

Prototype Sensor Architecture — Engineering Specification

Purpose: Engineering-level specification for the VSDSquadron Ultra prototype, mapping sensors to a real Indian EV battery pack (Tata Nexus EV). This document answers: exactly how many of each sensor, placed exactly where, measuring exactly what, and computing exactly what — so the prototype reflects a production-grade system when demonstrated to organizers.

1. Reference Battery Pack — Tata Nexus EV (Real Verified Data)

We choose the **Tata Nexus EV** as our reference because: - It is India's **best-selling electric car** (40%+ EV market share) - It uses **LFP chemistry** (the safer chemistry — if we detect anomalies here, NMC is covered) - It represents a real 4-wheeler, not a scooter or toy setup - Its pack architecture is **publicly documented** from teardowns and cell supplier data

Transparency note: Tata has sold the Nexus EV in multiple battery variants. The **40.5 kWh Max** variant has been teardown-verified and its exact cell configuration is documented. The newer **45 kWh prismatic** variant's exact S-P configuration is not publicly disclosed yet. We present BOTH — the verified config as our PRIMARY reference, and the newer pack as a derived secondary reference.

1.1 Verified Configuration — Nexus EV Max (40.5 kWh)

Source: Battery teardowns, BatteryDesign.net analysis, Guoxuan/Gotion cell datasheets, Reddit/Team-BHP teardown reports.

Parameter	Value	Source
Chemistry	LFP (LiFePO ₄)	Tata Motors confirmed, cell markings
Cell model	IFR32135-15Ah	Visible on cell markings in teardowns
Cell format	Cylindrical (32mm dia × 135mm height)	Physical teardown
Cell manufacturer	Guoxuan Hi-Tech (Gotion) via Tata AutoComp Systems JV	Industry reports, TACO press releases
Cell nominal voltage	3.2V	LFP standard, datasheet
Cell capacity	15 Ah	Datasheet: IFR32135-15Ah
Cell energy	48 Wh per cell (3.2V × 15Ah)	Derived
Pack configuration	104S8P	Teardown-verified
Series cells	104	104 cells in series
Parallel strings	8	8 cells in parallel per series position
Total cells	832	$104 \times 8 = 832$ cells
Pack nominal voltage	332.8V	$104 \times 3.2V$
Pack operating voltage	260V – 379.6V	$104 \times (2.5V – 3.65V)$
Pack capacity	120 Ah (parallel group: 8 × 15 Ah)	8 parallel × 15 Ah
Pack gross energy	39.9 kWh ($332.8V \times 120$ Ah)	Derived (40.5 kWh marketed = includes rounding)
Module count	~8 modules (estimated: 13S per module × 8 modules = 104S)	Exact module boundaries not publicly confirmed; 13S × 8 modules is most likely
Cells per module	13S8P = 104 cells per module	13 series × 8 parallel
Module voltage	41.6V nominal ($13 \times 3.2V$)	Derived
Max charge rate	~1C (50 kW DC fast charge → 120 Ah × 333V ≈ 40 kWh)	Spec sheet
Max discharge rate	~2C sustained (motor: 105 kW / 333V ≈ 315A peak)	143 Nm motor, 105 kW
Max continuous current	~120A per string (1C) = 15A per cell	Datasheet: 1C max cont. charge
Max peak current	~315A per string (motor demand) = ~39A per cell (~2.6C)	Motor peak demand

Also documented (for reference):

Variant	Config	Cells	Cell Type	Pack Energy
Nexon EV Prime (30.2 kWh)	100S7P	700	IFR32135-15Ah	33.6 kWh gross
Nexon EV Max (40.5 kWh)	104S8P	832	IFR32135-15Ah	39.9 kWh gross

1.2 Probable Configuration — New Nexon EV (45 kWh Prismatic)

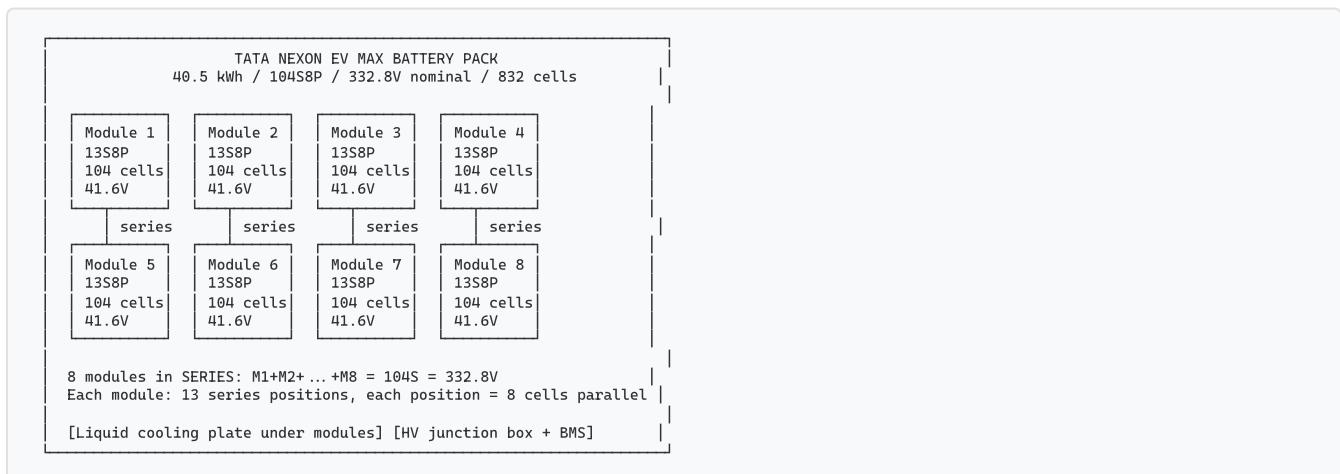
The 2024+ Nexon EV uses a **new prismatic LFP pack** (shared with Tata Curvv EV). Tata claims: - 62% reduction in number of modules (from ~8 cylindrical modules → ~3 prismatic modules) - 186 Wh/liter volumetric density (15% higher) - Cells supplied by **EVE Energy** (via Octillion Power Systems)

Derived configuration (engineering estimate):

