

EV Power Electronics

Understand how electric vehicles really work — explained from scratch for mechanical engineers, with no prior electronics needed.

✓ Zero electronics assumed

✓ Mechanical analogies throughout

✓ Worked examples

✓ Exam questions + solutions

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PART I

Setting the Stage

You already understand engines, gearboxes, and pumps. In these two chapters you will discover that an electric vehicle is built from the exact same ideas — only the "fluid" is electricity. By the end of Part I you will know just enough electrical vocabulary to follow everything that comes after. No prior electronics required. Promise.

01 Why an Electric Vehicle is a Power Electronics Machine

Open the bonnet of a petrol car and you see machinery you understand: pistons, a crankshaft, a gearbox, belts, a radiator. Open an electric car and you see... boxes. Sealed aluminium boxes connected by thick orange cables. Those boxes are **power electronic converters**, and this handbook is about what happens inside them. Here is the good news: every one of those boxes does a job you already understand mechanically — it just does it to electricity instead of to a rotating shaft or a flow of fluid.

The one idea that unlocks everything: the electrical gearbox

Ask yourself why a petrol car needs a gearbox. The engine spins fast but produces modest torque; the wheels need slower rotation but much higher torque, and that requirement changes constantly with speed and load. The gearbox **converts** power from one speed-torque combination to another, ideally without wasting much of it. Power in $\approx$ power out; only the **form** changes.

Electrical power works identically. Electrical power is **voltage $\times$ current**. Voltage is the "push" (think pressure, or torque). Current is "how much is flowing" (think flow rate, or shaft speed). A power electronic converter takes electrical power at one voltage-current combination and delivers it at another, conserving the product. That is **literally** a gearbox for electricity.

THE MASTER ANALOGY — HOLD ONTO THIS FOR THE WHOLE BOOK

A power converter is a gearbox for electricity. It changes the voltage-current combination (like changing the torque-speed combination) while keeping the total power almost the same. Just as a 4:1 gear reduction quadruples torque and quarters speed, a converter that quarters voltage will roughly quadruple current — power stays put. And just as gearboxes lose a little power to friction, converters lose a little to heat. The whole engineering game is minimising that loss while shrinking size and cost.

Why an EV needs so many electrical gearboxes

Here is the problem the boxes solve. Almost nothing in an EV speaks the same electrical "language":

- The **battery** stores energy as **DC** (steady, one-directional flow — like a constant shaft rotation) at a high voltage, say 350–400 volts.
- The **motor** needs **AC** (alternating, back-and-forth flow — like reciprocating motion) at a frequency that must change continuously with road speed.
- The **wall socket** at home gives AC at 230 volts.
- A **fast charger** on the highway gives DC at up to 1000 volts.
- The **lights, screens and computers** want DC at just 12 volts.

Every boundary between these worlds needs a converter to translate. That is why a modern EV carries at least four of them. Name them once now; we will meet each properly later:

The box	Its job (the translation it does)	Mechanical parallel
On-board charger (OBC)	Wall AC $\rightarrow$ battery DC (charging at home)	A gearbox matching an external drive to your machine

Traction inverter	Battery DC → motor AC (driving)	The main transmission — but electronic and infinitely variable
DC-DC converter (APM)	High-voltage DC → 12 V DC (accessories)	A reduction gearbox for the "small stuff"
Fast charger (off-board)	Grid AC → high-power DC straight into the battery	A heavy industrial drive that lives outside the vehicle

CHAPTER 1 — REMEMBER THIS

1. An EV replaces mechanical machinery with electronic boxes called **power converters** — gearboxes for electricity.
2. A converter changes the voltage × current combination while conserving power, exactly as a gearbox changes torque × speed.
3. An EV needs many converters because the battery (high-voltage DC), the motor (variable AC), the grid (230 V AC) and the accessories (12 V DC) all speak different electrical languages that must be translated.

This is what the EV industry is hiring for

The engineers who design, test and service these boxes are among the most in-demand professionals in India's EV sector. DIYguru's certified programmes take you from exactly this starting point to job-ready. See Chapter 13.

02 Electricity for Mechanical Engineers — the 30-Minute Crash Course

You do not need a degree in electrical engineering to understand EVs. You need about six ideas, and each one maps cleanly onto something you already know from fluids and mechanics. Read this chapter slowly once, and everything afterwards will click.

The translation table — the most useful half-page in this book

Electrical term	Symbol / unit	Mechanical / fluid twin	Plain meaning
Voltage	V, volts	Pressure / torque	The "push" that drives electricity. Higher voltage = stronger push.
Current	I, amperes (A)	Flow rate / shaft speed	How much electricity is actually moving per second.
Power	P, watts (W)	Power (same word!)	Rate of energy delivery. $P = V \times I$.
Energy	E, watt-hours (Wh)	Work / fuel in the tank	Power delivered over time. A battery's "size."
Resistance	R, ohms (Ω)	Pipe friction / a damper	Opposition to flow; turns electricity into unwanted heat.
Frequency	f, hertz (Hz)	Cycles per second (rpm)	How fast AC flips back and forth. India's grid: 50 Hz.

Idea 1 — Voltage is pressure, current is flow

Picture a water pipe. **Pressure** pushes water; **flow rate** is how much water actually moves. High pressure with a closed tap means no flow. Open the tap and flow depends on both the pressure and how much the pipe resists. Electricity is the same: **voltage** is the push, **current** is the flow, and **resistance** is the pipe's narrowness. This single picture explains most of what follows.

Idea 2 — Power is voltage times current

This is the most important formula in the entire book, and it is just the electrical version of "power = force $\times$ velocity" or "power = torque $\times$ angular speed."

$$P = V \times I$$

Power (watts) = Voltage (volts) $\times$ Current (amperes)

WORKED EXAMPLE 2.1 — READING A MOTOR'S NAMEPLATE

An electric scooter motor runs at 60 volts and draws 50 amperes at full throttle. What power is it delivering?

Use $P = V \times I$.

$$P = 60 \text{ V} \times 50 \text{ A} = 3000 \text{ W} = 3 \text{ kW}.$$

Answer: 3 kW — about the same as 4 horsepower.

Notice the trade-off hidden in this formula, and why it matters for EVs. To deliver the same 3 kW, you could use high voltage and low current (say $300 \text{ V} \times 10 \text{ A}$) or low voltage and high current ($30 \text{ V} \times 100 \text{ A}$). They give the same power — but high current means thicker, heavier, more expensive cables and more heat lost in them. This is exactly why modern EVs use high battery voltages: **higher voltage lets you move the same power with less current, so cables stay thin and losses stay low.** Remember this; it explains a hundred design decisions.

Idea 3 — Energy is power over time (the fuel tank)

Power is a **rate**; energy is the **total**. A 3 kW motor running for 2 hours consumes 6 kilowatt-hours (kWh) of energy. A battery's capacity is measured in kWh — it is the size of the fuel tank.

$$\text{Energy (kWh)} = \text{Power (kW)} \times \text{Time (hours)}$$

WORKED EXAMPLE 2.2 — ESTIMATING RANGE

An electric car has a 40 kWh battery and consumes about 6.5 kWh per 100 km. Roughly how far can it go?

Range = battery energy ÷ consumption rate.

$$\text{Range} = 40 \text{ kWh} \div 6.5 \text{ kWh/100km} = 6.15 \times 100 \text{ km}.$$

Answer: about 615 km on paper (real-world ~500 km after losses, AC, terrain).

