
Module 1: Foundations of DC Circuits

Module Description:

This module lays the groundwork for understanding electrical circuits by introducing fundamental concepts, basic circuit elements, and essential analysis techniques for direct current (DC) systems. By the end of this module, you'll have a solid understanding of how DC circuits behave and the tools to analyze them effectively.

Learning Objectives:

Upon successful completion of this module, you will be able to:

- **Define and differentiate between voltage, current, power, and energy.**
- **Identify and understand the function of resistors, inductors, and capacitors in DC circuits.**
- **Apply Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) to solve simple DC circuits.**
- **Utilize superposition, Thevenin's, and Norton's theorems for circuit simplification and analysis.**
- **Analyze the time-domain response of first-order RL and RC circuits under DC excitation, including calculating the time constant.**

Topics:

1. Introduction to Electrical Quantities

Electricity, at its core, is about the movement of charge. Understanding the fundamental quantities associated with this movement is crucial.

- **Charge (Q): The fundamental property of matter that experiences a force when placed in an electromagnetic field. The SI unit for charge is the Coulomb (C). One electron has a charge of approximately $-1.602\times10-19$ C.**
- **Current (I): The rate of flow of electric charge. It's the amount of charge passing through a point in a circuit per unit of time. The SI unit for current is the Ampere (A), which is defined as one Coulomb per second.**
  - **Formula: $I=dtdQ$**
  - **For constant current over time, $I=\Delta t\Delta Q$**
  - **Numerical Example: If 10 Coulombs of charge pass through a wire in 2 seconds, the current is $I=2$ s10 C=5 A.**
- **Voltage (V) (or Potential Difference): The electrical potential energy difference per unit charge between two points in a circuit. It represents the "push" or "pressure" that drives current. The SI unit for voltage is the Volt (V), which is defined as one Joule per Coulomb.**
  - **Formula: $V=dQdW$ (where W is energy)**
  - **For constant voltage, $V=\Delta Q\Delta W$**

    - Numerical Example: If 60 Joules of energy are required to move 5 Coulombs of charge between two points, the voltage is V=5 C60 J=12 V.
- Power (P): The rate at which energy is transferred or dissipated in a circuit. The SI unit for power is the Watt (W), which is defined as one Joule per second.
    - Formulas:
        - P=dtdW
        - P=V×I (This is a fundamental relationship: Power equals Voltage times Current)
        - Using Ohm's Law (discussed next), we can derive: P=I2R and P=RV2
    - Numerical Example: A light bulb operating at 120 V draws 0.5 A of current. The power consumed by the bulb is P=120 V×0.5 A=60 W.
- Energy (W): The capacity to do work. In electrical circuits, energy is consumed or stored. The SI unit for energy is the Joule (J). Energy is power multiplied by time.
    - Formula: W=P×t
    - Numerical Example: If a device consumes 60 W of power for 2 hours (7200 seconds), the energy consumed is W=60 W×7200 s=432,000 J or 432 kJ.

2. Circuit Elements

Circuit elements are the building blocks of electrical circuits.

- Resistors: Passive components that oppose the flow of electric current. This opposition is called resistance (R). The SI unit for resistance is the Ohm (Ω). Resistors convert electrical energy into heat.
    - Ohm's Law: The foundational law relating voltage, current, and resistance in a linear circuit element. It states that the voltage across a resistor is directly proportional to the current flowing through it.
        - Formula: V=I×R
        - This can be rearranged to find current: I=RV or resistance: R=IV.
    - Series Resistors: When resistors are connected end-to-end, they are in series. The total resistance is the sum of individual resistances.
        - Formula: Rtotal=R1+R2+R3+...+Rn
        - Numerical Example: Three resistors of 10Ω, 20Ω, and 30Ω are in series. Rtotal=10+20+30=60Ω.
    - Parallel Resistors: When resistors are connected across the same two points, they are in parallel. The reciprocal of the total resistance is the sum of the reciprocals of individual resistances.
        - Formula: Rtotal1=R11+R21+R31+...+Rn1
        - For two parallel resistors: Rtotal=R1+R2R1×R2
        - Numerical Example: Two resistors of 10Ω and 20Ω are in parallel. Rtotal=10+2010×20=30200=6.67Ω.
- Inductors: Passive components that store energy in a magnetic field when current flows through them. This property is called inductance (L). The SI unit for inductance is the Henry (H). In DC steady-state, an ideal inductor acts as a

short circuit (zero resistance) because the current is constant and there is no change in the magnetic field to induce a voltage.

