GENERAL ATOMICS ENERGY PRODUCTS
Engineering Bulletin 96-004

THE EFFECT OF REVERSAL ON CAPACITOR LIFE

November 2003

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

Capacitor Engineering Bulletin 96-004
The Effect of Reversal on Capacitor Life

Capacitor Engineering Department
General Atomics Energy Products, General Atomics Electronic Systems, Inc.
4949 Greencraig Lane, San Diego, CA 92123

Abstract

Reversal is a critical parameter in the selection or design of DC and energy discharge capacitors. This document will describe how this parameter effects the selection and design of capacitors for any given application.

I. WHAT IS REVERSAL?

Voltage reversal is defined as the changing of the relative polarity of the capacitor terminals, such as may be experienced during a ringing or oscillating pulse discharge, during AC operation, or as the result of DC charging the capacitor in the opposite polarity from which it had been previously DC charged.

Current reversal is defined as the changing of the direction of current flow through the capacitor.

In an underdamped RLC circuit, the energy in the circuit oscillates back and forth between the capacitance and the inductance. In this case, both the capacitor voltage and current oscillate with the same percentage of reversal.

Voltage reversal is usually described in terms of the percentage of the peak voltage that is experienced in the reverse polarity. In an AC application, the reversal is 100 %. In an overdamped discharge or DC application, the reversal is 0 %. Oscillating pulse discharges usually have greater than zero percent voltage reversal and less than 100 % reversal. Figure 1 shows some examples.

In more complicated circuits, current and voltage may not oscillate to the same degree, and the oscillations may not be cyclic. Although we cannot cover all such cases, the following sections describe how the current and voltage reversal each impact the capacitor.

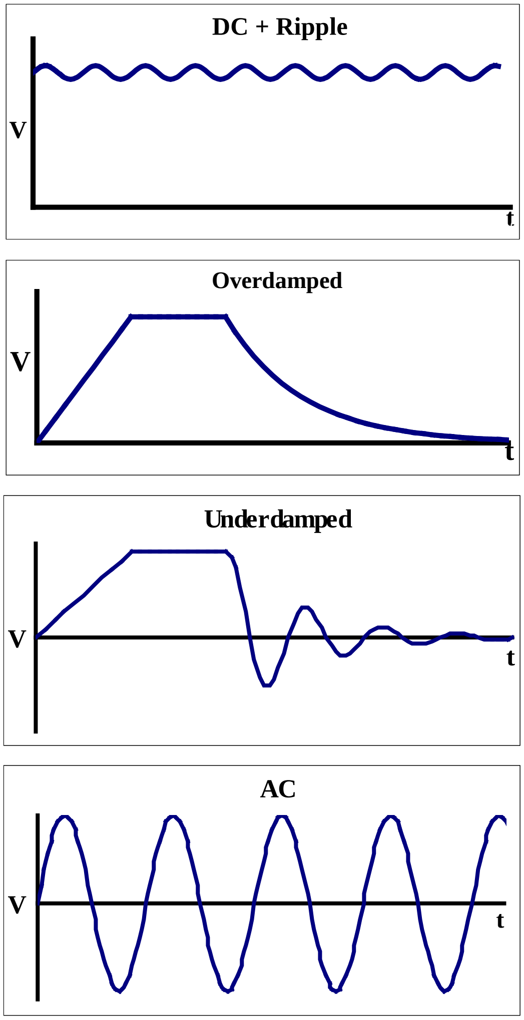


Figure 1: Examples of waveforms

II. SPECIFYING REVERSAL CONDITIONS

The "rated" voltage reversal of a capacitor should be the same or greater than that which is expected for "normal" discharges in an application.

The worst-case fault discharge must not exceed the "maximum" voltage reversal capability of the capacitor.

It is best to specify the number (or percentage) of fault discharges under each fault mode condition along with the associated voltage reversal, peak current, and ringing frequency.

Over-specification will result in larger and more costly capacitors than are necessary. Precision is especially critical in specifying high values of reversal.

III. HOW MUCH IS CAPACITOR LIFE AFFECTED?

DC capacitors must be designed for the highest level of voltage reversal (normal or fault) that may be experienced in service. High reversal ratings result in significant reductions in energy density and increases in size and cost. Table 1 illustrates this using General Atomics Energy Products (GAEP) Type C capacitors of the same size with different reversal ratings. Note that, in this case, the unit designed for 20 % voltage reversal can be operated at 80 % reversal, although there is a severe penalty in life.

