moto zero
by Transitions Lab

05

MODULE 5

Electric motorcycles

How electric two-wheelers turn stored electrochemical energy into traction, and how to inspect, diagnose and service their motors, controllers, batteries and chargers safely.



A technical course on how motorcycles work
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THE SERIES

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05 **Electric motorcycles**

Each chapter opens with learning objectives and closes with review questions and worked answers. Reference data comes from the K-Light 125 maintenance manual unless stated otherwise; always use the manual for the machine in front of you. Explorer exercises refer to the interactive anatomy explorer at transitionslab.org/motorcycle-anatomy.

CHAPTER 5.1

Architecture of an electric two-wheeler

LEARNING OBJECTIVES

- Classify electric two-wheelers by regulatory category (pedelec, speed pedelec, L1e moped, L3e motorcycle) and state the speed and power limits that define each.
- Trace the energy chain from charger to tyre contact patch and compare battery-to-wheel efficiency with the tank-to-wheel efficiency of a 125 cc petrol engine using worked numbers.
- Name every major component of an electric powertrain (battery, BMS, contactor and pre-charge, controller, motor, VCU, DC-DC converter, charger, HMI, CAN bus) and describe its function.
- Explain why a pre-charge circuit is needed and calculate its time constant.
- Place commercial platforms (Zero, Energica, Roam, Ather, Gogoro, Spiro, Ampersand) within the architecture by voltage class, battery strategy and drive layout.

Categories and regulatory limits

Electric two-wheelers span a power range of more than two orders of magnitude, from a 250 W bicycle hub motor to a 100 kW sports motorcycle, and the regulatory category a machine falls into decides whether it needs type approval, registration, insurance, a helmet and a licence. In Europe the framework is Regulation (EU) No 168/2013 on two- or three-wheel vehicles and quadricycles, which defines the L categories, together with EN 15194 for electrically power assisted cycles that sit outside it. Most other markets use similar thresholds, often copied from the UNECE definitions, although India, China and the East African states each have national variations.

Category	Typical examples	Speed limit	Power limit	Notes
Pedelec (EPAC, EN 15194)	City and cargo e-bikes	Assistance cuts off at 25 km/h	250 W maximum continuous rated power	Motor assists only while the rider pedals; legally a bicycle in the EU
Speed pedelec (L1e-B)	45 km/h e-bikes	45 km/h design speed	4 kW	Type-approved moped; registration plate, helmet and moped licence
E-moped (L1e-B)	Step-through e-scooters, NIU, Super Soco entry models	45 km/h	4 kW	Includes seated electric scooters in the 50 cc equivalent class
E-motorcycle L3e-A1	125-equivalent commuters, Roam Air, many Asian and African taxi machines	Above 45 km/h	11 kW continuous, power-to-mass ratio ≤ 0.1 kW/kg	The electric equivalent of the 125 cc learner class
E-motorcycle L3e-A2 and A3	Zero SR/F, Energica Ego, LiveWire	Above 45 km/h	A2 up to 35 kW; A3 unlimited	Class B high-voltage systems are normal at this level

Two points in this table need care. First, the power limits refer to **maximum continuous rated power**, measured as the power the motor can sustain for 30 minutes on a test bench (UNECE Regulation No 85 sets the measurement method), not peak power. A motorcycle with an 11 kW continuous rating can legitimately deliver 20 kW or more for a few seconds, which is why some L3e-A1 electric machines accelerate harder than a 125 cc petrol bike. Second, the word "e-scooter" covers two quite different machines: the seated step-through scooter, which is an L1e or L3e

vehicle, and the stand-up kick scooter, which most EU states regulate nationally as a personal light electric vehicle outside the L categories. This module deals with the seated machines and with motorcycles; the electrical principles apply equally to pedelecs and kick scooters, which simply operate at lower voltage (24–48 V) and power.

The speed and power thresholds shape the engineering. A pedelec motor must be torque- or cadence-sensed so it assists only while the rider pedals, and its 250 W continuous rating keeps the motor, controller and battery small enough for a 36 V or 48 V system with a 0.4–0.8 kWh battery. A 45 km/h moped needs roughly 1.5–3 kW at the wheel to hold top speed into a headwind and a 1.5–3 kWh battery for a useful range. An L3e-A1 commuter needs 3–11 kW continuous and 3–7 kWh, and by this point the battery voltage usually rises to 60–96 V to keep currents manageable. Full-size motorcycles with 40–100 kW peak motors use 100–400 V packs of 10–22 kWh, because the current at 48 V would be over 1,000 A and the cables, connectors and switching devices would become impractically heavy.

The energy chain

Tank-to-wheel versus battery-to-wheel

A petrol motorcycle converts chemical energy in the fuel into heat, then into mechanical work in the cylinder, with the second law of thermodynamics and the throttling, friction and heat losses discussed in Module 2 limiting the result. A small air-cooled single reaches perhaps 28–32 % brake thermal efficiency at its best operating point (wide throttle, mid-range speed), but in urban riding it spends most of its time at part throttle, idling or decelerating, where efficiency falls to 10–20 %. The electric machine skips the heat engine entirely: the battery delivers electrical energy directly, and each conversion step loses only a few percent.

$$\eta_{TTW\ (petrol,\ urban)} \approx 0.12 - 0.20$$

$$\eta_{BTW} = \eta_{battery} \times \eta_{controller} \times \eta_{motor} \times \eta_{transmission}$$

$$\eta_{BTW} \approx 0.96 \times 0.97 \times 0.90 \times 0.96 \approx 0.80$$

$$\eta_{GTB} = \eta_{charger} \times \eta_{charge,battery} \approx 0.90 \times 0.97 \approx 0.87$$

where η_{TTW} is **tank-to-wheel efficiency**, η_{BTW} is **battery-to-wheel efficiency**, and η_{GTB} is **grid-to-battery** (wall-plug) efficiency including charger losses and the battery's own charge inefficiency. The motor term is an average over a real riding cycle; motors reach 92–96 % at their best point but drop to 70–85 % at low speed and high torque, which is where an urban commuter spends much of its time. A chain or belt final drive loses 2–5 %, and a hub motor with no transmission avoids this loss but usually runs at a less favourable point on its efficiency map.

Worked comparison: 125 cc petrol versus a 125-equivalent electric motorcycle

A 125 cc EFI commuter such as the K-Light 125 or a Honda CG125 typically uses about 2.0–2.8 L/100 km in mixed riding. Take 2.5 L/100 km. Petrol has a lower heating value of about 32 MJ/L, or 8.9 kWh/L.

$$E_{fuel} = 2.5\ L/100\ km \times 8.9\ kWh/L \approx 22.3\ kWh/100\ km$$

$$E_{wheel\ (petrol)} = 22.3 \times 0.13 \approx 2.9\ kWh/100\ km$$

$$E_{battery\ (electric)} = 2.9 / 0.80 \approx 3.6\ kWh/100\ km$$

$$E_{grid\ (electric)} = 3.6 / 0.87 \approx 4.1\ kWh/100\ km$$

The electric machine therefore needs about 4 kWh from the grid where the petrol machine burns about 22 kWh of fuel, a factor of roughly five to six. Measured consumption of 125-equivalent electric commuters, typically 2–4 kWh/100 km at the battery terminals, agrees with this estimate; the spread depends on speed (aerodynamic drag

rises with the square of speed, so the same machine may use 2.5 kWh/100 km at 40 km/h and 5 kWh/100 km at 80 km/h), payload and terrain. Regenerative braking (Chapter 5.3) recovers some kinetic energy in stop-start traffic, which the petrol bike dissipates as heat in its brakes.

The comparison shows why electric two-wheelers are economically attractive in markets where motorcycles are working vehicles. A Nairobi boda boda covering 120 km a day burns about 3 L of petrol; the electric equivalent needs about 4–5 kWh of grid electricity. It also shows why the battery dominates the design: 22 kWh of petrol weighs about 18 kg including a light tank, while 3.6 kWh of lithium-ion battery weighs 18–25 kg. Petrol stores roughly 12,000 Wh/kg of chemical energy; a lithium-ion pack stores 120–180 Wh/kg at pack level. The efficiency of the electric drive recovers part of this gap, but not all of it, which is why electric motorcycles carry smaller usable energy, cover shorter ranges and are designed around swapping or fast charging.

> **NOTE** **Primary energy and emissions**
>
> Battery-to-wheel efficiency says nothing about how the electricity was generated. A well-to-wheel comparison must include power-station efficiency and transmission losses, and the emissions result depends on the grid mix. Kenya, where geothermal, hydro and wind supply roughly 85–90 % of grid electricity, gives an electric motorcycle a far lower carbon intensity per kilometre than a coal-heavy grid does. Battery manufacturing adds an embedded emission that is paid back over the first several thousand kilometres.

Component map

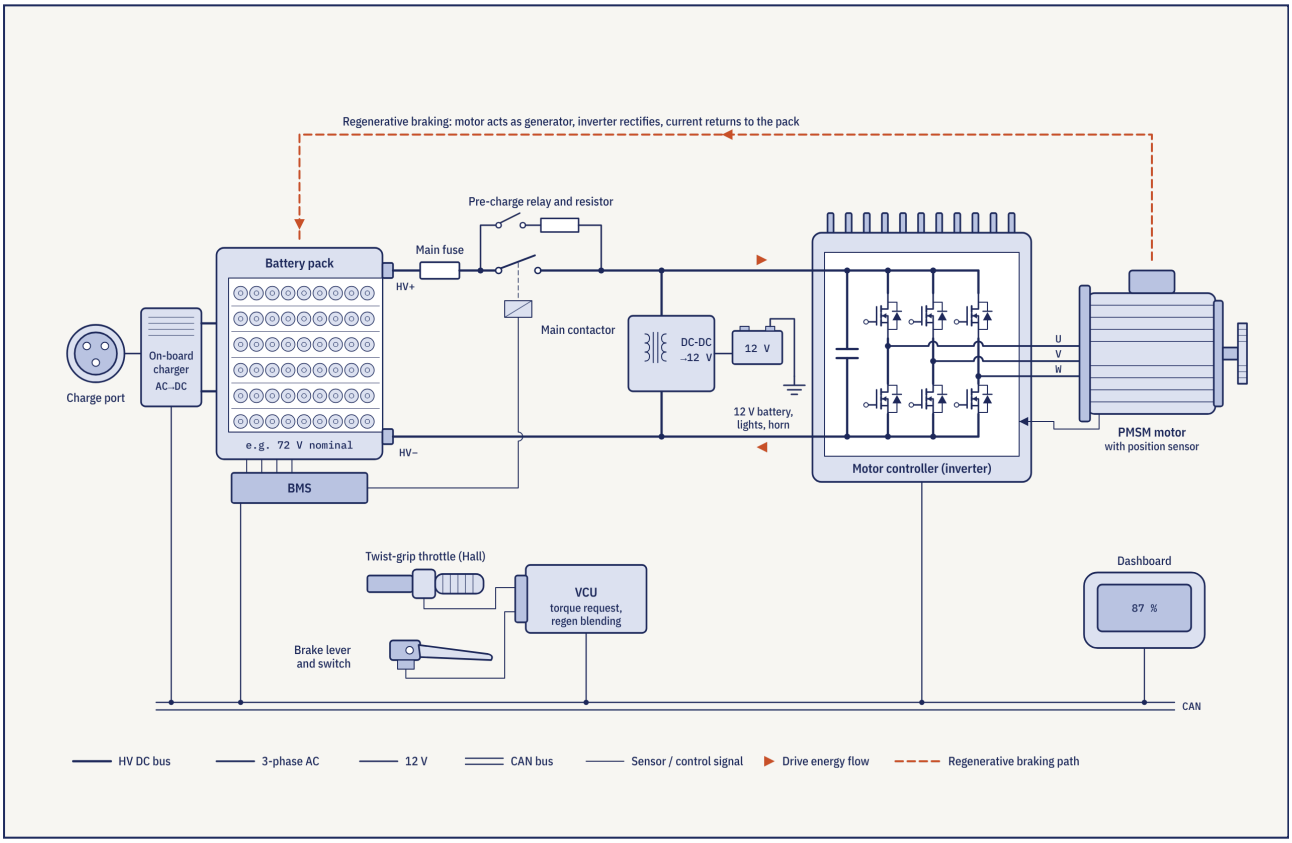


FIGURE 5.1 Block diagram of an electric motorcycle powertrain: battery pack and BMS, main fuse, pre-charge circuit and main contactor, motor controller with six-switch inverter, motor with position sensor, vehicle control unit, DC-DC converter to the 12 V system, charge port and charger, CAN bus linking the control units, throttle and brake inputs, and the regenerative energy path.



FIGURE 5.2 The electric scrambler in three-quarter view.
Render: Transitions Lab, CC BY-SA 4.0

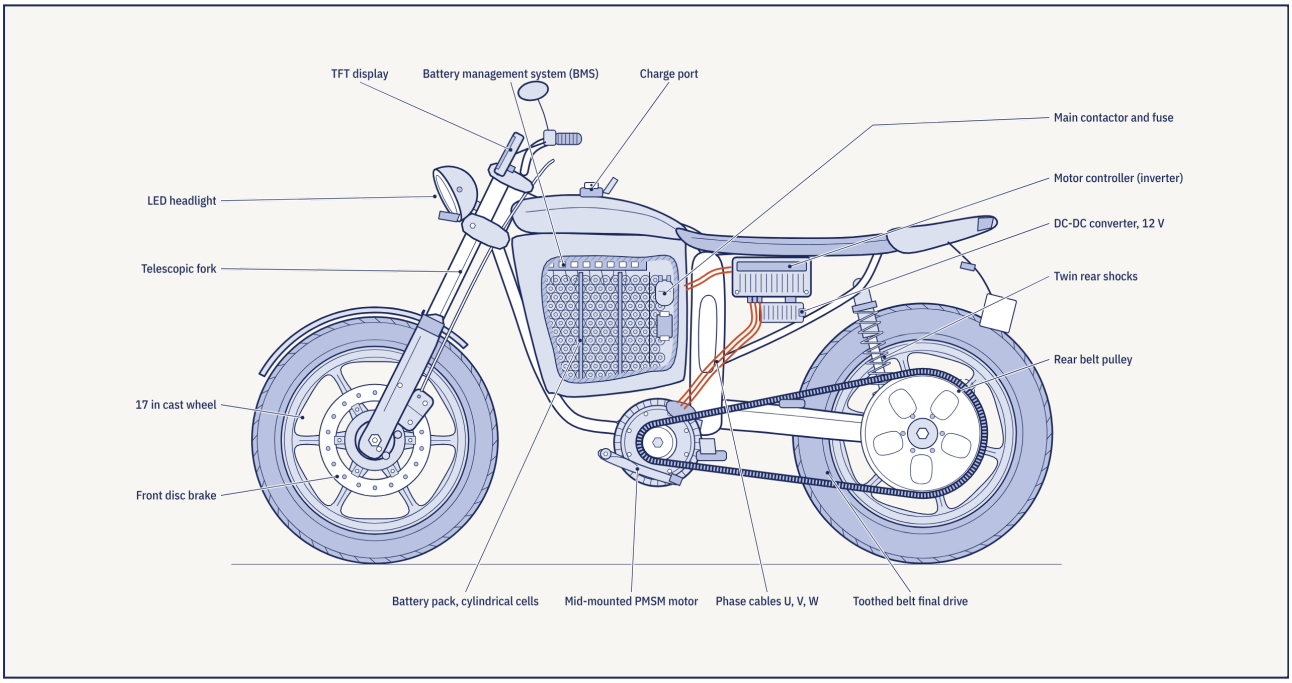


FIGURE 5.3 Electric motorcycle with the battery pack, mid-drive motor and controller shown inside the frame.



FIGURE 5.4 The course's electric scrambler. The battery pack fills the frame where a petrol engine would sit, with the motor and controller below it driving the rear wheel.

Render: Transitions Lab, CC BY-SA 4.0

An electric motorcycle has fewer moving parts than a petrol one but more control units. The traction path carries tens to hundreds of amps between the battery and the motor; the control path is a low-voltage network of sensors and processors that decides how much of that current flows and when.

Battery pack

The **battery pack** stores energy as lithium-ion (or increasingly sodium-ion) cells connected in series to build voltage and in parallel to build capacity (Chapter 5.4). It contains the cells, their mechanical holders and thermal interface, the busbars or nickel strips, temperature sensors, the **battery management system (BMS)**, a **main fuse**, and on high-voltage packs the contactors and a manual service disconnect. Its enclosure provides **ingress protection** (IP67 is normal for traction packs), crash protection and a vent path for gases released in a cell failure. Removable packs for swapping systems add a latching mechanism, a rugged connector with sequenced pins and handles; they are limited to roughly 10–15 kg so that a rider can lift them.

Battery management system

The BMS measures every series cell group's voltage, several cell and busbar temperatures and the pack current. From these it estimates state of charge (SOC) and state of health (SOH), balances cells, and protects the pack by opening the contactors or MOSFET switches if any limit is exceeded. It communicates allowed charge and discharge current limits to the controller and charger, typically over CAN, so that the controller reduces power as the battery becomes cold, hot or nearly empty.

Main fuse, contactor and pre-charge

The main fuse protects the wiring against a short circuit that the BMS cannot interrupt fast enough. It must be rated for DC: a DC arc does not self-extinguish at a current zero as an AC arc does, so DC fuses use sand-filled bodies and longer elements. The **main contactor** is an electromechanical relay, rated for hundreds of amps, that connects the pack to the controller when the ignition is switched on. High-voltage packs use two contactors (positive and negative) so that the pack is isolated on both poles when the vehicle is off; many 48–72 V packs use a MOSFET switch inside the BMS instead.

The controller has a large **DC-link capacitor bank** (typically 1,000–5,000 µF for a 72 V controller, a few hundred µF for a 400 V inverter using film capacitors) across its input to supply the ripple current of the switching inverter. If the contactor closed directly onto an empty capacitor, the only limit on the inrush current would be the wiring resistance and the capacitor's equivalent series resistance, a few milliohms, giving a spike of **thousands of amps** that pits or welds the contactor tips and stresses the capacitors. The **pre-charge circuit** prevents this by first connecting the capacitor through a resistor, letting it charge to near pack voltage, and only then closing the main contactor.

```
τ = R × C
V_C(t) = V_pack × (1 − e^(−t/τ))
P_R,initial = V_pack² / R
```

For a 72 V pack, a 2,000 µF capacitor bank and a 100 Ω pre-charge resistor, τ = 100 × 0.002 = 0.2 s. After 3τ (0.6 s) the capacitor reaches 95 % of pack voltage and after 5τ (1.0 s) over 99 %. The resistor dissipates 72² / 100 ≈ 52 W at the first instant but only for a fraction of a second, so a 5–10 W wirewound resistor rated for pulse energy is adequate; the energy it absorbs equals the energy stored in the capacitor, ½CV² = 0.5 × 0.002 × 72² ≈ 5.2 J. The controller or BMS normally checks that the DC-link voltage has reached **90–95 %** of pack voltage within a set time before it closes the main contactor; if not, it logs a pre-charge fault, because a slow pre-charge indicates a short or heavy leakage on the DC link.

Motor controller

The **motor controller** (also called the **inverter** or motor drive) converts battery DC into three-phase AC of variable frequency and amplitude, using six power switches (MOSFETs below about 150 V, IGBTs or silicon-carbide MOSFETs at higher voltages). It reads the throttle demand, motor position and phase currents, and regulates the motor torque. It also runs the motor as a generator during regenerative braking. Chapter 5.3 covers it in detail.

Motor

The traction motor is almost always a permanent-magnet synchronous machine (PMSM or BLDC), either in the rear wheel hub or mounted in the frame driving the wheel through a chain, belt or gear reduction. Chapter 5.2 explains the types.

Vehicle control unit and HMI

On simple machines the controller doubles as the vehicle brain. On more sophisticated machines a separate **vehicle control unit (VCU)** arbitrates between the rider's inputs (throttle, brake switches, ride-mode selector, side-stand switch), the BMS limits, the controller and the charger. It enforces **interlocks**: no drive torque with the side stand down or while a charging cable is connected, no regeneration when the BMS reports a full or cold battery. The **human-machine interface (HMI)** is the dashboard, often a TFT display that shows SOC, range estimate, power, ride mode and fault codes, and on connected machines (Ather, Gogoro, Zero) a telematics unit with a cellular modem that reports location, battery data and faults to the manufacturer and receives over-the-air software updates.

