Progress on a Transmission Ultracapacitor Integrating Emitter Turn-off Thyristor with Ultracapacitor[1]

Chong Han (SPEC–North Carolina State University, Raleigh, North Carolina, USA); chan@ncsu.edu
Ding Li, Bin Chen Zhong Du and Alex Q. Huang (SPEC–NCSU); Haresh Kamath (EPRI Solutions); Michael R. Ingram (Tennesee Valley Authority); Aty Edris (EPRI); Stanley Atcitty (Sandia National Laboratories[2])

I. Introduction

Energy storage systems (ESSs) are considered an 'enabling' infrastructure technology that can provide ride-through electricity during outages, enhance power quality, and improve utility reliability. The objective of this project is to develop and demonstrate next-generation, power-electronics-based ESSs, specifically: the transmission ultracapacitor (TUCAP).

The TUCAP combines advanced semiconductor technology (the emitter turn-off thyristor, or ETO), advanced converter technology (a cascaded multilevel converter, or CMC), and advanced energy storage technology (an Ultracapacitor or UCAP, which is one type of electrochemical capacitor or EC). It is expected that integrating TUCAP technology in flexible AC transmission systems (FACTS) will result in an ESS/FACTS that is capable of extremely fast response and that is less costly per kW/kVA than ESS/FACTS based on traditional storage/power electronics technologies. The success of the TUCAP technology depends on three factors—the characteristics and performance of the UCAP, the power rating and switching speed of the semiconductor switch that forms the base of the system's power electronics, and the topology and control of the TUCAP-based ESS/FACTS. Progress on the TUCAP project is presented below.

II. The ETO

The ETO is an advanced, high-power, high-frequency semiconductor switch that provides significant advantages over competing semiconductor switches [1]. Several characteristics make the ETO the most desirable choice for today's high-power applications. First, the ETO is a hybrid of two mature (*i.e.,* reliable and widely available) technologies—the gate turn-off thyristor, or GTO, and the metal oxide semiconductor field-effect transistor, or MOSFET—which reduces the overall cost of the device. The ETO's voltage and current ratings are determined by its GTO and can be easily scaled to 6 kA/6 kV without a major cost increase. The device features voltage-controlled turn-off, resulting in a significantly reduced gate-driver power requirement, which improves device efficiency. Its design also eliminates the need for a dv/dt snubber during turn-off (a major disadvantage of the GTO technology), which improves device efficiency and reduces the component count and, consequently, the cost of the device.

The ETO's fast switching speeds allow it to be used for high-frequency pulse width modulation (PWM) control in high-power systems. Optical-drive switching provides a great deal of control flexibility which allows the device to be used in a wide range of applications. The device is manufactured using proven press-pack packaging for high reliability. Finally, it is extremely easy to connect multiple ETO devices in parallel and/or series arrangements. The proposed TUCAP device is based on the specifications of the Gen-3 ETO shown in Figure 1(a). Figure 1(b) is a qualitative comparison with other competing technologies.

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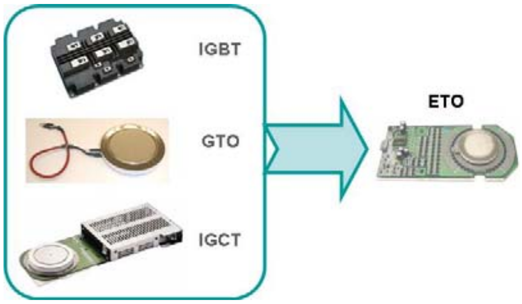


Characteristic	ETO	IGCT	IGBT
Conduction Losses	Good	Good	Poor
Positive Temperature Coefficient	Best	Poor	Good
Identical Switching Times	Best	Best	Good
Turn-Off Capability	Best	Good	Good
Built-In Current Sensing Capability	Yes	No	No
Control Power Needed	Low	Very High	Low
Cost per kW	Lowest	Low	Higher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