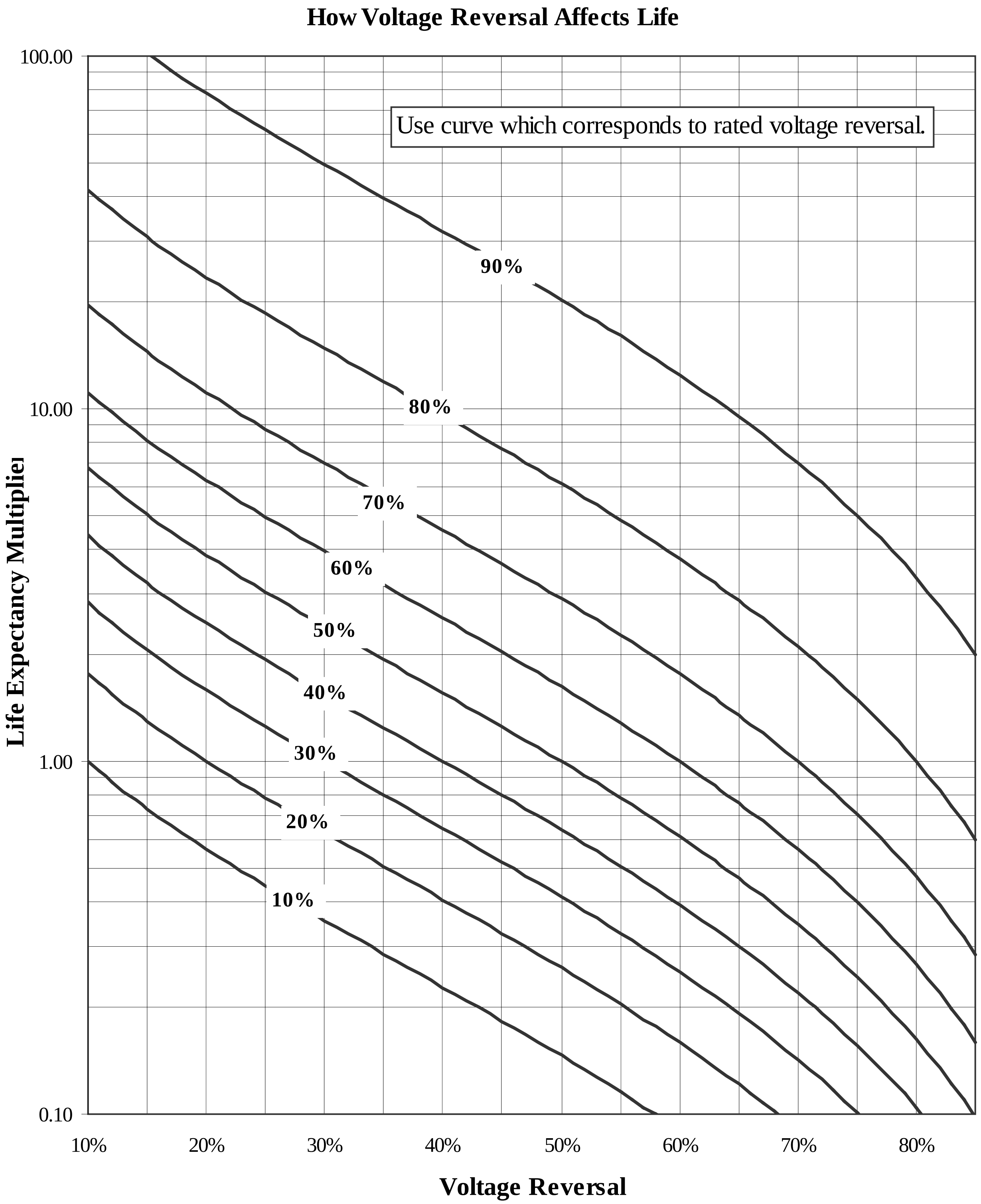
Comparison of Two Capacitor Designs

MODEL	Reversal Rating	Energy Stored (Joules)	Life at 80% VR (shots)
32001	80%	3600	50,000
32501	20%	4800	5,000

Table 1

The damage inflicted on a capacitor by a transient voltage reversal is a nonlinear function of the degree of reversal. As shown in Figure 2, the change in life between 80 and 85 % reversal is much greater than the change between 20 and 30 % reversal. Thus, greater precision and accuracy is desirable in specifying high values of reversal (> 50 %) for either normal or fault modes than is necessary when specifying low values.

