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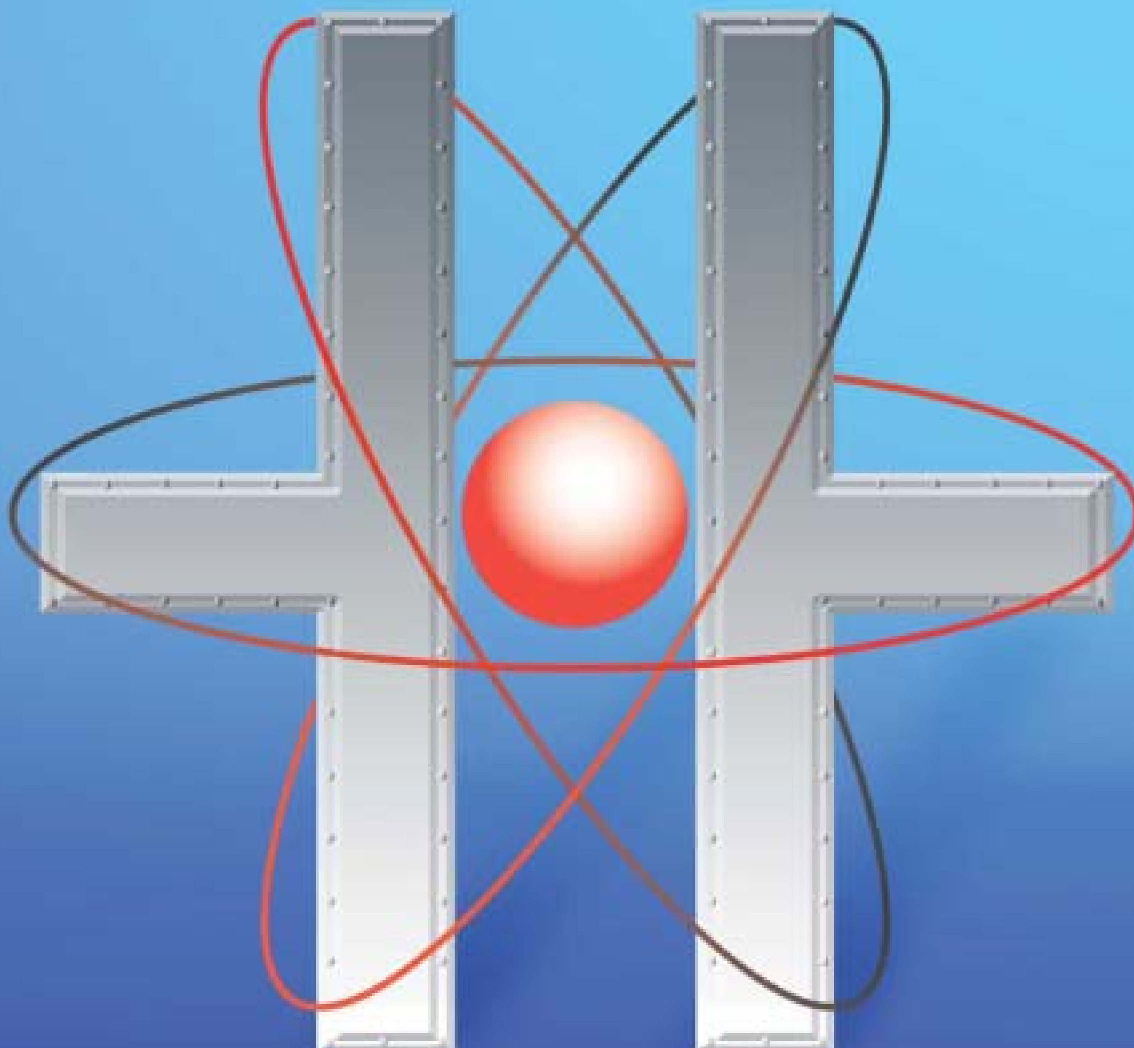

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Equivalent Series Resistance (ESR)

Many electrical engineers are familiar with a circuit model (Figure 1) of a non-ideal capacitor which includes a series inductance (the ESL) and a series resistance (the ESR). This model is very misleading because it often results in the assumption that the **equivalent** resistance is actually a true resistance, having essentially constant value over a wide range of conditions [7]. In truth, the Equivalent Series Resistance is the value of resistance which is equal to the total effect of a large and complex set of energy loss mechanisms occuring **under a particular set of measurement or operating conditions.**

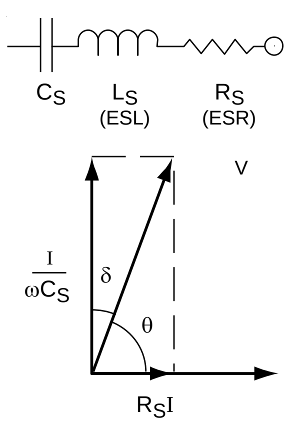

Figure 1. AC voltage signal applied to circuit below resonant frequency.

General Atomics Energy Products (GAEP) has attempted to avoid incorrect application of ESR information by not listing an ESR value in its standard product sales literature. Each customer who is concerned about this parameter is asked how the ESR value is to be used in his or her calculations or models. This allows us to tailor a measurement method to the requirements of a particular application. Although this is more complex and time-consuming, it is **the only way of assuring that the quoted ESR values have real meaning for the intended purpose.**

Capacitor manufacturers often define the ESR as the impedance measured at the resonant frequency of the capacitor, or the value of the ESR at a particular AC frequency (e.g. 100 kHz), usually measured with a bridge, LCR meter, or impedance analyzer at about 1 V. These are definitions which make it easy to measure the ESR but may be inadequate to describe the behavior of a high voltage capacitor under **actual operating conditions.**

In this Technical Note, we intend to briefly describe why the ESR does not behave like a simple resistance as the result of the physics of a capacitor. We will then examine several methods of measuring the ESR and how the exact test conditions affect the results of each. Finally, we will discuss how ESR values are often used and suggest how to specify the ESR and the proper measurement technique for your application.

Capacitor Physics and ESR

If we apply an AC voltage signal to the circuit of Figure 1 at a frequency well below the resonant frequency, we observe a phase shift between voltage and current which is less than 90 degrees. The difference between the phase angle and 90 degrees is the defect angle (δ), which can be used to determine the effective resistive impedance using:

$$\text{tangent}(\delta) = Zr/Zc = ESR \cdot \omega \cdot C \qquad (1)$$

where Zr and Zc are the resistive and capacitive impedances, ω is the angular frequency, and C is the capacitance. Note that tangent δ is the same as the dissipation factor, or DF [4].

The energy loss in the circuit is proportional to the power factor, PF, which is given by the cosine of the phase angle. The DF is approximately the same as the PF for small values (e.g. DF < 0.1 or 10 %).

If we assume that the energy dissipated is a constant fraction of the energy stored over all frequencies (constant DF), the ESR decreases with increasing frequency, as can be seen by rearranging equation (1):

$$ESR = DF/\omega C \sim 1/\omega \qquad (2)$$

Figure 2 illustrates the hypothetical constant-DF case.

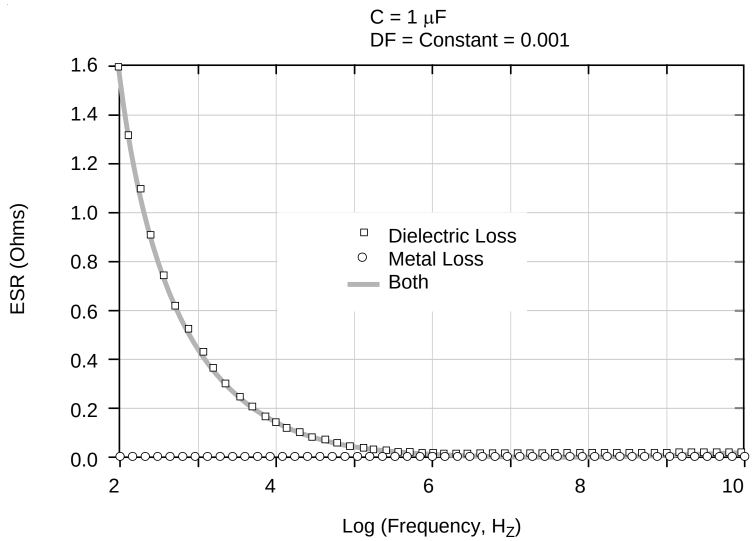

Figure 2. Hypothetical constant/DF case.