Parameter	Value	Derivation
Cell type	Prismatic LFP	Tata Motors confirmed
Cell model	Likely EVE LF105 or similar	EVE supplies to Octillion; Curvv 55 kWh uses 105Ah cells (Gotion)
Cell capacity	105 Ah (if EVE LF105) or ~120 Ah	Industry sources for Curvv EV
Cell voltage	3.2V	LFP standard
If 105 Ah cells:	45,000 Wh ÷ 3.2V ÷ 105Ah = ~134 cells at 1P → likely 134S1P (430V) too high. More likely ~112S1P (358V, ~37.6 kWh usable from ~42 kWh gross) — pack voltage matches 350V class	
Probable config	~112S1P to 120S1P with 105Ah cells, or ~104S1P with 130Ah cells	Any of these give ~330-385V nominal, matching Nexon's 350V-class inverter
Module count	~3 modules (from Tata's "62% reduction" claim: 8 → 3)	Tata press release
Cells per module	~35-40S1P per module	$112 \div 3 \approx 37$ series per module

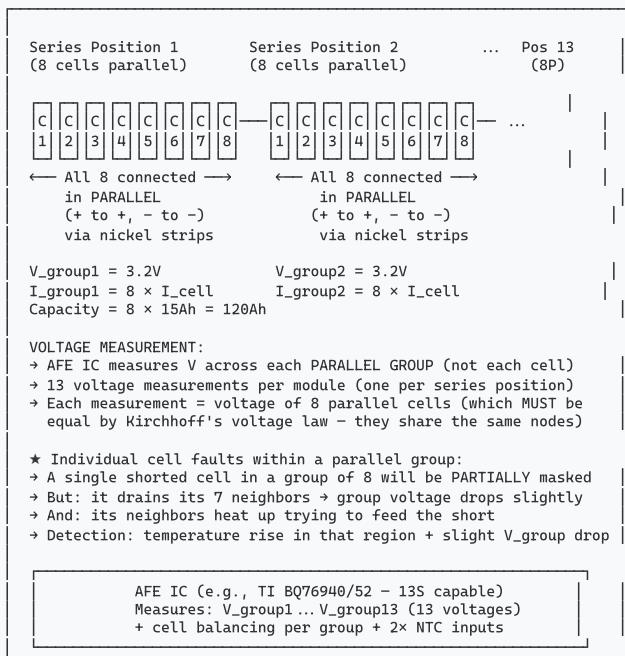
⚠ Important: The exact new prismatic config is NOT publicly confirmed. For our engineering specification, we use the **verified 104S8P cylindrical** as the primary reference throughout this document. The sensor architecture we design works for BOTH configurations — the difference is only in cell count and module count, not in the measurement principles.

1.3 Physical Layout — 104S8P Pack Architecture



1.4 Inside One Module (13S8P = 104 cylindrical cells)

MODULE N (13S8P – 13 series groups, each group = 8 parallel cells)



KEY DIFFERENCE FROM PRISMATIC 1P:

In a 104S8P pack, the AFE measures voltage across PARALLEL GROUPS, not individual cells. Each voltage reading = voltage of 8 cells connected in parallel.

Why this matters:

- A single cell with an internal short in a group of 8 parallel cells will pull down the group voltage by only $\sim(1/8)$ of the full deviation – the fault is partially hidden by the healthy 7 cells maintaining the node voltage.
- This is why temperature monitoring is even MORE critical in parallel-group architectures – temp may be the FIRST indicator when voltage is masked.

Critical engineering point: In a **series-parallel** pack like 104S8P, voltage is measured per **parallel group** (not per individual cell). This means we have **104 voltage channels** (one per series position), where each channel represents 8 cells connected in parallel. A fault in a single cell within a parallel group is partially masked by its 7 healthy neighbors — making temperature and gas detection even more important as complementary indicators.

1.5 What Changes for the New Prismatic Pack

Aspect	Old 104S8P Cylindrical	New ~112S1P Prismatic
Voltage per series position	3.2V (8 cells in parallel — fault partially masked)	3.2V (single cell — fault fully visible in voltage)
Voltage channels	104 (per parallel group)	~ 112 (per individual cell)
Current path	1 main path, I_{pack} splits into 8 parallel cells at each position	1 main path, $I_{\text{pack}} = I_{\text{cell}}$ (all current through each cell)
Cell current	$I_{\text{cell}} = I_{\text{pack}} / 8$ (e.g., 120A pack \rightarrow 15A per cell)	$I_{\text{cell}} = I_{\text{pack}}$ (e.g., 120A pack \rightarrow 120A per cell — cell must handle full current)
Thermal visibility	NTC covers 8 cells in a group, avg temp	NTC much closer to individual cell behavior
Fault detection sensitivity	Lower for voltage (parallel masking), higher emphasis on temp	Higher for voltage (direct cell measurement)
Module count	~ 8 modules	~ 3 modules
NTCs needed	$2 \text{ per module} \times 8 = 16$	$2 \text{ per module} \times 3 = 6$ (but modules are larger, may need more)

For our prototype and algorithm design, the 104S8P architecture is actually the HARDER case — detecting faults through parallel masking

is more challenging. If our algorithm works for 104S8P, it will work even BETTER for a 1P prismatic pack where faults are more directly visible.

2. Complete Sensor Inventory — Per Module and Per Pack

This is the engineering-level answer to "how many of each sensor and where."

2.1 Voltage Sensors

Sensor Type	Quantity	Level	What Exactly Is Measured	Measurement Point
Per-group voltage (AFE IC input)	13 per module × 8 modules = 104 measurements	Parallel-group level	Voltage across each parallel group (8 cells in parallel share the same voltage by Kirchhoff's law). V_{group_n} from the positive to negative node of that series position	Voltage sense wires (thin 24–26 AWG) spot-welded to busbar junctions between parallel groups. 14 sense wires per 13S module (one per group boundary)
Module voltage (AFE IC sum)	8 measurements (1 per module)	Module-level	Sum of 13 group voltages = module voltage. Calculated by AFE IC, not a separate sensor	Derived from per-group readings inside the AFE IC
Pack voltage	1 measurement	Pack-level	Total series voltage = sum of all 104 group voltages. Measured at the HV junction box terminals	Hall-effect isolated voltage transducer (e.g., LEM LV-25-P) or resistive voltage divider at the pack HV terminals, before the contactor

Why per-parallel-group and not per-individual-cell?

