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Diagnosing High-Voltage Faults: From the DTC to the Engineering Cause of Failure

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Abstract

High-voltage electric vehicles now form a routine part of dealership service work, and a stored diagnostic trouble code is often treated as the answer rather than as a starting symptom. This manual sets out a practice-oriented method for moving from a recorded code to a proven engineering cause of failure across the high-voltage architecture of compact premium battery electric vehicles, including Mercedes EQ, BMW i and i3, MINI Cooper SE, and Smart EQ. The introduction frames the problem against current market data, where electric car sales reached about 20 million units in 2025 and roughly one in four new cars sold was electric. The method combines four steps: reading the high-voltage architecture and wake-up logic, classifying intermittent shutdown by operating phase, locating isolation faults through safe circuit separation, and verifying the cause with measurements, logs, and thermal data before any part is replaced. Results are presented as an authored confidence ladder that gates high-voltage component replacement behind convergent evidence. The conclusion confirms each aim and offers a reporting format for service, warranty, and the customer. The material will interest dealership diagnostic technicians, warranty engineers, and service managers.

Keywords: *High-Voltage Diagnostics, Diagnostic Trouble Code, Isolation Resistance, Intermittent Shutdown, Pre-Charge and Contactors, HVIL, Freeze-Frame Analysis, Fault Timeline, Engineering Root Cause, Battery Electric Vehicle.*

CONTENT

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INTRODUCTION

Service departments meet high-voltage faults more often each year because the fleet itself has changed. The International Energy Agency reports that electric car sales passed 17 million in 2024 with a sales share above 20 percent, and that 2025 sales grew by about 20 percent to exceed 20 million units, lifting the global share to roughly 25 percent [1, 2]. About 5 percent of the global car stock was electrified by 2025 [2]. The United States sat near 10 percent of new car sales in 2025 [2], a level that still places a large and aging population of battery electric vehicles into independent and franchised workshops. As these cars leave their first owners, dealerships inherit faults that are intermittent, weather sensitive, and hard to reproduce on a lift [3].

A recurring problem in this work is the gap between a diagnostic trouble code and the physical reason a high-voltage system shut down. Published research on lithium-ion battery diagnostics has matured around fault mechanisms, fault features, and diagnosis procedures [4], and model-based methods now cover a wide range of cell and pack faults [5]. Statistical and data-driven detection of voltage faults in real-world fleets has also advanced [6, 7], with recent work extending to online and incipient multi-fault detection [8, 11, 12, 13]. Much of this literature targets engineering design and fleet monitoring rather than the bench reality of a single car with one stored code, a soaked battery, and a customer waiting. That gap is the focus here.

The aim of this manual is to give dealership technicians a repeatable method that converts a high-voltage diagnostic trouble code into a proven engineering cause of failure, so that component replacement follows evidence rather than probability. **The scientific** contribution is modest and clearly bounded: this work does not develop new hardware or a new test instrument, but it organizes existing measurements, logs, and OEM data into an authored confidence ladder that gates high-voltage part replacement behind convergent evidence. **Working hypothesis** is that most repeat high-voltage failures in these platforms trace to a cause outside the traction battery, often in the 12 V supply, the DC-DC path, pre-charge timing, connector integrity, or isolation contamination, and that a structured verification step reduces unnecessary battery replacement.

The scope is honest about its limits. The platform comparisons stay at the level of publicly known architecture and segment characteristics, since current and binding test procedures live in each manufacturer's service system, and the figures that carry relative levels are indicative rather than measured fleet statistics. The source base is deliberately small and verifiable rather than broad, which keeps every claim checkable but leaves some platform-specific detail to the reader's own service data. None of this changes the method, which is designed to work with whatever tools a given workshop already owns.

The wider value is practical and national in a quiet way. The United States is rebuilding domestic vehicle service capacity around electrified powertrains, and dealership diagnostic skill is part of that capacity. A technician who can separate a symptom from a cause keeps a usable battery out of the waste stream, shortens warranty disputes, and protects the resale value of a growing electric fleet. Linking that hands-on talent to a clear method is a small contribution to a country that needs more people who can service the cars it is buying.

CHAPTER 1. THE HIGH-VOLTAGE SYSTEM ARCHITECTURE AS THE BASIS OF DIAGNOSIS

The Roles of the HV Battery, Inverter and EME, DC-DC, OBC, Compressor, Heater, and Contactor Box in Start-Up Llogic

Diagnosis begins with a clear picture of what each high-voltage device is for and when it draws current. The high-voltage battery, often described in standards as the rechargeable energy storage system, is the source [20]. Its current reaches the rest of the car only through the contactor box, which holds the main contactors and the pre-charge path [17]. Downstream sit the inverter and the electric motor electronics, usually grouped as the EME, which convert direct current into the alternating current the traction motor needs. In parallel the DC-DC converter steps the high voltage down to feed the 12 V network, while the on-board charger handles alternating current from the wall during charging. The cabin heater and the air-conditioning compressor are also high-voltage loads in these platforms, and they matter for diagnosis because they switch large currents under thermal demand.