  - Energy Storage Formula: WL=21LI2
  - Numerical Example: An inductor of 5 H has 2 A of current flowing through it. Energy stored = 21×5 H×(2 A)2=0.5×5×4=10 J.

- Capacitors: Passive components that store energy in an electric field by accumulating electric charge. This property is called capacitance (C). The SI unit for capacitance is the Farad (F). In DC steady-state, an ideal capacitor acts as an open circuit (infinite resistance) because it becomes fully charged and no more current flows through it.
  - Charge Storage Formula: Q=C×V
  - Energy Storage Formula: WC=21CV2
  - Numerical Example: A capacitor of 100μF is charged to 12 V. Energy stored = 21×100×10−6 F×(12 V)2=0.5×100×10−6×144=0.0072 J or 7.2 mJ.

3. Ideal Sources

Sources provide the energy to drive circuits.

- Independent Voltage Source: Maintains a specified voltage across its terminals, regardless of the current flowing through it. The voltage is independent of other circuit variables. Represented by a circle with a "+" and "-" sign or an arrow indicating polarity.
- Independent Current Source: Maintains a specified current through its terminals, regardless of the voltage across it. The current is independent of other circuit variables. Represented by a circle with an arrow indicating the direction of current.
- Dependent Sources (Brief Introduction): These sources provide a voltage or current whose value depends on another voltage or current elsewhere in the circuit. There are four types:
  - Voltage-Controlled Voltage Source (VCVS)
  - Current-Controlled Voltage Source (CCVS)
  - Voltage-Controlled Current Source (VCCS)
  - Current-Controlled Current Source (CCCS)
    They are represented by a diamond shape. While not deeply explored in this DC fundamentals module, it's important to recognize their existence as they are common in amplifier and transistor circuit analysis.

4. Kirchhoff's Laws

Kirchhoff's Laws are fundamental for analyzing complex circuits.

- Kirchhoff's Current Law (KCL): States that the algebraic sum of currents entering a node (or junction) in an electrical circuit is equal to zero, or equivalently, the total current entering a node is equal to the total current leaving the node. This is based on the principle of conservation of charge.
  - Concept: What goes in must come out.
  - Formula: ∑Iin=∑Iout or ∑I=0 (at a node)

- **Numerical Example: If 3 A and 5 A enter a node, and 2 A leaves, then 3 A+5 A=2 A+Iunknown. Therefore, Iunknown=6 A leaving the node.**

- **Kirchhoff's Voltage Law (KVL): States that the algebraic sum of all voltages around any closed loop in a circuit is equal to zero. This is based on the principle of conservation of energy.**
  - **Concept: As you trace a path around a closed loop, the total voltage rise must equal the total voltage drop.**
  - **Formula: $\sum V=0$ (around a closed loop)**
  - **Numerical Example: In a series circuit with a 12 V battery and two resistors, R1 and R2, with voltage drops V1 and V2. By KVL, 12 V−V1−V2=0. If V1=4 V, then V2=12 V−4 V=8 V.**

5. Circuit Analysis Techniques

These techniques provide systematic ways to solve for unknown currents and voltages in circuits.

- **Series and Parallel Circuit Analysis:**
  - **Series Circuits:**
    1. **Current is the same through all components.**
    2. **Voltages add up across components to the total source voltage (KVL).**
    3. **Resistances add up to total resistance.**
  - **Parallel Circuits:**
    1. **Voltage is the same across all parallel components.**
    2. **Current divides among parallel branches (KCL).**
    3. **Reciprocals of resistances add up for total parallel resistance.**
- **Voltage Divider Rule (VDR): Used to find the voltage across a specific resistor in a series circuit.**
  - **Formula: Vx=Vtotal×RtotalRx (where Vx is the voltage across Rx, and Rtotal is the sum of resistances in the series circuit).**
  - **Numerical Example: A 24 V source is connected to two series resistors, R1=100Ω and R2=200Ω. Voltage across R2: V2=24 V×100Ω+200Ω200Ω=24 V×300200=16 V.**
- **Current Divider Rule (CDR): Used to find the current through a specific resistor in a parallel circuit with two branches.**
  - **Formula (for two resistors):**
    1. **I1=Itotal×R1+R2R2 (current through R1)**
    2. **I2=Itotal×R1+R2R1 (current through R2)**
  - **Numerical Example: A total current of 6 A enters a parallel combination of two resistors, R1=3Ω and R2=6Ω. Current through R1: I1=6 A×3Ω+6Ω6Ω=6 A×96=4 A.**
- **Nodal Analysis (Introduction): A systematic method for solving circuits by applying KCL at each non-reference node and solving the resulting simultaneous equations for the node voltages. A node is a point where two or more circuit elements connect. One node is chosen as the reference node (ground, usually 0 V).**
  - **Steps:**