Idea 4 — DC versus AC (steady rotation versus reciprocating motion)

DC (direct current) flows steadily in one direction — like a shaft turning at constant speed. Batteries and solar panels are DC. AC (alternating current) reverses direction many times per second — like a piston reciprocating. The grid and most motors use AC. India's grid alternates 50 times per second (50 Hz). A huge part of EV power electronics is simply **translating between DC and AC**: the inverter turns battery DC into motor AC; the charger's front end turns grid AC into DC.

DC VS AC, MECHANICALLY

DC is a motor spinning steadily in one direction. AC is a jigsaw blade going up-down-up-down. Neither is "better" — they suit different jobs. Batteries naturally store DC; the grid naturally distributes AC (it is easier to transform to different voltages); many motors naturally want AC. The converters are the translators that let these different worlds work together.

Idea 5 — Efficiency, and where the lost power goes

No converter is perfect. Efficiency is how much power comes out versus goes in, and the missing bit becomes heat — which is why EV boxes have cooling.

$$\text{Efficiency } (\eta) = \text{Power out} \div \text{Power in} \times 100\%$$

WORKED EXAMPLE 2.3 — HOW MUCH HEAT MUST BE COOLED?

A fast charger takes 100 kW from the grid and delivers 96 kW to the car. What is its efficiency, and how much heat must it dump?

$$\text{Efficiency} = 96 \div 100 \times 100\% = 96\%.$$

$$\text{Heat lost} = 100 - 96 = 4 \text{ kW}.$$

Answer: 96% efficient; 4 kW of heat to remove — like a small room heater running constantly.

Idea 6 — The motor connection you already know

One formula bridges electrical and mechanical worlds and will reassure you that this is all one subject. A motor's mechanical output power is torque $\times$ angular speed — pure mechanical engineering — and it equals (minus losses) the electrical power going in:

$$P_{\text{mech}} = T \times \omega \approx V \times I \times \eta$$

$$\text{Torque (N-m)} \times \text{angular speed (rad/s)} \approx \text{electrical power in} \times \text{efficiency}$$

This is why an EV motor delivers huge torque instantly: unlike an engine that must rev up, an electric motor can push maximum current — and therefore maximum torque — from zero rpm. The instant torque you feel in an EV is this formula in action.

CHAPTER 2 — THE SIX IDEAS IN ONE BREATH

- Voltage = pressure/push; current = flow; resistance = friction.
- Power $P = V \times I$ (the electrical version of torque $\times$ speed).
- Energy = power $\times$ time; a battery's kWh is its fuel-tank size.
- DC = steady one-way (batteries); AC = back-and-forth (grid, motors); converters translate between them.
- Efficiency = out/in; the rest becomes heat that must be cooled.
- Higher voltage moves the same power with less current — thinner cables, lower losses.

PART II

The Building Blocks

Every converter in every EV — no matter how complex it looks — is assembled from just five kinds of component and one clever trick. Learn these, and you can read the block diagram of anything. This is the "nuts, bolts and bearings" chapter of electronics.

03 The Five Components That Build Everything

You do not need to know hundreds of electronic parts. Five families do almost all the work in EV converters. Here is each one, what it does, and the mechanical component it behaves like.

1. The switch — an electronic valve (or clutch)

A **switch** is a device that turns current fully on or fully off — and in power electronics it does this astonishingly fast, tens of thousands to millions of times per second. It is never left half-open, because a half-open valve wastes energy as heat (imagine throttling a high-pressure line with a partly-closed valve — the valve gets hot). The two workhorse types:

- **MOSFET** — a fast, lighter-duty switch, ideal for lower voltages and high switching speeds. Think: a quick solenoid valve.
- **IGBT** — a heavier-duty switch for the high voltages and currents of traction. Think: a big industrial gate valve.

The switch is the **active** component — the one the control system commands. Everything else responds to it.

ANALOGY

A switch is a valve that is only ever fully open or fully shut, flicked open and closed thousands of times a second. It is also like a clutch — engaging and disengaging the flow of power on command. Keeping it fully-on or fully-off (never in between) is what keeps it cool and efficient.

2. The inductor — the flywheel

An **inductor** is a coil of wire. When current flows through it, it stores energy in a magnetic field — exactly as a spinning flywheel stores kinetic energy. Its defining behaviour: **the current through an inductor cannot change instantly**. Try to stop it suddenly and it fights back with a voltage spike (the electrical equivalent of water-hammer, or a flywheel's momentum resisting a sudden brake). Converters use inductors to keep current flowing smoothly during the "off" moments between switch flicks — just as a flywheel carries an engine smoothly through the gaps between power strokes.

3. The capacitor — the spring or accumulator

A **capacitor** stores energy in an electric field between two plates, like a compressed spring or a hydraulic accumulator storing energy under pressure. Its defining behaviour is the mirror image of the inductor's: **the voltage across a capacitor cannot change instantly**. Capacitors sit at the inputs and outputs of converters, smoothing out the pulsing from the switches so the outside world sees clean, steady voltage — exactly as an accumulator smooths pressure pulses from a piston pump.

FLYWHEEL & SPRING, TOGETHER

Almost every converter pairs an inductor (flywheel — smooths current) with a capacitor (spring/accumulator — smooths voltage). Together they turn the choppy output of a fast-switching valve into a smooth, steady supply. Whenever you see "LC filter" in EV literature, picture a flywheel and an accumulator working as a team.

4. The diode — the check valve

A diode lets current pass in one direction only and blocks it in the other — precisely a one-way check valve. It needs no control signal; it just automatically steers current the right way. Four diodes arranged in a bridge can turn AC (back-and-forth flow) into one-directional DC — the same idea as check valves turning a reciprocating pump's output into steady one-way flow.

5. The transformer — the gear pair with magnetic teeth

A transformer is two coils wound on a shared magnetic core. AC in one coil creates AC in the other, scaled by the ratio of turns — 10 turns to 1 turn gives a 10:1 voltage step-down (and a 1:10 current step-up), with power conserved. It is a gear pair whose "teeth" are magnetic. Two properties make it vital in EVs:

- **Voltage scaling** — step voltages up or down cleanly.
- **Isolation** — there is no metal connection between the two sides; power crosses through the magnetic field alone. This is a safety barrier (like a magnetic coupling that transmits torque with no shaft passing through the wall), keeping dangerous grid voltages away from the parts a human might touch.

One crucial rule you will meet again: **the faster a transformer's AC alternates, the smaller it can be**. This is why converters deliberately chop electricity to high frequencies — it shrinks the heavy magnetic parts from the size of a brick to the size of a matchbox.

CHAPTER 3 — THE FIVE BUILDING BLOCKS

- **Switch (MOSFET/IGBT)** = valve or clutch — the active, commanded part.
- **Inductor** = flywheel — smooths current; current can't jump.
- **Capacitor** = spring/accumulator — smooths voltage; voltage can't jump.
- **Diode** = check valve — one-way flow, automatic.
- **Transformer** = magnetic gear pair — scales voltage and provides safety isolation; shrinks as frequency rises.

04 The Central Trick: Switching & PWM

This chapter contains the single most important idea in all of power electronics. Once you see it, the whole field makes sense. It answers a simple question: how do you reduce a voltage without wasting the difference as heat?

The wrong way, and why nobody does it

Suppose you must turn 400 volts into 200 volts. The crude approach is to put a resistance in the way and burn off half the power as heat — exactly like riding the brakes to control speed downhill. For a phone charger this wastes little; for a 100 kW EV it would mean dumping 50 kW of heat. Impossible. So power electronics never throttles. Instead, it chops.

