CAPACITOR STORAGE

ENERGY STORAGE IN ELECTRICAL POWER SUPPLY SYSTEMS

Energy storage can be used to solve problems of mismatch between supply and demand. The availability of energy storage is particularly beneficial in electrical power supply systems which suffer disturbances or fluctuations. On the other hand, intrinsic energy storage in the power system can also cause problems during fault conditions. In transport applications, energy recovered during braking can be used during acceleration to supplement the primary energy source; for example, the overhead supply system for an electric locomotive or the internal combustion (i.c.) engine for a hybrid/electric vehicle. In this way, the primary power source can be buffered from the peak power requirement.

In power engineering, the three main objectives of energy storage are:

- To reduce the overall cost of delivered energy in transmission and distribution systems,
- To reduce the overall cost of fuel input, by charging from less expensive base load generators at night and during weekends and discharging such inexpensive energy daily instead of using more expensive oil, gas, or coal, and
- To improve the operation of a utility, by following the instantaneous variation in the demand for system regulation.

Surges in demand for electricity at certain times of the day can put a significant strain on the power generation system. Combined-cycle gas turbine (CCGT) plants, which can come on line rapidly and operate efficiently for short periods, are used to cope with increases in demand such as in the early evening when people return home and start to prepare a meal. One could argue that the energy stored in the gas is released and converted into electricity for distribution. Pump storage systems are used for similar purposes. In this case, water is stored in a large reservoir, often high up in mountainous areas. When demand rises, the water is allowed to fall down a large shaft to a turbine which drives the generator. The water is later pumped back to the reservoir during off-peak periods ready for the next surge in demand. Again, very rapid but short-term power generation is available through such environmentally friendly schemes.

Other disturbances experienced by electrical power supply systems include short periods of local disconnection during faults. Examples on an even shorter time scale (up to a few seconds) include dips in system voltage due to sudden increases in demand or again during faults and increases in the local system voltage due to a large regenerative load such as a container crane lowering a container. Alternative energy sources, particularly wind turbines, also create disturbances in the electric power supply. The fact that over a period of days and sometimes hours wind conditions can vary from light or no wind to gales generally causes few problems unless the only available source of power is a wind turbine [see, for example, Somerville (1)]. The gusting effect of the wind, however, results in large power fluctuation over periods of perhaps 2 s to 5 s. A range of problems can arise due to these fluctuations, particularly where many wind turbines are concentrated in a small area (2–4).

CCGT and pump storage schemes are not able to deal with such short-term problems. A variety of energy storage technologies have been proposed to absorb excess energy during periods where supply exceeds or is adequate to satisfy demand for release during periods of excess demand over supply. Pneumatic systems, in which excess energy is used to compress air, have been reported [see, for example, Musgrove and Slack (5)]. Such schemes involve large numbers of high-pressure gas cylinders to store significant quantities of energy. Flywheel systems, in which energy is stored in a rotating mass, have been the subject of considerable interest (6–11). Excess energy in the system is stored as kinetic energy by accelerating the flywheel and released by decelerating the flywheel. The key to success in such schemes is the ability to control the flow of energy into and out of the flywheel efficiently. Other issues include the safety aspects of containing a high-speed rotating mass (in some cases, rotating at over 50,000 rpm), the need to maintain a vacuum within the containment housing to reduce losses, and the electrical power conversion equipment. As a result, the flywheel energy storage systems which have been developed have struggled to achieve the cost targets at which they become viable.

Electrochemical batteries are also used to store energy in electric power supply applications. Of course, electrochemical batteries are direct current devices and power conversion equipment is required to control the flow of energy between a battery pack and a power distribution grid system (12). Electrochemical batteries are widely used as the power source in a range of other applications. The lead acid battery still commands a major position in the market, particularly for vehicle starter batteries, in uninterruptible power supply units, in electric vehicles (e.g., fork lift trucks, milk floats, and golf buggies, as well as evaluation electric cars and vans) and electric/hybrid vehicles whilst new forms, particularly lithium batteries, have taken a major share of the portable equipment market. However, all forms of an electrochemical battery generally suffer from the disadvantage of poor cycle life and low specific power, particularly on charge. They suffer when subjected to cycling about a partially charged stated or deep discharge.

Energy is also stored whenever magnetic or electric fields are produced. A magnetic field is created by flow of current in an electric circuit. The strength of the magnetic field, and hence the energy stored in the field, is determined by the dimensions of the field and the material in which it exists. The energy stored in the magnetic field is proportional to the square of the current flowing in the electric circuit. For efficient energy storage based on this principle, large quantities of current must flow in the circuit with minimal loss. This requires a circuit with very low resistance. To achieve low resistance, superconducting materials must be used to form the circuit. The resistance of superconducting materials becomes very small at very low temperatures within a few degrees of absolute zero [-273°C or 0 K (kelvin)]. Superconducting magnetic energy storage (SMES) has been developed [see, for example, De Winkel and Lamoree (13)]. Materials used are based on niobium which becomes superconducting at 9.2

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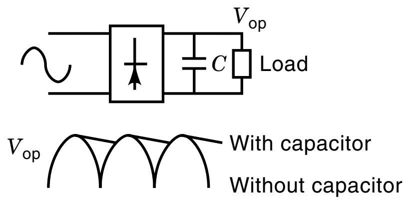


Figure 1. Use of capacitive energy storage for voltage waveform smoothing.

K. The viability of such technology depends to a great extent on the outcome of research to develop materials which become superconducting at higher, more easily maintainable temperatures. About 1987, it was discovered that oxides, such as yttrium barium copper oxide ($YBa_2Cu_3O_7$), become superconducting at temperatures as high as 80 K or 90 K, and thus, can be cooled by liquid nitrogen, [see Matthias (14) and Tanaka (15)].

An electric field is created and energy is stored when a potential difference exists across a region. The relationships between the potential difference, the electric charge, and energy stored in the field are functions of the dimensions of the field and the material in which the electric field exists. The ratio of electric charge to potential difference is referred to as capacitance. As will be shown in this article, the energy stored in an electric field is proportional to the square of the potential difference or the square of the electric charge in the region of the field. This is analogous to energy storage in a magnetic field; however, since the energy stored in the electric field is a function of potential difference (voltage) not current, superconducting materials and their associated refridgeration systems are not required in this case. Capacitive energy storage systems, however, require the development of structures (capacitors) which possess high values of capacitance but also techniques for efficiently charging and discharging the system.

A simple approach to the application of capacitive energy storage is found in electronic power supplies. A capacitor is placed after the rectifier in the power supply circuit (see Fig. 1) to smooth out the direct but fluctuating rectified voltage. The capacitor stores energy during the period when the rectifier output voltage, V_{op}, is high and supplies the load during the period when V_{op} is low.

The voltage across the capacitor varies as energy is stored or released. In the previous example, a small variation in voltage is tolerated in a trade-off between regulation performance and cost. Only a small portion of the energy stored is used since the voltage across the capacitor varies by only a small amount. More of the stored energy can be used if the capacitor voltage is allowed to change over a greater range. Whilst some systems will tolerate a wide variation in voltage, it is more common for the system voltage to be fixed within a narrow band. In such cases, a power electronic converter may be used in combination with the capacitor to control the flow of charge (current) into and out of the capacitor whilst maintaining the voltage presented to the system within which the energy store operates. This topic is expanded later in the article.

THEORY OF CAPACITOR ENERGY STORAGE

Fundamental Relationships

Conceptually a capacitor consists of two adjacent parallel conducting plates, as shown in Fig. 2(a), which are separated by an insulator called a dielectric. As the plates are electrical conductors, each contains a large number of mobile electrons, some of which are bouncing freely on the surface, and have a small negative charge. These plates can be charged either negatively or positively. For a plate to become charged negatively, extra electrons must be drawn from a source of negative charge to create a surplus of electrons. During this process, those electrons that have already entered the plate oppose or repel other electrons which try to join them. The flow of electrons will stop when the negative repelling force equals the charging force. Similarly, for a plate to become positively charged, electrons must be withdrawn toward a source of positive charge, to create a deficiency of electrons. The flow of electrons ceases when the positive attracting force equals the charging force.

The plates are then said to be charged. The difference in charge across the gap between the plates results in a potential difference and hence an electric field. Figure 2(b) shows lines of electrical flux between the plates which represent the field. Charges on the plates, such as those shown in Fig. 2(b), are associated with the electric field which appears as a potential gradient across the dielectric and potential difference between the two plates. The stored charge q (in coulombs) on a capacitor is proportional to the potential difference or applied voltage v (in volts), that is

$$q = Cv \tag{1}$$

The constant of proportionality C in Eq. (1) is referred to as the capacitance of the capacitor. The units of capacitance are farads (F); although μF (10^{-6} F) and pF (10^{-12} F) are more commonly used in practice.