Reading this layout as a system, rather than as a parts list, changes how a code is interpreted. A fault reported by the inverter may originate at the contactor box or at the 12 V supply that wakes the controllers. The figure below maps the source, the switching stage, and the loads so that a single code can be placed in context before any tool is connected.

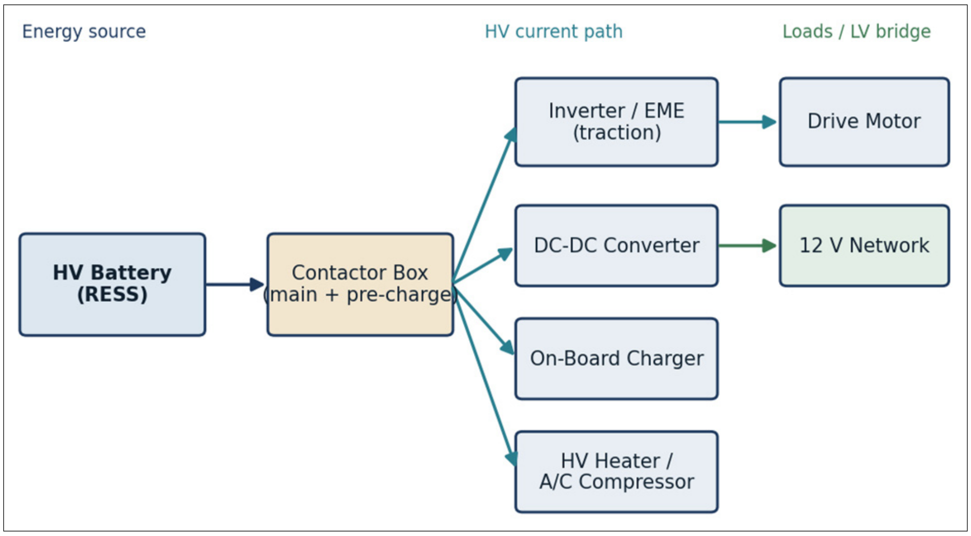

Figure 1. High-voltage system architecture and the high-voltage current path. (compiled by the author based on [16, 17, 20]).

Once the map is in mind, the technician can ask which device actually needed power at the moment of the fault. That question leads directly into the wake-up sequence, where the order of events decides whether a fault is a cause or a consequence.

The HV Wake-Up Sequence: Enable Conditions, Pre-Charge, Contactor Closure, and Isolation Monitoring

A high-voltage system does not simply switch on. It follows an ordered sequence, and a fault at any step leaves a different signature. The controllers first receive a wake-up request, usually from the 12 V side. Enable conditions are then checked, including controller communication and a healthy low-voltage supply. The pre-charge path closes next, bringing the link capacitors up gently through a resistor so that closing the main contactors does not produce a damaging inrush [17]. Only after the pre-charge voltage matches the pack within a tolerance do the main contactors close. The system then confirms isolation resistance before declaring the high-voltage bus ready [14, 18].

The sequence is shown below as a staged timeline. Reading a fault against these stages is the first analytical step, because a pre-charge timeout points toward the resistor, the link capacitance, or a leaking load, while an isolation abort points toward contamination or a damaged cable rather than a contactor.

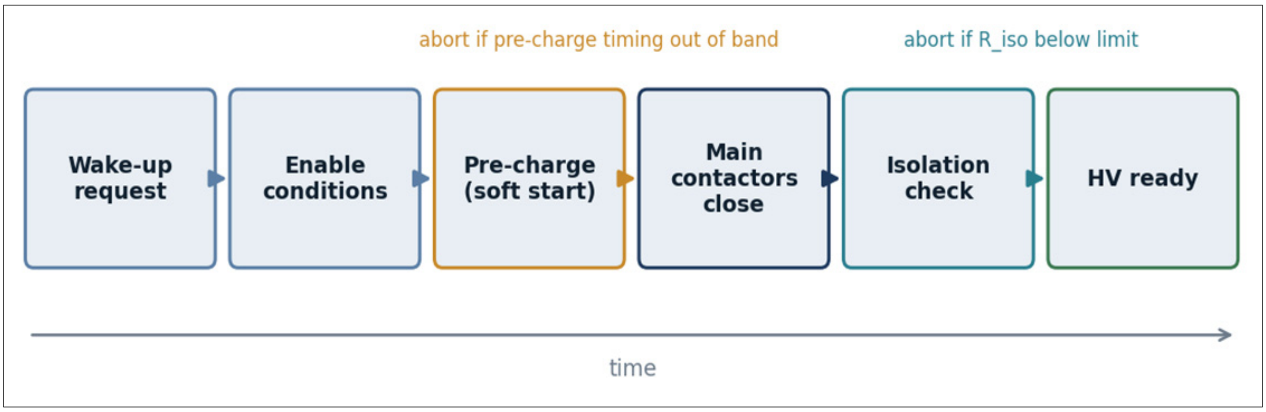

Figure 2. The high-voltage wake-up sequence with the two common abort points (compiled by the author based on [14, 17, 18]).

