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16-2: Charging and Discharging a Capacitor
16-3: The Farad Unit of Capacitance
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Topics Covered in Chapter 16

- 16-7: Parallel Capacitances
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- 16-9: Energy Stored in Electrostatic Field of Capacitance
- 16-10: Measuring and Testing Capacitors
- 16-11: Troubles in Capacitors
A capacitor consists of two conductors separated by a dielectric (insulator).

Capacitors store energy in the electric field.

Storage means the charge remains after the voltage source is disconnected.

The measure of how much charge is stored is the capacitance \( C \).

Components made to provide a specified amount of capacitance are called capacitors, or by their old name condensers.
16-1: How Charge Is Stored in the Dielectric

- Applying a voltage to a discharged capacitor causes a current to charge the capacitor.

- Connecting a path across the terminals of a charged capacitor causes current to flow which discharges the capacitor.

- A capacitor concentrates the electric field in the dielectric between the plates.
Charging continues until potential difference = applied voltage.

Electrons that accumulate on the negative side of the capacitor provide electric lines of force that repel electrons from the opposite side.

Fig. 16-1: Capacitance stores the charge in the dielectric between two conductors. (a) Structure.
The two main effects of a capacitor are charging and discharging.

Accumulation of charge results in a buildup of potential difference across the capacitor plates.

Closing the switch allows the negative battery terminal to repel free electrons in the conductor to plate A. The positive terminal attracts free electrons from plate B.

Charging continues until the capacitor voltage equals the applied voltage.
16-2: Charging and Discharging a Capacitor

- The effect of electric lines of force through the dielectric that results in storage of the charge.
- The electric field distorts the molecular structure so that the dielectric is no longer neutral.
- The dielectric can be ruptured by a very intense field with high voltage across the capacitor.

Fig. 16-2: (c) Stored charge remains in capacitor, providing 10 V without the battery.
16-2: Charging and Discharging a Capacitor

- The capacitor discharges when a conducting path is provided across the plates, without any applied voltage.
- Here, the wire between plates A and B provides a low-resistance path for discharge current.
- The stored charge in the dielectric provides the potential difference.
- When the positive and negative charges are neutralized, the capacitor is discharged and the voltage across it is zero.

Fig. 16-2 (d) Discharging the capacitor.

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The capacitor can store an amount of charge necessary to provide a potential difference equal to the charging voltage.

Any charge or discharge current flows through conducting wires to the plates but not through the dielectric.

Charge and discharge currents must be in opposite directions.

More charge and discharge current result in a higher value of $C$ for a given amount of voltage. The value of $C$ does not change with the voltage; it depends on the physical construction of the capacitor.
16-3: The Farad Unit of Capacitance

- The **farad (F)** is the basic unit of capacitance.

- One farad of capacitance equals one coulomb of charge stored in the dielectric with one volt applied.

- Most capacitors have values less than 1 F:
  - 1 µF (microfarad) = 1 × 10^{-6} F
  - 1 nF (nanofarad) = 1 × 10^{-9} F
  - 1 pF (picofarad) = 1 × 10^{-12} F
The amount of charge $Q$ stored in the capacitance is proportional to applied voltage. The relationship is summarized in the formulas:

- Charge on a capacitor, in coulombs: $Q = CV$
- Energy stored in a capacitor in joules: $\varepsilon = \frac{1}{2}CV^2$

Where:
- $Q =$ electrical charge in coulombs
- $C =$ capacitance in farads
- $V =$ voltage in volts
- $\varepsilon =$ energy in joules
Characteristics of Capacitors: Three Ways to Increase Capacitance

- A larger capacitor stores more charge for the same voltage.
- A larger plate area increases the capacitance:
  - More of the dielectric surface can contact each plate, allowing more lines of force between the plates and less flux leakage.
- A thinner dielectric increases capacitance.
  - When the plate distance is reduced, the electric field has greater flux density so the capacitance stores more charge.
Characteristics of Capacitors:

- **The dielectric constant** $K_\varepsilon$ indicates an insulator’s **relative permittivity**, or the ability of an insulator to concentrate electric flux.

- Its value is the ratio of flux in the insulator compared with the flux in air or vacuum.

