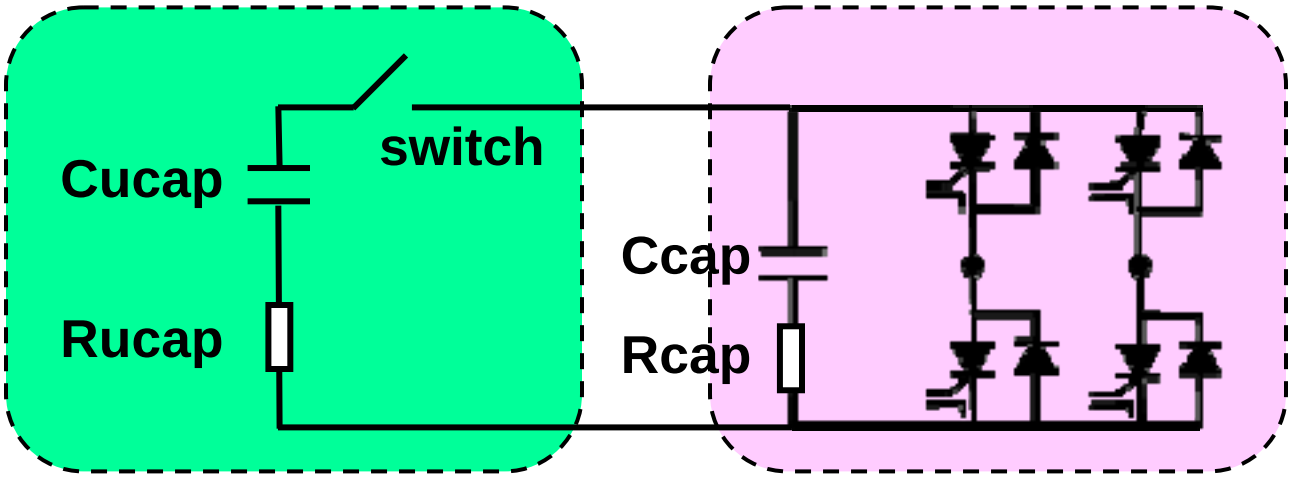



## Simulation results




## UCAP Model for TUCAP Design

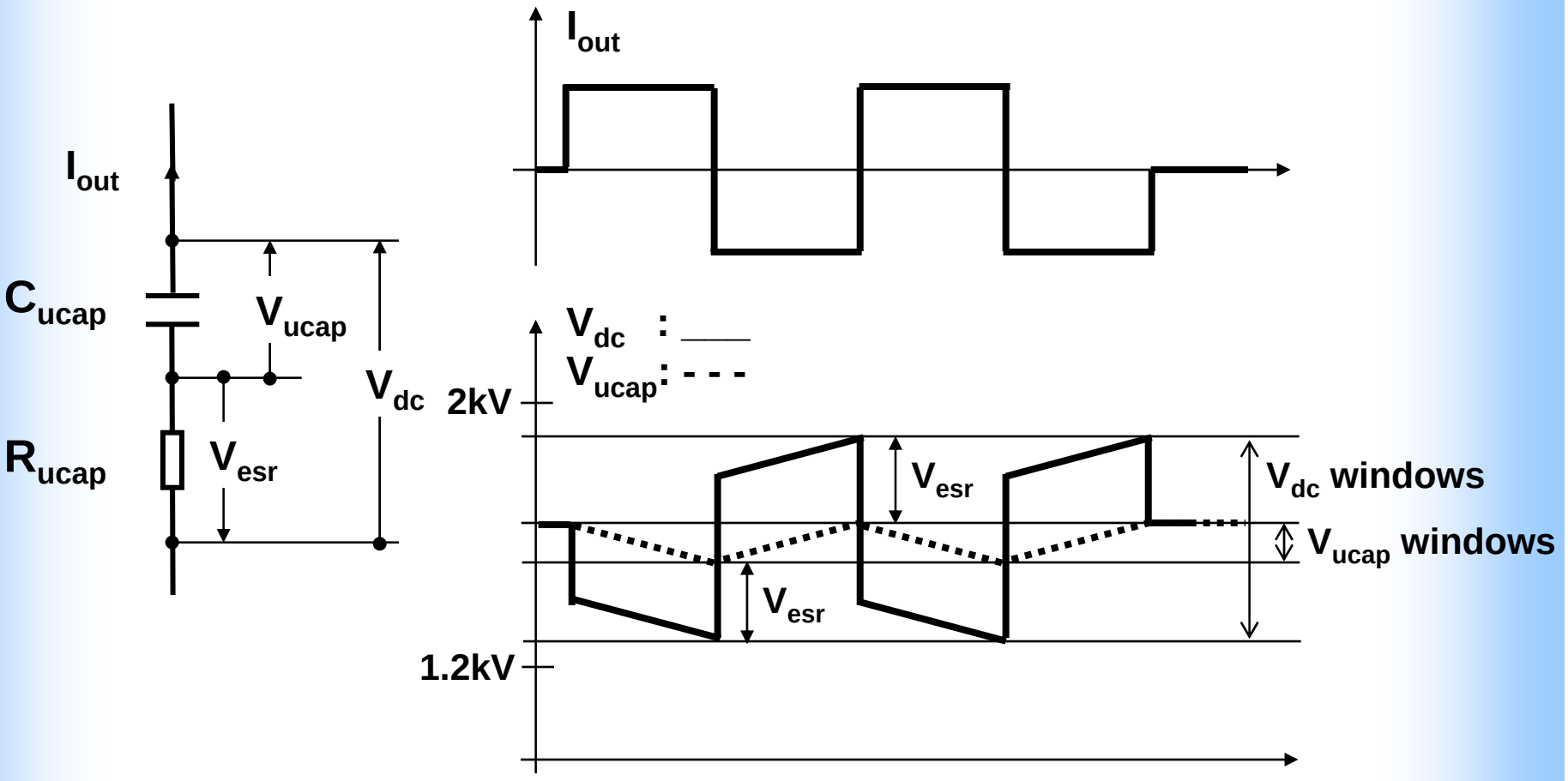
# Interface to Connect UCAP and ETO-Based VSC