In a 104S8P configuration, each series position has **8 cells in parallel**. By Kirchhoff's voltage law, all 8 cells in a parallel group share the same terminal voltage (they are connected + to + and – to –). The AFE IC measures voltage at each parallel group node.

Implication for fault detection:

EXAMPLE: 1 cell in parallel group 5 of Module 3 has an internal short

Group-Level voltage (what the AFE measures):

Group 5 = 3.18V (expected: 3.24V)
 → Only ~60mV drop because the 7 HEALTHY cells in the group are maintaining the node voltage. The fault is PARTIALLY MASKED.
 → In a 1P pack, the same fault would show ~490mV drop.

Why it's still detectable:

1. Even 60mV group-level deviation is significant → WARNING
2. The shorted cell draws current FROM its 7 neighbors
 → localized heating → NTC in that region rises
3. R_int of the GROUP changes (parallel combination shifts)
 → MULTI-PARAMETER CORRELATION catches what voltage alone misses.

This is WHY our correlation engine is essential – in parallel-group architectures, temperature and gas detection are MORE important than in 1P packs where voltage alone can identify faults.

2.2 Current Sensors

Sensor Type	Quantity	Level	What Exactly Is Measured	Measurement Point
Pack current (main HV)	1	Pack-level	Total current flowing through the main HV bus. In a 104S8P pack, this is the TOTAL current from all 8 parallel strings combined at each series position. $I_{pack} = 8 \times I_{cell}$ (at each position, current splits into 8 parallel cells).	Hall-effect current transducer (e.g., LEM DHAB s/14, ±500A, isolated) on the main HV bus at the pack output, between the battery terminal and the contactor
Isolation monitoring	1	Pack-level	Leakage current between HV bus and vehicle chassis (ground fault detection per AIS-156)	ISO resistance monitor IC (e.g., Bender ISOMETER, or software-based using voltage divider measurement)

Why only 1 current sensor for 832 cells?

Because the pack is **104S8P** — all parallel groups are connected in series. The **same total current** flows through each series position. At each position, the current splits equally among the 8 parallel cells. One high-accuracy current measurement at the pack level gives us: - Total pack current (I_{pack}) - Per-cell current estimate: $I_{cell} \approx I_{pack} / 8$

104S8P CURRENT FLOW:

[+] → Group 1 → Group 2 → ... → Group 104 → [CURRENT] → [-]
 (8P) (8P) (8P) (8P) SENSOR

I_pack flows through each GROUP in series.
 At EACH group, current splits into 8 parallel cells:

Group N: I_pack → Cell_1: I_pack/8
 → Cell_2: I_pack/8
 → Cell_3: I_pack/8
 → ...
 → Cell_8: I_pack/8

Example: I_pack = 120A (1C) → each cell sees 15A (1C)
 Example: I_pack = 315A (peak) → each cell sees ~39A (~2.6C)

★ If one cell in a parallel group has higher R_int,
 it will carry LESS current → its neighbors carry MORE
 → unequal heating within the group → detectable by NTC

2.3 Temperature Sensors

This is the most complex sensor category. We need MULTIPLE types in MULTIPLE locations.

A. Cell Surface Temperature (NTC Thermistors)

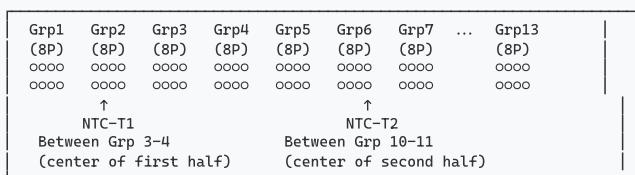
Sensor Type	Quantity	Level	What Exactly Is Measured	Placement
Cell surface NTC	2 per module × 8 modules = 16 NTCs	Module-level	Surface temperature of cells at 2 strategic locations within each module, representing thermal state of surrounding parallel groups	See placement diagram below

Why 2 per module, not 1 per cell (which would be 832)?

- 1 per cell (832 NTCs) is physically impossible and would be absurdly expensive.
- 1 per parallel group (104 NTCs) is still too many for a production BMS.
- **2 per module is the industry standard** (confirmed by BMS IC datasheets — BQ76940/52 has exactly 2 NTC inputs per IC).
- 2 per module captures the **thermal gradient** across the module (hottest point vs coolest point).
- In a cylindrical module with 104 cells, the NTCs are positioned between groups to sense the average temperature of surrounding cells.

Exact placement within each module (13S8P = 104 cylindrical cells):

MODULE N – NTC PLACEMENT (Top View, 13 series groups × 8 parallel cells)



WHY positioned between groups 3-4 and 10-11?
 → Edge groups (1, 2 and 12, 13) lose heat to module end-plates and outer walls → they run COOLER.
 → Interior groups are surrounded by cells on all sides.
 Heat accumulates MORE in the center of the module.
 → We place each NTC between two groups to capture the AVERAGE temperature of the hottest zone in each half.
 → The NTC bead sits wedged between cylindrical cells in the tight-packed arrangement – excellent thermal contact.

ATTACHMENT METHOD (cylindrical cells):
 → NTC 10kΩ bead (glass-encapsulated, rated to 200°C)
 → Thin bead wedged between adjacent cylindrical cells in the parallel group (cells are tightly packed)
 → Thermal paste or thermal adhesive pad for contact
 → Wire routed along the top of the module to the AFE board

B. Ambient Temperature

Sensor Type	Quantity	Level	Placement
Ambient NTC or digital sensor (on BMS master board)	1	Pack-level	Mounted on the BMS master PCB, thermally isolated from cells (≥ 10 cm distance, outside the module thermal mass). In the pack's air intake zone, before the coolant channel. Measures the temperature of air entering the pack.

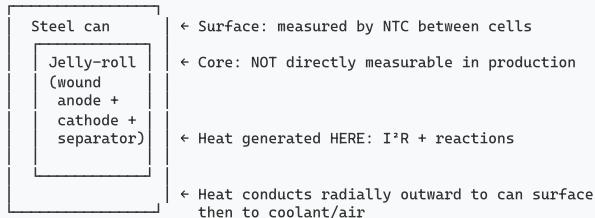
Sensor Type	Quantity	Level	Placement
Coolant inlet temperature	1	Pack-level	NTC probe clipped to the liquid coolant inlet pipe, measuring coolant temperature entering the pack. Used to validate thermal management system is functioning.
Coolant outlet temperature	1	Pack-level	NTC probe clipped to the liquid coolant outlet pipe. $\Delta T_{coolant} = T_{outlet} - T_{inlet}$ tells us how much heat the pack is rejecting.

