p. 9

Energy Storage and Dissipation Notes

Note 8

April 1971

Energy Storage Capacitors Of High Energy Density

by

P. Hoffman and J. Ferrante
Maxwell Laboratories, Inc.

Abstract

The capacitor requirements of modern EMP generators are such that conventional energy storage capacitors are not satisfactory. New concepts of capacitor design will make available high energy density units with reliable performance for future needs. A review of state-of-the-art energy storage capacitor characteristics is presented, delineating the effect of dominant operational mode on the physical shape and energy density of a number of capacitor types. A specialized configuration of energy storage capacitor, tailored to the requirements of EMP generators, is described and its performance characteristics detailed. These new capacitor concepts may be applied to specific applications in fusion research under certain circuit conditions which are discussed.

1. Introduction

The high voltage pulse discharge capacitor as we know it today owes its origin to the special demands of the nuclear weapon program in the late 1940's. In the late 1950's, it underwent intensive evolution to meet the experimental requirements of the controlled thermonuclear fusion program. In the early experiments, high voltage power factor correction capacitors were used; as the limitations of such capacitors for the pulse discharge applications became apparent, the capacitor industry was prompted to consider such novel factors as inductance, peak current capability and discharge life.

Rapid progress was made in the period 1955-1961: the paper/castor-oil capacitor was introduced, low-inductance capacitors capable of discharging up to 150 kA at 120 kV were developed. Only minor improvements were made until the mid-60's when the importance of the film dielectrics were realized. Today, the film capacitor offers the ultimate performance and reliability, but its cost tends to preclude its use in many applications.

Recent requirements for multi-megajoule, high-voltage systems -- EMP simulators, for example -- are posing new problems for the capacitor industry: extreme component reliability is required in order to provide adequate system reliability, new packaging configurations are desired and performance specifications are becoming stringent. It is no longer adequate to consider the capacitor as an independent element -- it must be considered as an integrated part of the total system.

2. Marx Generator Capacitors

Modern Marx generator capacitors have some special requirements not demanded of energy storage components used in banks similar to SCYLLAC. In addition to extremely low inductance and high peak current capability, the terminal face voltage gradient assumes an unusual importance. If multi-megavolt generators are to have practical dimensions, at least one dimension of the energy storage capacitor must be small; a factor not normally compatible with extremely high voltage.

High energy density has always been desirable so the large capacitor banks could be small in size with short transmission lines. In megajoule energy banks, the primary concern was always volume, not weight, or at least weight was not the primary concern. On the other hand, Marx generators tend to get tall, and the less weight to be supported, the better -- along with small size, of course. For Marx generators, the term "energy density" applies to weight.

With the previous statements in mind, let's look at some typical capacitors from a point of view other than low cost: Figure 1 shows some energy density values of energy storage capacitors of various types - all the way from D. C. filter units to a target value of 100 Joules/lb. established for a special EMP generator unit. Numbers 8, 9 and 10 are insulating case capacitors of relatively low energy content, although the energy density is high -- more on that later.

Figure 2 gives one an idea of the electrical stress on the dielectric of a variety of high voltage capacitors. Although everyone here is probably familiar with the well-known "Fifth Power Law" and kindred empirical constants which use dielectric voltage stress as the reference factor, one should be hesitant about jumping to conclusions regarding the reliability or longevity of the highly stressed items shown here. There are extenuating factors which carry considerable weight also.

Figure 3 shows the terminal face voltage gradient of several capacitors of conventional metal case design and also two currently available plastic case units. Number seven will almost certainly be achieved with an insulating case, or with no case at all in the commonly accepted sense.

Figure 4 shows the influence of energy content on energy density for one of the plastic case units included in the previous figures. This is an important factor in this particular capacitor because increased energy content results from increased length, the cross section dimensions staying the same. Even so, increased energy density goes with increased energy content to a degree dependent on the shape.

CODE

1. Commercial Paper-Oil High Voltage Filter Capacitor
2. 120 kV Energy Storage Capacitor
3. 1.85 μF, 60 kV Scyllac Capacitor
4. 14 μF, 20 kV ZEUS Capacitor
5. AURORA Plastic Case 45 kV Marx Generator Capacitor
6. MLI Type H, 60 kV Cylindrical Capacitor
7. MLI Type M, 12 kV Cylindrical Capacitor
8. SIEGE Plastic Case, 50 kV Marx Generator Capacitor
9. Target Value, High Energy Density Marx Capacitor

