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QUESTION BANK

Electric Drive Systems:

Batteries, Powertrains, and Transmissions

COURSE OVERVIEW

This question bank covers a comprehensive understanding of battery technologies, electric powertrains, and transmission systems in modern electric vehicles. It covers battery electrochemistry, materials, cell and pack design, thermal management, Battery Management Systems (BMS), e-drive, transmission, and e-axle technologies essential for EV propulsion.

Course Objectives:

- Understand the fundamentals and metrics of battery technologies.
- Analyze electrochemical principles and materials used in battery cells.
- Design and evaluate BMS hardware and software.
- Explore battery manufacturing, pack assembly, and thermal management.
- Apply testing protocols and diagnostics for battery systems.
- Understand e-drive, transmission, and e-axle systems in EVs.

Question Type Legend:

[Theoretical] Tests conceptual understanding and knowledge.

[Comparison] Requires comparison between two or more concepts, materials, or systems.

[Derivation] Mathematical derivation of formulas and equations from first principles.

[Formula & Calculation] Numerical problem-solving with formula application.

[Evaluator] Critical evaluation, analysis, and judgment of systems or approaches.

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MODULE 1

INTRODUCTION TO BATTERY TECHNOLOGY

Sub-Module 1.1: Introduction to Battery Technology

Q1 [Theoretical] (5 Marks)

Give an overview of battery technologies used in electric vehicles. Classify them and explain each type briefly.

Model Answer:

- Batteries are electrochemical devices that store and convert chemical energy into electrical energy.
- Classification: Primary (non-rechargeable) and Secondary (rechargeable) batteries.
- Lead-Acid Batteries: Low cost, mature technology, low energy density (~30–50 Wh/kg), used in starting/auxiliary systems.
- Nickel-Metal Hydride (NiMH): Energy density ~60–120 Wh/kg, used in hybrid EVs (Toyota Prius), moderate cycle life.
- Lithium-Ion (Li-ion): High energy density (~150–250 Wh/kg), long cycle life, dominant technology in modern EVs.
- Solid-State Batteries: Next-generation technology with solid electrolyte, higher safety, energy density >300 Wh/kg (emerging).
- Lithium-Sulfur (Li-S): Theoretical energy density ~2600 Wh/kg, under research stage.
- EV applications predominantly use Li-ion due to the best balance of energy density, cost, and cycle life.

Q2 [Comparison] (5 Marks)

Compare Lead-Acid and Lithium-Ion batteries across all major performance parameters. Why is Li-ion preferred in EVs?

Model Answer:

- Energy Density: Lead-Acid ~30–50 Wh/kg vs Li-ion ~150–250 Wh/kg — Li-ion is 4–5x better.
- Power Density: Lead-Acid ~75–300 W/kg vs Li-ion ~300–1500 W/kg — Li-ion delivers power faster.
- Cycle Life: Lead-Acid 200–500 cycles vs Li-ion 500–2000+ cycles — Li-ion lasts significantly longer.
- Weight: Lead-Acid is very heavy (lead plates); Li-ion is lightweight, improving vehicle range.

- Self-Discharge: Lead-Acid ~5%/month vs Li-ion ~2–3%/month — Li-ion retains charge better.
- Operating Temperature: Li-ion performs better across a wider range; Lead-Acid degrades rapidly in cold.
- Cost: Lead-Acid is cheaper upfront (~\$100–150/kWh) vs Li-ion (~\$120–150/kWh at pack level now).
- Environmental Impact: Lead-Acid contains toxic lead; Li-ion uses cobalt/lithium with mining concerns.
- Conclusion: Li-ion is preferred for EVs due to superior energy density, weight, cycle life, and efficiency.

Q3 [Theoretical] (5 Marks)

Discuss the historical development of battery technology and its influence on the evolution of electric vehicles.

Model Answer:

- 1800 – Alessandro Volta invented the Voltaic Pile: first true electrochemical battery.
- 1859 – Gaston Plante invented the Lead-Acid battery: first rechargeable battery, enabled early EVs.
- 1881–1900 – Early EVs used Lead-Acid packs; they outsold gasoline cars in 1900 in the USA.
- 1989 – NiMH battery developed; commercialized in early 1990s for portable electronics and HEVs.
- 1991 – Sony commercialized the first Li-ion battery, revolutionizing energy storage.
- 1997 – Toyota Prius launched with NiMH, proving hybrid EV commercial viability.
- 2008 – Tesla Roadster used Li-ion cells (18650 cylindrical), demonstrating long-range EV possibility.
- 2010–2020 – Rapid Li-ion cost reduction from ~\$1000/kWh (2010) to ~\$130/kWh (2020).
- 2020s – Solid-state, Li-S, and sodium-ion batteries emerging as next-generation solutions.

Q4 [Evaluator] (5 Marks)

Evaluate the environmental impact of battery technologies across their entire lifecycle. What mitigation strategies are adopted?

Model Answer:

- Raw Material Extraction: Mining lithium (Chile, Australia), cobalt (DRC), and nickel causes deforestation, water pollution, and soil degradation.
- Manufacturing Impact: Battery gigafactories consume large amounts of energy; carbon footprint ~60–100 kg CO₂/kWh of battery produced.

- Use Phase: EVs produce zero tailpipe emissions; overall lifecycle CO₂ is 50–70% lower than ICE vehicles.
- End-of-Life: Improper disposal of Li-ion packs causes leaching of toxic chemicals (Li, Co, Ni) into soil and groundwater.
- Recycling Rates: Currently only ~5% of Li-ion batteries are recycled globally vs >97% for Lead-Acid.
- Mitigation – Recycling: Hydrometallurgical (acid leaching) and pyrometallurgical (smelting) processes recover >90% of Co, Ni, Mn.
- Mitigation – Second Life: Used EV batteries (SOH ~70–80%) repurposed for grid storage, extending life by 5–10 years.
- Mitigation – Sustainable Sourcing: Adoption of cobalt-free chemistries (LFP), blockchain traceability for ethical sourcing.
- Regulatory Response: EU Battery Regulation 2023 mandates recycled content and carbon footprint labelling.

Q5 [Formula & Calculation] (5 Marks)

Define all key electrical metrics of a battery cell. A Li-ion cell has $V=3.7V$, capacity=50Ah. Calculate:

(a) Energy in Wh and kWh, (b) Power if discharged at 2C, (c) Time to discharge at 25A.

Model Answer:

- Key Metrics: Voltage (V) – terminal voltage under load; Capacity (Ah) – total charge storable.
- Energy (Wh) = Voltage x Capacity = $3.7 \times 50 = 185 \text{ Wh} = 0.185 \text{ kWh}$
- C-rate: Rate of charge/discharge relative to capacity. 1C = full discharge in 1 hour.
- 2C discharge current = $2 \times \text{Capacity} = 2 \times 50 = 100 \text{ A}$
- Power at 2C = $V \times I = 3.7 \times 100 = 370 \text{ W}$
- Time to discharge at 25A: $t = \text{Capacity} / \text{Current} = 50 / 25 = 2 \text{ hours}$
- Energy density = Energy / Mass (Wh/kg); Power density = Power / Mass (W/kg)
- Coulomb efficiency = (Discharge Ah / Charge Ah) x 100%; typically, 99–99.5% for Li-ion.
- SOC = (Remaining Capacity / Rated Capacity) x 100%; SOH = (Current max capacity / Initial rated capacity) x 100%.

Q6 [Formula & Calculation] (5 Marks)

Explain series and parallel battery combinations. A pack uses 10 cells in series and 3 strings in parallel (3P10S), each cell: 3.6V, 40Ah. Calculate pack voltage, capacity, energy, and energy density if pack mass = 18 kg.

Model Answer:

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- Series Connection: Voltages add, capacity remains same. $V_{total} = n \times V_{cell}$.
- Parallel Connection: Currents/capacities add, voltage remains same. $C_{total} = m \times C_{cell}$.
- Series-Parallel (3P10S): Combines both for desired voltage and capacity.
- Pack Voltage (series) = $10 \times 3.6 = 36 \text{ V}$
- Pack Capacity (parallel) = $3 \times 40 = 120 \text{ Ah}$
- Pack Energy = $V_{pack} \times C_{pack} = 36 \times 120 = 4320 \text{ Wh} = 4.32 \text{ kWh}$
- Pack Energy Density = $\text{Energy} / \text{Mass} = 4320 / 18 = 240 \text{ Wh/kg}$
- DOD (Depth of Discharge): Percentage of capacity actually used. DOD = 80% means 20% always reserved.
- Usable Energy = $\text{Pack Energy} \times \text{DOD} = 4320 \times 0.8 = 3456 \text{ Wh}$ (if DOD = 80%).

Q7 [Theoretical] (5 Marks)

Explain the current trends in battery technology for EVs. How are they shaping the future of electric mobility?

Model Answer:

- Solid-State Batteries: Replace liquid electrolyte with solid ceramic/polymer; safer, higher energy density, faster charging.
- Cell-to-Pack (CTP) Technology: Eliminates module layer, integrates cells directly into pack — BYD Blade, CATL CTP increases volumetric energy density by 50%.
- Silicon Anode: Si offers 10x theoretical capacity vs graphite; Panasonic, Tesla pursuing Si-dominant anodes.
- Lithium Iron Phosphate (LFP) Revival: Cobalt-free, safer, longer life, now used in Tesla Model 3/Y standard range.
- Ultra-Fast Charging: 350 kW+ DC chargers enabling <15 min charges; requires 4C+ capable cells.
- Battery as Structural Component: Cell-to-chassis (CTC) design; Tesla Cybertruck integrates battery as part of vehicle floor.
- AI-Based BMS: Machine learning algorithms for real-time SOC/SOH prediction with >99% accuracy.
- Sodium-Ion Batteries: Abundant, cheaper raw materials; CATL commercializing Na-ion for entry-level EVs.
- Global Battery Gigafactory Expansion: CATL, BYD, Samsung SDI, LG Energy scaling to TWh/year production.

Q8 [Evaluator] (5 Marks)

Critically evaluate the importance of energy density and power density in determining EV performance. How do these metrics influence vehicle design choices?

Model Answer:

- Energy Density (Wh/kg or Wh/L): Amount of energy stored per unit mass/volume — directly determines driving range.
- Higher energy density reduces pack weight for the same range, e.g., 250 Wh/kg NMC vs 160 Wh/kg LFP.
- Power Density (W/kg or W/L): Rate at which energy can be delivered — determines acceleration and peak power.
- Sports EVs need high power density (>1000 W/kg); range-focused EVs prioritize energy density.
- Trade-off: High energy density materials (NCA) are less thermally stable; high power cells have lower energy density.
- Vehicle Design Impact: High energy density allows smaller, lighter packs — improves range and reduces cost.
- High power density enables smaller motor-inverter systems — reduces under-hood volume.
- Ragone Plot: Graphical tool showing energy density vs power density trade-off for different chemistries.
- Optimal Design: Balance both metrics, e.g., NMC 811 achieves high energy AND power density for premium EVs.

Q9 [Formula & Calculation] (5 Marks)

Explain Wh, Ah, C-rate, Coulomb efficiency, and DOD with formulas. If a 100Ah battery is charged with 102Ah and discharges 99Ah, calculate Coulomb efficiency. Also find usable energy at 85% DOD if pack voltage = 400V.

Model Answer:

- Ampere-Hour (Ah): Charge capacity = Current x Time. 1 Ah = 3600 Coulombs.
- Watt-Hour (Wh): Energy = Voltage x Ah. Represents energy content.
- C-rate: $C = \text{Current (A)} / \text{Rated Capacity (Ah)}$. Defines charge/discharge speed.
- Coulomb Efficiency (CE) = $(\text{Discharge Ah} / \text{Charge Ah}) \times 100$
- $CE = (99 / 102) \times 100 = 97.06\%$
- DOD (Depth of Discharge) = $(\text{Used Capacity} / \text{Total Capacity}) \times 100\%$
- Total Energy = $400V \times 100Ah = 40,000 \text{ Wh} = 40 \text{ kWh}$
- Usable Energy at 85% DOD = $40 \times 0.85 = 34 \text{ kWh}$

- Significance: CE losses represent heat generation during cycling; DOD management extends battery life.

Q10 [Theoretical] (5 Marks)

What is State of Charge (SOC), State of Health (SOH), and Depth of Discharge (DOD)? Explain their significance in battery management.

Model Answer:

- SOC (State of Charge): Ratio of remaining charge to maximum charge. $SOC = (Q_{\text{remaining}} / Q_{\text{max}}) \times 100\%$.
- SOC = 100% when fully charged; SOC = 0% when fully discharged.
- SOC is used by BMS to estimate remaining range and prevent over-discharge.
- SOH (State of Health): Ratio of current maximum capacity to original rated capacity. $SOH = (C_{\text{current}} / C_{\text{rated}}) \times 100\%$.
- SOH = 100% for new batteries; battery considered end-of-life when SOH drops below 80%.
- SOH is used for predictive maintenance, warranty decisions, and second-life assessment.
- DOD (Depth of Discharge): Percentage of battery capacity that has been discharged. $DOD = 100\% - SOC$.
- Higher DOD reduces cycle life; Li-ion typically limited to 80% DOD for long life.
- Relationship: A battery with 90Ah capacity and current capacity of 81Ah has SOH = 90%. If 65Ah were used, DOD = 72.2%, SOC = 27.8%.

Q11 [Theoretical] (5 Marks)

What are the key metrics used to evaluate battery performance in EVs? Explain each with their units and significance.

Model Answer:

- Specific Energy / Energy Density (Wh/kg): Energy per unit mass; determines range. Li-ion: 150–250 Wh/kg.
- Volumetric Energy Density (Wh/L): Energy per unit volume; important for compact EV packaging.
- Specific Power / Power Density (W/kg): Power per unit mass; determines acceleration capability.
- Cycle Life (cycles): Number of charge-discharge cycles before capacity falls below 80% of rated. Li-ion: 500–2000 cycles.
- Coulombic Efficiency (%): Ratio of discharge to charge capacity per cycle; Li-ion >99%.
- Self-Discharge Rate (%/month): Rate of capacity loss when not in use; Li-ion ~2–3%/month.

- Operating Temperature Range (°C): Functional range; Li-ion: -20°C to 60°C.
- Round-Trip Efficiency (%): Energy out / Energy in x 100%; Li-ion ~90–95%.
- Cost (\$/kWh): Economic metric; current Li-ion pack cost ~\$120–150/kWh (2024).

Q12 [Evaluator] (5 Marks)

Evaluate the importance of batteries in EV performance, range, and overall vehicle architecture. What percentage does the battery contribute to vehicle cost?

Model Answer:

- Energy Source: Battery is the sole energy storage unit in BEVs, equivalent to the fuel tank in ICE vehicles.
- Range Determination: Driving range = (Pack Energy x Drivetrain efficiency) / (Energy consumption per km).
- Example: 75 kWh pack, 90% efficiency, 6 km/kWh consumption = $75 \times 0.9 / (1/6) = \sim 405$ km range.
- Power for Acceleration: Peak power from battery determines 0–100 km/h time; Tesla Model S Plaid: 1020 hp from ~100 kWh pack.
- Vehicle Weight: Battery pack is the heaviest single component; Tesla Model 3 pack ~480 kg (~30% of vehicle mass).
- Cost Contribution: Battery pack accounts for 30–40% of total EV cost (at \$130/kWh for 75 kWh pack = ~\$9,750).
- Design Influence: Skateboard platform (Tesla, GM Ultium) places battery flat on floor — lowers center of gravity, improves handling.
- Charging Time: Battery chemistry and thermal management determine fast-charging acceptance rate.
- Safety: Battery must survive crash loads, thermal events — major engineering challenge in EV design.

Sub-Module 1.2: Electrochemistry of Batteries

Q1 [Theoretical] (5 Marks)

Explain the basic principles of electrochemistry as applied to battery operation. Define oxidation, reduction, and redox reactions with examples.

Model Answer:

- Electrochemistry: Study of chemical reactions that produce or consume electrical energy at electrode-electrolyte interfaces.
- Oxidation: Loss of electrons by a species. Represented as: $M \rightarrow M^{n+} + ne^{-}$. Occurs at the anode.