C. Core vs. Surface Temperature Strategy

This is a critical engineering question. We CANNOT insert a thermocouple inside a cell (it would destroy the cell and void the warranty). So how do we estimate core temperature?

Strategy: Thermal Model Estimation (Core Temp = f(Surface Temp, Current, Time))

In a cylindrical LFP cell (IFR32135):



$$T_{core} = T_{surface} + \Delta T_{internal}$$

$\Delta T_{internal}$ depends on:

1. Per-cell current ($I_{cell} = I_{pack} / 8$) \rightarrow heat = $I_{cell}^2 \times R_{int}$
2. Cell thermal resistance ($R_{thermal}$) $\rightarrow \sim 2.0-4.0 \text{ } ^\circ\text{C/W}$ for cylindrical (higher than prismatic due to smaller surface area)
3. Cooling efficiency \rightarrow liquid vs air cooled
4. Duration of high-current event

ESTIMATION (1D lumped thermal model):

$$T_{core_estimated} = T_{surface} + (I_{cell}^2 \times R_{int} \times R_{thermal_cell})$$

Where:

$I_{cell} = I_{pack} / 8$ (parallel group splits current)
 R_{int} = measured online via $\Delta V_{group}/\Delta I_{pack}$ (AFE + current data)
 $R_{thermal_cell}$ = calibrated constant ($\sim 3.0 \text{ } ^\circ\text{C/W}$ for IFR32135 cylindrical)
 I_{pack} = pack current (from Hall sensor)

UNDER NORMAL OPERATION (1C discharge, $I_{pack} = 120A \rightarrow I_{cell} = 15A$):

$$\begin{aligned} \text{Heat/cell} &= 15^2 \times 3.5\Omega = 0.79W \text{ per cell} \\ \Delta T_{internal} &= 0.79W \times 3.0^\circ\text{C/W} \approx 2.4^\circ\text{C} \\ \rightarrow \text{If surface} &= 35^\circ\text{C}, \text{ core} \approx 37.4^\circ\text{C} - \text{well within limits} \end{aligned}$$

UNDER ABUSE (degraded cell with $8.0m\Omega$, drawing disproportionate heat):

$$\begin{aligned} \text{Heat/cell} &= 15^2 \times 8.0\Omega = 1.8W \text{ per cell} \\ \Delta T_{internal} &= 1.8W \times 3.0^\circ\text{C/W} \approx 5.4^\circ\text{C} \\ \rightarrow \text{Surface at } 40^\circ\text{C} &\rightarrow \text{Core at } \sim 45.4^\circ\text{C} - \text{starting to deteriorate} \end{aligned}$$

WORST CASE (2.6C peak, $I_{cell} = 39A$, degraded $R_{int} = 8.0m\Omega$):

$$\begin{aligned} \text{Heat/cell} &= 39^2 \times 8.0\Omega = 12.2W \text{ per cell} \\ \Delta T_{internal} &= 12.2W \times 3.0^\circ\text{C/W} \approx 36.5^\circ\text{C} \\ \rightarrow \text{Surface at } 40^\circ\text{C} &\rightarrow \text{Core at } \sim 76.5^\circ\text{C} - \text{SEI decomposition zone!} \\ \rightarrow \text{This is WHY core estimation matters.} \end{aligned}$$

Key insight: The surface temperature alone can UNDERESTIMATE core temperature by 10–80°C depending on current and cell health. Our thermal model bridges this gap without requiring invasive sensors.

D. Summary of ALL Temperature Sensors

Sensor	Quantity	Total	Per-What	Purpose
Cell surface NTC (10kΩ)	2 per module	16	Per-module (8 modules)	Cell surface temp, dT/dt , ΔT inter-group
Ambient air NTC	1	1	Per-pack	Ambient-compensated thresholds
Coolant inlet NTC	1	1	Per-pack	Thermal management validation
Coolant outlet NTC	1	1	Per-pack	Heat rejection monitoring
Total temperature sensors		19		

2.4 Gas Sensors

Sensor Type	Quantity	Level	What Is Measured	Placement
VOC / Gas sensor (BME680 or equivalent MOX sensor)	2	Pack-level	Total Volatile Organic Compounds (ethylene, CO, H ₂ , hydrocarbons) from electrolyte decomposition	Sensor 1: Inside the pack enclosure, at the HIGHEST point (gases rise). Near the pack exhaust/vent port, if one exists. Sensor 2: At the opposite end of the pack from Sensor 1, to detect spatial gas propagation direction and speed.
Dedicated H₂ sensor (optional, for LFP packs)	1	Pack-level	Hydrogen gas specifically (LFP cells produce 40–54% H ₂ during failure — the most dangerous gas for LFP)	Near the pack vent port. H ₂ is lighter than air → place at highest reachable point in enclosure.

Why 2 gas sensors, not 1?

SCENARIO: Cell 3 in Module 2 begins venting

With 1 gas sensor (at pack center):

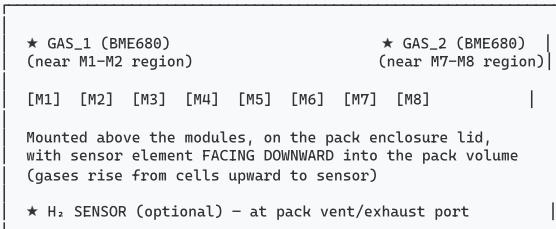
- Gas reaches sensor after diffusing across half the pack
- Delay: 5–15 seconds depending on pack volume and airflow
- We detect "gas is present" but NOT where it's coming from

With 2 gas sensors (at opposite ends):

- Sensor near Module 2 triggers FIRST
- Sensor far from Module 2 triggers LATER (or at lower concentration)
- TIME DIFFERENCE between sensor triggers = direction of gas source
- Localizes the fault to a REGION of the pack
- FASTER first-response (gas reaches nearest sensor sooner)

Placement detail:

PACK TOP VIEW – Gas Sensor Placement

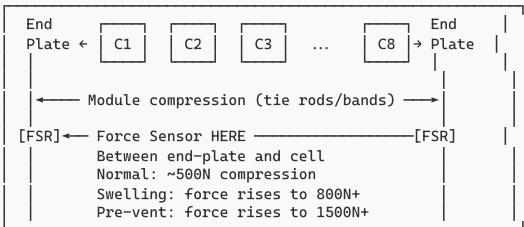


2.5 Pressure / Swelling Sensors

Sensor Type	Quantity	Level	What Is Measured	Placement
Barometric pressure (BME680 built-in)	2 (same BME680 as gas sensors)	Pack-level	Atmospheric pressure inside pack enclosure. A vent event causes pressure spike (>5 hPa in <2 seconds). An intact pack pre-vent shows slow pressure rise from internal gas accumulation.	Co-located with gas sensors (BME680 is 4-in-1: gas+pressure+temp+humidity).
Cell swelling / compression sensor (Load cell or FSR per module)	1 per module = 8 (ideal). 2 minimum (practical for prototype, placed on module end-plates of most thermally stressed modules)	Module-level	Mechanical force exerted by cells against module compression plates. Swelling increases force before any gas vents — earliest mechanical indicator.	Thin-film force sensors (FSR or strain gauge) placed between the module end-plate and the cell stack. As cells swell internally, force on end-plate increases.

Prismatic cell swelling detection:

SIDE VIEW – Swelling Detection per Module



WHY THIS WORKS:

- During gas generation (Stage 2-3), internal gas pressure causes the prismatic cell to bulge outward
- In a compressed module, the cell CANNOT freely expand – instead, force on the end-plate increases
- This force increase is detectable BEFORE the cell vents
- For LFP cells: swelling begins at ~100°C internal, well before vent at ~270°C – giving 10-30 MINUTES of warning

2.6 Complete Sensor Count Summary for Full Pack (104S8P)

Sensor Category	Sensor Type	Per-Group	Per-Module	Per-Pack	Total Count
Voltage	Parallel group voltage (AFE IC)	1	13	—	104
Voltage	Module voltage (derived)	—	1	—	8 (derived)
Voltage	Pack voltage (HV transducer)	—	—	1	1
Current	Pack current (Hall sensor)	—	—	1	1
Current	Isolation monitor	—	—	1	1
Temperature	Cell surface NTC	—	2	—	16
Temperature	Ambient air	—	—	1	1
Temperature	Coolant inlet	—	—	1	1
Temperature	Coolant outlet	—	—	1	1
Gas	VOC sensor (BME680)	—	—	2	2
Gas	H ₂ sensor (optional)	—	—	1	1
Pressure	Barometric (BME680 built-in)	—	—	2	2 (co-located)
Swelling	Module end-plate force	—	1 (ideal)	—	8 (ideal) / 2 (minimum)
				TOTAL	~131 active sensor channels (832 physical cells)

3. What We Compute With All These Inputs

3.1 Computed Parameters — Full List

Every raw sensor reading is processed into higher-level computed parameters. Here is the complete computation pipeline:

A. From Voltage Sensors (104 parallel-group voltages + 1 pack voltage)

Computed Parameter	Formula / Method	What It Tells Us	Anomaly Threshold
Parallel group voltage (V_group_n)	Direct reading from AFE IC, 104 individual values (1 per series position)	SOC per group, detect over/under-voltage, group imbalance. Note: individual cell faults partially masked by parallel cells	Warning: V < 2.7V or V > 3.55V
Group voltage deviation (ΔV_n)	$\Delta V_n = V_{group_n} - \text{mean}(V_{all_groups_in_module})$	Detects one group drifting away from its module peers. In 8P config, a single-cell ISC causes ~1/8 of the full voltage deviation	Warning:

Computed Parameter	Formula / Method	What It Tells Us	Anomaly Threshold
Max-min group spread (V_spread)	$V_{\text{spread}} = \max(V_{\text{all_104}}) - \min(V_{\text{all_104}})$	Overall pack balance health	Warning: > 50mV. Critical: > 150mV
Self-discharge rate (dV/dt at rest)	Measure $V_{\text{cell_n}}$ at t_1 and t_2 during rest (key-off, no load). $dV/dt = (V_2 - V_1) / (t_2 - t_1)$	Micro-internal short circuit — cell drains itself. Earliest electrical precursor	Warning: $dV/dt > 5\text{mV/hour}$ at rest. Critical: $> 20\text{mV/hour}$
Voltage ripple / instability	Standard deviation of $V_{\text{cell_n}}$ over 10-second window during steady-state operation	Loose connection, degraded contact, intermittent ISC	Warning: $\sigma(V) > 5\text{mV}$. Critical: $> 15\text{mV}$
SOC per cell (estimated)	Lookup table: $V_{\text{cell}} \rightarrow \text{SOC}$ based on LFP OCV curve (flat between 20-80% SOC)	Energy management, detect capacity fade	N/A (management, not safety)

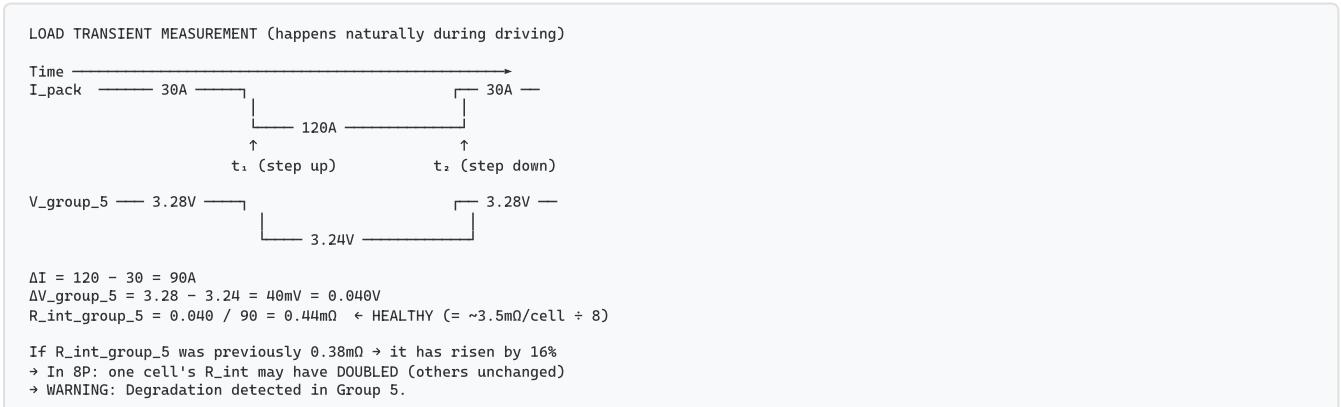
B. From Current Sensor (1 pack current)

