- **capacitors**

While many types of capacitors exist, two are widely used in EMC design:

– **tantalum electrolytic**

Small tantalum electrolytic capacitors can have large capacitances (1 - 1000 μF).

– **ceramic**

Ceramic capacitors typically have smaller capacitances (1 μF - 5 pF), but tend to exhibit ideal behavior over a much broader range of frequencies.

Although typically thought of in the context of dc operation, operating frequency is one of primary consideration in choosing capacitors. A table of various capacitors and their typical operating ranges is presented below.

Type	Approximate operating range
Tantalum electrolytic	1 - 1000 Hz
Large value aluminum electrolytic	1 - 1000 Hz
Ceramic	10 kHz - 1 GHz
Mica	10 kHz - 1 GHz

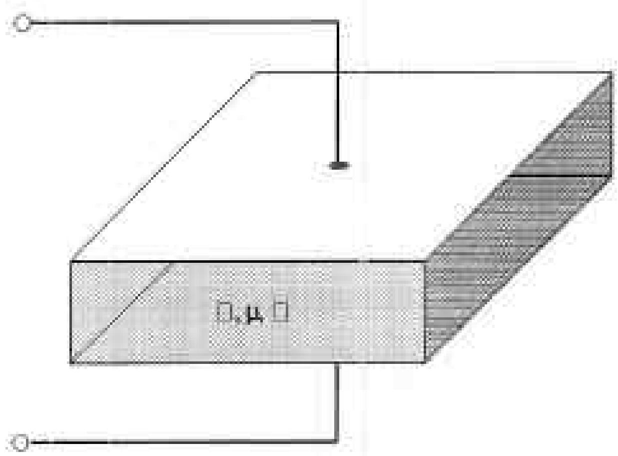

Figure 13. Generalized capacitor.

- **equivalent circuit of capacitor**

Both types of capacitors discussed above share the same basic configuration. Wire leads are connected to a pair of parallel plates, each having area A, which are usually separated by some type of dielectric material. A generalized equivalent circuit for capacitors can be constructed, however, specific component values may differ for different types of capacitors.

- The component leads introduce an associated inductance (L_{lead}) and capacitance (C_{lead}).
- A large resistance ($R_{dielectric}$) associated with the dielectric layer between the capacitor plates exists in parallel with the ideal bulk capacitance (C).
- The plates of the capacitor themselves introduce a resistance (R_{plates}).

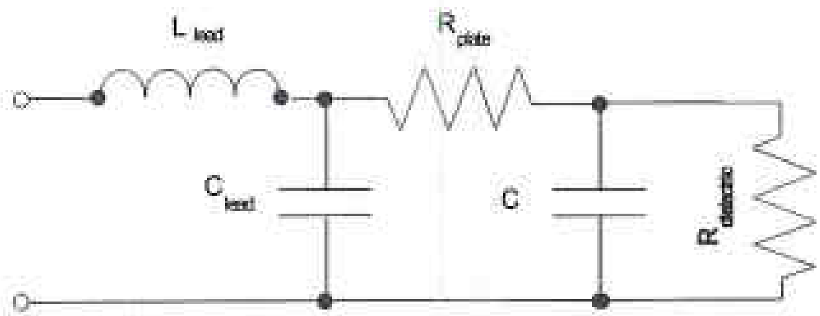

Figure 14. Equivalent circuit for capacitor.

- The lead capacitance is typically so small compared to the bulk capacitance that it may be neglected. Likewise, the resistance of the dielectric layer is typically so large that it may be represented as being an open circuit. Thus a simplified equivalent circuit may be developed consisting of a series combination of the lead inductance, the plate resistance, and the ideal bulk capacitance.
- The impedance associated with this simplified equivalent circuit is clearly

$$Z_{circuit} = j\omega L_{lead} + R_{plates} + \frac{1}{j\omega C} = R_{plates} + j\left(\omega L_{lead} - \frac{1}{\omega C}\right) .$$