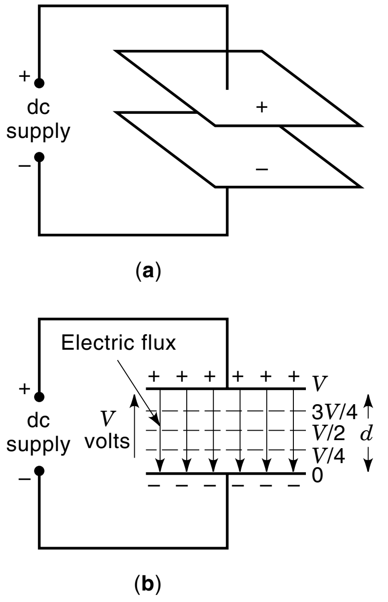


Figure 2. (a) Parallel plate capacitor. (b) Charge storage and electric field in a parallel plate capacitor.

As the capacitor is charged, a current i (in amperes) flows where

$$i = dq/dt = C\,dv/dt \tag{2}$$

The current is proportional to the rate of change of voltage (in volts per second, V/s). For example, if the voltage across 1 F changed by 1 V/s, the current is 1 A. To supply a current of 1 mA to 1 F, the voltage will rise at 1000 V/s.

The electric field strength E (alternatively referred to as the electric force, electric stress, or voltage gradient with units of volts per meter, V/m) is given by

$$E = v/d \tag{3}$$

where v is the potential difference across the dielectric or between the two plates and d is the dielectric thickness or spacing between the two electrodes.

The electric flux density D (also known as the total charge density with units of Coulombs per square meter, C/m^2) between the two electrodes, is expressed as

$$D = q/A \tag{4}$$

where q is the stored charge on a capacitor and A is the area of one plate.

In electrostatics, the ratio of total electric flux density D to electric field strength E is called absolute permittivity, ϵ, or dielectric constant, K, of a dielectric.

$$K = \epsilon = D/E = Cd/A \tag{5}$$

$$C = KA/d = \epsilon A/d \tag{6}$$

Permittivity of free space, sometimes referred to as the dielectric constant of a vacuum, is a constant $\epsilon_0 = 8.85 \times 10^{-12}$ F/m.

Energy Storage, Work Done, and Energy Density

If the voltage across a capacitor of capacitance C is raised, the charging current i is given by Eq. (2) and the instantaneous power p (in watts) received by the capacitor is

$$p = vi = vC\,dv/dt$$

The change in energy stored by the capacitor (in joules) in time dt is

$$dW = vC(dv/dt)\,dt = Cv\,dv$$

The total energy stored by a capacitor when potential difference is increased from $v = 0$ to $v = V$ is given by

$$W = \int_0^V Cv\,dv = \tfrac{1}{2}C(v^2)_0^V = \tfrac{1}{2}CV^2 \tag{7}$$

$$W = \tfrac{1}{2}C(Q/C)^2 = \tfrac{1}{2}Q^2/C \tag{8}$$

where Q is the total charge stored in the capacitor when the applied voltage is V.

The energy is supplied by the source and corresponds to work done by charges moving through distance d in the electric field with force (in newtons) of attraction or repulsion F. This force of attraction between oppositely charged plates is written as

$$F = W/d = \tfrac{1}{2}Q^2/Cd = \tfrac{1}{2}Q^2/\epsilon A = \tfrac{1}{2}E^2A$$

Volumetric energy density W^0 (in units of joules per cubic meter, J/m^3) for a capacitor with a dielectric thickness d and plate area A, will be

$$W^0 = W/Ad = [\tfrac{1}{2}CV^2]/(Ad)$$

and since $C = A/d$, $E = V/d$, and $D/E = \epsilon$, it follows that

$$W^0 = \tfrac{1}{2}\epsilon E^2 = \tfrac{1}{2}DE = \tfrac{1}{2}D^2/\epsilon \tag{9}$$

Energy storage capacity is often expressed in watt-hours (Wh) rather than joules and relates to the ampere-hour (Ah) capacity of the cell for a fixed system voltage such as a battery. Energy density or specific energy is defined as the energy that can be stored in a given weight (Wh/kg).

Properties of Dielectric Materials in Relation to Energy Storage Capacity

From Eq. (6), three parameters determine the storage capacity of a capacitor. These are

- The thickness of the dielectric material d: that is, the closer the plates are, the greater the capacitance (and the stronger the electric force that exists between the plates),
- The area A of the plates since a larger area of plate accumulates more charges than a small plate, and
- The dielectric material as defined by the absolute permittivity ϵ or dielectric constant K. Dielectric materials commonly used are air, vacuum, mica, paper, ceramic, plastic of certain types (polystyrene, polycarbonate, etc.), and metallic oxides. A good dielectric has
  - A very low electrical conductivity, hence a high insulating resistivity, to avoid leakage conduction which causes the dissipation of the stored energy in heat,
  - A high permittivity, and
  - A high electric strength to withstand large voltage gradient.

For determination of dielectric constant, all dielectric materials are compared to that of air as a reference. For example (if the gap between two electrodes is filled with any other dielectric material, the capacitance is multiplied by a factor, known as the dielectric constant.

The absolute permittivity of any medium may be expressed in terms of ϵ_0 as

$$\epsilon = \epsilon_0\epsilon_r$$

where ϵ_r is the dimensionless relative permittivity of the medium. It is given by

$$\epsilon_r = \text{(flux density of the field in the dielectric)}/\text{(flux density of the field in the vacuum)}$$

Dielectric Strength. The thickness of the dielectric in a capacitor determines its voltage rating. Before the voltage is ap-

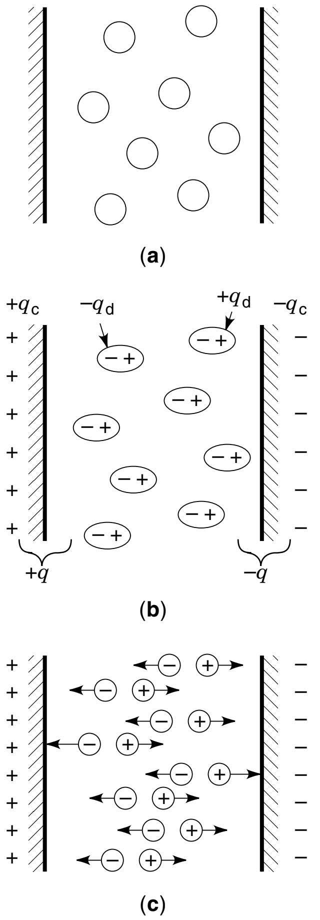


Figure 3. Polarization and breakdown in a dielectric material. (a) No p.d.; dielectric molecules unstrained, (b) p.d. applied; molecules polarized, (c) p.d. increased; molecules disrupted.

plied to the electrodes, the molecules of the dielectric material are neutral and unstrained. As the voltage is raised from zero, these molecules under the influence of electric field, rotate, stretch, and separate from each other and subsequently orientate their negative and positive charges in opposite directions. This is referred to as polarization of the dielectric. If the voltage is increased beyond the maximum voltage gradient of a dielectric, the dielectric breaks down (fails to insulate). The result of break down is a crack or puncture in the material which causes a flow of current in the dielectric. These processes are shown in Fig. 3.

The maximum voltage gradient is known as the dielectric strength (in V/m). This is given by

$$E_{\max} = V_{\max}/d$$

In high voltage engineering where capacitors are subject to high pulse powers, the problems associated with areas that are under high stress can be overcome by using a high permitivity material and avoiding sharp corners in conductors where the gradient tends to be high. In capacitor bushing, the use of an intersheath maintains the voltage at a suitable level. These improvements in the dielectric performance are called grading. Table 1 shows the dielectric constant and dielectric strength of various insulating materials.

Table 1. Properties of Dielectric Materials

Materials	Dielectric Constant (K)	Dielectric Strength (V/cm)
Air	1	32,000
Paper (oiled)	3–4	600,000
Paper (pressboard)	2	—
Cotton tape (rubbered)	2	—
Polyethylene	2–3	—
Mica	4–8	720,000
Glass	5–10	80,000
Porcelain	7	300,000
Titanates	100–200	40,000
Ceramics	6–1000	—
Polyvinyl chloride (PVC)	3–8	—
Ethylene propylene	2.8–3.5	—

Dielectric Absorption and Hysteresis. In the previous section it was mentioned that the dielectric molecules under the influence of an electric field become polarized and the effect of this is that some apparent charge is stored within the dielectric of the capacitor. This phenomena is called absorptive capacitance of the dielectric. If the power supply is alternating, each reversal of voltage will cause a reversal of polarity and electrical energy from the supply will be converted into heat within the dielectric. This loss is referred to as dielectric hysteresis.