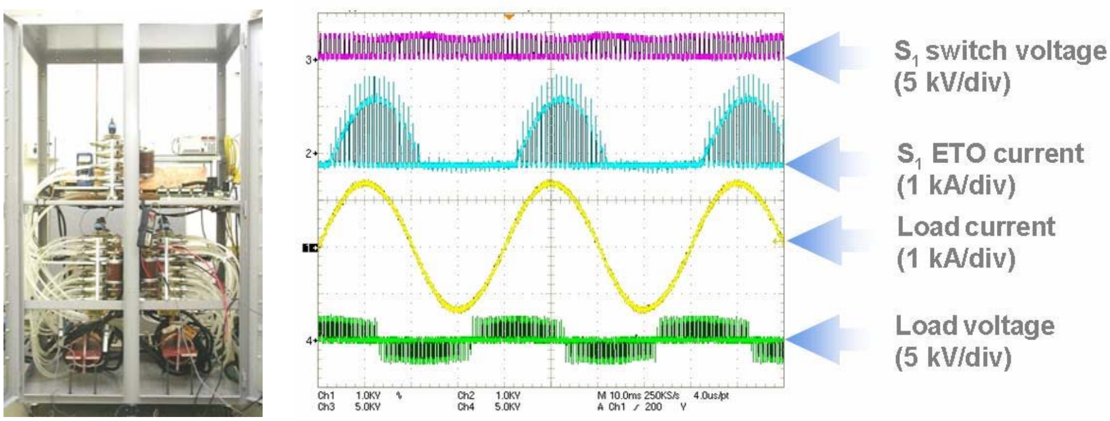
(a) Gen-3 ETO (b) Comparison with competitors

Figure 1. Emitter Turn-off Thyristor

III. ETO-based Power Electronics Conditioner

The design of any ESS/FACTS is based on several important considerations. The system's efficiency, reliability, and cost are all major (and interrelated) factors, as is the relative difficulty of manufacturing the system's hardware and packaging (which can affect both cost and reliability). In addition to being relatively easy to manufacture, the system's components should be scalable so they can be used across a wide range of potential applications. Consequently, a modular multilevel converter is preferred for high-power ESS/FACTS applications. Presently, the CMC, which is constructed using identical voltage-source converters (VSCs), is the most feasible topology for high-power ESS/FACTS, because of its compact structure, modularity, and scalability. Additionally, the CMC has a fast response time with low harmonics that result from high-frequency switching.

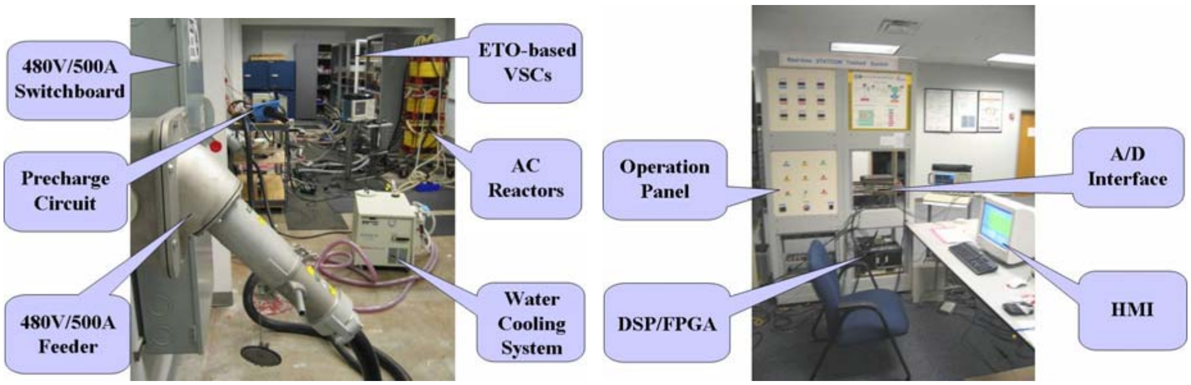
Using the Gen-3 ETO characteristics and thermal capability, a 1.5-MVA, modular, ETO-based, H-bridge VSC building block has been designed [2]. Three ETO-based VSC prototypes were built and verified around 1.5 MVA at their full rating with I_o = 1 kA, V_{dc} = 2 kV, f_{sw} = 1 kHz in open-loop testing. The prototype and the test results are shown in Figure 2.