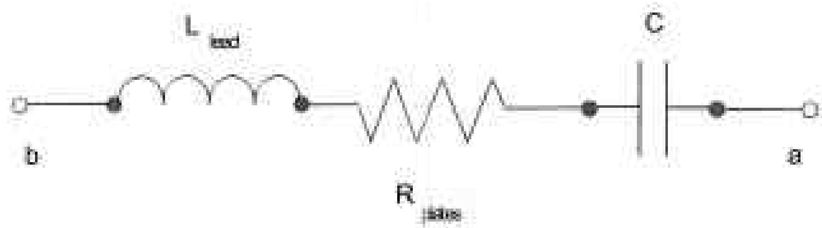

Figure 15. Simplified equivalent capacitor circuit.

Again the behavior of the generalized equivalent circuit is determined by examining this impedance expression over a wide range of frequencies:

- For dc operation, the lead inductance behaves as a short circuit, and the ideal bulk capacitance is an open circuit. Thus, the capacitor itself acts as an open circuit.

- As frequency is increased, the impedance, which is dominated by the ideal capacitance term, decreases linearly, until reaching a minimum when

$$\omega L_{lead} = \frac{1}{\omega C}.$$

At this point, the impedance is purely real, and the equivalent circuit is in resonance. This occurs at the self-resonant frequency of the capacitor, which is given by

$$\omega_o = \frac{1}{\sqrt{L_{lead} C}}.$$

- As frequency increases beyond self-resonance, the impedance increases linearly, with the inductive term dominating.

- As the frequency approaches infinity, the lead inductance begins to behave like an open circuit. Thus the maximum operating frequency of a capacitor is typically limited by the inductance of the capacitor and the device leads.