Dielectric Leakage and Conduction Currents. In general no dielectric is a pure insulator and every dielectric possesses a very high resistance in excess of 100 MΩ. Hence, the number of free electrons is low. If a voltage is applied between the plates, those free electrons in the insulator drift from cathode to anode. This is known as conduction current, which produces power loss within the dielectric. The presence of conduction current will be evident, if the applied voltage across a charged capacitor is maintained and the current settles at a small constant value, instead of falling to zero.

Another current which flows between the two plates is the leakage current. This current flows over the surface of the dielectric. The magnitude of the current depends on the applied voltage, the dielectric material, but not its resistivity, and the moisture content of the dielectric and the air between the two plates. An equivalent circuit of such a capacitor is shown in Fig. 4.

Although the effect of leakage current within a circuit is very small, if the voltage across a charged capacitor is measured regularly, decrease in voltage can be noted although with a very large time constant.

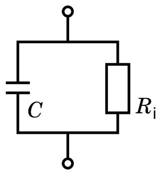


Figure 4. Equivalent circuit of capacitor with leakage.

The dielectric within a capacitor has a resistance R_i which is given by

$$R_i = d\rho/A \tag{10}$$

where ρ is the resistivity of the leakage path (in ohm-meters), d is the dielectric thickness (in meters), and A is the area of one plate (in square meters).

Combining Eq. (6) for capacitance with Eq. (10) gives

$$R_i = \epsilon\rho/C$$

where ϵ is the dielectric constant.

If a voltage V is applied across a capacitor which has a resistance R_i between its two plates, a leakage current I_i will flow. The value of this current is determined from the following relation

$$I_i = V/R_i$$

or

$$I_i = CV/\epsilon\rho$$

This indicates that the leakage current of a capacitor is proportional to its capacitance value. The power loss due to this current is $I_i^2R_i$, which is dissipated as heat in the capacitor.

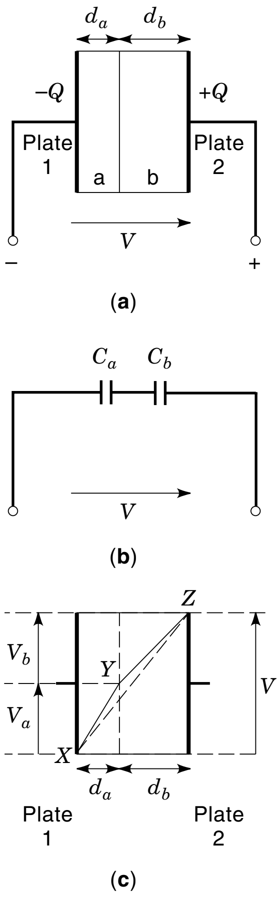
Composite Dielectric Capacitors. Figure 5(a) shows that the space between plates 1 and 2 is filled by dielectric a and dielectric b with a thickness of d_a and d_b, respectively. Assume that E_a and E_b are electric field strengths in dielectrics a and b. If the relative permittivities of dielectrics a and b are ϵ_a and ϵ_b, respectively, electric field strength in dielectric a is

$$E_a = V_a/d_a = D/\epsilon_0\epsilon_a$$

and electric field strength in dielectric b is

$$E_b = V_b/d_b = D/\epsilon_0\epsilon_b$$

This capacitor, as shown in Fig. 5(b), may be regarded as equivalent to two capacitances, C_a and C_b, connected in series. The electric field strengths E_a and E_b are represented in Fig. 5(c) by the lines XY and YZ, respectively. If the dielectric between plates 1 and 2 is homogeneous, the electric field strength is the XZ line.



(a)

(b)

(c)

Figure 5. (a) Vector diagram of pure capacitor. (b) Vector diagram of imperfect capacitor.

Connection of Capacitors

An individual capacitor may not be sufficient for applications requiring large amounts of energy storage. In other cases, the voltage rating of the individual capacitor may not be large enough to cope with the system voltage. In such examples, capacitors can be connected in parallel and series combinations.

Capacitors in Parallel. If a bank of capacitors of capacitance $C_1, C_2, C_3, \ldots, C_n$ are connected in parallel and the potential difference of each is raised to V volts, the total charge is the sum of the individual charges.

$$Q_{\text{total}} = Q_1 + Q_2 + \cdots + Q_n$$

or from Eq. (1)

$$C_{\text{total}}V = C_1V + C_2V + \cdots + C_nV$$

The equivalent capacitance is therefore

$$C_{\text{total}} = C_1 + C_2 + \cdots + C_n$$

The capacitance of n capacitors in parallel is the sum of their individual capacitances.

Capacitors in Series. For n capacitors connected in series, the total potential difference is the sum of their individual voltages.

$$V_{\text{total}} = V_1 + V_2 + \cdots + V_n$$

The charge Q on each capacitor is the same when connected in series and again using Eq. (1)

$$Q/C_{\text{total}} = Q/C_1 + Q/C_2 + \cdots + Q/C_n$$

The equivalent capacitance is therefore

$$1/C_{\text{total}} = 1/C_1 + 1/C_2 + \cdots + 1/C_n$$

Graphical Representation of Voltage, Charge, and Current

In a Direct Current Circuit. If a direct voltage V is applied to a capacitive circuit which contains a very small resistance, the capacitance C must accept a charge $Q = CV$ immediately, resulting in a very large current flowing for a very short period. If the voltage across the capacitor is increased or decreased uniformly, the charge Q will follow these changes with a constant charging or discharging current. Figure 6(a) shows these changes graphically.

In an Alternating Current Circuit. If an alternating voltage $V = V_{\max} \cos 2\pi ft$ with a constant amplitude and frequency is applied to a circuit containing a capacitance C and a very small resistance, the steady-state relations for charge and current are expressed as

$$Q = Q_{\max} \cos 2\pi ft$$

where, from Eq. (1), $Q_{\max} = CV_{\max}$ and

$$I = dQ/dt = d(CV_{\max} \cos 2\pi ft)/dt = -2\pi fCV_{\max} \sin 2\pi ft$$

respectively. All quantities are sinusoidal in shape. The maximum current is given by

$$I_{\max} = 2\pi f\, CV_{\max} = \omega CV_{\max}$$

and the root mean square (rms) current is

$$I_{\mathrm{rms}} = \omega CV_{\mathrm{rms}} \quad \text{or} \quad I_{\mathrm{rms}} = V_{\mathrm{rms}}/(1/\omega C) = V_{\mathrm{rms}}/X_{\mathrm{c}}$$

where $X_{\mathrm{c}} = 1/\omega C$ is the capacitive reactance.

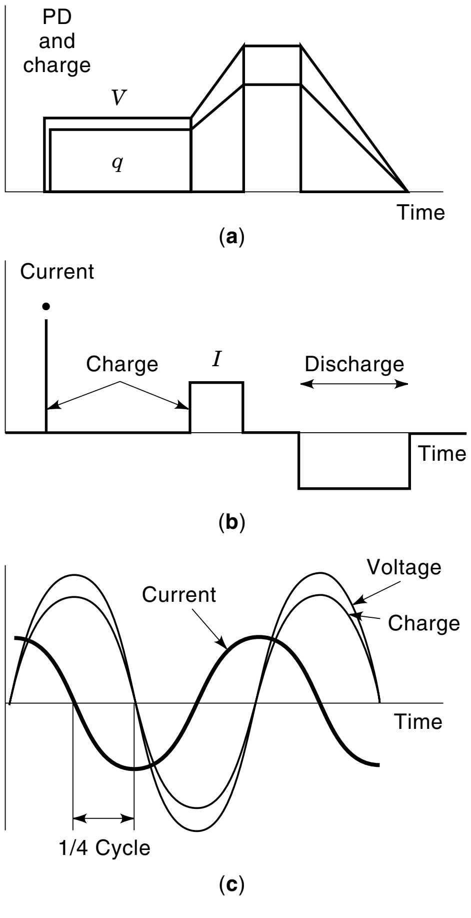


Figure 6. (a) Composite dielectric capacitor. (b) Equivalent circuit. (c) Potential distribution.

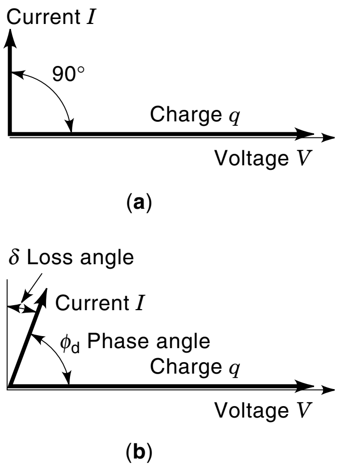


Figure 7. Relation between capacitor voltage, current and charge for (a) variable dc conditions, (b) ac conditions.

The graphical representation of voltage, charge, and current is shown in Fig. 6(b) while Fig. 6(c) shows the vector diagram of a pure capacitor.