The right way: chop, then smooth

Take the switch (our electronic valve) and flick it fully on and fully off, very fast. If it is on for half of each cycle and off for the other half, the **average** voltage that gets through is half the input — 200 volts. Then use the flywheel-and-spring pair (inductor + capacitor) to smooth those chops into clean, steady DC. Because the switch is only ever fully-on (almost no voltage across it) or fully-off (no current through it), it wastes almost nothing. Efficiency leaps to 95–99%.

The fraction of time the switch is on is called the **duty cycle**, written D . It is the master control knob of power electronics.

$$\text{Average output voltage} = D \times \text{Input voltage}$$

D = duty cycle = fraction of time the switch is ON (between 0 and 1)

THE DEFINITIVE PICTURE: FILLING A TANK WITH A FLICKING VALVE

Imagine filling a tank from a high-pressure line by flicking a valve rapidly open and shut, with an accumulator downstream smoothing the pulses into steady flow. Flick it open 25% of the time → the tank effectively sees 25% of the line pressure. Change the flick ratio and you change the output — smoothly, precisely, with almost no energy wasted in throttling. That flick ratio is the **duty cycle**. Adjusting it electronically is called **PWM — Pulse Width Modulation**.

PWM — Pulse Width Modulation

PWM is simply the technique of controlling output by adjusting the width of the "on" pulses — how long the valve stays open each cycle. Widen the pulses (higher duty cycle) for more output; narrow them for less. PWM is how nearly every converter, motor drive and charger controls its output. When you press an EV's accelerator, you are commanding the inverter's PWM to widen its pulses and feed more power to the motor.

WORKED EXAMPLE 4.1 — SIZING THE DUTY CYCLE

A DC-DC converter must produce 48 V from a 400 V battery to feed an auxiliary system. What duty cycle does it need?

Use Average output = $D \times \text{Input}$, so $D = \text{output} \div \text{input}$.

$$D = 48 \text{ V} \div 400 \text{ V} = 0.12.$$

Answer: a duty cycle of 0.12, i.e. the switch is ON just 12% of each cycle.

Why switch so fast? Two reasons

Converters switch at 20,000 to 1,000,000 times per second (20 kHz to 1 MHz). Why so fast? First, **smoother output**: the faster you chop, the easier the flywheel-and-spring pair smooths it, and the smaller they can be. Second, **smaller magnetics**: recall that transformers and inductors shrink as frequency rises. High-frequency switching is the reason a modern 7 kW charger fits in a box the size of a lunchbox rather than a suitcase. The limit is that every flick of the switch wastes a tiny bit of energy, so switching too fast eventually overheats the switch — a central trade-off that newer materials (Chapter 12) push further.

CHAPTER 4 — THE TRICK THAT RUNS THE WHOLE FIELD

1. You never reduce voltage by throttling (burning the difference as heat). You **chop** with a fast switch and **smooth** with an inductor-capacitor pair.
2. **Duty cycle (D)** = the fraction of time the switch is on = the master control knob. $\text{Output} \approx D \times \text{input}$.
3. **PWM** adjusts the pulse widths to control everything from a DC-DC converter's output to a motor's torque.
4. Fast switching gives smoother output and smaller magnetics — the reason EV converters are compact.

From concept to hardware

In DIYguru's hands-on labs, students build and probe real PWM converters — watching the chopped waveform smooth into clean DC on an oscilloscope. Reading about it is good; measuring it yourself is how it truly sticks.

PART III

The Four Core Converters

Combine the five components and the switching trick, and you get four fundamental machines. Every electrical gearbox in every EV is one of these four — or a combination of them. Master these and you have mastered the heart of EV power electronics.

05 DC-DC Converters: Buck & Boost

A DC-DC converter changes one DC voltage into another — a pure electrical gearbox. There are two basic types: the **buck** (steps voltage down) and the **boost** (steps voltage up). Together with their combination, they cover a huge fraction of EV electronics.

The buck converter — the reduction gearbox

The buck converter steps voltage **down**. It is exactly the "chop and smooth" circuit from Chapter 4: a switch chops the high input voltage, and an inductor-capacitor pair smooths the result. Its formula is the one you already know:

$$V_{\text{out}} = D \times V_{\text{in}}$$

Buck (step-down): output is the duty cycle times the input. Since $D \leq 1$, output $\leq$ input.



Fig. 5.1 — A buck converter stepping the 400 V battery down to 12 V for the accessory system. Chop, then smooth.

WORKED EXAMPLE 5.1 — THE ACCESSORY CONVERTER

An EV uses a buck converter to power its 12 V systems from the 400 V battery. What duty cycle is required, and if the 12 V side draws 20 A, what current comes from the battery (assume ideal, no losses)?

Duty cycle: $D = V_{\text{out}} \div V_{\text{in}} = 12 \div 400 = 0.03$.

Power out = $12 \text{ V} \times 20 \text{ A} = 240 \text{ W}$. With no losses, power in = power out = 240 W.

Battery current = $240 \text{ W} \div 400 \text{ V} = 0.6 \text{ A}$.

Answer: $D = 0.03$; battery supplies just 0.6 A to deliver 20 A at the low-voltage side.

Look at what that example shows: 0.6 A in, 20 A out. The converter traded voltage for current — a step-down gearbox trading speed for torque. Power was conserved (240 W both sides). This is the gearbox analogy made numerical.

The boost converter — the step-up gearbox

The boost converter steps voltage **up** — output higher than input. How can that be? Through the flywheel. When the switch closes, the inductor charges up from the source (you spin up the flywheel). When the switch opens, the inductor's stored energy has nowhere to go but forward, and it **adds its stored push on top of the source voltage**, delivering a higher output. Its formula:

$$V_{\text{out}} = V_{\text{in}} \div (1 - D)$$

Boost (step-up): as D approaches 1, output rises well above input.

WORKED EXAMPLE 5.2 — BOOSTING SOLAR TO THE BATTERY BUS

A solar panel produces 120 V. A boost converter must raise it to 400 V to charge the battery. What duty cycle is needed?

Rearrange $V_{\text{out}} = V_{\text{in}} \div (1 - D)$: so $(1 - D) = V_{\text{in}} \div V_{\text{out}} = 120 \div 400 = 0.3$.

Therefore $D = 1 - 0.3 = 0.7$.

Answer: a duty cycle of 0.7 boosts 120 V up to 400 V.

A buck-boost converter combines both, able to step voltage either up or down — useful when a source voltage (like a battery that sags as it drains) might be above or below the target. You will meet these three converters constantly; they are the workhorses of every EV's DC systems.

CHAPTER 5 — THE DC GEARBOXES

- Buck steps voltage down: $V_{\text{out}} = D \times V_{\text{in}}$. Trades voltage for current (speed for torque).
- Boost steps voltage up using the inductor's stored energy: $V_{\text{out}} = V_{\text{in}} \div (1 - D)$.
- Buck-boost does either direction.
- In all of them, power in $\approx$ power out — only the voltage-current combination changes.

06 Inverters: How the Battery Drives an AC Motor

The battery gives DC. Most EV motors want AC. The **inverter** is the converter that turns DC into AC — and it is arguably the single most important box in the vehicle, because it is the EV's true "transmission." It controls the motor's speed and torque, and it is why EVs need no conventional gearbox.

