CAPACITIVE STORAGE

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Summary

Capacitors have the ability to store and return electrical energy. The stored energy density is proportional to the square of the field strength and to the permittivity. While there is only one capacitance definition which is the amount of charge per unit voltage for linear capacitors, three different definitions of capacitance are necessary for nonlinear capacitors fed with DC voltages.

Energy storage capacitors can store only small amounts of energy, but due to their very low internal resistance they have the remarkable ability of providing very high discharge efficiency and extremely short discharge time.

They operate at DC voltages which permit the use of high field strength (E) values up to 250...500 V/μm. Their resistance and inductance must be as low as possible. These capacitors have wide application in impulse testing on high voltage (HV) equipment,

plasma research and nuclear fusion, lasers, magnetizing equipment, magnetic metal forming, etc.

The processes of charging and discharging of a capacitor are described by differential equations. The solution as RC or RCL circuits leads to transient currents of exponentially decaying amplitudes.

The peak current and the corresponding rise time are important in practice. If the supply voltage is constant, the energy efficiency of charging as an RC or RCL circuit is only 50%. It is possible to calculate the energies involved by charging in a much simpler manner and to interpret them graphically.As an example of the application of energy storage capacitors the operation of impulse magnetizers is explained briefly.

1. Introduction

A capacitor is a device that can store electric charges and electrostatic energy. In its general form it consists of two conductors separated by an insulator. Practically it has two parallel metal plates located as close as possible and separated by a thin insulator called a dielectric. The Leyden jar made in about 1746 was the earliest capacitor.

It was a thin walled glass vessel whose inside and outside surfaces were coated with a metal film. If a DC voltage is applied between the plates of a capacitor a positive charge $+Q$ appears on the surface of one plate and an equal negative charge $-Q$ appears on the surface of the other plate.

Because electric charges possess potential energy, capacitors can be used to store electrostatic energy. As examples of their wide application as energy storage elements we can cite their use in AC circuits, power electronic circuits, impulse current or voltage generation, pulsed welding equipment, magnetic metal forming, medical shock equipment, pulsed lighting equipment, plasma research and nuclear fusion etc.

As pure storage components they have limited applications because of their relatively small energy density. The applications may be in the steady or more often in the transient state of the capacitors.

2. Linear and Nonlinear Capacitors

The capacitance is the quantity that characterizes a capacitor. It is the measure of the charge of a plate, of the capacitor current, and of the electrostatic energy of the capacitor. We start therefore by clarifying how we define capacitance. For a wide range of applications the circuit components resistors, inductors, and capacitors may be considered to be linear. But there are important cases where these components are nonlinear.

The resistance of semiconductors, the inductance of coils containing iron and the capacitance of capacitors with barium titanate as dielectric are examples of the nonlinear behavior of circuit components.

These components have in the case of linearity, constant values of resistance, inductance, and capacitance, while these values vary as a function of current or voltage in the case of nonlinearity. When defining the capacitance we therefore distinguish between linear and nonlinear capacitors.

While there is only one capacitance definition for linear capacitors, we shall see that for nonlinear capacitors and for DC capacitor voltages, three definitions of capacitance are necessary [1]. We call them basic definitions of capacitance. They are similar to the definitions of inductance and resistance in the nonlinear case [2].

3. Capacitance Definition for Linear Capacitors

In this special, but most important case, the capacitance is the charge of one plate per unit voltage of this plate against the other.

$$C = \frac{Q}{U} ; [C] = \frac{[Q]}{[U]} = \frac{C}{V} = F . \qquad (1)$$

This is an essentially constant quantity depending on the configuration of the capacitor and the nature of the dielectric. For simplicity we considered here the positively charged plate, but the result does not change if the definition is applied to the other plate. The unit of capacitance is the farad, after M. Faraday who introduced the concept of capacitance. This is a derived unit and means one coulomb/volt.

It is a very large unit since a capacitor of 1F accumulates a charge of 1C when a voltage of only 1V is impressed across its terminals. In practice the much smaller units microfarad (μF), nanofarad (nF) and picofarad (pF) are used.