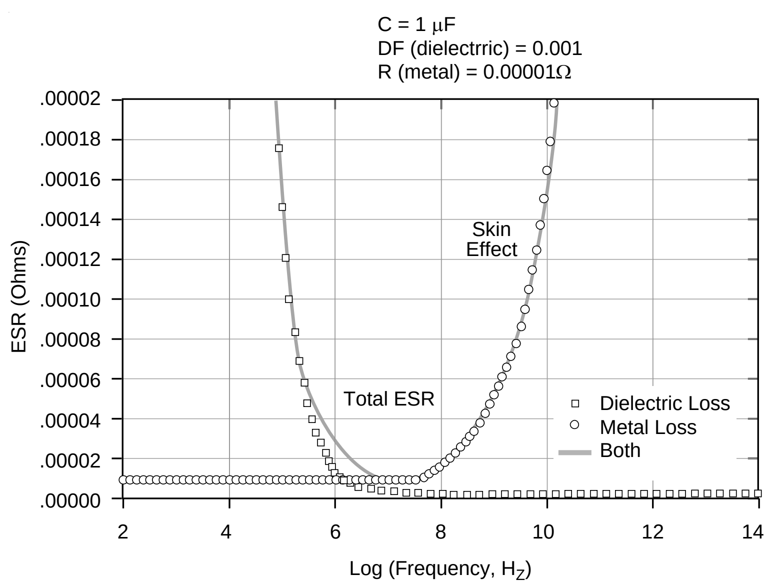

Figure 3. ESR as a function of frequency.

The ESR of a 1 μF capacitor has been modelled assuming that the dielectric losses result in a constant DF of 0.001 or 0.1% and the ohmic resistance is 0.01 milliohm. The resulting ESR is shown as a function of frequency in Figure 3. The ESR falls from a value of 1.6 ohm at 100 Hz to a value of 0.01 milliohm at 5 MHz. Above this frequency the ESR is largely determined by the ohmic resistance of the conductors, and remains relatively constant until the skin effect begins to reduce the effective thickness of the foil electrodes. The ESR then begins to increase in proportion to $f^{0.5}$ above about 30 MHz.

When examined more closely, the losses vary as a function of voltage, temperature, and other aspects of the waveform. This is because there are a variety of energy loss mechanisms which act within a capacitor. Some of these reside within the dielectric while others involve the conductors carrying the current. Below we describe some of these mechanisms and the operating parameters which strongly effect the magnitude of the losses which are associated with them.

Dielectric losses are usually the most important losses in a film capacitor. These losses are associated with the polarization and relaxation of the dielectric material in response to the application and removal of voltage from the capacitor. As such, the magnitude of the dielectric losses in a capacitor are, in general, both frequency and temperature dependent. In this case, the largest losses occur at low temperatures or high frequencies, where dipole orientation is most hindered. Dielectric losses (as defined here) are not voltage-dependent.

The dielectric losses of a given material can be described by its Dissipation Factor (DF). If the dielectric loss were the only loss mechanism operating in a capacitor, then the DF of the capacitor would be independent of its size and geometry and internal configuration. Capacitors of any size made with the same material would have the same DF when measured under identical conditions. The ESR could then easily be computed using equation (2). However, the capacitor DF and ESR do depend on the electrodes and their configuration, as described below.

Ferroelectric hysteresis losses are observed in certain high dielectric constant materials, most notably ceramics. These losses are a strong function of applied voltage. This loss mechanism arises when the internal polarization field has the same order of magnitude as the applied field. Under these conditions the dielectric response saturates. Capacitors made with such materials exhibit permanent polarization, variable capacitance as a function of voltage, and extreme sensitivity to reversals of voltage.

Dielectric conduction losses are caused by the actual transport of charge across the volume of the dielectric or across internal dielectric interfaces. These losses are largest at low frequencies and higher temperatures. Because conduction in a dielectric material can be strongly nonlinear (non-Ohmic), conduction losses are often strongly dependent on the voltage applied to the capacitor.

Interfacial polarization losses are closely related to dielectric conduction. Many high voltage capacitors contain two or three different materials within their dielectric systems – film and oil or paper, film and oil. Each material has different conduction properties and permittivity. As a result, the application of a DC voltage over a period of time will result in a build-up of conducted charge at the internal interfaces between materials. This polarization of the dielectric is largely a low-frequency phenomenon and the energy stored in this way is not available for discharge at high frequency. Again, since the conduction is nonlinear, interfacial polarization will also generally be nonlinearly voltage dependent.

This loss mechanism can be especially important in pulse discharge applications, where the capacitor is charged over a relatively long period of time and then discharged much more rapidly.

Partial discharge losses can occur within gas-filled or defective solid capacitors or even in liquid-filled capacitors at high voltages. It is also common to have external corona on capacitor terminals (which can be considered a capacitor energy loss mechanism). Partial discharges are most energetic at high rates of change of voltage (high dV/dt), such as during a capacitor pulse discharge. Also, reversal of the voltage such as in a highly oscillatory ringing capacitor discharge will cause more numerous, energetic, partial discharges.

Electromechanical losses result from the electrostriction (and sometimes piezoelectricity) acting within the capacitor dielectric itself and the flexing of internal wiring due to the Lorentz forces.

Ohmic resistance losses occur within the metallic electrodes, the internal wiring, and the terminals of the capacitor. (In electrolytic capacitors, ohmic resistance in the electrolyte itself represents the largest loss mechanism.) The resistance losses in the metal are quite constant as a function of temperature and frequency (until the skin depth in the electrodes becomes important, usually at several megahertz or higher). Losses in the internal wiring and the terminal can be important in high current applications, and should not be ignored. When high voltage capacitors are internally configured as a series string of lower voltage capacitor windings or units, the ohmic resistance within a given container size increases at the square of the voltage (or as the number of series elements).

Sparking between conductors or different points on the same conductor during the discharge has been reported to occur in pulse capacitors [3]. For example, capacitors manufactured with an inserted tab connection to the electrode foil which is only a pressure contact have been found to exhibit points of localized melting after pulse discharge operation resulting from sparks between the adjacent metallic surfaces [3]. This phenomenon probably is related to a high rate of change of the current (dI/dt) during the discharge, and therefore to both frequency and voltage.

Eddy current losses are important in Pulse Forming Networks (PFNs) or other situations where a high magnetic field can couple into any ferromagnetic materials used in the capacitor. These losses will depend strongly on frequency. Usually the internal inductance in a capacitor is small and will not generate significant eddy currents.

Measuring ESR

There are several techniques which can be used to measure the ESR under different conditions. Below we describe these methods and discuss what they actually are measuring in terms of the mechanisms discussed previously.

AC Bridge measurements involve the application of a sinusoidal AC signal to the capacitor at a particular frequency and the measurement of the phase angle. Note that this measurement of the ESR is equivalent to measuring the DF.

In practice, most manufacturers use a **low voltage** bridge, LCR meter, or impedance analyzer to make this measurement. High voltage AC bridge measurements are possible [5], but usually cannot be performed at the rated DC voltage due to capacitor stress limits.

One major drawback of the bridge measurement technique is that measurements are made at a discrete frequency, whereas pulse discharge applications typically involve two wide bands of frequency involved in charging and discharging. Some improvement can be made by measuring and reporting the ESR over a wide range of frequencies.

Another drawback is that the signal is sinusoidal, whereas pulse discharge applications generally involve charging to a DC voltage and either no reversal or less than 100% reversal on discharge.

Biased AC Bridge measurements are a possible solution to the high voltage DC application versus low voltage AC measurement problem. In theory it would be possible to bias the applied 1 V AC signal and measure the differential ESR at high DC voltage. By itself, this technique offers no advantage, but by making a continuous series of measurements over the full range of voltage and using computer-based analysis the data could be integrated to obtain the total effective ESR. This could be repeated over a range of frequencies to map out the behavior in the frequency and bias voltage domains.

This approach seems promising for a future line of research, but to our knowledge, has not been previously described or tested.

Short-circuit discharge of the capacitor is a technique which has been frequently used at GAEP. The method involves charging the capacitor to a voltage at which it is acceptable for a ringing discharge to occur without damaging the capacitor. The capacitor is then discharged through a low inductance, low resistance short circuit and the discharge waveform captured using a Rogowski coil or other sensor. Both the circuit inductance and resistance can be calculated from the period and the damping factor measured using this technique.

To improve the accuracy and sensitivity of this method, it is often necessary to connect multiple capacitors in series in the discharge circuit. One then replaces one of the capacitors with a direct short so as to determine the difference in the circuit resistance and inductance due to a single capacitor. This method allows the elimination of the residual resistance in the external buswork and switch [2]. It assumes that the difference in the resonant frequency of the circuit with different numbers of capacitors is not significant to the measurement.

A similiar method, developed for measuring low values of capacitor parasitic inductance, involves performing a series of ringing discharges while varying a small added external inductance. The dI/dt at the start of the discharge is estimated for each pulse and projected to zero external inductance [1].