DC-DC converter and 12 V system

Lights, horn, indicators, the dashboard and the control units run from a 12 V system, as on a petrol motorcycle. A **DC-DC converter** steps the traction voltage down to about 13.5–14.4 V, typically rated 150–500 W. Some machines keep a small 12 V lead-acid or lithium auxiliary battery so that the control electronics can wake up and close the main contactor; others power the low-voltage system only from the DC-DC converter and wake it from the traction pack directly. The DC-DC converter is isolated (transformer coupled) on high-voltage machines so that the 12 V chassis-referenced system has no galvanic connection to the traction circuit.

Charger and charge port

The **charger** converts AC mains to a controlled DC current for the battery. It may be on board (inside the motorcycle, with a mains inlet), off board (a portable brick or wall unit with a DC output plug) or part of a swap station that charges removable packs. DC fast-charging machines have a port that connects the pack, through the contactors, directly to an external charger that the BMS controls by digital communication. Chapter 5.5 covers charging.

CAN bus

The **controller area network** (CAN, ISO 11898) links the BMS, controller, VCU, charger, DC-DC converter and dashboard on a two-wire twisted pair (CAN-H and CAN-L) terminated with 120 Ω at each end, so a healthy bus measures **about 60 Ω** between CAN-H and CAN-L with the power off. Typical bit rates are 250 or 500 kbit/s. The BMS broadcasts cell voltages, temperatures, SOC and current limits; the controller broadcasts speed, torque, phase current, temperatures and faults. Many low-cost controllers use a UART or single-wire protocol to the dashboard instead of CAN, which limits diagnostic access.

Real platforms

Manufacturers make different choices within the same architecture. The specifications below are those published by the manufacturers at the time of writing; model years change them, so always check the current data for the specific machine being serviced.

Platform	Market	Architecture notes
Zero SR/F	Europe, North America	Frame-mounted Z-Force 75-10 interior permanent-magnet motor, belt final drive, fixed pack (17.3 kWh in recent versions), about 190 Nm peak motor torque
Energica Ego	Europe	Liquid-cooled permanent-magnet motor, chain drive, fixed pack of about 21.5 kWh at a nominal voltage of around 300 V, CCS DC fast charging
Roam Air	Kenya, East Africa	Two removable packs of 3.24 kWh each, 3 kW nominal motor, 90 km/h top speed, rated range of 180 km on both packs; designed for boda boda payloads

Platform	Market	Architecture notes
Ather 450 series	India	Frame-mounted PMSM with belt drive, fixed pack of about 2.9–3.7 kWh, connected dashboard, fast charging on the Ather Grid network using the LECCS connector
Gogoro	Taiwan and licensed partners	Removable packs of about 1.3 kWh (first-generation packs, 9 kg, Panasonic 18650 cells) exchanged at automated GoStations; two packs per scooter
Bajaj Chetak	India	Fixed pack of roughly 3 kWh class, step-through scooter with frame-mounted motor
Super Soco	China, export	48–72 V removable packs, rear hub motors on the smaller models
Spiro	Kenya, Uganda, Rwanda, Nigeria, Benin, Togo	Battery-swap motorcycles; over 50,000 machines and over 1,000 swap stations reported in late 2025
Ampersand	Rwanda, Kenya	Battery-swap motorcycles for taxi riders, swap price reported at about 2 USD for roughly 80 km

The table shows two families. Premium motorcycles (Zero, Energica) use fixed high-voltage packs of 13–22 kWh with on-board AC charging and, on some models, DC fast charging; their battery is the most expensive single part of the vehicle and is designed to last the life of the machine. Mass-market commuters and taxi machines in Asia and Africa use low-voltage packs (48–72 V, 1.3–3.5 kWh each), often removable, and increasingly separate battery ownership from vehicle ownership through swapping subscriptions, which turns the battery into a fleet asset maintained by the operator. That business model shapes engineering: swap packs must survive thousands of insertions, rough handling, shared use by many riders and charging at high rates in the station.

> EXPLORER EXERCISE · transitionslab.org/motorcycle-anatomy **Compare the drivetrain parts**
>
> Open the exploded diagram at transitionslab.org/motorcycle-anatomy and list every part from Engine (14) to Drive chain (22) and Battery (27) to Regulator/rectifier (29). For each, write which electric component replaces it, which remains unchanged, and which disappears (for example, Throttle body and injector has no electric equivalent; Battery becomes the auxiliary 12 V battery; Regulator/rectifier is replaced by the DC-DC converter).

REVIEW QUESTIONS

1. State the speed and power limits for a pedelec under EN 15194 and for an L1e-B moped under Regulation (EU) 168/2013.
2. Why do type-approval power limits refer to continuous rated power rather than peak power, and what consequence does this have for acceleration of electric L3e-A1 machines?
3. A 125 cc motorcycle uses 2.2 L/100 km. Calculate its fuel energy per 100 km, and the battery energy an electric equivalent with 80 % battery-to-wheel efficiency would need if the petrol machine's tank-to-wheel efficiency is 14 %.
4. List the conversion steps between the AC socket and the rear tyre of a plug-in electric motorcycle and give a typical efficiency for each.
5. What is the function of the pre-charge resistor, and what would happen to the main contactor without it?
6. A 96 V pack feeds a controller with 3,300 µF of DC-link capacitance through a 150 Ω pre-charge resistor. Calculate the time constant and the time to reach 95 % of pack voltage.
7. Why do high-voltage packs normally use contactors on both the positive and negative poles?

8. Explain why electric motorcycles above about 20 kW use pack voltages of 100–400 V rather than 48–72 V.
9. What resistance should you measure between CAN-H and CAN-L with the power off on a correctly terminated bus, and what does a reading of 120 Ω indicate?
10. Give two engineering consequences of designing a battery pack for a public swapping network rather than as a fixed pack.
11. Which petrol-motorcycle components from the F06 parts list have no counterpart on an electric motorcycle, and which are replaced by an electric component?

ANSWERS

1. A pedelec gives assistance only while the rider pedals, up to 25 km/h, with a maximum continuous rated motor power of 250 W. An L1e-B moped has a maximum design speed of 45 km/h and a maximum continuous rated power of 4 kW.
2. Continuous rated power, measured as the 30-minute power on a bench, reflects the sustained heat-limited capability of the motor and is a reproducible basis for classification. Because electric motors and controllers can deliver two to three times their continuous power for several seconds, an L3e-A1 machine with an 11 kW continuous rating may produce 20–25 kW peak and accelerate harder than a 125 cc petrol machine of the same category.
3. Fuel energy = 2.2 × 8.9 = 19.6 kWh/100 km. Wheel energy = 19.6 × 0.14 = 2.74 kWh/100 km. Battery energy = 2.74 / 0.80 ≈ 3.4 kWh/100 km.
4. Charger AC to DC, 88–94 %; battery charge and discharge (coulombic and resistive losses), 95–98 % each way; controller DC to three-phase AC, 95–98 %; motor electrical to mechanical, 85–95 % depending on the operating point; chain or belt final drive, 95–98 %. The product from socket to tyre is typically 70–75 %.
5. The pre-charge resistor limits the inrush current while the controller's DC-link capacitors charge, so that the main contactor closes with only a small voltage across its contacts. Without it the inrush, limited only by milliohms of wiring and capacitor resistance, would reach thousands of amps, causing arcing that pits or welds the contact tips and stresses the capacitors and fuse.
6. $\tau = R \times C = 150 \times 0.0033 = 0.495$ s. 95 % is reached at $3\tau \approx 1.49$ s.
7. Opening both poles fully isolates the pack from the vehicle wiring when the vehicle is off or a fault is detected. A single-pole break would leave the other pole connected, so an insulation fault on that side, combined with a second fault, could still expose a person to pack voltage. Double-pole isolation also provides redundancy if one contactor welds.
8. For the same power, current is inversely proportional to voltage ($I = P / V$). A 60 kW drive at 48 V would draw about 1,250 A, requiring heavy cables, large busbars and connectors and very large switching devices, with I^2R losses that rise with the square of current. At 300 V the same power needs 200 A.
9. About 60 Ω, which is two 120 Ω terminating resistors in parallel. A reading of 120 Ω means one terminating resistor is missing or one end of the bus is disconnected, which causes signal reflections and intermittent communication faults.
10. The pack must be light enough for a person to lift (roughly 10–15 kg, hence about 1.3–3.5 kWh); its connector and latch must tolerate thousands of insertions and contamination; the BMS must identify the pack, log its history and authenticate with both vehicle and station; and the pack must tolerate rough handling and a range of charging conditions because no single owner controls its use.
11. No counterpart: Fuel tank (though the space is often used for storage or the battery), Air filter box, Throttle body and injector, Exhaust header and catalytic converter, Silencer. Replaced: Engine by the motor and controller; ECU by the VCU and controller; Regulator/rectifier by the DC-DC converter; Battery by the traction pack plus a small 12 V auxiliary battery; Drive chain and sprockets remain on chain-drive machines, become a belt on others, and disappear with a hub motor.

CHAPTER 5.2

Electric motors

LEARNING OBJECTIVES

- Explain torque production from the Lorentz force and the origin of back-EMF, and convert between the torque constant Kt and the speed constant Kv.
- Distinguish brushed DC, BLDC and PMSM machines, surface and interior magnet rotors, hub and mid-drive layouts, axial-flux and induction motors.
- Interpret a torque-speed curve and an efficiency map, including base speed, constant-torque and field-weakening regions.
- Identify the loss mechanisms in a motor, the cooling methods used, and the temperature limits set by windings and rare-earth magnets.
- Calculate motor power from torque and speed, and road speed from motor speed, reduction ratio and tyre circumference.

Electromagnetic basics

Force on a conductor and torque

A conductor carrying current I through a magnetic field of flux density B experiences a force at right angles to both, the **Lorentz force**. In a motor many conductors, arranged in coils on a stator, sit in the field of magnets on a rotor (or the reverse), and the sum of the forces at the air-gap radius produces torque.

```
F = B × I × L
T = F × r
T = Kt × I
```

where F is force in newtons, B is flux density in tesla (0.8–1.1 T in the air gap of a rare-earth permanent-magnet motor), I is current in amperes, L is the active length of conductor in the field in metres, r is the air-gap radius and Kt is the **torque constant** in N·m/A. Kt bundles the number of turns, the magnet strength and the geometry, so for a given motor, torque is proportional to current. That proportionality is why the controller regulates current, not voltage, when it is asked for a torque.

Back-EMF and the speed constant

A conductor moving through a magnetic field has a voltage induced in it (Faraday's law). In a spinning motor this voltage opposes the supply and is called **back-EMF**. It is proportional to speed.

```
E = Ke × ω
ω = 2π × n / 60
Kv = n / E (rpm per volt)
Kt = Ke = 60 / (2π × Kv) ≈ 9.55 / Kv (SI units, ideal machine)
```

where E is back-EMF in volts, Ke is the **back-EMF constant** in V·s/rad, ω is angular speed in rad/s, n is speed in rpm and Kv is the **speed constant**, the no-load speed reached per volt of supply. In consistent SI units an ideal machine has Kt numerically equal to Ke, because the electrical power E × I converted equals the mechanical power T × ω. In practice data sheets quote line-to-line or per-phase, peak or RMS values, so the exact factor between Kt and Ke on a three-phase motor data sheet may differ by √3 or √2; check which convention is used before comparing two motors.

Back-EMF sets the motor's maximum speed for a given supply. As the motor speeds up, E rises until it approaches the voltage the controller can apply, the voltage left to drive current through the winding resistance and inductance falls towards zero, and torque collapses. A motor with Kv = 50 rpm/V supplied from a 72 V pack can reach roughly 50 × 72 = 3,600 rpm at no load, less under load because of resistive drop. Its torque constant is 9.55 / 50 ≈ 0.19 N·m/A, so 200 A gives about 38 N·m. A motor wound with fewer turns has a higher Kv (faster) and lower Kt (less torque per amp); it gives the same power but needs more current for the same torque. Choosing the winding is therefore a matching exercise between motor, pack voltage and controller current rating.

Worked calculation: power from torque and speed

$$P = T \times \omega = T \times 2\pi \times n / 60$$

A mid-drive motor delivering 190 N·m at 3,000 rpm produces P = 190 × 2π × 3,000 / 60 ≈ 59.7 kW. The same motor at 6,000 rpm with torque reduced to 95 N·m produces the same 59.7 kW: it is operating in the constant-power region described below. A commuter hub motor delivering 120 N·m at 600 rpm produces only 7.5 kW, because hub motors turn at wheel speed.

Motor types

Brushed DC motor

The oldest type uses a stationary field (permanent magnets or a field winding) and a rotating armature whose coils are switched by a mechanical commutator and carbon brushes, so that current in each coil reverses as it passes the poles. **Brushed motors** are simple to control (a single DC chopper sets the voltage) but the brushes wear, spark, limit maximum speed and add 5–10 % friction and contact loss. They survive on low-cost mobility scooters, some older e-bikes and early conversions, but have been displaced in all serious two-wheelers by brushless machines.

BLDC and PMSM

A brushless machine moves the windings to the stator, where they can be cooled through the housing, and puts the magnets on the rotor. **Electronic commutation** by the controller replaces the commutator, using a rotor position sensor or an estimate of position. Two variants are distinguished by the shape of their back-EMF.

Property	BLDC (trapezoidal)	PMSM (sinusoidal)
Back-EMF waveform	Trapezoidal, flat top for 120° electrical	Sinusoidal
Winding	Concentrated, often fractional-slot	Distributed or fractional-slot concentrated, shaped for sinusoidal EMF
Ideal drive	Six-step (block) commutation, two phases conducting	Sinusoidal currents, field-oriented control

Property	BLDC (trapezoidal)	PMSM (sinusoidal)
Position sensing needed	Three Hall sensors (60° resolution)	Encoder or resolver, or Hall sensors with interpolation
Torque ripple	Higher, at each commutation step	Low when driven sinusoidally
Typical use	E-bikes, low-cost hub motors	Ather, Zero, Energica, most modern motorcycles

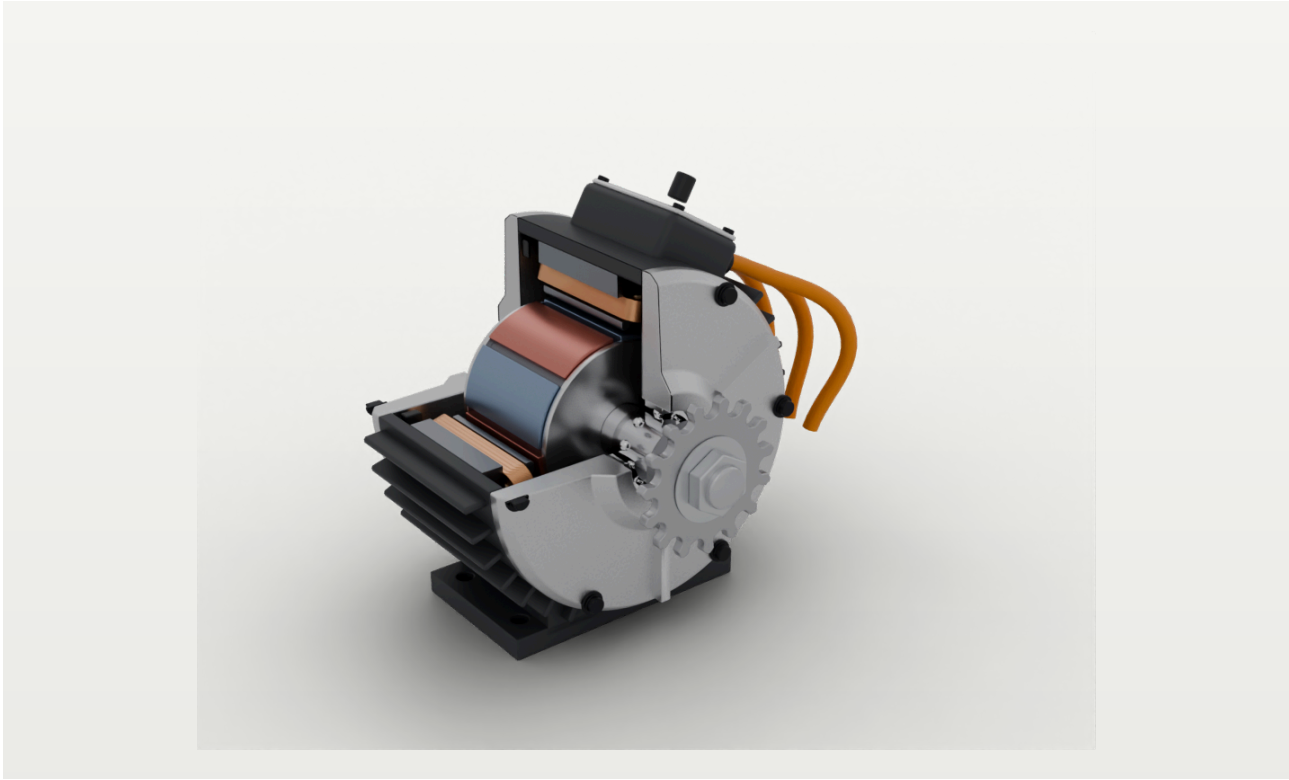


FIGURE 5.5 A permanent-magnet synchronous motor cut away: finned housing, 12-tooth stator with copper windings, rotor with alternating magnets, bearings and output shaft.

Render: Transitions Lab, CC BY-SA 4.0

In practice the boundary is blurred: most hub motors sold as "BLDC" have nearly sinusoidal back-EMF, and modern controllers drive them with sinusoidal or field-oriented control using Hall sensors for initial position and interpolation between Hall edges. The machine is physically the same; the drive strategy decides the smoothness and efficiency.

Pole pairs and electrical frequency

Permanent-magnet motors have several pairs of magnetic poles. The electrical frequency the controller must generate equals the mechanical speed times the **pole-pair count**.

```
f_e = p × n / 60
```

A hub motor with 23 pole pairs (46 magnets, a common e-bike and moped design) at 600 rpm runs at f_e = 23 × 600 / 60 = 230 Hz. A mid-drive motor with 5 pole pairs at 6,000 rpm runs at 500 Hz. Many poles give high torque density at low speed (the hub motor's case), while few poles keep frequency, and therefore iron loss and switching demands, within limits at high speed.

Surface and interior magnets

In a **surface permanent-magnet (SPM)** rotor the magnets are bonded to the rotor surface, sometimes retained with a carbon-fibre or glass-fibre sleeve. The rotor is magnetically round, so inductance along the magnet axis (Ld) equals inductance across it (Lq), and torque comes only from the magnet flux. SPM rotors are simple and give high torque per amp at low speed, which suits outer-rotor hub motors where centrifugal loads press the magnets against the rotor ring.

In an **interior permanent-magnet (IPM)** rotor the magnets sit in slots punched into the laminated rotor stack, often in a V or double-V shape. The iron bridges retain the magnets mechanically at high speed. Because the magnets have a permeability close to air, the rotor is magnetically salient: Lq is larger than Ld, often by a factor of 2–3. The saliency adds **reluctance torque**, the tendency of iron to align with a magnetic field, to the magnet torque. A controller that injects negative d-axis current exploits both (Chapter 5.3), and the same negative d-axis current weakens the effective magnet flux at high speed, extending the speed range. IPM machines are the standard choice for frame-mounted mid-drive motors on electric motorcycles; the Zero Z-Force motor, for example, is an interior permanent-magnet design.

Hub motor versus mid-drive

A **hub motor** places an outer-rotor machine inside the rear wheel: the stator is fixed to the axle, which is clamped in the swingarm and does not rotate, and the rotor forms the wheel hub, carrying the rim directly or through spokes. Phase and Hall wires leave through a hollow axle. There is no chain, belt or gearbox, no lubrication and almost no drive noise, and the large air-gap diameter gives high torque. The penalties are **unsprung mass** and limited cooling. A 3 kW moped hub motor weighs 10–15 kg against 3–5 kg for a conventional rear wheel hub and brake, so the rear suspension must control a much heavier wheel, which degrades grip and ride over bumps. The stator is sealed inside a rotating drum and sheds heat mainly through the axle and by air circulating inside the hub, so sustained hill climbing at low speed, where current and copper loss are highest, drives winding temperature up quickly. Geared hub motors (common on pedelecs) add a planetary reduction inside the hub so that a smaller, faster motor can be used.

A **mid-drive** mounts an inner-rotor motor in the frame and drives the wheel through a reduction: a toothed belt (Zero, Ather), a chain (Energica, many conversions) or a gear train. Unsprung mass is no greater than on a petrol bike, the motor sits low and central, and it can be air, oil or liquid cooled through a dedicated housing. The reduction lets the motor run at 3,000–12,000 rpm, where a small motor delivers high power, and the ratio can be chosen by sprocket size. Most electric motorcycles use a single fixed ratio; the motor's wide speed range removes the need for a gearbox.