- Reduction: Gain of electrons by a species. Represented as: $M^{n+} + ne^- \rightarrow M$. Occurs at the cathode.
- Redox Reaction: Simultaneous occurrence of oxidation and reduction. One species is oxidized; the other is reduced.
- Example (Li-ion discharge at anode): $LiC_6 \rightarrow C_6 + Li^+ + e^-$ (oxidation at anode).
- Example (Li-ion discharge at cathode): $Li_{1-x}CoO_2 + xLi^+ + xe^- \rightarrow LiCoO_2$ (reduction at cathode).
- Electromotive Force (EMF): Potential difference between cathode and anode. $E_{cell} = E_{cathode} - E_{anode}$.
- The spontaneity of a redox reaction is governed by the Gibbs Free Energy: $\Delta G = -nFE_{cell}$.
- If $\Delta G < 0$, the reaction proceeds spontaneously (discharging); if $\Delta G > 0$, energy input is needed (charging).

Q2 [Derivation] (5 Marks)

Derive the Nernst equation from first principles and explain its application to battery voltage prediction.

Model Answer:

- Starting point: Gibbs Free Energy relationship: $\Delta G = \Delta G^\circ + RT \ln Q$, where Q is the reaction quotient.
- Electrical work done by the cell: $\Delta G = -nFE$, and at standard conditions: $\Delta G^\circ = -nFE^\circ$.
- Substituting: $-nFE = -nFE^\circ + RT \ln Q$
- Dividing both sides by $-nF$: $E = E^\circ - (RT/nF) \ln Q$
- This is the Nernst Equation: $E = E^\circ - (RT/nF) \ln Q$
- At 25°C (T=298K), converting to log₁₀: $E = E^\circ - (0.0592/n) \log Q$
- Where: E = actual cell potential (V), E° = standard cell potential (V), R = 8.314 J/mol·K, F = 96485 C/mol, n = electrons transferred.
- Application: As Li-ion cell discharges, Li^+ concentration in electrolyte changes $\rightarrow Q$ changes $\rightarrow E$ decreases.
- Used in BMS for OCV-based SOC estimation: different SOC levels correspond to specific OCV values via Nernst.

Q3 [Theoretical] (5 Marks)

Explain the working of a Lithium-Ion cell in detail, including the energy transfer mechanism during both charging and discharging.

Model Answer:

- Li-ion cell components: Graphite anode, LiCoO₂/NMC/LFP cathode, liquid electrolyte (LiPF₆ in organic solvent), porous separator.
- DISCHARGING (Chemical to Electrical Energy):

- At Anode: $\text{LiC}_6 \rightarrow \text{C}_6 + \text{Li}^+ + \text{e}^-$ (Li de-intercalates from graphite, releases electrons to external circuit).
- Li^+ ions migrate through electrolyte from anode to cathode.
- Electrons flow through external circuit \rightarrow generates electric current.
- At Cathode: $\text{Li}_{1-x}\text{MO}_2 + x\text{Li}^+ + x\text{e}^- \rightarrow \text{LiMO}_2$ (Li intercalates into cathode lattice).
- CHARGING (Electrical to Chemical Energy):
- External voltage applied reverses the reactions: Li de-intercalates from cathode and re-intercalates into anode.
- SEI Layer: During first charge, a Solid Electrolyte Interphase forms on graphite anode — consumes some Li^+ (irreversible capacity loss) but protects anode thereafter.
- Energy efficiency: Approx. 90–95% round-trip efficiency due to ohmic losses and polarization.

Q4 [Theoretical] (5 Marks)

Explain how electrode potential is developed at an electrode. Describe the concept of standard electrode potential and electrochemical series.

Model Answer:

- When a metal electrode is immersed in its salt solution, metal ions dissolve into solution leaving electrons on electrode \rightarrow creates a potential difference.
- Oxidation Tendency: Active metals (Li, Na) readily give up electrons — higher tendency to oxidize.
- Reduction Tendency: Noble metals (Au, Pt) prefer to gain electrons — higher tendency to reduce.
- Standard Electrode Potential (E°): Measured against Standard Hydrogen Electrode (SHE = 0.00V) at 25°C, 1M concentration.
- $E^\circ(\text{Li}^+/\text{Li}) = -3.04\text{V}$ (most negative — strongest reducing agent — ideal anode material).
- $E^\circ(\text{F}_2/\text{F}^-) = +2.87\text{V}$ (most positive — strongest oxidizing agent).
- Cell potential: $E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} - E^\circ_{\text{anode}}$. For Li-ion: $\sim 3.6\text{--}4.2\text{V}$ depending on cathode material.
- LFP cathode $E^\circ \sim +3.4\text{V}$ vs Li/Li+; NMC811 cathode $E^\circ \sim +3.8\text{V}$ vs Li/Li+.
- The electrochemical series determines which materials are suitable for anode vs cathode in battery design.

Q5 [Formula & Calculation] (5 Marks)

A Li-ion cell has $E^\circ = 3.70\text{V}$. During operation, $[\text{Li}^+]$ at anode = 0.1M and at cathode = 2M, $n = 1$, $T = 298\text{K}$. Calculate actual cell voltage using the Nernst equation. Comment on voltage variation with SOC.

Model Answer:

- Nernst Equation: $E = E^\circ - (RT/nF) \ln Q$
- At 25°C: $E = E^\circ - (0.0592/n) \log Q$
- For Li-ion, reaction quotient $Q = [\text{Li}^+]_{\text{anode}} / [\text{Li}^+]_{\text{cathode}}$ (simplified for intercalation reaction)
- $Q = 0.1 / 2.0 = 0.05$
- $\log Q = \log (0.05) = -1.301$
- $E = 3.70 - (0.0592/1) \times (-1.301)$
- $E = 3.70 + 0.077 = 3.777 \text{ V}$
- As battery discharges: $[\text{Li}^+]$ at anode decreases, $[\text{Li}^+]$ at cathode increases $\rightarrow Q$ decreases $\rightarrow E$ decreases.
- This explains why OCV drops with decreasing SOC — fundamental basis of OCV-SOC curve used in BMS.

Q6 [Theoretical] (5 Marks)

Explain internal resistance in a battery. What are its sources, and how does it affect battery performance? Define the formula for terminal voltage.

Model Answer:

- Internal Resistance (R_{int}): Opposition to current flow within the battery itself.
- Sources of Internal Resistance:
 - (1) Ohmic Resistance: Resistance of electrodes, current collectors, electrolyte conductivity, separator.
 - (2) Charge Transfer Resistance: Resistance at electrode-electrolyte interface (Butler-Volmer kinetics).
 - (3) Diffusion Resistance (Warburg Impedance): Resistance due to slow ion diffusion in electrode materials.
- Terminal Voltage Formula: $V_{\text{terminal}} = E_{\text{OCV}} - I \times R_{\text{int}}$ (during discharge).
- During charge: $V_{\text{terminal}} = E_{\text{OCV}} + I \times R_{\text{int}}$.
- Effects on Performance: Voltage drop under load reduces usable energy; heat generated $= I^2 \times R_{\text{int}}$.
- Aging Effect: R_{int} increases with cycle count, temperature, and time — SOH indicator.
- Measurement: Electrochemical Impedance Spectroscopy (EIS) and DC pulse methods used to measure R_{int} .

Q7 [Comparison] (5 Marks)

Compare the electrochemical characteristics of Lead-Acid and Lithium-Ion batteries in detail, covering reactions, voltage, efficiency, and aging mechanisms.

Model Answer:

- Lead-Acid Reactions: Anode: $\text{Pb} \rightarrow \text{PbSO}_4 + 2\text{e}^-$; Cathode: $\text{PbO}_2 + \text{H}_2\text{SO}_4 + 2\text{e}^- \rightarrow \text{PbSO}_4 + \text{H}_2\text{O}$.
- Li-Ion Reactions: Anode: $\text{LiC}_6 \rightarrow \text{C}_6 + \text{Li}^+ + \text{e}^-$; Cathode: $\text{LiMO}_2 \rightarrow \text{Li}_{1-x}\text{MO}_2 + x\text{Li}^+ + x\text{e}^-$.
- Nominal Voltage: Lead-Acid = 2V/cell; Li-ion = 3.2–3.7V/cell (nearly double).
- Energy Density: Lead-Acid ~30–50 Wh/kg; Li-ion ~150–250 Wh/kg.
- Coulombic Efficiency: Lead-Acid ~70–85%; Li-ion ~99–99.5%.
- Cycle Life: Lead-Acid 200–500 cycles; Li-ion 500–2000+ cycles.
- Aging Mechanisms: Lead-Acid — sulfation (PbSO_4 crystallization), grid corrosion, water loss.
- Li-ion aging: SEI growth (anode), lithium plating, cathode structural degradation, electrolyte decomposition.
- Self-Discharge: Lead-Acid ~5–15%/month; Li-ion ~2–3%/month.

Q8 [Evaluator] (5 Marks)

Evaluate the impact of temperature on battery cell performance. How does temperature affect capacity, internal resistance, cycle life, and safety?

Model Answer:

- Effect on Capacity: At low temperature ($< 0^\circ\text{C}$): Li^+ ion diffusion slows, electrolyte viscosity increases \rightarrow up to 40% capacity loss.
- At high temperature ($> 45^\circ\text{C}$): Reaction kinetics improve but accelerated SEI growth reduces long-term capacity.
- Effect on Internal Resistance: R_{int} increases exponentially at low temperatures (Arrhenius relationship).
- Arrhenius relationship: $k = A \times \text{e}^{(-E_a/RT)}$; lower $T \rightarrow$ slower kinetics \rightarrow higher effective resistance.
- Effect on Cycle Life: For every 10°C rise above 25°C , calendar life is approximately halved (Arrhenius aging).
- Lithium Plating Risk: At low temperatures during charging, Li^+ cannot intercalate fast enough \rightarrow metallic lithium deposits (dendrites) form on anode \rightarrow safety risk.
- Thermal Runaway: Above $60\text{--}80^\circ\text{C}$: SEI decomposition; above 130°C : separator melts; above $150\text{--}200^\circ\text{C}$: exothermic reactions cascade \rightarrow fire/explosion.
- Optimal Range: Li-ion performs best between $20\text{--}30^\circ\text{C}$; thermal management systems maintain this range.
- Design Implication: Battery heaters needed for cold climates; cooling systems essential for hot climates and fast charging.

9 [Theoretical] (5 Marks)

Define cycle life and explain the mechanisms of battery aging. What factors accelerate aging and how can it be minimized?

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Model Answer:

- Cycle Life: Number of complete charge-discharge cycles before capacity falls to 80% of initial rated capacity.
- Typical values: Li-ion NMC ~500–1500 cycles; LFP ~2000–4000 cycles.
- Aging Mechanisms at Anode: SEI layer growth consumes active Li+, increasing R_{int} ; lithium plating during fast charging.
- Aging Mechanisms at Cathode: Structural phase transitions (e.g., NMC layered to spinel/rock-salt phase at high SOC); transition metal dissolution.
- Electrolyte Degradation: Oxidation at high potential; reduction at anode forms gases (CO₂, H₂).
- Factors Accelerating Aging: High temperature, extreme SOC operation (near 0% or 100%), high C-rates, deep cycling.
- Minimization Strategies: Limit SOC window to 20–80%; maintain temperature 20–30°C; charge at low C-rate.
- Battery Management: Smart BMS limits charge/discharge to safe operating window.
- Result: Well-managed Li-ion EV battery can last 10+ years or 150,000+ km (Tesla warranty: 8 years / 160,000 km).

Q10 [Formula & Calculation] (5 Marks)

A battery has OCV = 3.85V and internal resistance = 50 mΩ. It delivers 100A to a motor. Calculate: (a) terminal voltage, (b) power delivered to motor, (c) power lost internally, (d) efficiency.

Model Answer:

- Given: $E_{OCV} = 3.85V$, $R_{int} = 50 \text{ m}\Omega = 0.05\Omega$, $I = 100A$.
- (a) Terminal Voltage: $V_T = E_{OCV} - I \times R_{int} = 3.85 - 100 \times 0.05 = 3.85 - 5 = 3.35V$... (adjust for pack level: multiply by cell count or use pack values).
- Note: For a 100-cell series pack, $E_{OCV_pack} = 385V$, $R_{int_pack} = 5\Omega$.
- $V_{T_pack} = 385 - 100 \times 5 = 385 - 500$... this shows current must be adjusted. Let $I = 10A$ for pack:
- $V_T = 385 - 10 \times 5 = 385 - 50 = 335V$ (illustrates voltage sag under load).
- (b) Power to motor: $P_{motor} = V_T \times I = 335 \times 10 = 3350 \text{ W} = 3.35 \text{ kW}$
- (c) Power lost internally: $P_{loss} = I^2 \times R_{int} = 10^2 \times 5 = 500 \text{ W}$
- (d) Total power from battery: $P_{total} = E_{OCV} \times I = 385 \times 10 = 3850 \text{ W}$
- Efficiency = $P_{motor} / P_{total} = 3350 / 3850 = 87.0\%$

MODULE 2

BATTERY CELL DESIGN AND MANUFACTURING

Sub-Module 2.1: Materials Used in Battery Cells

Q1 [Theoretical] (5 Marks)

Describe the role and requirements of anode materials in Li-ion batteries. Compare graphite, lithium titanate (LTO), and silicon-based anodes.

Model Answer:

- Role of Anode: Stores lithium during charging via intercalation/alloying; releases Li^+ during discharge.
- Requirements: High specific capacity (mAh/g), low and flat voltage vs Li/Li^+ , structural stability during cycling, high electronic conductivity.
- Graphite (LiC_6): Most common; theoretical capacity 372 mAh/g; $E \sim 0.1\text{V}$ vs Li/Li^+ ; excellent cycle life; low cost.
- Limitation of Graphite: Capacity constrained; vulnerable to lithium plating at high C-rates and low temperatures.
- LTO ($\text{Li}_4\text{Ti}_5\text{O}_{12}$): $E \sim 1.55\text{V}$ vs Li/Li^+ ; zero-strain intercalation (excellent cycle life, 10,000+ cycles); fast charge/discharge but lower energy density.
- Silicon (Si): Theoretical capacity 4200 mAh/g (10x graphite); forms $\text{Li}_{22}\text{Si}_5$ alloy; major issue: 300% volume expansion during lithiation \rightarrow cracking, SEI breakdown.
- Solutions for Si: Use nano-silicon, Si-graphite blends (5–15% Si), buffer matrix structures.
- Current State: Panasonic/Tesla use $\sim 5\text{--}10\%$ Si in anode (2170 cells); Sila Nanotechnologies targeting Si-dominant anodes.
- Future: Silicon-dominant anodes could push cell energy density to 400+ Wh/kg.

Q2 [Comparison] (5 Marks)

Compare LFP, NMC, and NCA cathode materials across voltage, energy density, thermal stability, cost, and EV applications.

Model Answer:

- **LFP (LiFePO_4):** Nominal voltage 3.2V; energy density $\sim 150\text{--}170$ Wh/kg; excellent thermal stability (stable to 270°C); long cycle life (2000–4000 cycles); lower cost, no cobalt.
- **NMC (LiNiMnCoO_2):** Nominal voltage 3.6V; energy density $\sim 200\text{--}230$ Wh/kg; good balance of energy, power, cycle life; tunable by varying Ni:Mn:Co ratio.
- **NMC 811 (80% Ni):** Highest energy density in NMC family but reduced thermal stability.

- **NCA (LiNiCoAlO₂):** Nominal voltage 3.6V; energy density ~230–260 Wh/kg; high power capability; used by Tesla/Panasonic; thermal stability concerns.
- **Thermal Stability Ranking:** LFP > NMC 111 > NMC 532 > NMC 622 > NMC 811 > NCA.
- **Cost Ranking (\$/kWh):** LFP cheapest (no Co, no Ni at high levels); NCA most expensive.
- **EV Applications:** LFP — Tesla Model 3/Y standard range, BYD; NMC — BMW, VW, GM Ultium; NCA — Tesla Model S/X/Cybertruck.
- **Cycle Life:** LFP > NMC > NCA.
- **Future:** High-Ni, Co-free cathodes (LNMO, Li-rich) and single-crystal cathodes for improved performance.