How you make AC from DC: the H-bridge

Recall AC is back-and-forth flow. To create it from a steady DC source, you need to repeatedly **reverse** how the source connects to the motor — push, then pull, then push. This is done with an arrangement of four switches called an **H-bridge** (it looks like the letter H). Close one diagonal pair and current flows one way through the motor; close the other diagonal pair and it flows the opposite way. Alternate rapidly and you have created AC.

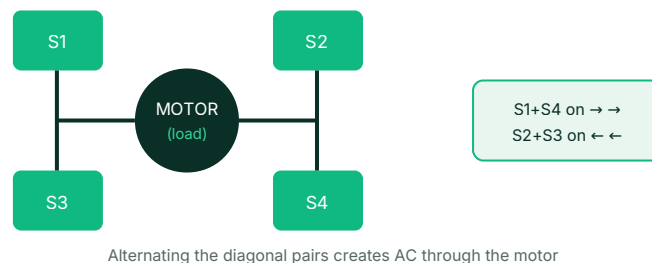


Fig. 6.1 — The H-bridge inverter. Alternating which diagonal pair of switches is closed reverses current through the motor, synthesising AC from DC.

PWM makes it a smooth, controllable sine wave

Simply flipping back and forth gives a crude, blocky AC. To make the smooth sine wave a motor prefers — and to control its **frequency** and **amplitude** — the inverter uses PWM (Chapter 4). By rapidly modulating the pulse widths within each half-cycle, it sculpts a clean sine wave of **any** frequency and strength. And here is the key: **the frequency of that AC sets the motor's speed, and the amplitude sets its torque.** The inverter can therefore command any speed and torque continuously — which is exactly why an EV needs no multi-gear transmission. The inverter is the transmission, with infinitely many ratios and no clutch.

ANALOGY

A conventional car changes the engine-to-wheel ratio in discrete steps with a mechanical gearbox. The inverter does the same job electronically and continuously — like a perfect infinitely-variable transmission that can also run in reverse and act as a brake, all with no moving parts beyond the motor itself.

Three-phase inverters

Real EV traction motors are usually **three-phase**: they have three sets of windings fed by three AC waves, each offset in timing, which together produce a smoothly rotating magnetic field that pulls the rotor around. A three-phase inverter simply uses six switches (three H-bridge "legs") instead of four. The principle is identical — chop and sculpt with PWM — just done three times over, offset in time. Don't be intimidated by

"three-phase"; it is three of the same thing working in a coordinated rhythm, like a three-cylinder engine firing in sequence for smooth power.

CHAPTER 6 — THE INVERTER

- An inverter turns DC into AC using switches (an H-bridge) that repeatedly reverse the connection to the motor.
- PWM sculpts a smooth sine wave and sets its frequency (→ motor speed) and amplitude (→ motor torque).
- Because it gives continuous speed/torque control, the inverter replaces the mechanical gearbox — it is the EV's transmission.
- Traction inverters are three-phase (six switches): three coordinated AC waves creating a rotating magnetic field.

07 Rectifiers & Power Factor: Charging from the Grid

To charge from a wall socket, you must do the inverter's job in reverse: turn the grid's AC into the DC a battery needs. The converter that does this is a **rectifier**, and it forms the front end of every charger.

The rectifier — AC to DC

The simplest rectifier is four diodes (check valves) in a bridge. Because a diode only passes current one way, the bridge "folds" the back-and-forth AC into lumpy one-directional DC — every backward swing is redirected forward. A capacitor (accumulator) then smooths the lumps into steady DC. Mechanically, it is four check valves turning a reciprocating pump's push-pull output into steady one-way flow, with an accumulator ironing out the pulses.

The problem a crude rectifier creates: bad power factor

A basic diode rectifier has an ugly side effect. It draws current from the grid in short, sharp gulps (only at the peaks of the AC), rather than as a smooth continuous sine wave. Picture a machine that loads its drive shaft in violent jerks rather than pulling smoothly — it is hard on everything upstream. The electricity grid dislikes jerky loads, and this "jerkiness" is measured by a number called **power factor**.

WHAT POWER FACTOR MEANS

Power factor describes how smoothly and cooperatively a device draws power from the grid. A power factor of 1.0 ("unity") means it draws a clean sine wave perfectly in step with the supply — a smooth, courteous load. A poor power factor means jerky, out-of-step gulps that stress the grid and waste capacity. Utilities penalise poor power factor. So good chargers are engineered to draw power smoothly — power factor near 1.0.

The fix: Power Factor Correction (PFC)

Real chargers add an actively-switched stage called **PFC — Power Factor Correction** — usually a boost converter driven by clever PWM — that forces the current drawn from the grid into a clean sine wave, perfectly aligned with the voltage. When you read that a charger has "unity power factor" or "active PFC," it means this: the charger is a smooth, well-behaved load that draws its power gracefully. It is a mark of a quality design and is legally required above certain power levels.

The full charger: two stages

Putting it together, a typical on-board charger has two stages in series — two gearboxes back to back:

1. **Stage 1 — Rectifier + PFC:** grid AC → smooth DC, drawing power politely (unity power factor).
2. **Stage 2 — Isolated DC-DC converter:** adjusts that DC to exactly what the battery needs, and provides safety isolation (via a high-frequency transformer) so grid voltages never reach the battery or the person touching the car.

WORKED EXAMPLE 7.1 — HOME CHARGING TIME

A 7.4 kW home charger (with 92% efficiency) charges a 40 kWh battery from empty. Roughly how long does it take?

Power actually reaching the battery = $7.4 \text{ kW} \times 0.92 \approx 6.8 \text{ kW}$.

Time = energy $\div$ power = $40 \text{ kWh} \div 6.8 \text{ kW} \approx 5.9 \text{ hours}$.

Answer: about 6 hours — a typical overnight home charge.

CHAPTER 7 — CHARGING FROM THE GRID

- A rectifier turns grid AC into DC (diodes = check valves folding AC into one-way flow).
- Power factor measures how smoothly a charger draws from the grid; 1.0 (unity) is ideal. Crude rectifiers have poor power factor.
- PFC (Power Factor Correction) forces a clean, in-step current — a courteous grid load, and legally required.
- An on-board charger is two stages: rectifier+PFC, then an isolated DC-DC converter that matches the battery and provides safety isolation.

PART IV

Inside the Vehicle

Now we assemble the whole car. You know the components, the switching trick and the four converters — time to see how they combine into a working electric vehicle, and to meet the two subsystems that most define an EV's character: the battery and the motor.

08 The Complete EV Powertrain, Box by Box

Here is the whole electric powertrain in one picture. Every green box is a converter you now understand. The orange cables carry high-voltage DC; the battery is the heart, and power flows outward to drive and inward to charge.