Losses Across a Capacitor. If a voltage is applied across a perfect dielectric, no dielectric loss can be detected and the induced capacitance current I_{c} leads the voltage by the phase angle $\phi = 90°$, as shown in Fig. 7(a). As a perfect dielectric cannot be achieved in practice, a small current I_{v} that is in phase with voltage V will exist. The summation of these two current vectors, as shown in Fig. 7(b), gives the current vector I that leads the voltage by the phase angle $\phi_d = 90° - \delta$. The cosine of the phase angle ϕ_d is the power factor of the dielectric, and δ is the dielectric loss angle. For a good dielectric, ϕ_d is close to 90°.

With an ideal capacitor, the current is given by

$$I = I_c = \omega CV$$

With a nonideal capacitor, the loss is

$$P_{\mathrm{loss}} = VI \cos \phi_d = VI \cos(90 - \delta) = VI \sin \delta = \omega CV^2 \sin \delta$$

When δ is small, it is expressed in radians and the power loss approximation is

$$P_{\mathrm{loss}} = CV^2 \delta$$

The losses of the capacitor are also expressed by the dissipation factor, which is defined as

$$\tan \delta = \omega R_i C$$

where R_i is the dielectric resistance or the resistance between the two plates.

Classification of Conventional Capacitors

Capacitors are often classified according to the material used for their dielectric. The main types include air, mica, paper, plastic, and ceramic and are used in electronic circuits where small value capacitors (farads, nanofarads, or picofarads) are normally required. Electrolytic capacitors have traditionally been used for storing large amounts of energy, particularly in electronic power supplies. In power engineering, where more energy storage is required, capacitors values are often quoted in farads. More recently, double layer capacitors (supercapacitors) have become available offering the potential for storing significantly larger quantities of energy than previous types although they are currently limited to low voltage applications.

Capacitors are generally manufactured to have a fixed value of capacitance but variable capacitors are used in some specific application. Producing capacitance values within close tolerance is quite difficult particularly for larger values.

Air Capacitors. These consist of two metal plates (i.e., aluminium). The capacitance of such capacitors is generally low, typically 1 pF to 500 pF. This is because their plates are spaced far enough apart to prevent arcing. In variable air capacitors one of the plates is fixed, the other viariable. Variable air capacitors are used where a variable capacitance and low losses are needed; typical examples are in radios and other electronic circuits.

Mica Capacitors. These capacitors consist of two metal foil plates with a sheet of thin mica between them. In their construction, alternate layers of metal foil and mica are clamped tightly together. Usually the whole capacitor is impregnated with wax, to exclude moisture, and placed in a bakelite case. For larger values, several layers of plates and thin sheets of mica dielectric are used. Mica is a good insulator but is expensive and is not used in capacitors above 0.1 F. In newer types of mica capacitors, a thin layer of silver is sputtered on both sides of the mica dielectric to form the plates. The capacitance of these capacitors is stable and does not change with temperature or age. They have high working voltage ratings. These capacitors can be manufactured as fixed or variable capacitors and are normally used in high-frequency circuits. A typical construction is shown in Fig. 8(a).

Paper Capacitors. A typical paper capacitor is shown in Fig. 8(b). The electrodes are layers of metal foil interleaved with paper. The length of the roll corresponds to its capacitance. The paper is usually impregnated with oil or wax and is placed in a plastic or aluminum container for protection. These capacitors are commonly used in the power circuits of household appliances. Paper capacitors up to 1 F are made in various working voltages. The capacitance of these capacitors changes with temperature and they deteriorate faster than most other types of capacitors.

Plastic Capacitors. Plastic capacitors such as polyester, polystyrene, and Teflon are relatively new as capacitor dielectrics. They are manufactured in very thin films, and metallized on one side. Two films are then rolled together, similar to the construction of paper capacitors. These capacitors can operate well under conditions of high temperature, have high working voltages rating (i.e., a few thousand volts), and their leakage resistance is high, around 100 MΩ.

Ceramic Capacitors. These are made in various shapes and sizes. All have basically the same construction. For example, for smaller values, a thin ceramic dielectric is coated on both sides with a metal and they are usually cup or disc shaped [see Fig. 8(c)]. Larger values are obtained by stacking up these ceramic layers. Each layer is separated from the next by more ceramic; these are normally a tube shape. In both arrangements, the plates are connected by electrodes and a final coating of ceramic is then applied to the outside to form a solid device for protection.

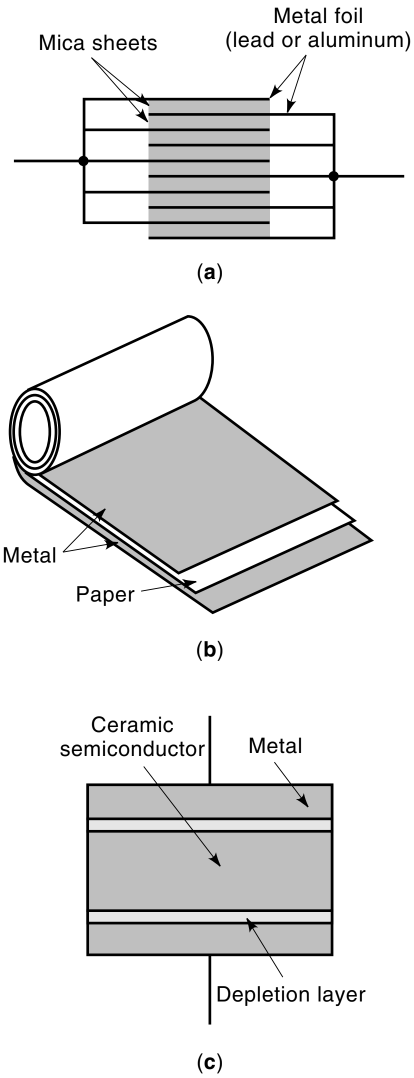


Figure 8. (a) Mica capacitor. (b) Paper capacitor. (c) Ceramic capacitor.

Certain ceramic materials such as compounds of barium titanate have a very high permitivity, thus enabling a very small separation between the plates and capacitors of high capacitance to be made from relatively small physical size. Ceramic capacitors are available in the range 1 pF to 1 F with a high working voltage rating up to a few thousand volts. The leakage resistance is typically 1000 MΩ. Ceramic capacitors are used in high-temperature situations and in high-frequency applications.

Polarized or Electrolytic Capacitors. According to the dielectric used, these capacitors are characterised as wet electrolytic capacitors or solid electrolytic capacitors. Wet electro-

Table 2. Types of Capacitor and Ratings

Type	Capacitance Range	Voltage Range	Comments
Ceramic	10 pF–1 F	50–1000 V	Small, cheap
Mica	1 pF–0.01 F	100–600 V	Good for RF
Glass	10 pF–1000 pF	100–600 V	Good for signal filter
Tantalum	0.1 F–500 F	up to 100 V	Small, polarised
Electrolytic	0.1 F–0.2 F	up to 600 V	Polarised, MV filtering
Oil	0.1 F–20 F	200 V–10 KV	Large, HV filtering

lytic capacitors are generally made of two metal foil sheets (usually of aluminum) separated by a layer of paper saturated with a chemical liquid, such as ammonium borate, called the electrolyte as shown in Fig. 9(a). The foils and the paper are rolled up together and sealed in a container. To determine the polarity of the capacitor, a dc voltage is applied between the two foils. The current flow causes a thin layer of aluminum oxide to develop on one foil sheet forming the positive electrode. The absorbent paper between the two metal foils is a conductor and does not act as a dielectric. The *oxide layer* is the dielectric. As the thickness of an oxide layer is small, for example for a working voltage of 100 V, only about 0.15 m, a high capacitance in the range of many thousand microfarads is achievable in a small space. The typical working voltage range is 6 V to 500 V.

The main disadvantage of this type of capacitor is that the insulation resistance is relatively low and that they must only be used where the applied voltage is direct. The most commonly used type is aluminum electrolytic capacitors. These capacitors are mainly used where a very large capacitance is needed, such as in rectifiers for reducing the fluctuating direct voltages. In ac systems, these can only be safely used if two capacitors [see Fig. 9(b)] are connected back to back, negative to positive and positive to negative.

Presently, solid electrolytic capacitors [see Fig. 9(b)] are much smaller in value but they do not possess some of the disadvantages of the wet electrolytic capacitors. For tantalum electrolytic capacitors, the wet electrolyte is replaced by layers of manganese dioxide and graphite. The anode plate consists of pressed, sintered tantalum powder coated with an oxide layer which forms the dielectric and the cathode is made of silver or copper plate. The layers of manganese dioxide and graphite have electronic conduction rather than the ionic conduction of the liquid electrolyte in the wet polarized capacitors. In these capacitors, the layer of manganese dioxide is coated on the oxide layer and the layer of graphite forms the connection with the cathode. Normally the whole structure is enclosed in a sealed container. Table 2 shows some advantages and disadvantages of traditional dielectric material used in capacitors.