The magnitude of the damage also depends on the rate of change of voltage during the reversal. The least damage is done when the rate of change of voltage is slow, as in the case of DC charging the capacitor with the terminal connections reversed. The greatest damage is done when the capacitor voltage "rings" or oscillates at a high frequency. The effect of frequency on life in GAEP Type C capacitors is shown in Figure 3.


How Voltage Reversal Affects Life
Use curve which corresponds to rated voltage reversal.
90%
80%
70%
60%
50%
40%
30%
20%
10%
100.00
10.00
1.00
0.10
Life Expectancy Multiplie
10%
20%
30%
40%
50%
60%
70%
80%
Voltage Reversal

<u>Figure 2</u>

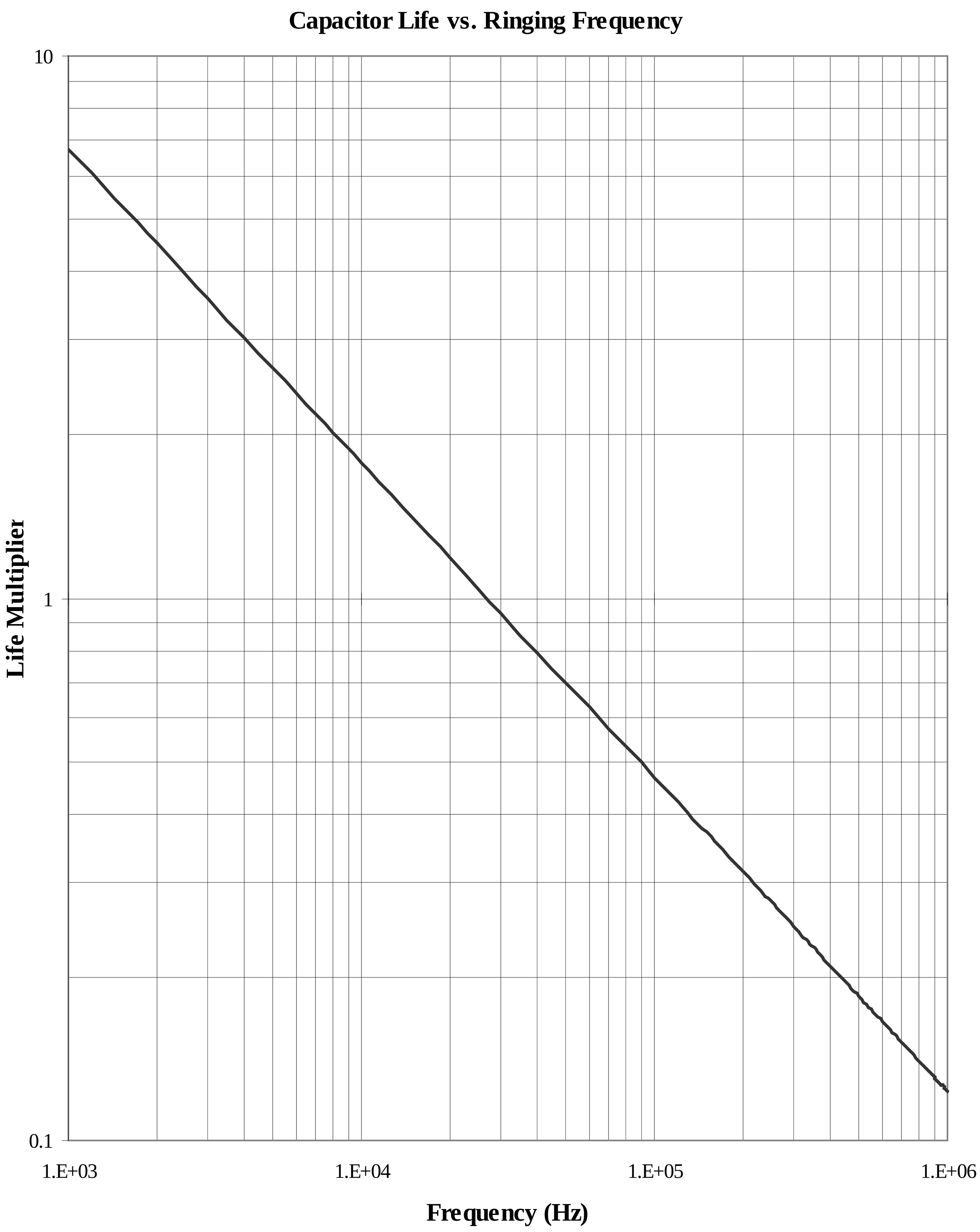

Capacitor Life vs. Ringing Frequency
10
1
0.1
Life Multiplier
1.E+03
1.E+04
1.E+05
1.E+06
Frequency (Hz)

