HVPACE

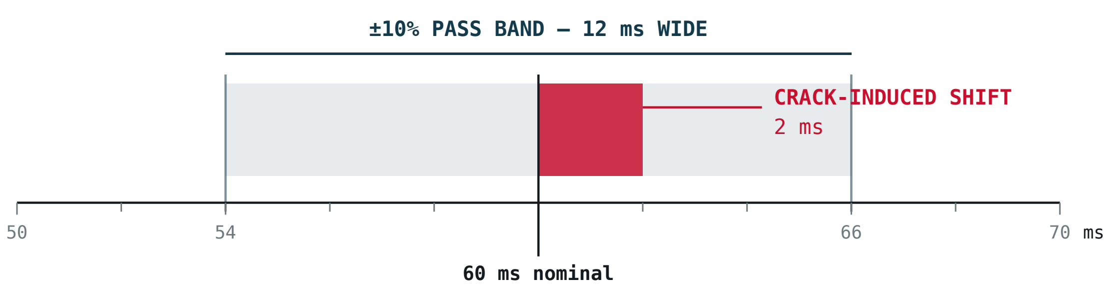
CIRCUIT BREAKER DIAGNOSTICS · CORE TECHNOLOGY NOTE

The defect your timing test cannot see

Mechanical vibration measurement and diagnostics for high-voltage circuit breakers

A conventional breaker timing set answers one question: are the operating parameters inside the allowed range? It was never designed to answer a different and more valuable question — is anything in the drive train getting worse? This paper explains why that gap exists, what it costs, and how vibration diagnostics closes it.

HVPACE Technical White Paper · Rev 1.0 · For asset managers, substation test and maintenance engineers, and switchgear manufacturers



Both quantities drawn to the same scale. The pass band is the instrument's resolution limit; the red block is the defect. Everything in this paper follows from that ratio.

01

Why breaker diagnostics needs rethinking

A high-voltage circuit breaker is the only item of plant on the network that is required to operate at the exact moment a fault occurs. It sits still for months or years, then has to complete energy release, transmission, contact separation and arc extinction within a few tens of milliseconds. That duty cycle — long dormancy, brief high stress — concentrates its reliability problem in the mechanical drive train rather than in the insulation.

Successive CIGRE international reliability surveys of high-voltage circuit breakers have consistently found that mechanical causes account for the largest share of major failures, well ahead of insulation, current-carrying and control-circuit causes. In practice, managing breaker health is largely a matter of managing the health of its mechanism and linkage.

Yet the instrument used almost universally to assess that health — the mechanical timing and travel analyser — was built around a measurement principle and an acceptance philosophy formed decades ago. Its purpose is to verify that operating parameters fall within an allowed range, not to detect degradation in progress. Those two purposes are not the same, and defects grow in the space between them.

> A timing set measures the **outcome** of an operation. Vibration measures the **process**. An acceptable outcome does not mean a healthy process — and almost every mechanical defect leaves a measurable trace in the process long before it moves the outcome.

02

Where conventional timing tests reach their limit

2.1 What the instrument measures

A typical timing analyser records opening time, closing time, close–open time, pole and interrupter discrepancy, the travel–time curve and the contact velocity derived from it, overtravel and rebound, coil current waveforms, and contact resistance. These quantities are the basis of factory and commissioning acceptance testing, and their value is not in question.

2.2 Four structural blind spots

The issue is not measurement accuracy. It is that these quantities cannot physically carry early-defect information. Four limitations are structural rather than incidental:

- **End-point measurement averages the defect away.** Time and velocity are the cumulative result of the whole kinematic chain. When one pin, link or shaft degrades locally, its effect is diluted by the compliance and clearance of every other element before it reaches the travel transducer, and survives only as a very small change in total time.
- **The acceptance band is far wider than the degradation.** The common criterion — within ±10% of the factory value, or within the manufacturer's stated range — is sized to accommodate manufacturing tolerance, temperature, operating voltage and lubricant condition. That width is an order of magnitude greater than the change an incipient defect produces.
- **Sampling bandwidth removes the impact information.** Travel and coil current are typically sampled at a few kilohertz with an effective bandwidth of a few hundred hertz. The energy from mechanical impacts, latch release, crack-face friction and loose-part rattle lies mainly between 1 and 20 kHz. That information is discarded at the acquisition stage — no amount of later analysis recovers it.
- **Pass/fail on a single test ignores direction.** Mechanical degradation is by nature monotonic and irreversible. Three successive closing times of 60.0, 61.2 and 62.4 ms are each individually “within tolerance”, yet the direction of travel is unambiguous. Conventional practice rarely retains history at sufficient resolution to see it, and does not test for it.