Computed Parameter	Formula / Method	What It Tells Us	Anomaly Threshold
Instantaneous current (I_pack)	Direct reading from Hall sensor, $\pm 500\text{A}$ range	Charge/discharge rate, detect overcurrent events. $I_{\text{cell}} = I_{\text{pack}} / 8$	Warning: $> 1.5\text{C} (> 180\text{A})$. Critical: $> 2.5\text{C} (> 300\text{A})$
C-rate	$C_{\text{rate}} = I_{\text{pack}} / \text{Capacity Ah} = I_{\text{pack}} / 120$	Operating intensity, used to adjust all thermal thresholds. 120 Ah capacity ($8 \times 15\text{ Ah}$ parallel group)	Inform context, not standalone alarm
Coulomb counting (SOC tracking)	$\text{SOC} = \text{SOC}_{\text{initial}} + \int (I_{\text{pack}} \times dt) / (\text{Capacity} \times 3600)$	State of charge estimation (complementary to voltage-based SOC)	N/A (management)
Current spike detection		dI/dt	=
RMS current (thermal load)	$I_{\text{rms}} = \sqrt{\text{mean}(I^2)}$ over 60s sliding window	Thermal stress metric — used to predict temperature rise	Feed to thermal model, not standalone alarm

C. From Voltage + Current Together → Internal Resistance

Computed Parameter	Formula / Method	What It Tells Us	Anomaly Threshold
Internal resistance per group (R_int_group_n)	$R_{\text{int_group_n}} = \Delta V_{\text{group_n}} / \Delta I_{\text{pack}}$ during a load transient ($> 5\text{A}$ change over $< 500\text{ms}$). This measures the PARALLEL COMBINATION of 8 cells' R_int. $R_{\text{int_group}} \approx R_{\text{int_cell}} / 8$.	EARLIEST reliable indicator of degradation. If one cell's R_int rises, the group R_int shifts measurably. In 8P: a 50% rise in one cell $\rightarrow \sim 6.25\%$ rise in group R_int \rightarrow detectable.	Warning: $R_{\text{int_group_n}} > 110\%$ of baseline (tighter threshold due to parallel masking). Critical: $> 130\%$ of baseline. Emergency: $> 160\%$ or rising $> 3\%/\text{hour}$
R_int trend (dR/dt)	Exponential moving average of R_int_n over days/weeks	Accelerating degradation \rightarrow approaching end-of-life or failure	Warning: dR/dt doubles in $< 1\text{ week}$
R_int cell-to-cell deviation	$\Delta R_n = R_{\text{int_n}} - \text{mean}(R_{\text{int_module}})$	One cell degrading faster than peers	Warning:

How R_int is measured in practice:



D. From Temperature Sensors → Thermal Computations

Computed Parameter	Formula / Method	What It Tells Us	Anomaly Threshold
Rate of temperature rise (dT/dt) per module	$dT/dt = (T(t) - T(t - 60s)) / 60s$, computed for each of the 16 NTCs	Self-heating → exothermic reaction inside cell. The hallmark of thermal runaway progression.	Warning: > 0.5°C/min. Critical: > 2°C/min. Emergency: > 5°C/min
Inter-module ΔT	$\Delta T_{max} = \max(T_{all_modules}) - \min(T_{all_modules})$	One module running hotter than others → localized fault or cooling failure	Warning: > 5°C. Critical: > 10°C
Intra-module ΔT	$\Delta T_{intra} =$	$T_{NTC1} - T_{NTC2}$	within same module
Delta T from ambient (ΔT_ambient)	$\Delta T_a = T_{cell_surface} - T_{ambient}$	Context-aware temperature anomaly. Eliminates false alarms from hot Indian summers.	See context-dependent table below
Estimated core temperature	$T_{core} = T_{surface} + (I_{cell}^2 \times R_{int_cell} \times R_{thermal})$ where $I_{cell} = I_{pack}/8$	Thermal model output. Estimates internal cell temperature that we cannot directly measure	Warning: $T_{core_est} > 65^\circ\text{C}$ (LFP). Critical: > 80°C. Emergency: > 100°C
Coolant ΔT	$\Delta T_{coolant} = T_{outlet} - T_{inlet}$	Heat rejection by cooling system. If $\Delta T_{coolant}$ suddenly drops while cells are hot → cooling failure	Warning: $\Delta T_{coolant} < 2^\circ\text{C}$ during high C-rate
Absolute temperature	Direct reading from 16 NTCs	Hard safety limit — regardless of context	Emergency: Any cell surface > 80°C (LFP)

Context-dependent ΔT_ambient thresholds (India-adapted):

Operating State	How Detected	ΔT_ambient Warning	ΔT_ambient Critical
Idle / Parked ($I < 2A$)	$I_{pack} \approx 0$ for > 5 min	> 8°C	> 15°C
Low discharge (< 0.5C, < 60A)	$0 < I < 60A$	> 12°C	> 20°C
Normal discharge (0.5–1C, 60–120A)	$60A < I < 120A$	> 18°C	> 28°C
High discharge (1–2C, 120–240A)	$120A < I < 240A$	> 22°C	> 32°C
Charging (< 1C, < 120A)	I_{pack} negative (charging)	> 18°C	> 28°C
Fast charging (~1C, ~120A DC)	I negative, > 100A	> 22°C	> 32°C