Figure 3

IV. HOW TO EXTEND CAPACITOR LIFE OR REDUCE CAPACITOR SIZE

If voltage reversal is significant in your application, it will impact either the size (and cost) or the life of the capacitor. The most obvious way to extend capacitor life is to minimize the degree of voltage reversal in the normal operating mode of your circuit.

In some cases, the reversal rating of the capacitor is determined by a fault mode. (Normal and fault discharge conditions should be clearly stated in specifying capacitors.) It is especially important to minimize the number of such fault discharges. If the expected fault is due to a capacitor failure, a fuse at the output of each capacitor may be preferable to a resistor. (Note: Such fuses are available from GAEP for use with our high energy capacitors.)

A diode and series resistance in parallel with the capacitor may be used to reduce voltage reversal. The smaller the series resistance, the lower the reversal on the capacitor.

For decaying oscillatory discharges with reversals much less than 100 %, if the voltage oscillation is stopped after the first reversal (such as by means of an opening switch), the total damage per pulse is only slightly reduced. In this case, most of the damage is inflicted by the much larger initial peak-to-peak change in voltage. On the other hand, for slowly decaying oscillations with reversals approaching 100 % (e.g. $Q > 10$), truncating the discharge will greatly extend capacitor life, since each cycle of the oscillation has a similar damaging effect.

In order to use an available capacitor under higher than rated reversal conditions without reducing life, reduce the charge voltage. The derating factor depends on the design of the capacitor. For GAEP Type C capacitors with 20 % voltage reversal ratings, Figure 4 shows the required voltage derating for operation at higher reversal.