Worked calculation: road speed from motor speed

```
n_wheel = n_motor / i
v = n_wheel × C_roll × 60 / 1000 (km/h)
```

where i is the overall reduction ratio and C_roll is the tyre rolling circumference in metres. A mid-drive motor turning at 5,000 rpm drives a belt with a 22-tooth front pulley and a 132-tooth rear pulley (i = 6.0) and a 140/70-17 tyre with rolling circumference of about 1.93 m.

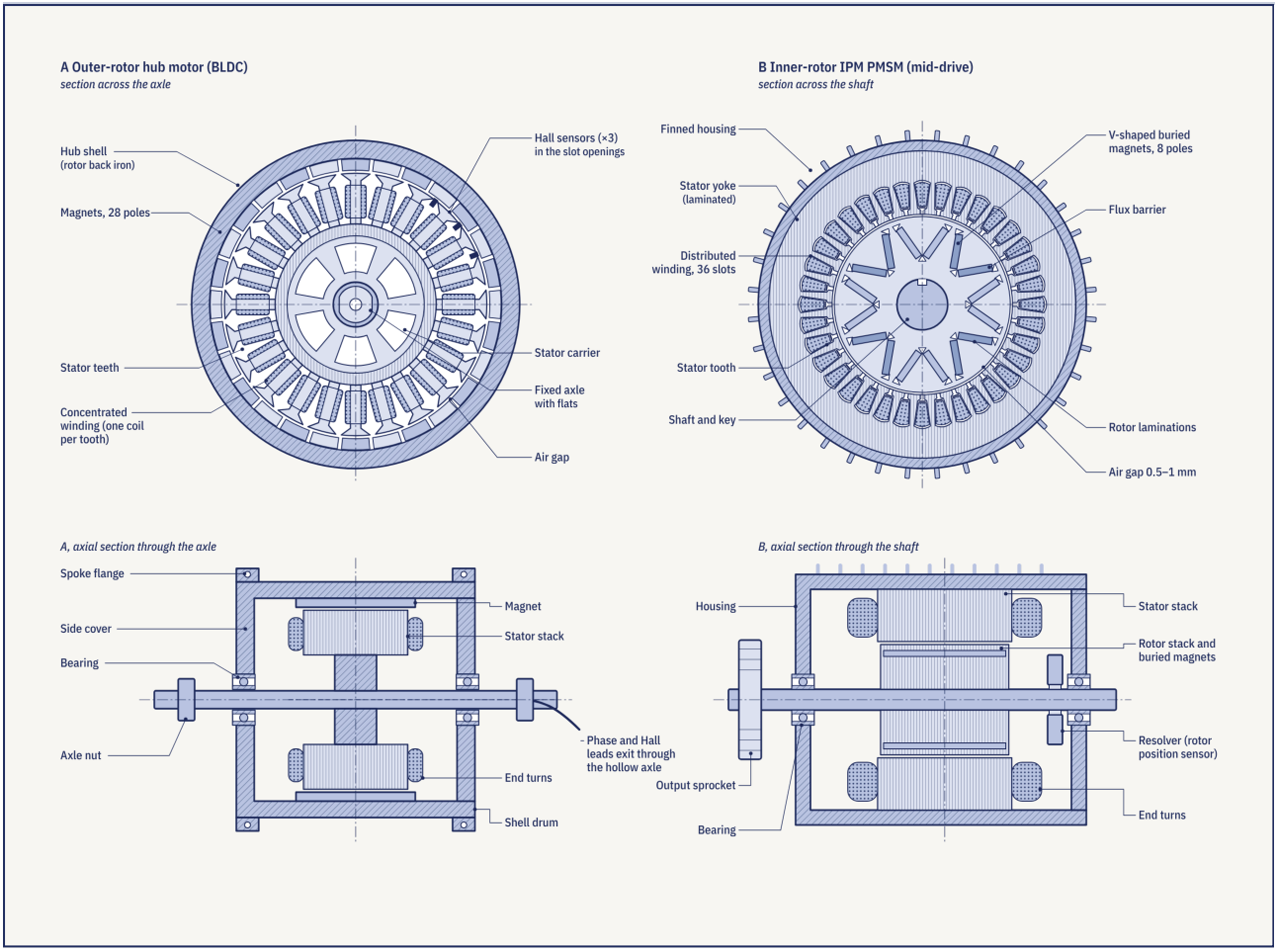


FIGURE 5.6 Sectional views of two electric motors: an outer-rotor hub motor with stator teeth, windings, surface magnets on the rotor ring, Hall sensors and wheel bearings; and an inner-rotor interior permanent-magnet synchronous motor for mid-drive mounting with laminated stator, distributed windings, V-shaped buried magnets, position sensor and bearings.

```
n_wheel = 5,000 / 6.0 = 833 rpm
v = 833 × 1.93 × 60 / 1000 ≈ 96 km/h
```

Wheel torque is motor torque multiplied by the ratio and the transmission efficiency, so 40 N·m at the motor becomes 40 × 6.0 × 0.97 ≈ 233 N·m at the wheel, and with a rolling radius of 0.307 m that gives a tractive force of about 760 N.

Axial-flux motors

In the radial-flux machines described so far, flux crosses a cylindrical air gap radially. In an **axial-flux machine** the flux crosses a flat disc-shaped gap parallel to the shaft, between a stator disc and one or two rotor discs carrying magnets. Torque is produced at a large mean radius in a short axial length, giving high torque density in a pancake shape; yokeless designs remove stator back-iron and save more mass. Axial-flux motors (Emrax, YASA and similar) appear in racing and some premium electric motorcycles, and some manufacturers place them within the swingarm pivot area or wheel. They are harder to manufacture: the air gap must be held to a fraction of a millimetre over a large diameter against strong axial magnetic attraction between rotor and stator, so bearing preload and structural stiffness are critical.

Induction motors

An **induction (asynchronous) motor** has no magnets: a rotating field from the stator induces currents in a squirrel-cage rotor of aluminium or copper bars, and the rotor runs slightly slower than the field (**slip**, typically 2–5 % at rated load). Induction motors avoid rare-earth cost and supply risk and have no back-EMF when unpowered, so they freewheel with no drag and cannot generate a dangerous voltage if the controller fails. Their drawbacks for two-wheelers are lower efficiency at partial load (rotor bar losses) and lower torque density, and they need a field-oriented controller that estimates slip. They are rare on motorcycles but appear in some industrial-derived conversions.

Torque-speed characteristics

A permanent-magnet motor driven by a current-limited controller from a fixed battery voltage has a torque-speed envelope with two regions separated by the **base speed**.

- **Constant-torque region** (0 to base speed): the controller can push its maximum current into the motor because back-EMF is still well below the available voltage. Torque is limited by current (controller rating, or the motor's thermal limit), so torque is flat and power rises linearly with speed.
- **Constant-power or field-weakening region** (above base speed): back-EMF has reached the voltage limit. The controller injects negative d-axis current to oppose the magnet flux, reducing effective back-EMF so that current can still flow. Torque falls roughly in inverse proportion to speed, so power stays roughly constant until the field-weakening current limit or mechanical speed limit is reached.

SPM motors have little inductance and therefore limited field-weakening range (perhaps 1.2–1.5 times base speed), whereas IPM motors with high saliency can reach 2.5–4 times base speed. This is why IPM mid-drives give motorcycles both strong low-speed torque and a usable top speed from a single reduction ratio. Base speed also falls as the battery discharges: a pack that sags from 84 V to 64 V under load drops base speed by nearly a quarter, which is why electric motorcycles lose top speed and mid-range punch at low SOC.

Peak and continuous curves differ. The peak curve, available for perhaps 10–30 s, is limited by controller current and magnet demagnetisation; the continuous curve is limited by winding and magnet temperature at steady state, and is typically 40–60 % of peak torque.

Efficiency maps

A motor **efficiency map** plots contours of constant efficiency on the torque-speed plane. Typical PMSM maps show a peak island of 93–96 % at medium speed and moderate torque. Efficiency falls at low speed and high torque, where copper loss (I^2R) dominates and little mechanical power is produced, and at high speed and low torque, where iron loss and field-weakening current dominate. A designer chooses the reduction ratio so that the motor operates near its best island in the riding the vehicle actually does: for a city taxi motorcycle, 30–50 km/h at moderate torque; for a touring motorcycle, 90–120 km/h cruise.

Losses and cooling

Loss	Mechanism	Depends on	Mitigation
Copper (stator I^2R)	Resistance of the windings	Square of phase current; resistance rises about 0.39 %/K for copper	More copper (slot fill), shorter end turns, cooling
AC copper	Skin and proximity effects crowd current at high frequency	Electrical frequency, conductor size	Stranded or Litz wire, hairpin geometry optimised for frequency

Loss	Mechanism	Depends on	Mitigation
Iron hysteresis	Repeated magnetisation of the steel	Frequency and flux density (roughly f × B^1.6–2)	Low-loss silicon steel
Iron eddy current	Currents induced in the laminations	$f^2 \times B^2 \times$ lamination thickness^2	Thin laminations (0.2–0.35 mm), insulated coatings
Magnet eddy current	Currents in conductive NdFeB magnets from harmonic fields	PWM and slot harmonics, high speed	Segmenting magnets axially and circumferentially
Mechanical	Bearing friction, windage, seal drag	Speed	Correct bearing preload and lubrication

Cooling routes heat from the windings, through slot insulation and stator iron, to the housing. Hub motors and small mid-drives are air cooled by fins on the housing. Larger mid-drives use a liquid jacket in the housing with water-glycol shared with the controller (Energica uses liquid cooling), or oil sprayed on the end windings. Winding insulation is rated by **thermal class**; class H (180 °C) is common in traction motors, and the motor temperature sensor (an NTC thermistor, KTY or PT1000 element embedded in the end windings) lets the controller derate before the limit. Each **10 K above rated temperature roughly halves insulation life**, so persistent overheating shortens motor life even if no immediate failure occurs.

Position sensing

The controller must know rotor position to apply current at the correct angle.

- **Hall-effect sensors**: three digital sensors spaced 120° electrical apart (sometimes 60°) inside the stator detect the magnet poles and give six distinct states per electrical cycle. They are cheap and adequate for six-step drive and for start-up of sinusoidal drives, but resolution is only 60° electrical. They need a 5 V (sometimes 12 V) supply and have open-collector outputs pulled up by the controller. Heat, water and broken wires are common causes of failure.
- Incremental or absolute encoders: optical or magnetic encoders give hundreds or thousands of counts per revolution. Magnetic encoders (a diametric magnet on the shaft end with a sensor chip) are compact and tolerant of dirt.
- **Resolvers**: a rotary transformer whose output windings carry an excitation carrier (typically 5–20 kHz) modulated by the sine and cosine of rotor angle. Resolvers have no electronics in the motor, tolerate high temperature and vibration, and are standard on high-voltage automotive and premium motorcycle drives.
- **Sensorless control**: the controller estimates position from back-EMF or a motor model. It works well above perhaps 5–10 % of rated speed but struggles at standstill, which is why sensorless hub motors may judder at take-off.

After a motor or sensor is replaced, the controller must learn the offset between sensor position and magnet position (**Hall angle** or encoder offset), usually by a self-learning routine with the wheel raised.

Rare-earth magnets and demagnetisation

Neodymium-iron-boron (NdFeB) magnets give **remanence** of 1.2–1.45 T and are the reason modern PM motors are compact. Their weakness is temperature. Remanence falls by about 0.11–0.12 % per kelvin, so a magnet at 120 °C has about 11 % less flux than at 25 °C, reducing torque per amp and back-EMF. More seriously, **coercivity**, the resistance to demagnetisation, falls by about 0.5–0.6 %/K. If a hot magnet experiences a strong opposing field, from high field-weakening current or a short-circuit fault, it can be **permanently partially demagnetised**, and the motor loses torque for ever.

Manufacturers grade NdFeB by maximum working temperature: standard N grades to about 80 °C, M 100 °C, H 120 °C, SH 150 °C, UH 180 °C and EH 200 °C. High-temperature grades add dysprosium or terbium, heavy rare earths that are costly and concentrated in a few supply chains, so grain-boundary diffusion processes that place them only at grain surfaces are now widespread. The **Curie temperature**, above which magnetism is lost entirely, is 310–400 °C, but practical damage occurs far below it. Ferrite magnets are cheaper and free of rare earths but have about a third of the remanence, so ferrite motors are larger and heavier for the same torque; they appear on low-cost scooters and as research alternatives. A motor that has lost magnet strength shows reduced back-EMF when spun by hand (measured as line-to-line voltage at a known speed) compared with the manufacturer's value or with an identical good motor.

> SAFETY **Spinning permanent-magnet motors generate voltage**
>
> A permanent-magnet motor generates voltage whenever it turns, even with the battery disconnected. Pushing a motorcycle with a mid-drive or hub motor, or spinning the rear wheel on a stand, produces back-EMF at the controller terminals and can charge the DC-link capacitors. A hub motor spun briskly by hand can produce tens of volts; a high-voltage IPM motor towed at road speed can generate several hundred. **Never disconnect or connect phase wires with the wheel turning**, and do not tow an electric motorcycle with the rear wheel on the ground unless the manufacturer permits it.

REVIEW QUESTIONS

1. A motor has a speed constant of 40 rpm/V. Calculate its torque constant in N·m/A and the torque it produces at 250 A, assuming an ideal machine.
2. Explain why back-EMF limits the top speed of a permanent-magnet motor and how field weakening extends it.
3. A mid-drive motor produces 110 N·m at 4,500 rpm. Calculate its mechanical power.
4. A motor turning at 7,200 rpm drives the rear wheel through a 9:1 reduction. The tyre's rolling circumference is 1.98 m. Calculate the road speed.
5. Distinguish trapezoidal and sinusoidal back-EMF machines and state the drive method suited to each.
6. Why does an interior permanent-magnet rotor produce reluctance torque while a surface magnet rotor does not?
7. List two advantages and two disadvantages of a hub motor compared with a mid-drive on a 5 kW motorcycle.
8. A hub motor has 20 pole pairs. What electrical frequency must the controller produce at 750 rpm?
9. Name three loss mechanisms in a PMSM and state how each varies with speed or current.
0. Why might a motor that has been repeatedly overheated produce less torque at the same phase current, and how could you check?
1. A rider reports that a hub-motor scooter judders and stutters when pulling away but runs normally above 15 km/h. Which position-sensing problem is most likely, and why does it affect only low speeds?

ANSWERS

1. Kt = 9.55 / Kv = 9.55 / 40 ≈ 0.239 N·m/A. Torque at 250 A = 0.239 × 250 ≈ 60 N·m.
2. Back-EMF rises in proportion to speed. When it approaches the maximum voltage the controller can apply from the battery, no voltage remains to drive current through the winding, so current and torque fall to zero. Field weakening injects a negative d-axis current that opposes the magnet flux, lowering the effective back-EMF so that the controller can keep driving q-axis current at higher speed, trading torque for speed at roughly constant power.

3. P = T × 2π n / 60 = 110 × 2π × 4,500 / 60 ≈ 51.8 kW.
4. Wheel speed = 7,200 / 9 = 800 rpm. v = 800 × 1.98 × 60 / 1000 ≈ 95 km/h.
5. A trapezoidal (BLDC) machine has back-EMF with a flat top over 120° electrical and suits six-step commutation with two phases conducting, using three Hall sensors. A sinusoidal (PMSM) machine has sinusoidal back-EMF and suits sinusoidal current drive under field-oriented control, ideally with an encoder or resolver.
6. Buried magnets have permeability close to that of air, so the magnetic path along the magnet axis (d-axis) has lower inductance than the path between magnets through iron (q-axis). This saliency (Lq > Ld) means the rotor iron tends to align with the stator field, producing reluctance torque proportional to (Ld – Lq) × id × iq. A surface magnet rotor is magnetically round, Ld ≈ Lq, so there is no reluctance torque.
7. Advantages: no chain, belt or gearbox to maintain, adjust or lose energy in; quiet; compact packaging that frees frame space for the battery. Disadvantages: high unsprung mass that degrades ride and grip; poor cooling at low speed and high torque; a fixed effective ratio set by the wheel; heavier and more expensive wheel and tyre changes.
8. f_e = p × n / 60 = 20 × 750 / 60 = 250 Hz.
9. Copper loss rises with the square of phase current (and with winding temperature); iron hysteresis loss rises roughly in proportion to electrical frequency and therefore speed; iron eddy current loss rises with the square of frequency; magnet eddy loss rises with speed and with PWM and slot harmonics; mechanical loss rises with speed.
10. Repeated overheating may have partially demagnetised the NdFeB magnets, especially if high field-weakening currents were applied while hot, which reduces the magnet flux and therefore Kt. It can be checked by spinning the motor at a known speed with the phases open and measuring line-to-line back-EMF with an oscilloscope or true-RMS meter, then comparing with the specification or a good motor. A lower back-EMF constant confirms magnet loss.
11. A faulty or intermittent Hall sensor (or wiring) is most likely. At low speed the controller relies on the Hall signals to commutate; a missing or wrong state causes it to energise the wrong phase, producing judder. Above a threshold speed many controllers switch to back-EMF-based (sensorless) estimation or interpolation, which does not depend on the Hall signals, so the fault disappears.

CHAPTER 5.3

Motor controllers and regenerative braking

LEARNING OBJECTIVES

- → Describe the three-phase inverter bridge, its gate drivers, DC-link capacitors and current sensing, and explain how PWM sets the phase voltage.
- → Compare six-step commutation with field-oriented control and explain the roles of d-axis and q-axis current.
- → Distinguish phase current from battery current and estimate one from the other.
- → Explain throttle maps, ride modes and regenerative braking, and calculate the energy recoverable in a stop.
- → List controller protections and the symptoms of common failures (shorted MOSFET, phase loss, Hall failure), and identify the parameters programmed into a controller.

The three-phase inverter

The controller's power stage is a **three-phase bridge**: three half-bridges (legs), one per motor phase, each with a high-side switch connecting the phase to the positive DC rail and a low-side switch connecting it to the negative rail. Six switches in total, with a freewheeling diode across each (on MOSFETs the intrinsic body diode, on IGBTs a separate co-packaged diode). Turning on the high-side switch of phase U and the low-side switch of phase V drives current from the battery through windings U and V; changing which switches are on rotates the field.

Switch technology follows voltage. Controllers for 48–96 V systems use silicon MOSFETs rated 100–150 V, often 12–36 devices in parallel per controller (2–6 per switch position) to share current; a typical TO-220 or TOLL MOSFET has an on-resistance of 1.5–4 mΩ. High-voltage drives (300–400 V) use IGBT modules or, increasingly, silicon-carbide MOSFETs rated 650–1,200 V, which switch faster with lower loss. **Gate drivers** translate the microcontroller's logic signals into the 10–15 V gate pulses each switch needs; the high-side driver floats with the phase node, using bootstrap or isolated supplies. A **dead time** of a few hundred nanoseconds to about 2 µs is inserted between turning one switch of a leg off and the other on, because if both conduct simultaneously (**shoot-through**) they short the DC link.

The **DC-link capacitors** (electrolytic in low-voltage controllers, film in high-voltage inverters) supply the high-frequency ripple current drawn by the switching bridge so that it does not have to come through the inductance of the battery cables. Ripple current heats the capacitors, and electrolytic capacitors dry out with heat and age, raising their equivalent series resistance; this is a common cause of controller failure after several years.

Current sensing uses shunt resistors in the low-side legs or the DC link on cheap controllers, and Hall-effect current transducers on the phase outputs on better ones. Accurate phase-current measurement is the basis of torque control and of overcurrent protection.

Pulse-width modulation

The battery voltage is fixed, so the controller varies the average voltage applied to each phase by switching at a fixed frequency (typically 8–20 kHz for MOSFET drives, chosen above the audible range or close to it, and 5–10 kHz for large IGBT drives) and varying the **duty cycle** D, the fraction of each period the high-side switch is on.

```
V_avg = D × V_DC
```

The motor's winding inductance smooths the current, so the motor responds to the average voltage. A higher switching frequency gives smoother current and less acoustic noise but higher switching losses in the transistors. The faint whine heard from some electric scooters at low speed is the PWM frequency or its subharmonics exciting the motor laminations.