Q3 [Theoretical] (5 Marks)

Explain the role, properties, and types of electrolytes in Li-ion batteries. What are the requirements of an ideal electrolyte?

Model Answer:

- **Role of Electrolyte:** Ionic conductor between anode and cathode; facilitates Li⁺ transport while blocking electron flow.
- **Requirements:** High ionic conductivity (>10⁻³ S/cm), wide electrochemical stability window (0–5V vs Li/Li⁺), chemically stable with electrodes, thermally stable, non-toxic.
- **Liquid Electrolyte:** LiPF₆ dissolved in organic solvents (EC/DMC, EC/DEC). Ionic conductivity ~10⁻² S/cm. Flammable — main safety concern in Li-ion.
- **Ionic Conductivity Formula:** $\sigma = \sum n_i q_i \mu_i$, where n = ion concentration, q = charge, μ = mobility.
- **Gel Polymer Electrolyte:** Semi-solid; higher safety, lower conductivity than liquid; used in pouch cells.
- **Solid Electrolyte:** Ceramic (LLZO, LISICON) or sulfide-based; non-flammable; enables solid-state batteries.
- **Ionic Liquid Electrolyte:** Room temperature molten salts; high stability, low vapor pressure, expensive.
- **Electrolyte Additives:** Vinylene carbonate (VC) improves SEI quality; LiDFOB improves low-temperature performance.
- **SEI Formation:** Electrolyte reacts with anode during first charge forming protective SEI — critical for long cycle life.

Q4 [Theoretical] (5 Marks)

What is the function of a separator in a battery cell? Explain its material, structure, and properties. What happens if the separator fails?

Model Answer:

- Function: Physically separates anode and cathode to prevent short circuit while allowing Li⁺ ion transport.
- Must be electronically insulating but ionically conducting (through pores filled with electrolyte).
- Materials: Polyethylene (PE), Polypropylene (PP), or multilayer PE/PP/PE; typical thickness 10–25 μm.
- Structure: Microporous membrane with pore size ~0.1–1 μm; porosity 40–50%.
- Key Properties: High porosity, low tortuosity (straight pores), good wettability, chemical stability, thermal stability.
- Thermal Shutdown Feature: PE separator melts at ~130°C, closing pores and stopping ion transport → shuts down reaction before thermal runaway.
- Ceramic-Coated Separators: Al₂O₃ or SiO₂ coating improves thermal stability to 200°C+ — used in high-performance EV cells.
- Separator Failure Consequences: Direct short circuit between anode and cathode → rapid heat generation → thermal runaway → fire/explosion.
- Failure causes: Physical penetration (nail, deformation), dendrite puncture, excessive shrinkage at high temperature.

Q5 [Theoretical] (5 Marks)

Explain the role of conductive additives and binders in battery electrodes. How do they affect cell performance?

Model Answer:

- Conductive Additives: Added to electrode slurry to improve electronic conductivity of active material (which is often poorly conductive).
- Common types: Carbon Black (Super P), Carbon Nanotubes (CNT), Graphene, VGCF (Vapor-Grown Carbon Fiber).
- Typical loading: 1–5 wt% of electrode; forms percolating conductive network.
- Effect: Reduces electrode resistance → improves rate capability (high C-rate performance) and utilization of active material.
- Excess additives reduce energy density (inactive material); optimization is critical.
- Binders: Polymeric materials that hold active material and conductive additives together and bind them to current collectors.
- Common binders: PVDF (polyvinylidene fluoride) for cathode; CMC+SBR (carboxymethyl cellulose + styrene-butadiene rubber) for graphite anode.

- Binder Properties Required: Good adhesion, chemical stability in electrolyte, flexibility to accommodate volume changes.
- PVDF limitation: Requires NMP (toxic solvent) for processing; water-based binders (CMC+SBR) are more sustainable.
- Effect on Performance: Insufficient binder → electrode delamination; excess binder → increased resistance and reduced capacity.

Q6 [Evaluator] (5 Marks)

Evaluate the sustainability challenges associated with battery material sourcing. What strategies are being adopted to address these challenges?

Model Answer:

- Lithium Sourcing: ~50% from brine (Chile/Argentina), ~30% from hard rock (Australia). Brine extraction uses vast water in desert regions.
- Cobalt Dependency: ~70% from DRC, often in artisanal mines with child labour and poor safety conditions (human rights concern).
- Nickel: High-grade nickel (Class 1) needed for batteries; mining causes significant soil/water contamination.
- Carbon Footprint: Li mining/processing: ~5 kg CO₂/kg Li; Co refining: ~7 kg CO₂/kg Co.
- Resource Depletion: At current EV growth rates, demand for Li could exceed supply by 2030 without new mines.
- Strategy 1 – Cobalt Reduction: Move to high-Ni NMC 811, NCA, or cobalt-free LFP chemistry.
- Strategy 2 – Recycling: Hydrometallurgical recovery of Li (80%), Co (95%), Ni (95%) from spent cells.
- Strategy 3 – Direct Lithium Extraction (DLE): New technology recovers Li from brines with 90% less water.
- Strategy 4 – Sodium-Ion: Uses abundant Na, Fe, Mn — eliminates Li, Co, Ni entirely (CATL commercializing).
- Strategy 5 – Circular Economy: Battery passport, extended producer responsibility, design for disassembly.

Q7 [Theoretical] (5 Marks)

Describe future material innovations in battery technology. Explain solid-state electrolytes, silicon anodes, and Li-S chemistries.

Model Answer:

- Solid-State Electrolytes: Ceramic (oxide-based LLZO, LISICON), sulfide-based (Li₆PS₅Cl, LGPS), and polymer-based.

- Benefits of SSE: Non-flammable, wide electrochemical window enables Li-metal anode, higher energy density.
- Challenges of SSE: Low ionic conductivity at room temperature, brittleness, high interface resistance with electrodes.
- Silicon Anodes: Theoretical capacity 4200 mAh/g vs 372 for graphite; volume expansion ~300% is key challenge.
- Solutions: Nano-Si particles, Si-C composites, pre-lithiation, elastic binders — reducing expansion to manageable levels.
- Lithium-Sulfur (Li-S): Theoretical energy density ~2600 Wh/kg; low cost (sulfur abundant); challenges: polysulfide shuttle, low cycle life.
- Lithium-Air (Li-O₂): Highest theoretical energy density ~3460 Wh/kg; open system uses O₂ from air; enormous technical challenges remain.
- Sodium-Ion Batteries: Na⁺ replaces Li⁺; uses Prussian blue analogue cathode; lower energy density (~120–160 Wh/kg) but much cheaper.
- Timeline: Si-dominant anodes and sulfide solid-state expected in EV cells by 2027–2030; Li-S 2030+.

Sub-Module 2.2: Battery Cell Design and Manufacturing

Q1 [Comparison] (5 Marks)

Compare cylindrical, prismatic, and pouch cell formats across structural design, thermal management, energy density, manufacturing, and EV applications.

Model Answer:

- Cylindrical Cells: Round format (e.g., 18650 = 18mm dia, 65mm height; 4680 = 46mm dia, 80mm height). Mechanically robust, standardized, good thermal stability.
- Cylindrical Advantages: Automated high-speed manufacturing, excellent cycle life, no swelling issues; used by Tesla, Samsung SDI.
- Prismatic Cells: Rectangular hard aluminum/steel case. Higher volumetric packing efficiency in modules. Sizes are not standardized.
- Prismatic Advantages: Space efficient, higher pack-level energy density; used by BMW, Panasonic EV cells.
- Prismatic Disadvantages: Thermal management more challenging; swelling of cells over life.
- Pouch Cells: Flexible laminated aluminum foil packaging. Lightest format, highest gravimetric energy density.
- Pouch Advantages: No metallic casing weight, flexible shape, easiest to scale capacity; used by LG Energy, SK On, Nissan (Leaf).

- Pouch Disadvantages: Requires external compression frame (swelling), less mechanical protection, more complex thermal management.
- Energy Density Ranking: Pouch \geq Prismatic $>$ Cylindrical (at cell level); trend reversing at pack level with CTP technology.

Q2 [Theoretical] (5 Marks)

Describe the complete manufacturing process of a Li-ion battery cell from raw materials to finished cell. Include key process steps.

Model Answer:

- Step 1 – Electrode Preparation: Active material, conductive additive, and binder mixed into slurry using NMP (cathode) or water (anode) solvent.
- Step 2 – Coating: Slurry coated onto current collector foil (Al for cathode, Cu for anode) using slot-die or doctor-blade coater.
- Step 3 – Drying: Coated foil passed through oven (80–140°C) to evaporate solvent; critical for porosity control.
- Step 4 – Calendaring: Dried electrode rolled under pressure to control thickness and density; improves energy density and cycle life.
- Step 5 – Slitting/Notching: Electrode rolls slit to correct width; tabs notched for electrical connections.
- Step 6 – Cell Assembly: (Cylindrical) Electrodes + separator wound into jellyroll; (Prismatic) stacked or wound; (Pouch) Z-fold stacking.
- Step 7 – Electrolyte Filling: Cell filled with electrolyte in dry room (<1% RH); electrolyte wets pores of electrodes and separator.
- Step 8 – Formation Cycling: First charge-discharge cycles (0.1C–0.2C) form SEI layer on anode; critical for long cycle life.
- Step 9 – Aging and Grading: Cells aged at 40–45°C for days to stabilize; sorted by capacity, impedance, self-discharge rate.
- Step 10 – Quality Testing: Capacity check, OCV measurement, EIS test, dimensional inspection before shipping.

Q3 [Evaluator] (5 Marks)

Evaluate the quality control challenges in battery cell manufacturing. What defects can occur and what are their consequences?

Model Answer:

- Electrode Defects: Uneven coating thickness → non-uniform current distribution → capacity variation and premature aging.
- Metal Particle Contamination: Fe, Cu, Ni particles from machinery can puncture separator → internal short circuit → thermal runaway.

- Moisture Contamination: H₂O reacts with LiPF₆ → HF formation → electrode degradation, gas generation, cell swelling.
- Misalignment: Anode overhang misalignment → dendrite formation at edges → short circuit.
- Electrolyte Filling Defects: Under-filling → insufficient wetting → high resistance; over-filling → electrolyte leakage.
- Formation Cycling Errors: Incorrect formation protocol → poor SEI quality → high initial capacity loss → reduced life.
- Quality Control Methods: X-ray inspection for electrode alignment; automated optical inspection (AOI) for coating defects; EIS for cell impedance screening.
- Yield Rates: Top manufacturers achieve >99% yield; even 1% defect rate translates to millions of defective cells per year at GWh scale.
- Consequences of Poor QC: Field failures, battery fires, costly recalls (e.g., Chevrolet Bolt recall 2021 cost GM ~\$2 billion).

exQ4 [Theoretical] (5 Marks)

Explain Life Cycle Assessment (LCA) of battery cells. What are the environmental hotspots and how can the battery industry reduce its carbon footprint?

Model Answer:

- **LCA Definition:** Systematic analysis of environmental impacts of a product across its entire life — from raw material extraction to end-of-life disposal.
- **Stages:** (1) Raw material extraction, (2) Material processing/refining, (3) Cell manufacturing, (4) Vehicle use phase, (5) End-of-life/recycling.
- **Environmental Hotspot 1 – Cathode Material:** NMC cathode production accounts for ~40% of cell carbon footprint; cobalt/nickel mining is energy-intensive.
- **Environmental Hotspot 2 – Cell Manufacturing:** Gigafactory energy consumption; electrode drying NMP solvent recovery; dry room HVAC.
- **Carbon Footprint:** Li-ion NMC cell production ~70–100 kg CO₂-eq/kWh; LFP ~50–60 kg CO₂-eq/kWh.
- **Use Phase:** EV with Li-ion battery produces 50–70% less lifecycle CO₂ than ICE vehicle (depending on grid mix).
- **Reduction Strategies:** Use of renewable energy in gigafactories (Tesla Gigafactories now >60% renewable); water-based electrode processing eliminates NMP.
- **End-of-Life:** Recycling recovers 90%+ of Co, Ni, Mn, Cu; reduces CO₂ for next battery by 30–40%.
- **Second Life:** Extends useful life of battery by 5–10 years before recycling, reducing per-km environmental impact.

Q5 [Formula & Calculation] (5 Marks)

A cylindrical 4680 cell has nominal voltage 3.7V and capacity 25Ah. (a) Calculate cell energy in Wh. (b) For an EV pack of 90 kWh, how many cells are needed? (c) If arranged in 100S configuration, how many parallel strings? (d) What is the pack voltage?

Model Answer:

- (a) Cell Energy = $V \times Ah = 3.7 \times 25 = 92.5 \text{ Wh}$
- (b) Number of cells = Pack Energy / Cell Energy = $90,000 \text{ Wh} / 92.5 \text{ Wh} = 973 \text{ cells}$ (approx. 974 cells).
- (c) Series cells = 100 (100S configuration); Pack voltage = $100 \times 3.7 = 370\text{V}$.
- (d) Total cells needed = 974; Series cells = 100; Parallel strings = $974 / 100 = 9.74 \rightarrow$ use 10 parallel strings (10P).
- Actual pack: $100\text{S} \times 10\text{P} = 1000 \text{ cells}$.
- Actual pack energy = $1000 \times 92.5 = 92,500 \text{ Wh} = 92.5 \text{ kWh}$ (slightly over target to account for cell-to-cell variation).
- Pack voltage = $100 \times 3.7 = 370\text{V}$ nominal; max charge voltage $\sim 100 \times 4.2 = 420\text{V}$.
- Pack capacity = $10 \times 25 = 250 \text{ Ah}$.
- Verification: $P = V \times Ah = 370 \times 250 = 92,500 \text{ Wh} = 92.5 \text{ kWh}$. Correct.

Q6 [Theoretical] (5 Marks)

Discuss emerging cell technologies including solid-state batteries, lithium-sulfur, and sodium-ion. Compare their readiness level for EV applications.

Model Answer:

- Solid-State Batteries (SSB): Replace liquid electrolyte with solid (ceramic/sulfide/polymer). Benefits: non-flammable, $>400 \text{ Wh/kg}$ potential, enables Li-metal anode.
- SSB Status: Toyota, Quantum Scape, Samsung SDI targeting 2027–2030 EV deployment. Manufacturing challenges remain (interface resistance, scalability, cost).
- Lithium-Sulfur (Li-S): Theoretical 2600 Wh/kg , sulfur is cheap/abundant. Challenge: polysulfide dissolution causes rapid capacity fade, low cycle life ($<200\text{--}300$ cycles currently).
- Li-S Status: OXIS Energy, Sion Power demonstrated aviation Li-S cells; EV application requires 500+ cycle improvement.
- Sodium-Ion (Na-ion): Na replaces Li — abundant, cheap; CATL launched commercial Na-ion packs (2023) for entry-level EVs.
- Na-ion performance: $\sim 120\text{--}160 \text{ Wh/kg}$; better low-temperature performance; no Li, Co, Ni requirement.

- Lithium-Air (Li-O₂): Theoretical 3460 Wh/kg; uses atmospheric O₂; TRL 3–4 (lab stage only).
- Technology Readiness Level (TRL): Li-ion = TRL 9; Na-ion = TRL 8; SSB = TRL 5–6; Li-S = TRL 4–5; Li-Air = TRL 2–3.
- Conclusion: Na-ion entering market now for specific use cases; solid-state by ~2027–2030 for premium EVs; Li-S and Li-Air are 2030+ technologies.

Q7 [Evaluator] (5 Marks)

Evaluate the cost structure of Li-ion battery cells and packs. What are the main cost drivers and how has the cost evolved? What is the significance of \$/kWh metric?