These methods suffer because the resonant frequency of the capacitor is generally well above the frequency range of interest to the user. Also, they involve a high reversal discharge which may not be representative of the application, and measure only the energy losses occuring during the discharge. Although such techniques can be used at higher voltages than the AC bridge, they often cannot be used above half rated voltage due to capacitor stress limitations.

Standing wave measurements using, for example, a Q-meter, can be made to determine the Q at the self-resonant frequency. The Q is just 1/DF, and so the ESR at the self-resonant frequency can be calculated. This method is a low voltage measurement technique and is restricted to the self-resonant frequency [1].

Calorimetric measurement of the heat generated in a capacitor under closely simulated operating conditions is relatively difficult, but yields direct information about the total energy losses in the capacitor which will result in self-heating. This method measures the total energy losses which discharging the capacitor [3],[6].

Energy efficiency measurements can be made under simulated operating conditions by measuring the input current and voltage and the output current and voltage as functions of time, calculating the power, and integrating to obtain the energy input and output. This method has been used to characterize nonlinear ferroelectric capacitors which have relatively low efficiencies. The precision necessary to measure the efficiency of very low loss capacitors has not been demonstrated [6].

Like the calorimetric method, the energy losses measured in this way result from both the charging and discharging portions of the cycle, and are not directly applicable to discharge circuit modelling.

How the ESR is Applied

Engineers specifying the ESR of a capacitor are usually concerned about either energy delivery to a low impedance load, self-heating of the capacitor under high average power conditions, or quality assurance.

In many instances, users of pulse discharge capacitors are concerned with efficient energy delivery from the capacitor to the load. In order to model the circuit and estimate the energy delivered, these engineers seek to estimate the resistance in the various components of the pulse circuit. Alternatively, the engineer may specify a maximum resistance budgeted to each component which will insure that the required energy is delivered.

In this case the user is only concerned about how much the delivered energy will be reduced by the energy loss mechanisms occuring in the capacitor during the discharge itself. Generally this will involve a wide band of frequencies proximate to the ringing frequency of the discharge. The most important of the possible loss mechanisms will be dielectric, ferroelectric (in ceramic and PVDF capacitors), electromechanical, partial discharge, ohmic conduction, and sparking.

As previously discussed, the ESR measured at the resonant frequency is not the worst-case value. The ESR is higher at lower frequencies.

To take this into account, GAEP recommends measuring the ESR at the resonant frequency using the high voltage short-circuit discharge technique. The equivalent dissipation factor can then be calculated using equation (1). This is constant over the range of frequencies of interest, and the effective ESR can be calculated from this using equation (2). If a single value of ESR is desired, this could be a weighted average using the spectral content of the pulse, calculated using Fourier or another transform method. Simpler alternatives would be to use the maximum value of ESR, or the value at the ringing frequency, in the circuit model.

When specifying the maximum allowable ESR, clearly it is most important to include the frequency or range of frequencies over which the limits are applicable.

Self-heating of capacitors is an important concern in high repetition-rate pulse discharge, AC, and other applications where the RMS current and average power are high. Limits on the ESR are sometimes specified as a means of assuring that thermal runaway, overheating, and capacitor failure are avoided.

For non-sinusoidal waveforms, GAEP recommends specifying limits on the dissipation factor rather than the ESR due to the large variation in ESR with frequency. Either the two frequency bands or the charging and discharging waveforms should also be specified.

To be absolutely certain that the capacitor will not overheat, the calorimetric or energy efficiency measurement techniques should be used under voltage, waveform, repetition rate, and environmental conditions which closely approximate those of the application.

ESR is sometimes specified as a quality assurance parameter to be included in the acceptance testing of each capacitor. A limitation may be placed on the value of the ESR in order to insure that no "deviant" capacitors pass the acceptance test. In this case, the test method and parameters should also be defined, but the choice of method may be considered less critical.

For simplicity, reproducibility, and economy, the low voltage bridge technique is usually preferable for this purpose. However, GAEP recommends specifying the dissipation factor rather than the ESR if this measurement technique is acceptable. (This will help to avoid improper use of the specified value by other engineers.) It may be desireable to measure the DF at two widely separated frequencies (e.g. 120 Hz and 10 kHz) in order to detect a wider range of potential defects or variations.

If another ESR measurement technique is to be specified, GAEP recommends calling out the short-circuit discharge method at a specified voltage.

Summary

The Equivalent Series Resistance is one of the most misunderstood and misapplied parameters used in specifying or describing capacitors. The ESR is often used as though it were an ideal resistance, constant over frequency and voltage. In reality, the ESR represents a complex set of loss mechanisms, many of which are strongly dependent on the measurement conditions. A number of measurement techniques are available depending on the intended use for the information.

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Charging Capacitors: Polarization and Leakage Currents

It is an unfortunate fact that "real" capacitors differ from ideal capacitors in many respects. Real capacitors include parasitic inductance and resistance, and vary in capacitance with temperature, frequency and voltage. This is especially true in high energy density capacitors, where dielectric materials and current conductors are highly stressed.

The behavior of real capacitors deviates farthest from the ideal capacitor model during low-frequency transients such as during DC charging. This can impact the selection or design of compact charging power supplies, time delays between the connection of charging circuits and discharge of the capacitor or bank, or system performance.

General Atomics Energy Products (GAEP) manufactures capacitors, charging power supplies and a variety of pulse power systems which utilize capacitors as energy storage, pulse discharge devices. Due to this experience, GAEP has a unique understanding of the physical behavior of capacitors and the problems associated with capacitor applications.

This experience has been important both in developing new capacitor technology and in assisting our customers in their applications.

Here we will describe the general behavior of real capacitors during charging and steady-state voltage conditions. We will examine the reasons for this behavior in terms of physical processes occurring within the capacitor dielectric. We will discuss possible impacts on system design. Finally, we will discuss measurement and characterization techniques.

Behavior Of Real Capacitors

Capacitors are often modeled using the "equivalent circuit" shown in Figure 1. This circuit includes a conductance or parallel resistance (Rp) which represents a current leakage path through the dielectric. The value of Rp is usually determined by measuring the insulation resistance or leakage current

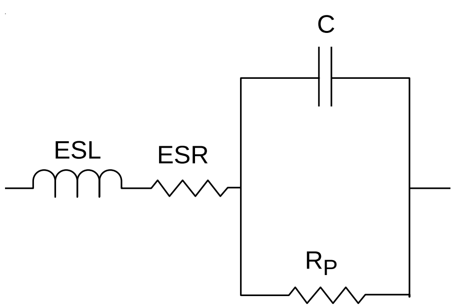

Figure 1. Circuit model of a capacitor which is commonly used.

one to five minutes after charging the capacitor. This model predicts that the leakage current is directly proportional to voltage and independent of time. To charge the capacitor (C) at some ramp rate (dV/dt), one would therefore supply a current (I):

$$I = I(\text{capacitive}) + I(\text{leakage})$$

$$= C\,(dV/dt) + V/Rp. \qquad (1)$$

In reality, this current would be insufficient to charge a real capacitor at the desired ramp rate. In addition, if one were to attempt to hold the voltage at some level by just supplying the leakage current (V/Rp), the capacitor voltage would drop to some measurably lower value before stabilizing.

These phenomena are mainly the result of time-dependent polarization currents within the capacitor dielectric. In addition, the assumption that the steady-state leakage current is directly proportional to voltage is not generally true.

If we apply a square wave voltage pulse to a capacitor, and measure the total charge input versus time by integrating the current, we observe the behavior seen in Figure 2. There is an initial steep rise in the absorbed charge corresponding to fast polarization processes. This is followed by a more gradual rise in total charge which is the result of slower polarization processes. Finally there is a continuous, linear increase in the total charge at a relatively low rate which is due to steady-state conduction.

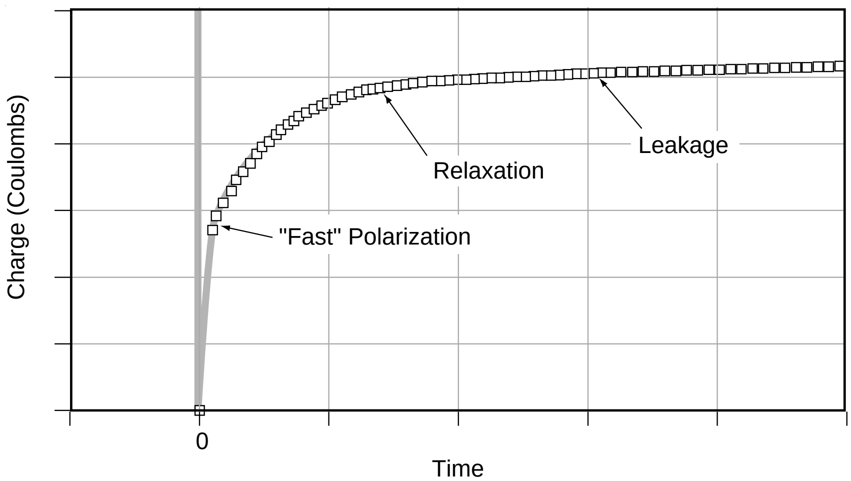

Figure 2. Typical dielectric response to a square wave voltage pulse.

