GENERAL ATOMICS ENERGY PRODUCTS
Engineering Bulletin

PROGRESS IN THE REDUCTION OF INDUCTANCE IN THE STANDARD 100kV ENERGY STORAGE CAPACITOR

R.A. Cooper, J.B. Ennis, F.W. MacDougall, and J.F. Bates

Presented at:
IEEE Pulsed Power Conference
June 2001

GENERAL ATOMICS
Energy Products
SORRENTO ELECTRONICS
4949 GREENCRAIG LN, SAN DIEGO, CA 92123-1506
858.522.8400
www.ga-esi.com

PROGRESS IN THE REDUCTION OF INDUCTANCE IN THE STANDARD 100kV ENERGY STORAGE CAPACITOR

R.A. Cooper, J.B. Ennis, F.W. MacDougall, and J.F. Bates.
General Atomics Energy Products, Sorrento Electronics.
4949 Greencraig Lane, San Diego, Ca. 92123

A.R. Miller
Titan Pulse Science Division
4855 Ruffner St., San Diego, Ca 92111

Abstract

The basic metal case low profile bushing energy storage capacitor design has changed little from the 1.85uF 60kV capacitor developed for the LANL SCYLLAC program in the late 1960's. Their enduring use testifies to a robust design. Today energy storage capacitors having a lower equivalent series inductance (ESL) will contribute to increasing the power capability of new or revised pulsed power machines. Lower ESL coupled with an improved terminal configuration for better integration with the system design, will produce faster discharge times and lower driver impedance, making higher power systems more sensible and energy efficient. A lower ESL capacitor that is compatible with existing proven hardware will also make upgrading more cost effective. This paper discusses the establishment of standardized test methods for determining the inductance of different SCYLLAC style energy storage capacitors; for example Maxwell Type C capacitors, which are now manufactured by General Atomics Energy Products, a part of Sorrento Electronics, and units from Aerovox. The effects leading to imprecision in inductance measurements will be noted. The inductance of existing designs will be compared with new hardware compatible prototype configurations with a goal of reducing the inductance up to 50%.

I. SCYLLAC STYLE CAPACITOR

The basic high voltage, low inductance energy storage capacitor was developed for the Los Alamos National Laboratories' SCYLLAC program, in the late 1960's. This 1.85uF 60kV, 3.3kJ design set the standard for metal case capacitors with a case size of 11 x 14 x 25 inches and a dish shaped bushing with coaxial terminal. See Figure 1.

As technology advanced to meet demand for higher energy densities, the Scyllac design evolved through the 2.8uF 60kV(mid 1970's), the 1.3uF 100kV(1980) and the 3uF 100kV design in the mid- 1980's. An important Sandia National Laboratories life test program [1] to validate capacitors for new, larger, pulsed power systems helped drive the 3uF design.

Today the operating parameters, required life and reliability drive the capacitance and energy density. During this time the basic capacitor has changed little and numerous Marx generator configurations were developed using the same Scyllac style capacitor, making it a standard component in pulse power systems.

Figure 1. GAEP's Scyllac Style Capacitor

II. LOWER CAPACITOR INDUCTANCE

Today energy storage capacitors having a lower equivalent series inductance will contribute to increasing the power capability of new or revised pulsed power machines. A lower capacitor ESL with improved terminal configuration for better integration with the system design will produce benefits. These benefits are reduced system inductance, lower driver impedance, faster discharge times and higher peak currents, making higher power or more reliable systems more sensible and energy efficient.

While not based on type C capacitors the recent LANL Atlas program is an example of the performance obtainable from a low inductance cap and integrated switch design. 96 parallel 240kV Marx generators having two railgap switched dual capacitor stages each, deliver 28 MA in < 5 u sec.

We asked ourselves three questions: What is the inductance of the current Scyllac units? If lower ESL is important, can it reduced? What is best way to measure

Table 1. Test Capacitors.

Model No.	Meas. Cap	100 kV Insulation	Case Size	Construction	Dielectric
X32081	**3.47 uF**	**STD**	**11 x 14 x 14.5**	**Standard**	**Paper / PPL / Dry**
X32080	**3.264 uF**	**Mixed**	**11 x 14 x 14.5**	**Lower Inductance**	**Paper / PPL / Dry**
	Rated Cap				
32827	3.0 uF	STD	11 x 14 x 25	Standard	All Paper / Castor Oil
32865	2.4 uF	STD	11 x 14 x 25	Standard	All Paper / Castor Oil
SX210E23	2.1 uF	STD	11 x 14 x 25	Standard	Paper / PPL / DOP

the ESL? Many existing systems already use this style capacitor; therefore, a lower ESL version would be more cost effective than a complete new design.