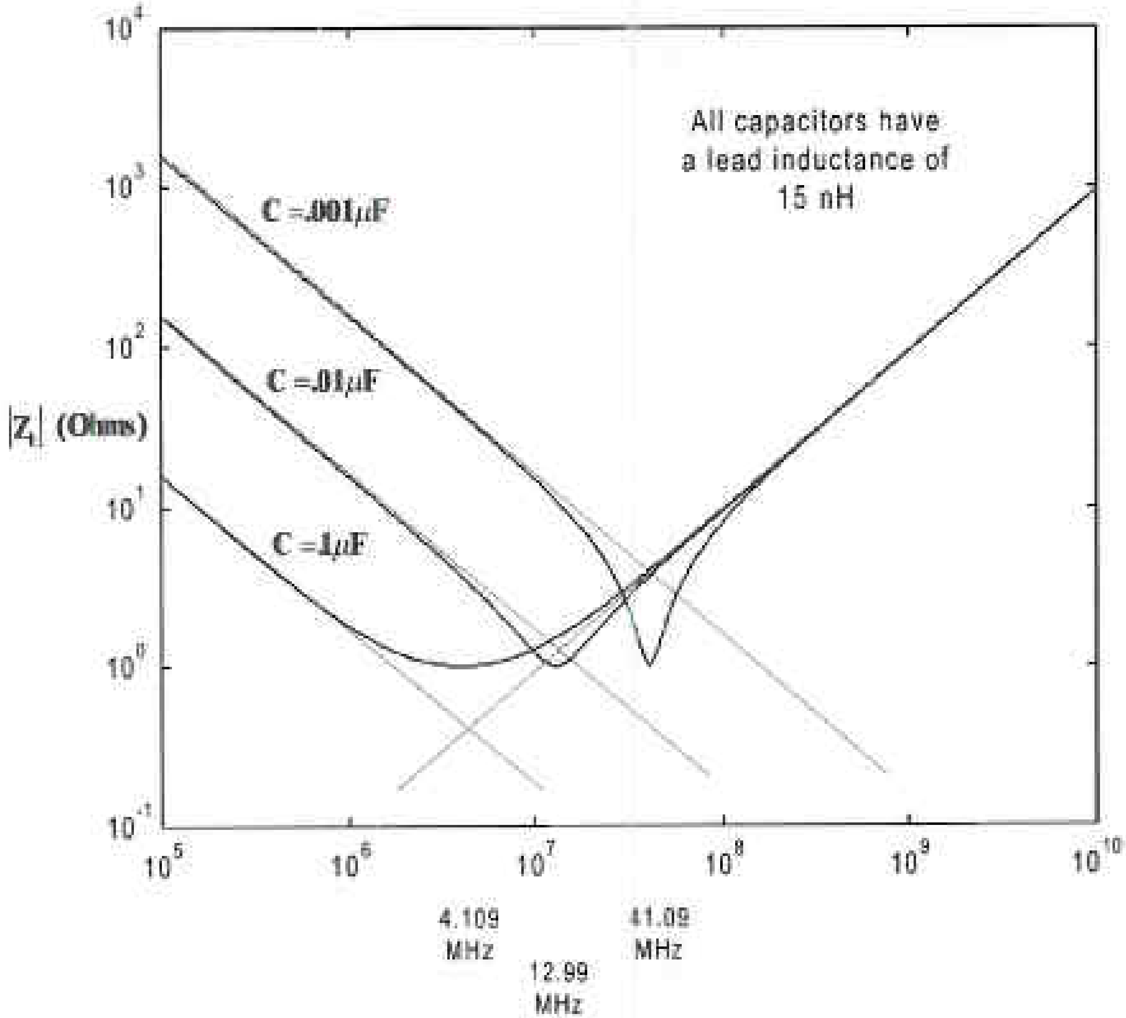

Figure 16: Plot of frequency dependent behavior of equivalent circuit for various capacitors.

A plot of the responses of the equivalent circuits for various capacitors is shown in Figure 16. The response of 0.001 μF, 0.01 μF, and 0.1 μF capacitors is shown. Here the lead inductances are all 15 nH, and the plate resistances are 1Ω. The resonant frequencies are seen to occur at 4.109 MHz, 12.99 MHz, and 41.09 MHz.

- **Inductors**

Although all inductors consist of a coil of wire, many variations on the actual method of device construction exist. Inductors may be wound on cores made of non-magnetic material, or, more commonly, on materials with magnetic properties such as ferrite.

Due to their physical geometry, inductors, more than any other type of common circuit element, tend be sources of stray magnetic fields. Likewise, inductors are also more susceptible to effects due to external magnetic fields than other basic circuit elements. The type of inductor

Super Capacitor Theory

- Activated Carbon sheets
  - immersed in electrolyte
- Construction similar to battery
- Two electrodes immersed in electrolyte
- Difference is the electrolyte is not used to store potential energy
- However, since electrolytes do have impurities
  - Chemical reactions leading to
    - ESR rise
    - Finite Lifetime

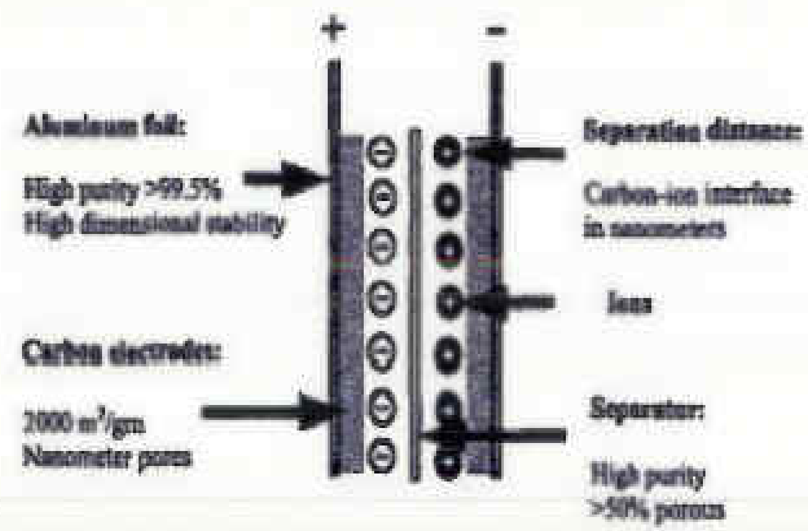

Fig. 1. A carbon double layer supercapacitor

Super Capacitor Theory

KF values

- Instead of ratings such as micro-farad, mili-farad, or pico farad, rated as kili-farad
- Large Capacitance in small package.
  - 5000 Farad, 27 Volts, in Coke bottle
- Efficiency
  - No chemical energy storage
  - No die off like batteries
  - Increased Efficiency, resulting in longer life span