(a) 1.5-MVA ETO-based VSC (b) 1.5-MVA ETO-based VSC

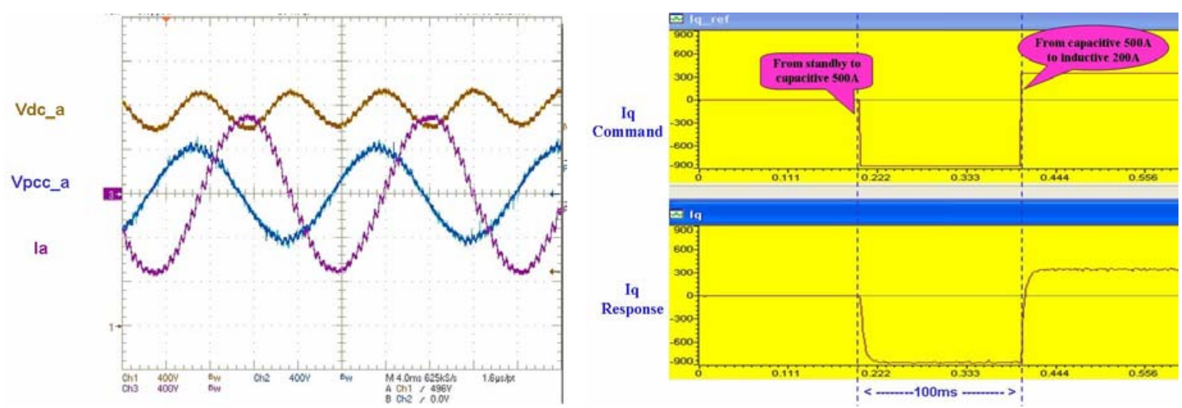
Figure 2. 1.5-MVA ETO-based Modular VSC and Its Full-rating Test Results

The three prototype VSCs were integrated to create a 3-level, CMC-based, static synchronous compensator (StatCom). The resulting 4.5-MVA, ETO-based StatCom, shown in Figure 3, was demonstrated at V_{ac} = 480 V, I_o = 500 A, V_{dc} = 2 kV, f_{sw} = 1 kHz (the power rating limit of the NCSU lab) and is now ready for integration with a UCAP to create the TUCAP system. The experimental results are provided in Figure 4. Figure 4(a) shows the 500-A reactive current injected into the grid while the DC bus voltage is maintained at 2 kV with 18% peak-to-peak ripple. Figure 4(b) shows the fast dynamic response (subcycle) capability of the ETO-based power electronics conditioner that results from the high-frequency switching.



(a) Power Stage Setup (b) Controller Setup

Figure 3. The 480-V/500-A Test Setup for the 4.5-MVA ETO-based StatCom



(a) 500-A Capacitive Mode (b) Step Transient Response

Figure 4. Demonstration Results of a 4.5-MVA ETO-based StatCom

IV. Ultracapacitor Measurement

Electrochemical capacitors, such as the UCAP, provide thousands of times the energy density of conventional electrolytic capacitors and have added advantages over other high-power energy storage devices (*e.g.,* high power density, low cost, long life, deep charge/discharge capability, wide operating temperature range, extremely low maintenance requirements). The UCAP string for the TUCAP system comprises 45 series-connected EC modules and has a rated DC-bus voltage of 2 kV. Each 45-V module comprises 30 series-connected, 1.5-V UCAP cells. The string structure is shown in Figure 5.