Because each abort lands at a known stage, the same sequence becomes a checklist. That checklist is also where manufacturers differ, which is the subject of the next subsection.

Differences in Diagnostic Logic Across Mercedes EQ, BMW i and i3, MINI Cooper SE, and Smart EQ

The physics of pre-charge and isolation is shared, but the way each platform reports and gates faults is not. MINI Cooper SE and the BMW i3 share BMW Group engineering, so their high-voltage state handling and code structure follow a related logic. Mercedes EQ models follow Mercedes-Benz service architecture, and the Smart EQ line carries its own lineage from the Daimler period and later ownership changes. These are public facts about origin rather than internal procedures, and the practical lesson is that a technician should not carry a habit from one platform into another without checking the current service system.

The table below summarizes architecture-level traits that are publicly known and that shape first-look diagnosis. It is qualitative by design, and binding procedures must come from each manufacturer's current service data.

Table 1. Platform-level traits that shape first-look high-voltage diagnosis (compiled by the author based on public platform information and [18, 20]).

Platform	Engineering lineage	First-look emphasis	Watch item
Mercedes EQ	Mercedes-Benz BEV architecture	Code plus freeze-frame, system state	Thermal and charging context
BMW i3	BMW Group i architecture	HV state machine, fault memory	Range-extender variants differ
MINI Cooper SE	BMW Group, shared with i3 path	Compact pack, group code logic	12 V health on wake-up
Smart EQ	Daimler lineage, later JV	Small pack, simpler HV layout	Connector and soak effects

Whatever the platform, the stored code is still only a label for a symptom. The final subsection explains why that label should never be treated as the diagnosis.

Why a DTC is a Consequence and Not a Diagnosis: Working with Fault Memory and Freeze-Frame

A diagnostic trouble code records that a monitored value crossed a threshold. It does not record why. Research on battery diagnosis separates the cause, the symptom, and the fault for exactly this reason, since a symptom such as an unstable voltage can follow from several distinct causes [4]. In a workshop this means that a single isolation code can come from a wet connector, a damaged cable, a degraded load, or a sensor problem, and the code alone cannot tell them apart.

Fault memory and freeze-frame data narrow the field. The freeze-frame stores the operating context at the moment the threshold was crossed, which lets the technician reconstruct conditions instead of guessing. The funnel below shows how a symptom-level code is progressively narrowed toward an engineering cause.

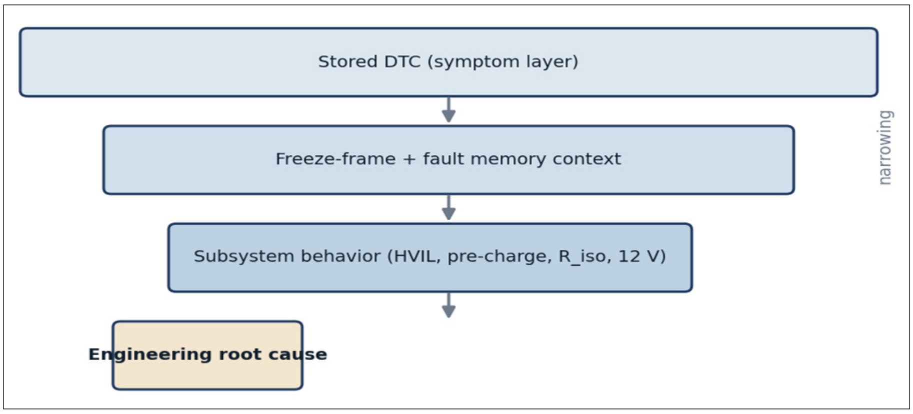

Figure 3. Narrowing a symptom-level code toward an engineering cause (compiled by the author based on [4, 5]).

This funnel sets up the rest of the manual. Chapter 2 takes the hardest version of the problem, the fault that will not stay present long enough to measure, and shows how the same context data turns an intermittent event into a traceable sequence.

CHAPTER 2. A METHOD FOR FINDING THE CAUSES OF INTERMITTENT HV SHUTDOWN

Classifying Floating Faults: Wake-Up, Drive, Charging, Thermal Load, and the Sleep and Wake Cycle

Intermittent faults resist diagnosis because they appear and clear before a meter can settle. A useful first move is to classify the fault by the operating phase in which it occurs, since each phase loads the high-voltage system differently. A fault that only appears at wake-up points toward enable conditions, the 12 V supply, or pre-charge. A fault during drive points toward dynamic load, vibration, and connector movement. A charging fault implicates the on-board charger and its isolation path. A thermal-load fault appears when the heater or compressor draws current, and a sleep and wake fault often follows a long soak with humidity.

The classification below ties each phase to the contributors worth checking and to the data the technician should capture before the fault clears. Capturing the right data first is what makes the difference between a reproducible case and a guess.