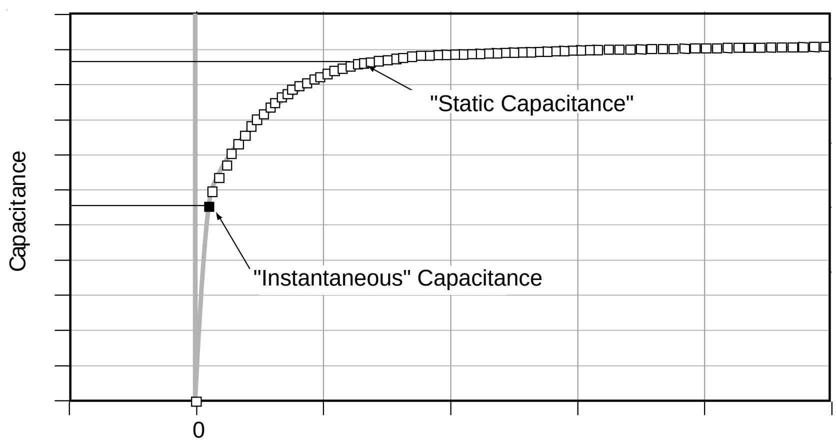

Figure 3. Effective capacitance versus time in Figure 1.

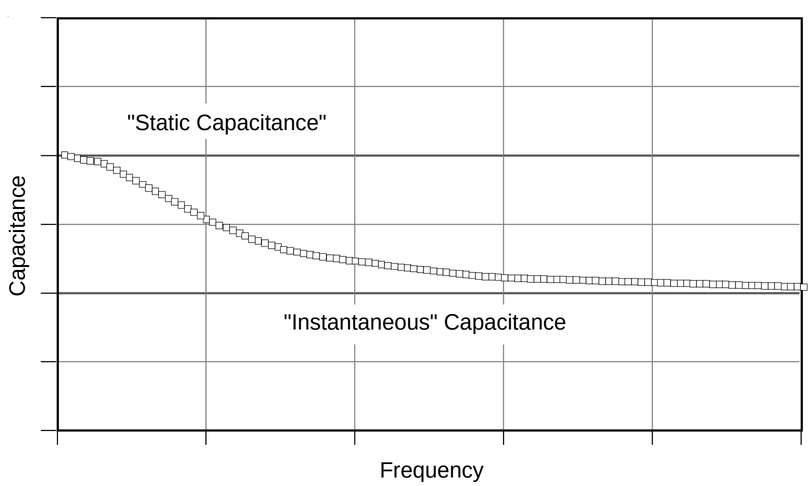

Figure 4 Capacitance versus frequency in Figure 2.

The time scale in Figure 2 is not indicated because there are several different polarization mechanisms which act on different time scales. Thus, the charge-time graph on one time scale looks qualitatively the same as the charge-time graph on a much longer or much shorter time scale, whether in microseconds or thousands of seconds.

Ignoring the leakage current and considering only the polarization of the dielectric, the graph of Figure 3 is the time-dependence of the capacitance. The capacitance (C) is equal to the charge stored (Q) divided by the applied voltage (V):

$$C = Q/V \qquad (2)$$

so that Figure 3 is similar to Figure 2 in form. If we transform this to a capacitance versus frequency plot, we would obtain a curve like that shown in Figure 4.

If we measure the current drawn by the capacitor when charged with a square voltage pulse, we obtain the result shown in Figure 5. Alternatively, if we charge the capacitor rapidly and then disconnect it from the power supply, we will observe a rapid initial voltage drop as the polarization continues and the capacitance increases, as illustrated by Figure 6. This drop cannot be fit to a pure exponential decay. After the static capacitance value has been reached, the voltage drop due to leakage current is at a much smaller pace, and can usually be fit to a pure exponential decay.

The effect of this time-dependent capacitance is mostly seen during charging of the capacitor. The energy and charge which must be supplied to bring the capacitor to some voltage over a period of seconds or minutes is often greater than expected based on the value of capacitance measured at a higher frequency (60, 120, or 1000 Hz are typical). Yet the energy available for a fast discharge is very close to that predicted from the measured capacitance. The difference is certainly an energy loss, but it is not due to leakage current alone.

Another way of observing this phenomenon is to charge a capacitor with a constant current power supply, for which the output current is set to be the ideal minimum value given by Equation 1. The resulting voltage ramp will look something like that shown in Figure 7. The rate of voltage rise will tend to roll-off toward the end of charge. This may be at first attributed to nonlinear conduction, but it may in fact be a stronger function of the charge time than of the charge voltage.

There is another effect of the time-dependent capacitance, known as **dielectric absorption**, which is observed after discharging the capacitor. If the capacitor is charged slowly, so that the static capacitance has been charged, and then discharged rapidly, followed by opening of the circuit, a residual voltage will appear across the capacitor terminals. The voltage is usually a small fraction of a percent of the peak charge voltage, but can be several percent in some types of capacitors with polar dielectrics. This residual voltage is due to the energy which was stored in the slow polarization mechanisms that was not released during the fast pulse discharge. This energy will redistribute itself amongst all of the available

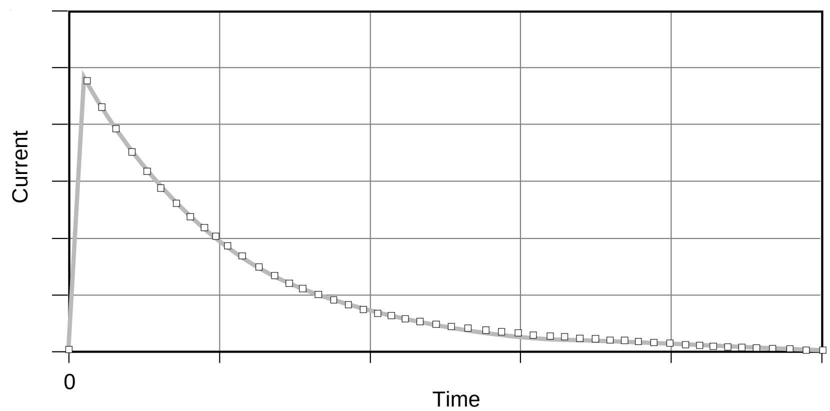

Figure 5. Charging current for square voltage pulse.

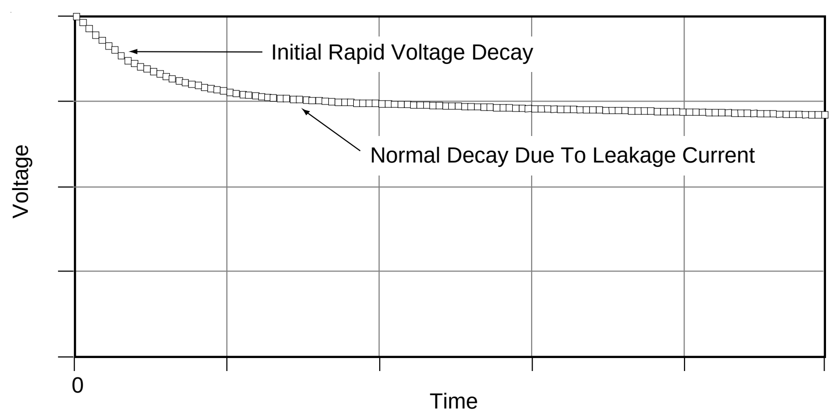

Figure 6. Voltage decay after disconnecting power supply.