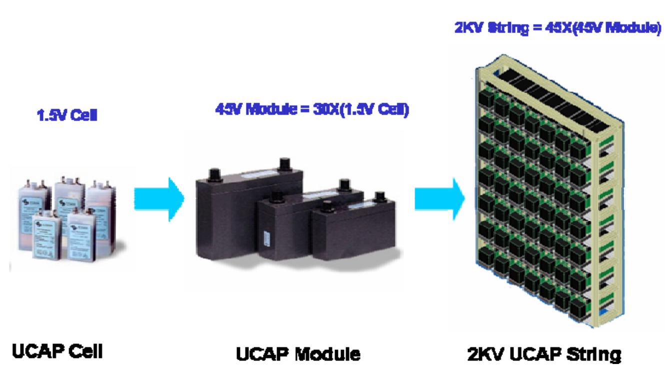
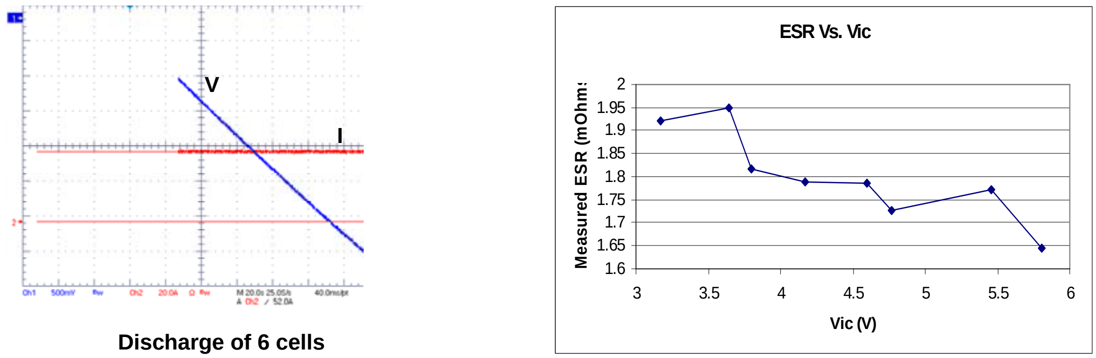


Figure 5. Structure of a 2-kV UCAP String

Cell-based testing was conducted to determine the UCAP's capacitance and equivalent series resistance (ESR), which are shown in Figure 6. The UCAP's capacitance was determined by applying a constant-current discharge with C=I*dt/dv. As shown in Figure 6(a), dv/dt was almost constant. Consequently, UCAP capacitance can be modeled as a constant. For the ESMA Model 30EC402 cell, the test result was 10 kF, which was consistent with the model's specifications as listed on its datasheet [3]. The cell's ESR was calculated by measuring the output voltage drop from no-load to steady-state load and dividing it by the load current. As shown in Figure 6(b), the cell's open-circuit voltage, as related to UCAP energy storage, has no significant effect on the UCAP's ESR. Consequently, the ESR can also be modeled as a constant. The measured ESR of the 1.5-V cell was 0.3 mΩ, which also matches the datasheet. Thus, the UCAP is modeled with both constant capacitance and ESR.

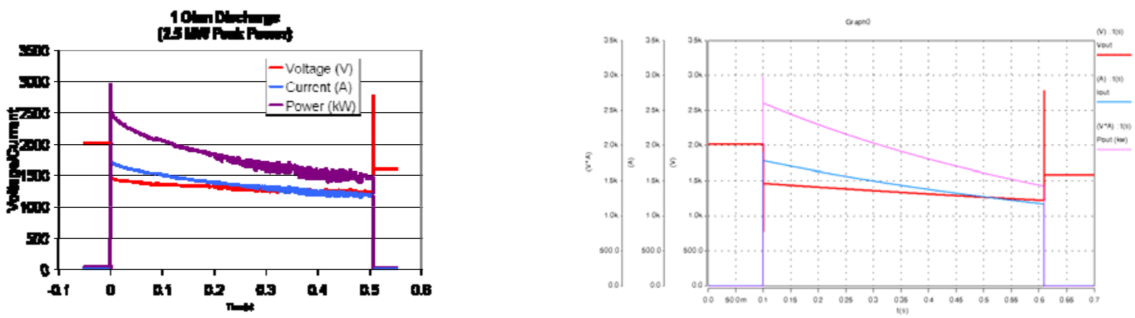


(a) Capacitance Measurement (b) ESR Measurement

Figure 6. Measurement Results of UCAP Cells

V. TUCAP Modeling and Control

A 2-kV UCAP string was built (using ESMA 30EC502 cells) and tested at EPRI Solutions. The string's 1-Ω DC discharge through an ETO-based DC circuit breaker is shown in Figure 7(a). A 2-kV UCAP model was simulated using the capacitance and ESR obtained from the test results. The results for the simulated 1-Ω DC discharge are shown in Figure 7(b) and, when compared to the test results, verify the accuracy of the UCAP model.



