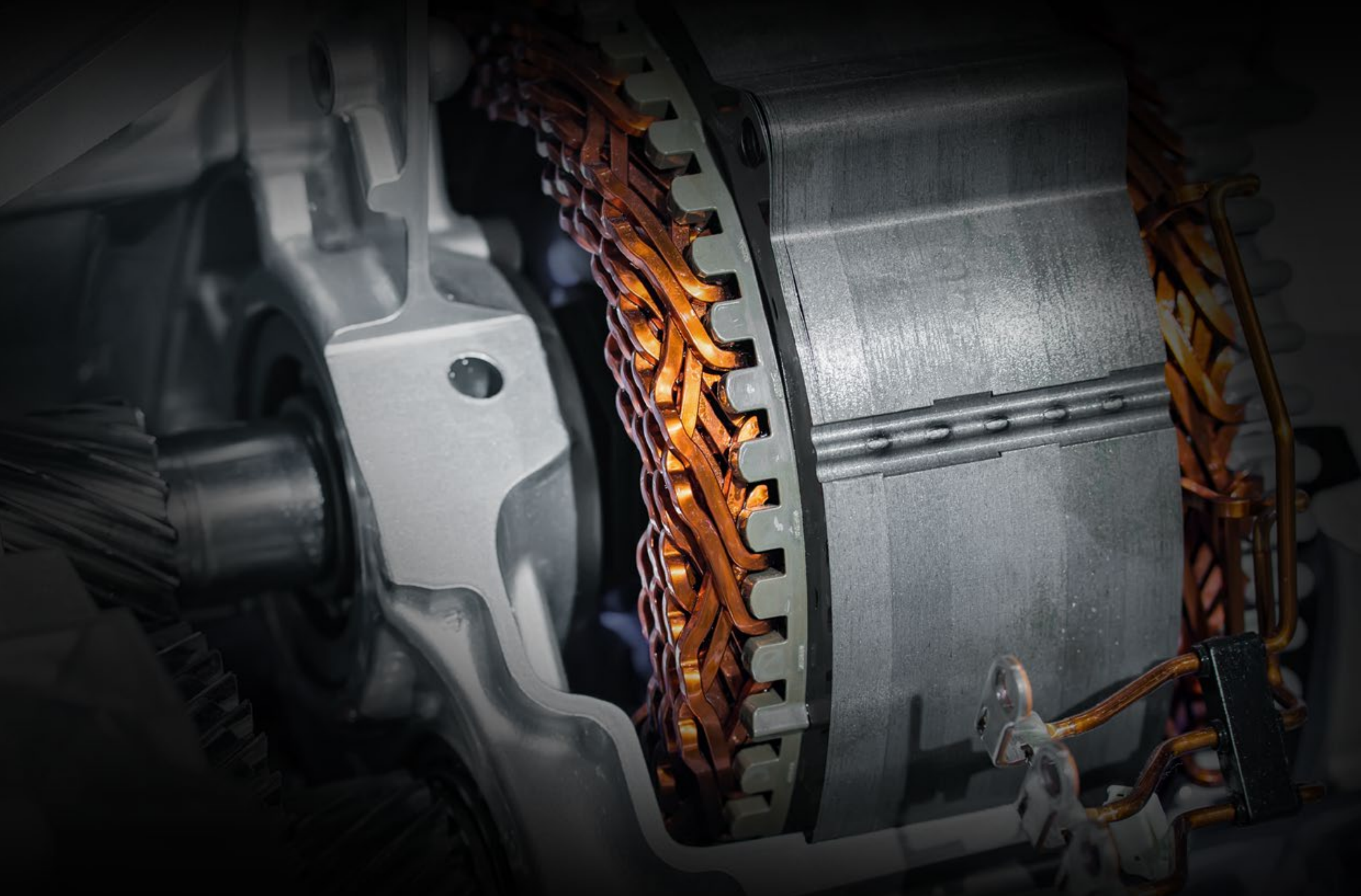
Polytec

Application //

Laser Doppler Vibrometry for analyzing high-voltage electric motor terminals



Reliable electric mobility starts with the details //

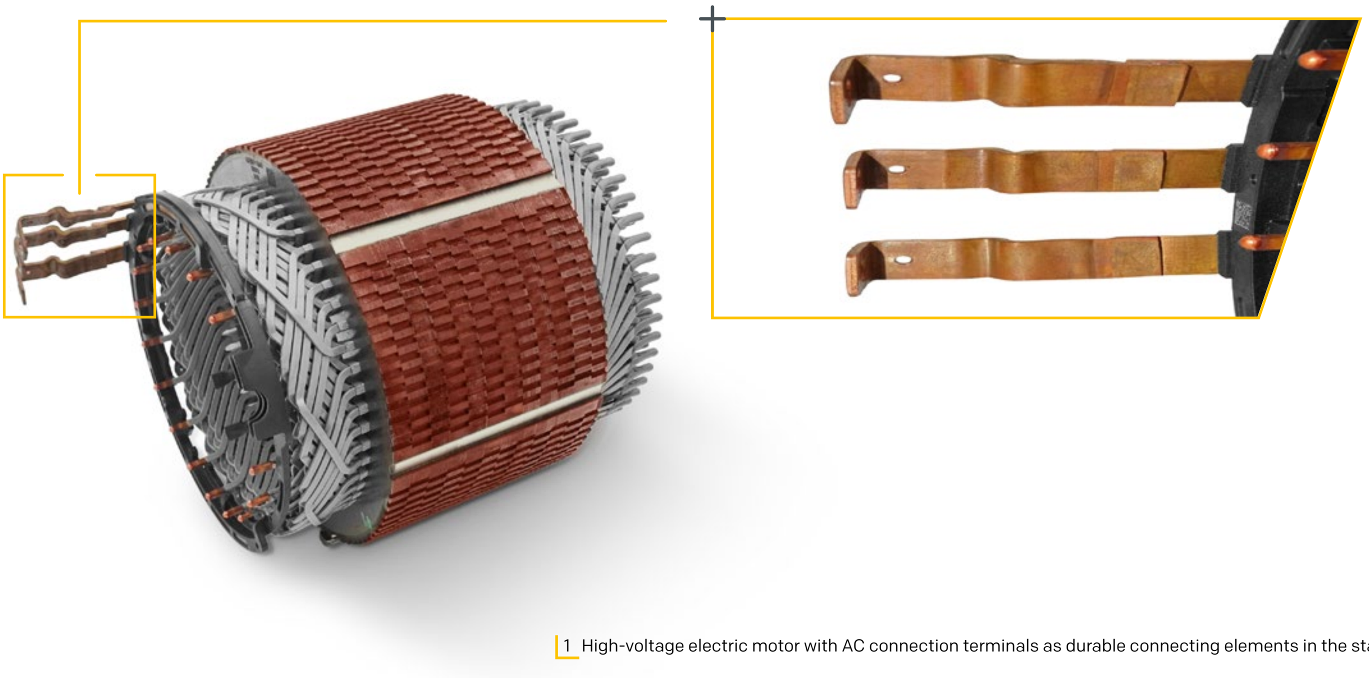
LASER DOPPLER VIBROMETRY PROVIDES INSIGHTS INTO THE VIBRATION BEHAVIOR OF HIGH-VOLTAGE ELECTRIC MOTOR TERMINALS

This application note describes the methodological analysis and evaluation of the vibration characteristics of AC terminals in the stator of a high-voltage electric motor on test benches at MAHLE International GmbH. By using a laser Doppler vibrometer (LDV), two different designs of the connection terminals were examined under realistic load conditions to gain insights into their service life, damage mechanisms, and structural characteristics. The results provide practical recommendations for the development, testing, and quality assurance of high-voltage components.

Modern high-voltage electric motors, such as the one shown in Fig. 1, rely on reliable and durable connection elements in the stator, known as AC connection terminals. These not only conduct electricity to the windings but must also compensate for mechanical movement between the connection board and the stator.

HIGH STRESS MEETS HIGH DEMANDS

Due to high current densities, strong vibrations, and thermal stresses during vehicle operation, these components are exposed to both electrical and mechanical stresses. For developers, test engineers, and quality assurance specialists, the targeted analysis of the dynamic behavior of these components offers important insights for optimizing design and material selection to prevent premature failures.