**1. DC-link capacitor is required to be UCAP's "filter" to carry high-frequency current component so that UCAP only need handle dc current with low-frequency ripple, and in this case, ESL and stray inductance won't generate spike on UCAP output voltage;**

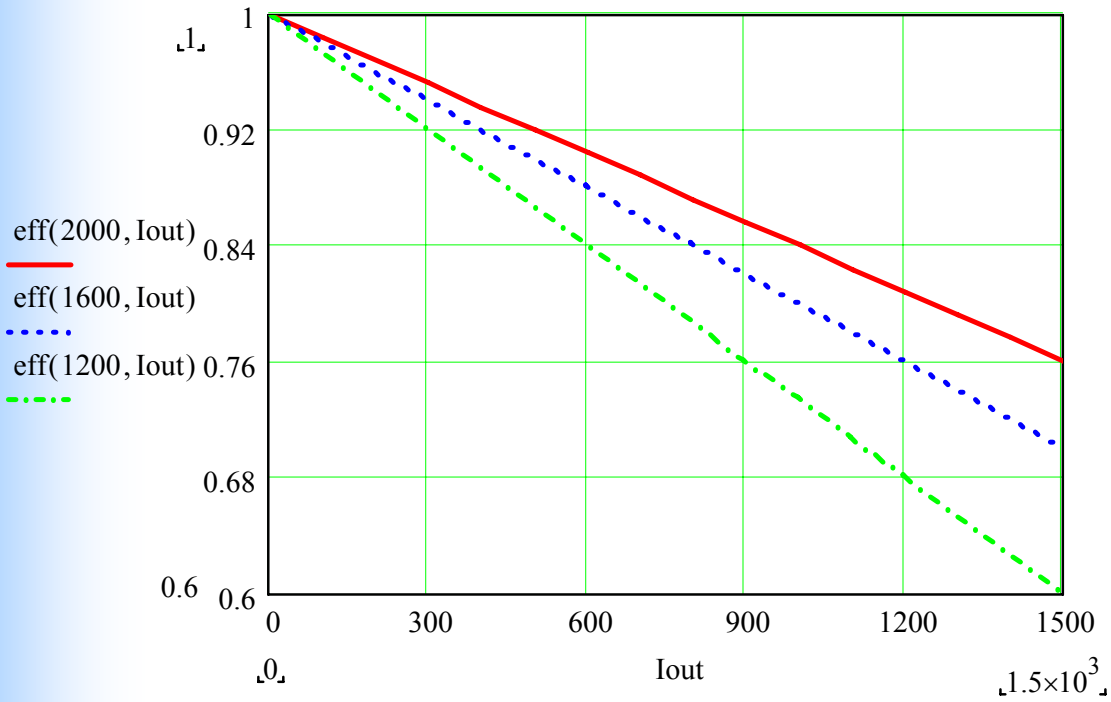
**2. Additional benefit about DC-link cap is that TUCAP can be converted back into STATCOM when UCAP is disconnected.**