Model Answer:

- \$/kWh Metric: Standard cost benchmark; represents the cost of storing one kilowatt-hour of energy. Below \$100/kWh is considered grid parity for EVs.
- Historical Cost Reduction: 2010: ~\$1,000/kWh; 2015: ~\$350/kWh; 2020: ~\$130/kWh; 2024: ~\$100–120/kWh (pack level).
- Cost Breakdown (cell level): Cathode material ~40–50% of cell cost; anode ~10%; electrolyte ~8%; separator ~6%; manufacturing ~15–20%.
- Cathode Cost Driver: Cobalt price volatility (peak \$95,000/tonne in 2018); driving shift to high-Ni, low-Co, or cobalt-free chemistries.
- Scale Effect: CATL, BYD, LG ES at GWh scale achieve significant manufacturing cost reduction through automation and yield improvement.
- Cell-to-Pack (CTP): Eliminates module packaging costs; improves volumetric energy density by 50% → reduces \$/kWh at pack level.
- Labor and Energy: China's competitive advantage in manufacturing cost (~30% lower labor + cheaper energy in cell production).
- Future Target: BloombergNEF projects pack costs to reach \$60/kWh by 2030 with solid-state and Na-ion contributions.
- Significance: Every \$10/kWh reduction in 75 kWh pack = \$750 reduction in EV price → directly impacts consumer adoption rate.

MODULE 3

BMS HARDWARE, SOFTWARE AND INTEGRATION

Sub-Module 3.1: Battery Management Systems (BMS) – Hardware

Duration: 3 hrs | Total Questions: 10 | All Questions: 5 Marks

Q1 [Theoretical] (5 Marks)

Define a Battery Management System (BMS). Explain its major hardware components and their individual functions.

Model Answer:

- BMS Definition: An embedded electronic system that monitors, controls, and protects a battery pack to ensure safe, efficient, and long-lasting operation.
- Component 1 – Cell Voltage Sensing ICs: Measures individual cell voltages (resolution $\pm 1\text{mV}$); detects overvoltage/undervoltage conditions.
- Component 2 – Current Sensor: Measures pack current using shunt resistor (Hall-effect sensor for isolation); data used for SOC estimation.
- Component 3 – Temperature Sensors: NTC thermistors placed on cells and bus bars; monitors thermal hotspots for cooling control.
- Component 4 – Microcontroller Unit (MCU): Central processor; executes BMS algorithms (SOC, SOH, balancing, fault detection) in real-time.
- Component 5 – Communication Interface: CAN bus, LIN, SMBus, or I2C for data exchange with vehicle ECU, charger, and display.
- Component 6 – Protection Circuits: Overvoltage, undervoltage, overcurrent, and short-circuit protection using MOSFETs or dedicated protection ICs.
- Component 7 – Cell Balancing Circuitry: Passive (bleed resistors) or active (DC-DC converters) circuits to equalize cell voltages.
- Component 8 – Gate Driver Circuits: Control switching of contactors and MOSFETs; ensure proper turn-on/off timing.
- Component 9 – Isolation Barrier: Galvanic isolation between HV battery domain and LV control domain (ISO-SPI, optocouplers).

Q2 [Theoretical] (5 Marks)

Explain the types of contactors used in BMS (semiconductor type vs relay type). Describe their working principles, advantages, and disadvantages.

Model Answer:

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- Contactors are high-power switches that connect/disconnect the battery pack from the vehicle drivetrain.
- Relay-Type Contactors: Electromechanical device; coil energized by low-voltage control signal → magnetic field → physical contacts close.
- Relay Advantages: Low on-state resistance, suitable for high current (100–500A); simple control; cost-effective.
- Relay Disadvantages: Mechanical wear, slower switching (5–20ms), spark generation during switching, audible click, vibration sensitivity.
- Semiconductor-Type Contactors: Use high-power MOSFETs or IGBTs; no moving parts; electronic switching.
- Semiconductor Advantages: Fast switching (microseconds), no mechanical wear, no arcing, silent operation, compact.
- Semiconductor Disadvantages: Higher on-state resistance (conduction losses), more complex gate driver circuitry, higher cost.
- EV Application: Most EVs use relay-type contactors (main positive, main negative, precharge) for main HV circuit; semiconductor switches for balancing and protection at cell level.
- Safety Feature: Contactors open automatically when BMS detects a fault condition (overcurrent, thermal event, crash signal from ECU).

Q3 [Theoretical] (5 Marks)

Explain the working principle and control strategy of a pre-charge circuit in a BMS. Why is it essential?

Model Answer:

- Problem: EV inverters contain large DC-link capacitors (100–2000 μF). When main contactor closes suddenly, capacitor draws huge inrush current (potentially kA-level).
- Effect of Inrush Current: Welding of main contactor contacts, voltage spikes damaging electronics, fuse blowing.
- Pre-Charge Circuit: Consists of a pre-charge resistor (typically 50–200 Ω) in series with a pre-charge relay connected in parallel with main positive contactor.
- Pre-Charge Sequence:
 - Step 1: Main negative contactor closes (ground path established).
 - Step 2: Pre-charge relay closes — current flows through pre-charge resistor, slowly charging capacitor.
 - Step 3: BMS monitors capacitor voltage. When $V_{\text{cap}} \geq 90\text{--}95\%$ of battery voltage, pre-charge complete.
 - Step 4: Main positive contactor closes (full current path); pre-charge relay opens.
- Formula: $V_{\text{cap}}(t) = V_{\text{bat}} \times (1 - e^{-(t/RC)})$; time constant $\tau = R \times C$.
- Example: $R = 100\Omega$, $C = 1000\mu\text{F} \rightarrow \tau = 0.1\text{s}$; capacitor reaches 95% in $\sim 3\tau = 0.3$ seconds.

- Resistor Power: $P = V^2 / R = (400)^2 / 100 = 1600\text{W}$ peak; must be rated for short-duration pulse power.

Q4 [Formula & Calculation] (5 Marks)

A 400V EV battery system has a DC-link capacitor of 1500 μF . Pre-charge resistor = 150 Ω . Calculate: (a) time constant τ , (b) time to reach 95% voltage, (c) peak inrush current without pre-charge, (d) peak current with pre-charge.

Model Answer:

- (a) Time constant: $\tau = R \times C = 150 \times 1500 \times 10^{-6} = 150 \times 0.0015 = 0.225$ seconds
- (b) Time to reach 95% of V_{bat} : $t = -\tau \times \ln(1 - 0.95) = -0.225 \times \ln(0.05) = -0.225 \times (-2.996) = 0.674$ seconds
- (c) Peak inrush current WITHOUT pre-charge (ideal): $I_{\text{peak}} = V / R_{\text{wire}}$ (assume wire resistance 0.1 Ω): $I = 400 / 0.1 = 4000$ A — dangerously high!
- (d) Peak current WITH pre-charge resistor: $I_{\text{peak}} = V_{\text{bat}} / R_{\text{precharge}} = 400 / 150 = 2.67$ A — safely limited.
- Pre-charge resistor power dissipation: $P = V^2 / R = 400^2 / 150 = 1067$ W (peak, reduces exponentially).
- Energy dissipated in resistor: $E = 0.5 \times C \times V^2 = 0.5 \times 0.0015 \times 400^2 = 120$ J.
- Pre-charge relay opens after capacitor voltage $\geq 380\text{V}$ (95% of 400V).
- Without pre-charge: main contactor contacts would weld due to 4000A arc.
- Conclusion: Pre-charge circuit is essential to protect contactors and power electronics in any EV HV system.

Q5 [Theoretical] (5 Marks)

Explain the sensors used in BMS for voltage, current, and temperature measurement. Describe their working principles and accuracy requirements.

Model Answer:

- Voltage Measurement: Cell monitoring ICs (e.g., Texas Instruments BQ79600, Analog Devices ADBMS6815) measure individual cell voltages with 16-bit ADC resolution (± 0.5 –1mV accuracy).
- Measurement Method: Differential voltage measurement; flying capacitor or delta-sigma ADC architecture for high accuracy.
- Voltage Accuracy Importance: 1mV error at 3.7V = 0.027% error in SOC — cumulative errors can result in significant range prediction inaccuracy.
- Current Measurement – Shunt Resistor: Low-resistance shunt (0.1–1m Ω) in series with pack; $V = I \times R_{\text{shunt}}$; voltage measured by differential amplifier. Cost-effective, accurate, no isolation.

- Current Measurement – Hall Effect Sensor: Magnetic field produced by current in conductor measured by Hall sensor; provides galvanic isolation; suitable for HV isolation.
- Temperature Measurement: NTC (Negative Temperature Coefficient) thermistors; resistance decreases with temperature. $R(T) = R_0 \times e^{(B(1/T - 1/T_0))}$.
- NTC Accuracy: $\pm 1-2^\circ\text{C}$ over -40°C to $+85^\circ\text{C}$ range; multiple sensors needed per module (cells vary in temperature).
- PT100/PT1000: Platinum RTDs for higher accuracy ($\pm 0.1^\circ\text{C}$) but higher cost; used in BMS validation systems.
- Current Sensor Bandwidth: Must respond to transient currents during regenerative braking and acceleration; bandwidth $> 1\text{kHz}$ required.

Q6 [Theoretical] (5 Marks)

What are the communication interfaces used in BMS? Explain CAN bus protocol and its importance in automotive BMS applications.

Model Answer:

- BMS Communication Interfaces: CAN (Controller Area Network), LIN (Local Interconnect Network), SPI, I2C, UART, ISO-SPI, and increasingly CAN-FD and Ethernet.
- CAN Bus (ISO 11898): Differential two-wire serial communication; 1 Mbps standard, 5–8 Mbps CAN-FD.
- CAN Frame Structure: SOF (start of frame) → Arbitration ID (11 or 29 bit) → DLC → Data (0–8 bytes) → CRC → ACK → EOF.
- CAN Advantages: High noise immunity (differential signaling), multi-master architecture (multiple nodes can transmit), fault confinement (error counters isolate faulty nodes).
- BMS CAN Messages: SOC, SOH, pack voltage, pack current, max/min cell voltage, max/min temperature, fault codes, contactor states.
- Internal Cell Monitoring: ISO-SPI used between MCU and cell monitoring ICs for daisy-chain communication across cell voltage levels (provides isolation).
- LIN Bus: Single-wire, lower cost, 20 kbps; used for auxiliary BMS functions (e.g., cell module communication).
- AUTOSAR Architecture: Modern BMS software built on AUTOSAR platform; CAN communication defined by AUTOSAR COM stack.
- Cybersecurity: BMS CAN messages can be spoofed; automotive cybersecurity (ISO 21434) requires authentication and encryption for BMS communication.

Q7 [Evaluator] (5 Marks)

Evaluate the safety standards applicable to BMS hardware design (ISO 26262, IEC 62133, UN 38.3). How do they influence BMS design decisions?

Model Answer:

- ISO 26262 (Functional Safety – Road Vehicles): Defines ASIL (Automotive Safety Integrity Level) A–D for automotive systems.
- BMS typically requires ASIL B–D for safety-critical functions (contactor control, overcharge protection).
- ISO 26262 Requirements: Hardware safety requirements, diagnostic coverage, single-point fault metrics (SPFM), residual fault tolerance.
- Impact on BMS Hardware: Redundant voltage sensing, independent protection ICs, watchdog circuits, self-test routines.
- IEC 62133: Safety standard for portable sealed secondary cells and batteries used in portable applications. Tests include overcharge, overdischarge, short circuit, crush, and temperature.
- UN 38.3: Transport safety standard for Li batteries; mandatory for shipment. Tests include altitude simulation, thermal, vibration, shock, external short circuit, impact, overcharge.
- ISO 16750 / IEC 61851: Automotive environmental testing (vibration, temperature cycling, EMC) — BMS hardware must pass these for vehicle integration.
- AEC-Q100: Qualification standard for automotive ICs — all semiconductors in BMS must be AEC-Q100 qualified (temperature range -40°C to $+125^{\circ}\text{C}$).
- Design Impact: Safety standards drive hardware redundancy, increase component count and cost by 20–30%, but are non-negotiable for homologation and liability.

Q8 [Theoretical] (5 Marks)

Explain the hardware design considerations for a BMS in an automotive EV. Include PCB design, isolation, protection, and environmental robustness.

Model Answer:

- HV-LV Isolation: Galvanic isolation required between HV battery domain and LV microcontroller domain. Methods: optocouplers, digital isolators, isolated DC-DC converters.
- Creepage and Clearance: IEC 60664 defines minimum distances between HV and LV conductors on PCB to prevent arcing. At 800V, clearance $>8\text{mm}$ in air required.
- PCB Material: FR4 standard material; high-Tg FR4 or polyimide for high-temperature applications in battery modules.

- EMC Design: Battery switching generates EMI; BMS PCB needs good decoupling capacitors, ground planes, filtered connectors, and cable shielding.
- Thermal Management: BMS electronics can generate 2–5W; passive heatsink or thermal pad to PCB chassis required to maintain junction temperature.
- Connector Design: HV connectors must be HVIL (High Voltage InterLock Loop) equipped; detect connector separation before HV is exposed.
- Vibration Resistance: Automotive PCBs must survive 5–50 Hz, 20g vibration (ISO 16750-3); components soldered, underfilled, or conformal-coated.
- Wide Temperature Operation: All BMS components rated -40°C to +125°C (AEC-Q100 Grade 1) for under-hood applications.
- Redundancy: Critical monitoring paths (contactor control, overcurrent protection) use redundant circuits; single component failure should not cause loss of protection.

Q9 [Comparison] (5 Marks)

Compare the protection features required in BMS hardware: overvoltage, undervoltage, overcurrent, short circuit, and over-temperature. For each, explain the threshold, detection method, and action taken.

Model Answer:

- Overvoltage Protection: Threshold typically 4.20–4.25V/cell for NMC (varies by chemistry). Detected by cell voltage sensing IC. Action: open main contactor / stop charging immediately.
- Undervoltage Protection: Threshold typically 2.5–3.0V/cell. Detected by cell voltage sensing IC. Action: open main contactor / stop discharge / alert driver.
- Overcurrent Protection (Discharge): Pack-level; threshold ~2–3x rated continuous current. Detected by current sensor. Action: open contactor (within 100ms); fuse as backup.
- Short Circuit Protection: Very high current event (>10x rated). Detected by current sensor rate-of-rise or dedicated short circuit detection IC. Action: open contactor within <1ms.
- Over-Temperature Protection: Typically 45–55°C charge limit; 60–65°C discharge limit. Detected by NTC sensors. Action: reduce current, activate cooling, open contactor if critical.
- Under-Temperature Protection: 0–5°C charging limit (prevents lithium plating). Detected by NTC sensors. Action: disable charging or activate battery heater.
- Cell Imbalance: Detected when max–min cell voltage difference exceeds threshold (e.g., >200mV). Action: activate cell balancing.
- Isolation Fault: Insulation Monitoring Device (IMD) detects leakage from HV to chassis (<500Ω/V resistance). Action: alert driver, open HV if critical.

- All protections form layered defense: software → hardware protection IC → fuse → contactor → physical disconnect.

Q10 [Formula & Calculation] (5 Marks)

A BMS monitors a 96S1P Li-ion pack (each cell: 3.7V nominal, 4.2V max, 2.8V min, $R_{int}=25\text{m}\Omega$). Calculate: (a) pack nominal voltage, (b) pack max voltage, (c) pack min voltage, (d) pack internal resistance, (e) voltage drop at 200A, (f) power lost in internal resistance.

Model Answer:

- (a) Pack nominal voltage = $96 \times 3.7 = 355.2 \text{ V}$
- (b) Pack max voltage = $96 \times 4.2 = 403.2 \text{ V}$
- (c) Pack min voltage = $96 \times 2.8 = 268.8 \text{ V}$
- (d) Pack internal resistance = $96 \times 25 \text{ m}\Omega = 96 \times 0.025 = 2.4 \Omega$
- (e) Voltage drop at 200A = $I \times R_{pack} = 200 \times 2.4 = 480 \text{ V}$ — This exceeds pack voltage! Correct: I should be lower for 96S1P pack.
- Realistic continuous current for 1P string: $\sim 50\text{A}$. Voltage drop = $50 \times 2.4 = 120\text{V}$ — still high. Let $I = 20\text{A}$:
- Voltage drop at 20A = $20 \times 2.4 = 48\text{V}$. Terminal voltage = $355.2 - 48 = 307.2\text{V}$
- (f) Power lost = $I^2 \times R_{pack} = (20)^2 \times 2.4 = 400 \times 2.4 = 960 \text{ W}$
- Efficiency = $(V_{terminal} \times I) / (V_{OCV} \times I) = 307.2 / 355.2 = 86.5\%$ (at this load). Thermal management must dissipate 960W.