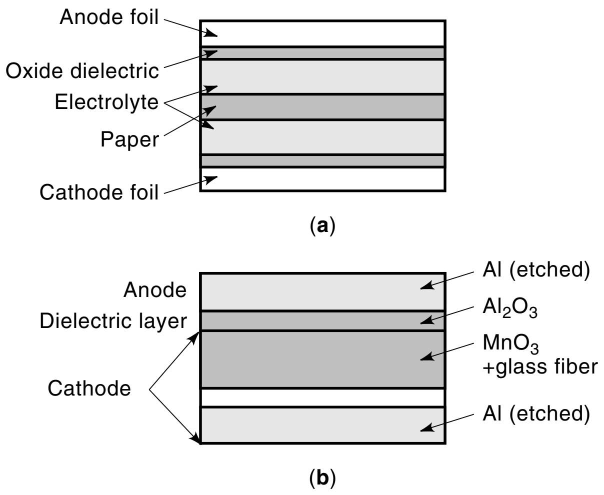


Figure 9. (a) Wet electrolytic capacitor. (b) Solid electrolytic capacitor.

Intrinsic Capacitive Energy Storage

Where ever an electric field exists, capacitance is formed. Thus the power distribution system itself possesses capacitance. Although the intrinsic capacitance of a section of the power supply system is relatively small, the energy stored influences the behavior of the system under fault conditions and cannot be ignored.

Capacitance within Cables. Cables may have one or more conductors within a protective sheath. The conductors are separated from each other and from the sheath by insulating materials.

For a single conductor cable, assume that a potential difference V exists between the conductor and the sheath of a cable. If the charge on the conductor and the sheath are $+Q$ and $-Q$ C/m of length according to Coulomb's law, the electric flux density at a radius of x (in meters) is

$$D = Q/2\pi x$$

Since from Eq. (5), $E = D/\epsilon$

$$E = Q/2\pi\epsilon x$$

If the potential gradient at radius x is dv/dx, the potential difference between the conductor with radius R and the sheath with radius r is given by

$$V = \int_r^R E\,dx$$

or

$$V = (Q/2\pi\epsilon)\ln(R/r)$$

where ϵ is absolute permittivity of the insulator.

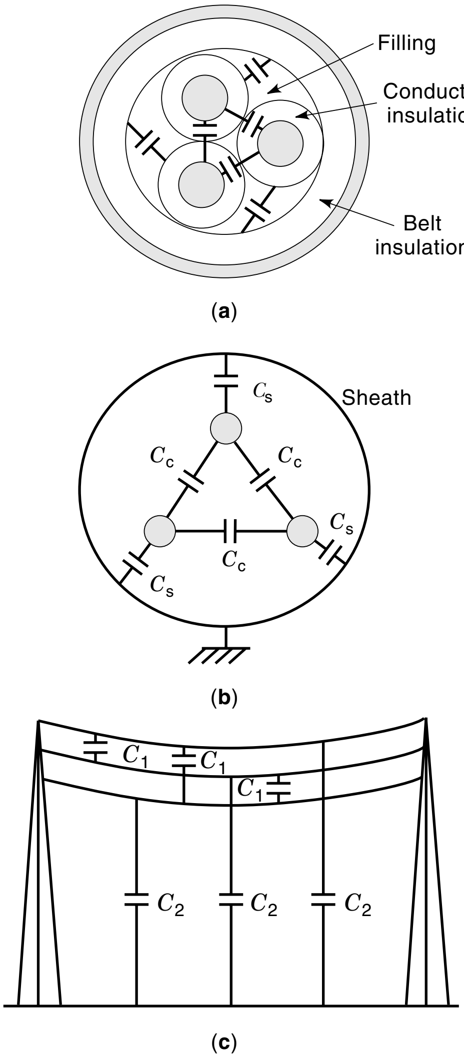


Figure 10. (a) Three conductor belted cable. (b) Equivalent circuit. (c) Representation of three phase overhead transmission line.

The capacitance between conductor and sheath is

$$C = Q/V \text{ or } C = (2\pi\epsilon)/[\ln(R/r)] \qquad \text{F/m}$$

Three Conductor Belted Cable. As shown in Fig. 10(a), in three conductor belted cables, there are two insulators; one is the conductor insulation with thickness T and the other is the belt insulation of thickness t. Because of these two insulations, there are capacitances of C_c between the conductors and capacitances of C_s between each conductor and the sheath as shown in Fig. 10(b). Further derivation of appropriate formulae is beyond the scope of this article but can be found in Ref. 16.

Overhead Lines. Calculation of all the parameters for determination of capacitance are again beyond the scope of the present discussion. A single-phase overhead line consists of two identical conductors 1 and 2 with radius r_1 and r_2 respectively, separated by a distance D. With a potential difference V_{12} between the two conductors, and charges of $+Q$ and $-Q$ C/m carried by conductors 1 and 2 respectively, the capacitance (in farads per meter) between conductors is

$$C_{12} = Q/V_{12} \text{ or } C_{12} = 2\pi\epsilon/\ln[D_2/r_1 \cdot r_2]$$

If $r_1 = r_2 = r$, then

$$C_{12} = \pi\epsilon/\ln(D/r)$$

Figure 10(c) shows a representation of a three phase line with equal spacing D. The line to neutral capacitance is given by

$$C_n = 2\pi\epsilon/\ln(D/r) \quad \text{F/m}$$

If the spacing between the conductors is not the same, D is replaced by $D_{eq} = (D_{12} \cdot D_{23} \cdot D_{31})^{1/3}$ in the above equation.

Power Capacitors

The reactive power of capacitors is used to improve power factor and voltage, thereby reducing the losses, in power supply systems. If capacitors are connected in series with the line, the reactive power is proportional to the square of the load current whilst for shunt (parallel) connected capacitors, it is proportional to the square of the voltage.

The electrodes of power capacitors are usually made of high purity annealed aluminium foil or metal spray. The dielectric is made of paper, mixed paper–plastic film, typically polypropylene, or plastic film. These dielectrics are designed to have a working voltage gradient of 10 to 50 MV/m.

Normally, these capacitors are in the form of banks and can be connected in a number of configurations such as grounded star, ungrounded star, double star with neutral floating, double star neutral grounded, and delta. For high voltage, star connections are normally used. In star connection banks, the neutral of the capacitors is grounded only if the system or substation transformer is effectively grounded. The capacitors may be of the switched and nonswitched type, depending on the loading, voltage, etc.

On long and heavily loaded 11 kV distribution systems, the shunt capacitors are usually pole mounted. If a number of capacitor banks are used in parallel, it may be necessary to use series reactors to limit the inrush current.

With 0.415 kV distribution systems, capacitors are installed on individual lines or at consumer loads to reduce system losses and improve the system voltage. These also provide a reduction in kilovolt-ampere demand. For example the capacity (kVAR) required to improve the power factor of an existing kilowatt system, say from $\cos\phi_e$ to a desired power factor $\cos\phi_d$, can be calculated from the following equation:

$$\text{kVAR} = \text{kW}(\tan\phi_e - \tan\phi_d)$$

Also, where there is variation in load demand, the voltage at various buses must be controlled in order to keep the receiving end voltage (V_R) at a specific value within a permissible band of voltage variations. To achieve this, a local VAR generator which consists of a bank of three phase static capacitors, as shown in Fig. 11, must be arranged. The VAR balance equation at the receiving end is

$$Q_R + Q_C = Q_D$$

Where Q_R is the a fixed amount of VARs drawn from the line by the load, Q_D is the varying VAR demand of the load, and Q_C is the varying VAR provided to the line to compensate for Q_D.

If V_R is the line voltage in kilovolts and X_C is the per phase capacitive reactance of the capacitor bank (star connection), the desired reactance of the capacitor bank can be determined by compensating for total inductive reactance of the load and even the transmission line. The expression for the VAR fed into the line can be written as

$$I_C = I_R - I_L$$

that is

$$I_C = jV_R/\sqrt{3X_C}$$

or

$$jQ_C(\text{3-phase}) = 3V_R(-I_C^*)/\sqrt{3}$$

Therefore, Q_C (3-phase) $= V_R^2/X_C$ and $C = 1/\omega X_C$.

Local capacitive compensation similar to the one shown previously can be made automatic by using the signal from the VAR meter installed at the receiving end of the line. Nowadays, the capacitor bank switching is achieved using silicon controlled rectifiers (SCR).

Supercapacitors

The term *supercapacitor* is commonly used to describe double layer capacitors. These are electrochemical energy storage devices that are able to store more energy per unit weight than traditional capacitors. For capacitance values larger than 1000 F, the term *ultracapacitor* is also used. For clarity, the term supercapacitor will be used in the following sections.