# Issue 1: Large ESR




**With large Rucap, UCAP operating voltage window (available energy) is utilized inefficiently.**

# Issue 2: UCAP Efficiency




$$eff := 1 - \frac{Pesr}{Pucap}$$

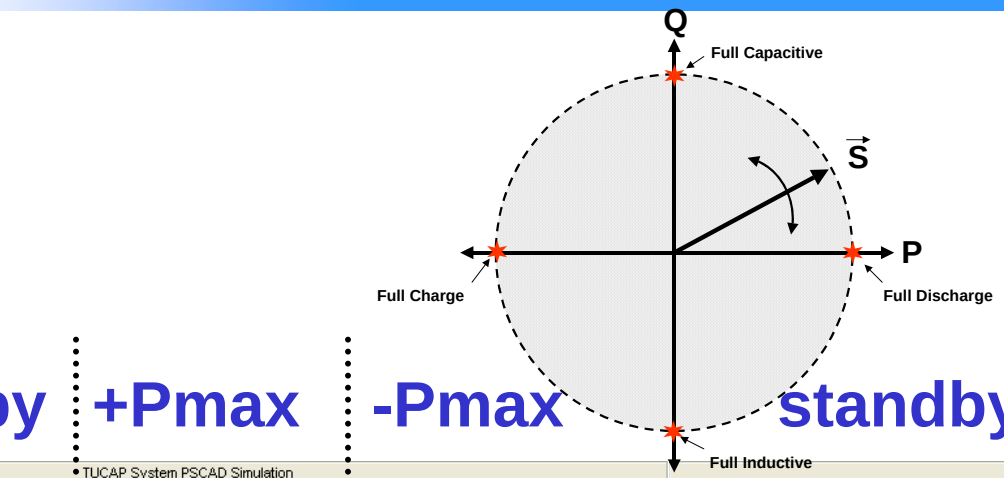
$$eff(Vucap, Iout) := 1 - \frac{Rucap \cdot Iout}{Vucap}$$

**With large Rucap, UCAP internal loss on ESR increases with increasing $I^2$; therefore, UCAP efficiency is not high for large current operation**