- **Dielectric strength** is the ability of a dielectric to withstand a potential difference without arcing across the insulator.
  - This voltage rating is important because if the insulator ruptures, it provides a conducing path through the dielectric.
### 16-3: The Farad Unit of Capacitance

- **Dielectric Constant** $K_\varepsilon$

  \[ C = K_\varepsilon \frac{A}{d} \times 8.85 \times 10^{-12} \text{ F} \]

- The value of a capacitor is:
  - Proportional to plate area (A) in meters.
  - Inversely proportional to the spacing (d) between the plates in meters.
  - Proportional to the dielectric constant ($K_\varepsilon$) of the material between the plates.
### 16-3: The Farad Unit of Capacitance

**Dielectric Constant $K_\varepsilon$**

<table>
<thead>
<tr>
<th>Material</th>
<th>$K_\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air or vacuum</td>
<td>1</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>7</td>
</tr>
<tr>
<td>Ceramic</td>
<td>80 – 1200</td>
</tr>
<tr>
<td>Glass</td>
<td>8</td>
</tr>
<tr>
<td>Mica</td>
<td>3 – 8</td>
</tr>
<tr>
<td>Oil</td>
<td>2 – 5</td>
</tr>
<tr>
<td>Paper</td>
<td>2 – 6</td>
</tr>
<tr>
<td>Plastic</td>
<td>2 – 3</td>
</tr>
<tr>
<td>Tantalum oxide</td>
<td>25</td>
</tr>
</tbody>
</table>
16-4: Typical Capacitors

- Capacitors are classified by dielectric.
  - air, mica, paper, plastic film, ceramic, electrolytic.
- They can be connected to a circuit without regard to polarity (except for electrolytic capacitors).
- The polarity of the charging source determines the polarity of the capacitor voltage.
- Capacitors block dc voltages and pass ac signal voltages.
Types of Capacitors:

- **Mica**: Typically used for small capacitance values of 10 to 5000 pF.
- **Paper**: Typically used for medium capacitance values of 0.001 to 1.0 µF.
- **Film**: Very temperature-stable. Frequently used in circuits where this characteristic is a necessity, such as radio frequency oscillators and timer circuits.
16-4: Typical Capacitors

- Types of Capacitors:
  - **Ceramic**: Available in a wide range of values because $K_\varepsilon$ can be tailored to provide almost any desired value of capacitance. Often used for temperature compensation (to increase or decrease capacitance with a rise in temperature).
  - **Surface-mount**: Also called **chip capacitors**. Like chip resistors, chip capacitors have their end electrodes soldered directly to the copper traces of the printed-circuit board.
16-4: Typical Capacitors

- Types of Capacitors:
  - **Variable capacitors:****
    - Fixed metal plates form the **stator**.
    - Movable plates on the shaft form the **rotor**.
    - Air is the dielectric.
    - Capacitance is varied by rotating the shaft to make the rotor plates mesh with the stator plates.
    - Common applications include the tuning capacitor in radio receivers.

Fig. 16-1(b): Air-dielectric variable capacitor. Length is 2 in.
16-4: Typical Capacitors

- Voltage Rating of Capacitors
  - The **voltage rating** of capacitors specifies the maximum potential difference of dc voltage that can be applied without puncturing the dielectric.
  - The potential difference across the capacitor depends upon the applied voltage. It is not necessarily equal to the voltage rating.
  - A voltage rating higher than the potential difference applied provides a safety factor for long life in service.
  - The breakdown rating is lower for ac voltage because of the internal heat produced by continuous charge and discharge.
16-5: Electrolytic Capacitors

- Electrolytics provide the most capacitance in the smallest space with the least cost.
- Electrolytics have a very thin dielectric film, which allows it to obtain very large $C$ values.

Fig. 16-9: Construction of aluminum electrolytic capacitor. (a) Internal electrodes. (b) Foil rolled into cartridge.
16-5: Electrolytic Capacitors

- **Polarity**
  - Electrolytics are used in circuits that have a combination of dc and ac voltage. The dc voltage maintains the required polarity across the electrolytic capacitor to form the oxide film.
  - **If the electrolytic is connected in opposite polarity, the reversed electrolysis forms gas in the capacitor. It becomes hot and may explode.**
    - This phenomenon only occurs with electrolytic capacitors.
16-5: Electrolytic Capacitors

- Leakage Current
  - A disadvantage of electrolytics is their relatively high leakage current, caused by the fact that the oxide film is not a perfect insulator.