(a) DC Discharge Testing Results (b) Simulation Results with the Extracted Model

Figure 7. Measurement Results of UCAP Cells

Also seen in Figure 7 are voltage and current spikes during the UCAP's turn-on and turn-off transients. The spikes are the result of equivalent series inductance (ESL) and stray inductance, which can degrade the UCAP and significantly reduce its life. The interface for connecting the UCAP and the modular VSC (shown in Figure 8) will mitigate such an effect. A DC-link capacitor is used as a 'filter' to carry the high-frequency current component so that the UCAP only handles dc current with low-frequency ripple; in this case, ESL won't generate a spike on the output voltage. An inherent benefit of this topology is that the TUCAP can be easily converted into a StatCom for reactive power compensation when the UCAP is disconnected.

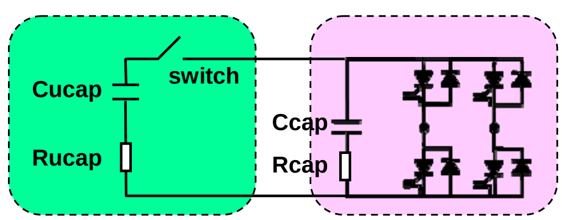
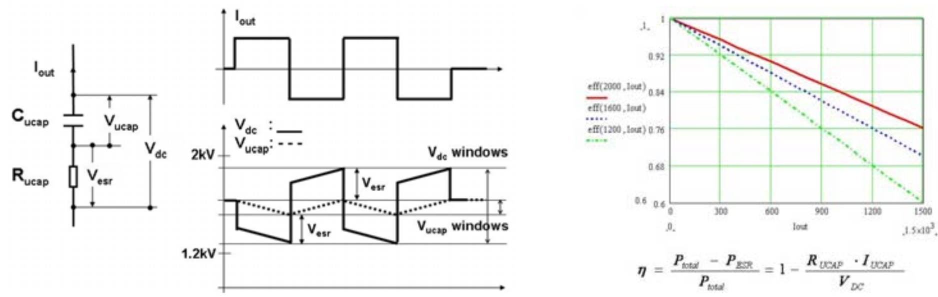


Figure 8. ETO-based VSC/UCAP Interface

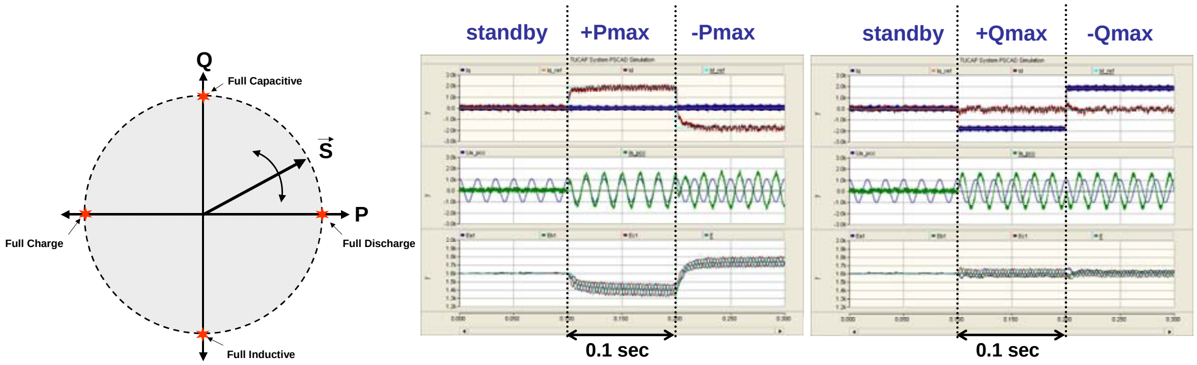
Because of the inherent features of the 2-kV UCAP string (which consists of 1,350 series-connected, 1.5-V cells), the ESR of the string is at least equal to the sum of the individual resistances of the series-connected cells (*i.e.,* not small for a 2-kV string operating at high-current). The high ESR can manifest itself in one of two ways: a large, internal voltage drop or a decrease in efficiency. Figure 9(a) shows that, during high-current operation, the ESR results in a large, internal voltage drop that can significantly weaken the utilization of the available voltage windows. For example, the 2-kV UCAP string has an available voltage window between 1,200 and 2,000 V; for 1-kA operation, the internal voltage drop related to ESR is about ±300 V. At the UCAP's normal operating voltage (1,600 V) the voltage window (available energy for charge/discharge) should be 400 V (if the ESR is negligible); with the large (300-V) internal drop, the voltage window is reduced to 100 V. Additionally, Figure 9(b) shows that UCAP efficiency decreases consistently with increasing output current; during high-current (>1 kA) charge/discharge the efficiency is less than 80%.