1 High-voltage electric motor with AC connection terminals as durable connecting elements in the stator

When tiny cracks have major consequences //

In this application, the goal is to characterize the vibro-mechanical behavior of AC connection terminals with a lamellar design and to compare two different geometries, S-type and L-type, in terms of their service life and damage resistance in a resonance dwell test (Fig. 2).

FROM MICROCRACK TO SYSTEM FAILURE

A crack in the lamellae, as shown in Fig. 4, reduces the conductive cross-section and thus the conductivity of the terminal. Resistance increases, causing the component to heat up. This can lead to total failure.

Furthermore, if the fins "stand out," there is a risk of an electrical short circuit with the housing, which would render the motor unusable. In addition to electrical conductivity, which is impaired by cracks in the material, the focus is particularly on the influence of component geometry on resonance behavior, natural modes, and material damping. The objective is to provide reproducible criteria for evaluating the mechanical integrity and damage development of the terminals under realistic conditions.

2 AC connection terminals in the S-type + L-type variants

Visualizing vibrations—without affecting the component //

The two clamp designs were evaluated using an electrodynamic vibration test bench, on which the test specimens were tested in resonance tests and subsequent dwell tests until a damage-induced frequency drop occurred. In these tests, a sinusoidal excitation force was applied across the frequency range (sinusoidal sweep). This allowed resonance frequencies, response amplitudes, and the transfer function to be precisely determined without damaging the clamps due to excessive energy.

LASER DOPPLER VIBROMETRY AS A KEY TECHNOLOGY

A central element of the methodology was the use of a VibroFlex QTec Laser Doppler Vibrometer (LDV) from Polytec GmbH (Fig. 3), which offers decisive advantages over conventional accelerometers.

While conventional sensors distort the vibration behavior of lightweight structures due to their mass and the joint damping of the adhesive bond, the LDV enables non-contact and thus feedback-free measurement of the small and delicate lamellar clamps. For the measurement, it is sufficient to align and position the measuring laser on the test specimen, which not only shortens the measurement time but also significantly simplifies the placement of the component.

For the development and testing departments of suppliers and manufacturers, the question arises as to whether they should build the necessary measurement infrastructure themselves or rely on the expertise of specialized measurement service providers. Companies operating as measurement service providers typically have suitable measurement systems and extensive application knowledge, enabling them to perform complex analyses efficiently and to reproducible quality standards.

The advantage here lies not only in the availability of the latest technology, but above all in up-to-date expertise regarding test design, error prevention, and result interpretation. The latter is particularly important when new or critical component geometries are being examined for the first time.

Ideally, a company is able to establish the necessary measurement infrastructure as well as the expertise regarding test design, error prevention, and result interpretation on its own. This was the case at MAHLE International GmbH, where the AC connection terminals were characterized under constant conditions at room temperature. The resonance frequency was continuously monitored using an LDV. The LDV system was integrated into the shaker control via defined interfaces, allowing the test to be conducted with constant local amplitude values.

3 VibroFlex QTec sensor head

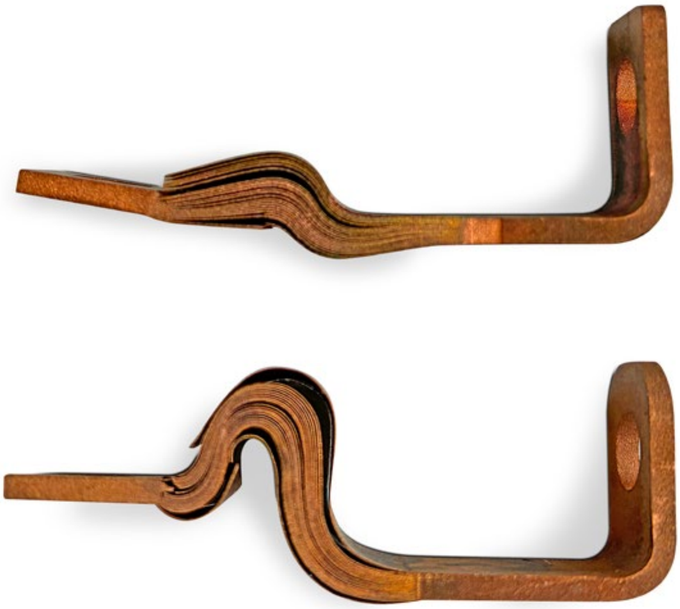
From resonance testing to damage detection //

The objective of the test is the objective detection of damage initiation during the resonance test. To this end, a switching criterion is defined.