1. **Identify all nodes in the circuit.**
2. **Choose a reference node (ground).**
3. **Assign node voltages to the remaining non-reference nodes.**
4. **Apply KCL at each non-reference node, expressing currents in terms of node voltages and resistances using Ohm's Law (I=V/R).**
5. **Solve the system of linear equations for the unknown node voltages.**

- **Mesh Analysis (Introduction): A systematic method for solving circuits by applying KVL around each independent mesh (loop) and solving the resulting simultaneous equations for the mesh currents. A mesh is a loop that does not contain any other loops within it.**
  - **Steps:**
    1. **Identify independent meshes (loops) in the circuit.**
    2. **Assign a circulating mesh current to each independent mesh.**
    3. **Apply KVL around each mesh, expressing voltage drops in terms of mesh currents and resistances using Ohm's Law.**
    4. **Solve the system of linear equations for the unknown mesh currents.**

6. Circuit Theorems

These theorems simplify circuit analysis by reducing complex circuits into simpler equivalent forms.

- **Superposition Theorem: States that in any linear circuit containing multiple independent sources, the current or voltage at any point is the algebraic sum of the currents or voltages produced by each independent source acting alone, with all other independent sources turned off (voltage sources replaced by short circuits, current sources by open circuits). Dependent sources are never turned off.**
  - **Steps:**
    1. **Consider one independent source at a time.**
    2. **Turn off all other independent sources (voltage sources become short circuits, current sources become open circuits).**
    3. **Calculate the desired current/voltage due to that single active source.**
    4. **Repeat for all independent sources.**
    5. **Algebraically sum the results from each step to find the total current/voltage.**
- **Thevenin's Theorem: States that any linear two-terminal circuit containing independent and/or dependent sources can be replaced by an equivalent circuit consisting of a single voltage source, VTh, in series with a single resistor, RTh.**
  - **VTh (Thevenin Voltage): The open-circuit voltage across the two terminals of the original circuit.**
  - **RTh (Thevenin Resistance): The equivalent resistance looking back into the two terminals with all independent sources turned off (voltage**

sources shorted, current sources opened). If dependent sources are present, a test voltage (Vtest) or current (Itest) is applied, and RTh=Vtest/Itest (or RTh=Voc/Isc where Voc is open-circuit voltage and Isc is short-circuit current).
    - Applications: Simplifies analysis of circuits connected to varying loads.
- Norton's Theorem: States that any linear two-terminal circuit containing independent and/or dependent sources can be replaced by an equivalent circuit consisting of a single current source, IN, in parallel with a single resistor, RN.
    - IN (Norton Current): The short-circuit current flowing between the two terminals of the original circuit.
    - RN (Norton Resistance): The equivalent resistance looking back into the two terminals with all independent sources turned off (same as RTh, so RN=RTh).
    - Relationship to Thevenin: Thevenin and Norton equivalent circuits are interchangeable. VTh=IN×RN and IN=VTh/RTh.
- Maximum Power Transfer Theorem: States that for a given source with internal resistance RS, the maximum power is transferred to the load when the load resistance (RL) is equal to the source resistance (RS).
    - Condition: RL=RS (or RL=RTh if considering a Thevenin equivalent circuit).
    - Maximum Power Formula: Pmax=4RSVS2 (where VS is the source voltage).
    - Numerical Example: A 10 V source has an internal resistance of 5Ω. To achieve maximum power transfer, the load resistance should be 5Ω. The maximum power transferred would be Pmax=4×5Ω(10 V)2=20100=5 W.