Commutation strategies

Six-step (block) commutation

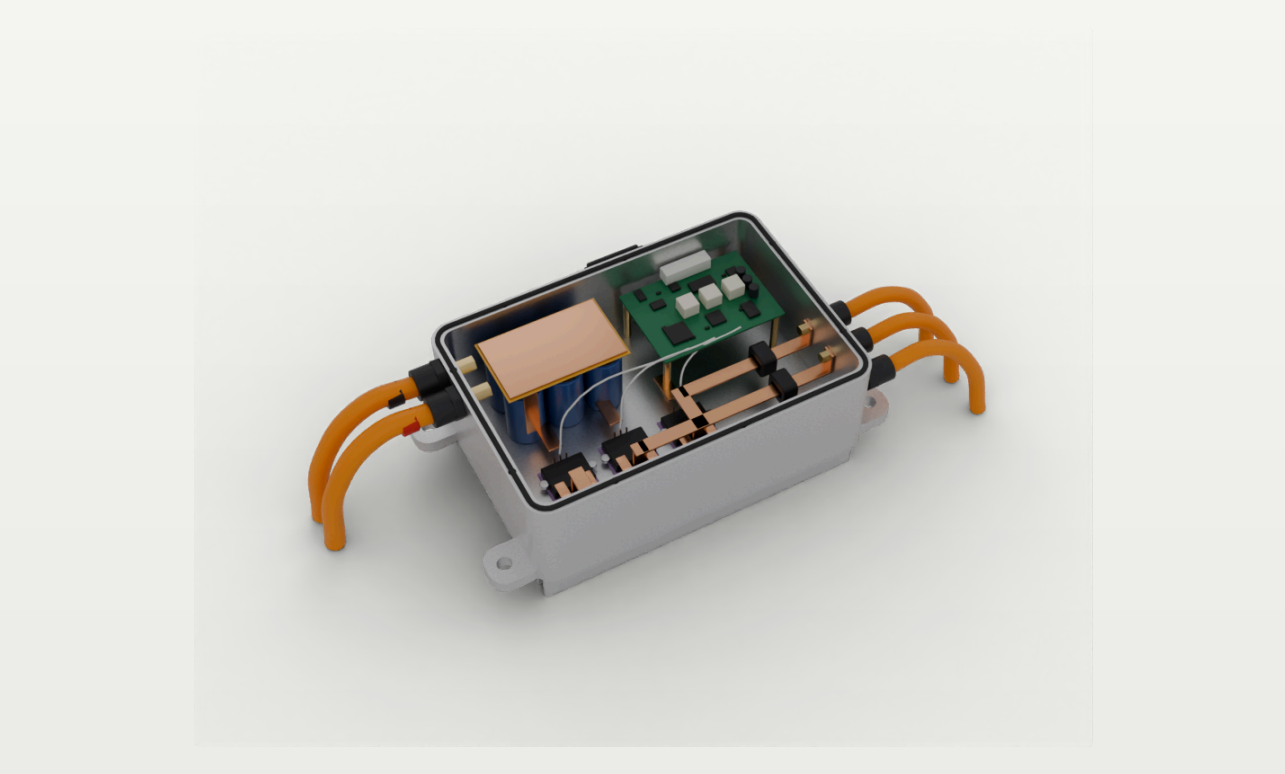


FIGURE 5.7 A motor controller with the lid removed: heat sink, six power switches, DC-link capacitors, copper busbars and gate-driver board.

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The simplest strategy reads the three Hall sensors, which give six states per electrical cycle, and for each state switches on one high-side and one low-side transistor so that two phases carry current and the third floats. The current switches abruptly every 60° electrical, producing torque ripple of 10–15 %, which is felt at low speed as a slight graininess and heard as a buzz. **Six-step** drive suits trapezoidal BLDC motors and is still used on cheap e-bike and moped controllers because it needs little processing.

Field-oriented control

Field-oriented control (FOC, also called vector control) treats the three phase currents as a single current vector rotating with the rotor and controls its two components independently.

- The **Clarke transform** converts the three measured phase currents (iu, iv, iw) into two orthogonal stationary components (iα, iβ).
- The **Park transform** rotates those into a frame fixed to the rotor, using the measured rotor angle: id along the magnet axis and iq at 90° electrical to it.
- Two PI regulators control id and iq to their set points. The outputs are transformed back and applied to the bridge through **space-vector PWM**, which uses the DC link voltage about 15 % more effectively than simple sinusoidal PWM.

In the rotor frame the currents are DC quantities at steady state, which makes them easy to regulate precisely. The q-axis current produces torque with the magnet flux; the d-axis current either strengthens or weakens the field.

```
T = (3/2) × p × [ψm × iq + (Ld − Lq) × id × iq]
```

where p is the number of pole pairs, ψm is the magnet flux linkage, and Ld and Lq are the d- and q-axis inductances. For a surface magnet motor Ld ≈ Lq and the second term vanishes, so id is held at zero below base speed. For an IPM motor Lq > Ld, so a negative id adds reluctance torque; the controller follows a **maximum-torque-per-ampere (MTPA)** trajectory that splits current between id and iq to get the most torque for a given current magnitude. Above base speed it increases negative id to weaken the field. FOC gives smooth torque down to zero speed, 2–5 % better efficiency than six-step in practice, quieter operation and precise regenerative braking, and it is the standard on any modern motorcycle controller.

Phase current and battery current

Controllers have two current limits, and confusing them is a common source of misunderstanding. **Battery current** is the DC current drawn from the pack. **Phase current** is the current in the motor windings, which sets torque. They are linked by power balance, not equality: the inverter acts as a step-down converter, so at low speed, where the motor needs little voltage, phase current can be several times battery current.

```
V_DC × I_batt × η_inv ≈ P_motor,in
I_batt ≈ D_eff × I_phase (approximate, low speed)
```

Consider a 72 V controller with a 300 A phase limit and a 120 A battery limit pulling away from rest. At 5 km/h the motor's back-EMF and resistive drop require only about 20 % of the available voltage, so the effective duty is about 0.2 and full 300 A phase current draws only about 60 A from the battery. Full rated torque is available. As speed rises, the duty and battery current rise; at about 40 % duty, 300 A phase current would require 120 A from the battery, and above that speed the battery limit governs, so phase current and torque must fall. The **phase limit therefore sets launch torque**, and the **battery limit sets peak power** (72 V × 120 A ≈ 8.6 kW in this example, less the voltage sag). Raising the phase current limit improves pull-away but heats the motor and transistors; raising the battery current limit increases power but stresses the pack and BMS.

Throttle maps and ride modes

A Hall-effect throttle grip outputs a voltage that rises from about 0.8 V closed to about 4.2 V wide open on a 5 V supply; the dead bands at each end let the controller detect a broken wire (signal below about 0.5 V or above 4.5 V) as a fault rather than a command. The controller converts throttle position into a torque request (most modern motorcycles) or a speed request (some scooters and pedelecs) using a **throttle map**. A torque-mode throttle feels like a petrol engine's throttle; a speed-mode throttle feels like cruise control and can surge.

Ride modes change the throttle map, the torque and power ceilings, top-speed limit and regenerative braking strength. An Eco mode might cap battery current at half the Sport value, limit top speed to 60 km/h and apply strong regen; a Rain mode softens the initial throttle curve and reduces maximum torque to limit wheelspin. **Traction control** on premium machines compares front and rear wheel speeds and cuts torque within milliseconds if the rear spins, which an electric drive can do far faster and more finely than an engine management system cutting ignition.



FIGURE 5.8 A TFT dashboard showing ride mode, speed and battery state.
Render: Transitions Lab, CC BY-SA 4.0

> NOTE **Instant torque**
>
> A permanent-magnet motor produces maximum torque from zero rpm with a response time of a few milliseconds. A 190 N·m mid-drive with a 6:1 reduction can apply over 1,100 N·m to the rear wheel instantly, enough to break traction on a wet road or lift the front wheel. Throttle maps deliberately slow the torque rise (rate limiting, often 50–200 ms to full torque) to make the machine controllable.

Regenerative braking

When the controller commands **negative q-axis current**, the motor's torque opposes rotation and the machine acts as a generator: kinetic energy flows back through the inverter into the battery. The rider triggers regen by closing the throttle (off-throttle regen, simulating engine braking), by operating the brake lever (brake switch triggers regen, often on the rear lever only) or by a separate regen control.

Energy recoverable

$$E_k = \tfrac{1}{2} \times m \times v^2$$

A 125-equivalent electric motorcycle and rider of 250 kg at 50 km/h (13.9 m/s) carry $E_k = 0.5 \times 250 \times 13.9^2 \approx 24{,}100$ J, or 6.7 Wh. Not all of it can be recovered: rolling resistance and aerodynamic drag absorb some during deceleration, the friction brakes take a share in hard stops, and each conversion (tyre, transmission, motor as generator, inverter, battery charge) loses energy. A round-trip efficiency from kinetic energy back to the wheel of about 60–70 % means perhaps 4 Wh is returned per stop. Over 100 km of city riding with one stop every 400 m (250 stops), that is about 1 kWh, compared with a consumption of 3–4 kWh/100 km, but in practice recovery is lower

because many decelerations are partial and riders use the friction brakes. Measured range gains from regen in urban use are typically 5–15 %; on long descents, such as the escarpment roads west of Nairobi, regen recovers much more and reduces brake fade.

Limits on regeneration

- Battery state of charge: a full battery cannot accept charge without exceeding its maximum cell voltage, so the BMS sets the charge-current limit to near zero above about **90–95 % SOC**. A rider who charges to 100 % and immediately descends a hill has no regen until some charge is used.
- Temperature: lithium-ion cells charged below about **0–10 °C** risk lithium plating on the anode, so the BMS limits charge current (including regen) when cells are cold. Hot cells and a hot controller or motor also reduce regen limits.
- Current limits: regen current is limited by the battery's charge-current rating, which is usually lower than its discharge rating (often 0.5–1C charge against 2–5C discharge).
- Traction and stability: regen acts on the rear wheel only (on almost all motorcycles), and the rear wheel carries less load under braking because of weight transfer. Strong regen can lock or slide the rear tyre on a low-grip surface, so regen is coordinated with ABS or reduced when wheel slip is detected.
- Low speed: back-EMF falls with speed, and below 5–10 km/h little power can be recovered, so regen fades out and the friction brakes must stop the machine.

Stop-lamp logic must take account of regen: a strong off-throttle regen decelerates the machine as hard as light braking, and following traffic needs warning. Vehicle regulations for cars switch the stop lamp on above a deceleration of the order of 1.3 m/s² and forbid it below about 0.7 m/s² for regen alone, and motorcycle manufacturers apply similar logic in the VCU.

Protections

Protection	What it monitors	Typical threshold or action
Overcurrent (phase)	Phase current sensors, desaturation detection of transistors	Hard trip within microseconds at 1.2–1.5 times the phase limit
Overvoltage	DC-link voltage, especially during regen into a full battery or if the contactor opens while regenerating	Regen reduced, then shutdown above about 1.2 times maximum pack voltage
Undervoltage	DC-link voltage	Power foldback near the low-voltage cut-off, then shutdown to protect cells
Controller overtemperature	Heatsink NTC, sometimes transistor junction estimate	Derating from about 80–90 °C heatsink, shutdown about 100–110 °C
Motor overtemperature	Winding NTC or KTY sensor	Derating from about 120–140 °C, shutdown at the insulation class limit
Throttle fault	Throttle signal out of the valid range at power-up or during riding	Drive disabled; throttle must be closed at power-up
Position-sensor fault	Illegal Hall states (000 or 111), resolver signal loss	Fault code, limp mode or shutdown
Stall protection	High current with zero speed for a set time	Current reduced to prevent motor and transistor overheating
Interlocks	Side stand, brake switch, seat switch, charge cable	Drive inhibited

Controller faults and failure modes

Shorted MOSFET or IGBT

Overcurrent, overheating, voltage spikes or a gate-drive failure can make a transistor **fail short**. If a low-side switch shorts, the corresponding phase is permanently connected to the negative rail. When the motor turns, the back-EMF drives current through the short and through the body diodes of the other low-side switches, producing a braking torque: the wheel becomes notchy or locks when pushed, and at speed a shorted switch can generate sudden rear-wheel braking torque. If the switch fails while the opposite switch in the same leg turns on, it creates a shoot-through that usually blows the main fuse. Diagnosis: with the controller isolated and disconnected from the motor, measure with the diode test between each phase terminal and the B+ and B– terminals. A good leg reads about 0.3–0.6 V in the forward direction of the body diode and open circuit in the reverse; a shorted switch reads near 0 V in both directions.

Phase loss

A broken phase wire, burnt connector or open winding causes **phase loss**: the motor is left running on two phases. The machine may refuse to start from rest or start only after a push, vibrates and growls, draws high current and loses power. Phase connectors are high-current bullet or lug connections; a loose or corroded one heats, discolours the insulation and eventually burns open. Check by measuring line-to-line phase resistance (Chapter 5.6).

Hall sensor failure

A dead Hall sensor gives a constant high or low output, producing an illegal state sequence; the controller logs a Hall fault, refuses to run or runs roughly and with high current. Hall sensors fail from heat (the sensors sit in the stator near the windings), water ingress through the axle cable, or a shorted 5 V supply caused by a chafed cable. Some controllers can switch to sensorless mode as a fallback, giving poor take-off but normal running at speed.

Other failures

Capacitor ageing (rising ripple, swollen cans, intermittent cut-outs under load), water ingress through cable glands, cracked solder joints from vibration and thermal cycling, and burnt battery connectors (especially high-current Anderson or XT90 connectors that are repeatedly unplugged under load) are the remaining common causes. Many low-cost controllers have a **power-on self-test** that flashes a fault code on an LED or the dashboard; the code table in the service documentation is the first diagnostic reference.

Parameter programming

Controllers for light electric motorcycles (Kelly, Sabvoton, Votol, Fardriver, ASI and others) are programmed by laptop software or a phone app over a USB-to-serial, Bluetooth or CAN link. Typical parameters are listed below; changing them alters performance, legal category and reliability.

Parameter	Effect
Battery current limit (A)	Peak power drawn from the pack; must not exceed BMS and cell ratings
Phase current limit (A)	Launch torque; limited by transistor and motor ratings
Low-voltage and high-voltage cut-off (V)	Protects cells from over-discharge and the DC link from overvoltage
Motor pole pairs and Hall angle	Must match the motor; set by a self-learning routine after motor or sensor replacement
Throttle range and curve	Closed and full voltages, response shape, ramp rate

Parameter	Effect
Speed limit and ride modes	Top speed and power per mode; may define the legal category
Regen current and voltage limits	Regenerative braking strength and the maximum voltage permitted during regen
Field-weakening current	Top speed above base speed; excessive values overheat or demagnetise the motor

> SAFETY **Derestricting changes the vehicle category**
>
> Raising the speed or continuous power limit of a type-approved electric moped or L3e-A1 motorcycle **changes its type approval**, invalidates insurance and may require a different licence. It also overloads components selected for the original rating: a battery current increase from 60 A to 100 A in a pack of 21700 cells may push each cell beyond its continuous discharge rating and shorten its life or cause overheating.

REVIEW QUESTIONS

1. Draw or describe the three-phase bridge and name the six switch positions. Why is dead time inserted between the switches of one leg?
2. A 72 V controller applies a duty cycle of 35 % to a phase. What is the average phase voltage relative to the negative rail?
3. Explain the difference between six-step commutation and field-oriented control in terms of the number of phases conducting, torque ripple and position-sensor requirements.
4. In FOC, what do id and iq represent, and why is negative id used in an IPM motor?
5. A controller has a 250 A phase limit and an 80 A battery limit on a 60 V pack. Estimate the battery current at full phase current when the effective duty is 0.25, and the peak electrical power available at the battery limit.
6. A 220 kg motorcycle with rider decelerates from 60 km/h to rest using regen only, with 65 % of the kinetic energy returned to the battery. How many watt-hours are recovered?
7. Give four reasons why regenerative braking may be weak or absent.
8. With the controller disconnected, the diode test between phase W and B− reads 0.02 V in both directions. What is the fault, and what symptom would the rider have reported?
9. A Hall-effect throttle reads 0.15 V at the controller with the grip closed. What will the controller do and what is the likely cause?
0. Why does raising the phase current limit improve pull-away but not top speed?
1. List four parameters that must be set when a controller is fitted to a different motor.

ANSWERS

1. Each phase leg has a high-side switch (U+, V+, W+) connecting the phase to the positive rail and a low-side switch (U−, V−, W−) connecting it to the negative rail, each with an antiparallel diode. Dead time ensures one switch of a leg is fully off before the other turns on; without it both could conduct briefly (shoot-through), shorting the DC link through the leg and destroying the transistors.
2. V_avg = 0.35 × 72 = 25.2 V.
3. Six-step commutation energises two phases at a time with the third floating, switching every 60° electrical according to Hall states, giving 10–15 % torque ripple and needing only three Hall sensors. FOC drives all three

phases with sinusoidal currents controlled in the rotor reference frame, giving low torque ripple, but needs a continuous rotor angle from an encoder, resolver, interpolated Hall signals or an observer.

4. id is the current component aligned with the magnet flux (d-axis) and iq the component at 90° electrical to it, which produces magnet torque. In an IPM motor Lq > Ld, so negative id combined with iq produces additional reluctance torque (MTPA operation), and at high speed negative id weakens the effective field so the motor can exceed base speed.
5. $I_{batt} \approx 0.25 \times 250 = 62.5$ A, within the 80 A limit. Peak electrical power at the battery limit $\approx 60 \times 80 = 4.8$ kW, less voltage sag.
6. $v = 60 / 3.6 = 16.7$ m/s. $E_k = 0.5 \times 220 \times 16.7^2 \approx 30{,}600$ J. Recovered $= 0.65 \times 30{,}600 \approx 19{,}900$ J ≈ 5.5 Wh.
7. Battery near full charge (BMS charge limit near zero); cells too cold for charging; battery, motor or controller overheated; low speed with little back-EMF; ride mode set to low regen; wheel slip detected on a low-grip surface; regen disabled because of a fault such as a brake switch or BMS communication error.
8. A shorted low-side switch in phase W. The rider would have reported a notchy, braking or locking rear wheel when pushing the machine, a loss of power, a fault code, or a blown main fuse.
9. The signal is below the valid range (about 0.5 V), so the controller treats it as a throttle fault and disables drive. The likely cause is an open signal wire, a missing 5 V supply to the throttle (shorted or broken supply wire, failed controller regulator) or a failed throttle Hall sensor.
10. Phase current sets torque, and at low speed the controller can deliver full phase current with only a small battery current, so more phase current gives more launch torque. Top speed is set by back-EMF reaching the battery voltage and by the battery current limit (power); phase current is not the limiting quantity there.
11. Motor pole-pair count, Hall sensor angle or encoder offset (by self-learning), phase current limit matched to the motor's rating, motor temperature sensor type and thresholds, field-weakening current, and the direction of rotation.

CHAPTER 5.4

Batteries and the BMS

LEARNING OBJECTIVES

- → Compare NMC, NCA, LFP, LMFP and sodium-ion cells by voltage window, energy density, cycle life and safety, and the cylindrical, prismatic and pouch formats.
- → Calculate pack voltage, capacity, energy, C-rate, internal resistance and heat for a series-parallel pack such as 20S10P.
- → Explain how SOC and SOH are estimated and the limitations of coulomb counting and OCV methods.
- → Describe the functions of a BMS, including passive and active balancing, protection and contactor control.
- → Explain thermal runaway, propagation and its mitigation, the causes of calendar and cycle ageing, and the routes to second life and recycling.

Cells

A lithium-ion cell stores energy by moving lithium ions between two electrodes through an electrolyte. During discharge, ions leave the graphite **anode**, cross a porous polymer **separator** soaked in electrolyte (a lithium salt, usually LiPF6, in organic carbonate solvents) and insert into the metal-oxide or phosphate **cathode**, while electrons flow through the external circuit and do work. Charging reverses the process. On the first charge, the electrolyte reacts with the anode surface to form a thin **solid electrolyte interphase (SEI)**, which passivates the graphite and allows stable cycling; slow growth of this layer is the main cause of ageing.

Chemistries

The cathode material decides most of a cell's properties, and the names of chemistries refer to it.