E. From Gas Sensors → Gas Computations

Computed Parameter	Formula / Method	What It Tells Us	Anomaly Threshold
Gas resistance ratio (per BME680)	$GR_ratio = Gas_R_current / Gas_R_baseline$ (baseline = EMA over hours of normal operation)	Electrolyte decomposition → gas leaks into pack enclosure → MOX sensor resistance DROPS. Ratio < 1.0 = gas detected.	Warning: $GR_ratio < 0.7$ (30% drop). Critical: $GR_ratio < 0.4$ (60% drop)
Gas rate of change (dGR/dt)	Rate of change of gas resistance over 30-second window	Sudden vent event vs. slow leak. Rapid drop = cell vent (Stage 3). Slow drift = gradual electrolyte seepage (Stage 2).	Warning: $dGR/dt > 20\%$ /min. Critical: > 50%/min (vent event)
Spatial gas gradient	GR_sensor1 vs. GR_sensor2 at same timestamp	Which END of the pack is the gas source? Sensor that triggers first → gas is from that region's modules.	Informational → localize fault module region
Humidity-compensated gas	$GR_compensated = GR_raw \times f(humidity)$ (BME680 provides humidity reading)	Raw gas resistance is affected by humidity. Monsoon = 90%+ RH → false gas readings if not compensated.	Use compensated value for all thresholds

F. From Pressure Sensors

Computed Parameter	Formula / Method	What It Tells Us	Anomaly Threshold
Enclosure pressure delta	$\Delta P = P_{current} - P_{baseline}$ (baseline = EMA over hours, compensated for altitude and weather changes)	Cell vent event → sudden pressure spike inside pack enclosure. Pre-vent gas accumulation → slow pressure rise.	Warning: $\Delta P > 2$ hPa sustained over 30s. Critical: $\Delta P > 5$ hPa in < 5 seconds (vent event)
Pressure rate of change (dP/dt)	Rate of pressure change over 5-second window	Distinguishes slow leak from explosive vent. Vent = pressure spike in <2 seconds.	Critical: $dP/dt > 2$ hPa/s

G. From Swelling Sensors

Computed Parameter	Formula / Method	What It Tells Us	Anomaly Threshold
Module compression force	Direct reading from force sensor / strain gauge on end-plate	Gas generation inside cells → cells swell → force on end-plate increases. Occurs BEFORE vent — earliest mechanical indicator.	Warning: Force > 130% of baseline. Critical: > 160% of baseline
Swelling rate (dF/dt)	Rate of force change over 60-second window	Slow swelling (thermal expansion during charge) vs. rapid swelling (gas generation)	Warning: dF/dt > 10%/min. Critical: > 30%/min

4. The Correlation Engine — Avoiding False Alarms, Ensuring Fast True Alarms

4.1 Why Correlation Is Non-Negotiable

Every SINGLE parameter alone has an unacceptable false positive rate:

Parameter Alone	False Positive Rate	Common False Triggers
Temperature > threshold	15–25%	Indian summer (48°C ambient), high C-rate, parked in sun
Voltage deviation	10–15%	Normal SOC changes, load transients, cell aging variation
Gas resistance drop	5–15%	Humidity changes (monsoon), sensor drift, ambient VOCs (petrol fumes near fuel station)
Current spike	20%+	Regenerative braking, motor transients, AC compressor cycling
Pressure change	5–10%	Altitude change (Ghat roads), weather front, door slam vibration
Swelling increase	10–15%	Normal thermal expansion during charge, temperature cycling

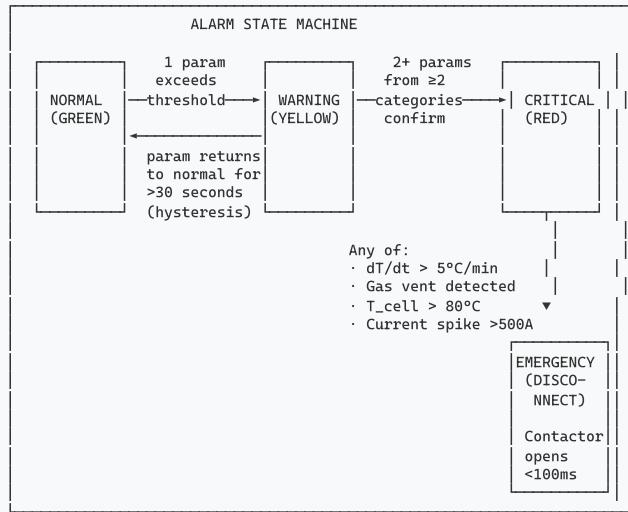
With 2+ independent parameter categories confirming: < 1% false positive rate.

4.2 Correlation Matrix — What Confirms What

CONFIRMATION MATRIX: Parameter A (row) confirms Parameter B (column)							
	Temp↑	dT/dt↑	ΔV	R_int↑	Gas	Pressure	Swelling
Temp↑	—	SELF	GOOD	GOOD	STRONG	STRONG	STRONG
dT/dt↑	SELF	—	GOOD	STRONG	STRONG	STRONG	STRONG
ΔV	GOOD	GOOD	—	STRONG	OK	OK	OK
R_int↑	GOOD	STRONG	STRONG	—	OK	OK	OK
Gas	STRONG	STRONG	OK	OK	—	STRONG	STRONG
Pressure	STRONG	STRONG	OK	OK	STRONG	—	STRONG
Swelling	STRONG	STRONG	OK	OK	STRONG	STRONG	—

STRONG = Independent physics path. If both trigger, confidence ≈ 99%.
(e.g., Gas + Temperature = chemical decomposition confirmed)
GOOD = Correlated but partially dependent. Boosts confidence to ~95%.
(e.g., Temp↑ + ΔV = electrical/thermal fault)
OK = Weakly correlated. Useful for context, not standalone confirmation.
SELF = Same measurement family (e.g., Temp and dT/dt are from same NTC)

4.3 Alarm Escalation State Machine with Correlation



STATE TRANSITIONS:

NORMAL → WARNING: Single parameter exceeds its warning threshold.
Actions: Log event. Increase sampling rate to 10 Hz. Alert cloud.

WARNING → NORMAL: All parameters return to normal range for >30s.
(Hysteresis prevents oscillation in borderline conditions)

WARNING → CRITICAL: At least 2 parameters from DIFFERENT categories (thermal + electrical, or chemical + mechanical, etc.) exceed their respective thresholds simultaneously.
Actions: Sound audible alarm. Send push notification. Reduce max charge/discharge rate. Prepare contactor for disconnect.