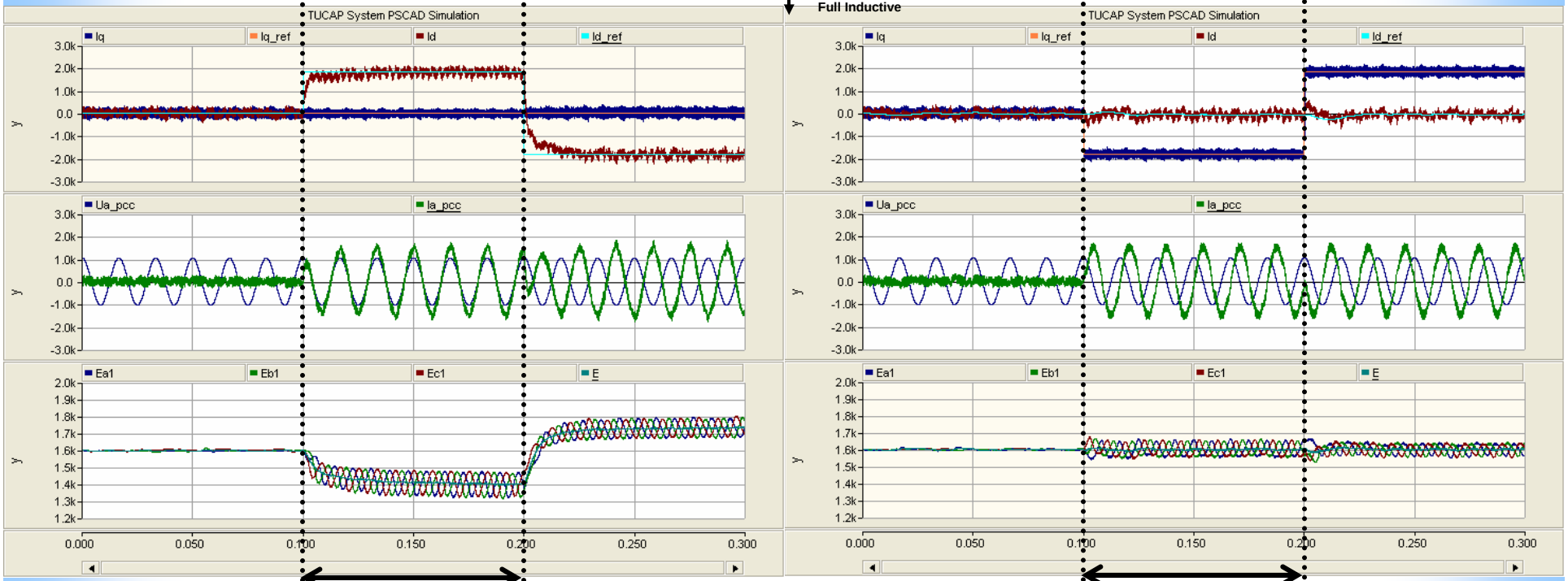
# TUCAP System Specification

| **Three-Level ETO-based TUCAP** | |
|---|---|
| Configuration | Three-Phase Three-Wire Wye-Connection |
| PCC Line-to-line Voltage | 1280V |
| Individual DC Bus Voltage | 1200V ~ 2000V |
| Rated RMS Reactive Current | 1060A |
| Individual Switching Frequency | 1kHz |
| UltraCAPacitor Impedance | (320m-j/(ω ×3F)) Ω/Phase |
| DC-link Capacitor Impedance | (0.071m-j/(ω ×11.9mF)) Ω/Phase |
| Coupling Reactor Impedance | (8.72m+j ω ×230 μ H) Ω/Phase |