$$C = \frac{\epsilon A}{d}$$

$A\uparrow$ porous media

$d\downarrow$ nm scale

Super-capacitor Applications

- Super-capacitors vs. Batteries
  - Batteries absorb ~60%
  - Super-capacitors absorb ~95%
  - I^2*R losses
  - Super-capacitors have a longer lifetime
  - Operate over a larger voltage range
  - Much larger Power Density (W/kg)
  - Limited Energy Density (W*h/kg)
- Used together battery life increases by about 250%

Sup C: 1hr
Recharge Batt: 10hr

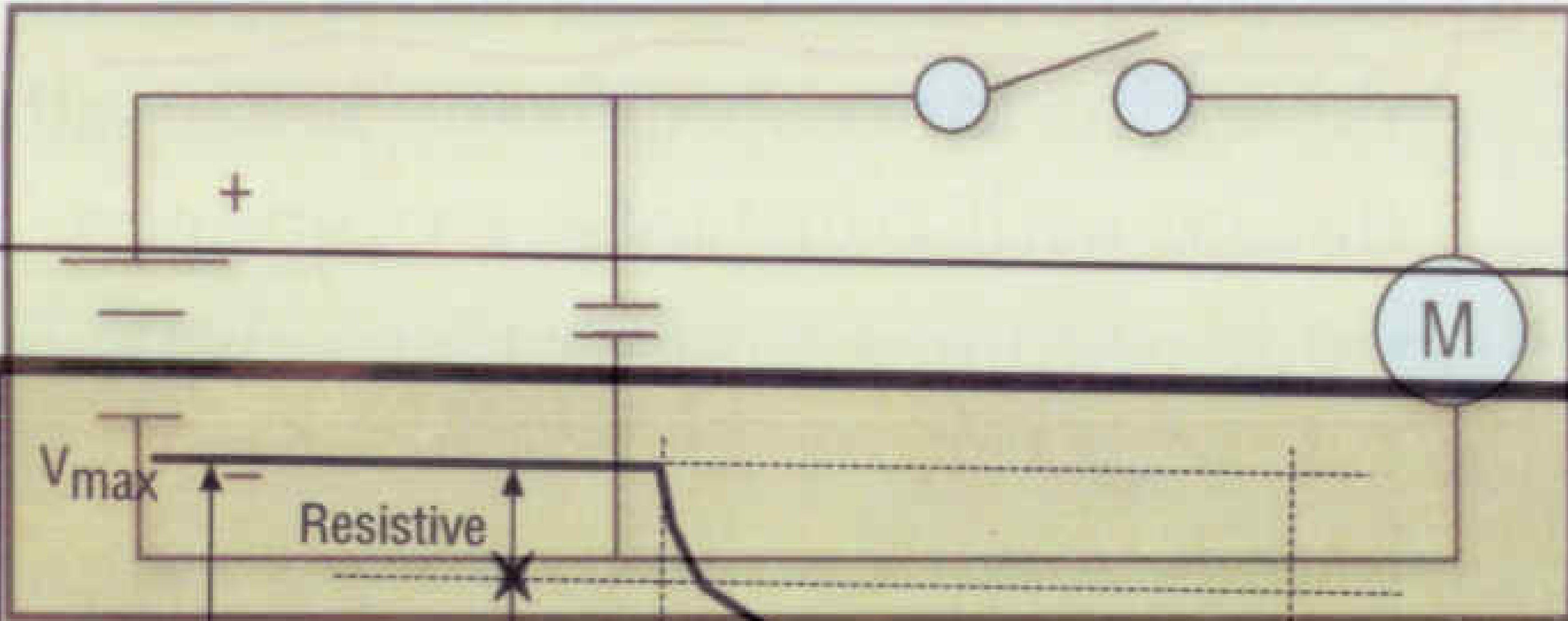

Fig. 1. *Battery/ultracapacitor/motor arrangement.*