In supercapacitors, energy is stored by distributing charges across a relatively larger surface area than in conventional devices. They are also capable of delivering and absorbing energy at higher power rating than electrochemical batteries and possess far longer cycle life. Quite early in the development of supercapacitors, in 1994, charge and discharge cycles in excess of 500,000 repetitions were reported by Murphy and Kramer (17), some 500 times greater than a well-developed battery system. This emerging energy storage technology is increasingly being used for pulsed, high-energy, and high-power applications.

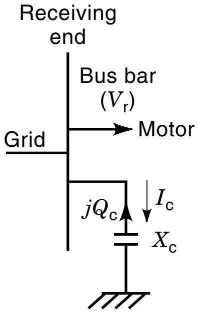


Figure 11. Power capacitor used as VAR generator at distribution busbar.

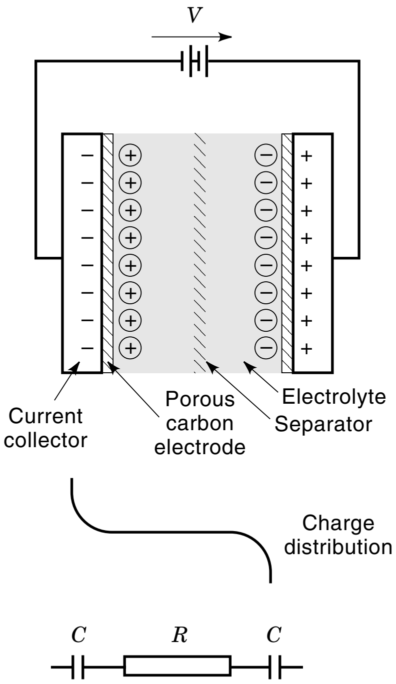


Figure 12. Basic configuration of a double layer capacitor.

In a supercapacitor, an electronic conductor is immersed in an electrolytic solution. Ions from the solution naturally align themselves with electronic charges on the surface of the electronic conductor. This alignment leads to a layer of charges on the surface of the conductor and a layer of charges in the electrolytic solution, hence the term "double layer." In general, positive charges and negative charges are distributed facing each other at an extremely short distance in the boundary between the solid and liquid material (18). The amount of charge stored in the double layer can be increased if a potential is applied between the solution and the conductive material. This can be achieved by placing a second electrode in the solution. When a potential is applied between the two electrodes, charge is absorbed in the double layer region on both electrodes. The basic configuration of a double layer capacitor, shown diagrammatically in Fig. 12, resembles a battery construction rather than a traditional capacitor. As shown in Fig. 12, this system is equivalent to two capacitors in series separated by an internal resistance.

Activated carbon fiber or powder is the most commonly used electrode material in supercapacitors because it is relatively inert and offers a very high surface area of conductive material. The manufacturing process of activated carbon can easily be modified to control the porosity, surface area, density, pore size, and pore volume of the fiber or powder. Control of the manufacturing process allows activated carbon material to be produced to match particular electrolytic solutions. To prevent short circuiting of the two electrodes, a porous separator which is permeable to ions but provides electrical insulation is placed between the electrodes. Both the separator and the electrodes are impregnated with an electrolytic solution (electrolytic solutions determine the maximum withstanding voltage: that is, the voltage at which electrolysis takes place). The separator allows ionic current to flow through the cell while preventing electrical conduction between the two electrodes. On the back of each active electrode, a current collecting plate is often added to reduce ohmic losses in the capacitor. If these plates are nonporous, they can be used as part of the capacitor seal. Voltage is then applied to the polarized electrodes through the collector.

A supercapacitor is very much the same as a battery except that the nature of charge storage in the electrode active material is capacitive: that is, the charge and discharge processes involve only translation of ionic and electronic charges through electronically or ionically conducting domains, respectively. Energy is stored in a supercapacitor by charge separation within the micropores of the high surface area materials. These materials typically do not undergo chemical changes as do the materials in batteries. This storage mechanism is the primary reason supercapacitors are capable of extremely high cycle lives. Energy densities of supercapacitors are much higher than those of ordinary capacitors, but typically lower than those of advanced batteries. Supercapacitors store several hundred times the energy of conventional capacitors.

Supercapacitors can be classified with respect to the material being used in the electrodes (19). Currently, the materials being used include carbon/metal fiber composites; foamed (aerogel) carbon, activated, synthetic, monolithic carbon; doped conducting polymer films on carbon cloth; and mixed metal oxides coating on metal foil (e.g., Ru/Ta-oxide). All of these materials are used with organic electrolyte. Other materials used are conducting polymers, noble metal oxides, or redox polymers (20).

The energy density of supercapacitors employing aqueous solutions (18) is limited by the low breakdown potential of water. In practice, this limits the voltage rating of such devices to less than 1 V. The low operating voltage also limits the power density of a capacitor stack as more cells must be connected in series to obtain the same operating voltage. Among the other disadvantages of aqueous-based capacitors, the highly corrosive nature of these solutions also necessitates the use of very expensive materials within the structure.

Organic-based electrolytic solutions offer a much higher operating voltage than aqueous-based systems (21). Cell voltages as high as 2.5 V to 3.0 V are achievable, leading to increases in both energy and power capability. These solutions also allow aluminum to be used in the composite electrodes, current collector, and cell casing, resulting in greatly reduced material cost of the capacitor.

Other research has focused on a class of materials that combine the characteristics of a capacitor and a battery (22,23). In *redox* supercapacitors, faradic charge transfer takes place as in a battery. In these devices, capacitance arises from faradic reaction and is known as *pseudocapacitance.* Redox supercapacitors store more charge than a conventional double layer capacitor and discharge more quickly than a conventional battery. The versatility of the electronically conducting polymers (ECP) enables different configurations to be used. Arbizanni et al. (24) report three different redox supercapacitor configurations with an increasing charge storage capacity and operating potential range. These are

- A symmetric supercapacitor based on a *p*-doped ECP.
- An unsymmetric supercapacitor based on two *p*-doped ECPs which are dopable at different potential ranges.
- A symmetric supercapacitor with a *p*- and *n*-doped ECP.

In the so-called Evans hybrid capacitor, the cathode in an electrolytic capacitor is replaced with a large capacitance value electrochemical cathode. Because the electrochemical requires little volume, available space is used to increase the size of the anode. The resulting capacitor has several times the energy density of the original.

Supercapacitor Technology. In 1991, the US Department of Energy (DOE) established a program to develop and evaluate supercapacitors as an enabling technology for electric/hybrid vehicles. Near-term and advanced goals for energy density (5 Wh/kg and 15 Wh/kg), power density (500 W/kg and 1600 W/kg), and volumetric energy density (11 Wh/L) were set. Development, testing, and evaluation activities have been coordinated by the Idaho National Engineering Laboratory (INEL) from where a substantial collection of publications has emerged, particularly from Burke (now Institute of Transport Studies, Davis, University of California) including, for example, Refs. 25 and 26. Progress within the program to 1997 is reviewed by Murphy et al. (27).

A number of industrial groups have supercapacitor development programs including, in Japan, Panasonic (28) and, in the United States, Maxwell Laboratories Inc. (29,30), Argonne National Laboratory (23), and SAFT (31).

Maxwell Laboratories, Inc. has fabricated nonaqueous, carbon-based, 24 V supercapacitors. With eight cell, bipolar stacks they have achieved specific energies of 4.5 Wh/kg and specific powers in excess of 1 kW/kg.

At Idaho National Engineering Laboratory, as reported by Burke (19), research on a 3 V cell has resulted in an energy density of 5 Wh/kg at a constant power density of 2.5 kW/kg. In his paper, Burke (19) suggests that up to an energy density of 200 Wh/kg with low cost and long life cycle can be achieved.

Presently, supercapacitors are manufactured in the form of single cell (spiral wound) and multicell (prismatic and bipolar). The bipolar cell arrangement is used to increase the operating voltage of supercapacitors, in which individual cells are stacked in series. Because one side acts as the positive electrode and the other side acts as the negative electrode in an adjacent cell, this type of arrangement is called bipolar (H. I. Becker, US Patent No. 2,800,616,1957).

The optimum design is to reduce ohmic losses. This is usually achieved by separating adjacent cells with only current collector plates. These plates must be nonporous so that no electrolytic solution is shared between cells (18,26).

With the prismatic cell (wound design) arrangement, a thin, large surface area cell forms a continuous winding curve around a central axis in a single cell housing (A. Yoshida and K. Imoto, US Patent No. 5,150,283,1992). Blank et al. (32) report that bipolar design has increased efficiency over the wound design. This is because, in prismatic cell arrangement, cells are stacked in series and the resistance of the lead wires adds to ohmic losses.