Chemistry	Nominal / max / min cell voltage	Cell energy density	Cycle life to 80 %	Notes
NMC (nickel manganese cobalt oxide)	3.6–3.7 / 4.2 / 2.5–3.0 V	200–270 Wh/kg	1,000–2,000	Dominant in premium packs and most 21700 cells; high-nickel grades (NMC 811) give the highest energy
NCA (nickel cobalt aluminium oxide)	3.6 / 4.2 / 2.5 V	220–280 Wh/kg	800–1,500	High energy, used in Panasonic cylindrical cells
LFP (lithium iron phosphate)	3.2–3.3 / 3.65 / 2.5 V	150–205 Wh/kg	2,000–6,000	No cobalt or nickel, high thermal stability, flat voltage curve, poorer in cold
LMFP (lithium manganese iron phosphate)	about 3.7 / 4.3 / 2.5 V	180–230 Wh/kg	1,500–3,000	LFP with manganese to raise voltage and energy
Sodium-ion (layered oxide or Prussian-blue cathode, hard-carbon anode)	3.0–3.1 / 3.9–4.0 / 1.5–2.0 V	100–160 Wh/kg	2,000–5,000 (manufacturer claims)	No lithium, good cold performance, can be stored and shipped at 0 V

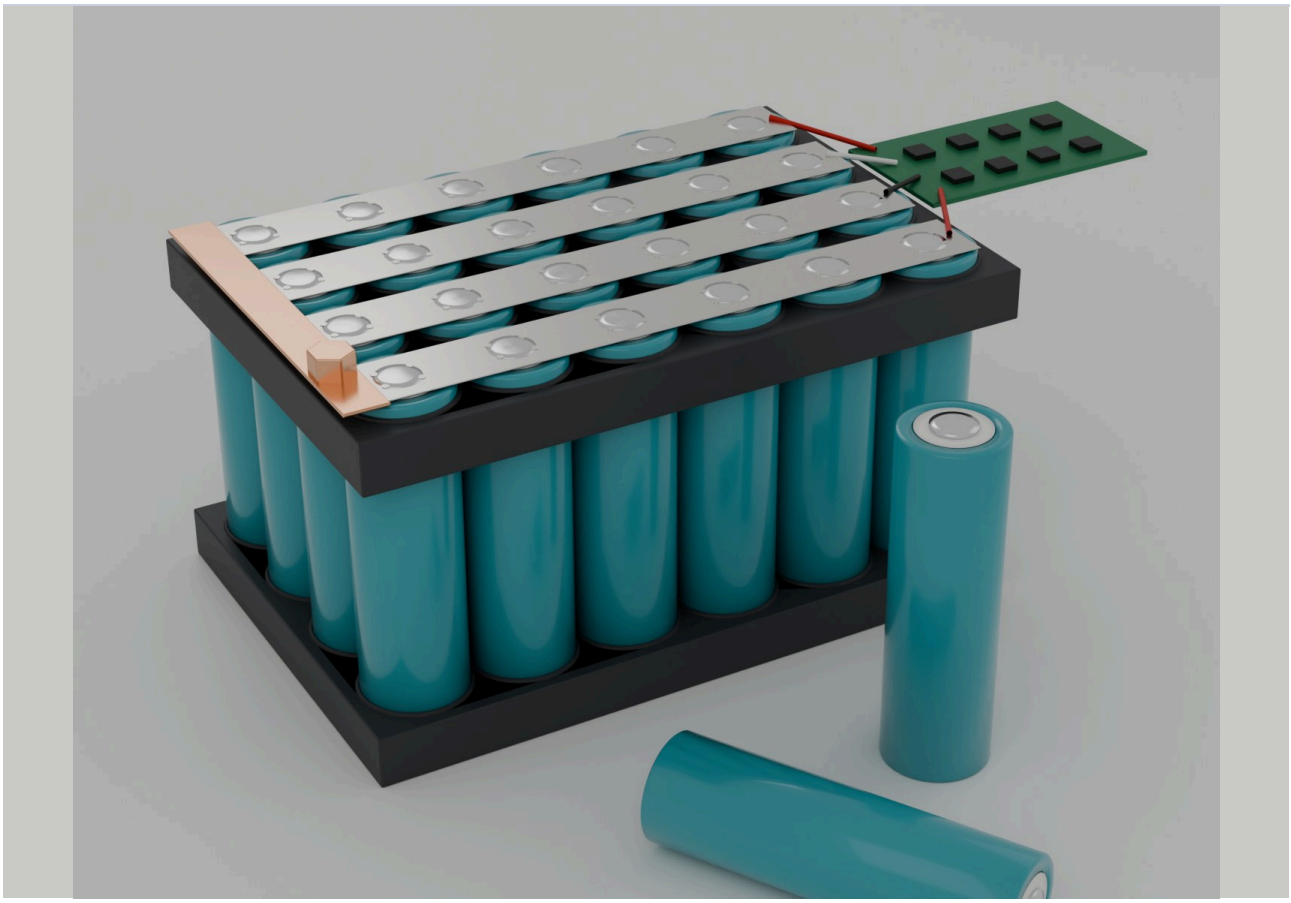


FIGURE 5.9 A 24-cell module of 21700 cylindrical cells: moulded cell holders top and bottom, spot-welded nickel strips joining each parallel group of six cells, a copper busbar and terminal, and balance leads running to the BMS board; two loose cells show the positive cap and the insulating ring.

Render: Transitions Lab, CC BY-SA 4.0

Pack-level energy density is lower than cell density, because holders, busbars, BMS, enclosure and cooling add mass: a **cell-to-pack mass ratio** of 60–75 % is typical for two-wheeler packs, so 250 Wh/kg NMC cells give packs of 150–180 Wh/kg. Energy density is a trade against **power density**: cells optimised for high discharge rates (thin electrodes, more current collector) store less energy than energy cells of the same size.

LFP is spreading in commuter and swap packs because its cycle life suits fleets that cycle batteries daily, it contains no cobalt or nickel, and its cathode does not release oxygen in a thermal event, so failures are less violent. Its penalties for two-wheelers are lower energy (heavier for the same range), poor performance below 0 °C and a voltage curve so flat between 20 % and 80 % SOC that voltage-based SOC estimation is almost useless. Sodium-ion cells are entering the market for low-cost scooters, using abundant materials and tolerating cold and deep discharge, at the cost of lower energy density.

Cell formats

Format	Dimensions	Typical capacity	Mass	Characteristics
18650 cylindrical	18 mm diameter × 65 mm	2.5–3.5 Ah	45–48 g	Mature, cheap, used in early Gogoro packs and many e-bike packs
21700 cylindrical	21 mm × 70 mm	4.0–5.0 Ah	65–70 g	About 50 % more energy per cell than 18650; now the standard for two-wheeler packs

Format	Dimensions	Typical capacity	Mass	Characteristics
4680 and larger cylindrical	46 mm × 80 mm	about 20–25 Ah	about 350 g	Emerging; fewer cells and welds per pack
Prismatic	Rigid aluminium can, e.g. 50–300 Ah	20–300 Ah	0.5–5 kg	Few large cells, simple pack assembly, common for LFP
Pouch	Laminated foil envelope	10–80 Ah	0.2–1 kg	Best packing efficiency; needs external compression and protection

Cylindrical cells have a steel can that resists swelling and a built-in **current interrupt device (CID)** and vent that operate on excessive internal pressure, and many include a **PTC** element; their failure is contained per cell. Their round shape leaves gaps that are used for cooling and spacing. Prismatic and pouch cells reduce the number of cells and connections but each failure releases more energy.

Pack arithmetic

A pack described as **xSyP** has x cell groups in **series** and y cells in **parallel** within each group. Series connection adds voltage; parallel connection adds capacity (ampere-hours) and current capability.

```
V_pack = S × V_cell
Q_pack = P × Q_cell
E_pack = V_pack,nom × Q_pack
N_cells = S × P
```

Worked example: 20S10P with 21700 NMC cells

Cell data: nominal 3.6 V, maximum 4.2 V, discharge cut-off 2.5 V (practical cut-off about 3.0 V under load), capacity 5.0 Ah, mass 70 g, internal resistance 15 mΩ, continuous discharge rating 15 A.

```
V_nom = 20 × 3.6 = 72 V
V_max = 20 × 4.2 = 84 V
V_min = 20 × 3.0 = 60 V (practical)
Q_pack = 10 × 5.0 = 50 Ah
E_pack = 72 × 50 = 3,600 Wh = 3.6 kWh
N_cells = 200, cell mass = 200 × 0.070 = 14 kg
```

At a 70 % cell-to-pack mass ratio the pack weighs about 20 kg, giving 180 Wh/kg. This is the scale of a 125-equivalent commuter battery: at 3.6 kWh/100 km it gives about 100 km of range. Note that the pack's full voltage of **84 V** is above the **60 V DC** threshold for high-voltage class B (Chapter 5.6), even though the system is commonly sold as "72 V".

C-rate

The **C-rate** expresses current relative to capacity: 1C discharges the full capacity in one hour.

```
C-rate = I / Q
```

For the 50 Ah pack, 150 A is 3C, and each cell carries 150 / 10 = 15 A, exactly its continuous rating. A 3 kW nominal motor at 72 V draws about 45 A (0.9C), while a 10 kW peak demand draws about 150 A even before voltage sag. Charging at 10 A is C/5 and takes about five hours; a 1C fast charge (50 A) would take about an hour to 80 % and requires a cell rated for 1C charging.

Internal resistance and heat

Every cell has an **internal resistance** made up of ohmic resistance of electrodes, current collectors and electrolyte, plus charge-transfer and diffusion effects that appear over longer time scales. Under load the terminal voltage sags by I × R, and the cell dissipates $I^2 \times R$ as heat.

```
R_pack = (S / P) × R_cell + R_interconnect
R_pack = (20 / 10) × 0.015 + 0.010 = 0.040 Ω
ΔV = I × R_pack = 150 × 0.040 = 6.0 V
P_heat = I² × R_pack = 150² × 0.040 = 900 W
```

At 150 A the pack voltage sags from 72 V to about 66 V and 900 W is generated inside the pack. If the full demand is sustained for 60 s, the heat is 54 kJ; with a cell thermal mass of about 14 kg × 1,000 J/(kg·K) = 14 kJ/K, the cells warm by about 3.9 K, which is acceptable. A sustained climb at 100 A for 20 minutes generates $100^2 \times 0.04 \times 1{,}200$ = 480 kJ, a potential temperature rise of over 30 K if little heat escapes, which is why sealed air-cooled packs derate on long hills in hot climates. Internal resistance roughly doubles between 25 °C and 0 °C and rises with ageing, so a cold or old pack sags more and reaches the low-voltage cut-off earlier.

State of charge and state of health

State of charge (SOC) is the remaining charge as a fraction of the present full capacity. It cannot be measured directly; the BMS estimates it.

- **Coulomb counting** integrates current over time: $SOC = SOC_0 - (1/Q) \int I\,dt$. It responds well to load changes but accumulates error from current-sensor offset (a 0.5 A offset on a 50 Ah pack gives a 1 % error per hour), and it needs an accurate value of the present capacity Q, which falls as the pack ages.
- **Open-circuit voltage (OCV)** methods use the relationship between rested cell voltage and SOC. After 30 minutes to several hours of rest, cell voltage settles near its equilibrium value, which a lookup table converts to SOC. OCV is accurate for NMC, whose curve slopes steadily from about 3.3 V empty to 4.2 V full, but almost useless for LFP in the 20–80 % range, where voltage changes by only tens of millivolts.
- Practical BMSs combine both: coulomb counting during use, corrected by OCV after rest and by reaching full charge (a known reference point). Advanced systems use model-based estimators such as the **extended Kalman filter**, which combine a cell model with measurements to correct drift continuously (Plett's texts describe these methods in detail).

State of health (SOH) compares the present pack to its new condition, usually by capacity (present capacity divided by rated capacity) and sometimes by internal resistance. The conventional end of first life for a traction battery is **80 % of rated capacity**, at which point range is reduced by a fifth; many manufacturers' battery warranties are defined in these terms.

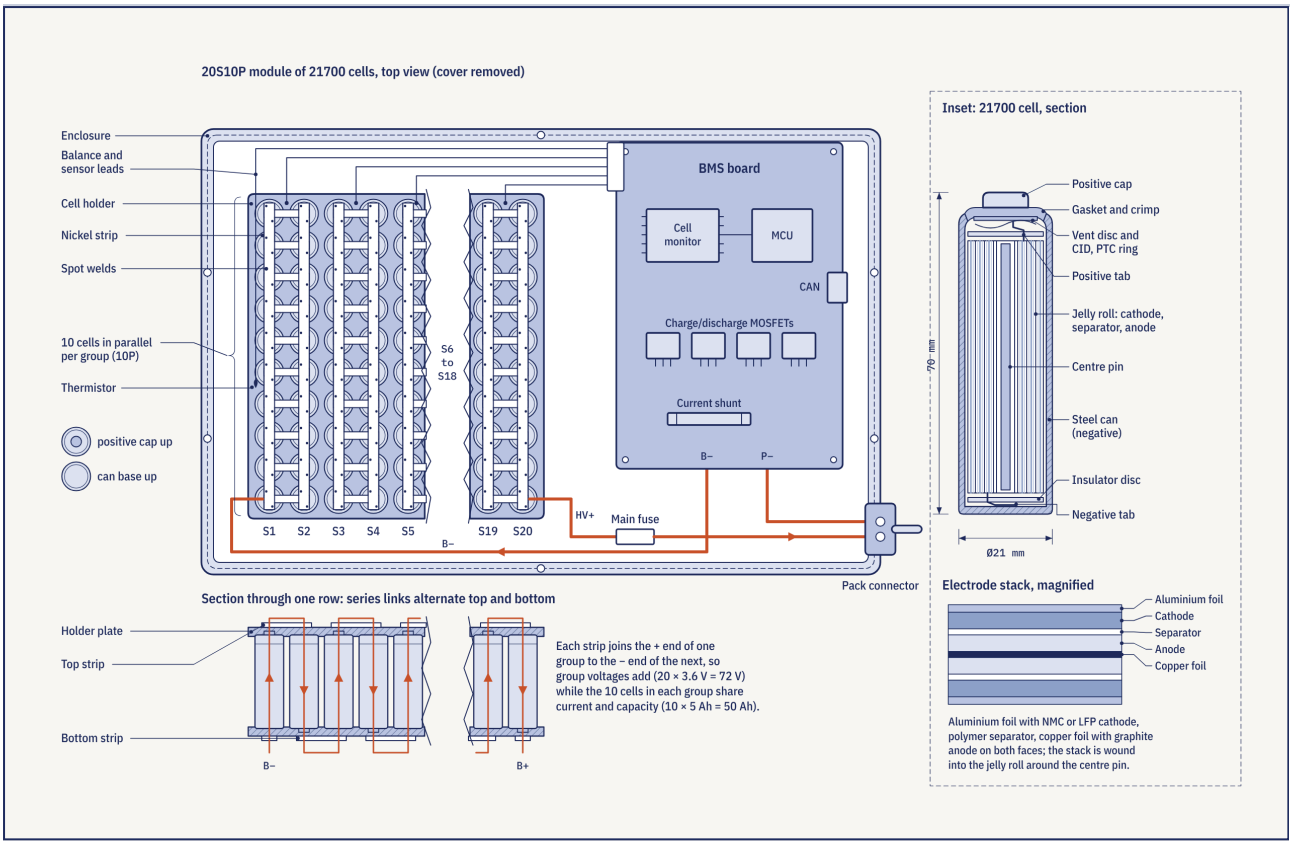


FIGURE 5.10 Battery pack construction: 21700 cylindrical cells in cell holders arranged in series-parallel groups on the 20S10P pattern, nickel strips and busbars, BMS board with balance leads and thermistors, enclosure and main connector, with an inset section through one cylindrical cell showing jelly-roll electrodes, separator, can, vent and current interrupt device.

The battery management system

Cell monitoring

The BMS measures the voltage of every series group (20 measurements in a 20S pack) with an analogue front-end chip; a typical cell-monitoring IC handles 12–18 cells, so larger packs daisy-chain several. Measurement accuracy of a few millivolts is needed because the decisions it supports (full charge at 4.20 V, imbalance of 20 mV) are fine. Temperature sensors (NTC thermistors) sit between cells at several locations, on busbars and on the BMS's own power switches. A shunt resistor or Hall sensor measures pack current.

Balancing

Cells in a series string drift apart in SOC because of small differences in self-discharge, capacity and temperature. Because the whole string must stop charging when the highest cell reaches its maximum and stop discharging when the lowest reaches its minimum, an unbalanced pack loses usable capacity. **Balancing** corrects this.

- **Passive balancing** switches a bleed resistor across any group that is above the others, typically at 30–200 mA, near the top of charge, dissipating the excess as heat. It is cheap and universal, but slow: correcting a 1 Ah imbalance at 100 mA takes 10 hours, so a badly drifted pack may need several long charges.
- **Active balancing** transfers charge from high cells to low cells using switched capacitors, inductors or small transformers, at currents up to a few amperes, with efficiency of 80–90 %. It recovers capacity faster and is used in larger packs and second-life systems.



FIGURE 5.11 An HV traction battery enclosure with cooling fins, HV connector, orange cable and service disconnect.
Render: Transitions Lab, CC BY-SA 4.0

Balancing hides small cell differences; it cannot repair a cell with high self-discharge, which will drift down again within days and shows up as a persistently low group.

Protection

Condition	Typical NMC limit	BMS action
Cell overvoltage	4.20–4.25 V	Stop charge and regen
Cell undervoltage	2.8–3.0 V (under load), 2.5 V absolute	Reduce, then stop discharge
Discharge overcurrent	Set by cell and pack rating	Reduce limit, then open switch
Short circuit	Several times rated current	Open switch within 100–500 µs (MOSFET BMS) or rely on fuse
Charge temperature	Typically **0–45 °C**	No charging outside this range; reduced rate near the limits
Discharge temperature	Typically −20 to 60 °C	Derate, then stop
Insulation fault (HV packs)	Below about 100 Ω/V	Warning, then contactor open

Low-voltage packs (up to about 72 V) usually switch with banks of MOSFETs in the negative path inside the BMS. In a **common-port** BMS, charging and discharging share one connector; in a **separate-port** BMS, charging has its own lower-rated path. High-voltage packs use contactors driven by the BMS or VCU, with a pre-charge relay and resistor (Chapter 5.1).

Communication and logging

The BMS reports SOC, SOH, cell voltages, temperatures and the present **allowed charge and discharge current limits** to the controller, charger and dashboard, normally over CAN. A swappable pack also authenticates itself to the vehicle and station, and logs cycles, energy throughput, maximum and minimum temperatures, overcurrent events and faults in non-volatile memory. These logs settle warranty claims and tell a fleet operator which packs to retire. Some BMSs enter a deep-sleep mode when a pack is stored, drawing microamps, because an always-on BMS drawing 10 mA would drain 1 Ah in 100 hours and could over-discharge a stored pack over months.

Thermal management and thermal runaway

Lithium-ion cells perform and age best between about 15 °C and 35 °C. Two-wheeler packs are mostly passively air cooled through the enclosure, sometimes with aluminium heat spreaders or phase-change material between cells; premium packs use liquid cold plates or, in Zero's case, a sealed pack shedding heat through its case. Hot climates are a design issue: a pack parked in East African sun can reach 50–60 °C before it is ridden.

Thermal runaway is a self-sustaining chain of exothermic reactions in a cell. Its typical sequence in an NMC cell is:

1. 80–120 °C: the SEI layer decomposes, exposing graphite to electrolyte, which reacts and generates more heat.
2. About 130–170 °C: the polyethylene or polypropylene separator melts and shrinks, allowing internal short circuits.
3. About 180–250 °C: the charged cathode decomposes and releases oxygen, which burns the flammable electrolyte inside the cell. Temperature rises within seconds to 600–900 °C.

The cell vents flammable and toxic gases (hydrogen, carbon monoxide, hydrocarbons, electrolyte vapour and **hydrogen fluoride**), often ejects burning material, and the vent jet can exceed 1,000 °C. Triggers are internal short circuits from manufacturing defects or lithium dendrites, mechanical damage (crash, penetration, crushing), overcharge, external short circuit, and external heating. LFP cells enter runaway at higher temperatures and release much less heat because the phosphate cathode does not release oxygen, but they still vent flammable gas.

Propagation is the spread of runaway from one cell to its neighbours. In a densely packed module, a single failed cell can heat its neighbours past their trigger temperature within tens of seconds, and the whole pack burns. Pack designers slow or stop this with cell spacing, mica or aerogel barriers between cells or groups, intumescent coatings, directed vent channels that carry hot gas away from other cells, and fusing of each cell (fusible links in the nickel strip or wire-bonded cells) so that an internally shorted cell is disconnected from its parallel neighbours. India's revised AIS-156 and UNECE R136 include requirements to test or demonstrate the absence of hazardous propagation (Chapter 5.5).

Ageing

Capacity fade and resistance growth have two broad causes.