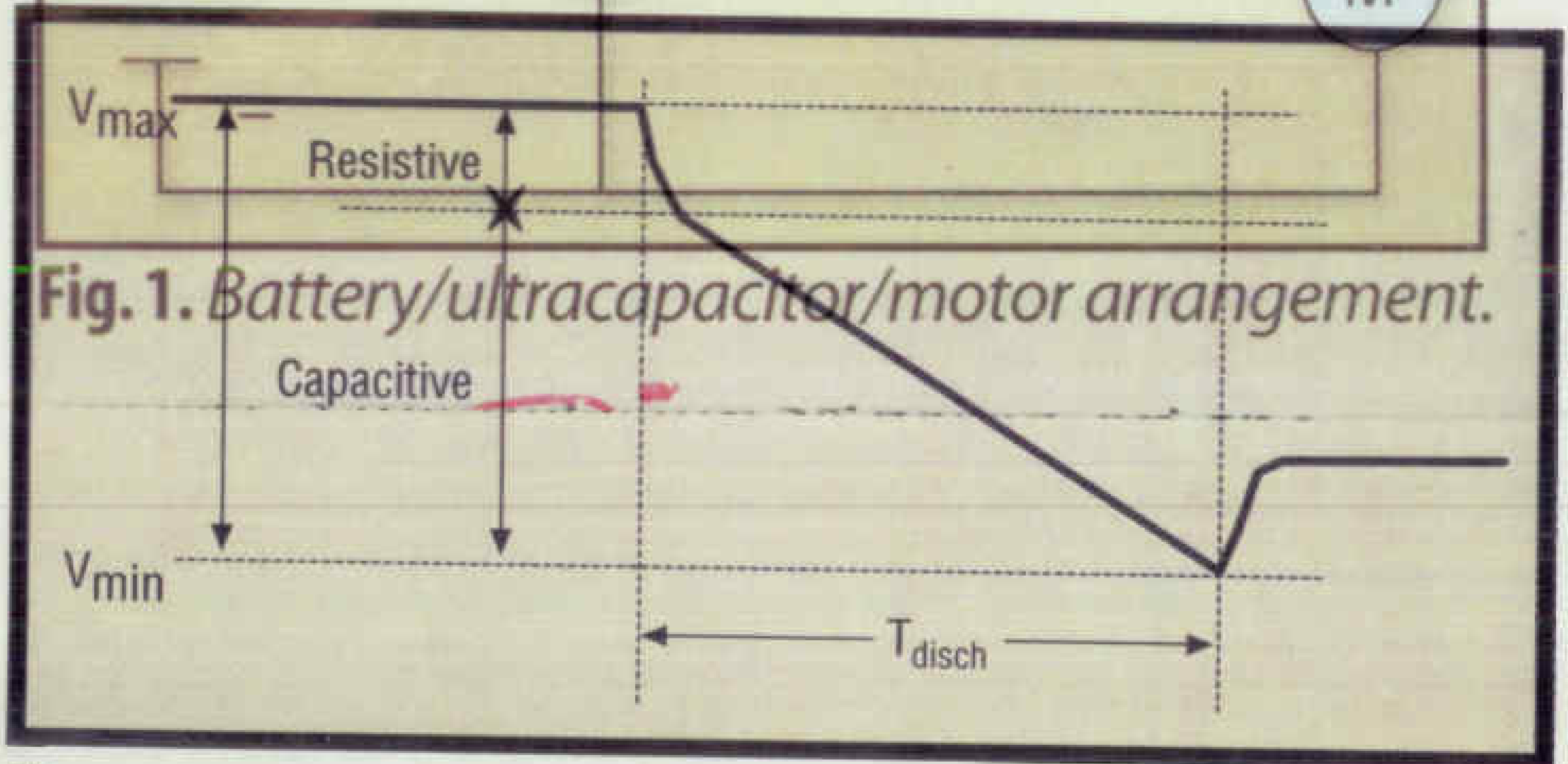

Fig. 5. *Discharge profile of an ultracapacitor.*

rating. Because sustained overvoltage

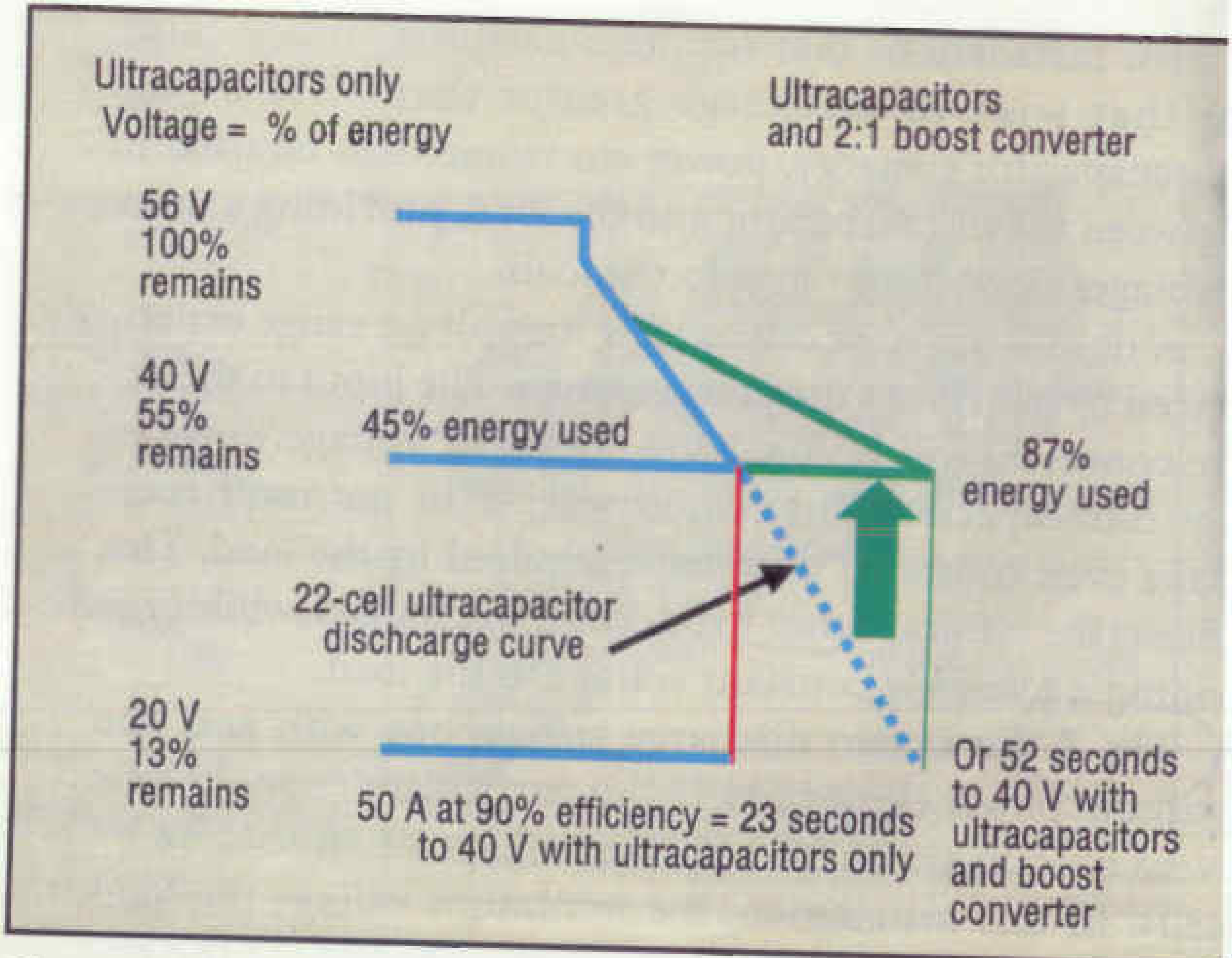

Fig. 4. *Discharge curves for ultracapacitors with and without power electronics.*