Table 2. Classification of intermittent high-voltage faults by operating phase (compiled by the author based on [4, 7, 12])

Phase	Trigger window	Common contributors	Data to capture
Wake-up	Key-on, controller start	12 V supply, pre-charge, enable logic	12 V level, pre-charge time, codes
Drive	Load and vibration	Connector movement, EME, cabling	Speed, load, freeze-frame
Charging	AC or DC charging	OBC, isolation on charge path	Charge type, isolation reading
Thermal load	Heater or A/C active	Compressor, heater, current spikes	Temperature, load current
Sleep / wake	After long soak	Humidity, isolation, parasitic drain	Soak time, humidity, SOC

With the phase identified, the next step is to read the freeze-frame context that surrounds the event, since the same phase can hide several different causes.

Reading the Freeze-Frame by SOC, Temperature, Humidity, Soak Time, and 12 V State

Freeze-frame analysis turns a single code into a small story about the car. State of charge, pack temperature, ambient humidity, soak time, and the 12 V level together describe the conditions that allowed the fault to appear. Statistical studies of real-world fleets show that voltage faults correlate with measurable operating parameters rather than appearing at random [6, 7], which supports reading these values as evidence rather than as background.

The profile below compares a normal start, a marginal start, and a frame captured just before a shutdown. The pattern matters more than any single bar. A pre-shutdown frame with high humidity, long soak, and a low 12 V level points toward an isolation or supply problem rather than a cell defect.

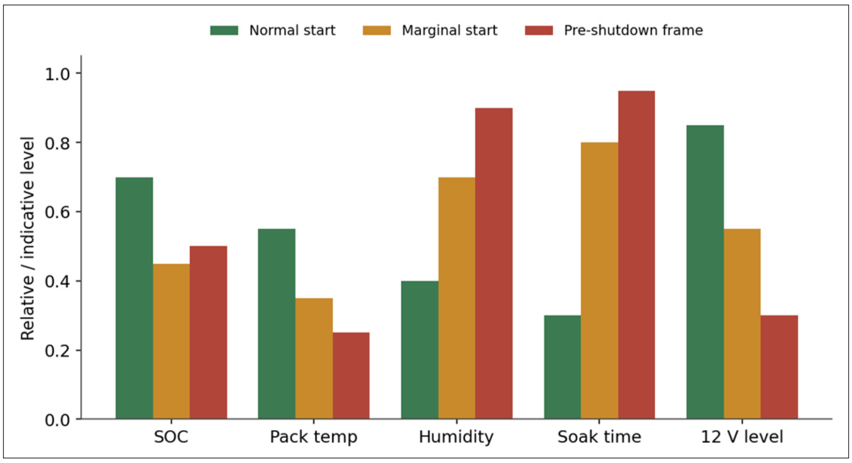

Figure 4. Indicative freeze-frame parameter profiles for three start conditions (compiled by the author based on [6, 7]; levels are indicative).

Reading the context tells the technician what to suspect. The next step is to confirm or clear those suspects with targeted checks that add no new risk to the car or the person.

Checking HVIL, Pre-charge, Contactor State, and DC-DC Enable without Adding Risk

Once a high-voltage fault is suspected, the checks themselves must be safe. The high-voltage interlock loop is a low-voltage circuit that runs in series through the high-voltage connectors and covers, so that any opening commands the contactors to open within milliseconds [16]. Confirming HVIL continuity and, where used, its resistance coding is a low-risk first check. Pre-charge can be assessed through the voltage rise time during the wake-up sequence, contactor state through behavior during closure and a stuck or welded test, and DC-DC enable through whether the 12 V network is supported once the bus is live [17].

The order of these checks matters. The decision flow below moves from a de-energized verification through the low-voltage safety circuit and into measured behavior, so that each result either clears a suspect or passes the case to the next layer.

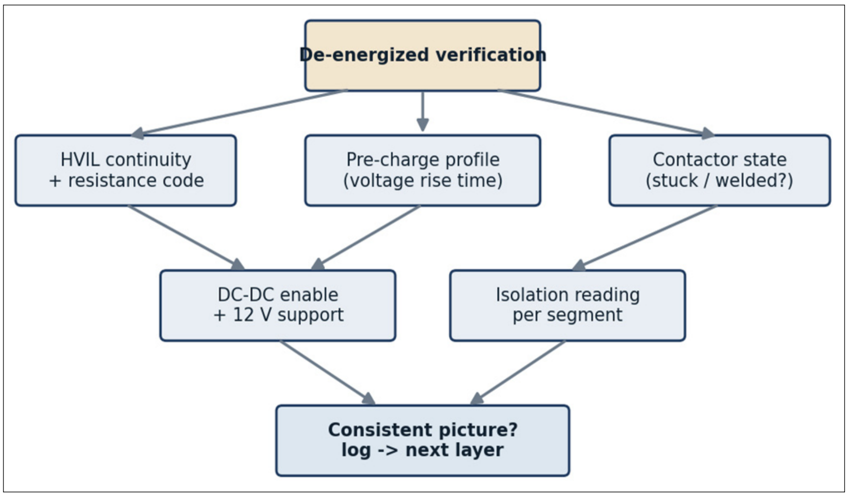

Figure 5. A staged, low-risk check sequence for HVIL, pre-charge, contactor, and DC-DC (compiled by the author based on [14, 16, 17, 18]).