# Simulation Results: Independent ±P and ±Q Control

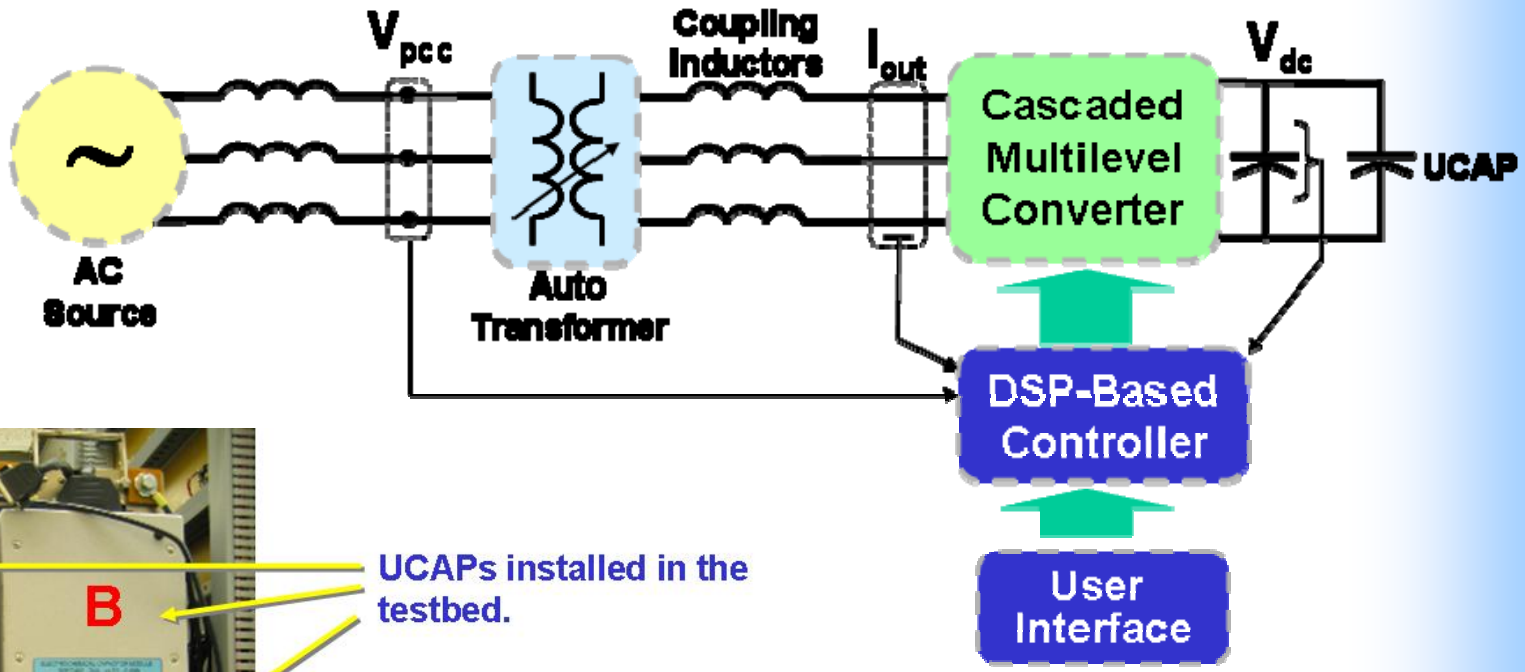


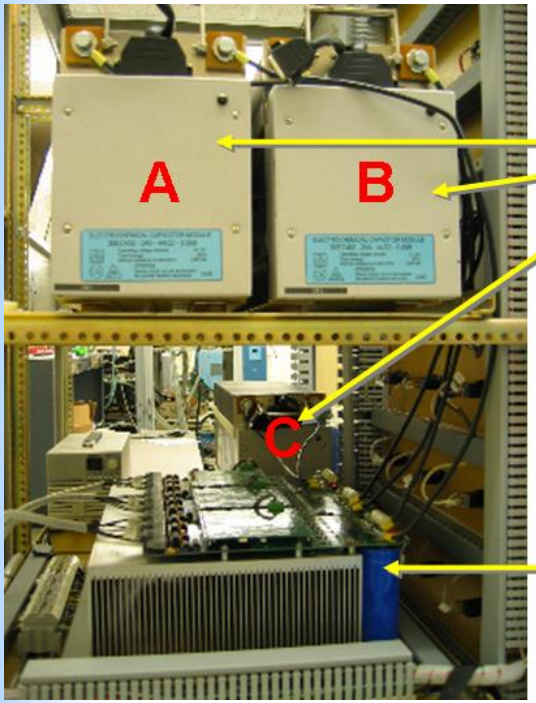

**standby** **+Pmax** **-Pmax** **standby** **+Qmax** **-Qmax**




**0.1 sec** **0.1 sec**

# TUCAP Scaled-Down Testbed



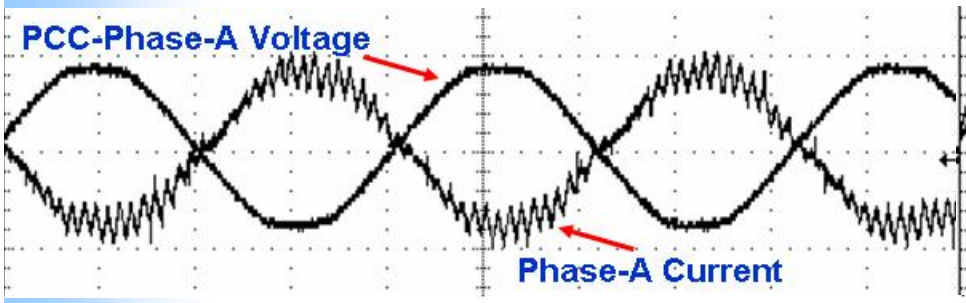




UCAPs installed in the testbed.