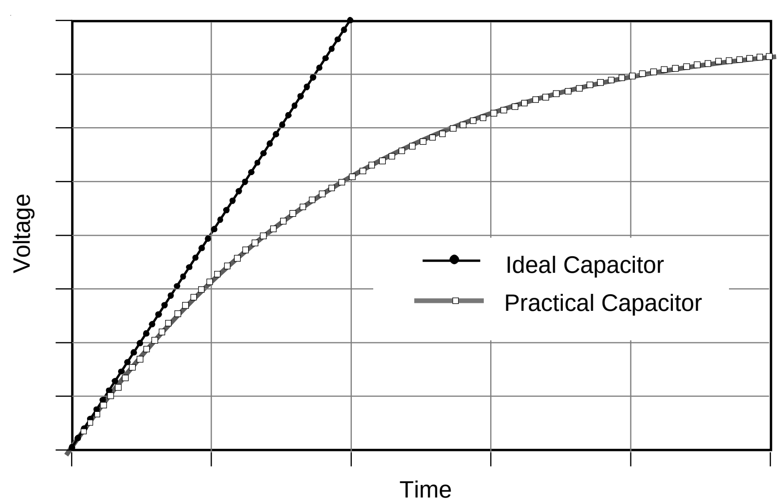

Figure 7. Charging ramp with ideal current.

polarization mechanisms after the circuit is opened, so that a fast discharge from this residual voltage is then possible. In high voltage systems, this effect can create a safety hazard. For this reason, capacitors should normally be kept shorted when not in operation.

Clearly the charging behavior of capacitors is more complicated than indicated by the simple model commonly used. In the next section we will explore why this is true.

Dielectric Physics

There are four basic mechanisms of polarization which can be taking place within the dielectric of a capacitor: electronic, atomic or distortion, permanent dipole orientation, and interfacial. Each process has its own characteristic frequency regime and loss characteristics.

Figure 8 shows the frequency dependence of the dielectric permittivity and loss which is expected from these polarization mechanisms.

Note that electronic and atomic polarizations occur at optical frequencies, while dipole orientation and interfacial polarization occur in the electrical/electronic frequency regime.

Electronic polarization is due to the distortion of electron orbits within the atom by the applied field.

Atomic or deformation polarization is due to the displacement of atomic nuclei relative to one another in response to the applied field.

Permanent dipole orientation polarization is due to the rotation and alignment with the field of molecules or parts of molecules which have a permanent dipole moment.

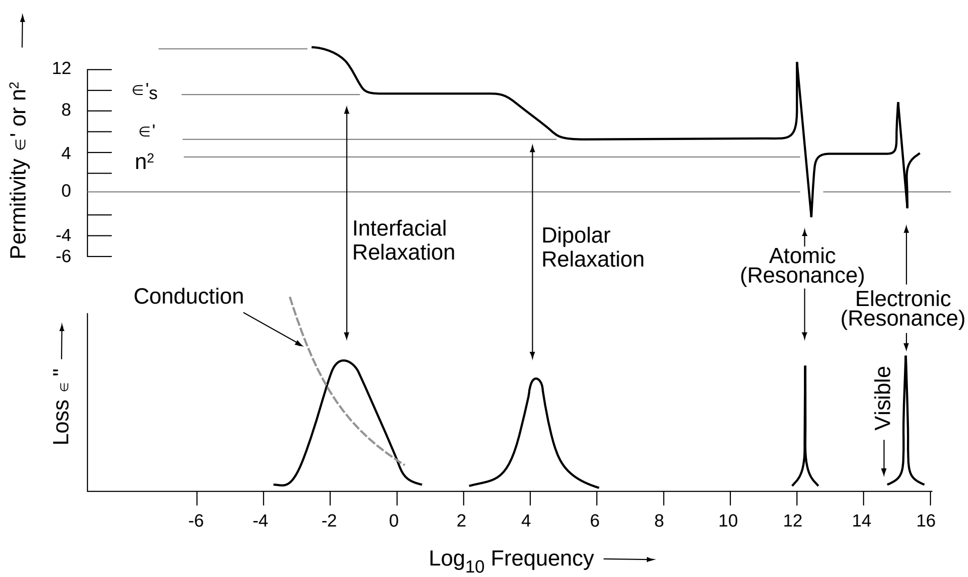

Figure 8. Generic frequency dependence of dielectric permittivity and loss.

Interfacial (or Maxwell-Wagner) polarization is due to differences in the conductivities of different materials or phases within a dielectric system, causing charge to accumulate at interfaces. Examples of different materials and phases found in capacitor dielectrics include epoxy and mica paper; liquid, paper, and film in impregnated mixed-dielectric capacitors; the crystals and boundary layers in a ceramic, and crystalline and amorphous regions within polymers. There may also be interfacial polarization at the electrode-dielectric interface.

We also must mention ferroelectric behavior, such as that observed in barium titanate perovskite ceramics, which is due to dipoles aligning and creating a polarization field of the same magnitude as the applied field. Since the dipoles respond to the local field, which is a combination of both the applied and polarization fields, the dielectric behavior is no longer proportional to the applied field, and various nonlinear effects can be observed. These effects include saturation of the polarization at high fields, permanent polarization, and high losses in AC voltage applications.

Very slow polarization over seconds or minutes is generally due to interfacial polarization. The smaller the difference in conductivity between the phases, the slower the polarization process. In some extreme cases, the steady-state leakage current value is not reached for months.

Thus, a better circuit model of a capacitor involves several parallel capacitances, each with its own loss mechanism and response time constant, as shown in Figure 9. Note that the parallel resistance included in this schematic is considered to be variable, depending on voltage and temperature.

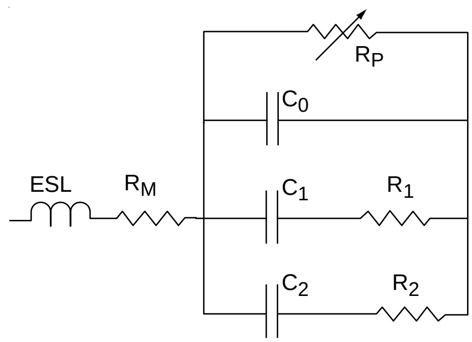

Figure 9. An improved circuit model of a capacitor.

Conduction in a dielectric may be non-ohmic at high fields such as those applied in energy storage capacitors. The conductivity at the operating voltage can be much larger than the conductivity measured at lower voltage. This can result in different interfacial polarization behavior at different voltages. The conductivity of dielectrics generally increases with temperature, exacerbating the non-ideal behavior.
A variety of non-ohmic conduction processes in dielectrics have been described, including Joule heating, space-charge-limited conduction, Poole-Frenkel trap-barrier lowering, Schottky emission and Fowler-Nordheim tunneling. Non-ohmic behavior may be observed in polymers at applied fields exceeding 0.1 MV/cm [1]. Note that typical applied fields in film capacitors at rated voltage range from 0.4 MV/cm to 1.6 MV/cm. The highest fields are experienced in limited life, high energy density, energy storage capacitors.

We have shown that the charging behavior of capacitors is dominated by the intrinsic properties of their dielectrics. In the next section, we describe how capacitor charging behavior can impact systems and circuit design.

Implications For Systems

The advancement of technology leads to continuous reduction in design margins and a need for greater accuracy and precision in design and manufacturing. In terms of design, it is necessary to improve models of components which are to be used in a system to account for behavior which might previously have been ignored or perhaps even unobservable.

There is a definite need to improve models of capacitor behavior currently being used in circuit and systems design. This is evidenced by the increasing number of reported deviations of actual behavior from expected behavior in completed systems. Though these are usually minor in impact today, they represent weaknesses of the existing models which may have major impacts in the future. We base the following discussion on actual reports of problems or “curiosities”.

Undersized power supplies are already a major concern. As we have already pointed out, a power supply specified using a capacitance value measured at 1kHz and an insulation resistance measured using a traditional test regimen is likely to provide insufficient power to charge a capacitor or bank of capacitors at the desired rate. The prime energy store (fuel or battery) may be insufficient to provide the number of charge/discharge cycles specified. This is especially true in designing with little or no capability beyond the specified ratings.

This type of problem is related to the energy efficiency of the capacitor, defined as the ratio of energy output to energy input. In repetitively pulsing applications, capacitors which are inefficient will generate more heat internally and may fail as a result. In pulsed power applications, capacitor energy efficiency is often much lower than expected based on power factor or dissipation factor measurements made at low voltage using an AC signal. Some engineers may be surprised to learn that true capacitor energy efficiencies may be as low as 70 to 90 percent in pulsed power operations.

The key here is to measure the joules and the coulombs actually required to charge the capacitor to voltage in the specified time frame. For large capacitors or banks, this can be done using a small model capacitor made with exactly the same dielectric system as in the full-size capacitor, and then scaling with capacitance. (A technique used by GAEP is outlined in the next section.)

Voltage decay is another significant issue. Using a traditional measurement of insulation resistance (made minutes after charging), an engineer may predict a voltage drop a few seconds after the power supply is disconnected which is much smaller than that which actually occurs. The result is that the system may not deliver the current, power, and energy expected at a given charge voltage. This may be overcome by increasing the charge voltage or the charge and hold time, but this may impact capacitor life or other aspects of system performance.