To gain an insight into the parameters of the capacitance let us consider the important case of a parallel-plate capacitor. If we neglect the fringing field at the edges, the field between the plates is completely uniform. Then the voltage U is merely the product of the field strength E and the distance d between the plates. Similarly the charge Q or the electric flux Ψ is the product of the electric flux density D and the area A of each plate.

$$E = \text{const.} ; U = E.d ; \ \Psi = Q = \varepsilon EA = DA . \qquad (2)$$

Using these relationships and the definition of the capacitance we obtain

$$C = \frac{Q}{U} = \frac{\varepsilon EA}{Ed} = \frac{\varepsilon_r \varepsilon_0 A}{d} \ ; \ \varepsilon = \varepsilon_0 \varepsilon_r \ . \qquad (3)$$

Thus the capacitance depends on three variables. It is directly proportional to the relative permittivity ε_r of the dielectric and to the area A of one plate and inversely proportional to the distance d between the plates. The increasing of the area means the increasing of the material quantity.

We see here the advantage of using a small distance and a dielectric of high permittivity. Unfortunately most of usual dielectrics have an ε_r = 2…6. For air ε_r = 1.0006 ≅ 1. But there are also dielectric materials with an ε_r =10^3…10^4. If the permittivity remains constant and independent of the applied voltage, the capacitor is said to be linear; in the reverse case the capacitor is nonlinear.

3.1. Energy Stored in a Linear Capacitor

The usefulness of capacitors in various applications is due to their ability to store and return electrical energy. It is important to know its expression and its variables. Its expression is different for the linear and nonlinear case. In the former case a simple expression may be deduced.

$$W_e = \int_0^Q U dQ = \frac{1}{C}\int_0^Q Q\, dQ = \frac{Q^2}{2C} = \frac{CU^2}{2} = \frac{QU}{2} \qquad (4)$$

It shows the quadratic dependence on the voltage.

Although the above expression of the capacitor energy gives the impression that electric charges are the seat of the stored energy, the electrical work W_e during the charging of a capacitor is indeed stored in the electrostatic field. This field is always the seat of the electrostatic energy, hence also of the capacitor energy. From this point of view we can get a more informative expression of the energy. To this purpose let us take again the simple plate capacitor with constant permittivity and without fringing and replace the equations (2) in the equation (4)

$$W_e = \frac{1}{2} DEA\, d = \frac{1}{2} DE\, V = \frac{\varepsilon E^2}{2} \cdot V \;;\quad V = A \cdot d \qquad (5)$$

$$w_e = \frac{W_e}{V} = \frac{DE}{2} = \frac{\varepsilon E^2}{2} = \frac{D^2}{2\varepsilon}, \qquad (6)$$

where w_e is the density of the electrostatic energy and V is the active volume in which the energy is stored.

The new relationship shows how the density of the stored energy can be increased. There are only two possibilities. First increasing E which may be very efficient as it acts with its square. In practice E is limited by the breakdown of the insulation so that its value must always lie under a permissible value for a given dielectric. The other technical possibility is to use dielectrics with high ε_r. There is no upper limit to this interesting way of obtaining high energy density. We need only to develop adequate dielectrics. Dielectrics like barium titanate with an ε_r value reaching 10^4 are already in use in some special capacitors.

Although the basic relationship (5) has been derived for the special case of the plate capacitor, it can be applied also to the general case of non-homogenous fields with constant permittivity because in a differential volume *dV* the field may be always considered as homogeneous. Hence the energy density w_e and the electrostatic energy W_e may be calculated according to the general expressions

$$dW_e = \frac{dQ.dU}{2} = \frac{D\,dA \cdot Eds}{2} = \frac{DE}{2}dV\,;\; w_e = \frac{dW_e}{dV} = \frac{DE}{2} = \frac{\varepsilon E^2}{2} = \frac{D^2}{2\varepsilon}; \quad (7)$$

$$W_e = \int_V w_e\, dV = \frac{1}{2}\int_V DE\, dV\,. \quad (8)$$

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Biographical Sketch

Ilhami Cetin received his B.S. and M.S. degrees from Electrical Engineering Department in Karlsruhe Technical University in Germany in 1957. He worked as an electrical engineer in Germany, Switzerland and United Kingdom. He also worked as a chief in High Voltage Laboratory of Condensateurs-Fribourg and as development engineer in, which is now known as, Zurich-Oerlikon Factory of ABB. He returned to Turkey in 1965 and between years 1965-1971 he worked as an instructor in Engineering Schools. In 1971, he became an Associate Professor in Istanbul Technical University and started working in this university in 1972. In 1978, he became a Professor and worked until he retired in 1998.