In order to increase the *efficiency* of supercapacitors, the contact resistance which is the resistance between the particles in the electrode structure must be low. Also, the resistance must also be small between adjacent cells in stack structure. These two resistances are called internal resistance.

For large capacitance, a large surface area is needed, whilst to increase the working voltage, a solution with high potential breakdown is necessary. The organic-based electrolytic solutions provide the best performance. These solutions possess a much larger operating voltage range than aqueous-based systems (33).

Researchers at Lawrence Livermore National Laboratory (LLNL) have applied carbon aerogel material to an *aerocapacitor.* Carbon aerogel is one of the world's lightest materials and its large surface area can fulfill the need for compact ultracapacitor size. Aerocapacitors are inexpensive and have shown potential to be easily produced. Because of the large surface area provided by an aerogel, it can deliver at least 50 times more power in a given space than batteries. In addition, its conductivity is higher than that of capacitors made from other forms of carbon and carbon powders because of a honeycomb structure. LLNL researchers have developed carbon aerogels the size of grapes with effective surface areas the size of two basketball courts. The aerocapacitors have shown capacities of up to 40 F/cm^3 and excellent performance at temperatures as low as -30°C. Power densities have been shown to be more than 7 kW/kg. Aerocapacitors also hold onto stored energy over a period of weeks (21).

Recently, Lassegues and co-workers (21) studied the possibility of replacing the liquid electrolyte by a proton conducting polymer electrolyte. Their main interest was to build an all-solid thin-film device free from problems of leaks and corrosion. Their results so far suggest that the lifetime of such a supercapacitor is unlimited. Rudge and co-workers (20) demonstrated that electrochemical capacitors with a combination of high capacitive energy density and low material cost can be constructed using conducting polymers. They have demonstrated that energy densities of up to 39 Wh/kg can be achieved using a combination of both *n*- and *p*-doped conducting polymers for a capacitance ranging up to 1000 F.

Research suggests (Refs. 11–14 of Ref. 34) that for energy densities considerably greater than 5 Wh/kg in combination with low resistance ($<0.01\ \Omega \cdot \text{cm}^2$) devices may require pseudocapacitance which requires an active electrode material. Materials could be carbon composites, mixed Ru/Ta-oxide, conducting polymers, redox powders, or fibers or other high surface area materials.

Supercapacitors offer considerable potential for energy storage systems: however, most commercially available supercapacitors, designed for much lower power applications, are small and store only several hundred joules (tens of milliwatt hours). The largest commercially available device, manufactured by Panasonic, stores 1.1 Wh of energy (28). For power supply applications, high voltage stacks (many supercapacitors connected in series) capable of much higher quantities of energy must be developed.

Basic Equivalent Circuit of a Supercapacitor. The system of two electrodes in an electrolytic solution represents the basic constituents of a supercapacitor. This system is equivalent to two capacitors in series separated by an internal resistance. The capacitance of each electrode can be represented by the following equation:

$$C = K_e/dA$$

Where K_e is the effective dielectric constant in the interface region, d is the distance of charge separation across the double layer, and A is the active interfacial surface area of the solution and electrode. Typically K_e/d is in the range of 10 F/cm^2 to 30 F/cm^2.

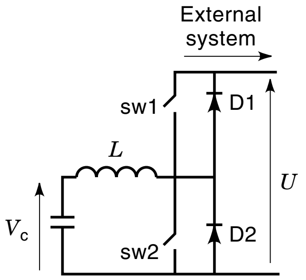


Figure 13. Power electronic converter for bidirectional power control in capacitor energy storage.

The electric double layer capacitor has a very large capacitance. Hence it cannot be measured by using an LCR (inductance/capacitance/resistance) meter as would be the case for conventional capacitors. To determine the capacitance of a supercapacitor with a maximum usable voltage E_o (in volts), the charging time constant τ of capacitor C is measured and the capacitance found from

$$C = \tau/R_c$$

where τ represents the time in seconds elapsed until V_c reaches a value of $[1 - (1/e)]\,E_o$, and R_c is the series protection resistor which is fixed for a specified type of the supercapacitor.

Integration of Supercapacitor Energy Storage. In the case of an electrochemical battery, energy is absorbed and delivered at approximately constant voltage. For a supercapacitor, as for any other capacitor, the voltage across the device varies as energy is stored or released. A power electronic converter must be used in combination with the supercapacitor to control the flow of charge (current) into and out of the supercapacitor whilst maintaining the voltage presented to the system within which the energy store operates (35,36). The form of power electronic converter which can achieve bidirectional energy flow between a supercapacitor and the main power system and load is shown in Fig. 13. Power devices SW1 and SW2 control the energy flow into and out of the supercapacitors. Energy is stored in the supercapacitors by appropriate switching of power device SW1 [forward converter mode (37)] and returned to the link with the main power supply system by appropriate switching of power device SW2 [boost converter mode (37)].

The exact configuration of supercapacitor, power electronics, and load depends on the application. For example, in an electric/hybrid vehicle, by appropriate control of the power electronic converter, energy from the supercapacitors can be used to accelerate the dc motor which drives the wheels. The

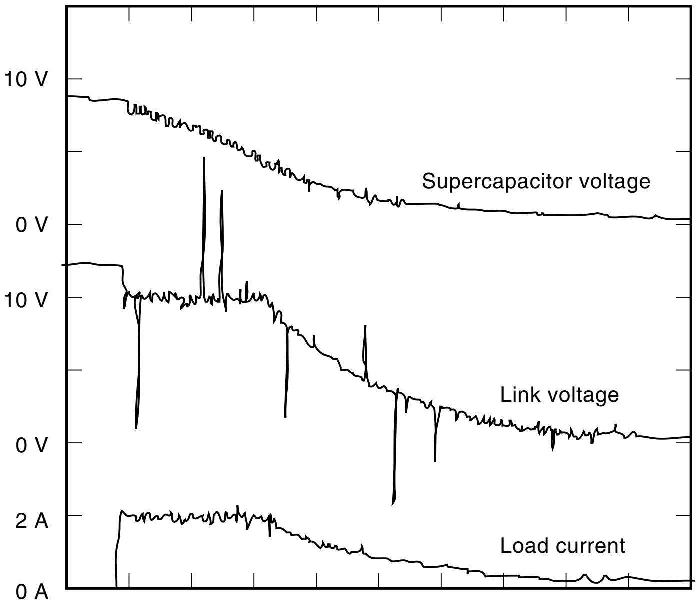


Figure 14. Practical demonstration of energy storage discharge. (a) Top trace; supercapacitor voltage. (b) Middle trace; load voltage. (c) Bottom trace; load current.

motor would be connected to the supercapacitor system by a second power converter. The main system power source would include an i.c. engine-driven generator in an electric/hybrid vehicle or an electrochemical battery in a purely electric vehicle. In such a system, regenerated energy can be returned to the supercapacitors during braking. For an uninterruptible power supply application, a second power converter would be required to feed an ac load. The discharge of the supercapacitors can be controlled such that the link between the two converters can be maintained at a set voltage, hence mimicking the action of a battery.

Figure 14 shows results from a test in which a supercapacitor converter is controlled to maintain the link voltage at 10 V. The supercapacitors (four 3 V, 60 F devices connected in series) are initially charged to about 8 V (top trace): that is, about 480 J of stored energy. The voltage to the load is maintained at 10 V for about 11 s (trace 2) and the load draws a current of about 2 A during the 11 s period (bottom trace). The energy returned from the supercapacitors during this time is 220 J. The system cannot control the link voltage beyond this point and the remainder of the energy is delivered with a reducing link voltage. With optimization of the system, the load voltage can be maintained at the specified level for longer resulting in a more effective energy storage device. Optimization involves the application of sophisticated control algorithms and reduction in losses in the power converter (38).

SOME APPLICATIONS

Capacitors can potentially be used as primary energy store in applications from portable equipment through low power lighting to meeting the problems of fluctuating energy demand in electrical power systems and electric/hybrid vehicles. The need now is to develop high-voltage versions capable of storing much larger quantities of energy.

For electric/hybrid vehicles, supercapacitors could accept and store high-energy pulses recovered from regenerative braking. Other applications would include pulse power sources for starting an i.c. engine or energization of a coil for the projection of a weapon. Capacitor storage could find application in most of today's electronic devices for storing electrical energy, for example in communications and medical applications.

When supercapacitors are available which are capable of high-voltage operation and peak power density around 500 W/kg to 700 W/kg, they could be used in power systems. The supercapacitors would receive energy from and deliver energy to a three phase ac electric grid network using a power electronic converter. Overall cost efficiency of the system will be the key to future success of capacitor energy storage.