(a) UCAP Voltage Window Utilization (b) UCAP Efficiency

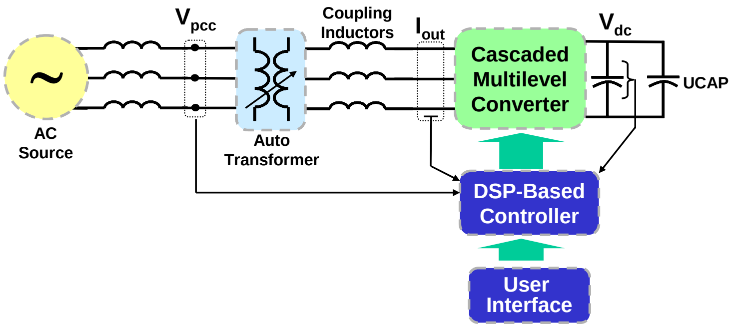
Figure 9. UCAP ESR-Related Issues at High Current Operation Condition

Considering the topology in Figure 8 and the ESR-related issues described by Figure 9, the TUCAP system's control strategy was designed to allow it to perform as an independent, four-quadrant controller. As shown in Figure 10(a), any combined real and reactive power command on or inside the circle is designed to respond in a sub cycle. Step-response simulation results for four typical cases ($+P_{max}$, $-P_{max}$, $+Q_{max}$, $-Q_{max}$) are plotted in Figure 10(b-c), which verifies the control strategy and fast response of the TUCAP system. To validate the simulation results and to develop the control hardware, a scaled-down test bed system (shown in Figure 11) was built. A three-level CMC was constructed using low-power IGBT modules. Three 45-V ESMA 30EC402 UCAP modules were individually shunt-connected with DC-link capacitors on each phase of the VSC. Figure 12 shows the results of experiments conducted in four typical operation modes ($+P_{max}$, $-P_{max}$, $+Q_{max}$, $-Q_{max}$). Figure 13 shows the step change from +Q to –P and from –Q to +P. These experiments verify all of the TUCAP control hardware, software simulation results, UCAP modeling, and TUCAP control strategy.

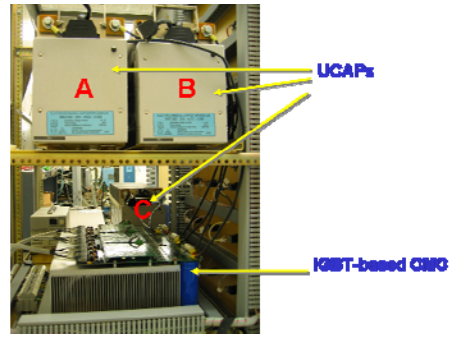


(a) Typical Operating Range (b) Real Power Compensation (c) Reactive Power Compensation