A related issue is the current required to maintain voltage on a capacitor once it has been charged. In some applications, it is desirable to have two separate power supplies; one charges the capacitor, the other provides a small current to maintain the voltage. If the specified rating of the sustaining power supply is based on the wrong assumptions, it may be unable to maintain the desired voltage.

Again, the prevention is a measurement of the actual behavior of the proposed capacitor (or a scale model) under simulated operation conditions, including voltage, charge time, hold time (power supply connected), and delay time (power supply disconnected). These aspects of system operation should be defined at the time the capacitor is being specified.

Dielectric absorption is both a safety concern and a technical concern. From a safety standpoint, high voltage systems should be designed to maintain a short-circuit between terminals of a capacitor when the system is not in use. Otherwise, dangerous voltages may appear across the capacitor terminals long after the power supply is shut down. From a technical standpoint, a capacitor displaying absorption will behave slightly differently from one cycle to the next, until an equilibrium condition is reached. Generally the energy efficiency will improve over the first few cycles in a DC application, whereas it would first decrease in an AC application where polarity is reversed on each charge cycle.

These examples of the potential impacts on systems of not properly characterizing capacitor behavior are drawn from actual experiences in the industry. The need to upgrade our existing models is becoming increasingly apparent.

Measurement and Characterization Techniques

The best way to determine whether a capacitor is suitable for an application is to test it under conditions which simulate the actual operation required. Traditional methods for characterizing the charging behavior of capacitors have some definite weakness in this regard. GAEP has developed improved test techniques which are useful to better define capacitor behavior for critical applications.

Traditional measurement procedures [2] which relate to the charging behavior of capacitors include “insulation resistance” tests, “leakage current” tests, and “dielectric absorption” tests. These tests are performed as required for certain military and other specifications. They are useful as qualification tests for a new design or a new manufacturer, but are seldom used as acceptance tests or for screening.

The insulation resistance (self-discharge or bleed down) measurement begins by charging a capacitor to a specified voltage and maintaining that voltage for a specified period of time (typically 1-5 minutes). The power supply is then disconnected from the capacitor, leaving the capacitor high voltage terminal connected only to a high impedance voltage probe. The voltage is measured either at one point in time or at various time intervals (e.g. 10, 20, 30, 60, 90, 120 seconds) after the disconnection. The voltage versus time data is fit to an exponential decay

$$V(t) = V_o e^{-t/RC} \quad (3)$$

and the "insulation resistance" is equal to the RC time constant, often expressed in megohm-microfarads (seconds). The equivalent resistance itself can be calculated by dividing out the measured capacitance.

The obvious problem with this technique is that it assumes (as will engineers using the capacitor specification) that the voltage decay fits an exponential - that there is a constant parallel resistance value causing the decay. In fact, closer examination of the early portions of the decay curve (which may be of most interest to the user) often shows that it does not fit a pure exponential for the reasons already described. A second concern is that the result will vary depending on the previous operational or test history of the capacitor.

The measured value may depend very strongly upon the voltage and times specified. To maximize catalog ratings, some manufacturers will minimize the voltage and maximize the hold and measurement times in their test specification. Generally the insulation resistance measured increases with operation time or voltage aging until the dielectric begins to degrade late in the life of the capacitor. The insulation resistance may decrease if the capacitor is stored for a long period without use; it will recover after being tested or operated at voltage.

The "leakage current" may be measured in a similar test regime. In this case, the power supply is not disconnected, and the current provided by the supply to maintain a constant voltage is measured. The measurement is made after a specified period of time (typically 60 seconds). Depending on the capacitance, the DC leakage current will be in the picoampere to milliampere range. Note that the power supply must be extremely stable; AC ripple will generate a relatively large AC current. Instruments are commercially available to do this specific type of testing on small capacitances.

The leakage current test suffers from the same limitations as those of the insulation resistance test. Generally the current measured in the first few minutes will include not only the true leakage current but also a capacitive charging component, which may dominate. A plot of the current versus time would reveal this.

"Dielectric absorption" of capacitors may be characterized by using a test regime which begins by charging the capacitor to a specified voltage (V_o) and holding that voltage for a specified period of time. The capacitor is then disconnected from the power supply and discharged through a specified load for a specified time. The discharge switch is then opened for a period equal to the hold time. The recovery voltage (V_r) on the capacitor is then measured using a high impedance probe. The dielectric absorption is defined as the ratio of the voltages (V_r / V_o).

The results of this test will vary if any of the specified times are changed. Generally, the longer the hold time at voltage, the greater the recovery voltage. The shorter the discharge time, the greater the recovery voltage. The delay time before measurement is also critical. The recovery voltage will gradually increase with the delay time until the delay time equals the hold time, beyond which the recovery voltage must decline. Another point is that the capacitor terminals should have been shorted for a time prior to beginning the test which is at least equal to the total duration of the test, or else prior voltage history may have an effect on the results.

Scientists in GAEP's Capacitor Research and Development Laboratory have developed a technique to measure the energy and coulombic charge required to charge a capacitor to a given voltage, and the energy and charge delivered by the capacitor in discharging through a specified load. This technique involves simultaneously measuring the current and voltage during both phases of the cycle, calculating the instantaneous power, and then integrating to obtain the energy and the charge. Using this technique we can measure the energy efficiency of capacitors under accurately simulated operating conditions. A similar technique, used to measure an effective equivalent series resistance (ESR) was described in reference [3].

This methodology allows us to specify the optimum power supply to charge a capacitor or bank in a given amount of time. Variations on this technique can be used to generate plots of voltage decay versus time which occurs when the power supply is disconnected from the capacitor or bank, or the current required to maintain a given voltage. The tests are normally performed at rated or operating voltage. Since the behavior is dominated by the intrinsic properties of the dielectric system, it is generally sufficient to test a small "model" capacitor to very accurately predict the behavior of larger capacitors or even large banks of capacitors.

Summary

Capacitor application engineers are frequently asked why capacitors are not behaving as expected, indicating that the deviations of actual capacitor behavior from the models successfully used in the past are becoming measurable and significant today. GAEP is responding to the needs of industry by providing understanding of the fundamental dielectric physics involved and developing new test methods which simulate specified operations and measure capacitor response.

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Metallized Electrode Capacitors for Pulsed Power Applications

Metallized paper capacitors were first developed in Germany during World War II. The use of metallized electrodes in capacitors has since become very widespread in low to medium voltage applications. For many years, metallized electrodes were not used in high voltage or high energy capacitor applications due to the very limited current-carrying capacity of the electrode and termination in comparison to discrete foils. This barrier gradually broke down, beginning first with large DC filter capacitors and then encompassing power factor correction capacitors (1).

More recently, metallized capacitors have been introduced in some pulsed power applications including medical cardiac defibrillators and electromagnetic launchers, where relatively slow (millisecond) discharges are the norm. The advantages of using metallized electrodes in such applications include higher energy density and longer life, greater reliability and safety, and reduced costs.

General Atomics Energy Products (GAEP) has pioneered the use of metallized electrode capacitors in pulsed power applications, achieving both record energy densities and unprecedented cost reductions. In the laboratory we have demonstrated 2.7kJ/kg capacitors delivering 100's of Joules, and larger capacitors at somewhat reduced energy densities. Capacitors with energy densities of up to 1.5kJ/kg in sizes ranging from 10's of Joules up to 50kJ and beyond are now available commercially.

This bulletin will compare the metallized electrode technology to discrete foils and provide an understanding of the advantages and disadvantages of each in capacitor design. Finally, typical applications for metallized electrode capacitors will be described.