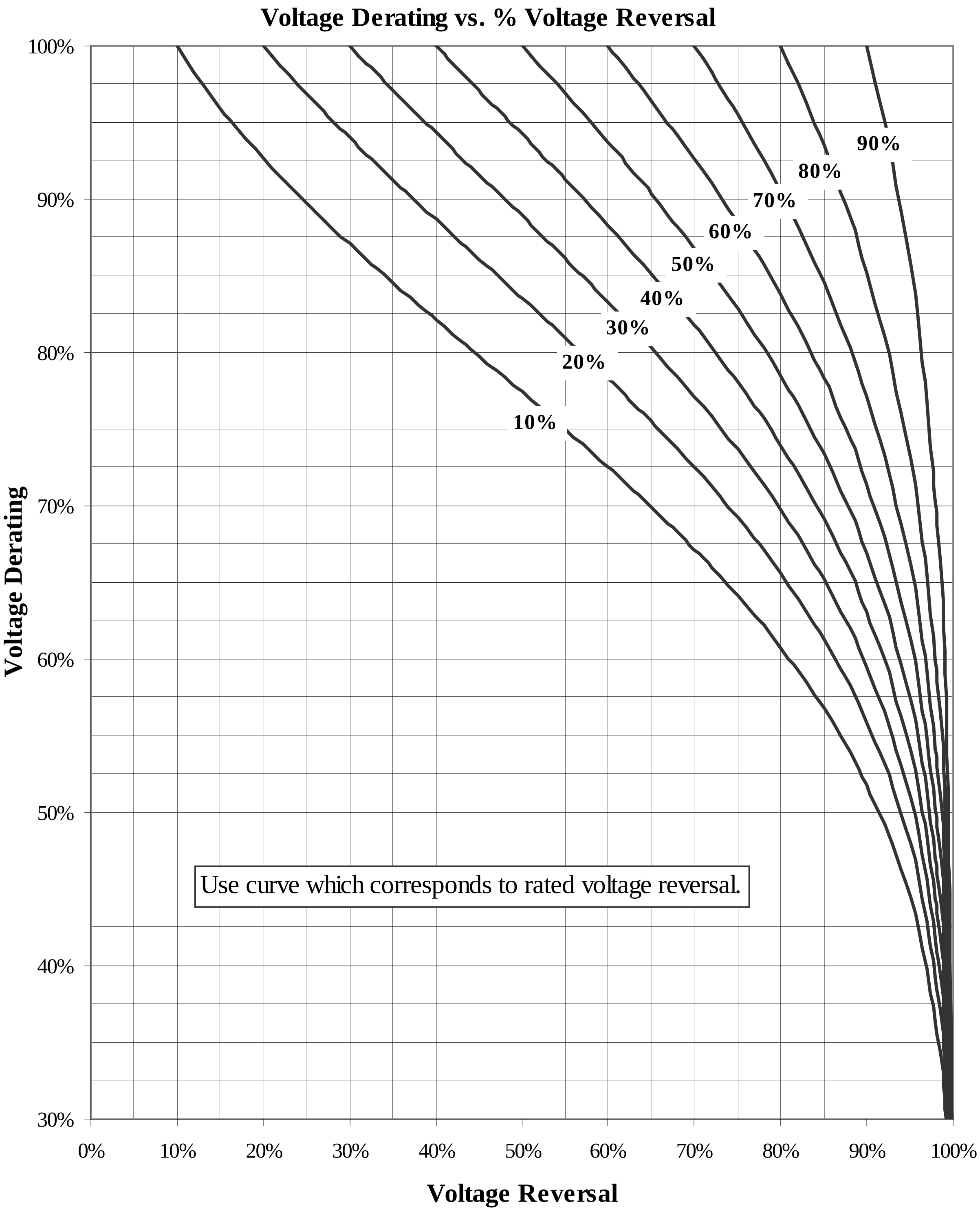

Voltage Derating vs. % Voltage Reversal
Voltage Derating
Voltage Reversal
100%
90%
80%
70%
60%
50%
40%
30%
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Use curve which corresponds to rated voltage reversal.

Figure 4

V. WHY REVERSAL IS IMPORTANT

The stresses on capacitors caused by reversal include increased electric fields in the dielectric, increased electrical losses and heating in the dielectric, and increased losses and heating in the conductors. In the following paragraphs we will discuss these phenomena in greater detail.

A. Electric Fields

Reversals in voltage have a major impact on the magnitude of the electric fields in the capacitor dielectric.

Dielectric overstresses result from the superposition of the applied reverse electric field and the remnant polarization field from the original DC polarity. At typical pulse capacitor discharge rates, the electronic, atomic, and permanent dipole polarizations will reverse almost in phase with the applied field. However, inherently "slow" polarization mechanisms acting in the dielectric such as interfacial polarization associated with charge injection and ionic conduction will not. The longer the capacitor spends DC charged in one polarity, the greater the magnitude of the remnant polarization field. This remnant polarization field (which is anti-parallel to the applied DC field) is added to the applied field during a voltage reversal, increasing the total field within the dielectric. Excessive fields can result in immediate breakdown or may produce partial discharges, treeing, or other degradations.

Even in AC applications, where interfacial polarization may not have time to build up, charge can be injected from the electrodes into the adjacent dielectric, especially at sharp edges, one half-cycle, and then return to the electrode in the next half-cycle in a partial discharge process. These discharges degrade the dielectric locally and will eventually result in breakdown. Therefore, long life AC capacitor elements are designed to operate at voltage levels where such charge injection is negligible. DC capacitors, on the other hand, can usually be operated at much higher stresses and can therefore be made smaller.

B. Heating

The current waveform is used to determine the internal heating of a capacitor due to various energy loss mechanisms.

The energy dissipated in the capacitor during a single charge/discharge cycle (J_{cap}) depends on the "action" (A) of the current waveform and the equivalent series resistance (ESR) of the capacitor.

$$J_{cap} = A \times ESR \quad \text{[Joules]}$$

The action is the value of Joule's integral:

$$A = \int_0^T I(t)^2 dt \quad \text{[Amps}^2\text{-sec] or [Joules/ohm]}$$

In RLC circuits, underdamped, oscillating current pulses have much higher action than overdamped, single polarity pulses of the same peak current. Thus, they heat the capacitor more.