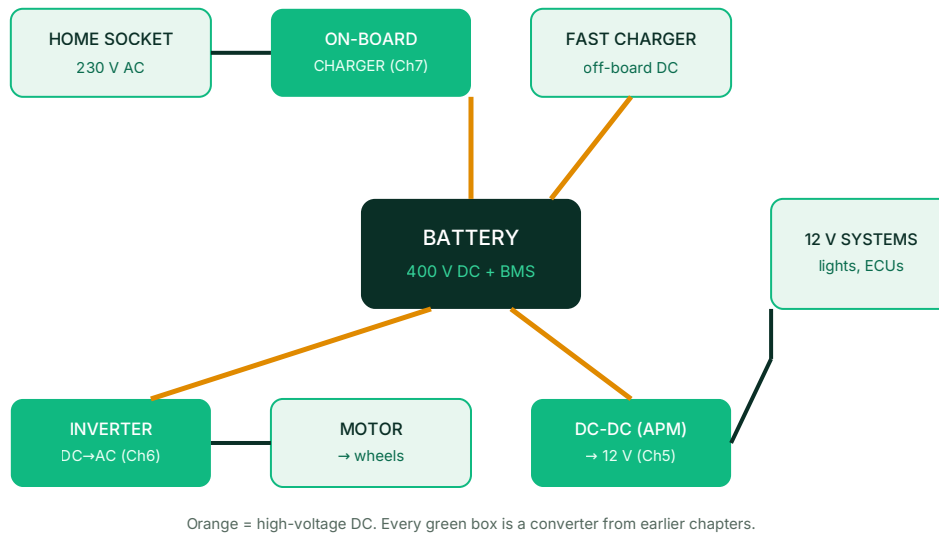


Fig. 8.1 — The complete EV powertrain. You now understand every green box in this diagram.

Following the power — two journeys

When you drive: the battery sends high-voltage DC to the **traction inverter**, which converts it to three-phase AC and feeds the **motor**, which turns the wheels. Meanwhile the **DC-DC converter (APM)** quietly steps the high voltage down to 12 V for the lights, screens and computers. The accelerator pedal simply tells the inverter's PWM how much power to deliver.

When you charge: at home, the **on-board charger** takes 230 V AC and converts it to the DC the battery needs (slowly, limited by its power rating). At a highway fast charger, the conversion happens in the big **off-board charger** cabinet, which sends high-power DC straight into the battery — bypassing the on-board charger, which is why it is so much faster.

The most important design theme: fewer, smarter boxes

Notice that these boxes are never all working hard at once. When you drive, the charger sits idle. When you charge, the inverter sits idle. This observation drives a major research direction — building **reconfigurable** converters where one set of switches does several jobs, cutting cost, weight and volume. It matters most for India's small, price-sensitive vehicles (two- and three-wheelers), where every rupee and kilogram counts. You do not need the details now; just know that "integration" and "reduced part count" are what the cutting edge is chasing.

CHAPTER 8 — THE WHOLE POWERTRAIN

- Driving: battery → inverter → motor → wheels; DC-DC also feeds the 12 V systems.
- Charging: home → on-board charger (slow); highway → off-board fast charger straight to the battery (fast).
- The battery, governed by its BMS, is the hub of all power flow.
- A key frontier: combining functions into fewer, smarter converters to cut cost and weight.

09 Batteries & the Battery Management System

The battery is the fuel tank, the single most expensive part of an EV, and the component whose care determines the vehicle's life and safety. As a mechanical engineer, think of it as a pressure vessel with a delicate chemistry inside — powerful, valuable, and unforgiving if mistreated.

Cells, modules, packs

An EV battery is built up from small **cells** (each like a slightly-larger AA battery, around 3.7 volts). Connect many in series and their voltages add: about a hundred cells in series make a 350–400 V pack. Group cells into **modules**, and modules into the full **pack**. A 40 kWh car pack might contain several thousand cells. The chemistry is almost always lithium-ion, prized for storing a lot of energy in little weight.

Five things every engineer must know about lithium cells

#	Fact	Why it matters
1	Voltage indicates fill level, roughly: ~3.0 V empty, ~4.2 V full.	But it lags and sags under load, so "fuel gauging" is genuinely hard (see SOC below).
2	Charging too fast — especially when cold or nearly full — permanently damages the cell.	Like forcing fluid into a vessel so hard the liner cracks. Damage accumulates and can cause fires.
3	Heat is the enemy. Degradation roughly doubles for every 10°C hotter.	Critical in India's climate; a major reason EV batteries need thermal management.
4	Cells must be kept balanced — all at similar charge levels.	One weak cell in a long series string limits and endangers the whole pack.
5	The standard safe charging recipe is CC-CV (below).	Every charger follows it.

The universal charging recipe: CC-CV

Every lithium battery is charged in two phases, which map perfectly onto filling a pressure vessel:

- **Constant Current (CC):** pump a fixed, safe current in while the voltage rises. (Fill at a steady flow rate.)
- **Constant Voltage (CV):** once the cell reaches its maximum safe voltage, hold that voltage steady and let the current naturally taper toward zero as the cell tops up. (Hold at rated pressure and let inflow trickle to a stop.)

This is why the last 10–20% of charging is slow: the battery is in the CV "trickle" phase. It is also why fast-charging figures are usually quoted to 80% — beyond that, CC-CV deliberately slows down to protect the cell.

WORKED EXAMPLE 9.1 — THE "C-RATE"

Charging speed is often given as a "C-rate": 1C means charging the whole capacity in one hour. If a 40 kWh battery is fast-charged at 2C, what charging power is that, and how long (ideally) to fill?

2C means $2 \times$ the capacity per hour = $2 \times 40 \text{ kWh} = 80 \text{ kW}$ of power.

Time (ideal) = capacity $\div$ rate = $1 \div 2 \text{ hour} = 30 \text{ minutes}$ (to ~80%, before CV slows it).

Answer: 80 kW, roughly 30 minutes to 80%. Higher C-rates charge faster but stress the cell more.

The Battery Management System (BMS) — the pack's brain

A pack of thousands of delicate, powerful cells cannot be left unsupervised. The **BMS (Battery Management System)** is the electronic control unit that watches over it — the battery's dedicated ECU. Its jobs:

- **Monitor** every cell's voltage, plus currents and temperatures across the pack.
- **Protect** — cut off charging or discharging if any limit (voltage, current, temperature) is exceeded, preventing fires.
- **Balance** — keep all cells at similar charge so no cell is over-stressed.
- **Estimate** the three key "gauges" the driver and vehicle need:

Gauge	What it means	Everyday parallel
SOC — State of Charge	How full the battery is right now (0–100%).	The fuel gauge.
SOH — State of Health	How much of the original capacity remains after ageing (a pack at 80% is near end-of-life).	Engine wear / odometer health.
RUL — Remaining Useful Life	How much life is left before replacement.	A maintenance prognosis.

Crucially, none of these can be measured directly — you cannot see inside a sealed cell. The BMS must **estimate** them from voltage, current and temperature history. Doing this accurately is a serious engineering challenge, and increasingly uses machine learning. It is one of the hottest skill areas in the EV industry — every carmaker and battery company wants engineers who understand BMS.

CHAPTER 9 — BATTERIES AND THE BMS

- Packs are built from thousands of ~3.7 V lithium cells in series/parallel; capacity is measured in kWh.
- Cells are damaged by fast/cold/full charging and by heat (degradation doubles per 10°C); India's climate makes thermal care vital.
- **CC-CV** is the universal charge recipe: fixed current, then fixed voltage with tapering current (why the last 20% is slow).
- The **BMS** monitors, protects, balances, and estimates **SOC** (fuel gauge), **SOH** (health) and **RUL** (life left) — a top EV career skill.

Battery engineering is where the jobs are

BMS design, battery testing and battery-safety handling are among the most sought-after EV skills in India. DIYguru runs dedicated, hands-on battery and BMS certification programmes aligned to ASDC standards.

10 Charging: Slow, Fast, and Wireless

Charging is where most people first meet EV power electronics, and where a lot of the industry's engineering effort goes. Let us organise the whole landscape simply.