Sub-Module 3.2: Battery Management Systems (BMS) – Software

Duration: 3 hrs | Total Questions: 7 | All Questions: 5 Marks

Q1 [Theoretical] (5 Marks)

Explain the key software functions of a BMS. How do they collectively ensure battery safety, performance, and longevity?

Model Answer:

1. State Estimation: Real-time calculation of SOC, SOH, SOE (State of Energy), SOP (State of Power) — foundation of all other BMS functions.
2. Cell Balancing Control: Algorithm compares cell voltages/SOCs; activates appropriate balancing circuit to equalize cells.
3. Thermal Management: Reads temperature sensors; controls cooling pump/fan speed or heater based on temperature maps.

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- 4. Fault Detection and Management: Monitors all parameters against thresholds; classifies faults by severity; executes protection actions (reduce power, shutdown).
- 5. Contactor Control: Manages startup/shutdown sequence (pre-charge, main contactors) with proper timing and state machine logic.
- 6. Communication Management: Formats and transmits CAN messages with battery data; receives charging commands from charger/EVSE.
- 7. Data Logging: Records cell voltages, temperatures, current, SOC, fault events with timestamps for diagnostics and warranty claims.
- 8. Charge Control: Implements CC-CV charging algorithm; communicates maximum charge current and voltage limits to charger.
- 9. Power Limit Management: Calculates and communicates maximum discharge/charge power limits to vehicle ECU based on SOC, temperature, SOH.
- 10. Safety Arbitration: Final gatekeeper function — makes go/no-go decisions when multiple parameters are at limits simultaneously.

Q2 [Formula & Calculation] (5 Marks)

Explain SOC estimation using Coulomb Counting. A 200Ah battery starts at SOC = 100%. It discharges at 50A for 1.5 hours, then at 100A for 30 minutes. Calculate final SOC. Discuss the limitations of Coulomb Counting.

Model Answer:

- Coulomb Counting Formula: $SOC(t) = SOC(0) - (1/Q_{rated}) \times \int I(t)dt$
- Step 1: Discharge at 50A for 1.5 hours = 90 minutes.
- Charge removed = $50A \times 1.5h = 75 Ah$
- SOC after Step 1 = $100\% - (75/200) \times 100\% = 100\% - 37.5\% = 62.5\%$
- Step 2: Discharge at 100A for 0.5 hours = 30 minutes.
- Charge removed = $100A \times 0.5h = 50 Ah$
- SOC after Step 2 = $62.5\% - (50/200) \times 100\% = 62.5\% - 25\% = 37.5\%$
- Final SOC = 37.5%
- Limitations of Coulomb Counting:
 1. Error accumulation: Current sensor errors integrate over time (1% sensor error can cause 10% SOC error over long drive cycle).
 2. Requires accurate initial SOC (reset typically done at full charge using OCV).
 3. Coulombic efficiency variation: $CE < 100\%$ not always accounted for; temperature affects CE.
 4. Does not account for capacity fade with aging → SOH correction needed.
 5. Practical BMS uses Coulomb Counting + OCV correction + Kalman Filter for robust estimation.

Q3 [Theoretical] (5 Marks)

Explain SOH estimation methods. What parameters are used? How is SOH used in BMS to manage aging?

Model Answer:

- SOH Definition: $SOH = (\text{Current Maximum Usable Capacity} / \text{Initial Rated Capacity}) \times 100\%$.
- SOH = 100% at beginning of life; EV warranty typically guarantees $\geq 70\text{--}80\%$ SOH at end-of-warranty period.
- Method 1 – Capacity-Based SOH: Periodic full discharge test measures actual Ah capacity. $SOH = C_{\text{measured}} / C_{\text{rated}}$. Accurate but requires controlled test conditions.
- Method 2 – Internal Resistance Based: R_{int} increases as battery ages (SEI growth, contact degradation). $SOH_R = (R_0 / R_{\text{measured}}) \times 100\%$.
- Method 3 – Incremental Capacity Analysis (ICA): dQ/dV vs V plot; peaks correspond to phase transitions in cathode. Peak shifts and amplitude changes indicate aging.
- Method 4 – Differential Voltage Analysis (DVA): dV/dQ vs Q plot; similar information to ICA but from different perspective.
- Method 5 – Data-Driven / ML Methods: Neural networks or SVMs trained on aging data to predict SOH from voltage/current/temperature patterns.
- BMS Application of SOH: Recalibrate SOC estimation (C_{rated} in Coulomb Counting replaced with $C_{\text{current}} = SOH \times C_{\text{rated}}$).
- SOH-based Power Limiting: As SOH decreases, R_{int} increases \rightarrow power limits reduced to prevent excessive voltage drop.
- Second-Life Trigger: When $SOH \leq 80\%$, BMS flags battery for EV retirement; battery may be repurposed for stationary storage.

Q4 [Comparison] (5 Marks)

Compare active and passive cell balancing methods in detail. Include circuit topology, energy efficiency, cost, speed, and suitability for different applications.

Model Answer:

- WHY BALANCING IS NEEDED: Cell-to-cell capacity spread (2–5% from manufacturing) causes unequal SOC during cycling. Unbalanced pack limited by weakest cell \rightarrow capacity loss, premature aging.
- PASSIVE BALANCING: Excess energy from high-SOC cells dissipated as heat through bleed resistors.

- Passive Circuit: MOSFET + resistor in parallel with each cell; activated when cell voltage exceeds threshold.
- Passive Advantages: Simple circuit, low cost (\$1–5/cell), easy control logic.
- Passive Disadvantages: Energy wasteful (10–30% balance energy lost as heat); slow (limited by heat dissipation); increases thermal load.
- ACTIVE BALANCING: Energy transferred from high-SOC cells to low-SOC cells using energy storage elements.
- Active Topologies: Capacitor-based, inductor-based (Buck-Boost), transformer-based, DC-DC converter.
- Active Advantages: Energy efficient (90–95% transfer efficiency); faster balancing; suitable for large packs.
- Active Disadvantages: Complex circuit (additional inductors, capacitors, controllers), higher cost (\$10–30/cell), more failure modes.
- Comparison: Passive — balancing speed 0.1–0.5A; Active — balancing current 1–5A. For large EV packs (>100 cells), active balancing preferred for efficiency.

Q5 [Theoretical] (5 Marks)

Explain fault detection and diagnostics in BMS software. What types of faults are detected and what actions are taken?

Model Answer:

- Fault Detection Approach 1 – Threshold-Based: Compare measured parameter against safe operating limits (SOA). Simple but misses gradual degradation.
- Fault Detection Approach 2 – Model-Based: Compare measured behavior against expected model behavior (observer-based); detects subtle deviations.
- Fault Detection Approach 3 – Data-Driven: Machine learning models trained on historical fault data to detect anomalies.
- Cell Voltage Faults: Overvoltage (>4.2V), undervoltage (<2.8V), cell imbalance (>200mV spread), cell voltage drop anomaly.
- Thermal Faults: Over-temperature (>60°C discharge), under-temperature (<0°C charging), thermal runaway precursor (rapid dT/dt).
- Current Faults: Overcurrent, short circuit, charging overcurrent.
- BMS Internal Faults: Sensor failure (open/shorted NTC, disconnected cell wire), communication timeout, microcontroller watchdog reset.
- Fault Severity Levels: Warning (reduce power limits, alert driver) → Error (limit to limp-home mode) → Critical (open contactors, shutdown).
- Fault Recording: Diagnostic Trouble Codes (DTCs) stored in non-volatile memory with timestamp, SOC, temperature context — readable by workshop scan tool.

- ISO 15765 (CAN diagnostics) / AUTOSAR Diagnostic Event Manager (DEM) standards govern fault handling in automotive BMS.

Q6 [Theoretical] (5 Marks)

Explain the software architecture of a BMS. How is AUTOSAR used in modern automotive BMS development?

Model Answer:

- BMS Software Layers (Bottom to Top):
- Layer 1 – Microcontroller Abstraction Layer (MCAL): Direct hardware access; ADC drivers, SPI drivers, CAN drivers, GPIO, PWM. Hardware-dependent.
- Layer 2 – ECU Abstraction Layer: Provides hardware-independent APIs; abstracts specific MCU peripherals from upper layers.
- Layer 3 – Services Layer: OS (AUTOSAR OS/FreeRTOS), Memory Management, CAN communication stack, Diagnostic services (UDS).
- Layer 4 – Application Layer: BMS algorithms — SOC estimation, SOH, balancing, fault detection, contactor control, thermal management.
- AUTOSAR (Automotive Open System Architecture): Standard middleware framework defining SW-Components (SWC), Ports, Interfaces, and Run-Time Environment (RTE).
- AUTOSAR Benefits: Portability across MCU platforms, standardized interfaces between SW modules, simplified integration of third-party algorithms.
- MATLAB Simulink Integration: Algorithm models (SOC, SOH, balancing) developed in Simulink → auto-code generation → AUTOSAR-compliant C code.
- Real-Time Requirements: BMS tasks execute on periodic schedules: voltage measurement (1ms), SOC update (100ms), balancing (1s), CAN transmission (10ms).
- Safety: AUTOSAR Safety Extension (SEooC) provides mechanisms for ASIL-decomposition, redundant calculations, E2E communication protection.

Q7 [Theoretical] (5 Marks)

What is the role of MATLAB Simulink in BMS software development? Explain the model-based design workflow for BMS algorithms.

Model Answer:

- Model-Based Design (MBD): Develop and test BMS algorithms as simulation models in MATLAB/Simulink before writing any C code.
- Step 1 – Plant Modeling: Create accurate Li-ion battery electrical model (equivalent circuit model) in Simulink for simulation.

- Step 2 – Algorithm Development: Implement SOC estimator (Coulomb counting, Extended Kalman Filter), balancing logic, fault detection in Simulink blocks.
- Step 3 – Software-in-the-Loop (SIL) Testing: Test algorithm model against simulated battery data; verify logic correctness without hardware.
- Step 4 – Automatic Code Generation: Simulink Embedded Coder generates optimized C code directly from verified Simulink model.
- Step 5 – Hardware-in-the-Loop (HIL) Testing: Generated code runs on BMS ECU; simulated battery (battery simulator hardware) connected; real-time testing.
- Step 6 – Parameter Calibration: Battery model parameters identified from cell characterization tests (pulse discharge, EIS) and imported into Simulink.
- Benefits: 50–70% reduction in software development time; fewer coding errors; automatic documentation; easy algorithm modification.
- Extended Kalman Filter (EKF) in Simulink: Used for optimal SOC/SOH estimation combining Coulomb Counting with voltage model correction.

Sub-Module 3.3: Battery and BMS Integration

Duration: 2 hrs | Total Questions: 2 | All Questions: 5 Marks

Q1 [Theoretical] (5 Marks)

Explain the battery and BMS hardware interface diagram for an EV. Describe the HV connections, LV connections, and signal interfaces.

Model Answer:

- HV Connections (High Voltage – typically 300–800V DC):
- Pack Positive Terminal → Main Positive Contactor → HV Bus (+) → Inverter / OBC / DC-DC Converter.
- Pack Negative Terminal → Main Negative Contactor → HV Bus (-) → common ground for HV loads.
- Pre-charge relay + resistor in parallel with main positive contactor (prevents inrush current at startup).
- Service Disconnect (Manual Service Disconnect – MSD): Physical interlock allowing technicians to manually isolate HV pack.
- HVIL Loop: High Voltage Interlock Loop continuously monitors connector integrity; opens contactors if any HV connector is disconnected.
- LV Connections (Low Voltage – 12V/24V):
- BMS MCU power supply from 12V system battery.
- Cell voltage sense wires from each cell connection to BMS cell monitoring ICs.
- Temperature sensor wires (NTC thermistors) from module temperature sensors.
- Contactor coil control signals from BMS MCU to relay driver circuits.

- CAN bus wires (CANH/CANL) to vehicle CAN network.
- Isolation: Galvanic barrier between HV cell monitoring circuit and LV MCU using ISO-SPI or CAN transceiver with integrated isolation.

Q2 [Evaluator] (5 Marks)

Evaluate the different BMS integration architectures: centralized, distributed, and modular BMS. Compare their advantages and suitability for different EV applications.

Model Answer:

- Centralized BMS: Single BMS PCB manages all cells in the pack. All cell sense wires run to one central unit.
- Centralized Advantages: Lower cost (single PCB), simpler BMS software, easy calibration.
- Centralized Disadvantages: Long wiring harness increases noise and weight; difficult to scale to large packs; single point of failure.
- Centralized Suitable For: Small packs (<50 cells), two-wheelers, small EVs.
- Distributed BMS (Module-level BMS): Each battery module has its own Cell Monitoring Unit (CMU); CMUs communicate with central Battery Control Unit (BCU) via CAN/daisy-chain.
- Distributed Advantages: Short cell sense wires at module level; scalable to any pack size; easier fault isolation.
- Distributed Disadvantages: More hardware cost (multiple CMUs), more complex communication architecture.
- Modular BMS: BMS hardware embedded within each standard battery module; hot-swap capability; data center battery applications.
- Industry Practice: Most modern EVs use distributed architecture (CMU per module + BCU for pack-level control): Tesla, BMW i3, Nissan Leaf.
- Trend: Cell-to-Pack designs require re-evaluation of distributed architecture as module boundaries disappear.

MODULE 4

THERMAL MANAGEMENT FOR BATTERY PACKS

Sub-Module 4.1: Battery Pack Design and Assembly

Duration: 2 hrs | Total Questions: 6 | All Questions: 5 Marks

Q1 [Theoretical] (5 Marks)

Explain module and pack architecture in EV battery systems. How are cells grouped into modules and modules into packs? What are the design trade-offs?

Model Answer:

- Cell → Module → Pack Hierarchy: Cells are the smallest unit; modules group 8–24 cells for easier handling, thermal management, and electrical management; modules combine into complete pack.
- Module Design: Cells arranged in series-parallel configuration; busbar connections between cells; CMU electronics mounted on module; cooling channel integrated.
- Pack Structure: Module assembly in mechanical frame/housing; HV busbars connect modules in series; BMS electronics compartment; cooling system; HV connectors; crash protection.
- Series Connection across Modules: Modules connected in series to achieve desired pack voltage (e.g., 16 modules x 24V = 384V pack).
- Skateboard Platform: Battery pack forms structural floor of vehicle (Tesla, Volkswagen MEB, GM Ultium) — lowest center of gravity, excellent crash protection.
- Cell-to-Pack (CTP): Eliminates module layer; cells placed directly into pack structure — higher volumetric efficiency, fewer parts, lower cost. Used by BYD Blade, CATL.
- Cell-to-Chassis (CTC): Battery cells integrated into vehicle body structure — maximum space utilization, structural benefit; Tesla Cybertruck, upcoming designs.
- Trade-offs: Modularity vs energy density; serviceability vs integration; thermal uniformity vs compactness.
- Pack Voltage Trend: 400V (mainstream) vs 800V (premium/fast-charging): Porsche Taycan, Hyundai Ioniq 5/6, Kia EV6 use 800V architecture for faster charging.

Q2 [Formula & Calculation] (5 Marks)

Explain the electrical design of a battery pack. A pack requires 75 kWh energy at 400V nominal. Each cell is 3.7V, 60Ah. Design the cell configuration (series, parallel). Calculate pack current at 150kW power.

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Model Answer:

- Step 1: Number of series cells for pack voltage: $N_{\text{series}} = V_{\text{pack}} / V_{\text{cell}} = 400 / 3.7 = 108.1 \rightarrow$ use 108 cells in series.
- Actual pack voltage = $108 \times 3.7 = 399.6\text{V} \approx 400\text{V}$. Correct.
- Step 2: Pack capacity needed: $C_{\text{pack}} = \text{Energy} / \text{Voltage} = 75,000 \text{ Wh} / 399.6\text{V} = 187.7 \text{ Ah}$
- Step 3: Number of parallel strings: $N_{\text{parallel}} = C_{\text{pack}} / C_{\text{cell}} = 187.7 / 60 = 3.13 \rightarrow$ use 4 parallel strings.
- Step 4: Verify actual energy: $E = V_{\text{pack}} \times (N_{\text{parallel}} \times C_{\text{cell}}) = 399.6 \times (4 \times 60) = 399.6 \times 240 = 95,904 \text{ Wh} = 95.9 \text{ kWh}$ (slightly over spec — acceptable).
- Total cells = $N_{\text{series}} \times N_{\text{parallel}} = 108 \times 4 = 432$ cells.
- Step 5: Pack current at 150 kW: $P = V \times I \rightarrow I = P / V = 150,000 / 399.6 = 375.4 \text{ A}$
- Current per cell string = $375.4 / 4 = 93.8 \text{ A}$ per string.
- C-rate per cell = $93.8\text{A} / 60\text{Ah} = 1.56\text{C}$ discharge rate.
- This is within normal operating range for most Li-ion cells.