2.3 The arithmetic: 2 ms inside 60 ms

Take a 110 kV breaker with a rated closing time of 60 ms. Under a ±10% criterion, any value between 54 and 66 ms is accepted — an acceptance band 12 ms wide.

Now consider a drive shaft in that same mechanism carrying an established fatigue crack. The crack reduces torsional stiffness, the drive develops additional elastic lag, and closing time changes by typically 1 to 2 ms. In other words:

> **The defect is real and present, but its amplitude is a fraction of the acceptance band. The “pass” verdict is not technically wrong. The instrument was simply designed not to resolve that scale.**

More important still: a 2 ms offset that represents monotonic drift away from that unit's own history means something entirely different from 2 ms of random scatter. The acceptance band conceals not only the magnitude but the direction.

TABLE 1

Conventional timing tests: what each quantity can and cannot reveal

MEASURED QUANTITY	TYPICAL RESOLUTION	DETECTS	CANNOT DETECT
Opening / closing time	0.1 ms, judged on ±10%	Severe binding, coil faults, mechanism failure	Elastic lag and stiffness loss at the 1–2 ms level
Travel–time curve	kHz sampling, few hundred Hz bandwidth	Short travel, clearly low velocity, damper failure	Local defects outside the transducer's kinematic path
Contact velocity	Differentiated from travel	Low stored energy, general rise in resistance	Cracks, pin wear, loosening fasteners
Pole discrepancy	0.1 ms	Clearly unequal drive between poles	Abnormal energy transfer within a single pole
Coil current waveform	kHz sampling	Armature binding, supply voltage issues, trip faults	Everything the mechanism does after latch release
Contact resistance	Static measurement	Surface oxidation, loose connections	Any information about motion

03

Case: a shaft that passed its last test

3.1 The component

The part shown below is the drive shaft between the operating mechanism and the breaker body. It sits between the mechanism output and the interrupter linkage, carries the entire opening and closing torque, and is one of the most highly stressed single elements in the drive train — with no redundancy whatsoever.

Figure 1 — Fracture surface of the drive shaft between operating mechanism and breaker body. Site photograph.

3.2 Reading the fracture surface

The macroscopic fracture shows two distinctly different regions: one relatively flat and dark, carrying friction and oxidation marks, corresponding to slow crack growth under repeated alternating load; and one rough and brightly metallic, corresponding to the instant when the remaining cross-section could no longer carry the torque and tore through.

That combination is characteristic of fatigue fracture. The crack initiated at a stress concentration, advanced incrementally with each operation, progressively reduced the load-bearing section, and finally separated during one ordinary switching operation. The engineering implication is direct:

> This was not an accidental overload. It was a progressive process spanning hundreds or thousands of operations and quite possibly years. Throughout that period the defect was present in the equipment — and available to be found.

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Note: the above is a macroscopic assessment. Where a fracture is to be used in formal
failure or liability determination, it should be supported by SEM examination of the
fracture surface for striations and initiation site, together with material
composition and hardness verification.
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3.3 From mechanical defect to explosion risk

A fractured drive shaft breaks the kinematic connection between the mechanism and the interrupter. The possible consequences include failure to open on command, contact travel that stops short or is severely slow, and loss of mechanical control during an operation.

The most dangerous of these is the intermediate case: the contacts begin to part but never achieve sufficient gap and opening velocity, so the arc is not extinguished at a current zero and continues to burn inside the interrupter. In an SF_6 or vacuum interrupter, sustained internal arcing raises internal pressure and decomposes the insulating medium rapidly, creating a real risk of enclosure rupture and explosion — with direct consequences for adjacent plant and for anyone in the substation.

