6.S: Direct-Current Circuits (Summary)

Key Terms

ammeter	instrument that measures current
electromotive force (emf)	energy produced per unit charge, drawn from a source that produces an electrical current
equivalent resistance	resistance of a combination of resistors; it can be thought of as the resistance of a single resistor that can replace a combination of resistors in a series and/or parallel circuit
internal resistance	amount of resistance to the flow of current within the voltage source
junction rule	sum of all currents entering a junction must equal the sum of all currents leaving the junction
Kirchhoff's rules	set of two rules governing current and changes in potential in an electric circuit
loop rule	algebraic sum of changes in potential around any closed circuit path (loop) must be zero
potential difference	difference in electric potential between two points in an electric circuit, measured in volts
potential drop	loss of electric potential energy as a current travels across a resistor, wire, or other component
RC circuit	circuit that contains both a resistor and a capacitor
shock hazard	hazard in which an electric current passes through a person
terminal voltage	potential difference measured across the terminals of a source when there is no load attached
thermal hazard	hazard in which an excessive electric current causes undesired thermal effects
three-wire system	wiring system used at present for safety reasons, with live, neutral, and ground wires
voltmeter	instrument that measures voltage

Key Equations

Terminal voltage of a single voltage source	$V_{terminal} = \varepsilon - Ir_{eq}$
Equivalent resistance of a series circuit	$R_{eq} = R_1 + R_2 + R_3 + \cdots + R_{N-1} + R_N = \sum_{i=1}^{N} R_i$
Equivalent resistance of a parallel circuit	$R_{eq} = (\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N})^{-1} = (\sum_{i=1}^{N} \frac{1}{R_i})^{-1}$
Junction rule	$\sum I_{in} = \sum I_{out}$
Loop rule	$\sum V = 0$
Terminal voltage of N voltage sources in series	$V_{terminal} = \sum_{i=1}^{N} \varepsilon_i - I \sum_{i=1}^{N} r_i = \sum_{i=1}^{N} \varepsilon_i - Ir_{eq}$
Terminal voltage of N voltage sources in parallel	$V_{terminal} = \varepsilon - I \sum_{i=1}^{N} (\frac{1}{r_i})^{-1} = \varepsilon - Ir_{eq}$
Charge on a charging capacitor	$q(t) = C\varepsilon(1 - e^{-\frac{t}{RC}}) = Q(1 - e^{-\frac{t}{\tau}})$
Time constant	$\tau = RC$

Current during charging of a capacitor	$I = \frac{\varepsilon}{R} e^{-\frac{t}{RC}} = I_o e^{-\frac{t}{RC}}$
Charge on a discharging capacitor	$q(t) = Qe^{-\frac{t}{\tau}}$
Current during discharging of a capacitor	$I(t) = -\frac{Q}{RC} e^{-\frac{t}{\tau}}$

Summary

10.2 Electromotive Force

- All voltage sources have two fundamental parts: a source of electrical energy that has a characteristic electromotive force (emf), and an internal resistance r. The emf is the work done per charge to keep the potential difference of a source constant. The emf is equal to the potential difference across the terminals when no current is flowing. The internal resistance **r** of a voltage source affects the output voltage when a current flows.
- The voltage output of a device is called its terminal voltage $V_{terminal}$ and is given by $V_{terminal} = \varepsilon - Ir$, where I is the electric current and is positive when flowing away from the positive terminal of the voltage source and r is the internal resistance.

10.3 Resistors in Series and Parallel

- The equivalent resistance of an electrical circuit with resistors wired in a series is the sum of the individual resistances:

$$R_s = R_1 + R_2 + R_3 + \cdots = \sum_{i=1}^{N} R_i \quad .$$

- Each resistor in a series circuit has the same amount of current flowing through it.
- The potential drop, or power dissipation, across each individual resistor in a series is different, and their combined total is the power source input.
- The equivalent resistance of an electrical circuit with resistors wired in parallel is less than the lowest resistance of any of the components and can be determined using the formula

$$R_{eq} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots\right)^{-1} = \left(\sum_{i=1}^{N} \frac{1}{R_i}\right)^{-1} \quad .$$

- Each resistor in a parallel circuit has the same full voltage of the source applied to it.
- The current flowing through each resistor in a parallel circuit is different, depending on the resistance.
- If a more complex connection of resistors is a combination of series and parallel, it can be reduced to a single equivalent resistance by identifying its various parts as series or parallel, reducing each to its equivalent, and continuing until a single resistance is eventually reached.

10.4 Kirchhoff's Rules

- Kirchhoff’s rules can be used to analyze any circuit, simple or complex. The simpler series and parallel connection rules are special cases of Kirchhoff’s rules.
- Kirchhoff’s first rule, also known as the junction rule, applies to the charge to a junction. Current is the flow of charge; thus, whatever charge flows into the junction must flow out.
- Kirchhoff’s second rule, also known as the loop rule, states that the voltage drop around a loop is zero.
- When calculating potential and current using Kirchhoff’s rules, a set of conventions must be followed for determining the correct signs of various terms.
- When multiple voltage sources are in series, their internal resistances add together and their emfs add together to get the total values.
- When multiple voltage sources are in parallel, their internal resistances combine to an equivalent resistance that is less than the individual resistance and provides a higher current than a single cell.
- Solar cells can be wired in series or parallel to provide increased voltage or current, respectively.

10.5 Electrical Measuring Instruments

- Voltmeters measure voltage, and ammeters measure current. Analog meters are based on the combination of a resistor and a galvanometer, a device that gives an analog reading of current or voltage. Digital meters are based on analog-to-digital converters and provide a discrete or digital measurement of the current or voltage.
- A voltmeter is placed in parallel with the voltage source to receive full voltage and must have a large resistance to limit its effect on the circuit.

- An ammeter is placed in series to get the full current flowing through a branch and must have a small resistance to limit its effect on the circuit.
- Standard voltmeters and ammeters alter the circuit they are connected to and are thus limited in accuracy.
- Ohmmeters are used to measure resistance. The component in which the resistance is to be measured should be isolated (removed) from the circuit.

10.6 RC Circuits

- An **RC** circuit is one that has both a resistor and a capacitor.
- The time constant τ for an **RC** circuit is $\tau = RC$.
- When an initially uncharged ($q = 0$ at $t = 0$) capacitor in series with a resistor is charged by a dc voltage source, the capacitor asymptotically approaches the maximum charge.
- As the charge on the capacitor increases, the current exponentially decreases from the initial current: $I_0 = \varepsilon/R$.
- If a capacitor with an initial charge **Q** is discharged through a resistor starting at $t = 0$, then its charge decreases exponentially. The current flows in the opposite direction, compared to when it charges, and the magnitude of the charge decreases with time.

10.7 Household Wiring and Electrical Safety

- The two types of electric hazards are thermal (excessive power) and shock (current through a person). Electrical safety systems and devices are employed to prevent thermal and shock hazards.
- Shock severity is determined by current, path, duration, and ac frequency.
- Circuit breakers and fuses interrupt excessive currents to prevent thermal hazards.
- The three-wire system guards against thermal and shock hazards, utilizing live/hot, neutral, and ground wires, and grounding the neutral wire and case of the appliance.
- A ground fault circuit interrupter (GFCI) prevents shock by detecting the loss of current to unintentional paths.

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