The fundamental split: AC (on-board) vs DC (off-board) charging

The key question is *where the AC-to-DC conversion happens*:

- **AC charging (slow)**: the wall gives AC, and the conversion to DC happens *inside the car*, in the on-board charger (Chapter 7). The car's on-board charger is small and light (to save space and cost), so its power — and hence charging speed — is limited, typically 3.3 to 22 kW. Great for home and overnight.
- **DC charging (fast)**: to charge fast you need a big, powerful converter — too big to carry in the car. So it lives *outside*, in the roadside charger cabinet, which does the AC-to-DC conversion itself and sends high-power DC straight into the battery, bypassing the on-board charger entirely. This is why DC fast chargers (50 to 350 kW) are so much quicker.

WHY FAST CHARGING MUST BE OFF-BOARD

The AC-to-DC converter for 150 kW is heavy and bulky — you would not want to carry it in every car any more than you would carry a petrol refinery. So it stays at the "station" and pumps ready-made DC into the vehicle. The car carries only a small converter for slow home charging. This division of labour is the core logic of the whole charging ecosystem.

The charging levels you'll hear about

Type	Typical power	Where the conversion is	Time to charge (indicative)
AC Level 1 (home socket)	~2–3 kW	On-board	Very slow — overnight+ for a car
AC Level 2 (home/public wallbox)	7–22 kW	On-board	A few hours
DC Fast Charging	50–350 kW	Off-board (roadside cabinet)	20–40 min to 80%

In India you will hear plug standards like **CCS2** (the international DC fast-charge connector adopted for cars), **Type 2** (AC), and the indigenous low-cost **Bharat AC-001 / DC-001** standards created for the two- and three-wheelers that dominate Indian roads. The plug differs; the physics is exactly what you have learned.

Bidirectional charging: the car as a power source (V2G, V2H, V2L)

Recall from Chapter 4 that switching converters are naturally reversible. So a suitably-designed charger can run **backwards**, pushing energy out of the battery. This unlocks:

- **V2L (Vehicle-to-Load)**: plug appliances directly into the car — run tools at a worksite, lights at a campsite. Increasingly common.
- **V2H (Vehicle-to-Home)**: the car powers your house during an outage — hugely relevant in India. Your EV becomes a giant backup battery.
- **V2G (Vehicle-to-Grid)**: parked EVs feed energy back to the grid at peak demand, earning money and stabilising supply. A parked fleet becomes a distributed power plant.

Wireless charging

Finally, charging with no plug at all. **Wireless (inductive) charging** uses two coils — one in a pad on the ground, one under the car — coupled through a magnetic field across the air gap. It is essentially a transformer (Chapter 3) split in half, with air where the core used to be. Because the gap weakens the coupling, both coils are tuned to **resonance** (like two tuning forks that ring in sympathy) to transfer energy efficiently. Convenient — park and charge automatically — though slightly less efficient than a cable, and still maturing. It is an active research area, especially for buses and taxis that could charge while waiting.

CHAPTER 10 — CHARGING, ORGANISED

- AC charging converts to DC **inside** the car (small on-board charger, so slow); DC fast charging converts **outside** and sends DC straight in (big cabinet, so fast).
- Levels: home socket (slow) → AC wallbox (hours) → DC fast (20–40 min to 80%).
- Bidirectional charging lets the car power loads (V2L), a home (V2H) or the grid (V2G) — the EV as a mobile battery.
- Wireless charging = a transformer split across an air gap, tuned to resonance; convenient, still maturing.

11 Motors, Traction Inverters & Regenerative Braking

The motor turns electricity into motion. As a mechanical engineer you will find motors intuitive — they are, after all, rotating machines. Here is what you need to know about EV motors and the electronics that command them.

How an electric motor works, in one paragraph

Every motor exploits one fact: electric currents create magnetic fields, and magnetic fields push on each other. Feed AC into the motor's stationary windings (the **stator**) and you create a magnetic field that **rotates**. The spinning field drags the **rotor** (and the shaft, and the wheels) around with it. Control the rotating field's speed and strength — which the inverter does via PWM — and you control the motor's speed and torque. That is the whole principle.

The three motor types you'll meet in EVs

Motor type	Character	Where used
PMSM — Permanent Magnet Synchronous Motor	Most efficient and compact; uses permanent magnets in the rotor. Slightly costlier (magnet materials).	Most modern electric cars.
BLDC — Brushless DC Motor	A close cousin of PMSM; robust, cost-effective, simple to control.	Dominant in Indian e-2-wheelers and e-3-wheelers.
Induction Motor (IM)	Rugged, no magnets (cheaper, no rare-earths), very reliable; slightly less efficient.	Some cars and many commercial vehicles.

All three are driven by the same kind of three-phase inverter you met in Chapter 6. The differences are in the motor's construction and the fine details of the control, not in the basic power electronics.

The traction inverter — the most worked component

The **traction inverter** is the big inverter that drives the main motor. It is the most electrically stressed converter in the car — handling the full driving power, often 50 to 200+ kW — and it is where the highest-performance switches (IGBTs, and increasingly silicon-carbide devices, Chapter 12) are used. Its PWM, commanded by your accelerator pedal, sets the motor's speed and torque moment to moment. When engineers talk about an EV's "performance," they are largely talking about the motor-and-inverter pair.

Regenerative braking — recovering energy for free

Here is one of the most elegant ideas in EVs, and it costs no extra hardware. Recall that converters are naturally reversible and that a motor and a generator are the same machine run in opposite directions. When you lift off the accelerator or brake, the inverter simply runs the process **backwards**: the wheels now spin the motor, the motor acts as a **generator**, and the inverter (now acting as a rectifier) sends that energy **back into the battery**. The car slows down because taking energy out of the wheels applies a braking force — and that energy, instead of being wasted as heat in friction brakes, is recovered.

REGEN BRAKING, MECHANICALLY

A conventional brake converts the car's kinetic energy into wasted heat in the brake pads. Regenerative braking instead uses the motor as a generator to convert that kinetic energy back into stored electrical energy — like a flywheel-and-clutch system that recaptures a vehicle's momentum rather than throwing it away. This is a big reason EVs are so efficient in city driving, where there is constant stopping and starting.

WORKED EXAMPLE 11.1 — INSTANT TORQUE

Why can a modest 3 kW scooter motor feel so punchy off the line compared to a 3 kW petrol engine?

From Chapter 2: motor torque depends on current, and an electric motor can draw large current from zero rpm.

A petrol engine makes little torque at low rpm and must rev up; an electric motor delivers near-maximum torque instantly at 0 rpm.

Answer: the electric motor delivers peak torque from a standstill — instant acceleration — while the engine must build revs first.

CHAPTER 11 — MOTORS AND MOTION

- Motors work by creating a rotating magnetic field (via AC in the stator) that drags the rotor around; the inverter's PWM sets its speed and torque.
- EV motors: PMSM (efficient, most cars), BLDC (Indian 2W/3W), Induction (rugged, magnet-free) — all driven by three-phase inverters.
- The traction inverter is the most powerful, hardest-working converter in the vehicle.
- Regenerative braking runs the motor as a generator to recover braking energy into the battery — free efficiency, no extra hardware, great in city driving.

PART V

Frontiers & Your Career

You now understand how an electric vehicle works, from the flick of a switch to the spin of a wheel. These last two chapters show where the technology is heading — and how you, as a mechanical engineer, can turn this knowledge into one of the most future-proof careers in India.

12 What's Next: SiC, GaN, V2G and the Road Ahead

EV power electronics is advancing fast. You do not need deep detail on the frontier — but knowing the vocabulary lets you follow industry news and speak credibly in an interview. Here are the movements that matter.