In this case, the breaker had passed its most recent routine mechanical timing test on every parameter.

04

The physics behind vibration diagnostics

4.1 An operation is a sequence of impacts

Mechanically, an opening or closing operation is not one smooth movement. It is a rapid succession of discrete events: coil armature impact, latch release, spring energy release, cam and roller engagement, linkage acceleration, torque transfer through the drive shaft, contact touch or separation, damper impact, and mechanism end-stop.

Each event is a structural impact that excites broadband transient elastic waves. These propagate through the mechanism housing, the support frame and the pole column to the outer surface of the equipment, where an accelerometer mounted on the enclosure captures them in full. Vibration is therefore, physically, an event-by-event record of the entire operation rather than a summary of its outcome.

4.2 Signal model: event timing convolved with structural response

The acquired signal carries two kinds of information: when each mechanical event occurred and how much energy it released (the time-domain fingerprint), and how the structure itself transmits vibration (the frequency-domain fingerprint). A drive-train defect alters both, measurably.

The decisive difference from a timing set is temporal resolution. Vibration channels are typically sampled between 25.6 kHz and 100 kHz, locating individual impact events to within 10–100 μs — one to two orders of magnitude finer than a millisecond-scale acceptance criterion. At that resolution, "2 ms inside 60 ms" is no longer noise. It is a statistically significant signal.

4.3 How defects map to signal features

TABLE 2

Typical mechanical defects and their vibration signatures

DEFECT	PHYSICAL MECHANISM	OBSERVABLE SIGNATURE
Fatigue crack in shaft or link	Reduced section stiffness; crack faces opening and closing under alternating load	Key event timings drift in one direction; non-linear harmonics and sidebands appear in the impact response; crack “breathing” adds high-frequency transients
Pin wear and increased clearance	Lost motion before load is transmitted	Event intervals lengthen; first impact energy falls while subsequent impact energy rises; low-amplitude secondary impacts appear
Loose fasteners	Components free to strike a second time after each impact	Repeating weak impact clusters follow the main events; high-frequency energy share increases; shot-to-shot repeatability degrades markedly
Lubrication failure, corrosion, binding	Higher friction, reduced velocity	The whole event sequence stretches; impact peaks fall; mid-band energy distribution shifts
Damper degradation	Insufficient absorption of end-of-travel energy	End-stop impact energy rises sharply; structural ring-down persists longer
Operating spring fatigue	Reduced released energy	Sequence fails to compress in time as expected; initial impact energy falls monotonically

4.4 A measured signal

The trace below was recorded on a 110 kV high-voltage circuit breaker. The upper plot is the raw signal; the lower plot is the same record after de-trending and adaptive noise suppression.

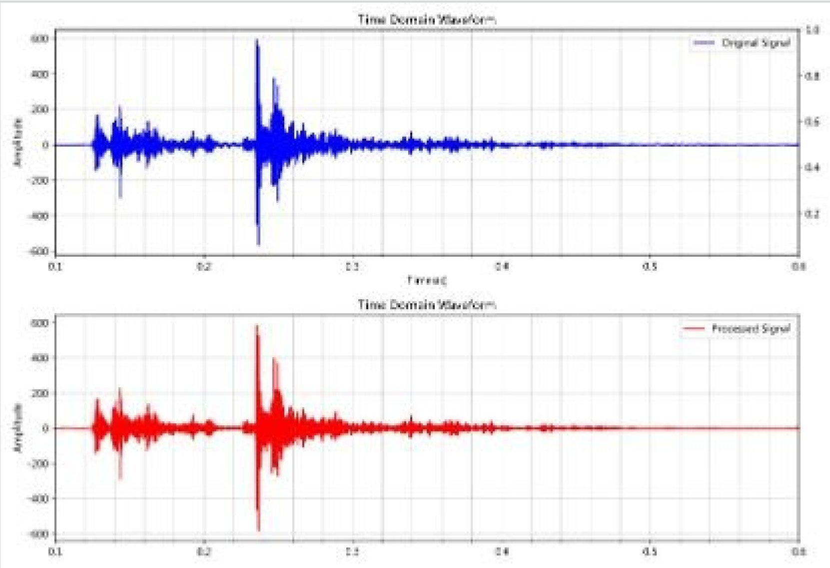

Figure 2 — Mechanical vibration signal from a 110 kV circuit breaker. Upper: raw signal. Lower: after processing.