Q3 [Theoretical] (5 Marks)

Explain the mechanical design requirements for an EV battery pack. What structural loads must it withstand and what materials are used?

Model Answer:

- Structural Requirements: Pack must serve as structural member of vehicle (skateboard platform) while protecting cells from crash, vibration, and environmental exposure.
- Crash Protection: Pack must withstand side, front, rear, and bottom impact forces without cell damage. FMVSS 305 and NCAP requirements mandate no fire within 5 minutes post-crash.
- Materials: Aluminum alloy (6xxx, 7xxx series) — lightweight, high strength, good thermal conductivity; used for pack enclosure, module frames.
- Steel: Used in pack base plate/skid plate for bottom impact protection (stones, road debris); high-strength steel reduces weight.
- Composite Materials: CFRP (carbon fiber reinforced polymer) in high-performance EVs (e.g., BMW i3) for lightweight module housing.
- Vibration and Shock: ISO 16750-3 requires survival through random vibration (5–2000 Hz, 1.5g) and mechanical shock (30g, 11ms).
- IP Rating: Battery pack must achieve IP67 (dust-tight, submersion 1m/30min) or IP6K9K (high-pressure water jet) for underbody location.
- Thermal Runaway Propagation Prevention: Pack design must contain thermal runaway to single module/cell without propagating to rest of pack — vent channels, firewall materials.

- Sealing: Silicone or EPDM gaskets at all joints; pressure vent to prevent pack pressure buildup from off-gassing.

Q4 [Theoretical] (5 Marks)

Explain the complete assembly process of a battery pack. What are the critical process steps and quality checks at each stage?

Model Answer:

- Step 1 – Cell Receiving Inspection: Incoming cells checked for OCV, impedance, and visual defects; cells sorted by capacity and self-discharge rate.
- Step 2 – Cell-to-Module Assembly: Cells placed in module housing with defined orientation; inter-cell compression pads inserted (prevents vibration damage).
- Step 3 – Cell Electrical Connections: Laser welding or ultrasonic welding of busbars to cell terminals; resistance spot welding for cylindrical cells.
- Quality Check: 100% weld pull test and resistance measurement of each weld to ensure $<0.5\text{m}\Omega$ connection.
- Step 4 – CMU Installation: Cell monitoring unit PCB installed on module; cell sense wires connected; temperature sensor plugged in.
- Step 5 – Module-to-Pack Assembly: Modules placed in pack enclosure; HV busbar connections between modules; torque-controlled fastening.
- Step 6 – Cooling System Integration: Cooling plate bonded to bottom of cells/modules using thermally conductive adhesive; coolant hoses connected.
- Step 7 – BMS Installation and Electrical Connections: Main BMS PCB installed; HV connectors, LV harness connected; grounding checked.
- Step 8 – Pack Sealing: Lid sealed with adhesive/mechanical fasteners; IP testing (IP67 leak test with nitrogen pressure).
- Step 9 – End-of-Line Testing: Full formation cycle, capacity check, impedance measurement, CAN communication test, insulation resistance $>100\text{M}\Omega$.
- Step 10 – Final Inspection: Visual check, label application, dimensional check before vehicle installation.

Q5 [Theoretical] (5 Marks)

Explain the testing and validation requirements for EV battery packs. What standards apply and what tests are performed?

Model Answer:

- Electrical Performance Tests: Capacity test (rated Ah at 0.2C to cutoff voltage), power capability test (SOP determination), charge acceptance test.

- Cycle Life Testing: Accelerated aging protocol (e.g., 1C CC-CV charge, 1C discharge) to verify cycle life target (800–1500 cycles to 80% SOH).
- Thermal Performance Tests: Temperature rise measurement at rated current; thermal runaway propagation test (induced in one cell, check propagation).
- Mechanical Tests: Vibration test (IEC 62660-2, road simulation profiles), shock test, crush test, penetration test (nail penetration for TR).
- Environmental Tests: IP67 water submersion, salt spray (IEC 60068-2-11), thermal cycling (-40°C to +85°C, 500 cycles), humidity cycling.
- Safety Tests: External short circuit (SAE J2929), overcharge test, overdischarge test, forced discharge.
- UN 38.3 Transport Tests: Altitude, thermal, vibration, shock, external short circuit, impact, overcharge, forced discharge — mandatory for all Li battery transport.
- EMC Testing: Pack emissions and immunity per CISPR 25 / ISO 11452 for vehicle electromagnetic compatibility.
- Standards: IEC 62660 (Li-ion cells), ISO 12405 (EV battery packs), SAE J2929, GB/T 31486 (China).
- Vehicle-Level Validation: Pack installed in vehicle; real-world drive cycle testing, charge-discharge cycles, extreme temperature (-30°C, +50°C) range testing.

Q6 [Evaluator] (5 Marks)

Evaluate different battery recycling methods. Compare pyrometallurgical, hydrometallurgical, and direct recycling processes.

Model Answer:

- Need for Recycling: Global EV fleet growth will generate millions of tons of spent Li-ion batteries annually by 2030; contain valuable Co, Ni, Li, Mn, Cu.
- Pyrometallurgy (Smelting): Batteries fed into high-temperature furnace (1200–1400°C); metals (Co, Ni, Cu) recovered as alloy; Li, Mn lost to slag; electrolyte burned.
- Pyrometallurgy Pros: Simple process, handles any battery chemistry, no disassembly needed.
- Pyrometallurgy Cons: High energy consumption, poor Li recovery (<30%), air pollution, no graphite recovery, loss of plastic/aluminum.
- Hydrometallurgy (Chemical leaching): Batteries mechanically shredded → electrode black mass separated → dissolved in acid (H₂SO₄ or HNO₃) → individual metals precipitated by pH adjustment or solvent extraction.
- Hydrometallurgy Pros: High recovery rates (Li >80%, Co >95%, Ni >95%), better purity, lower energy than pyro.
- Hydrometallurgy Cons: Complex process, chemical waste, multiple steps, requires pre-processing/shredding.

- Direct Recycling: Preserve cathode material structure; gently recover cathode particles, re-lithiate, and reuse directly.
- Direct Recycling Pros: Highest value retention, lowest energy input, maintains cathode microstructure.
- Direct Recycling Cons: Requires sorted, pure input streams; technically complex; still in scale-up phase (Ascend Elements, Battery Resources).
- EU Regulation: By 2031, batteries must contain 16% recycled Li, 85% recycled Co, 85% recycled Ni, 6% recycled Pb.

Sub-Module 4.2: Battery Testing and Diagnostics

Duration: 2 hrs | Total Questions: 5 | All Questions: 5 Marks

Q1 [Theoretical] (5 Marks)

Explain the different types of battery testing: performance, safety, and reliability testing. What parameters are measured in each?

Model Answer:

- Performance Testing Objective: Quantify electrical performance under controlled conditions.
- Performance Tests: Capacity test (0.2C discharge, measure actual Ah), discharge rate capability (at 0.2C, 1C, 2C, 3C — measures available capacity vs C-rate), charge acceptance, self-discharge rate measurement.
- DCIR (DC Internal Resistance) Test: Apply discharge pulse (10s at 1C); $\Delta V/\Delta I = R_{int}$. Increases with aging.
- HPPC (Hybrid Pulse Power Characterization): Standard DOE protocol; 10s discharge + 10s rest + 10s charge at multiple SOC points; maps power capability across SOC.
- Safety Testing Objective: Verify battery does not pose risk under abuse conditions.
- Safety Tests: Overcharge test (charge beyond 4.3V/cell), overdischarge, external short circuit, forced internal short (nail penetration), crush test, thermal abuse (130°C, 150°C oven), drop test.
- Pass Criteria for Safety: No fire, no explosion, no electrolyte leakage outside 1 minute after test (UN 38.3 criteria).
- Reliability Testing Objective: Verify long-term performance over required service life.
- Reliability Tests: Accelerated cycle aging (1C charge-discharge 1000 cycles), calendar aging (storage at different SOC/temperature), thermal cycling (-40°C to +70°C, 300 cycles).
- Failure Criteria: Capacity < 80% of initial, or DCIR > 200% of initial value.

Q2 [Theoretical] (5 Marks)

Explain Electrochemical Impedance Spectroscopy (EIS) as a diagnostic technique for batteries. What information does it provide?

Model Answer:

- EIS Principle: Small AC perturbation signal (5–10mV) applied to battery at multiple frequencies (10mHz to 100kHz); impedance $Z = V_{AC} / I_{AC}$ measured at each frequency.
- Nyquist Plot: Imaginary part ($-Z''$) vs real part (Z') plotted; different frequency regions reveal different battery processes.
- High Frequency Region: Pure ohmic resistance R_0 (electrolyte + contact resistance) — gives x-axis intercept.
- Mid Frequency Semicircle: Charge transfer resistance (R_{ct}) and double-layer capacitance (C_{dl}) at electrode-electrolyte interface.
- Low Frequency Region: Warburg impedance — diffusion-limited lithium transport in electrode solid phase.
- Equivalent Circuit Model (ECM): Battery modeled as $R_0 + (R_{ct} \parallel C_{dl}) +$ Warburg element; parameters extracted by curve fitting.
- Diagnostic Use 1 – SOC Estimation: At specific frequency, impedance changes with SOC → map used for OCV-free SOC estimation.
- Diagnostic Use 2 – SOH Assessment: R_{ct} and R_0 both increase with aging → quantify degradation mode.
- Diagnostic Use 3 – Lithium Plating Detection: Characteristic inductive loop at low frequency in Nyquist plot indicates Li plating.
- Practical EIS: HIOKI, Gamry instruments used in lab; on-vehicle BMS EIS using intermittent current interruption method being developed.

Q3 [Evaluator] (5 Marks)

Evaluate predictive maintenance approaches for EV battery systems. How can data analysis and machine learning be used for battery health prognosis?

Model Answer:

- Predictive Maintenance Goal: Predict when battery health will reach critical threshold (e.g., SOH=80%) before it happens — avoiding unexpected failure.
- Data Sources: BMS logs of voltage, current, temperature, charge events, fault codes — terabytes of data per fleet over years.
- Traditional Approaches: Empirically fitted degradation models (e.g., capacity fade = $f(\text{cycles, temperature, DOD})$); simple but not adaptable to individual battery variation.

- Cycle Counting: Simple method — count equivalent full cycles (EFC). SOH predicted = $f(\text{EFC}, T_{\text{avg}}, \text{DOD}_{\text{avg}})$.
- Machine Learning Approaches: Recurrent Neural Networks (LSTM) trained on fleet data to predict remaining useful life (RUL) from historical patterns.
- Physics-Informed ML: Combines physical battery model constraints with ML predictions — more data-efficient, better extrapolation.
- Incremental Capacity Analysis (ICA): Automated detection of ICA peak shifts over cycles to quantify degradation modes (loss of lithium inventory, loss of active material).
- Prognosis Output: Expected capacity at next 100/500/1000 cycles; estimated date when SOH will cross 80%; recommended service actions.
- Fleet Analytics: Cloud-based analytics compare individual battery against fleet population; outliers flagged for inspection before customer complaint.
- Business Impact: Predictive maintenance reduces warranty costs, enables proactive battery replacements, optimizes second-life timing.

Q4 [Theoretical] (5 Marks)

Explain the failure modes and failure analysis of Li-ion battery cells and packs. How are root causes identified?

Model Answer:

- Failure Mode 1 – Capacity Fade: Gradual capacity loss due to: (a) SEI growth consuming Li^+ , (b) cathode structural degradation, (c) loss of active material contact.
- Failure Mode 2 – Power Fade: Increase in DCIR due to SEI growth, electrode cracking, contact resistance increase; manifests as reduced acceleration capability.
- Failure Mode 3 – Internal Short Circuit (ISC): Dendrite penetration of separator, metallic particle contamination, or mechanical deformation causes direct contact between electrodes → thermal runaway.
- Failure Mode 4 – External Short Circuit: External fault (wiring, accident) causes high current → overheating → thermal runaway.
- Failure Mode 5 – Lithium Plating: Charging at high rates or low temperatures → Li metal deposits on anode → dendrite growth → ISC risk.
- Failure Mode 6 – Gas Generation: Electrolyte decomposition produces CO_2 , H_2 , CH_4 → cell swelling → mechanical stress → separator rupture.
- Failure Analysis Methods: Teardown analysis (disassemble post-failure cell in glovebox), scanning electron microscopy (SEM) for electrode morphology, X-ray diffraction (XRD) for phase analysis.
- CT Scanning: Non-destructive 3D imaging of internal cell structure — detects electrode delamination, dendrites, electrolyte dry areas.

- FMEA (Failure Mode and Effects Analysis): Systematic analysis of all possible failure modes → severity × probability × detectability = Risk Priority Number (RPN).
- 8D Problem Solving: Structured root cause analysis and corrective action for field failures.

Q5 [Formula & Calculation] (5 Marks)

A 60Ah NMC battery pack delivers 20A at 350V for 2.5 hours. After 500 cycles, the same battery delivers only 20A at 340V for 2.1 hours. Calculate: (a) initial energy delivered, (b) energy after aging, (c) capacity fade %, (d) SOH.

Model Answer:

- (a) Initial Energy = $V \times I \times t = 350 \times 20 \times 2.5 = 17,500 \text{ Wh} = 17.5 \text{ kWh}$
- Initial Discharge Capacity = $I \times t = 20 \times 2.5 = 50 \text{ Ah}$ (at 20A discharge rate from 60Ah rated capacity).
- (b) Energy after aging = $340 \times 20 \times 2.1 = 14,280 \text{ Wh} = 14.28 \text{ kWh}$
- Aged discharge capacity = $20 \times 2.1 = 42 \text{ Ah}$.
- (c) Capacity fade % = $[(50 - 42) / 50] \times 100 = [8/50] \times 100 = 16\%$ capacity fade
- Note: Based on measured discharge capacity (not rated). If using rated capacity of 60Ah:
- SOH = $(42 / 60) \times 100 = 70\%$ — this battery is below the 80% end-of-life threshold.
- (d) SOH = 70% — battery should be flagged for replacement or second-life assessment.
- Energy retained = $(14.28 / 17.5) \times 100 = 81.6\%$ — energy also reduced (lower voltage and lower capacity).
- Pack voltage sag at same current: $350\text{V} \rightarrow 340\text{V}$ suggests internal resistance increase = $\Delta V/I = 10/(20) = 0.5\Omega$ increase per cell string.

MODULE 5

FUTURE TRENDS AND INNOVATIONS

Sub-Module 5.1: Thermal Management for Battery Packs

Duration: 2 hrs | Total Questions: 5 | All Questions: 5 Marks

Q1 [Theoretical] (5 Marks)

Explain the importance of thermal management in battery packs. What happens without proper thermal management?

Model Answer:

- **Optimal Temperature Window:** Li-ion batteries perform best between 20–40°C. Outside this range, performance, life, and safety are compromised.
- **Effect of High Temperature (>45°C):** Accelerated SEI growth → rapid capacity fade; electrolyte decomposition; increased self-discharge; thermal runaway risk.
- **Effect of Low Temperature (<0°C):** Increased electrolyte viscosity → higher internal resistance → capacity reduction up to 40%; lithium plating risk during charging.
- **Thermal Gradients:** Temperature non-uniformity within pack (>5°C differential) causes unequal aging → cells age differently → pack imbalance → reduced usable capacity.
- **Without Thermal Management:** Pack lifetime reduced by 50–70%; safety risk from thermal runaway; reduced range in cold weather; slow charging in cold weather.
- **Thermal Runaway Risk:** Above 60°C, exothermic reactions begin; without cooling, can cascade to fire within seconds.
- **Impact on Charging Speed:** Fast charging (DC fast charge) generates significant heat; thermal management limits the maximum sustainable charge rate.
- **BMS-Thermal Management Integration:** BMS sets power limits based on temperature — without thermal control, power limits become restrictive, degrading driving experience.
- **Industry Requirement:** Automotive-grade TMS must maintain all cells within ±5°C of target temperature across all operating conditions.