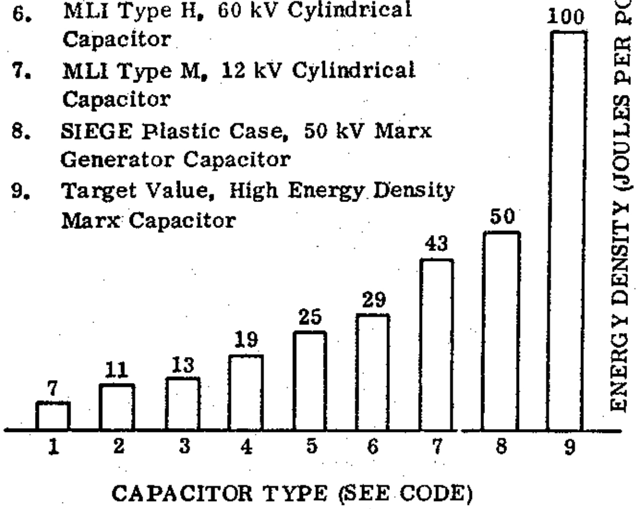

Figure 1. Capacitor energy density

CODE

1. Commercial Paper-Oil Filter Capacitor
2. Commercial Plastic-Paper-Oil Filter Capacitor
3. Standard Paper-Castor Oil Energy Storage Capacitor
4. Maxwell Type H Energy Storage Capacitor
5. AURORA Marx Generator Capacitor
6. SIEGE Plastic Case Capacitor
7. Probable Value for High Energy Density Marx Capacitor

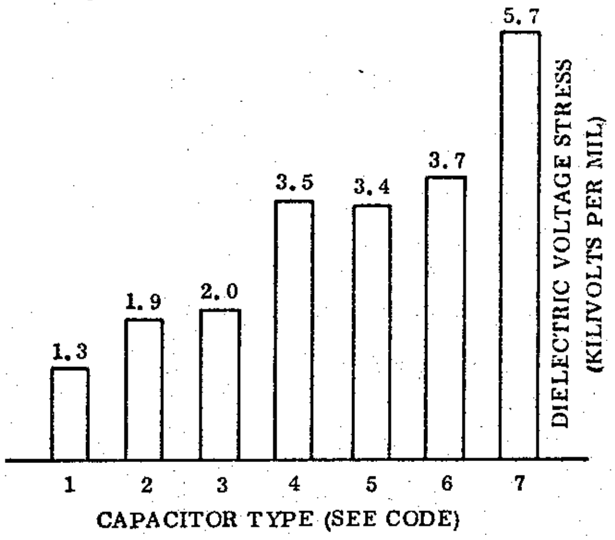

Figure 2. Energy storage capacitors dielectric voltage stress

CODE

1. 14 μF, 20 kV ZEUS Capacitor
2. 1.85 μF, 60 kV Scyllac Capacitor
3. 120 kV Energy Storage Capacitor
4. 50 kV Marx Generator Capacitor - P.C. Co.
5. Maxwell SIEGE 50 kV Capacitor
6. Maxwell AURORA 45 kV Capacitor
7. Target Value, High Energy Density Marx Capacitor