CRITICAL → EMERGENCY: Any SINGLE parameter reaches emergency threshold (these are physics-based limits where thermal runaway is imminent).
Actions: IMMEDIATE contactor disconnect (<100ms). Full alarm. Lock out re-energization until manual reset by technician.

EMERGENCY bypasses all intermediate states:
ANY single emergency-level reading → IMMEDIATE DISCONNECT.
This is the fail-safe that does not require correlation.

4.4 Fault Scenarios and Correlation Signatures

Fault Scenario	Cell Voltage	R_int	Temperature	dT/dt	Gas	Pressure	Swelling	Confidence
ISC (dendrite)	↓ slow drop at rest	↑ significant	↑ localized	↑ moderate	—	—	—	HIGH (V + R + T)
SEI degradation	↓ slight	↑↑ primary indicator	— initially	— initially	—	—	—	MEDIUM (R alone initially, confirm with T over time)
Overcharge	↑ above 3.65V	↓ slightly	↑	↑	—	—	↑ slight	HIGH (V + T + swell)
Thermal runaway Stage 2	↓	↑	↑↑	↑↑	↑ begins	↑ slight	↑	VERY HIGH (all categories)
External short circuit	↓↓ rapid	—	↑ rapid	↑↑↑	—	—	—	HIGH (V drop + I spike + T rise)
Cooling system failure	—	—	↑ all modules	↑ uniform	—	—	—	HIGH (all modules simultaneously → not cell fault, it's system fault)
Hot ambient (false alarm if not compensated)	—	—	↑ (but $\Delta T_{ambient}$ is normal)	—	—	—	—	LOW → REJECTED by ambient compensation
High C-rate (normal operation)	↓ normal sag	—	↑ (but proportional to I^2)	↑ (but proportional to I^2)	—	—	—	LOW → REJECTED by C-rate context

5. Prototype Mapping — How This Scales Down to VSDSquadron Ultra Demo

For the prototype on VSDSquadron Ultra, we simulate ONE MODULE (a small cell group) instead of the full 8-module, 832-cell pack:

5.1 Prototype Sensor Mapping

Full Pack Sensor	Prototype Equivalent	Qty in Prototype	Notes
104× group voltage (AFE IC)	INA219 (pack V+I) + simulated per-group via potentiometers or ADS1115 ADC	1 INA219 + 1 ADS1115 (4 channels)	Measure 4 representative parallel-group voltages. Demonstrate per-group detection.
1× Hall-effect current sensor	INA219 (shunt-based, ±3.2A range)	1	Adequate for prototype current levels (<3A)
16× cell surface NTC	4× NTC 10kΩ thermistors (1 per simulated group) + 1× ambient NTC	5	Demonstrates per-group thermal monitoring
2× BME680	1× BME680	1	Gas + pressure + temp + humidity
8× swelling sensors	1× FSR402 (between 2 prototype cells)	1	Demonstrates swelling detection concept
Contactor disconnect	Relay + MOSFET on GPIO	1	Demonstrates safety disconnect

5.2 What the Prototype Demonstrates to Organizers

1. **Per-cell voltage monitoring** → detect cell deviation and ISC signature
2. **Internal resistance calculation** → demonstrate R_int computation from V and I
3. **dT/dt and ΔT** → rate-of-rise and inter-cell temperature differential
4. **Ambient-compensated thresholds** → show that the same 45°C cell temp triggers alarm in winter but not in Indian summer (because ΔT_ambient differs)
5. **Gas detection** → BME680 detects VOC changes (can simulate with isopropyl alcohol vapor)
6. **Pressure detection** → BME680 detects enclosure pressure changes (can simulate by blowing into sealed enclosure)
7. **Multi-parameter correlation** → demonstrate that single-parameter anomaly → WARNING, but two categories → CRITICAL, and emergency threshold → DISCONNECT
8. **Sub-100ms contactor disconnect** → relay clicks within 100ms of emergency condition

The algorithm running on the prototype is IDENTICAL to what would run on the production pack. Only the sensor count and hardware interface differ. The correlation engine, state machine, and threshold logic are the same firmware.

6. Summary — The Engineering Answer

Question	Engineering Answer
What pack?	Tata Xenon EV Max, 40.5 kWh, 104S8P LFP cylindrical (IFR32135-15Ah, Guoxuan), 8 modules × 104 cells, 832 total cells , 332.8V nominal
How many voltage sensors?	104 parallel-group voltages (via AFE ICs, 13 per module × 8 modules) + 1 pack-level HV transducer. Each measurement = voltage of 8 parallel cells
How many current sensors?	1 pack-level Hall-effect sensor (104S8P = one total current path; $I_{cell} = I_{pack}/8$ at each position)
How many temperature sensors?	16 cell-surface NTCs (2 per module × 8 modules) + 1 ambient + 2 coolant = 19 total
Where are temp sensors placed?	NTCs wedged between cells in interior groups (between groups 3-4 and 10-11 in each 13S module), capturing the hottest zone and thermal gradient. Especially critical in 8P architecture where voltage masking makes temp the primary fault indicator.
Core vs. surface strategy?	Surface measured directly by NTC. Core ESTIMATED via 1D lumped thermal model: $T_{core} = T_{surface} + I_{cell}^2 \cdot R_{int} \cdot R_{thermal}$ ($I_{cell} = I_{pack}/8$).
How many gas sensors?	2 BME680 at opposite ends of pack (spatial gradient detection) + 1 optional H ₂ sensor

Question	Engineering Answer
How many pressure sensors?	2 (built into the BME680s) — co-located with gas sensors
How many swelling sensors?	8 ideal (1 per module end-plate) or 2 minimum (most thermally stressed modules)
Total sensor channels?	~131 active sensor channels for the full pack (832 physical cells)
What is computed?	V_group, ΔV_group, V_spread, self-discharge, V_ripple, I_pack, I_cell (=I_pack/8), C-rate, dI/dt, R_int per group, dR/dt, T_surface, T_core_est, dT/dt, ΔT_inter-module, ΔT_intra-module, ΔT_ambient, gas_ratio, gas_direction, pressure_delta, dP/dt, swelling_force, dF/dt, SOC, SOH
How are false alarms avoided?	Multi-parameter correlation engine requiring 2+ independent categories to escalate. Context-aware thresholds (ambient temp, C-rate, charge state). 30-second hysteresis. Tighter voltage thresholds for 8P parallel masking.