Q2 [Comparison] (5 Marks)

Compare air cooling, liquid cooling, and phase change material (PCM) cooling strategies for EV battery packs. Evaluate each for heat transfer coefficient, uniformity, complexity, and suitability.

Model Answer:

- AIR COOLING: Forced air flow over cells/modules. Heat transfer coefficient: $h \approx 20\text{--}50 \text{ W/m}^2\text{K}$ (convective). Simple, lightweight, low cost.
- Air Cooling Suitability: Nissan Leaf (original), low-power EVs; suitable for mild climates and moderate power applications.
- Air Cooling Limitations: Poor at high ambient temperatures, inadequate for fast charging, poor temperature uniformity across large packs.
- LIQUID COOLING: Coolant (50% water-glycol) circulated through cooling channels/plates adjacent to cells. $h \approx 500\text{--}3000 \text{ W/m}^2\text{K}$. Much higher heat removal rate.
- Liquid Cooling Types: Cold plate (cells sit on cooled aluminum plate), cooling channels between cells (prismatic), cooling tubes (cylindrical cells — Tesla snake tube, BMW tube array).
- Liquid Cooling Suitability: Dominant in high-performance EVs (Tesla, BMW, VW, GM); required for fast charging (>50kW).
- Liquid Cooling Limitations: Added weight/volume, risk of leaks, pump/chiller energy consumption.
- PHASE CHANGE MATERIAL (PCM): PCM (paraffin wax, salt hydrate) absorbs latent heat during phase transition (solid→liquid). $h_{\text{effective}}$ very high during phase change.
- PCM Advantages: Passive cooling (no pump/fan), excellent temperature stability during thermal events, lightweight.
- PCM Limitations: Once fully melted, loses cooling capacity; requires regenerative cooling to re-solidify; limited to specific temperature range.
- Summary: Liquid cooling is dominant in commercial EVs for performance and reliability; PCM offers promising hybrid approach.

Q3 [Formula & Calculation] (5 Marks)

A battery module has 12 cells in series (each 60Ah, $R_{\text{int}}=20\text{m}\Omega$). Module current = 80A. Calculate: (a) heat generated per cell, (b) total heat for module, (c) temperature rise after 30 minutes if module thermal mass = 3 kg, $C_p = 900 \text{ J/kg}^\circ\text{C}$, (d) minimum cooling power required to maintain steady temperature.

Model Answer:

- (a) Heat generated per cell: $Q_{\text{cell}} = I^2 \times R_{\text{int_cell}} = 80^2 \times 0.020 = 6400 \times 0.020 = 128 \text{ W per cell}$
- (b) Total heat for 12 cells: $Q_{\text{total}} = 12 \times 128 = 1536 \text{ W} = 1.536 \text{ kW}$
- (c) Temperature rise: $Q = m \times C_p \times \Delta T \rightarrow \Delta T = Q_{\text{energy}} / (m \times C_p)$
- Energy generated in 30 min = $P \times t = 1536 \times (30 \times 60) = 1536 \times 1800 = 2,764,800 \text{ J}$

- $\Delta T = 2,764,800 / (3 \times 900) = 2,764,800 / 2,700 = 1024^\circ\text{C}$ — extremely dangerous if no cooling!
- This shows why active cooling is absolutely essential for high-current operation.
- (d) Minimum cooling power = heat generation rate = 1536 W = 1.536 kW
- Practical cooling system must remove $\geq 1536\text{W}$ to maintain steady-state temperature.
- With liquid cooling at $\Delta T_{\text{coolant}} = 10^\circ\text{C}$ rise: Flow rate needed = $Q / (\dot{m} \times C_{p_water} \times \Delta T) = 1536 / (\dot{m} \times 4186 \times 10) \rightarrow \dot{m} = 0.0367 \text{ kg/s} \approx 2.2 \text{ L/min}$.
- Conclusion: Even modest currents generate significant heat — thermal management is non-negotiable.

Q4 [Theoretical] (5 Marks)

Explain thermal runaway in Li-ion batteries: mechanism, stages, detection, and prevention strategies.

Model Answer:

- Definition: Thermal runaway is a self-sustaining, auto-accelerating exothermic reaction sequence in a battery cell that results in cell destruction and potentially fire.
- Trigger Events: Internal short circuit (dendrite, contamination), external short circuit, overcharge, mechanical abuse (crash, nail penetration), external heating.
- Stage 1 (Onset, 80–100°C): SEI layer decomposition begins; mildly exothermic; electrolyte starts to break down; gas generation begins.
- Stage 2 (Propagation, 100–150°C): Binder (PVDF) reactions; separator melts/shrinks → internal short circuit; cathode decomposition releases O₂.
- Stage 3 (Propagation, 150–250°C): Anode-electrolyte reaction accelerates; cathode lithium + O₂ → rapid combustion; vent opens releasing hot gas.
- Stage 4 (Full Runaway, >250°C): Complete cell destruction; fire/explosion; risk of cell-to-cell propagation.
- Detection: Rapid temperature rise ($dT/dt > 1^\circ\text{C/s}$), gas sensor (CO, H₂), pressure sensor, accelerometer.
- Prevention Strategies: (1) BMS prevents overcharge and overdischarge; (2) Thermal management keeps $T < 45^\circ\text{C}$; (3) Separator with thermal shutdown feature; (4) Flame retardant electrolyte additives.
- Pack-Level Mitigation: Fire-resistant barriers between modules; vent path to outside vehicle; 5-minute warning to occupants; UN ECE R100 standard compliance.

Q5 [Theoretical] (5 Marks)

Explain thermal modeling of battery systems. What types of thermal models are used and how are they applied in design?

Model Answer:

- Purpose of Thermal Modeling: Predict temperature distribution within cells, modules, and packs under different operating conditions before building physical prototype.
- 0D Lumped Thermal Model: Battery treated as single thermal mass. $\Delta T = Q_{gen} / (m \times C_p)$. Simplest model; no spatial information; used for pack-level temperature estimation in BMS.
- 1D Thermal Model: Temperature distribution along one dimension (e.g., along cell height). Accounts for thermal conductivity in one direction.
- 3D Thermal Model (CFD): Full 3D temperature distribution using computational fluid dynamics. Solves heat conduction ($k\nabla^2 T$) + convection + generation. Most accurate; computationally expensive.
- Electrochemical-Thermal Coupled Model: Electrochemical model (current distribution, SOC) coupled with thermal model — heat generation calculated from actual electrochemistry. Most physically accurate.
- Heat Generation Equation: $q = I^2 \times R_{int} + I \times T \times (dU/dT)$ [Ohmic heating + entropic heat].
- Thermal Conductivity Values: Li-ion cell: axial $k_z \approx 30\text{--}40$ W/mK; radial $k_r \approx 0.5\text{--}1$ W/mK (anisotropic — much better along winding axis).
- Model Validation: Model parameters (R_{int} , C_p , k) identified from calorimetry and EIS tests; model validated against thermocouple measurements on actual cells.
- Application: FEA-based thermal models (ANSYS, COMSOL) used to optimize cooling plate geometry, coolant flow rate, cell spacing in pack design stage.

Sub-Module 5.2: Future Trends and Innovations

Duration: 2 hrs | Total Questions: 3 | All Questions: 5 Marks

Q1 [Evaluator] (5 Marks)

Evaluate solid-state battery technology. Compare it with conventional Li-ion batteries and assess challenges preventing commercialization.

Model Answer:

- Solid-State Battery (SSB): Replaces liquid electrolyte with solid ceramic, sulfide, or polymer electrolyte.
- Advantages – Safety: No flammable liquid electrolyte; dramatically reduced fire risk; allows battery cooling simplification.
- Advantages – Energy Density: Enables Li-metal anode (theoretical capacity 3860 mAh/g vs 372 for graphite); potential >400 Wh/kg cell level.
- Advantages – Voltage Window: Solid electrolytes stable at higher voltages → enables 5V cathodes → higher energy density.

- Advantages – Cycle Life: No electrolyte decomposition; potentially >5000 cycles (Toyota claims 1200 cycles at 500 Wh/L).
- Challenge 1 – Interface Resistance: High resistance at solid electrode/solid electrolyte contact; poor mechanical contact worsens on cycling.
- Challenge 2 – Li Dendrite: Paradoxically, Li-metal dendrites can still propagate through grain boundaries in oxide electrolytes; sulfide electrolytes are more susceptible.
- Challenge 3 – Manufacturing: Cannot use existing wet electrode manufacturing; dry process required; coating solid electrolyte thin layers at scale is unproven.
- Challenge 4 – Cost: Oxide SSE (LLZO) processing requires sintering at 1000°C+; sulfide SSE sensitive to moisture; both 10x more expensive than liquid electrolyte currently.
- Timeline: Toyota targeting 2027 SSB EV; QuantumScape (VW backed) targeting 2026; Samsung SDI 2027. Most analysts expect 2028–2032 for meaningful volume production.

Q2 [Theoretical] (5 Marks)

Explain fast charging technology for EVs. What are the technical challenges and how are they addressed at cell, pack, and infrastructure levels?

Model Answer:

- Fast Charging Definition: DC fast charging at power levels >50kW; ultra-fast charging >150kW; extreme fast charging (XFC) >350kW.
- Time to Charge: 350kW charger on 100kWh pack → $100\text{kWh} / 350\text{kW} = 0.286\text{h} = 17$ minutes to 80% SOC (accounting for CC-CV taper).
- Cell-Level Challenges: High current → rapid Li⁺ intercalation → concentration gradient → mechanical stress → cracking; lithium plating risk at low temperatures.
- Cell-Level Solutions: Larger electrode surface area (thinner electrodes), doping graphite with silicon, single-crystal cathode particles (no grain boundary cracking), optimized electrolyte formulation.
- 4C-capable cells: CATL Shenxing Plus (2024): 4C charge rate, 10 min to 80%; BYD Blade cell: ~3C; Porsche/Audi 800V system: supports 270kW.
- Pack-Level: 800V architecture reduces current at same power ($I = P/V$; 350kW at 800V = 437A vs 875A at 400V) → thinner wires, less heat.
- Thermal Management at XFC: Heat generation = $I^2 \times R_{\text{int}}$; at 4C, heat generation is 16x that at 1C — liquid cooling with chiller mandatory.
- Infrastructure: CCS (Combined Charging System), CHAdeMO, NACS (Tesla standard adopted by major OEMs); 800V-capable chargers needed for XFC.

- Grid Impact: 350kW charger draws equivalent power of ~100 residential homes; smart charging, battery buffers at charging stations needed.

Q3 [Theoretical] (5 Marks)

Explain second-life applications for EV batteries. What is the technical and economic justification? What are the challenges?

Model Answer:

- Second-Life Concept: EV batteries retired from vehicles (SOH ~70–80%) repurposed for stationary energy storage applications.
- Why Second Life: At SOH 80%, cell capacity is still significant (~60kWh from 75kWh pack); too much value to waste by direct recycling.
- Applications: Grid-scale energy storage (peak shaving, frequency regulation), commercial building backup power (UPS), renewable integration (solar/wind pairing), EV charging buffer.
- Technical Process: Battery disassembly → cell/module testing (capacity, impedance) → re-grouping cells with matched SOH → new pack assembly with compatible BMS.
- Economic Benefit: Second-life battery cost \$50–80/kWh vs \$400/kWh for new battery storage → competitive for stationary storage.
- Case Study: BMW i3 batteries in Vattenfall grid storage (Hamburg); Nissan Leaf batteries in 4R Energy project (Japan); Volkswagen repurposing batteries as mobile charging stations.
- Challenge 1 – Safety: Aged cells have higher IR, gas generation risk; need rigorous testing before second-life deployment.
- Challenge 2 – Technical Heterogeneity: Different SOH values across cells from same pack; balancing becomes critical.
- Challenge 3 – Economic Uncertainty: Battery price falling rapidly → new battery cost approaching second-life cost → narrowing value window.
- Challenge 4 – Standardization: No industry standard for battery module connectors or communication protocols → each reuse application requires custom adaptation.

Sub-Module 5.3: E-Drive and Transmission System for an EV

Duration: 2 hrs | Total Questions: 6 | All Questions: 5 Marks

Q1 [Theoretical] (5 Marks)

Explain the role of the E-Drive system in an EV. How do the motor, inverter, and transmission work together to propel the vehicle?

Model Answer:

- E-Drive System: Integrated assembly of electric motor + power electronics inverter + transmission that converts electrical energy from battery into mechanical motion at wheels.
- Battery → Inverter: DC power from battery (300–800V) fed to inverter.
- Inverter → Motor: Inverter converts DC to three-phase AC using PWM switching; frequency and amplitude of AC controlled to achieve desired motor speed and torque.
- Motor → Transmission: Motor shaft rotates at high speed (up to 10,000–20,000 RPM); transmission (reduction gear) reduces speed and multiplies torque.
- Transmission → Wheels: Output shaft connected to drive axle → wheels rotate.
- Torque-Speed Relationship: $P = T \times \omega$; at constant power, doubling speed halves torque.
- Regenerative Braking: Process reverses — wheel drives motor; motor acts as generator; inverter converts AC to DC → charges battery. Recovers 10–30% of kinetic energy.
- Control Hierarchy: Driver pedal position → Vehicle Control Unit → Motor Control Unit → Inverter PWM signals → Motor torque.
- Performance Metrics: Peak power (kW), continuous power (kW), peak torque (Nm), base speed (RPM where peak torque ends), field weakening range (beyond base speed).

Q2 [Derivation] (5 Marks)

Derive the torque equation for a Permanent Magnet Synchronous Motor (PMSM). Explain the role of the d-axis and q-axis in torque production.

Model Answer:

- PMSM Coordinate Transformation: dq0 transformation (Park's transformation) converts three-phase ABC frame to rotating dq reference frame aligned with rotor flux.
- In dq frame, rotor magnetic flux (from permanent magnets) is aligned with d-axis. Flux linkage: $\psi_d = \psi_{pm} + L_d \times i_d$; $\psi_q = L_q \times i_q$.
- Voltage Equations in dq frame: $v_d = R_s \times i_d + L_d \times di_d/dt - \omega_e \times L_q \times i_q$
- $v_q = R_s \times i_q + L_q \times di_q/dt + \omega_e \times (L_d \times i_d + \psi_{pm})$
- Power Equation: $P_{mech} = (3/2) \times \omega_e \times [\psi_{pm} \times i_q + (L_d - L_q) \times i_d \times i_q]$
- Torque Equation: $T = P/\omega_{mech} = (3/2) \times p \times [\psi_{pm} \times i_q + (L_d - L_q) \times i_d \times i_q]$
- where p = pole pairs, ψ_{pm} = magnet flux linkage, L_d = d-axis inductance, L_q = q-axis inductance.

- For Surface PMSM (SPMSM): $L_d = L_q$, so reluctance torque term = 0. $T = (3/2) \times p \times \psi_{pm} \times i_q$.
- This shows torque is purely proportional to q-axis current i_q — hence Maximum Torque Per Ampere (MTPA) for SPMSM: set $i_d = 0$.
- For Interior PMSM (IPMSM): $L_q > L_d$; reluctance torque $(L_d - L_q) \times i_d \times i_q$ adds to magnet torque. MTPA requires negative i_d for maximum torque efficiency.

Q3 [Theoretical] (5 Marks)

Explain Sinusoidal PWM (SPWM) and Space Vector PWM (SVPWM) techniques for three-phase inverter control. Compare their performance.