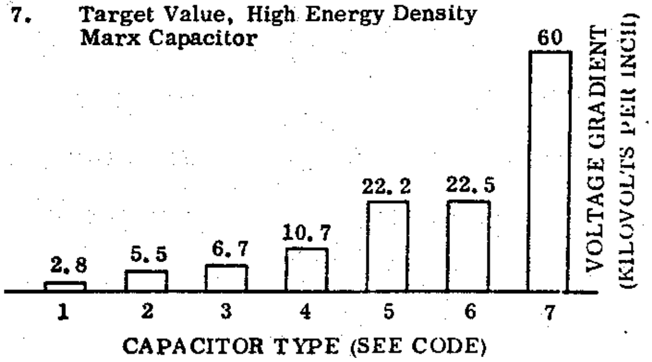

Figure 3. Vertical voltage gradient based on minimum case dimension

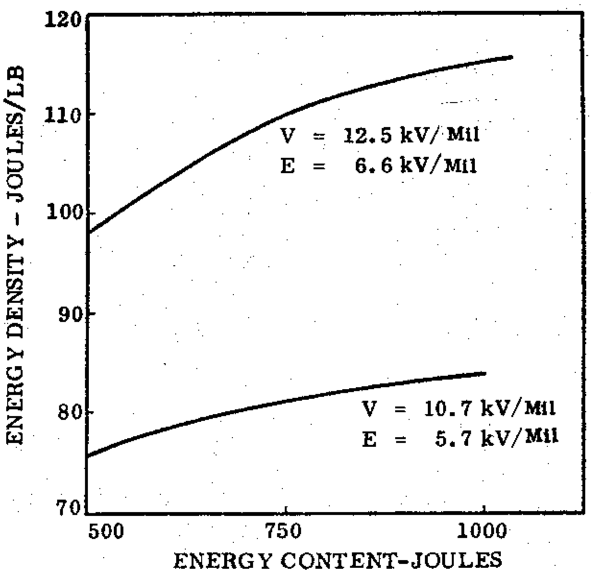

Figure 4. Energy content coefficient of energy density

The foregoing figures are not presented with the idea in mind of disparaging the characteristics or capabilities of conventional energy storage capacitors. Each capacitor type represented was designed and produced to fill a need which existed then and still exists. What was intended was to confirm the point that the need for specialized capacitors in various activities where pulsed power was required resulted in significant improvements in all performance factors of such capacitors.

3. High Energy Density Capacitor Design

Another case in point is that of the dynamic situation concerned with power capacitors used by the public and private utilities. Traditionally, that business has always been conservative and slow to accept new ideas. When the burgeoning need for electrical power required technological advances in every phase of the power distribution business, the capacitor manufacturers responded. The present film capacitor represents a 200 percent increase in energy density in the past ten years, with comparable savings in costs per KVAR and installation expense. The operating costs are halved as a result of reduced dielectric losses.

Special capacitors are needed for the new generation of EMP generators, as well. In these applications, high unit energy content is not necessarily desirable. Since the total energy involved is often in the megajoule area, it quickly becomes apparent that reliability has become a major factor -- not extreme life; but reliable, predictable short life, and at high energy density.

To expand on this theme, consider the fact that most heavy duty energy storage capacitors consist of parallel assemblies of multiple pads or windings. A typical unit -- such as the 1.85 μF - 60 kV capacitor described in Gren Boicourt's paper on the SCYLLAC capacitor development -- has 12 parallel windings, each consisting of eight series sections, or 96 vulnerable elements, the failure of any one of which will cause failure of the capacitor. If a distribution of the intrinsic dielectric strength of each section -- 96 in all -- was plotted, one would probably see the familiar bell-shaped curve shown here. The maximum operating voltage must obviously be a value chosen to be well below the minimum value on the statistical distribution. Even greater safety factor is needed to allow for variations in voltage from one series section to another, variations caused by normal manufacturing tolerances in setup and winding.

If a means of sorting out the substandard pads in every winding could be found, we could skew the distribution in this manner and increase the operating voltage -- and the energy density -- at virtually no additional cost.

If we examine the design of most of the heavy duty energy storage capacitors in use today, we will probably find that the dielectric system consists of multiple layers of Kraft paper impregnated with castor oil. Both materials are excellent for the purpose, of course, but paper particularly has a fairly wide range of performance capability. Any attempt to perform a selective sorting operation on a paper pad is hindered by the fact that the paper contains about 6 percent moisture and that moisture isn't distributed evenly across the width of the web. Paper benefits tremendously from vacuum drying and oil impregnation. The dielectric strength is increased fourfold or more, and the quality is surprisingly uniform through a pad.

Reliability is most easily achieved by lowering the stress on the performing elements. This avenue is contrary to our need for high energy density, so a better means of improving performance is needed.

Before drying, it is virtually impossible to perform a meaningful sorting operation on a paper dielectric pad. One can find gross errors by this method, but that is not enough if our purpose is to obtain maximum energy density and reliability. Also, before drying and impregnation, one is not testing the true quality of a paper dielectric.

From the foregoing, it can be seen that -- good as it is -- paper dielectric may not be the best route to maximum energy density. A material which can be evaluated in a subassembly stage should permit sorting with a great amount of accuracy and should be capable of operation close to the low limits of a narrow performance distribution.

A plastic film dielectric -- alone, or in combination with paper -- can be tested, in pad form, directly from a winding machine at a voltage greater than the design operating value. If used with paper, the 6 percent moisture seems to grade the electrical stress and permit more effective culling. There are many combinations of plastic films and paper, of course, and the proper sorting voltage for each one must be empirically determined, but this procedure is a dependable means of increasing the performance level where the dielectric strength of the materials is the limiting factor. It is one of the procedures we use to achieve high energy density and retain reliability of the capacitors.

An example of the result of fairly conservative voltage sorting of pads immediately after winding is shown in Figure 5. These windings have no series sections, but the pads are connected in series during installation.