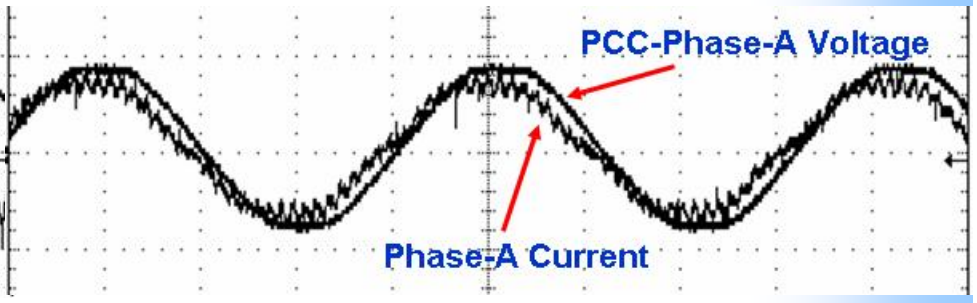
Power stage of the cascaded-based STATCOM.

**A TUCAP testbed, comprising low-power IGBT-based CMC and UCAP modules, is built for controller development**

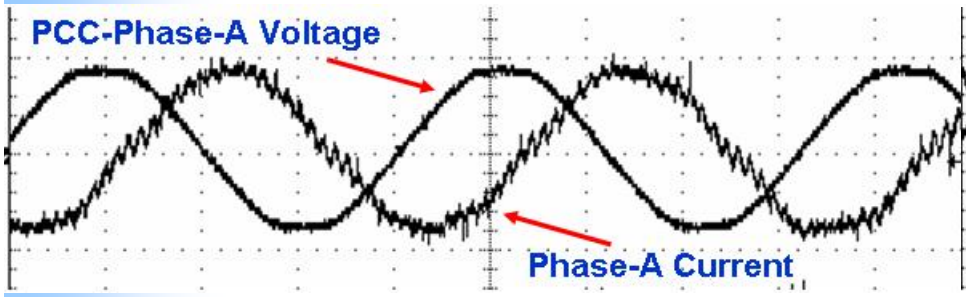
# Testbed Steady-State Testing Results



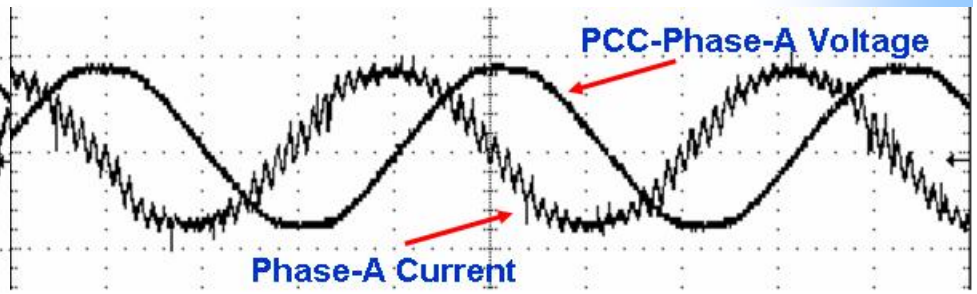

(a) Full Charge Mode




(b) Full Discharge Mode

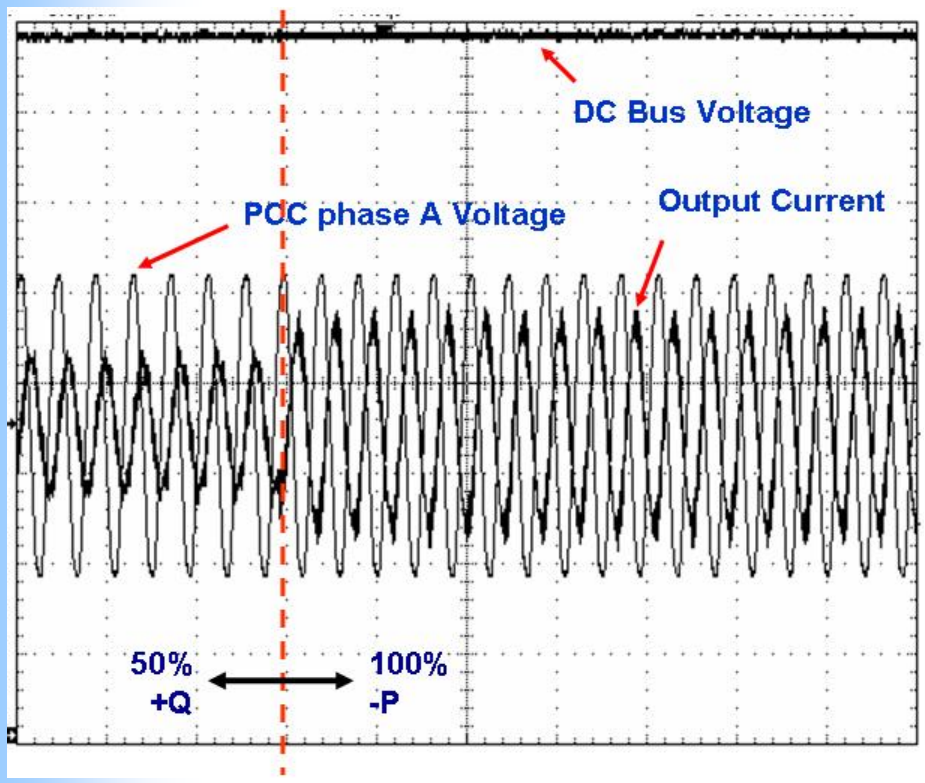



(c) Full Capacitive Mode