- **Calendar ageing** proceeds with time whether or not the battery is used. SEI growth consumes lithium and electrolyte. It accelerates with temperature (roughly doubling for each 10 K rise, an Arrhenius dependence) and with high SOC, because a highly charged anode is more reactive. A pack stored at 100 % SOC at 40 °C may lose 10–20 % of capacity in a year; stored at 40–60 % SOC at 15–25 °C, a few percent.
- **Cycle ageing** depends on the number and depth of cycles, the current and the temperature. Deep cycles (100 % **depth of discharge**) stress electrode particles mechanically more than shallow ones; cycling between 20 % and 80 % can give two to three times as many equivalent full cycles as 0–100 %. High charge rates and charging below about 10 °C promote **lithium plating** on the anode, metallic lithium that is lost from cycling and can form dendrites that pierce the separator.

Practical rules for owners and fleets follow: avoid leaving a pack at 100 % for long periods, charge to 80–90 % for daily use where the system allows it, store at 40–60 % in a cool place, keep it out of direct sun, avoid fast charging a cold pack, and never let a pack sit fully discharged, because cell voltage falling below about 2 V dissolves the copper current collector and makes the cell unsafe to recharge.

Second life and recycling

A traction pack retired at 70–80 % SOH still stores most of its energy and can serve for years in less demanding **second-life** applications: stationary storage for solar systems, telecom towers, swap stations or homes. Swap operators can do this efficiently because they own uniform packs with complete usage histories. Second-life use requires testing each module's capacity, resistance and self-discharge, rebuilding with a new BMS, and certification of the new product.

At end of life, cells are recycled. **Pyrometallurgical** recycling smelts cells and recovers cobalt, nickel and copper as alloy, losing lithium and aluminium to slag. **Hydrometallurgical** recycling shreds cells into "black mass" and leaches it with acids to recover lithium, nickel, cobalt and manganese salts at high yields. **Direct recycling**, which recovers cathode material intact for re-lithiation, is under development. LFP has lower material value per kilogram, so its recycling economics depend on lithium recovery and regulation. In the EU, Regulation (EU) 2023/1542 on batteries introduces minimum recycled-content rules, collection targets and a digital battery passport, and treats batteries for light means of transport and for L-category vehicles as specific categories with their own obligations.

> SAFETY **Damaged and swollen packs**
>
> A pack that has been dropped, crashed, submerged or that shows swelling, a sweet solvent smell, hissing, smoke, heat without use, or electrolyte leakage must **never** be charged or reinstalled. Move it outdoors to a non-combustible area away from buildings and vehicles if this can be done safely, and treat it as hazardous waste for specialist handling.

REVIEW QUESTIONS

1. List the nominal and maximum cell voltages of NMC, LFP and sodium-ion cells.
2. A pack is built as 16S8P from 21700 NMC cells of 4.8 Ah and 3.6 V nominal. Calculate nominal and maximum voltage, capacity and energy.
3. The pack in question 2 delivers 120 A. Calculate the C-rate and the current per cell.
4. A 24S6P pack uses cells with 18 mΩ internal resistance, and interconnects add 15 mΩ. Calculate the pack resistance, the voltage sag and heat generated at 100 A.
5. Why is OCV-based SOC estimation difficult for LFP, and how does a BMS compensate?
6. A coulomb counter has a 0.3 A offset on a 40 Ah pack. How large is the SOC error after 10 hours without correction?
7. Explain the difference between passive and active balancing, and calculate how long passive balancing at 80 mA takes to remove a 0.6 Ah imbalance.
8. Describe the sequence of reactions in NMC thermal runaway with approximate temperatures.
9. A fleet operator wants to maximise pack life. Give four operating rules and explain the mechanism behind each.
0. Why must a charger not charge a pack whose cell temperature is −5 °C?
1. What distinguishes a common-port BMS from a separate-port BMS?

2. A pack reads 96 % SOH by capacity but its internal resistance has risen by 60 %. What symptoms will the rider notice?

ANSWERS

1. NMC: 3.6–3.7 V nominal, 4.2 V maximum. LFP: 3.2–3.3 V nominal, 3.65 V maximum. Sodium-ion: about 3.0–3.1 V nominal, 3.9–4.0 V maximum.
2. Nominal voltage = 16 × 3.6 = 57.6 V; maximum = 16 × 4.2 = 67.2 V; capacity = 8 × 4.8 = 38.4 Ah; energy = 57.6 × 38.4 ≈ 2,212 Wh ≈ 2.2 kWh.
3. C-rate = 120 / 38.4 ≈ 3.1C; current per cell = 120 / 8 = 15 A.
4. R_{pack} = (24 / 6) × 0.018 + 0.015 = 0.072 + 0.015 = 0.087 Ω. Sag = 100 × 0.087 = 8.7 V. Heat = 100^2 × 0.087 = 870 W.
5. Between about 20 % and 80 % SOC the LFP voltage curve is nearly flat, changing by only tens of millivolts, so measurement error and hysteresis produce large SOC errors. The BMS relies on coulomb counting and corrects it at the steep ends of the curve, especially at full charge where the voltage rises sharply, and may use model-based estimators.
6. Error = 0.3 A × 10 h = 3 Ah; 3 / 40 = 7.5 % SOC.
7. Passive balancing dissipates excess charge from high cells as heat in bleed resistors; active balancing transfers charge from high to low cells via capacitors, inductors or transformers, with little loss and at higher current. Time = 0.6 Ah / 0.08 A = 7.5 h of balancing.
8. At about 80–120 °C the SEI decomposes and the exposed anode reacts with electrolyte; at about 130–170 °C the separator melts, causing internal short circuits; at about 180–250 °C the cathode decomposes and releases oxygen, which burns the electrolyte and drives temperature to 600–900 °C within seconds, with venting of flammable and toxic gases.
9. Avoid long periods at 100 % SOC (high SOC accelerates SEI growth); keep packs cool and out of sun (ageing rate roughly doubles per 10 K); limit depth of discharge, for example 20–80 % for daily cycling (reduces mechanical stress on electrodes); do not fast charge cold packs (prevents lithium plating); do not store packs empty (prevents over-discharge and copper dissolution).
10. Charging graphite anodes below about 0 °C causes lithium to deposit as metal on the anode surface rather than inserting into the graphite. This plating permanently reduces capacity and can form dendrites that pierce the separator, creating an internal short-circuit risk.
11. A common-port BMS uses the same terminals and the same switching MOSFETs for charge and discharge; a separate-port BMS has a separate, usually lower-current, charge path and connector, so charging and discharging can be controlled and protected independently.
12. Range at gentle riding will be nearly normal, but under hard acceleration and on hills the voltage will sag more, reducing peak power and triggering the low-voltage cut-off earlier, especially in cold weather or at low SOC. The pack will also run hotter under load and may derate on long climbs.

CHAPTER 5.5

Charging, swapping and standards

LEARNING OBJECTIVES

- Distinguish on-board and off-board charging and describe the constant-current, constant-voltage charge profile.
- Calculate charging time and energy from charger power, pack size and efficiency.
- Describe DC fast charging for two-wheelers, including CCS2, India's LECCS connector and proprietary systems.
- Explain swappable battery systems in Japan, Taiwan, India and East Africa and the trade-offs of swapping against plug-in charging.
- Identify the safety and transport standards that apply to two-wheeler batteries and chargers (IEC 62133, UN 38.3, UNECE R136, ISO 13063, AIS-156) and estimate solar charging yields.

On-board and off-board charging

A battery accepts only DC, so every charging system contains a rectifier and a controlled DC-DC stage. The question is where that hardware sits. An **on-board charger** is built into the motorcycle, which then needs only a mains cable to a standard socket or a Type 2 inlet; the charger adds 2–6 kg and occupies space, and its power is limited by mass and cooling to roughly 0.6–6.6 kW. Zero and Energica fit on-board chargers and offer accessory or optional higher-power units. An **off-board charger** is a separate unit, from a 300–1,000 W portable brick for a scooter or e-moped to a wall-mounted unit, connected to the vehicle by a DC plug; this saves mass on the vehicle and is normal for 48–72 V commuters and for removable packs, which are often carried indoors and charged on a desk-top charger.

In both cases the charger is a slave to the BMS. On simple systems the charger follows a fixed profile and the BMS opens its charge MOSFETs if any cell reaches its limit; on communicating systems the BMS sends the charger a requested voltage and current over CAN, and the charger will not start until it receives a valid message, which prevents an incompatible charger from charging a pack.

The CC/CV profile

Lithium-ion cells are charged with a **constant-current, constant-voltage (CC/CV)** profile.

1. Pre-charge (only if the pack is deeply discharged): a small current, typically C/10 or less, until cells exceed about 3.0 V (NMC).
2. **Constant current**: the charger delivers its rated current while pack voltage rises. Around 70–85 % of the energy goes in during this phase.
3. **Constant voltage**: when pack voltage reaches the set point (4.20 V per cell for NMC, giving **84.0 V** for 20S; 3.65 V per cell for LFP), the charger holds voltage and current tapers as the cells' internal voltage approaches the terminal voltage.
4. Termination: the charger stops when current falls below a threshold, typically C/20 to C/10. Lithium-ion cells must **not** be float charged at maximum voltage.

The set-point voltage is the most important charger parameter. A charger set 0.05 V per cell too high (4.25 V) adds only a few percent capacity but substantially accelerates ageing; one set for the wrong cell count is dangerous. A 72 V NMC pack charger must deliver 84.0 V, a 72 V LFP pack (typically 24S) 87.6 V, and these are **not interchangeable**.

Worked example: charge time

A 3.6 kWh, 72 V pack (20S10P, 50 Ah) is charged from 10 % to 100 % with a 15 A off-board charger.

```
P_charge ≈ 80 V × 15 A = 1.2 kW (average pack voltage during CC)
E_to_battery = 0.9 × 3.6 kWh = 3.24 kWh
t_CC ≈ (0.80 × 3.24) / 1.2 ≈ 2.2 h (to about 80 % of the energy)
t_CV ≈ 0.6–1.0 h
E_from_grid = 3.24 / (0.92 × 0.97) ≈ 3.63 kWh
```

The full charge takes about three hours, and the grid supplies about 3.6 kWh including charger (92 %) and battery charge (97 %) losses. The CV taper makes the last 20 % slow, which is why fast-charging times are always quoted to 80 %. On a standard European 230 V, 16 A socket, the practical limit for a charger is about 3.0–3.6 kW; on a 13 A UK or Kenyan socket, 2.5–3.0 kW.

DC fast charging

A **DC fast charger** puts the AC-to-DC conversion in a stationary unit and connects its DC output to the pack through the vehicle's contactors, bypassing the on-board charger. The vehicle's BMS controls the session by digital communication, requesting voltage and current in real time. Two-wheeler packs are small, so even a 1C rate is only 3–20 kW, and the limits are the cells' charge rating, cooling and the connector.

- **CCS2 (Combined Charging System, Type 2 Combo)**: the European car standard, used on some large electric motorcycles such as the Energica range and other premium machines. It reuses car infrastructure but the inlet is large and heavy for a motorcycle, and many car chargers have a minimum output current or voltage (often 150–200 V) that low-voltage two-wheeler packs cannot use. Motorcycles fitted with CCS normally have packs of 300 V or more for this reason.
- **LECCS (Light Electric Combined Charging System)**: a combined AC and DC connector for light electric vehicles, approved as an Indian standard by the Bureau of Indian Standards in 2023. It was based on Ather Energy's connector, which Ather opened to other manufacturers, and has been adopted by Ather and Hero MotoCorp, whose networks became interoperable. It is far smaller than CCS2 and suited to the 50–100 V packs of Indian scooters and motorcycles.
- **Proprietary systems**: many manufacturers use their own DC connectors and chargers, which lock riders into one network. The IEC 61851-3 series addresses DC charging of light electric vehicles, and China and Japan have their own light-vehicle charging work.

Fast charging generates heat (I^2R in the cells at high current, plus entropic heat), and cold cells cannot accept high current without lithium plating, so the BMS reduces current when cells are cold or hot. A pack that charges from 20 % to 80 % in 40 minutes at 25 °C may take twice as long at 5 °C.

Battery swapping

Battery swapping replaces a depleted removable pack with a charged one in under a minute, separating the vehicle from its most expensive and slowest-to-refill component. It suits riders who cannot charge at home, taxis that cannot wait, and markets where battery cost is the main barrier to purchase, because the operator owns the battery and the rider pays per swap or by subscription.

Gogoro (Taiwan)

Gogoro introduced its swap network in Taiwan in 2015. First-generation Gogoro packs hold about 1.3 kWh, weigh about 9 kg and use Panasonic 18650 cells; scooters carry two packs. The automated GoStation reads each pack's identity and history, charges packs in its slots and releases a charged pack in seconds. Gogoro licenses its battery and vehicle platform to other manufacturers, and by 2020 it already operated about 1,700 sites in Taiwan. The system shows the main engineering requirements of swapping: a pack that identifies and authenticates itself, a connector rated for thousands of insertions, and a station that controls charge rate and temperature to maximise pack life.

Japan: the Swappable Batteries Motorcycle Consortium

In 2019 Honda, Kawasaki, Suzuki and Yamaha formed the **Swappable Batteries Motorcycle Consortium** to agree common specifications for swappable motorcycle batteries and swap stations in Japan. In 2022 the four manufacturers and the energy company ENEOS created **Gachaco**, which operates a swap service in Tokyo using the Honda Mobile Power Pack e:, a pack of about 1.3 kWh and about 10 kg. A common pack lets one network serve machines from several manufacturers, avoiding the duplicated infrastructure of competing proprietary systems.

India

India's market for electric two- and three-wheelers combines fixed-battery scooters with fast charging (Ather, Bajaj, TVS, Ola) and swap networks serving delivery fleets and three-wheelers. NITI Aayog published a draft battery swapping policy in April 2022, proposing interoperability standards for packs, connectors and the communication between pack, vehicle and station, and the Bureau of Indian Standards has since issued standards for swappable battery systems. The policy debate illustrates the tension between interoperability, which lowers infrastructure cost for riders, and proprietary packs, which let each manufacturer optimise and protect its design.

East Africa

East African swap networks serve the boda boda and delivery sectors, where riders cover 100–200 km a day and cannot afford downtime or a battery purchase. **Spiro** reported more than 50,000 electric motorcycles and more than 1,000 swap stations across Kenya, Uganda, Rwanda, Nigeria, Benin and Togo in late 2025. **Ampersand** operates in Rwanda and Kenya, reporting a swap price of about 2 USD for roughly 80 km of riding, which it presents as cheaper than petrol. **Roam** follows a different path, selling the Roam Air with two removable 3.24 kWh packs that riders charge at home or at Roam hubs. Rider surveys and press reports from Kenya show demand for more flexible networks, because a proprietary swap network ties the rider's daily income to the density and reliability of one operator's stations.

Swapping and plug-in charging compared

Factor	Swapping	Plug-in (fixed pack)
Refuelling time	1–3 minutes	1–5 h AC; 20–60 min DC to 80 %
Vehicle purchase price	Lower (battery leased)	Higher (battery included)
Infrastructure	Stations with stock of 1.5–3 packs per vehicle in service	Sockets, wall boxes and fast chargers
Pack size per module	Limited by lifting mass, about 1.3–3.5 kWh	Free, 3–22 kWh
Pack life management	Operator controls charge rate, temperature and retirement	Owner behaviour decides
Interoperability	Only within one network or consortium standard	Standard connectors possible

Safety, transport and approval standards

Several overlapping documents govern two-wheeler batteries and charging. Standards (ISO, IEC, EN, BIS) define test methods and requirements; regulations (UNECE, EU, national) make some of them mandatory for type approval or transport.

Document	Scope	Key content
IEC 62133-2	Safety of portable sealed secondary lithium cells and batteries	Cell- and battery-level tests: external short circuit, free fall, thermal abuse, crush, overcharge, forced discharge; often cited for cells used in light-vehicle packs
UN 38.3 (UN Manual of Tests and Criteria, Part III, sub-section 38.3)	Transport of lithium batteries	Tests T1 altitude, T2 thermal cycling, T3 vibration, T4 shock, T5 external short circuit, T6 impact or crush, T7 overcharge, T8 forced discharge. Required before any lithium cell or pack may be shipped by air, sea or road
UNECE Regulation No 136	Electric safety of L-category vehicles with electric power trains	Protection against electric shock (insulation, isolation resistance, IP protection), and REESS tests: vibration, thermal shock, mechanical shock, drop for removable packs, fire resistance, external short circuit, overcharge, over-discharge, over-temperature and (since amendment) overcurrent protection
ISO 13063 series	Electrically propelled mopeds and motorcycles: safety specifications	Part 1 on-board energy storage, Part 2 vehicle operational safety, Part 3 protection against electric shock
ISO 18243	Lithium-ion traction battery packs and systems for electric mopeds and motorcycles	Test specifications and safety requirements
EN 50604-1	Secondary lithium batteries for light electric vehicles	Safety requirements for LEV batteries such as pedelec and e-moped packs
EN 15194	Electrically power assisted cycles	Pedelec definition, mechanical, electrical and EMC requirements
IEC 61851 and IEC 62196	Conductive charging systems and connectors	Charging modes, control pilot signalling, connector types (Type 2, CCS)
AIS-156 (India)	Electric safety of L-category vehicles, India's counterpart of UNECE R136	After a series of scooter fires in 2022, amended with phased requirements including cell testing, a thermal propagation test, higher ingress protection for the traction battery and BMS requirements

UN 38.3 matters to any workshop that orders replacement packs or returns a pack under warranty: a lithium battery shipped alone is dangerous goods (UN 3480, or UN 3481 when packed with or in equipment), a whole battery-powered vehicle is UN 3171, and a damaged or defective battery requires special packaging and carrier approval. A replacement cell or pack from an unknown supplier without a UN 38.3 test summary is a warning sign of uncertain quality.

Connectors

Connector	Typical use	Notes
Domestic AC socket (Schuko, BS 1363, Type G) with cable to on-board charger	Scooters and motorcycles with on-board chargers	Limited to about 2.3–3.6 kW; use of extension reels is a fire risk

Connector	Typical use	Notes
IEC 62196 Type 2 inlet	Premium motorcycles in Europe	Single or three-phase AC, Mode 3 with control pilot
CCS2 (Type 2 Combo)	Large high-voltage motorcycles	DC fast charging up to the vehicle's limit
LECCS	Indian scooters and motorcycles	Combined AC and DC, compact
XLR, GX16, Anderson SB, XT60/XT90	Off-board chargers and pack connections on light vehicles	Not rated to break current under load; must be connected and disconnected with the charger off
Proprietary swap connectors	Swap packs	Sequenced pins (ground and communication first, power last), wiping contacts

> SAFETY **Charging indoors**
>
> Most two-wheeler battery fires reported in cities start during charging, frequently with non-original chargers, damaged packs or modified batteries. Charge only with the charger specified for the pack, on a non-combustible surface, away from escape routes, with a smoke alarm nearby, and **never** charge a pack that has been dropped, flooded or shows swelling.

Grid and solar charging

A two-wheeler places a small load on the grid: a 1.2 kW charger draws about 5 A at 230 V, less than a kettle. The concern is aggregate load: a swap station charging 40 packs at 1 kW each draws 40 kW, comparable to a small commercial building, and needs a three-phase supply and, in markets with an unreliable grid, backup or storage. Kenya's energy regulator introduced a dedicated electricity tariff for e-mobility charging in 2023 to encourage off-peak charging.

Solar charging is straightforward because daily two-wheeler energy needs are small. A boda boda covering 120 km a day at 3.5 kWh/100 km needs about 4.2 kWh at the battery, or about 4.8 kWh from the solar system after charger and storage losses.

```
E_PV = P_peak × H_peak × PR
E_PV = 1.5 kWp × 5.0 h × 0.75 ≈ 5.6 kWh/day
```

where P_peak is the array's rated power, H_peak is daily peak sun hours (about 5–6 in Nairobi and much of East Africa) and PR is the performance ratio (0.7–0.8) accounting for temperature, soiling, inverter and wiring losses. A 1.5 kWp array, about four to five modules occupying 7–8 m², can supply one heavily used taxi motorcycle; charging during the day requires either a second pack (charged while the first is in use) or stationary storage, which is a natural application for second-life packs.



FIGURE 5.12 A Type 2 / CCS2-style charging inlet with hinged cap.
Render: Transitions Lab, CC BY-SA 4.0

> EXPLORER EXERCISE · transitionslab.org/motorcycle-anatomy **Compare energy flows**
>
> On the explorer at transitionslab.org/motorcycle-anatomy, set the bore slider to 52.4 mm and the stroke slider to 57.8 mm and confirm a displacement of about 125 cc, then move the RPM slider to 7,500 rpm. If this engine delivers 8 kW at 30 % thermal efficiency, it consumes fuel energy at about 27 kW. Compare that with the 1.2 kW drawn by the charger in the worked example, and with a petrol pump delivering 30 L/min, which transfers fuel energy at about 16 MW (30 × 8.9 kWh per minute).