The pads from which these data points were obtained were dripotted at a D.C. voltage 10 percent greater than their rated charge voltage as a process control measure. A significant amount of lesser quality pads were culled by this method. Finished capacitors had a very low failure rate on over-voltage test after finishing and the pad test data shown here predicts a high degree of reliability for the capacitors.

The process control procedure just described has other advantages than elimination of weak sections. It is an effective means of safeguarding against substandard material, particularly so when more than one supplier is involved. Variations in other operations are monitored by this type of test, and we were able to maintain surveillance of equipment function for several items solely from the results of the dripot test.

As part of a project to increase energy density to the greatest degree, the voltage between foils has been pushed beyond the point normally considered prudent. Hayworth[1] reports a life proportional to $E^{-4}V^{-3.5}Q^{-2.2}$ for polyester films in a report covering tests limited to an inter-foil voltage of 5 kV at the top end. Experience with paper dielectric energy storage capacitors indicates that a maximum

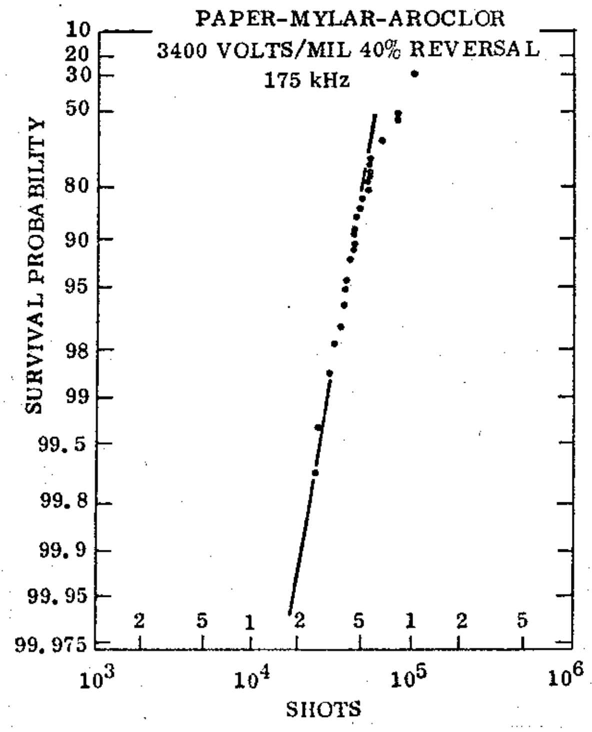

Figure 5. Survival probability versus shot life

12,500 Volts/Pad

Dielectric Stress 6578 V/mil

Type	Impregnant	Sample Number	Voltage	Voltage Reversal	Shots	Joules/ Lb.
4 ea. pads	Castor Oil	1	50 kV	0	5,196	141
in series	Castor Oil	2	50 kV	0	14,153	141
"	Castor Oil	3	50 kV	0	51,106	141
"	Maxol A	4	50 kV	0	62,237	141
"	Maxol A	5	50 kV	0	27,400	141

Figure 6. Shot life unit test data

section voltage of 8.5 to 9.0 kV must be observed unless one is to pay a severe penalty in low reliability and short life. Although our test program is far from finished, interim results give promise of inter-foil voltage values at least as high as 12.5 kV, partially made possible by the ability to sort out substandard components in a dripot test.

The target values of 100 Joules per pound for energy density, and 60 kV per inch for voltage, are worthy goals. Figure 6 shows the results of some tests made to prove the feasibility of achieving 100 Joules per pound employing a caseless capacitor construction. These capacitors were tested at 50 kV (12.5 kV/pad) and were actually tested in a plastic case in order to compare impregnants. The energy content of the units was around 825 Joules, an average value for unit capacitor energy content for many of our Marx generators. Maxol A is a proprietary impregnating material permitting flexibility in physical design while maintaining good electrical characteristics.

The high energy density capacitors described here were designed specifically for use in compact Marx generators. The techniques used to obtain high energy density were, in part, useful because of the type of material used. For this reason, the cost of a given volume of capacitor is markedly higher than the paper-castor oil units so widely used. The benefits derived from higher energy density are usually compounded, so the net results can be a net saving in cost where the operating conditions can be met.

Acknowledgement

Appreciation is extended to Mr. Richard Fitch and Mr. William King of Maxwell Laboratories for their contributions of ideas and information for this paper.

Reference

1. IEEE Transactions on Electrical Insulation, May 1968, "The Behavior of Polyester Film Energy Storage Capacitors", Bruce R. Hayworth, Maxwell Laboratories, Inc.

← reference
ESDN 7