These checks produce a set of timed observations. Assembling those observations in the correct order is what finally reveals the cause, which is the subject of the last subsection in this chapter.

Building a Fault Timeline: Reconstructing the Sequence of Events before the HV System Stopped

A fault timeline places every captured event on a single axis so that cause and consequence separate naturally. The point is to recover order. A pre-charge deviation that precedes an isolation warning, which in turn precedes the shutdown, tells a very different story than an isolation warning that appears first. Online and incipient fault studies stress that early features often precede the obvious fault by a measurable interval [8, 11, 13], and the workshop version of that idea is simply to ask what happened first.

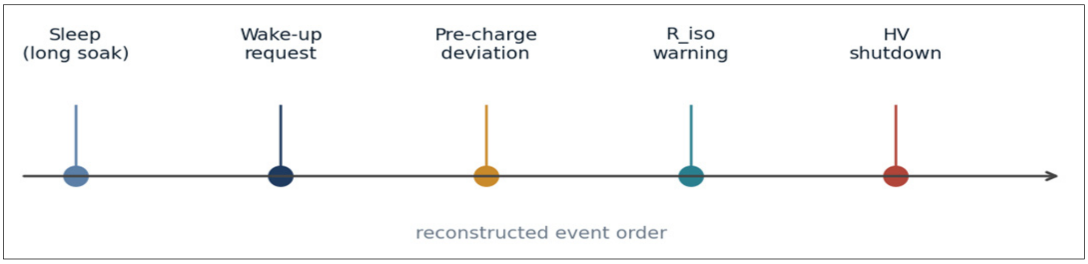

Figure 6. A reconstructed fault timeline from soak to high-voltage shutdown (compiled by the author based on [8, 11, 13].

When the timeline points toward isolation, the question becomes where the leakage sits and how to find it without energizing a contaminated circuit. Chapter 3 takes up isolation faults as a dealer-level methodology.

CHAPTER 3. ISOLATION FAULT METHODOLOGIES IN DEALERSHIP PRACTICE

Isolation Resistance as a System Indicator: Battery, Cables, EME, OBC, Heater, and Compressor

Isolation resistance is measured between the high-voltage conductors and the chassis, and it behaves as a system reading rather than a single-component value [14, 18]. Every high-voltage device sits in parallel across that measurement, so a single low reading can come from the battery, the cables, the EME, the on-board charger, the heater, or the compressor. Insulation monitoring devices calculate high-side and low-side resistance from measured bus voltages and flag a fault when the value or its trend crosses a limit [15].

Because the measurement is a parallel network, the worst contributor dominates. The chart below ranks the components by how often each is the source of a low reading in field practice, as an indicative guide rather than a measured statistic.

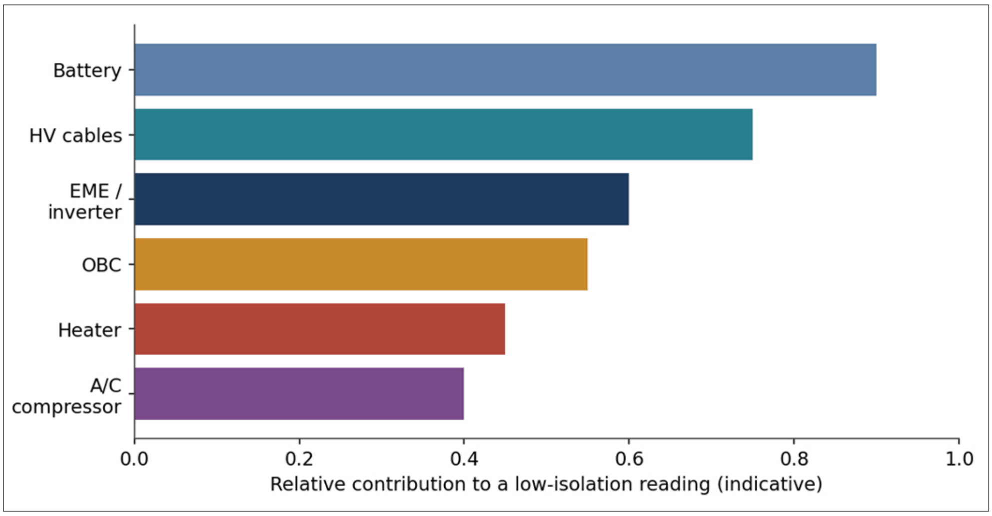

Figure 7. Indicative ranking of components as the source of a low isolation reading (compiled by the author based on [14, 15]; ranking is indicative).

Knowing that the reading is a system value explains why it drifts with conditions. The next subsection looks at what pushes isolation down in the first place.

The Effect of Moisture, Coolant Intrusion, Collision, Poor Repair, and Temperature on HV Isolation

Isolation faults are often environmental rather than structural. Moisture across a connector, coolant intrusion into a heater or a cooled component, collision damage that pinches a cable, a previous repair that left a gap in the isolation barrier, and temperature swings all reduce the measured resistance. Many of these are intermittent, which is why they pair so well with the soak and humidity context captured in Chapter 2.