Two principal event clusters are clearly resolved: the first near 0.13 s, corresponding to mechanism release and drive loading, and the second near 0.23 s, the highest in amplitude, corresponding to the main mechanical impacts and end-of-travel strike. Free decay of the structural ring-down follows.

Processing suppresses low-frequency drift and background noise, sharpening the onset and end of each event so that every event can be located in time and integrated for energy independently. That is the core observable of the method: not *how many milliseconds in total*, but *at what instant, and with how much energy, each individual step occurred*.

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The HVPACE measurement and diagnostic system

5.1 Measurement chain

- **Sensors.** Piezoelectric accelerometers on the mechanism housing, the body drive section and the pole base, with range and frequency response covering the impact band. Mounting position and coupling method are standardised so that successive measurements remain comparable.
- **Synchronised channels.** Vibration is acquired on a common time base with coil current, travel and auxiliary switch signals, so that mechanical events can be referred precisely to the electrical sequence.

- **Acquisition.** High sampling rate and high dynamic range, preserving the rise edge and high-frequency content of each impact transient intact.

5.2 Signal processing

- **Pre-processing.** De-trending and baseline correction remove sensor low-frequency drift and mounting stress effects.
- **Noise suppression.** Wavelet and adaptive filtering reject substation electromagnetic and mechanical background while preserving the steep edges that carry the diagnostic information.
- **Event extraction.** Adaptive thresholding on short-time energy and signal envelope identifies and marks the onset and duration of each mechanical event automatically.
- **Sequence alignment.** Dynamic time warping and related methods align the current event sequence against the baseline fingerprint, removing bulk offset caused by trigger differences.

5.3 Feature set

Once events are extracted, a structured feature set is computed for each operation, forming that unit's mechanical operating fingerprint:

- **Time domain.** Absolute event instants, intervals between adjacent events, event durations, peak acceleration, RMS, crest factor.
- **Energy.** Integrated energy per event, energy distribution across events, total energy.
- **Frequency and time–frequency.** Spectral centroid, wavelet-packet band energy distribution, high-frequency energy share, time–frequency ridges.
- **Statistical.** Shot-to-shot consistency across repeated operations, entropy, correlation and waveform distance against baseline.

5.4 Criteria: baseline deviation and trend, not a fixed band

This is where the method departs from conventional practice. The system does not ask whether a value falls within ±10% of a factory figure. It applies two independent lines of evidence:

- **Against itself.** The measurement taken early in service, or after major overhaul, becomes that unit's own baseline fingerprint. Every later measurement is compared against it, examining both the size of the deviation and whether it is monotonic over time.

- **Against the fleet.** Feature distributions are built across units of the same type, batch and duty, identifying statistical outliers.

The logic condenses to a single sentence: **one deviation is data, consecutive deviations in the same direction are a trend, and a trend is a defect.**

TABLE 3

Alarm grading framework — thresholds calibrated per breaker type

LEVEL	SIGNATURE	INTERPRETATION	RECOMMENDED ACTION
NORMAL	Deviation within measurement repeatability, no directional bias	Mechanical condition consistent with baseline	Continue at the planned monitoring interval
WATCH	Small deviation in isolated features, no sustained trend	May reflect duty or mounting variation	Shorten the interval, repeat the measurement
ALERT	Consecutive same-direction drift in key event timings or energies	Mechanical degradation in progress	Schedule targeted inspection, localise the suspect element
DEFECT	New events, significant redistribution of energy, or loss of repeatability	Substantive defect present in the drive train	Plan an outage; inspect drive components as a priority

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A complement to timing tests, not a replacement

To be unambiguous: vibration diagnostics does not replace mechanical timing testing. Timing parameters are the standard basis of acceptance, they carry formal status, and no commissioning or maintenance process should omit them. What vibration diagnostics addresses is the part of the problem that timing tests cannot physically cover — early, local, progressive mechanical degradation.