REVIEW QUESTIONS

1. Describe the four phases of a CC/CV charge and state the CV set-point voltage for a 20S NMC pack and a 24S LFP pack.
2. A 2.2 kWh, 57.6 V pack is charged from 20 % to 100 % with an 8 A charger at an average pack voltage of 62 V. Estimate the charge time, assuming the CV phase adds 40 minutes.
3. Calculate the energy taken from the grid for question 2 if the charger efficiency is 90 % and battery charge efficiency 97 %.
4. Why do most CCS2 car chargers not suit a 72 V electric motorcycle?
5. What is LECCS, which body approved it, and why was it developed instead of using CCS2?
6. List three engineering requirements a swappable pack must meet that a fixed pack need not.
7. Name the eight UN 38.3 tests and state when UN 38.3 compliance is required.
8. What is the scope of UNECE R136, and how does AIS-156 relate to it?

9. A swap station in Kigali holds 30 packs and charges each at 0.8 kW. What supply power does it need, and how many 1.3 kWh packs can it fully recharge per hour of steady operation, ignoring CV taper?

10. Size a solar array for a delivery rider using 3.0 kWh per day at the battery, with 85 % charging-chain efficiency, 5.5 peak sun hours and a performance ratio of 0.75.

11. Why must XT90 or Anderson connectors on an off-board charging circuit not be unplugged while current is flowing?

ANSWERS

1. Optional pre-charge at low current for deeply discharged cells; constant current at the rated charger current until the set-point voltage is reached; constant voltage with tapering current; termination when current falls to about C/20–C/10, with no float charge. Set points: 20 × 4.20 = 84.0 V for 20S NMC; 24 × 3.65 = 87.6 V for 24S LFP.
2. Energy to add = 0.8 × 2.2 = 1.76 kWh. Charger power ≈ 62 × 8 = 0.50 kW. CC time for about 80 % of that energy ≈ (0.8 × 1.76) / 0.50 ≈ 2.8 h; remaining energy in CV adds about 40 min, so total ≈ 3.5 h.
3. E_grid = 1.76 / (0.90 × 0.97) ≈ 2.02 kWh.
4. Many CCS2 chargers have a minimum output voltage of about 150–200 V, above the 60–84 V range of a 72 V pack, and are designed for currents and connector sizes far above two-wheeler needs; the CCS2 inlet is also large and heavy for a motorcycle.
5. LECCS (Light Electric Combined Charging System) is a compact combined AC and DC charging connector for light electric vehicles, approved as an Indian standard by the Bureau of Indian Standards in 2023, based on Ather's open-sourced connector. It was developed because the CCS2 connector is too large, heavy and costly for scooters and does not match their low pack voltages.
6. A lifting mass of roughly 10–15 kg or less; a connector and latch rated for thousands of insertion cycles with sequenced pins; identification and authentication between pack, vehicle and station; tolerance of drops and rough handling (R136 includes a drop test for removable packs); logging of history for the operator.
7. T1 altitude simulation, T2 thermal test, T3 vibration, T4 shock, T5 external short circuit, T6 impact or crush, T7 overcharge, T8 forced discharge. Compliance is required before lithium cells or batteries can be transported by air, sea, rail or road, including replacement packs and vehicles shipped with batteries.
8. UNECE R136 sets requirements for the electric safety of L-category vehicles (L1e to L7e) with electric power trains, covering shock protection and REESS safety tests. AIS-156 is India's equivalent standard for L-category vehicles, amended after 2022 battery fires with additional requirements such as thermal propagation testing.
9. Supply power = 30 × 0.8 = 24 kW (plus station losses). Each pack at 0.8 kW needs 1.3 / 0.8 ≈ 1.6 h, so the station recharges about 30 / 1.6 ≈ 18 packs per hour.
10. Required PV output = 3.0 / 0.85 ≈ 3.53 kWh/day. P_peak = 3.53 / (5.5 × 0.75) ≈ 0.86 kWp, so a 0.9–1.0 kWp array (two or three modules).
11. These connectors are not designed to break DC current. Unplugging under load draws an arc that does not self-extinguish as an AC arc would, burning and pitting the contacts, which raises their resistance, causes overheating in later use and can cause burns.

CHAPTER 5.6

Safety, diagnosis and service

LEARNING OBJECTIVES

- → Define high-voltage class B and explain why many 60–96 V two-wheeler systems fall within it.
- → Select PPE, insulated tools and test instruments, and carry out safe isolation with zero-voltage verification and lock-out/tag-out.
- → Perform insulation resistance, phase resistance, Hall sensor, throttle, contactor and pre-charge, cell balance and capacity tests and interpret the results.
- → Respond correctly to a lithium-ion battery fire and to a damaged pack.
- → Plan routine maintenance for an electric motorcycle and assess the legal and engineering issues in converting a petrol motorcycle to electric.

High-voltage definitions

UNECE Regulations No 100 (cars) and No 136 (L-category vehicles) classify electrical circuits by working voltage.

Voltage class	DC	AC (RMS)
A	**0–60 V**	0–30 V
B	**above 60 V and up to 1,500 V**	above 30 V and up to 1,000 V

Class B circuits require protection against direct contact (insulation, barriers, enclosures to IP protection levels), protection against indirect contact (equipotential bonding of exposed conductive parts), **orange cable insulation**, high-voltage warning labels on enclosures, and monitoring or design to maintain **isolation resistance** of at least **100 Ω/V** for DC circuits and **500 Ω/V** for AC circuits between live parts and the chassis.

The working voltage is the highest voltage a circuit can reach, not the nominal label. A "48 V" NMC pack (13S, 54.6 V maximum) stays within class A. A "60 V" pack (16S or 17S, 67.2–71.4 V maximum) and every "72 V" or "96 V" pack is **class B when charged**, as are the 100–400 V packs of full-size electric motorcycles. Many workshops treat 48–96 V scooters as low voltage because they look like e-bikes; they are not, and a 72 V pack can deliver short-circuit currents of several thousand amperes, enough to vaporise a spanner and cause arc-flash burns even where the shock risk to dry skin is moderate.

SAFETY **What makes a two-wheeler pack dangerous**

Three hazards exist even when the voltage is low enough that a shock may not be fatal: arc flash and molten metal from a short circuit across the pack terminals or busbars; heat and fire from damaged cells; and stored energy in DC-link capacitors and in a spinning permanent-magnet motor. Treat every traction pack as **live** until it has been isolated and verified, and remove watches, rings and metal jewellery before working near it.

PPE, tools and instruments

- **Insulating gloves** to EN 60903 / IEC 60903, Class 0 (maximum use voltage 1,000 V AC and 1,500 V DC), worn with leather over-gloves to protect against cuts. Inspect before every use by rolling the cuff to trap air and checking for leaks, and retest electrically every six months.

- **Eye and face protection**: safety glasses as a minimum; an arc-rated face shield when working on exposed busbars or opening a pack.
- **Insulated tools** to IEC 60900 (marked with the double triangle and 1,000 V rating), and insulated or covered terminals so that no uninsulated metal can bridge two potentials.
- Non-conductive footwear, an insulating mat and a clear work area with barriers and warning signs around the vehicle.
- A **CAT III 1,000 V** (or CAT IV) rated digital multimeter with intact, shrouded test leads; a milliohm meter or a current source for low-resistance tests; an **insulation resistance tester** with 250 V, 500 V and 1,000 V ranges; an oscilloscope for Hall and throttle signals; and a CAN interface with the manufacturer's diagnostic software.
- A rescue hook (insulated hook for pulling a person away from a live circuit) and a CO2 or powder extinguisher for electrical fires in the surroundings, with water or an aqueous vermiculite dispersion (AVD) extinguisher for battery cooling.

Safe isolation procedure

The detailed sequence is given in Job sheet 5.6.1. Its principles are:

1. Switch off and remove the key, so the VCU opens the contactors, and disconnect the 12 V auxiliary battery so control units cannot re-close them.
2. Remove the **service disconnect** (a plug or fuse that physically breaks the pack string, usually near mid-pack on high-voltage machines) or unplug the removable pack or main pack connector, and keep it in your pocket.
3. **Wait** for the DC-link capacitors to discharge through their bleed resistors: typically **5–10 minutes**, or the manufacturer's stated time. The time follows the RC discharge law; for 2,000 µF with a 10 kΩ bleeder, $\tau = 20$ s and $5\tau = 100$ s, but a failed bleeder leaves the capacitor charged for hours, which is why the next step is never skipped.
4. **Verify zero voltage** at the controller DC input and at the motor phase terminals with a CAT III meter, using the **live-dead-live** method: prove the meter on a known live source, test the isolated circuit, then prove the meter again.
5. Apply **lock-out/tag-out**: lock or cover the service disconnect socket, tag the vehicle with the technician's name, date and status, and keep the removed disconnect under the technician's control.

Insulation resistance testing

An insulation fault, from a chafed cable, water in a connector or a motor winding breaking down to its frame, can be invisible until a second fault creates a shock path. The test applies a DC voltage between the isolated high-voltage circuit and the chassis and measures the resulting leakage. Disconnect control electronics (controller, BMS, DC-DC converter) from the circuit under test unless the manufacturer specifies an in-circuit test, because 500 V can destroy semiconductors. Use a test voltage at or above the system's maximum working voltage: 250 V or 500 V for systems up to about 100 V, 500 V or 1,000 V for 300–400 V systems.

```
R_iso,min = 100 Ω/V × V_max
```

For an 84 V pack the regulatory minimum is 100 × 84 = 8.4 kΩ, but this is a type-approval floor for a working vehicle. A healthy motor, harness or pack should read in the megaohms, usually above **1 MΩ** and often above 100 MΩ; a value that falls with each test, or that is far below a sister vehicle's, indicates moisture or damaged insulation.

Fire risks and response

Lithium-ion fires differ from petrol fires: the burning cells generate their own heat and oxygen-containing decomposition products, so smothering does not stop them, and cells that have cooled can re-ignite hours or days later. Gases released include hydrogen fluoride, which forms hydrofluoric acid on contact with moisture, and carbon monoxide.

- If smoke or venting begins, evacuate the area and call the fire service. Do not try to open the pack.
- Large quantities of water are the most effective means of cooling cells and limiting propagation; an AVD extinguisher can suppress a small pack. Class D powders and CO2 do not cool cells and do not stop runaway.
- If it is safe, move the vehicle or pack outdoors, at least 5–10 m from buildings and other vehicles. Never move a burning or venting pack.
- After a fire or a severe event, quarantine the pack outdoors in a non-combustible area or a container for at least 24–48 hours, monitor it with a thermal camera or thermometer, and hand it to a specialist recycler as damaged dangerous goods.
- A pack that has been submerged in water, particularly salt water, may short internally and should be treated as damaged.

Diagnosis

Reading fault codes

Start every diagnosis by reading stored and active fault codes, freeze-frame data and live values with the manufacturer's tool, or by counting LED flash codes on low-cost controllers. Live data (cell voltages, pack current, phase current, temperatures, throttle voltage, Hall state, SOC) usually separates battery, controller and motor faults faster than any physical test. Record the codes before clearing them, and check for software updates that address known faults.

Phase resistance balance

The three motor windings must be equal. Measure line-to-line resistance U-V, V-W and W-U with the phases disconnected from the controller. Values are small (typically **20–200 mΩ** for hub motors, 5–30 mΩ for mid-drive motorcycles), so a normal multimeter's lead resistance (about 0.1–0.3 Ω) swamps them: use a four-wire milliohm meter, or pass a known DC current (for example 10 A from a current-limited bench supply) and measure the voltage drop at the terminals.

```
R = V / I
Imbalance (%) = (R_max − R_min) / R_avg × 100
```

The three readings should agree within about **5 %**. A higher reading on two pairs sharing one phase indicates a high-resistance joint or broken strand in that phase; an open circuit means a broken winding or connector; a low reading on one pair suggests shorted turns, often accompanied by overheating and a burnt smell. Also test insulation between each phase and the motor casing.

Hall sensor test

With 5 V applied (normally by the controller with the connector back-probed), rotate the wheel slowly by hand in the forward direction and record the three Hall outputs (high about 4.5–5 V, low below 0.5 V). A healthy sensor set with 120° spacing steps through six valid states per electrical cycle, for example **101, 100, 110, 010, 011, 001**, with exactly one sensor changing at each step. The states **000 and 111 are illegal** for 120° spacing and indicate a dead sensor, a shorted or open signal wire or a missing supply. Each sensor's output should switch cleanly; a slow or noisy edge on the oscilloscope indicates a weak sensor or interference.

Throttle signal

A Hall throttle has three wires: 5 V supply, ground and signal. Back-probe the signal with the key on and the drive disabled (wheel raised): the closed throttle should read about **0.8 V** and wide open about **4.2 V**, rising smoothly without dropouts as the grip is turned slowly. A reading near 0 V or near 5 V at rest indicates a broken ground, broken signal or failed sensor; a stuck or jumpy reading indicates a worn sensor, water ingress or a chafed cable at the handlebar.

Contactor and pre-charge

Check that the contactor coil receives its drive voltage at key-on, and measure coil resistance against specification with power off (tens to hundreds of ohms depending on coil voltage). With the contactor closed under load, the voltage drop across the main contacts should be no more than about **50–100 mV** at rated current; higher drop indicates pitted contacts that will overheat. A contactor that remains closed with no coil voltage is welded and must be replaced, and the cause (failed pre-charge, short circuit) found. To test pre-charge, measure DC-link voltage at key-on: it should rise to **at least 90–95 %** of pack voltage within the specified time (typically 0.2–2 s) before the main contactor clicks. A slow rise points to a failed pre-charge resistor, a leaking capacitor or a short downstream.

Cell voltage imbalance

Read the cell group voltages from the BMS at rest, after at least 30 minutes without load or charge.

Spread between highest and lowest group (NMC, at rest)	Interpretation
Below 10–20 mV	Normal
20–50 mV	Drifting; allow full balance charges and recheck
50–100 mV	Investigate the low group: high self-discharge, a failed parallel cell or a broken balance lead
Above 100 mV, or a group below 3.0 V at rest	Fault; remove from service for pack inspection

A group that drifts low again within days after balancing has a cell with high self-discharge, an internal soft short that can become a fire initiator.

Capacity test

Charge the pack fully and let it rest, then discharge at a constant current of C/3 to C/5 into an electronic load or a calibrated test bench to the manufacturer's cut-off voltage, recording ampere-hours and watt-hours. SOH equals measured capacity divided by rated capacity. A road test with logged data gives an approximate answer, but temperature, speed and payload make it far less repeatable than a bench test.

Maintenance compared with petrol motorcycles

An electric motorcycle needs no engine oil, oil filter, spark plugs, valve adjustment, air filter, fuel filter, coolant for an engine (although liquid-cooled machines need controller and motor coolant), exhaust service or clutch adjustment. Service intervals are therefore longer and labour per year lower. The remaining items still need attention:

- **Wheel and motor bearings**: hub motors carry the bearings in the motor; check for play and roughness, and check axle nut torque and torque arms, which resist motor reaction torque in the dropouts.
- **Final drive**: belt drives (Zero, Ather) need tension checks and inspection for cracked teeth and stone damage, with no lubrication; chains wear faster than on a petrol machine of similar power because of the motor's instant torque, so check slack and wear length as in Module 4.
- **Brakes**: regen reduces rear pad wear, but discs and calipers used less often corrode and seize, especially in wet or salty conditions. Brake fluid replacement every two years still applies.
- **Tyres**: electric machines are often heavier and deliver torque abruptly, so rear tyres may wear faster; check pressure weekly.
- **Connectors and wiring**: inspect high-current connectors for discolouration, looseness and corrosion, and check the charge port pins for burns. Apply contact protection only where the manufacturer specifies it.
- **12 V system**: the auxiliary battery, if fitted, fails like any other and can prevent the machine from waking.
- **Software**: controller, BMS and dashboard updates fix bugs and change behaviour; record the installed versions at every service.
- **Battery health**: read SOH and imbalance, check pack mounting and seals, and advise the owner on charging habits.

Converting petrol motorcycles to electric

Retrofit conversion, replacing the engine, tank and exhaust of a petrol motorcycle with a motor, controller and battery, is attractive in markets with large fleets of serviceable petrol frames, such as the boda boda fleets of East Africa, and is the subject of commercial kits and research.

Legal issues come first. A conversion changes the vehicle's propulsion and usually its mass, power and category. In the EU and the UK it requires inspection and individual approval or re-registration by the national authority (in the Netherlands the RDW) and the original type approval no longer covers the vehicle. India has published standards for retrofit electric conversion kits (AIS-123), and other markets have their own rules; insurance must be informed in every case.

Engineering issues follow:

- **Mass and weight distribution**: a 3.6 kWh pack (about 20 kg) and a hub or mid-drive motor (10–20 kg) replace an engine and fuel of similar mass, but battery placement changes the centre of gravity and front-rear weight split, which affects steering (Module 4) and braking.
- **Structural mounting**: the engine is often a stressed member of the frame; removing it can reduce frame stiffness, and the battery mounts must withstand crash and vibration loads.
- **Drive line**: a mid-drive must align with the original rear sprocket and chain line; the motor's torque at low speed may exceed what the original chain and sprockets were designed for.
- **Brakes and suspension**: added mass and changed weight distribution may require uprated springs; a hub motor's unsprung mass needs damping changes.
- **Electrical safety**: fusing at the battery, correctly rated cables, isolation from the frame for class B systems, IP protection, a contactor and pre-charge, and an interlock that prevents drive while charging.
- **The 12 V system**: lights, horn and indicators previously supplied by the alternator need a DC-DC converter.

Job sheet 5.6.1: Safe isolation and zero-voltage verification

Tools and materials	Reference values
Class 0 insulating gloves with leather protectors, safety glasses, insulated tools, CAT III 1,000 V multimeter, proving unit or known live source, lock-out device and tag, warning signs	Class B threshold: above 60 V DC. Capacitor discharge wait: manufacturer's time, typically 5–10 min. Zero-voltage acceptance: below about 1 V DC between all tested points

1. Park the vehicle on its centre stand or a paddock stand with the rear wheel off the ground, on a level floor, in a barriered area with warning signs. Remove jewellery and watches.
2. Read and record fault codes and SOC, then switch off and remove the key. Confirm the dashboard is dark and the contactor has opened (audible click on most machines).
3. Disconnect the 12 V auxiliary battery negative terminal, or remove the 12 V main fuse, so no control unit can close the contactors.
4. Put on gloves (after an air-leak test) and glasses. Remove the service disconnect, main pack connector or removable pack, and keep it on your person.
5. Note the time and wait at least the manufacturer's discharge time. Do not rotate the rear wheel during this time, because the motor would recharge the DC link.
6. Prove the multimeter on a known live source (for example the 12 V battery or a proving unit) on the DC voltage range.
7. Measure between controller B+ and B−, then between each of B+ and B− and the chassis, then between each pair of motor phases and between each phase and B−. All readings must be below about 1 V. A reading above this means the circuit is not dead: stop, wait longer, and investigate a failed bleeder or a second energy source.
8. Prove the multimeter again on the known live source to confirm it did not fail during the test.
9. Fit the lock-out device or cover to the service disconnect socket, attach the tag with your name, date and "Do not energise", and only then begin work.
10. On completion, reverse the procedure: remove the lock and tag only when all covers are refitted and all personnel are clear, refit the disconnect, reconnect the 12 V battery, switch on and check for fault codes.

Pass criteria: all measured voltages below about 1 V DC, meter proven before and after, service disconnect under the technician's control, lock-out and tag fitted before any high-voltage component is opened.