In RLC pulse discharge applications, the action is virtually all in the discharge pulse (there is negligible contribution from the charging current), and is therefore given by:

$$A = \frac{J}{R} = 0.5\left(\frac{C}{R}\right) \times V^2 \quad \text{[Joules/ohm]}$$

where R is the total discharge circuit resistance. This simply says that all of the energy in the capacitor is eventually dissipated in the circuit resistance. The portion of the energy which is dissipated within the capacitor depends on the ratio of its ESR to the circuit resistance:

$$\frac{J_{cap}}{J} = \frac{ESR}{R}$$

The ESR is not a true ohmic resistance and is a strong function of frequency, voltage, voltage reversal, temperature, and other parameters (See Equivalent Series Resistance (ESR), www.gaep.com/techbulletins/engineering_bulletins.pdf). Extreme caution must be taken in applying an ESR value measured under one set of conditions to calculations which apply under a different set of conditions.

The ESR includes a number of energy loss mechanisms, the two most important of which for the present discussion are dielectric loss and electrode resistance.

The dielectric loss results from motion of bound charge within the dielectric (displacement current) such as molecular dipole rotation, in response to an applied field. It is usually reported as a dimensionless number, the dissipation factor (DF), since the losses vary linearly with the capacitance.

The electrode resistance is purely ohmic, with the skin effect becoming important only at very high frequencies. There are two basic types of electrodes used in film capacitors, discrete foils and metallizations. Foil electrode capacitors provide minimum ESR at high frequencies. Metallized electrodes can be used for relatively low frequency discharges (less than 10 kHz) where the ESR is dominated by the dielectric loss.

GAEP rates its capacitors based on the peak linear current density (A/cm) and specific action (A^2-sec/cm^4) in the electrode. These translate to "rated" and "maximum" (fault) peak current and voltage reversal specifications for each capacitor design.

VI. HOW VOLTAGE REVERSAL AFFECTS CAPACITOR DESIGN

The effect of reversal on a particular capacitor varies with the design of the capacitor, the voltage at which it is being operated, the temperature, the pulse repetition rate, and other factors. The critical aspects of the design are the dielectric materials, the rated voltage and rated electric field, and the type of electrode and internal connections.

The resistance of different dielectrics to the effects of voltage reversal are quite varied. The best choice for high reversal discharge applications is often Kraft paper. Mixed dielectrics such as paper and polypropylene laminates are more susceptible to damage in voltage reversal than all-paper dielectrics because of interfacial polarization. All-polypropylene DC capacitors are highly susceptible to foil edge failure at even moderate voltage reversal.

Dry capacitors should be used in high reversal applications only at low voltage (less than 1 kV) and low stress. A liquid impregnant should be incorporated in the dielectric to suppress partial discharges. The exact choice of impregnant is also important, as some materials are able to absorb gases and other decomposition products better than others.

Metallized capacitors are more robust than foil capacitors in terms of their ability to survive high reversal discharges without immediate failure. As long as action ratings are not exceeded, high reversals simply accelerate the rate of capacitance loss. If peak current or action ratings are exceeded, however, failure of the internal connections may occur, resulting in large capacitance loss, increased DF and ESR, and reduced voltage capability.

Capacitors designed to operate for long lifetimes (>10^7 pulses) at relatively low electric field stresses will be more robust in the event of fault condition reversals, and capacitors being operated at well below their rated voltage will also be more likely to survive.

GAEP has life test data under varied conditions on capacitors built using a wide variety of dielectric/electrode systems. This data, combined with empirically derived life-scaling equations, is used to predict the life of a given capacitor under a given set of conditions. The reversal factor in these calculations takes the form:

$$\frac{L}{L_0} \cong \left(\frac{Q}{Q_0}\right)^{-q}$$

where L is the life, Q is the circuit quality factor, q is an experimentally-determined exponent, and the subscript "o" refers to the reference life data and Q value. This type of equation was used to generate Figure 2.

Our competitors often use peak-to-peak voltage to describe the effects of reversal on capacitors. However, a common sense argument shows that the peak-to-peak voltage is not a sufficient criteria:

> At very high degree of reversal, greater than 95%, several voltage oscillations of any single discharge will have about the same peak-to-peak voltage swing. So, a single discharge at high reversal has the same effect on life as some number of individual pulse discharges at low reversal, with the same peak-to-peak voltage. Thus, there is a non-linear effect on life with reversal.

The equation GAEP uses accounts for the highly nonlinear effects of voltage reversal through the use of the Q-factor. As a reminder, the Q-factor can be derived from the reversal using:

$$Q = \frac{-\pi}{2\ln(\%VR)}$$

This relationship can be seen in Figure 5.