Figure 10. TUCAP Simulation Results

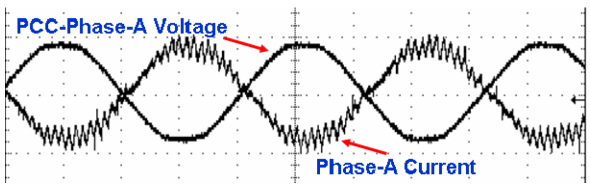


(a) Schematic of the TUCAP Testbed

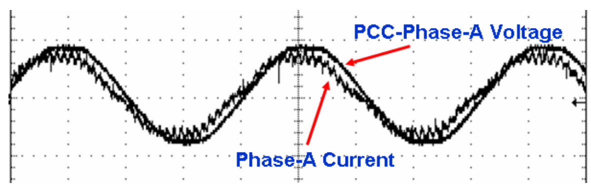


(b) Scaled-down TUCAP Testbed

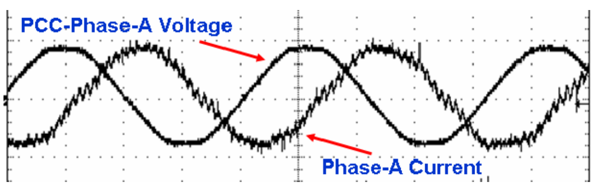
Figure 11. TUCAP Testbed



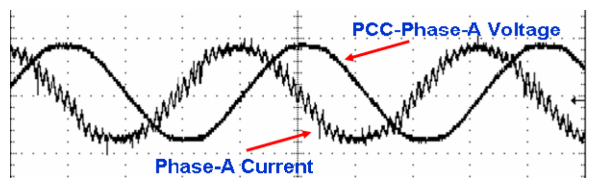
(a) Full-charge Mode



(b) Full-discharge Mode

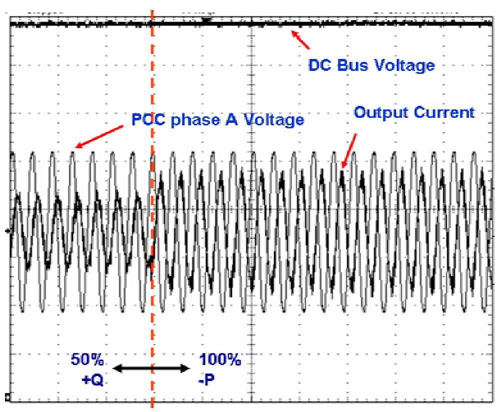


(c) Full-capacitive Mode

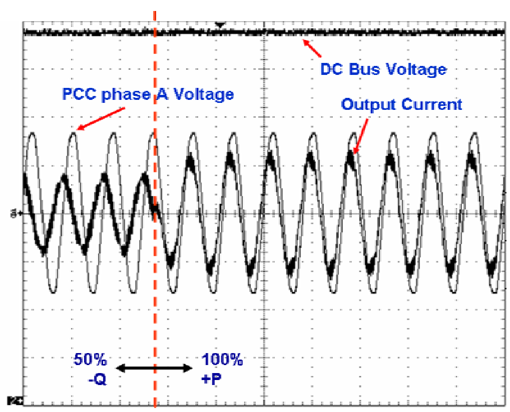


(d) Full-inductive Mode

Figure 12. Experimental Results for Four Operating Modes on the Scaled-down TUCAP Testbed



(e) Step Change from +Q to -P



(f) Step Change from -Q to +P

Figure 13. Experimental Results for Step Change on the Scaled-down TUCAP Testbed

VI. Conclusion

The ETO, as an emerging high-frequency power electronics switch, provides significant advantages over its competitors and will result in a fast response ESS/FACTS with reduced overall cost per kW/kVA.

The compactness, modularity and fast-switching capability of the ETO-based VSC were demonstrated, as was the TUCAP's power electronics conditioner. A 4.5-MVA ETO-based StatCom was demonstrated and is ready for integration with UCAP strings for a field demonstration at the system's full rating. With the developed UCAP model, a topology and control strategy that addressed the UCAP's features and ESR-related issues were designed for the TUCAP system. Simulation results and experimental results on a scaled-down TUCAP test bed were consistent and verified the TUCAP modeling and control, and validated the TUCAP system's control hardware.

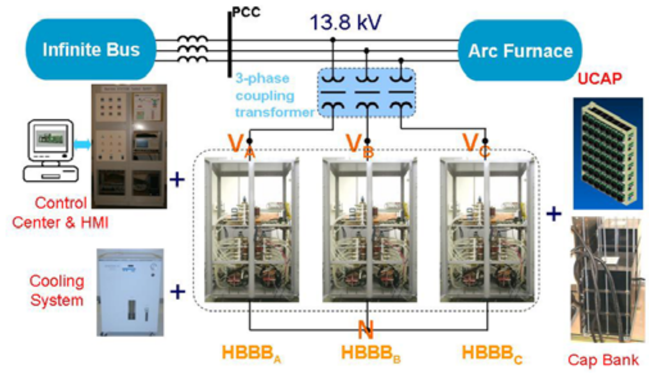


Figure 14. TUCAP Field Demonstration Plan

In summary, by combining the advantages of the ETO semiconductor switch, a CMC, advanced control technology, and a UCAP, TUCAP systems are promising ESSs for high-power applications. An example of a full-rating field demonstration of the TUCAP system is shown in Figure 14.

Acknowledgements

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References

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[3] http://www.esma-cap.com