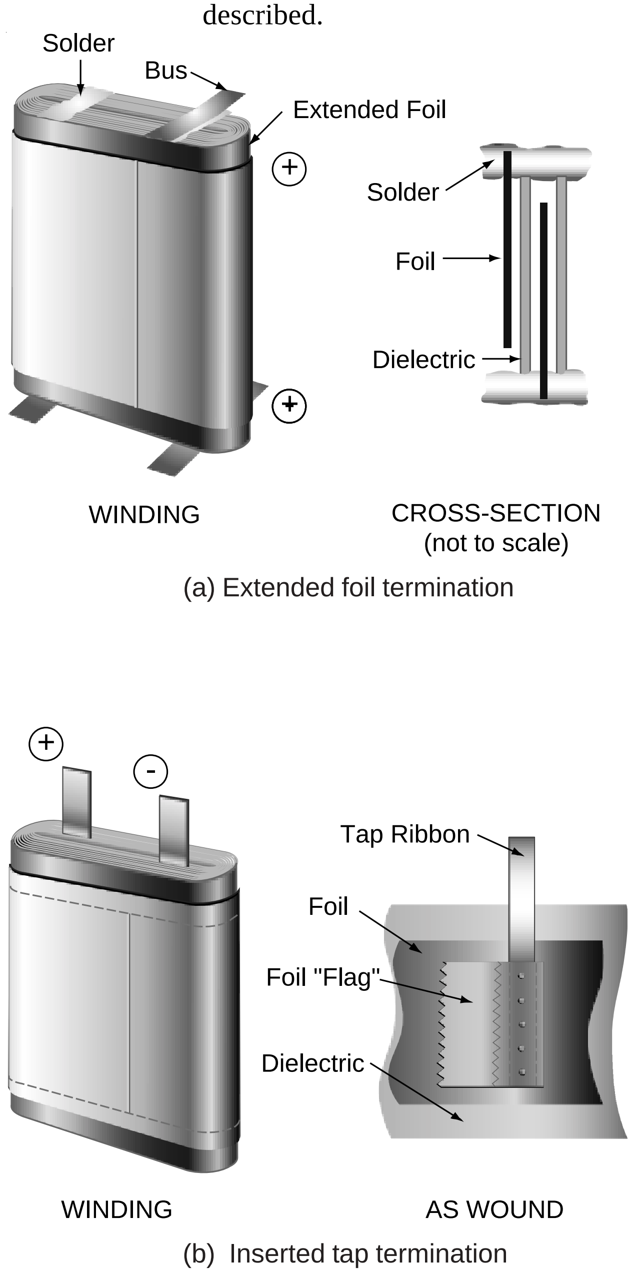

Figure 1. Foil capacitor terminations.

Metallized Versus Foil Electrodes

Most pulsed power capacitors have been built using discrete aluminum foil electrodes with a thickness ranging from about 4 microns (0.15 mil) to more than 12 microns (0.48 mil). Terminations are normally made by either soldering directly to extended foils or by inserting flag-shaped taps during the winding process, as illustrated in Figure 1.

Metallized electrodes are made by vacuum vapor deposition of aluminum, zinc, or an alloy directly on the surface of a dielectric material such as paper or film. The nominal thickness of the metal layer is in the range from about 250 to 1000 Angstroms or 0.025 to 0.1 micron. This results in a surface resistivity ranging from a fraction of an ohm to about 10 ohms per square. Since typical high voltage capacitor dielectric thicknesses range from 12 to 60 microns, metallized electrodes have negligible thickness in comparison.

Masks are used during the metallized process to provide "margins" on opposite edges of the two opposing polarity electrodes. The margins prevent a flashover between the two electrodes at the ends of the winding. During the capacitor winding operation, the two electrodes are extended from opposite edges of the winding by a small amount to expose some of the electrode for purposes of termination. This is similar to the extended foil construction. Figure 2 illustrates these features.

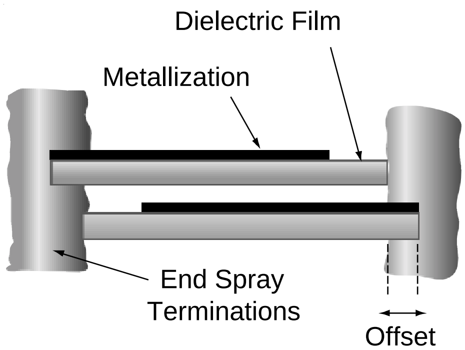

Figure 2. Cross-section of a typical metallized electrode capacitor (not to scale).

For higher current applications, the thickness of the metallization at the termination edges can be increased or reinforced during the metallizing process. This reduces the surface resistivity in this most critical region by a factor of 3-4. Many pulse power applications require such "heavy edge" or "reinforced edge" patterns.

The substrate for the metallization can be virtually any of the common dielectrics used in capacitors. Kraft paper which is of high density or lacquered to provide a smooth surface can be metallized after sufficient pre-drying. Films such as polypropylene and polytetrafluoroethylene (PTFE or "Teflon") can be metallized after treatment of the surface to enhance adhesion. Many other polymer films require no pre-treatment, including poloycarbonate or polyethylene terephthalate (PET). The processing of metallized capacitors is designed to minimize changes in dimension by shrinkage or swelling which could disrupt the metal layer.

Termination of the metallized electrode is done by either flame-spraying or arc-spraying a solderable alloy onto each end of the winding. Masks may be used to leave gaps in the sprayed metal layer for subsequent drying and impregnation.

There are many variations of the metallized electrode concept which have been used in various capacitor products. One of these is a double-metallized paper used like a discrete foil; commonly known as "soggy foil" [2]. Kraft paper is metallized on both sides to provide twice the current-carrying capacity. The natural roughness of the paper aids in impregnation. This technology was developed for use in AC power capacitors. Figure 3 is a schematic cross-section of this type of capacitor.

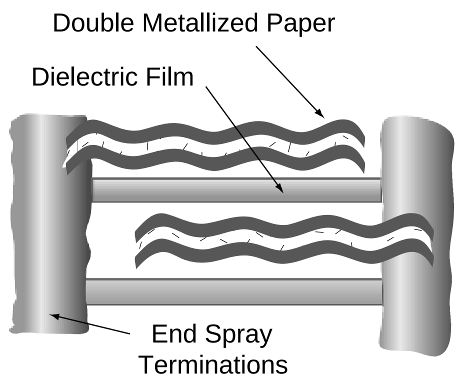

Figure 3. Cross-section of a "soggy-foil" (double metallized) capacitor (not to scale).

Another variation which is becoming popular is the segmentation of the metallized layer to provide what are essentially fusible links within the capacitor. This technology has the potential of improving the safety of metallized polypropylene capacitors used in low to medium voltage AC applications. Segmented electrodes are discussed in more detail in the next section.

Self-healing or "clearing"

One of the advantages of metallized capacitors over discrete foil capacitors is their ability to self-heal in the event of a dielectric breakdown. This improves reliability, permits higher stresses and therefore higher energy densities to be achieved, and results in a "soft" failure mode rather than a catastrophic short-circuit.

If a dielectric breakdown occurs, current flows from surrounding areas of the capacitor through the breakdown arc. In a foil capacitor, virtually all of the stored energy is dissipated in the arc itself, resulting in significant damage to the capacitor. A breakdown in a large energy storage capacitor may rupture its container.

In a metallized capacitor, the current flowing into the arc has a high enough current density to heat and vaporize the metallization immediately surrounding the breakdown arc. There is a rapid rise in the local gas pressure from the pyrolization of the organic substrate, and the arc length increases as the area of the metallization that is being vaporized increases. Finally the arc is extinguished by this process, which is essentially the same as that which occurs in a fuse.

The energy dissipated in the clearing process is in the range of microjoules to joules [3]. A sound which may be described as a "snap" can some-times be heard. The capacitor continues to operate normally during and after the clearing event.

As a result of a dielectric breakdown, there is an area of the metallized electrode which has been cleared or removed, resulting in a small loss of capacitance. The area cleared depends on voltage and other design and manufacturing variables, but is typically between a few square millimeters and a few square centimeters. In large capacitors, it takes hundreds or thousands of clearings to cause a few percent loss of capacitance. Figure 4 is a photograph of the site of a clearing on metallized paper, magnified about 10X.

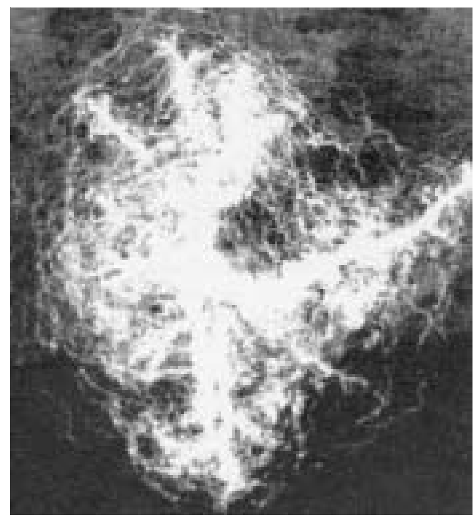

Figure 4. Photograph of a clearing site (~10x).

Each clearing generates small amounts of chemical byproducts including gases, water, and carbon. These byproducts may have a negative effect on capacitor electrical parameters such as insulation resistance (IR) and dissipation factor (DF). Again, the effect is usually not measurable until a very large number of clearings have occurred. A buildup of internal gas pressure may also be observed at the end of the capacitor's life.

Figure 5 shows the typical behavior of various parameters of a metallized capacitor during the life of the capacitor.