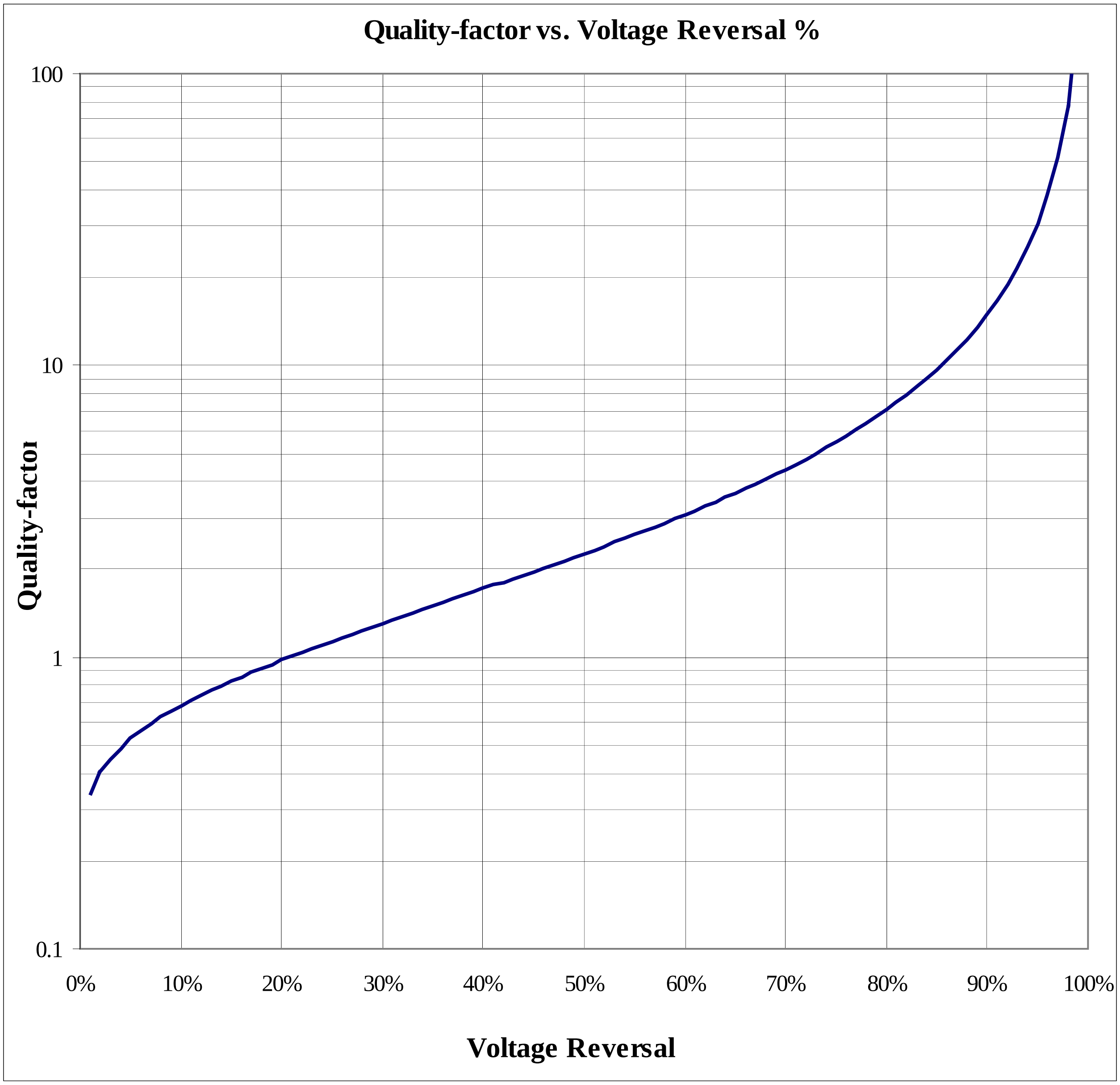


Figure 5

Note that the action and RMS current are also non-linearly related to the degree of current reversal.

VII. SUMMARY

Both voltage and current reversal are important factors in the design and selection of capacitors. Their effects are strongly non-linear. Precise knowledge of reversal conditions in both normal and fault conditions is useful in minimizing capacitor size and cost and maximizing life and reliability. Reduction of the degree of reversal on a capacitor is often technically and economically beneficial.