7. Time-Domain Analysis of First-Order Circuits

These circuits contain one energy-storage element (either an inductor or a capacitor) and exhibit a transient response when a DC source is applied or removed.

- Time Constant (τ): A crucial characteristic of first-order RL and RC circuits. It represents the time required for the circuit's voltage or current to rise or fall by approximately 63.2% of its final steady-state value when charging or discharging.
    - After one time constant (τ), the response reaches ~63.2% of its final value.
    - After five time constants (5τ), the response is considered to have reached its steady-state value (99.3% change).
- RL Circuits (Natural and Step Response):
    - Consist of a resistor (R) and an inductor (L).
    - Time Constant for RL Circuit: τ=RL (units: seconds)
    - Natural Response (Discharge): Occurs when the source is removed and the inductor dissipates its stored energy through the resistor. The current decays exponentially.
        - Formula for Current: I(t)=I0e−t/τ=I0e−Rt/L (where I0 is the initial current in the inductor).

- **Step Response (Charge): Occurs when a DC voltage source is applied to the RL circuit. The current builds up exponentially towards a steady-state value.**
  - **Formula for Current: $I(t)=I_{final}(1-e^{-t/\tau})=I_{final}(1-e^{-Rt/L})$ (where I_{final} is the steady-state current, typically V_{source}/R).**
- **Numerical Example: An RL circuit has $R=10\Omega$ and $L=50$ mH. $\tau=\frac{50\times10^{-3}\text{ H}}{10\Omega}=5$ ms. If a 10 V source is applied, $I_{final}=10\text{ V}/10\Omega=1$ A. The current after one time constant would be $I(5\text{ ms})=1\text{ A}(1-e^{-1})\approx0.632$ A.**

- **RC Circuits (Natural and Step Response):**
  - **Consist of a resistor (R) and a capacitor (C).**
  - **Time Constant for RC Circuit: $\tau=R\times C$ (units: seconds)**
  - **Natural Response (Discharge): Occurs when the source is removed and the capacitor discharges its stored energy through the resistor. The voltage across the capacitor decays exponentially.**
    - **Formula for Voltage: $V(t)=V_0e^{-t/\tau}=V_0e^{-t/RC}$ (where V_0 is the initial voltage across the capacitor).**
  - **Step Response (Charge): Occurs when a DC voltage source is applied to the RC circuit. The voltage across the capacitor builds up exponentially towards the source voltage.**
    - **Formula for Voltage: $V(t)=V_{final}(1-e^{-t/\tau})=V_{final}(1-e^{-t/RC})$ (where V_{final} is the steady-state voltage, typically the source voltage).**
  - **Numerical Example: An RC circuit has $R=1$ kΩ and $C=1\mu$F. $\tau=1000\Omega\times1\times10^{-6}$ F$=1$ ms. If a 5 V source is applied, the voltage across the capacitor after one time constant would be $V(1\text{ ms})=5\text{ V}(1-e^{-1})\approx3.16$ V.**

Activities/Assessments:

To reinforce your learning and test your understanding, the following activities and assessments are recommended:

- **Quizzes on Basic Definitions and Ohm's Law: Short, multiple-choice or fill-in-the-blank quizzes to check your grasp of voltage, current, power, energy, and the direct application of Ohm's Law.**
- **Problem-Solving Exercises Applying KCL/KVL: A set of guided problems where you apply Kirchhoff's Current Law and Kirchhoff's Voltage Law to find unknown currents and voltages in simple to moderately complex DC circuits. Solutions with detailed steps will be provided.**
- **Worked Examples and Practice Problems for Thevenin/Norton Theorems: Step-by-step worked examples demonstrating the application of Thevenin's and Norton's theorems to simplify circuits. Followed by a series of practice problems for you to solve independently.**
- **Simulation Exercises for RL/RC Circuits: Using a free circuit simulator (e.g., Falstad Circuit Simulator, LTSpice, or similar), you will build simple RL and RC circuits. You'll then observe their charging and discharging characteristics,**

measure time constants, and compare simulated results with theoretical calculations. Instructions for using a chosen simulator will be provided.

- **Module Quiz: A comprehensive quiz covering all topics in Module 1, including definitions, formulas, circuit analysis techniques, theorems, and first-order circuit responses. This quiz will assess your overall understanding of the foundations of DC circuits.**