The schematic below shows the qualitative point. Under dry, nominal conditions the resistance stays well above the decision limit, while high humidity or coolant ingress drags it down toward and below that limit as stress increases. The curves are illustrative and are meant to explain behavior, not to provide measured values.

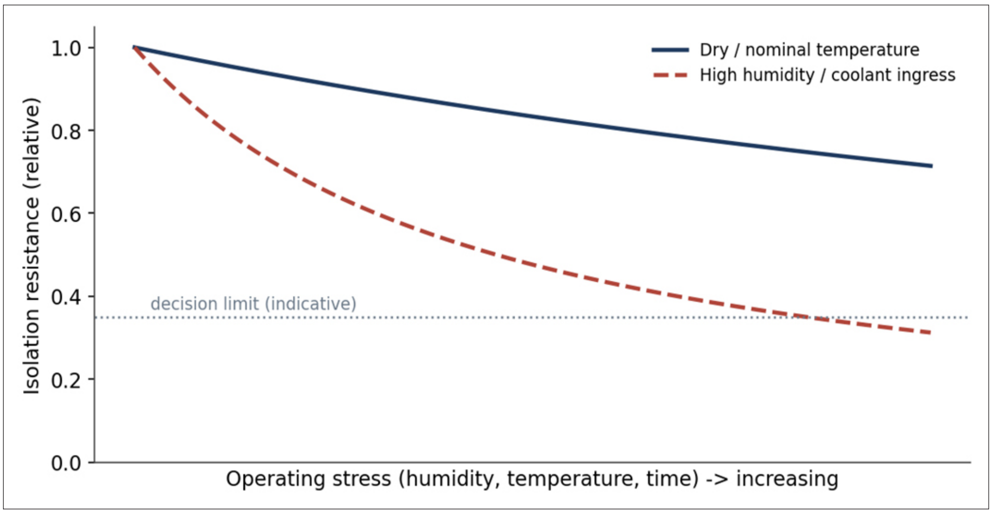

Figure 8. Qualitative effect of environmental stress on isolation resistance (compiled by the author based on [14, 15]; curves are illustrative).

If conditions can move the reading, the technician needs a way to find which loop actually leaks. That is the localization problem, addressed next.

A Localization Algorithm: Safe Circuit Separation and the Interpretation of Results

Localization works by division. Because the measurement is a parallel network, separating the battery from the rest of the high-voltage system splits the problem in two. If the pack alone reads low after the pack disconnect is opened, the leakage is internal. If the pack alone reads normal, the leakage is external, and the external loops to the EME, the on-board charger, the heater, and the compressor can be segmented one at a time [15, 18]. The key safety rule is to perform these separations in a de-energized, verified state and to re-energize only what the procedure allows.

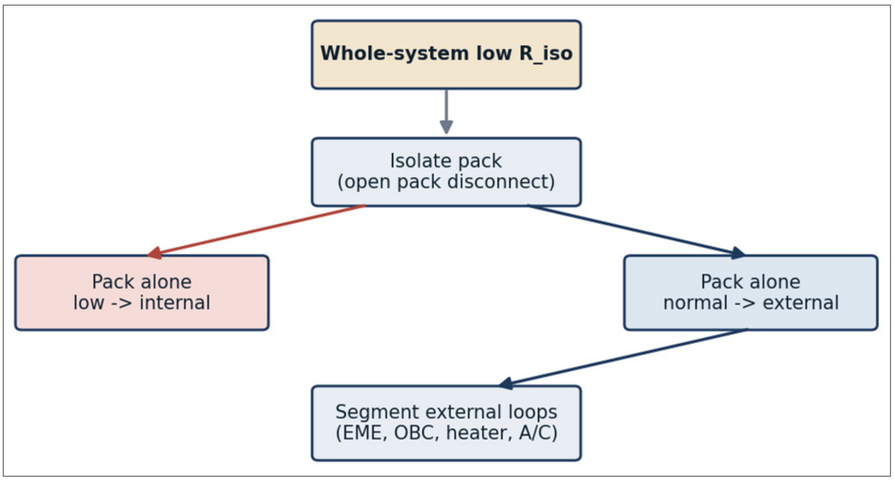

Figure 9. A safe localization algorithm based on circuit separation (compiled by the author based on [15, 18]).

Localization tells the technician where the fault is. It has not yet decided what to do about it, which depends on whether the component can be restored, must be replaced, or makes the car unsafe to operate.

Decision Criteria: Restore, Replace the Component, Quarantine the Battery, or Prohibit Operation

The last step in isolation work is a decision, and that decision should follow the finding rather than the easiest action. A reading that recovers fully after drying and cleaning supports a restore and return. A single external component that holds a low value supports replacing that component. A pack that reads low internally supports quarantine and a controlled, safety-led process. Structural or collision damage, or a reading that will not clear, supports prohibiting operation until the hazard is removed.

The matrix below pairs each finding with an indicative condition and a decision. It is a guide to reasoning, and it does not replace the manufacturer's safety procedure for a damaged or unstable battery.

Table 3. Decision criteria for isolation findings (compiled by the author based on [14, 15, 18, 20]).