TABLE 4

Capability comparison

DIMENSION	CONVENTIONAL TIMING ANALYSER	VIBRATION MEASUREMENT AND DIAGNOSTICS
What is measured	The outcome of the operation — time, velocity, travel	The whole process — each mechanical event
Time resolution	Milliseconds	Microseconds (10–100 μs)
Effective bandwidth	A few hundred Hz	Above 10 kHz, covering the impact band
Acceptance logic	Fixed band around a rated value, e.g. ±10%	Deviation from the unit's own baseline, and its direction
Coverage	The kinematic path containing the transducer	The full drive train, including the link between mechanism and body
Detection stage	After degradation moves a parameter out of range — late	Before degradation reaches the end-point parameters — early
Typical findings	Binding, failure to operate, clearly low velocity	Cracks, loosening, increased clearance, lubrication failure, damper decay
Role	Compliance acceptance and functional verification	Condition assessment, trending and risk warning

07

What it delivers

- **Catastrophic failures avoided.** Events such as shaft fracture, failure to operate and internal arcing move from “sudden, in service” to “known, before the outage” — directly reducing both plant loss and personnel risk.
- **Condition-based maintenance made defensible.** The transition from fixed-interval overhaul to condition-based intervention needs quantified, traceable evidence. This provides it, avoiding unnecessary strip-down of healthy units without letting degraded ones through.
- **Narrower inspection scope.** Event-level localisation narrows the suspect region to a specific part of the drive train, reducing exploratory dismantling and the reassembly risk that comes with it.
- **An asset health record.** Each unit's operating fingerprint accumulates over time, becoming a data asset for whole-of-life management, spares planning and end-of-life decisions.

- **Useful at acceptance.** Establishing the baseline at factory or commissioning stage also exposes assembly inconsistency, raising the quality of what enters the network.

08

Boundaries and correct use

For the conclusions to remain sound, the conditions the method depends on should be stated as plainly as its capabilities:

- **It needs a baseline.** Diagnosis rests on comparison against the unit's own history, so baseline quality sets the ceiling on diagnostic capability. The baseline is best established early in service or immediately after overhaul.
- **It needs repeatable mounting.** Variation in sensor position, coupling and mounting torque introduces feature scatter, and must be controlled by a standardised work procedure.
- **It needs duty normalisation.** Operating voltage, ambient temperature and lubricant condition all affect mechanical response, and must be recorded and allowed for when trending.
- **It needs expert interpretation.** An abnormal feature indicates that the dynamic behaviour of some element has changed. Final identification of the defect still requires knowledge of the specific mechanism design and, where warranted, physical inspection.
- **It does not replace standard testing.** Timing, contact resistance, insulation and gas testing all remain part of the regime.

09

Conclusion

A conventional timing set's verdict of “pass” is a judgement made at millisecond resolution against an acceptance band of ±10%. That is entirely sufficient for verifying that the equipment functions. It is not sufficient for finding mechanical degradation in progress. The fractured shaft described here is the direct consequence of that gap: the defect existed in the equipment for a long time, every routine test during that period returned a normal result, and it ended in a fracture that left the breaker one operation away from sustained internal arcing.

Vibration measurement and diagnostics purpose-built for high-voltage switchgear — microsecond timing resolution, bandwidth that reaches the impact spectrum, event-level feature extraction, and criteria based on a unit's own baseline and trend — moves the diagnostic window from the outcome of the operation to the process of the operation, so the defect is identified before it reaches the end-point parameters.

> **For asset management the value reduces to one sentence: it turns an explosion that might have happened into a work order raised several months in advance.**

About HVPACE

HVPACE specialises in performance assessment, defect diagnostics and testing technology for high-voltage switchgear. The vibration measurement and diagnostic method described here is one of our core diagnostic technologies, applied to factory and commissioning acceptance, in-service condition assessment, verification before and after overhaul, and technical investigation of failures.

If you have breakers where the timing results look acceptable but the behaviour does not, that is exactly the case this method was built for.