1. Better switches: silicon carbide (SiC) and gallium nitride (GaN)

The switches you met in Chapter 3 are traditionally made of silicon. New materials — **silicon carbide (SiC)** and **gallium nitride (GaN)**, called "wide bandgap" semiconductors — switch faster, run hotter, and waste less energy. The payoff: converters become smaller, lighter, more efficient, and can charge faster. SiC is already in premium EV traction inverters and fast chargers; GaN is spreading in chargers.

ANALOGY

Switching from silicon to SiC/GaN is like switching from steel to titanium: the same component, but far better performance-to-weight — so the whole machine around it can shrink and improve. This single materials shift is quietly enabling much of the progress in EV range and charging speed.

2. Higher voltages: the 800-volt architecture

Recall from Chapter 2 that higher voltage moves the same power with less current, and hence less loss and thinner cables. Premium EVs are moving from 400 V to **800 V** systems, which enables dramatically faster charging (more power without impossibly thick cables) and lighter wiring. Expect this to trickle down over time.

3. Smarter, combined converters

As Chapter 8 noted, the boxes are rarely all busy at once. A major research thrust is **integration** — building reconfigurable converters where one set of switches performs several jobs (charging, driving, powering accessories), cutting cost, weight and volume. This matters enormously for India's affordable 2- and 3-wheelers, where cost is everything.

4. The vehicle as part of the grid (V2G)

As bidirectional charging (Chapter 10) matures and regulations catch up, millions of parked EVs could become a vast, distributed energy store — soaking up cheap solar power by day and feeding it back at peak demand, earning owners money and stabilising a renewable-heavy grid. This is one of the most exciting long-term possibilities in the entire energy transition.

5. Made-for-India engineering

Most global EV technology is designed for temperate climates. India's heat, dust, humidity and variable grid demand **indigenous** engineering — batteries and charging designed for tropical conditions, ultra-low-cost converters for mass-market two- and three-wheelers, and solar-integrated charging for towns with weak grids. This is a genuine frontier where Indian engineers — perhaps you — will lead, not follow. National research missions and skilling initiatives are being built around exactly this need.

CHAPTER 12 — THE ROAD AHEAD

- SiC & GaN switches (the "titanium upgrade") make converters smaller, cooler, faster-charging.
- 800 V architectures cut current and enable ultra-fast charging.
- Integrated converters combine functions to slash cost and weight — vital for Indian 2W/3W.
- V2G turns parked EV fleets into a distributed power plant for a renewable grid.
- India-specific tropical, low-cost, solar-integrated engineering is a frontier where Indian engineers can lead.

13 Careers in EV Power Electronics — and How to Get There

Here is the payoff for reading this far. Everything you have learned maps directly onto real jobs — and India's EV industry is desperately short of people who understand these boxes. As a mechanical engineer who now grasps EV power electronics, you sit in a rare and valuable position: you understand both the vehicle and its electronics.

The roles this knowledge opens

Role	What you'd do	Chapters that prepared you
EV Powertrain / Integration Engineer	Design how the battery, inverter, motor and converters work together in a vehicle.	1, 8, 11
Battery / BMS Engineer	Design battery packs, thermal systems, and the BMS that keeps them safe and healthy.	9
Charging Infrastructure Engineer	Design, deploy and maintain home and public charging stations.	7, 10
Power Electronics Design Engineer	Design the converters themselves — chargers, inverters, DC-DC units.	3–7
Motor / Traction Drive Engineer	Design and tune motors and the inverters that drive them.	6, 11
EV Test & Validation Engineer	Test and certify EV systems for performance and safety.	All
EV Service & Diagnostics Technician	Diagnose and repair EVs — high demand as the fleet grows.	8, 9, 11

Why a mechanical engineer is well-placed — not disadvantaged

You might worry that power electronics "belongs" to electrical engineers. In practice, the EV industry needs people who understand **systems** — how the electronics, the thermal design, the mechanical packaging and the vehicle dynamics all fit together. Your mechanical background gives you an edge in thermal management (cooling those lossy converters and hot batteries), in packaging and integration, in motor mechanics, and in manufacturing. Add the power electronics understanding from this book, and you become the rare engineer who can bridge both worlds — exactly what employers struggle to find.

Your next steps

1. **Cement the fundamentals.** Re-read the chapters, do the self-test in Appendix C, and make sure the analogies feel natural.
2. **Get hands-on.** Reading is not enough — you need to build, measure and break real converters, battery systems and motor drives. This is where structured, lab-based training makes the difference between knowing **about** EVs and being **employable** in EVs.

3. **Earn a recognised certification.** Industry-recognised credentials (ASDC, AICTE-aligned) signal to employers that your skills are real and job-ready.
4. **Build a portfolio.** Projects, internships and live industry problems turn knowledge into a track record.

This is exactly what DIYguru was built for

DIYguru is India's largest ASDC-certified EV skilling organisation — 50,000+ professionals trained across 52 programmes, recognised by AICTE (NEAT) and ASDC, with hands-on labs, industry projects and placement support through our dedicated EV jobs platform. Whether you want to design converters, engineer batteries, or service EVs, there is a structured pathway from exactly where this book leaves you to a job in the industry. Explore programmes at diyguru.org — and take the first step from understanding EVs to building your career in them.

CHAPTER 13 — YOUR CAREER

- Every concept in this book maps to a real, in-demand EV job — from powertrain and BMS to charging, motors and service.
- A mechanical engineer who understands EV power electronics is rare and valuable: you bridge the vehicle and its electronics.
- The path forward: cement fundamentals → get hands-on → earn recognised certification → build a portfolio.
- Structured, lab-based training is what converts knowledge into employability.

A The One-Page Formula Sheet

Every formula in this book, in one place. If you understand each of these and could explain it with its mechanical analogy, you have mastered the fundamentals.

Formula	Meaning	Mechanical analogy
$P = V \times I$	Power = Voltage $\times$ Current	Power = torque $\times$ speed
$E = P \times t$	Energy = Power $\times$ Time (battery kWh)	Total work; fuel in tank
$\eta = P_{\text{out}} / P_{\text{in}}$	Efficiency (rest becomes heat)	Gearbox efficiency
$V_{\text{out}} = D \times V_{\text{in}}$	Buck (step-down) converter	Reduction gearbox
$V_{\text{out}} = V_{\text{in}} / (1 - D)$	Boost (step-up) converter	Step-up gearbox (flywheel energy)
$V_{\text{avg}} = D \times V_{\text{in}}$	PWM average output; D = duty cycle	Valve-flick ratio
$P_{\text{mech}} = T \times \omega$	Motor output = torque $\times$ angular speed	(It is mechanical)
Range = Capacity / Consumption	kWh $\div$ (kWh per km)	Tank size $\div$ fuel economy
Charge time $\approx$ Capacity / Power	kWh $\div$ kW (to ~80%)	Tank $\div$ fill rate
C-rate	Charge/discharge rate vs capacity (1C = full in 1 h)	Fill speed relative to tank size

THE TWO YOU MUST NEVER FORGET

$P = V \times I$ — the definition of power, and the reason high voltage means low current means thin cables.

Output $\approx$ D $\times$ Input — the duty cycle is the master control knob of all power electronics.