- Tantalum Capacitors
  - This type of electrolytic capacitor features:
    - Larger $C$ in a smaller size.
    - Longer shelf life
    - Less leakage current than other electrolytics.
    - Higher cost than aluminum-type electrolytics.
The value of a capacitor is always given in either microfarads or picofarads. 

- If a capacitor (other than an electrolytic one) is marked using a whole number then C is in picofarads
- If a capacitor is marked using a decimal fraction then C is in microfarads

- The coding depends on the type of capacitor and its manufacturer.
16-6: Capacitor Coding

- Film-Type Capacitors

Fig. 16-11: Film capacitor coding system.

<table>
<thead>
<tr>
<th>Multiplier</th>
<th>Tolerance of Capacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>For the Number</td>
<td>Multiplier</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>1,000</td>
</tr>
<tr>
<td>4</td>
<td>10,000</td>
</tr>
<tr>
<td>5</td>
<td>100,000</td>
</tr>
<tr>
<td>8</td>
<td>0.01</td>
</tr>
<tr>
<td>9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Examples:
152K = 15 × 100 = 1500 pF or 0.0015 μF, ±10%
759J = 75 × 0.1 = 7.5 pF, ±5%

Note: The letter R may be used at times to signify a decimal point, as in 2R2 = 2.2 (pF or μF).
Ceramic Disk Capacitors

Fig. 16-13: Ceramic disk capacitor coding system.

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Mica Capacitors

Fig. 16-16: Three different coding systems used with mica capacitors.
Chip Capacitors

- Make sure it is a capacitor and not a resistor.
- Capacitors feature:
  - A solid-color body.
  - End electrodes completely enclose the end of the part.

- There are three popular coding systems for chip capacitors. All systems represent values in picofarads. Examples of the systems follow on the next slides.
This system uses a **two-place** coding in which a letter indicates the first and second digits of the capacitance value and a number indicates the multiplier.

### Fig. 16-17: Chip capacitor coding system.
Alternate Two-Place Code
• Values below 100 pF—Value read directly

05 = 5 pF
82 = 82 pF

• Values 100 pF and above—Letter/number code

A1 = 10 × 10 = 100 pF
N3 = 33 × 1000 = 33000 pF = 0.033 μF

Multiplier (1–9)
Value (1st and 2nd significant digits)

<table>
<thead>
<tr>
<th>Value (24 Value Symbols)—Uppercase Letters Only</th>
<th>Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-10 F-16 L-27 R-43 W-68</td>
<td>1 = × 10</td>
</tr>
<tr>
<td>B-11 G-18 M-30 S-47 X-75</td>
<td>2 = × 100</td>
</tr>
<tr>
<td>C-12 H-20 N-33 T-51 Y-82</td>
<td>3 = × 1000</td>
</tr>
<tr>
<td>D-13 J-22 P-36 U-56 Z-91</td>
<td>4 = × 10,000</td>
</tr>
<tr>
<td>E-15 K-24 Q-39 V-62</td>
<td>5 = × 100,000 etc.</td>
</tr>
</tbody>
</table>

Fig. 16-18: Chip capacitor coding system.

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16-6: Capacitor Coding

Fig. 16-19: Chip capacitor coding system.

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### Tantalum Capacitors

<table>
<thead>
<tr>
<th>Color</th>
<th>Rated Voltage</th>
<th>Capacitance in Picofarads</th>
<th>Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Brown</td>
<td>6</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Red</td>
<td>10</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Orange</td>
<td>15</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Yellow</td>
<td>20</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Green</td>
<td>25</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Blue</td>
<td>35</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Violet</td>
<td>50</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Gray</td>
<td>—</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>White</td>
<td>3</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

**Fig. 16-20: Tantalum capacitor coding system.**

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Connecting capacitances in parallel is equivalent to increasing plate area.

Total $C$ is the sum of individual $C$s:

$$C_T = C_1 + C_2 + \ldots \text{ etc.}$$

Voltage is the same across parallel capacitors.
Connecting capacitances in series is equivalent to increasing the thickness of the dielectric. Total $C$ is less than the smallest individual value.

$$C_{EQ} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots \text{ etc.}}$$
Capacitors are used in series to provide higher working voltage rating for the combination (e.g., each of 3 equal Cs in series has 1/3 the applied voltage).