Model Answer:

- Three-Phase Inverter: Six switching devices (IGBTs/MOSFETs) arranged in three half-bridges; each phase connected to one half-bridge midpoint.
- SPWM Principle: Three sinusoidal reference signals (120° apart) compared with high-frequency triangular carrier wave. Switch fires HIGH when reference $>$ carrier; LOW when reference $<$ carrier.
- SPWM Modulation Index: $m_a = V_{reference_peak} / V_{carrier_peak}$. $m_a = 1 \rightarrow$ maximum linear modulation.
- SPWM Output: Phase voltage contains fundamental + odd harmonics at multiples of carrier frequency (harmonics at $f_{carrier} \pm 2f_{fundamental}$, $f_{carrier} \pm 4f_{fundamental}$ etc.).
- SPWM DC Bus Utilization: $V_{phase_peak} = m_a \times (V_{dc} / 2)$. Maximum $V_{phase_peak} = V_{dc}/2$ at $m_a=1$. DC utilization = 78.5%.
- SVPWM Principle: Treats three-phase system as single rotating space vector; uses 8 switching states (6 active + 2 zero vectors); vectors combined over switching period to produce desired output.
- SVPWM Advantages over SPWM: DC bus utilization = 90.7% (15% better than SPWM); lower THD (Total Harmonic Distortion); easier digital implementation.
- SVPWM DC Bus Utilization: $V_{phase_peak} = V_{dc}/\sqrt{3} = 0.577 V_{dc}$. Compared to SPWM: $0.577/0.5 = 1.155 \rightarrow$ 15.5% more output voltage.
- SVPWM is now the industry standard for EV motor control due to superior performance; implemented in DSP/FPGA in motor controller.

Q4 [Formula & Calculation] (5 Marks)

An EV motor has rated power 150kW, maximum torque 350Nm at base speed. Calculate: (a) base speed, (b) if vehicle wheel radius = 0.35m, gear ratio = 9:1, calculate tractive force and vehicle acceleration if vehicle mass = 2000kg.

Model Answer:

- (a) Base Speed Calculation: $P = T \times \omega \rightarrow \omega = P / T = 150,000 / 350 = 428.6 \text{ rad/s}$
- $N_{\text{base}} = \omega \times 60 / (2\pi) = 428.6 \times 60 / 6.283 = 4094 \text{ RPM}$
- (b) Tractive Force Calculation:
- Motor torque at peak = 350 Nm.
- Torque at wheel = Motor torque x Gear Ratio x Drivetrain efficiency (assume $\eta = 0.95$)
- $T_{\text{wheel}} = 350 \times 9 \times 0.95 = 2992.5 \text{ Nm}$
- Tractive force = $T_{\text{wheel}} / \text{wheel radius} = 2992.5 / 0.35 = 8550 \text{ N}$
- Vehicle Acceleration: $F = m \times a \rightarrow a = F / m = 8550 / 2000 = 4.275 \text{ m/s}^2$
- This gives 0–100 km/h time: $v = a \times t \rightarrow t = v/a = (100/3.6) / 4.275 = 27.78 / 4.275 = 6.5 \text{ seconds}$ (ideal, neglecting drag and friction).
- Wheel speed at base speed: $n_{\text{wheel}} = N_{\text{base}} / \text{Gear_Ratio} = 4094 / 9 = 455 \text{ RPM}$
- Vehicle speed at base speed: $v = \omega_{\text{wheel}} \times r = (455 \times 2\pi / 60) \times 0.35 = 47.65 \times 0.35 = 16.7 \text{ m/s} = 60 \text{ km/h}$.

Q5 [Theoretical] (5 Marks)

Explain the transmission system of a typical EV. Why do most EVs use single-speed transmission? How is the reduction ratio determined?

Model Answer:

- EV Transmission: Unlike ICE vehicles needing 6–8 speed gearbox, EVs use single fixed-ratio reduction gear because electric motors have fundamentally different torque-speed characteristics.
- Motor Characteristics: Peak torque available from 0 RPM (stall torque); constant power region extends from base speed to maximum speed — no torque hole at low speed.
- ICE Need for Multi-Speed: Gasoline engines produce maximum torque in a narrow RPM band (2000–5000 RPM); gearbox matches engine to wheel speed across vehicle speed range.
- EV Single Speed Advantage: Simpler, lighter, more efficient (no clutch losses), lower manufacturing cost, instant torque delivery.
- Reduction Ratio Determination: $\text{Gear Ratio} = \text{Motor Max Speed} / \text{Wheel Max Speed}$.
- Example: Motor max speed = 15,000 RPM; Vehicle max speed = 200 km/h; Wheel radius = 0.35m.
- Wheel RPM at 200 km/h: $v = 200/3.6 = 55.6 \text{ m/s}$; $\omega_{\text{wheel}} = v/r = 55.6/0.35 = 158.8 \text{ rad/s} = 1517 \text{ RPM}$.
- $\text{Gear Ratio} = 15,000 / 1517 = 9.89 \approx 10:1$.
- Higher ratio: More torque at wheels (better acceleration), lower top speed.
- Lower ratio: Higher top speed, less tractive force.

- Two-speed transmission (Porsche Taycan, Audi e-tron GT): First gear for maximum acceleration; second gear for high-speed efficiency at motorway.

Q6 [Evaluator] (5 Marks)

Explain how an E-Drive system is mapped to various drive cycle requirements. What is a drive cycle and how does it influence powertrain design?

Model Answer:

- Drive Cycle Definition: Standardized speed-time profile representing real-world driving conditions, used for vehicle emission and efficiency testing and powertrain design.
- Common Drive Cycles: WLTP (Worldwide Harmonized Light Vehicles Test Procedure) global standard; UDDS (Urban Dynamometer Driving Schedule) US city driving; HWFET — US highway; NEDC (outdated Europe).
- Drive Cycle Parameters Used: Maximum speed, peak acceleration, average power demand, energy consumption per km.
- WLTP Profile: Low phase (0–56 km/h), Medium (56–76 km/h), High (76–97 km/h), Extra-high (97–131 km/h); total 30 min, 23.25 km.
- Powertrain Mapping Process: Calculate required wheel force and power at each second of drive cycle → determine motor operating points (T, N) → overlay on motor efficiency map.
- Motor Efficiency Map: 2D contour plot of efficiency (%) vs torque and speed; motor operates in high-efficiency region for most of WLTP cycle.
- Gear Ratio Optimization: Choose ratio to place most-used drive cycle operating points in motor's high-efficiency island (typically 90–96% efficiency).
- Peak vs Continuous Rating: Drive cycle determines required continuous motor power; peak power (for acceleration) determined by max acceleration requirement.
- Result: Optimized E-Drive achieves system efficiency >88% over WLTP cycle; gear ratio, motor size, and inverter specifications all derived from drive cycle analysis.

Sub-Module 5.4: E-Axle Systems for an EV

Q1 [Theoretical] (5 Marks)

Explain the concept of an E-Axle in EVs. What components are integrated and what are the advantages over conventional separate drivetrain systems?

Model Answer:

- E-Axle Definition: A fully integrated electrified axle module that combines electric motor, power electronics (inverter), and transmission (gearbox + differential) into a single compact unit.
- Components in E-Axle: (1) Electric motor (PMSM or IM), (2) Three-phase inverter, (3) Single-speed reduction gearbox, (4) Differential, (5) Thermal management system, (6) Motor control unit (MCU).
- Comparison – Conventional: Separate motor + separate inverter + separate gearbox + separate differential; connected by shafts and cables; large packaging footprint.
- Advantage 1 – Compactness: All components in one unit; frees up vehicle space; enables flexible vehicle architecture (front + rear E-axle independently).
- Advantage 2 – Weight Reduction: Integrated housing eliminates separate casings; shared cooling reduces weight by 15–25% vs separate components.
- Advantage 3 – Efficiency: Optimized component placement reduces power transmission losses; integrated thermal management improves efficiency.
- Advantage 4 – Modularity: Same E-axle module can be used on different vehicle platforms; reduces development cost.
- Advantage 5 – All-Wheel Drive Capability: Independent E-axle on front and rear enables torque vectoring AWD without mechanical coupling.
- Industry Examples: Mercedes-Benz eATS (electric axle transmission system), ZF EVSys800, Bosch eAxle, Continental VDO eAxle; used in Mercedes EQS, BMW iX, Ford Mustang Mach-E.

Q2 [Comparison] (5 Marks)

Discuss the design and functional aspects of an E-Axle. Compare radial-flux and axial-flux motor configurations for E-Axle applications.

Model Answer:

- E-Axle Design Aspects: The motor, gearbox, and inverter must share a common housing with integrated oil/water cooling, acoustic isolation (gear whine), and sealing.
- Motor-Gearbox Coaxial Arrangement: Motor and gearbox share the same axis of rotation — most compact configuration.
- Motor-Gearbox Offset Arrangement: Motor parallel to gearbox; connected by countershaft — better motor integration into axle geometry.
- RADIAL FLUX MOTOR (RFM): Conventional cylindrical motor; flux crosses radially (rotor to stator). Used in >95% of current E-axles.

- RFM Advantages: Mature manufacturing, high power density achievable, well-understood thermal management.
- RFM Limitations: Increasing motor length increases weight and axial package space.
- AXIAL FLUX MOTOR (AFM): Disc-shaped motor; flux crosses axially (face to face). Examples: YASA (Mercedes AMG EQE), Magnax.
- AFM Advantages: Higher torque density (Nm/kg), shorter axial length (disk form), better heat rejection from large face area.
- AFM Limitations: Complex manufacturing (Halbach array magnets, PCB stator winding), thermal management challenges, higher cost.
- AFM Power Density: YASA 750R achieves 25 kW/kg vs typical RFM PMSM ~5–10 kW/kg.
- Trend: Axial flux motors increasingly adopted for premium E-axles due to superior power density.

Q3 [Formula & Calculation] (5 Marks)

An E-Axle has a PMSM rated 200kW continuous, 400kW peak. Motor max speed = 16,000 RPM. Gear ratio = 10:1, wheel radius = 0.33m. Calculate: (a) max wheel torque at peak power from base speed, (b) vehicle top speed at motor max speed, (c) tractive force at peak torque.

Model Answer:

- Given: $P_{\text{peak}} = 400,000\text{W}$; Gear ratio = 10:1; $r_{\text{wheel}} = 0.33\text{m}$; $N_{\text{motor_max}} = 16,000\text{ RPM}$.
- Assume base speed (where peak torque ends): $N_{\text{base}} = 4,000\text{ RPM}$ (typical for high-torque E-axles).
- (a) Torque at motor base speed: $T_{\text{motor}} = P / \omega = 400,000 / (4000 \times 2\pi/60) = 400,000 / 418.9 = 954.9\text{ Nm}$
- Wheel torque = $T_{\text{motor}} \times \text{Gear Ratio} \times \eta$ (assume $\eta=0.97$) = $954.9 \times 10 \times 0.97 = 9262.5\text{ Nm}$
- (b) Vehicle top speed at $N_{\text{motor_max}} = 16,000\text{ RPM}$:
 - Wheel RPM = $16,000 / 10 = 1600\text{ RPM}$
 - $\omega_{\text{wheel}} = 1600 \times 2\pi / 60 = 167.6\text{ rad/s}$
 - $v_{\text{vehicle}} = \omega_{\text{wheel}} \times r = 167.6 \times 0.33 = 55.3\text{ m/s} = 199.1\text{ km/h} \approx 200\text{ km/h}$
- (c) Tractive Force = Wheel Torque / Wheel Radius = $9262.5 / 0.33 = 28,068\text{ N} \approx 28.1\text{ kN}$
- Vehicle acceleration: $a = F/m$ (e.g., $m=2200\text{kg}$): $a = 28,068 / 2200 = 12.76\text{ m/s}^2$ — exceptional acceleration (0–100 in ~2.2s).

Q4 [Theoretical] (5 Marks)

Explain the control strategies used in E-Axle systems, including torque vectoring and regenerative braking control.

Model Answer:

- Basic Torque Control: Driver accelerator pedal → Vehicle Control Unit (VCU) calculates demanded wheel torque → E-Axle MCU calculates required motor torque command → SVPWM inverter control.
- Speed Control (Cruise Control): Outer speed control loop generates torque command based on speed error; inner current/torque control loop executes the command.
- MTPA (Maximum Torque Per Ampere): Control algorithm that optimizes d-q current ratio to extract maximum torque for minimum current → reduces copper losses → improves efficiency.
- Field Weakening Control: Above base speed, applying negative d-axis current to weaken effective flux → allows motor to operate beyond base speed at reduced torque.
- Regenerative Braking Control: When driver releases accelerator or applies brakes, VCU commands negative torque → motor acts as generator → captured energy returned to battery.
- Torque Vectoring (Dual-Motor or Twin-Motor E-Axle): Independent control of torque to left and right wheels through differential gear control.
- Torque Vectoring Application: In cornering, inner wheel decelerates, outer wheel accelerates → yaw moment aids cornering → improved agility (Rivian quad-motor, Lamborghini Revuelto).
- Traction Control: When wheel slips detected (rapid wheel speed increase), torque reduced to regain grip — replaces mechanical limited-slip differential.
- Energy Management in AWD: VCU decides front/rear torque split based on efficiency maps; at light loads, one axle disconnected for efficiency.

Q5 [Evaluator] (5 Marks)

Evaluate the thermal management requirements for an E-Axle system. How does integrated cooling work, and what are the challenges?

Model Answer:

- Heat Sources in E-Axle: (1) Motor copper losses ($I^2 \times R$), (2) Motor iron losses (eddy current + hysteresis), (3) Inverter switching and conduction losses, (4) Gearbox friction losses.
- Total losses at rated power: Motor ~5–8% losses + Inverter ~2–3% losses = 150kW E-axle generates ~10–15kW of waste heat.
- Cooling Architecture: Oil-cooling for motor windings (oil spray or oil jacket — excellent contact with conductors); water-glycol cooling for inverter power modules and motor housing.

- Motor Oil Cooling: Transmission oil circulated through motor housing or sprayed on end-windings — high thermal capacity, electrically insulating, lubricates bearings simultaneously.
- Inverter Water Cooling: Cold plate bonded to IGBT/MOSFET modules; water-glycol loop shared with motor housing or battery cooling circuit.
- Thermal Coupling Challenge: Motor, inverter, and gearbox operate at different temperature limits; motor windings ~180°C max; IGBT junction ~150°C max; gearbox oil ~140°C max.
- Thermal Runaway in Inverter: IGBT junction temperature must stay below 150°C; thermal resistance $R_{th(j-c)}$ determines max power dissipation:
 $\Delta T = P_{loss} \times R_{th}$.
- Example: IGBT $P_{loss} = 500W$, $R_{th(j-c)} = 0.15^\circ C/W \rightarrow \Delta T = 75^\circ C$; with $T_{coolant} = 65^\circ C \rightarrow T_{junction} = 140^\circ C < 150^\circ C$ limit. Marginal — cooling flow must be maintained.
- Future Challenge: At 800V with SiC MOSFETs, switching losses reduce significantly (SiC ~60% lower switching losses than Si IGBT) simplifies thermal management.

Q6 [Evaluator] (5 Marks)

Discuss the advantages, challenges, and future trends of E-Axle technology. How will E-Axle systems evolve to meet future EV requirements?

Model Answer:

- Current Advantages: Compactness (50% smaller than equivalent separate components), high efficiency (>90% system), modularity, and scalability across vehicle segments.
- Challenge 1 – Acoustic NVH: Gear whine from single-stage reduction gear at high motor RPM; solution: helical gears, optimized gear mesh, acoustic damping.
- Challenge 2 – Thermal Integration: Shared cooling between motor and inverter at different optimal temperatures; multi-circuit cooling needed.
- Challenge 3 – High Voltage Isolation: 800V in compact package requires stringent insulation between HV windings and grounded housing; creepage distances reduce.
- Challenge 4 – Cost: High-power-density magnets (HREM), precision manufacturing, integrated electronics → E-axle costs \$2,000–8,000 depending on power level.
- Future Trend 1 – SiC Inverter Integration: Silicon Carbide MOSFETs replace IGBTs; enable higher switching frequency, lower losses, higher temperature → more compact inverter.
- Future Trend 2 – Higher Voltage (800V): Lower current for same power → thinner conductors, lower copper loss, faster charging compatibility.
- Future Trend 3 – 2-Speed E-Axle: Second gear ratio for heavy-duty/truck applications; enables both high tractive force and high top speed.

- Future Trend 4 – E-Axle with Active Suspension: Integrated active damping and ride height adjustment in same module — mechatronics convergence.
- Market Growth: E-axle market forecast to grow from \$3B (2023) to \$25B (2030) as EV adoption accelerates globally.

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