B Plain-English Glossary

Term	Plain meaning (with the analogy)
AC	Alternating current — flows back and forth (like reciprocating motion). Grid and motors use AC.
APM	Auxiliary Power Module — the DC-DC converter that makes 12 V for lights and electronics.
BMS	Battery Management System — the battery pack's brain: monitors, protects, balances, estimates SOC/SOH/RUL.
Boost converter	Steps DC voltage up, using the inductor's stored energy. A step-up gearbox.
Buck converter	Steps DC voltage down by chopping and smoothing. A reduction gearbox.
Capacitor	Stores energy in an electric field; smooths voltage. A spring or accumulator.
CC-CV	Constant Current then Constant Voltage — the universal battery charging recipe.
C-rate	How fast a battery is charged/discharged relative to its size. 1C = full in one hour.
Current (I)	How much electricity flows, in amperes. Flow rate / shaft speed.
DC	Direct current — steady, one direction (like constant rotation). Batteries are DC.
Diode	Lets current flow one way only. A check valve.
Duty cycle (D)	Fraction of time a switch is ON — the master control knob. The valve-flick ratio.
Efficiency (η)	Power out $\div$ power in; the rest becomes heat.
Energy	Power $\times$ time, in watt-hours; a battery's fuel-tank size.
GaN / SiC	Wide-bandgap semiconductor materials for faster, cooler, smaller switches. The "titanium upgrade."
H-bridge	Four switches that reverse current through a load to make AC from DC.
IGBT	A heavy-duty power switch for high voltage/current. A big industrial gate valve.
Inductor	Stores energy in a magnetic field; smooths current. A flywheel.
Inverter	Converts DC to AC; drives the motor and sets its speed/torque. The EV's transmission.
kWh	Kilowatt-hour — the unit of battery energy (tank size).
MOSFET	A fast, lighter-duty power switch. A quick solenoid valve.
OBC	On-Board Charger — converts wall AC to battery DC inside the car (slow charging).
PFC	Power Factor Correction — makes a charger draw a clean, in-step current from the grid.
Power (P)	Rate of energy flow = $V \times I$. Same idea as mechanical power.

Power factor	How smoothly a device draws grid power; 1.0 (unity) is ideal.
PMSM / BLDC / IM	Motor types: permanent-magnet synchronous (cars), brushless DC (2W/3W), induction (rugged).
PWM	Pulse Width Modulation — controlling output by adjusting pulse widths. How converters and motors are controlled.
Rectifier	Converts AC to DC (diode bridge). The reverse of an inverter.
Regenerative braking	Using the motor as a generator to recover braking energy into the battery.
Resistance (R)	Opposition to current flow; wastes energy as heat. Pipe friction.
SOC / SOH / RUL	State of Charge (fuel gauge) / State of Health (remaining capacity) / Remaining Useful Life.
Switch	Turns current fully on/off very fast (never half-way). A valve or clutch.
Transformer	Two coils that scale AC voltage and provide safety isolation. A magnetic gear pair.
V2G / V2H / V2L	Vehicle-to-Grid / -Home / -Load — the car supplying power outward.
Voltage (V)	The electrical "push," in volts. Pressure or torque.

C Final Self-Test — 25 Questions with Solutions

Cover the answers and attempt each. Aim for 20/25. If you get there, you genuinely understand EV power electronics — a remarkable achievement from a standing start. Solutions follow each block.

Concepts (1–10)

1. What is the master analogy for a power electronic converter?
2. Write the formula for electrical power and give its mechanical equivalent.
3. Why do EVs use high battery voltages (e.g. 400 V or 800 V)?
4. What is the difference between DC and AC, with a mechanical picture for each?
5. Name the five building-block components and their mechanical twins.
6. Why is voltage never reduced by throttling (series resistance) at power scale?
7. What is "duty cycle," and what is the buck-converter output formula?
8. Why do converters switch at very high frequencies (two reasons)?
9. What does an inductor smooth, and what does a capacitor smooth?
10. What does "efficiency 96%" tell you about the heat a converter produces?

Answers: 1) A gearbox for electricity — changes the voltage-current combination while conserving power. 2) $P = V \times I$; equals torque $\times$ angular speed. 3) Higher voltage moves the same power with less current, so cables are thinner and losses lower. 4) DC = steady one-way flow (constant rotation), batteries; AC = back-and-forth (reciprocating motion), grid/motors. 5) Switch=valve/clutch, inductor=flywheel, capacitor=spring/accumulator, diode=check valve, transformer=magnetic gear pair. 6) It burns the voltage difference as heat (riding the brakes) — impossible at tens of kW. 7) Fraction of time the switch is ON; $V_{\text{out}} = D \times V_{\text{in}}$. 8) Smoother output (easier filtering) and smaller magnetics. 9) Inductor smooths current; capacitor smooths voltage. 10) 4% of input power becomes heat that must be cooled.

Converters & the vehicle (11–18)

1. What does an inverter do, and why does it let an EV skip a mechanical gearbox?
2. What is a rectifier, and what unwanted effect does a crude one have?
3. What does PFC do and why does it matter?
4. Trace the power path when an EV is being driven.
5. Trace the power path when an EV is fast-charging, and why it's faster than home charging.
6. What are the two phases of CC-CV charging, and why is the last 20% slow?
7. What three "gauges" does a BMS estimate, and why must they be estimated?
8. Explain regenerative braking in terms of a motor and an inverter running backwards.

Answers: 11) Converts DC to AC and sets the motor's speed (via frequency) and torque (via amplitude) with PWM — continuous control replaces gears. 12) Converts AC to DC; a crude one draws jerky current (poor power factor). 13) Forces a clean, in-step grid current (unity power factor) — a courteous load; legally required above certain power. 14) Battery DC → inverter → AC motor → wheels; DC-DC also feeds 12 V systems. 15) Grid AC is converted to DC in the off-board cabinet and sent straight into the battery, bypassing the small on-board charger — big external converter = more power = faster. 16) Constant Current (fixed flow, rising voltage), then Constant Voltage (fixed voltage, tapering current); the CV taper makes the top-up slow. 17) SOC (fuel gauge), SOH (health), RUL (life left); you can't see inside a sealed cell, so they're inferred from voltage/current/temperature. 18) The wheels spin the motor as a generator; the inverter acts as a rectifier and returns energy to the battery, slowing the car.

Numericals & frontier (19–25)

1. A motor runs at 72 V and draws 40 A. What power (kW)?
2. A buck converter makes 24 V from 96 V. What duty cycle?
3. A boost converter must make 400 V from 200 V. What duty cycle?
4. A 50 kWh battery consumes 5 kWh/100 km. Estimated range?
5. A 30 kWh battery charges at 1.5C. What power, and rough time to ~80%?
6. What are SiC and GaN, and why do they matter?
7. What is V2G, and why is it exciting for a renewable grid?

Answers: 19) $P = 72 \times 40 = 2880 \text{ W} = 2.88 \text{ kW}$. 20) $D = 24 \div 96 = 0.25$. 21) $(1-D) = 200 \div 400 = 0.5$, so $D = 0.5$. 22) $50 \div 5 = 10 \times 100 = 1000 \text{ km on paper}$ (~800 real-world). 23) $1.5 \times 30 = 45 \text{ kW}$; $\sim 1/1.5 \text{ h} \approx 40 \text{ min to } \sim 80\%$. 24) Wide-bandgap semiconductor switches — faster, cooler, more efficient, enabling smaller converters and faster charging (the "titanium upgrade"). 25) Vehicle-to-Grid: parked EVs feed stored energy back to the grid at peak demand — a distributed store that can soak up daytime solar and stabilise a renewable-heavy grid.

You've done something impressive

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