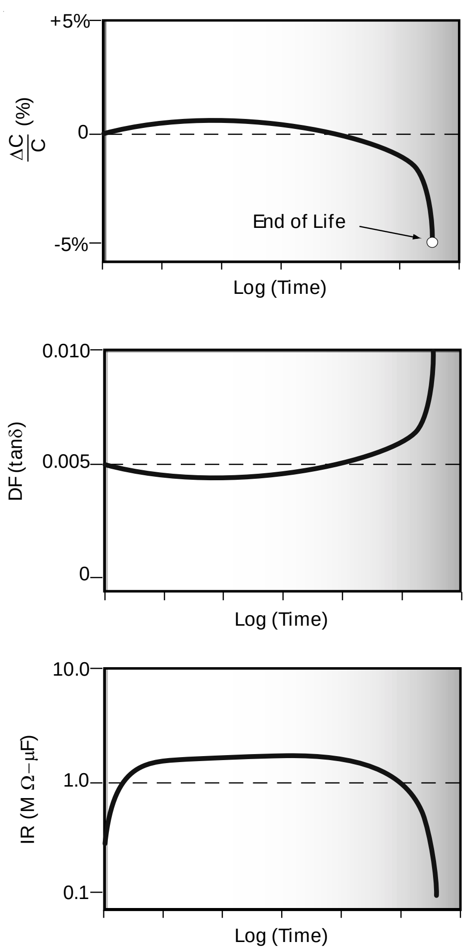

Figure 5. Typical variation of electrical parameters during life of a metallized electrode capacitor.

Some metallized capacitors have been developed which provide an additional safety feature beyond that of clearing. These capacitors have a metallized electrode which is segmented to force current to flow along prescribed paths. In the event of a dielectric breakdown, the current flow into that particular segment will be high enough to cause a fusing action of the metallization at the entry point to that path and away from the actual breakdown site [4]. Figure 6 illustrates this approach.

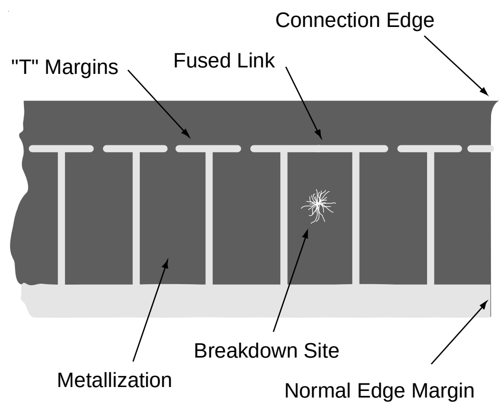

Figure 6. Segmented metallization pattern and fusing operation

Advantages of Metallized Capacitors

In applications which permit the use of metallized electrodes, they offer many advantages over foils. Energy density is significantly higher in metallized capacitors than in foil capacitors for two reasons: (1) the reduced volume occupied by the electrodes themselves, and (2) the higher dielectric stress levels which may be safely applied to achieve a given lifetime and reliability.

The reduced electrode volume is especially important in low voltage (<1000 V) applications where the thickness of a discrete foil would be the same or even greater than that of the optimum dielectric.

Reliability of metallized capacitors is improved over foil capacitors because of the elimination of the largest source of single-point failures. Whereas in a foil capacitor the first dielectric breakdown produces a catastrophic failure, in a metallized capacitor hundreds to thousands of such events must occur to cause a capacitance loss which brings the device out of tolerance.

Lifetime of metallized capacitors is significantly greater than that of foil capacitors of comparable or event greater size and weight. Factors of two to ten improvements are easily achieved.

The soft failure mode of metallized capacitors is usually preferable to a catastrophic short circuit. The capacitance begins to measurably decrease near the end of life, and the insulation resistance and dissipation factor may degrade as well. It is even possible to utilize the buildup of internal gas pressure to provide a disconnect feature.

Cost of metallized capacitors can be smaller than that of comparable foil capacitors due to reductions in the volume of raw material used in manufacturing the capacitor.

These advantages have resulted in the introduction of metallized capacitor technology in virtually every film capacitor market.

Limitations of Metallized Capacitors

Unfortunately, metallized electrodes cannot be used in every application due to significant performance limitations imposed by the use of very thin electrodes.

The peak power and "action" (defined as the integral of the square of the current with respect to time) per unit length of the connected edge of the metallized electrode must be limited to prevent damage. The end connections are the weak links in the capacitor due to the relatively high resistivity at this interface. Peak power in excess of the rating can cause the end connections to physically separate from the ends of the winding.

The limitation on current means that a metallized capacitor is less tolerant to external faults or short-circuit conditions than a foil capacitor. It also means that metallized capacitors cannot be used in applications which require combinations of high voltage and high peak current.

The range of voltage which can be provided with metallized electrode capacitors is considerably more limited than in discrete foil capacitors. Whereas metallized capacitors are optimal at low voltage, the internal resistance of their electrodes limits series connection capability and restricts the high voltage end of the range to below 50 kV. In comparison, foil capacitors have been built for fast pulse peaking circuits with ratings above one megavolt.

The metallized electrode has greater resistivity than a foil electrode. At low frequency (into the kilohertz range) the parasitic resistance of a capacitor is dominated by the losses in its dielectric, and the resistance of the metallization is negligible. At higher frequencies the resistance in the metallization will dominate and the equivalent series resistance (ESR) or dissipation factor (DF) will be significantly greater than in a foil capacitor. Most metallized capacitors are safely used in DC filtering applications, 60 Hz-400 Hz AC, and pulse discharges with millisecond pulse width. GAEP engineers have developed special designs which allow metallized electrodes to be used in some applications at considerably higher frequency and shorter pulse width, but the fastest discharge capacitors still require discrete foils.

Another important limitation of metallized capacitors is their relatively poor thermal conductivity. In foil capacitors, the metal foils provide a significant conduction path out of the winding not only for current but also for heat. By comparison, the metallized electrode is a very poor thermal conductor. This is important in continuous duty, high RMS current applications such as AC or repetitive pulsing, where losses in the dielectric and the metallization itself can generate significant heat. The worst case result is a large temperature buildup at the center of the capacitor which can result in bulk dielectric failure.

Metallized capacitors used for high average power applications must be designed to minimize the heat generated internally through the choice of dielectric materials. In addition, the geometry of the capacitor must be such as to minimize the distance that heat must travel to exit.

Gas generation due to self-healing in metallized capacitors, sometimes resulting in internal pressurization and distortion of the container at the end of life, is considered a disadvantage in some applications. As already mentioned, in such situations the internal pressure can be used to provide a disconnect safety feature to the capacitor, or can be sensed externally using a mechanical switch or sensor to trigger a safety interlock device.

Applications

Metallized electrode capacitors have become the standard for low duty applications involving low frequency (<1000 Hz) pulse discharges and requiring high energy densities. Two examples are medical cardiac defibrillators and electric guns.

Defibrillator capacitors are typically rated at voltages less than 6 kV and store up to 500 Joules of energy. Discharge frequencies are of the order 100 Hz, and typical peak currents are less than 200 Amps. The application is essentially "single shot," with less than five cycles required over a period of minutes. Lifetimes of thousands of shots are required with high reliability.

Early defibrillator capacitors were essentially DC filter capacitors which were re-rated for the required reliability and life. Later, special designs incorporating polyvinylidene fluoride (PVDF) achieved the energy densities needed for portable defibrillators used by paramedics. These capacitors were not only expensive, but suffered from low energy efficiency and restricted operating temperature range due to the ferroelectric properties of PVDF.

Metallized electrode capacitors have now displaced PVDF capacitors in this market, by offering not only higher energy density (up to 1 J/cc) and lower cost (1/3 the cost of PVDF units), but also improved reliability. GAEP has delivered more than 200,000 such capacitors to defibrillator manufacturers worldwide.

Electric gun testbeds built in the last few years have often utilized metallized electrode capacitors. The capacitor banks in these systems typically store 10-50 MJ at 15-24 kV and deliver pulses of several milliseconds duration. The higher energy density of metallized capacitors has allowed smaller facilities to be used to house the capacitor banks, at significant overall cost savings. GAEP has supplied over 52 MJ of metallized energy storage capacitors for this particular application.

Metallized energy storage capacitor banks are also being utilized in Inertial Confinement Fusion (ICF) experiments such as those being conducted by the Department of Energy at Lawrence Livermore National Laboratory (Beamlet) and the University of Rochester (OMEGA).
Other applications include mobile hard rock mining (shock wave generation) systems, flashlamp drivers used in food processing and xerography, and laser rangefinders.

Summary

Metallized electrode capacitors offer many advantages over foil capacitors in low average power applications. Higher energy density, longer life, and higher reliability are a few of the benefits of this technology. General Atomics Energy Products is supplying large numbers of these capacitors for medical defibrillator, electric gun, and other pulse discharge and DC applications. We invite you to inquire how GAEP's metallized electrode capacitors can benefit your application.

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