Capacitor Storage in Transport Applications

Capacitors are already extensively used for voltage smoothing and power factor correction purposes. There is now widespread interest in their use as intermediate energy storage devices in a variety of heavy duty applications, including electric and hybrid vehicles. The reason is their superior power density and cycle life relative to their nearest counterpart, the electrochemical battery. The hybrid vehicle provides a good example on an application where such properties are required. In a hybrid vehicle, operating under urban conditions, an energy storage device is required to provide for the rapidly fluctuating power demands made by the vehicle traction system and, in particular, to provide the capacity to absorb large transient levels of regenerated power during braking. Such energy storage devices could be subjected to several charge/discharge cycles per minute, which would render electrochemical batteries unsuitable for this purpose.

A disadvantage of capacitors as energy storage devices is their relatively low-energy density. However, in the intermediate storage applications mentioned here, high-energy density may not be a critical requirement, particularly, as in a hybrid scheme, where it can be combined with a high-energy low-power device, such as a generator set, to give the required ratio between energy and power levels. This ratio, which has the units of time, is a useful parameter in the specification of an energy storage system and is often referred to as the time constant, being the time for which it can deliver its rated power.

In hybrid vehicles, energy storage is required to provide for vehicle acceleration and deceleration, which, in urban conditions, takes place over a period of 5 s to 10 s. This suggests the required time constant and also indicates the unsuitability of electrochemical batteries for this application, which generally have charge times of at least 20 min. The suitability of various types of energy storage for a particular application can be illustrated by a Ragone plot of specific energy (Wh/kg) versus specific power (W/kg). Figure 15 shows such a plot for batteries and supercapacitors on logarithmic scales (29).

Projected onto this plot is a locus corresponding to a time constant T_C of 10 s. The power requirement for a 1 tonne vehicle is estimated to be 50 kW (supplemented by about 25 kW of primary power). In order that the mass of the energy storage should be no more than 10% of the total vehicle mass, the specific power should be at least 500 W/kg for adequate performance. This indicates that most projected ultracapaci-

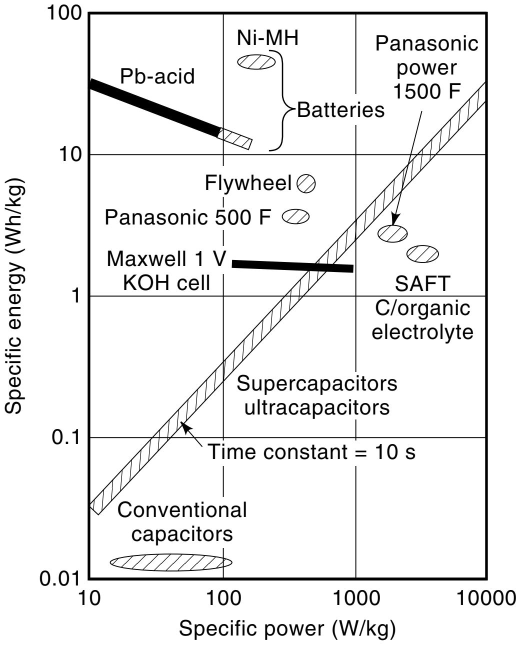


Figure 15. Ragone plot showing comparison of various forms of energy storage.

tors (i.e., in excess of 1000 F) would meet the specific power and energy requirements for hybrid vehicles and could be manufactured to have the required time constant so as to minimize the overall weight. Electrochemical batteries are shown to be lacking the required specific power and this is particularly the case during charging. Battery-based systems, therefore, tend to suffer a weight penalty, which is a disadvantage in mobile applications and can generally increase installation and maintenance costs.

Capacitors as Intermediate Storage

Capacitors compare favorably with other forms of energy storage, as is shown on Fig. 16, where similar data for a variety of forms, including i.c. engine/fuel tank systems, are plotted using linear scales. The line joining two energy sources forms a locus on the plot for a variable combination of the two. As an example, in conventional vehicle design, a fuel tank is combined with an i.c. engine to give a propulsion system with a time constant of about 2 h, representing the time taken to use up the fuel running the vehicle continuously at maximum power. Therefore, by use of a hybrid combination of a primary power supply of high specific energy with an intermediate energy storage system of high specific power (possibly based on the supercapacitor), power supply units can be designed with a specified time constant, in which weight is minimized.

The incorporation of supercapacitors as intermediate energy storage, in combination with a primary power source, could lead to significant weight reductions, improved performance, and reduced maintenance costs in comparison with other forms of electrical energy storage. Only the flywheel/alternator system can provide comparable power density and cycle life. This has the advantage of a higher output voltage capability and that its ac output permits state of the art power conversion methods. This form of energy storage is already finding applications in hybrid bus propulsion systems. Supercapacitors potentially offer the opportunity for weight reduction but considerable development is required to provide controlled power conversion between the relatively low and varying voltages across the capacitors (typically 1.5 V to 3 V per capacitor) and the prime mover, without unacceptable power losses in conversion.

Pulse Power Units

Capacitors are also used for the generation of high-voltage and high-current pulses. In operation these capacitors are under stress of high electromagnetic and electric field strength and therefore need to have the ability to withstand high peak currents and voltages. For this reason they need to possess a high voltage breakdown strength, high dielectric constant, and low dissipation factor.

Controlled current pulse powers are already being used for nuclear and conventional firing sets, weapons, laser excitation, communication radar, welding, and for the actuator of air bags. High-voltage pulses are used in rail guns and particle accelerators. Another application of pulse power is in power engineering, where integrity of equipment such as transformers, switchgears, bushings, and cables which are installed in generation, transmission, or utilization systems are examined. Transient disturbances such as lightning strokes and switching operations are usually followed by a steep fronted travelling wave on the system. For example, if a voltage wave of this type reaches a power transformer, unequal stress distribution could appear along its windings which may lead to break down of the insulation system. The most severe test that equipment used in power engineering will be subjected to during its lifetime results from the superimposition on the system of transient voltages.

There are a number of circuits available for the generation of these pulses. Figure 17 shows the basic circuit of a high voltage pulse unit which primarily consists of two coils, L_2 and L_3, and two capacitors C_1 and C_2, where $C_1 \gg C_2$. The high

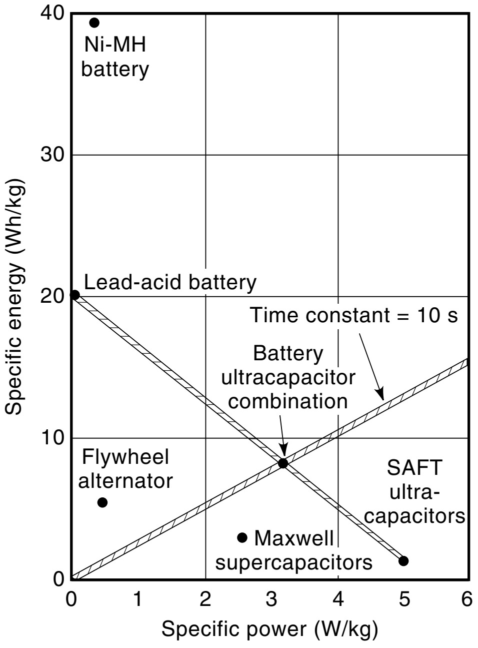


Figure 16. Design of energy storage systems for given time constant.

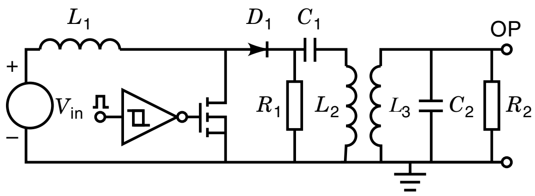


Figure 17. Simple high voltage pulse generator.

voltage side coil has a larger number of turns. The capacitance C_1 is charged from a direct current and the frequency of the pulse is controlled by MOSFET and its associated triggering circuits. The pulse shape in terms of rise, decay, and duration is controlled by R_1 and R_2 as well as the electronic circuitry shown in Fig. 17.

The approximate voltage relationship is given by:

$$V_2/V_1 = \sqrt{\eta}C_1/C_2$$

where V_1 is the maximum voltage to which C_1 is charged, V_2 is the maximum voltage to which C_2 is charged, η is the efficiency of the energy transfer from the low voltage side to the high voltage side of the circuit, and C_1 and C_2 are the capacitances for C_1 and C_2, respectively.

SUMMARY

Capacitor storage is widely used for power conditioning where relatively low levels of energy storage are needed, and in certain applications where high power pulses are required. Electrolytic capacitors are available with capacitance up to the order of 1 F. However, supercapacitors of up to 1500 F are now under development. Once the problem of internal resistance and voltage rating can be overcome, these devices could well become the prime candidate for primary and intermediate energy storage applications in the future.

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CARRIERS, HOT. See HOT CARRIERS.

CARRIER TRANSPORT IN SEMICONDUCTORS. See TRANSPORT IN SEMICONDUCTORS, DYNAMICS OF CARRIERS.

CARRY CIRCUITS. See BiCMOS LOGIC CIRCUITS.