A. Capacitor Inductance

Intrinsic capacitor inductance is due to windings, internal connections, case, insulation design and output terminal; fundamentally the magnetic flux produced in the capacitor by the discharge current. Inductance measurements therefore require a complete circuit for current, including external connections and a switch which add inductance. Capacitor inductance is defined as that part of the circuit within the capacitor envelope or with the closest fitting short circuit across the terminals. Elements external to the capacitor usually dominate the circuit inductance making accurate measurements of the small internal components difficult. Most of the capacitor inductance is associated with the terminal (or header) and the connections to it. Various approaches to inductance reduction (many proprietary, most empirical) are constrained by the standard terminal design. Inductance reduction generally increases electrical stress and can decrease reliability. Control of inductance by design requires knowledge of current density, its distribution and analytic models for calculation. Current distribution (electronic and displacement) can be difficult to determine making inductance predictions uncertain. Our approach to inductance reduction is to reduce the magnetic flux inside the capacitor. This reduction was measured by the methods described later.

B. Benefits of Lower Inductance

In Marx generator driver water transfer capacitor based pulse power systems, Marx capacitor inductance reduction makes sense as part of an overall effort to reduce system inductance. By itself, this reduction can also have a non-negligible affect. In a typical high energy Marx 60 capacitors can contribute 1.8uH to the ~12uH total. A reduction of 10nH per capacitor is ~5% of this total. Water breakdown stress scales like the inverse 1/3 power of the charge time or the 1/6 power of the inductance and the increase in a predicted breakdown stress is only about 1%. However, the increase in reliability is such that the failure rate due to water breakdown decreases ~15% for a system operated at 80% of the predicted critical stress and this is non-negligible.

III. PROTOTYPE TEST CAPACITORS

GAEP manufactured two dry capacitors for these tests. One, X32081, in the standard 100kV configuration and the other, X32080, used a number of inductance lowering techniques. Both were insulated for 100kV operation and used a dielectric system of paper and polypropylene film to allow the discharge testing without impregnation. X32081 is a reference capacitor to benchmark variations in size, dielectric materials or impregnation affecting the inductance. The shorter length also permitted easier handling and assembly. Table 1 shows standard full size 2uF to 3uF 100kV capacitors from both General Atomic Energy Products (ex-Maxwell) and Aerovox used for inductance comparison.

IV. INDUCTANCE TEST METHODS

The two methods used to measure inductance were a ringing discharge setup built by Richard Miller of Titan and a standing wave method by Bob Cooper of General Atomics. Both require a test plus a calculation. The standing wave setup is simple and quick enough for production testing while the ringing discharge requires moderate voltage (5 to 10kV). Bruce Hayworth [2] discussed various test methods in his paper on the subject and concluded the standing wave was difficult for inductance lower than ~50nH. He suggested a variable-inductance multiple discharge method. Tests comparing these two methods at General Atomic on other low inductance capacitors had shown that a comparable result was obtained. One of the goals of this paper is to show a standing wave test with proper equipment is comparable to a ringing discharge when measuring at low inductance.

A. Ringing Discharge Method

The basis for this method is that if the capacitance is known then circuit inductance may be determined from the period of the an oscillatory discharge waveform. If the external circuit inductance is small compared to the capacitor and exactly calculable (e.g. coaxial) it may be subtracted from the measurement leaving only the switch, which initiated the discharge, to be accounted for. To maximize signal to noise ratio and to test a representative current level, 5 to 10kV is used. A solid dielectric switch is used to minimize inductance, contributing <½ nH in these tests. Experience with gas sparkgaps shows that they add inductance and switch resistance contributes to imprecise determination of capacitor resistance. Essentially this is a one shot determination of circuit inductance, similar to the multi-shot method described by Hayworth [1], where circuit inductance is plotted against external inductance with the zero external inductance value being that of the capacitor. Here the external inductance is that of a coaxial "top hat" or "shorting cap" with a solid dielectric switch between the shorting cap and an extension of the "hot" center terminal. A Rogowski coil picks up the discharge waveform, see Fig. 2.