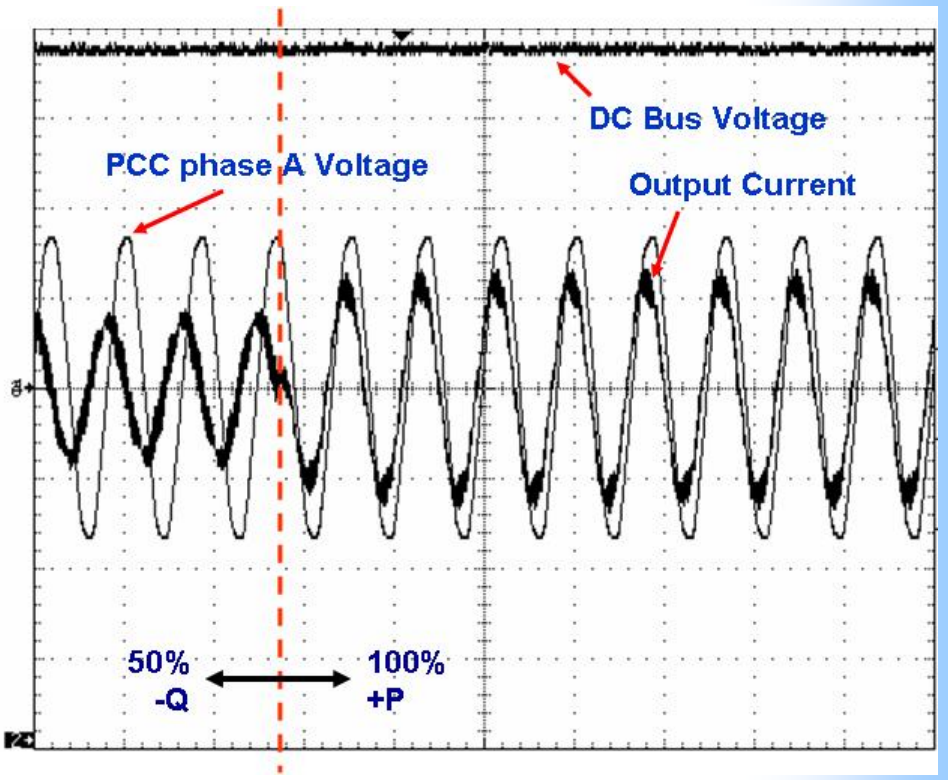



(d) Full Inductive Mode

# Testbed Step Transient Response

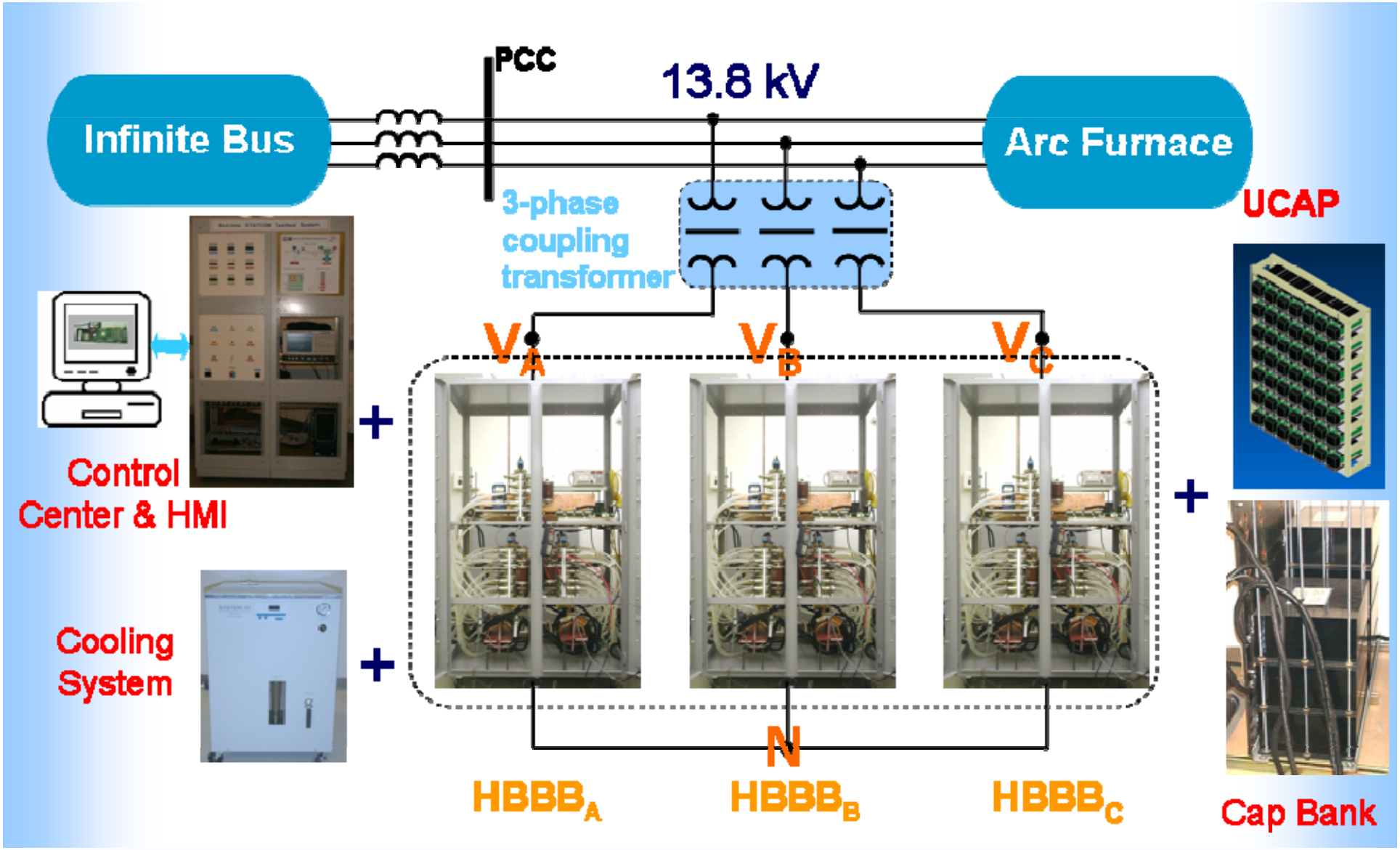



(e) Step change from +Q to -P




(f) step change from -Q to +P

# Future Plan: 4.5 MVA STATCOM/TUCAP Field Demonstration



# Conclusion

**Further R&D in Device, Converter and Control will result in advanced Power Conversion System for Energy Storage System:**

- **New-generation ETO is under development;**
- **New-generation modular converter is under design;**
- **Novel control strategy, software and hardware is in the progress ;**

**For FY2005-2006, the team efforts and system integration will focus on the full-rating field demonstration:**

- **ETO Device (NCSU);**
- **PCS and Control (NCSU);**
- **Energy Storage (EPRI solutions, Sandia Lab);**
- **Field Demonstration (NCSU, TVA, EPRI, DOE).**

# Acknowledgement

SPEC

# Thank you