Job sheet 5.6.2: Testing motor phases and Hall sensors

Tools and materials	Reference values
Safe-isolation equipment, milliohm meter or 10 A current-limited bench supply with multimeter, insulation tester, 5 V supply or back-probing pins, oscilloscope (optional)	Line-to-line resistance typically 20–200 mΩ (hub), 5–30 mΩ (mid-drive), balance within 5 %. Phase to casing insulation above 1 MΩ at 500 V. Valid Hall states: six, with no 000 or 111

1. Isolate the vehicle as in Job sheet 5.6.1.

2. Disconnect the three phase connectors and the Hall sensor connector at the controller. Inspect the phase connectors for heat discolouration, melted insulation and loose crimps; record any found.
3. Measure U-V, V-W and W-U resistance with the milliohm meter, or by passing 10 A from the bench supply and measuring voltage at the motor-side terminals. Calculate resistance and imbalance. Imbalance above 5 % indicates a poor joint or winding damage; an open reading indicates a broken phase.
4. Measure insulation from each phase to the motor casing at 500 V with the Hall connector disconnected and the Hall wires kept clear. Below 1 MΩ indicates moisture or winding insulation failure.
5. Supply 5 V and ground to the Hall connector (from a bench supply with 1 kΩ pull-up resistors to each signal line, or by back-probing with the controller connected and powered, if the job sheet for the vehicle permits this with the phases disconnected).
6. Rotate the wheel slowly forward and record the three signal states over at least one full electrical cycle. Confirm six valid states in a repeating sequence with one bit changing per step and no 000 or 111.
7. If a state is missing, measure the supply at the sensor end, check continuity of each signal wire through the axle cable, and inspect for water in the connector before condemning the sensor.
8. Optionally, spin the wheel at a steady speed with phases open and measure line-to-line back-EMF on the oscilloscope: the three waveforms should be equal in amplitude and 120° apart.
9. Reconnect, run the controller's Hall self-learning routine if a sensor or motor was replaced, and test on the stand.

Pass criteria: phase resistance balanced within 5 %, no open phase, insulation above 1 MΩ, six valid Hall states in correct sequence, equal back-EMF amplitudes.

Job sheet 5.6.3: Battery pack inspection and cell balance check

Tools and materials	Reference values
Safe-isolation equipment, diagnostic software or BMS app, CAT III multimeter, insulation tester, torch, infrared thermometer	Cell group spread at rest below 20 mV (NMC). No group below 3.0 V at rest. Pack enclosure undamaged and dry. Insulation pack-to-enclosure above 1 MΩ

1. With the pack installed and the vehicle at rest for at least 30 minutes, connect the diagnostic tool and record SOC, SOH, pack voltage, each group voltage, temperatures, cycle count and stored BMS faults.
2. Calculate the spread between highest and lowest group. Compare with the table in this chapter.
3. Check that the sum of group voltages equals the measured pack voltage within about 0.5 %; a mismatch indicates a faulty measurement channel or balance lead.
4. Isolate the vehicle (Job sheet 5.6.1) and remove the pack following the manufacturer's procedure. Inspect the enclosure for cracks, dents, swelling, corrosion, water marks, damaged seals and burnt connector pins; inspect the vent for blockage.
5. Measure the pack voltage at its terminals and compare with the BMS reading.
6. Measure insulation resistance from each pack terminal to the enclosure (if metallic or with a conductive mount) at the specified test voltage.
7. Do not open a sealed pack unless you are trained and authorised and the manufacturer permits it. If authorised, check balance lead connections, busbar torque marks and thermistor locations, and look for discoloured nickel strips indicating overheating.

8. If the spread exceeds 20 mV, perform a full charge with the vehicle's charger and leave it connected for the balancing period specified (often several hours), then rest the pack and recheck.
9. If the same group falls again within 48–72 hours, or any group is below 3.0 V at rest, tag the pack as defective and arrange replacement or specialist repair.

Pass criteria: no physical damage or ingress, BMS and terminal voltages agree, group spread below 20 mV at rest after balancing, no group below 3.0 V, insulation above 1 MΩ, no stored critical BMS faults.

Job sheet 5.6.4: Controller and throttle fault diagnosis

Tools and materials	Reference values
Safe-isolation equipment, multimeter with diode test, back-probe pins, oscilloscope (optional), diagnostic software, controller wiring diagram	Throttle closed about 0.8 V, fully open about 4.2 V, supply 5.0 V ± 0.25 V. Body diode forward drop about 0.3–0.6 V. Pre-charge to 90–95 % of pack voltage before contactor closure

1. Read and record fault codes and live data. Check throttle voltage, brake switch and side-stand switch states, and Hall state in live data before any physical test.
2. With the wheel raised and key on, back-probe the throttle connector: confirm 5 V supply and good ground (below 0.1 V between throttle ground and controller B−), then slowly open the throttle and watch the signal rise smoothly from about 0.8 V to about 4.2 V.
3. Check each interlock: brake switches must change state when the levers are pulled (many controllers cut drive when a brake switch is closed), and the side-stand switch must allow drive only when the stand is up.
4. Measure pre-charge: at key-on, record DC-link voltage at the controller input over time; it must reach 90–95 % of pack voltage before the contactor clicks.
5. Isolate the vehicle (Job sheet 5.6.1) and disconnect the motor phases and battery from the controller.
6. Use the diode test between each phase terminal and B+ (red lead on phase) and B− (black lead on phase), then reverse the leads. Each switch position should read about 0.3–0.6 V in one direction and open in the other. A reading near 0 V in both directions is a shorted switch.
7. Inspect the controller for swollen capacitors, burnt odour, water ingress at cable glands and loose high-current terminals.
8. If the controller tests good and faults persist, verify programming parameters (battery and phase limits, low-voltage cut-off, pole pairs) against the manufacturer's values and repeat the Hall self-learning routine.
9. Road test after repair, monitoring phase current, battery current and temperatures.

Pass criteria: throttle signal within range and smooth, interlocks function, pre-charge within limits, no shorted or open power switches, parameters match specification, no fault codes after road test.

Troubleshooting

Symptom	Likely cause	Check	Remedy
No power, dashboard dark	Discharged or disconnected 12 V battery; BMS in sleep or protection; blown main fuse; key switch fault	12 V voltage; pack voltage at connector; main fuse continuity; BMS fault codes	Charge or replace 12 V battery; wake BMS with charger; find cause of fuse failure before replacing
Dashboard on, no drive	Side stand or brake switch active; throttle fault; contactor not closing; controller fault	Live data interlock states; throttle voltage; contactor click and coil voltage; fault codes	Repair switch or wiring; replace throttle; test contactor and precharge circuit
Judder at take-off, normal at speed	Hall sensor or wiring fault; wrong Hall angle after repair	Hall state sequence (Job sheet 5.6.2)	Repair wiring or replace sensor; run self-learning
Motor growls, vibrates, low power	Open phase or high-resistance phase connector	Phase resistance balance; connector discolouration	Repair or replace connector or winding
Rear wheel notchy or locks when pushed	Shorted controller switch; shorted motor winding	Diode test on controller; phase resistance; push with phases disconnected	Replace controller or motor
Sudden cut-out under hard acceleration	Low-voltage cut-off from weak cell group or high pack resistance; BMS overcurrent	Logged minimum cell voltage under load; group spread; BMS events	Balance or repair pack; reduce battery current limit
Range has fallen sharply	Capacity loss (SOH); cell imbalance; cold weather; dragging brake; tyre pressure	SOH and capacity test; group spread; wheel spin-down test	Balance, repair or replace pack; repair brake; inflate tyres
No regenerative braking	Battery full or cold; regen disabled in ride mode; brake switch fault	SOC and temperature; mode settings; fault codes	Ride to lower SOC; warm pack; correct settings or switch
Charger does not start	Pack too cold or hot; BMS fault; charger-pack communication; blown charge fuse; wrong charger	Pack temperature; BMS faults; charger LED code; charge port pins	Bring pack to 10–30 °C; repair BMS or port; use correct charger
Charge port or connector hot	Pitted or loose pins; corrosion	Visual inspection; resistance of contacts	Replace connector; investigate unplugging under load
Insulation fault warning	Water ingress; chafed cable; motor winding to casing	Insulation resistance of each subsystem in turn	Dry and reseal; repair cable; replace motor
Controller overheats and derates	Blocked cooling fins; failed coolant pump; excessive current limits; overloaded vehicle	Heatsink temperature trend; coolant flow; parameter settings	Clean; repair cooling; restore original limits

REVIEW QUESTIONS

1. State the DC and AC voltage limits of class B under UNECE R100 and R136. Is a "60 V" 17S NMC pack class B?
2. Calculate the minimum isolation resistance required for a pack with a maximum working voltage of 116 V, and state what reading you would expect from a healthy system.
3. Why must the zero-voltage check be carried out with the live-dead-live method?
4. A controller's DC link has 4,700 µF of capacitance and a 22 kΩ bleed resistor. How long does it take to fall to under 1 % of its initial voltage?

5. A motor's line-to-line resistances measure U-V 62 mΩ, V-W 73 mΩ and W-U 74 mΩ. Calculate the imbalance and identify the probable faulty phase.
6. Recording Hall states while turning a wheel gives 101, 100, 100, 010, 011, 001. What does this sequence suggest?
7. The throttle signal at rest reads 4.9 V. What faults could cause this, and what will the controller do?
8. Cell groups at rest read between 3.912 V and 3.986 V. Interpret this and state the next steps.
9. List six maintenance items on an electric motorcycle that remain the same as or more important than on a petrol motorcycle.
0. Why are Class D powder and CO2 extinguishers ineffective against a lithium-ion pack fire, and what should be used?
1. Give three legal and three engineering issues in converting a Bajaj Boxer to electric drive.
2. Voltage drop across a closed main contactor is 0.35 V at 120 A. Calculate the power dissipated in the contacts and state what action is needed.

ANSWERS

1. Class B covers above 60 V up to 1,500 V DC and above 30 V up to 1,000 V AC RMS. A 17S NMC pack reaches 17 × 4.2 = 71.4 V when fully charged, so it is class B.
2. R_iso,min = 100 × 116 = 11.6 kΩ. A healthy system should read well above 1 MΩ, typically tens to hundreds of megaohms.
3. Proving the meter on a known live source before and after the test confirms that the meter, its leads and its fuse were working; otherwise a dead meter would show zero on a live circuit and the technician would wrongly believe the circuit was safe.
4. τ = R × C = 22,000 × 0.0047 = 103.4 s. Falling below 1 % requires e^(−t/τ) < 0.01, so t > 4.6τ ≈ 476 s, about 8 minutes.
5. R_avg = (62 + 73 + 74) / 3 ≈ 69.7 mΩ. Imbalance = (74 − 62) / 69.7 × 100 ≈ 17 %, well above 5 %. The two high readings (V-W and W-U) share phase W, while U-V, which excludes W, is normal, so phase W has a high-resistance joint, crimp or damaged strands. Check the W connector and crimp first, then the winding termination.
6. The state 110 is missing and 100 repeats, so the sensor that should go high at that step (the middle bit) is changing late or not at all at that position, indicating a faulty or intermittent sensor, a poor connection, or a damaged magnet ring. Check that sensor's output and wiring.
7. The signal is near the 5 V supply, which may be caused by a broken ground wire to the throttle (sensor output floats high), a signal wire shorted to the 5 V supply, or a failed sensor. The controller will detect an out-of-range signal and disable drive, preventing an unintended full-throttle command.
8. The spread is 74 mV, in the 50–100 mV band. Investigate the lowest group for a failed parallel cell, high self-discharge or a poor balance lead connection; perform full balancing charges, then recheck after 48–72 hours; if the same group drifts low again, the pack needs specialist repair.
9. Brakes (including corrosion of little-used discs and fluid replacement), tyres, wheel and motor bearings, final drive chain or belt, high-current connectors and charge port, 12 V auxiliary battery, software updates, suspension, and battery health checks.
10. They do not remove heat from the cells, and the runaway reaction does not depend on atmospheric oxygen, so cells continue heating and propagating after the flames are knocked down. Large volumes of water (or an AVD extinguisher on small packs) are used to cool the cells, and the pack must be monitored for re-ignition.
11. Legal: the original type approval no longer covers the vehicle; it must be inspected and approved or re-registered by the national authority; insurance and licensing category may change. Engineering: battery mass and position change weight distribution and steering; the frame may lose stiffness where the engine was a stressed member;

the drive line and chain must handle the motor's low-speed torque; electrical safety (fusing, isolation, pre-charge, interlocks) and a DC-DC converter for 12 V loads are required.

12. P = V × I = 0.35 × 120 = 42 W, far above the few watts of a healthy contactor (50–100 mV drop gives 6–12 W). The contacts are pitted or the terminals loose; check terminal torque and replace the contactor, and investigate the pre-charge circuit, whose failure is a common cause of contact damage.

Glossary

Back-EMF: the voltage generated in a motor's windings by the rotating magnet field, proportional to speed and opposing the supply voltage.

Balancing: equalising the state of charge of series cell groups, by bleeding charge from high groups (passive) or transferring it between groups (active).

Base speed: the motor speed above which back-EMF reaches the available voltage and torque must fall; the boundary between constant-torque and field-weakening operation.

Battery management system (BMS): the electronics that monitor cell voltages, temperatures and current, estimate SOC and SOH, balance cells, communicate current limits and protect the pack.

BLDC motor: brushless DC motor; a permanent-magnet machine with trapezoidal back-EMF, typically driven by six-step commutation from Hall sensors.

C-rate: current expressed as a multiple of the battery's capacity; 1C discharges the rated capacity in one hour.

CAN bus: controller area network, a two-wire differential serial bus (ISO 11898) linking vehicle control units, terminated with 120 Ω at each end.

CC/CV charging: constant-current then constant-voltage charge profile used for lithium-ion batteries.

Class B voltage: working voltage above 60 V and up to 1,500 V DC, or above 30 V and up to 1,000 V AC RMS, under UNECE R100 and R136.

Contactor: a heavy-duty electromechanical switch that connects or isolates the traction battery.

Coulomb counting: estimating SOC by integrating the measured battery current over time.

DC-DC converter: a converter that steps traction voltage down to about 14 V for lights, horn and control electronics.

DC link: the DC input of the inverter, including its capacitor bank.

Dead time: a short interval in which both switches of an inverter leg are off, to prevent shoot-through.

Depth of discharge (DoD): the fraction of capacity removed in a cycle.

Field-oriented control (FOC): motor control that regulates current in a reference frame rotating with the rotor, as d-axis (flux) and q-axis (torque) components.

Field weakening: injecting negative d-axis current to reduce effective magnet flux so that a permanent-magnet motor can run above base speed.

Hall sensor: a semiconductor sensor that switches in a magnetic field; three are used to detect rotor position in 60° electrical steps.

Hub motor: an outer-rotor motor built into the wheel hub, driving the wheel without a transmission.

Interior permanent-magnet (IPM) motor: a PMSM with magnets buried in the rotor laminations, which produces reluctance torque and allows wide field weakening.

Internal resistance: the effective resistance of a cell that causes voltage sag and I^2R heating under load.

Isolation resistance: the resistance between high-voltage circuits and the vehicle chassis; at least 100 Ω/V for DC circuits under R100 and R136.

Kt (torque constant): torque produced per ampere of motor current, in N·m/A.

Kv (speed constant): no-load motor speed per volt, in rpm/V; Kt ≈ 9.55 / Kv in SI units for an ideal machine.

LECCS: Light Electric Combined Charging System, a compact AC and DC charging connector for light electric vehicles adopted as an Indian standard.

LFP: lithium iron phosphate cathode chemistry; lower energy, long cycle life, high thermal stability.

Lithium plating: deposition of metallic lithium on the anode, caused by charging too fast or too cold; reduces capacity and creates short-circuit risk.

Lock-out/tag-out: physically securing an isolation point and labelling it so that a system cannot be re-energised during work.

Mid-drive: a frame-mounted motor driving the rear wheel through a chain, belt or gear reduction.

MTPA (maximum torque per ampere): the split of current between d and q axes that gives the most torque for a given current magnitude in an IPM motor.

NMC: nickel manganese cobalt oxide cathode chemistry; high energy density, the most common chemistry in premium packs.

Pedelec: an electrically power assisted cycle under EN 15194, with assistance only while pedalling, up to 25 km/h and 250 W continuous.

Phase current: current in the motor windings, which sets motor torque; distinct from battery current.

PMSM: permanent-magnet synchronous motor with sinusoidal back-EMF, driven by sinusoidal currents.

Pre-charge circuit: a resistor and relay that charge the controller's DC-link capacitors before the main contactor closes, limiting inrush current.

Propagation: the spread of thermal runaway from one cell to its neighbours.

PWM (pulse-width modulation): switching a voltage on and off at fixed frequency with variable duty cycle to set an average voltage.

Regenerative braking: operating the motor as a generator to slow the vehicle and return energy to the battery.

REESS: rechargeable electrical energy storage system, the regulatory term for a traction battery.

Resolver: a rotary transformer that gives rotor angle as sine and cosine modulated signals; tolerant of heat and vibration.

Service disconnect: a removable plug or fuse that breaks the battery string for safe isolation.

Six-step commutation: drive in which two phases conduct at a time and current switches every 60° electrical according to Hall sensor states.

Solid electrolyte interphase (SEI): a passivating film formed on the anode by electrolyte reaction; its slow growth causes calendar ageing.

State of charge (SOC): remaining charge as a fraction of present full capacity.

State of health (SOH): present capacity (or resistance) relative to the new battery; 80 % capacity is the usual end of first life.

Swappable battery: a removable pack exchanged for a charged one at a station, usually owned by the network operator.

Thermal runaway: a self-accelerating sequence of exothermic reactions in a cell leading to venting, fire and very high temperatures.

UN 38.3: the set of tests (T1 to T8) that lithium cells and batteries must pass before transport.

VCU (vehicle control unit): the controller that coordinates rider inputs, BMS limits, motor controller and charger and enforces interlocks.

Further reading

Textbooks

- Hughes, A. and Drury, B. *Electric Motors and Drives: Fundamentals, Types and Applications*, 5th edition. Newnes (Elsevier), 2019.
- Larminie, J. and Lowry, J. *Electric Vehicle Technology Explained*, 2nd edition. Wiley, 2012.
- Plett, G. L. *Battery Management Systems, Volume I: Battery Modeling* and *Volume II: Equivalent-Circuit Methods*. Artech House, 2015.
- Hendershot, J. R. and Miller, T. J. E. *Design of Brushless Permanent-Magnet Machines*. Motor Design Books, 2010.
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- Ehsani, M., Gao, Y., Longo, S. and Ebrahimi, K. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*, 3rd edition. CRC Press, 2018.

- Warner, J. *The Handbook of Lithium-Ion Battery Pack Design: Chemistry, Components, Types and Terminology*. Elsevier, 2015.
- Cossalter, V. *Motorcycle Dynamics*, 2nd edition. Lulu, 2006.
- Foale, T. *Motorcycle Handling and Chassis Design: The Art and Science*. Tony Foale Designs, 2002.
- Robert Bosch GmbH. *Bosch Automotive Handbook*, latest edition. Wiley.

Regulations and standards

- Regulation (EU) No 168/2013 on the approval and market surveillance of two- or three-wheel vehicles and quadricycles.
- Regulation (EU) 2023/1542 concerning batteries and waste batteries.
- UNECE Regulation No 136: Uniform provisions concerning the approval of vehicles of category L with regard to specific requirements for the electric power train.
- UNECE Regulation No 100: Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train.
- UNECE Regulation No 85: Measurement of the net power and the maximum 30 minutes power of electric drive trains.
- UN Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, Part III, sub-section 38.3.
- EN 15194: Cycles. Electrically power assisted cycles. EPAC bicycles.
- EN 50604-1: Secondary lithium batteries for light electric vehicle applications. General safety requirements and test methods.
- IEC 62133-2: Secondary cells and batteries containing alkaline or other non-acid electrolytes. Safety requirements for portable sealed secondary lithium cells and batteries.
- IEC 61851 series: Electric vehicle conductive charging system; IEC 62196 series: plugs, socket-outlets and vehicle connectors.
- ISO 13063 series: Electrically propelled mopeds and motorcycles. Safety specifications.
- ISO 18243: Electrically propelled mopeds and motorcycles. Test specifications and safety requirements for lithium-ion battery systems.
- ISO 11898: Road vehicles. Controller area network (CAN).
- IEC 60903 (live working, gloves of insulating material) and IEC 60900 (live working, hand tools for use up to 1,000 V AC and 1,500 V DC).
- AIS-156: Specific requirements for L category electric power train vehicles, Automotive Research Association of India, with amendments.
- NITI Aayog. *Draft Battery Swapping Policy*. Government of India, April 2022.

Course source documents

- MAVCC. *Motorcycle Mechanic*, teacher edition. Mid-America Vocational Curriculum Consortium, 1988.
- KS/Qianjiang. *K-Light 125 maintenance manual* (manuel d'entretien).
- Hero Honda. *Technician starter kit, Unit 2: The Motorcycle*.
- Solomon R. Guggenheim Museum. *The Art of the Motorcycle*. Guggenheim Museum Publications, 1998.

Companion resource

- Transitions Lab. *Motorcycle anatomy explorer*. transitionslab.org/motorcycle-anatomy.

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Workshop procedures are general guidance. Specifications differ between machines: always confirm values and torque settings in the manufacturer's service manual, and observe the safety notes in Module 1 and Module 5.