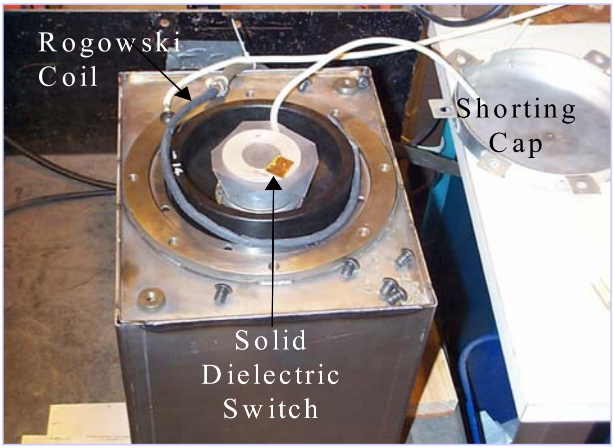

Figure 2. Ringing Discharge Setup – Shorting Cap off.

Since the conductor dimensions are easily measured, and if we define the capacitor inductance as beginning at the plane of the ground ring, the external inductance may be calculated as:

$$L_{ext.} = 2\, l \ln r_o / r_i \ \text{nH}, \qquad (1)$$

where the length l of the center conductor is in cm, r_o and r_i are the outer and inner radii of the coaxial terminal. Subtract the value from that determined from the capacitance and period. The solid switch contribution can be estimated from the same formula taking an arc channel diameter of ~.001 cm and length of <.013 cm (5 mils) giving ~0.25 nH. A sharp point driven through copper tape mechanically deforms the dielectric to produce an intrinsic strength breakdown with a very short resistive phase. See Fig. 3. The key to this measurement is the solid dielectric switch and calculable external inductance. For the hardware used here the external inductance is 4.83nH.

B. Standing Wave Method

The standing wave method consists of a signal generator and vacuum tube voltmeter connected by coaxial cables to a copper hat formed over the capacitor's Scyllac bushing. See Fig. 4. One adjusts the frequency from the signal generator until one finds the minimum voltage response. At this resonant frequency the inductance can be calculated (See Eq. 2).

$$L = (4\pi^2 f^2 C)^{-1} \qquad (2)$$

Figure 3. Ringing Discharge Setup

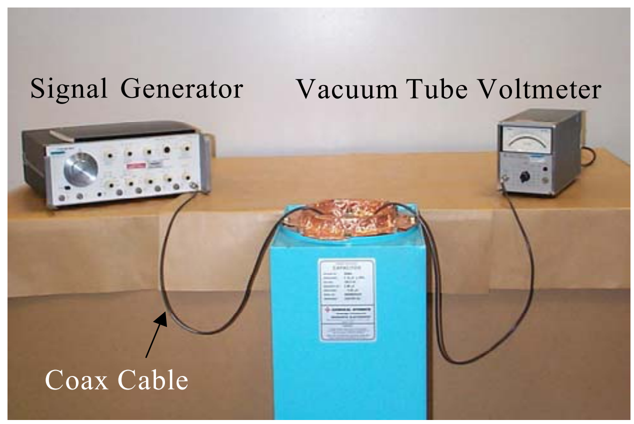

Figure 4. Sanding Wave Inductance Setup.

The copper hat is form fitted over the bushing to minimize external inductance. The braids of the coax cable are soldered to the hat near the center and the coaxial center conductors soldered to a brass washer.

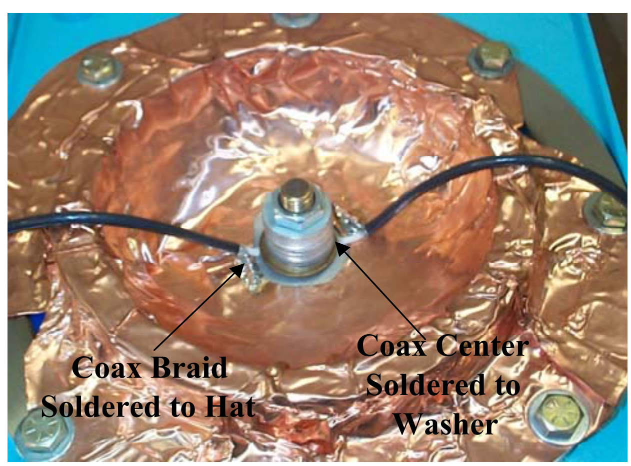

Figure 5. Copper Top Hat and Coax Cable.