Finding	Indicative condition	Decision
Recovers after drying	Moisture across a connector	Restore, document, return
Single external component low	Heater, A/C, or OBC leak	Replace that component
Pack internal low	Internal isolation loss	Quarantine, follow safety process
Collision or structural damage	Pinched or cut HV cable	Prohibit operation until repaired
Repeated borderline, no clear source	Drifting reading near limit	Monitor, re-measure under stress

These criteria assume the technician trusts the measurement. The final chapter examines where OEM guided tests stop short of proof and how engineering verification closes that gap.

CHAPTER 4. THE LIMITS OF OEM DIAGNOSTICS AND ENGINEERING VERIFICATION

When a Guided Test Reaches a Probable but Unproven Cause

OEM guided tests are structured and useful, and they often end at a probable cause rather than a proven one. The test follows a decision tree built around codes and a set of pass and fail checks, and it stops when a likely component is named. The literature reflects the same boundary: model-based and data-driven methods produce a likely fault under their assumptions, and their accuracy depends on the operating conditions and the data available [5, 8]. In a workshop, a probable cause is an invitation to a part swap, and a part swap on probability is the main source of repeat visits.

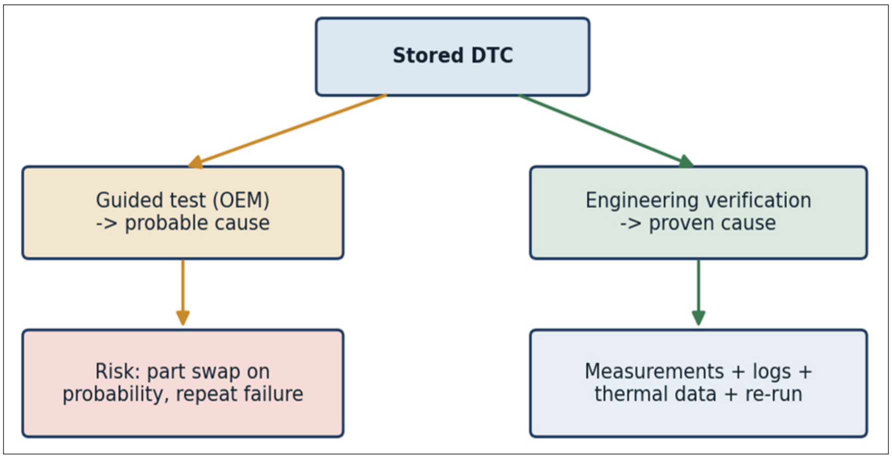

Figure 10. The guided-test path and the engineering-verification path from a single code (compiled by the author based on [4, 5, 9, 10]).

The way past a probable cause is to add evidence from independent sources until they agree. That combination is the subject of the next subsection.

Combining the OEM Scanner, Measurements, Logs, Thermal Data, and Controlled Re-Runs

Verification means convergence. The OEM scanner supplies the code and the freeze-frame, direct measurement supplies isolation and voltage values, vehicle and charge logs supply history, thermal data supplies the load context, and a controlled re-run tries to reproduce the event under known conditions. No single source proves a cause, but when several independent sources point at the same component, confidence rises to the level where replacement is justified [5, 8].

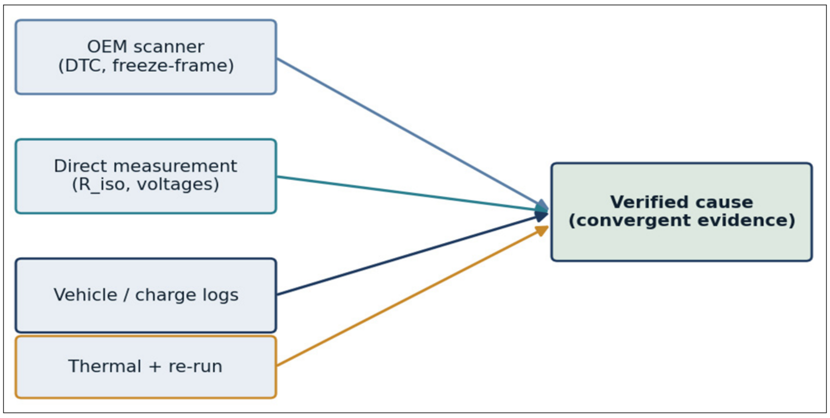

Figure 11. Convergence of independent evidence toward a verified cause (compiled by the author based on [5, 8]).

When evidence does not converge, the temptation is to replace the high-voltage battery and hope. The next subsection looks at the predictable errors that follow from that habit.

Typical Diagnostic Errors: Replacing the Battery Instead of Finding the 12 V, DC-DC, or CAN Cause

A costly and common error in high-voltage diagnosis is treating the battery as the default suspect. A wake-up fault driven by a weak 12 V supply, a DC-DC converter that fails to support the low-voltage network, a pre-charge resistor at the end of its life, or a communication fault on the vehicle bus can all present as a high-voltage no-start. Replacing the pack removes the symptom for a while if the new pack ships with a healthy 12 V state, which makes the wrong conclusion look correct until the fault returns.