Voltage across each C is inversely proportional to its C. A smaller C has a larger proportion of applied voltage.

- All have the same charge because they’re in one current path. With equal charge, the smaller C has the greater potential difference.

- Charging current is the same in all parts of the series path.
The electrostatic field of the charge stored in the dielectric has electric energy supplied by the voltage source that charges $C$.

Energy = $\varepsilon = \frac{1}{2} CV^2$ (joules)
- $C =$ capacitance (farads)
- $V =$ voltage across the capacitor
- $\varepsilon =$ electric energy (joules)

Stored energy is the reason why a charged capacitor can produce electric shock even when it is not connected into a circuit.
A capacitance meter is a piece of test equipment specifically designed to measure the capacitance value of capacitors.

For nonelectrolytic capacitors, lead polarity does not matter.

Discharge the capacitor before applying the meter.

It is important to know conversions from nanofarads to micro- or picofarads because meters do not measure nanofarads.
Leakage Resistance of a Capacitor

- **Leakage resistance** is a resistance in parallel with a capacitor that represents all leakage paths through which a capacitor can discharge.

- There are three leakage paths of possible discharge:
  - Through the dielectric.
  - Across the insulated case or body between the capacitor leads.
  - Through the air surrounding the capacitor.
Leakage Resistance of a Capacitor

- As a general rule, the larger the capacitor, the lower its leakage resistance.

- Leakage current is temperature-sensitive. The higher the temperature, the greater the leakage (because of lower leakage resistance).
Dielectric absorption is the ability of a capacitor to completely discharge to zero. It is sometimes referred to as battery action or capacitor memory.

Dielectric absorption is due to the dielectric of the capacitor retaining a charge after supposedly discharged.

The effect of dielectric absorption is that it reduces the capacitance value of the capacitor.

All capacitors have at least some dielectric absorption.

Dielectric absorption can be checked using a capacitor-inductor analyzer.
Equivalent Series Resistance (ESR)
- Dielectrics cannot instantaneously follow the cycle of continuous charge, discharge, and reverse charging that an applied ac voltage causes.
- If the ac voltage is of high frequency, there may be a difference in the applied voltage and the actual voltage in the dielectric.
- Loss is the result of hysteresis in the dielectric.
- Losses increase with frequency.
Equivalent Series Resistance (ESR)

- Losses can be represented as a resistor in series or parallel with an ideal capacitor.
- Resistances can be lumped into one ESR; this is an accurate and convenient way to represent all losses of a capacitor.
- ESR is most often a problem in capacitors used in high-frequency filtering operations, e.g., computer power supplies.
16-10: Measuring and Testing Capacitors

Fig. 16-28: Resistances representing losses in a capacitor. (a) Series and parallel resistance represents capacitor losses. (b) Equivalent series resistance (ESR) represents the total losses in a capacitor.
Open- or short-circuited capacitors are useless because they cannot store charge.

Leaky capacitor is equivalent to a partial short circuit: it loses its insulating properties gradually, lowering its resistance.

Except for electrolytics, capacitors do not deteriorate with age while stored, since there is no applied voltage.

All capacitors can change value over time, but some are more prone to change than others. Ceramic capacitors often change value by 10 to 15% during the first year.
16-11: Troubles in Capacitors

- Checking Capacitors with an Ohmmeter
  - The highest ohm range, such as R x 1 MΩ is preferable.
  - Disconnect one side of the capacitor from the circuit to eliminate any parallel resistance paths that can lower the resistance.
  - Keep fingers off the connection, since body resistance lowers the reading.
Checking Capacitors with an Ohmmeter (Continued)

- For a good capacitor, the meter pointer moves quickly toward the low-resistance side of the scale and then slowly recedes toward infinity.
- When the pointer stops moving, the reading is the dielectric resistance of the capacitor which is normally very high.
- Electrolytic capacitors will usually measure a much lower resistance of about 500 kΩ to 10 MΩ.

**NOTE:** In all cases, discharge the capacitor before checking with the ohmmeter.
Checking Capacitors with an Ohmmeter (Continued)

- When the ohmmeter is initially connected, its battery charges the capacitor.
- This charging current is the reason the meter pointer moves away from infinity.
- Maximum current flows at the first instant of charge. Then the charging current decreases as the capacitor voltage increases toward the applied voltage; therefore, the needle pointer slowly moves toward infinite resistance.