These connections are 180? from each other to minimize cross coupling. A layer of 5mil polyester insulation separates the hat from the capacitor center electrode, while the outside of the hat bolts to the ground ring. A special brass bolt provides contact while holding the brass washer in place as seen in Fig. 5. This configuration provided very stable and reproducible measurements. External inductance here is the added volume created by the high voltage barrier. The dimensions of this volume are measurable and inductance calculable and in this case the external inductance is .78 nH.

demonstrated a reduction of ~20% and are working on further reductions.

The inductance of General Atomics Energy Products standard 100 kV Scyllac style capacitors measured 27 to 29nH. A similar Aerovox unit measured about 30nH. Compared to the reference capacitor (X32081), the X32080 prototype design exhibited a 5nH ESL reduction. The measurements using the both the Ringing Discharge and Standing Wave methods were satisfyingly comparable after subtracting the external inductance. A better fitting copper hat can reduce the greater difference

Table 2 Inductance Measurements.

INDUCTANCE MEASUREMENTS OF 100kV INSULATED SCYLLAC TYPE CAPACITORS									
Manufacturer	Capacitor Model No.	Cap. uF	Raw Discharge Meas. NH	External Inductance Correction nH	Inductance Value nH	Raw Standing Wave Meas. NH	External Inductance Correction nH	Inductance Value nH
Maxwell /GAEP	32827	3.14	32	4.83	**27.17**	28.7	0.78	**27.92**
Aerovox	SX210E23	2.097	34.9	4.83	**30.07**	33	0.78	**32.22**
GAEP (STD)	***X32081***	***3.47***	***30.53***	***4.83***	***25.7***	***26***	***0.78***	***25.22***
GAEP (Low L)	***X32080***	***3.264***	***25.56***	***4.83***	***20.73***	***20.2***	***0.78***	***19.42***
GAEP	32865	2.53				28.7	0.78	**27.92**
GAEP	32864	2.058				29.1	0.78	**28.32**

V. INDUCTANCE MEASUREMENTS

Measurements using both methods were made on four different capacitors. Two additional 100kV designs used only the Standing Wave Method. The results in Table 2 show that the two methods closely agree after correction for the external inductance. For the GAEP capacitors, the difference varies from about .5 to 1.3nH. The 2+nH difference in the Aerovox measurement can be attributed to poor fitting of the copper hat. GAEP Models 32827, 32865 and 32864 are all standard 11 x 14 x 25" 100kV capacitors with the only significant difference being their capacitance. All of the GAEP capacitors have nearly the same measured inductance, 27 to 29nH. The Aerovox unit measured about 30nH.

The inductance measurements show a reduction of ~5nH between the reference Model X32081and the low ESL Model X32080. X32081 had a 2+nH lower inductance than the completed capacitors, perhaps due in part to the drying process where the paper dielectric shrinks, increasing the headspace under the Scyllac bushing or the shorter case length.

VI. SUMMARY

Lower equivalent series inductance in the standard Scyllac style energy storage capacitor provides a cost-effective means to upgrade existing pulse power machines and performance advantages in new systems. We have

in the Standing wave measurement of the Aerovox unit. The measured prototype inductance of about 20nH is probably the minimum for this style of capacitor representing a reduction of about 30%. A 50% reduction will require a redesigned terminal. Production of such an ultra-low inductance capacitor entails resolution of a number of manufacturing issues.

System inductance is still a function of the integration of capacitor and switch. Improvements in this area could take better advantage of a lower inductance Scyllac or, as in the case of LANL Atlas program, the development of an integrated capacitor and switch.

VII. REFERENCES

Published conference proceedings:

[1] L. X. Schneider, S. R. Babcock, G. e. Laderach, "Lifetime Testing of Commercially Available 3.0 uF, 100 kV Pulsed-Power Capacitors," in *Proc. IEEE PPC '89*, 1989, p. 902.

Periodicals:

[2] Bruce Hayworth, "How to Tell A Nanohenry from a Microfarad," *EID – Electronic Instrumentation,* April 1972*,* Pages 36 – 39.