The table below lists common misdiagnosis patterns together with the cause that is often missed. The pattern is consistent: an expensive component is replaced because it carried the code, while a cheaper upstream cause goes unexamined.

Table 4. Common misdiagnosis patterns and the cause often missed (compiled by the author based on [4, 5, 9, 10]).

Observed action	Apparent reason	Cause often missed
HV battery replaced	Low isolation code	External component or wet connector
Battery replaced	Intermittent shutdown	12 V supply or DC-DC dropout
Contactor blamed	No high-voltage start	Pre-charge resistor or enable logic
Module swap	Voltage spread	Sensor or communication fault

Avoiding these errors is partly a matter of evidence and partly a matter of how the finding is written down. The final subsection sets out a report format that records the proof.

The Format of the Final Diagnostic Conclusion for Service, Warranty, and the Customer

A diagnostic conclusion is only as good as its record. A report that states the proven cause, the evidence behind it, and the action taken protects the technician, supports a warranty claim, and gives the customer a clear account. The aim is a short document that any of the three audiences can read without translation, and that another technician could follow to reach the same conclusion.

The structure below separates the summary from the evidence and from the action, so that each audience finds what it needs. It is deliberately compact, since a report that is too long is rarely read.

Table 5. A structure for the final diagnostic conclusion (compiled by the author based on [4, 5, 18]).

Section	Content	Audience
Summary	Stated cause in one or two sentences	Customer, service
Evidence	Codes, measurements, logs, thermal data	Warranty, technician
Root cause	The proven component and why	Warranty engineer
Action and safety	Repair, restore, or quarantine plus safety	Service, customer

With a verified cause and a clear record, the method comes full circle, from a stored code to a proven failure. The results and discussion that follow propose how to formalize that path as a single authored protocol.

DISCUSSION

The chapters above describe a method that is already implicit in good practice. The contribution of this manual is to make it explicit as a confidence ladder that gates high-voltage component replacement. The idea is simple. A finding is assigned a confidence level based on the evidence held, and a high-voltage component is replaced only when the evidence reaches the level that justifies it. Below that level, the correct action is to gather more evidence, not to swap a part.

We propose four levels. At the symptom level the technician holds only a stored code, and no replacement is justified. At the context level the freeze-frame and the operating phase narrow the field, which supports targeted checks but not replacement. At the localization level a safe circuit separation has identified where the fault sits, which supports replacing a clearly identified external component. At the verified level several independent sources converge on the same cause, which justifies replacing a high-voltage component, including the battery, with a documented record. This ladder is an authored framework, not a manufacturer procedure, and it is meant to sit alongside the OEM guided test rather than to replace it.

Table 6. Proposed diagnostic confidence ladder for high-voltage component replacement (compiled by the author as an original proposal, informed by [4, 5, 8, 19]).

Level	Evidence held	Allowed action
Symptom	Stored DTC only	No replacement; read context
Context	Freeze-frame, phase, history	Targeted low-risk checks
Localization	Safe separation result	Replace identified external part
Verified	Convergent independent evidence	Replace HV component, document

The discussion point worth making is that this ladder changes the default. In current practice the default action under uncertainty is often to replace the high-voltage battery, because it removes the symptom. The ladder makes the default action the gathering of one more independent measurement, which is cheaper and which protects a usable battery. For a dealership the practical gain is fewer repeat visits, cleaner warranty records, and a defensible reason for every high-voltage part fitted. For the wider fleet the gain is fewer serviceable batteries scrapped on a probable cause.

There is a second authored recommendation. Workshops should keep a short internal record of resolved high-voltage cases, indexed by platform, phase, and proven cause. Over time this record becomes a local evidence base that sharpens the context level of the ladder, since a technician can compare a new freeze-frame against past confirmed outcomes on the same platform. This is a low-cost step that turns each repair into future diagnostic value.

CONCLUSION

This manual set out to convert a high-voltage diagnostic trouble code into a proven engineering cause of failure, and each aim stated in the abstract has been met. Chapter 1 established the architecture and the wake-up sequence as the basis for reading any code in context, and it explained why a code is a symptom rather than a diagnosis. Chapter 2 gave a method for intermittent shutdown, built on phase classification, freeze-frame reading, low-risk checks, and a reconstructed timeline. Chapter 3 treated isolation resistance as a system indicator, explained how the environment moves it, and provided a safe localization algorithm with clear decision criteria. Chapter 4 set the limits of OEM guided tests and showed how convergent evidence verifies a cause, while naming the misdiagnosis patterns that drive repeat visits.

The working hypothesis held up within the scope of this work. Many repeat high-voltage failures in these platforms trace to causes outside the traction battery, in the 12 V supply, the DC-DC path, pre-charge, connectors, or isolation contamination, and a structured verification step reduces unnecessary battery replacement. The authored confidence ladder formalizes that step. The material is aimed at dealership diagnostic technicians, warranty engineers, and service managers who need a repeatable way to defend a high-voltage repair decision. Used consistently, it links a technician's hands-on skill to measurable value for the workshop, the customer, and a growing national electric fleet.

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