CLEAR CRITERIA FOR THE ONSET OF DAMAGE

A relative frequency drop of 15 Hz indicated the occurrence of material failure, typically a crack in the outer lamellae. The test bench detected the event automatically.

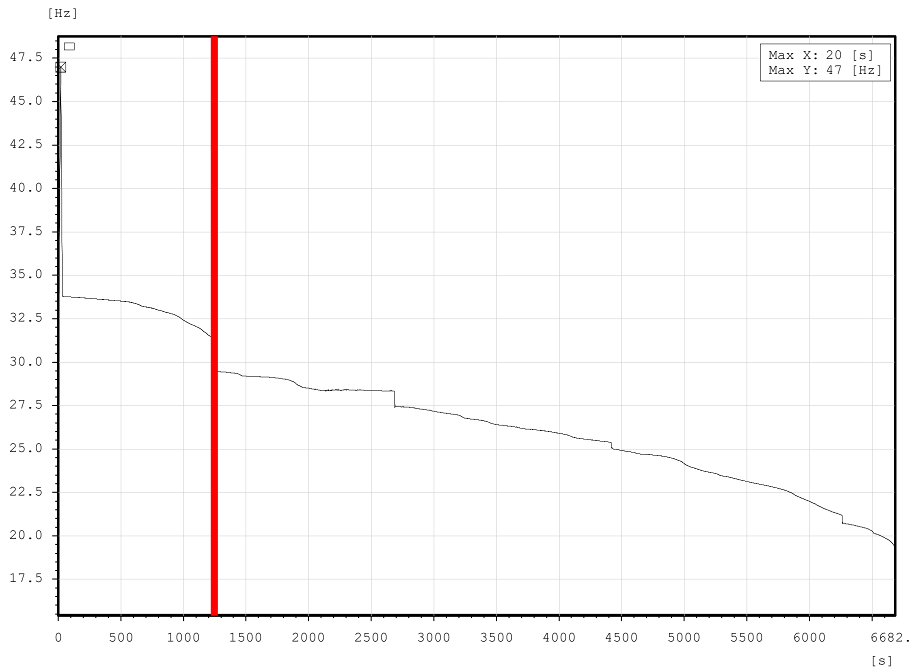
The non-destructive measurement of the LDV system provides repeatable data with high amplitude resolution. Even critical areas are accessible during the test due to the laser's free positioning capability.



4 Cracks in the lamellae

Large variation, clear findings //

A total of 13 specimens of both geometric variants were subjected to a complete resonance dwell test. For all test specimens, a crack or initial crack in the outer lamellae was documented as the damage pattern. The first lamella crack was reliably detected based on the first distinct drop in resonance frequency (Fig. 5).



5 A sudden and sharp drop in resonance frequency (red marker) indicates initial defects or cracking in the clamp structure

GEOMETRY ALONE DOES NOT DETERMINE SERVICE

The statistical analysis revealed significant differences in the variation of service life between the two clamp variants: The L-type design showed failure times ranging from 6,056 vibration cycles to 57,322 cycles. The S-type variant ranged from 902 cycles to over 113,772 cycles.

This underscores the need to include additional influencing factors such as material quality and production parameters in the evaluation. Measuring the natural frequency with the LDV proved to be the only reliable method, particularly for the fatigue-sensitive lamellae, since even slight weight loads from attaching accelerometers or sensor cabling would have significantly distorted the results.

Decreases in resonance frequency indicate critical crack formation even before the test specimen fails and a complete electrical failure occurs. For one test specimen, the precise time measurement via dwell tests allowed the time window between the first lamella crack and complete failure to be narrowed down and specifically utilized for FE model validation (finite element model validation).

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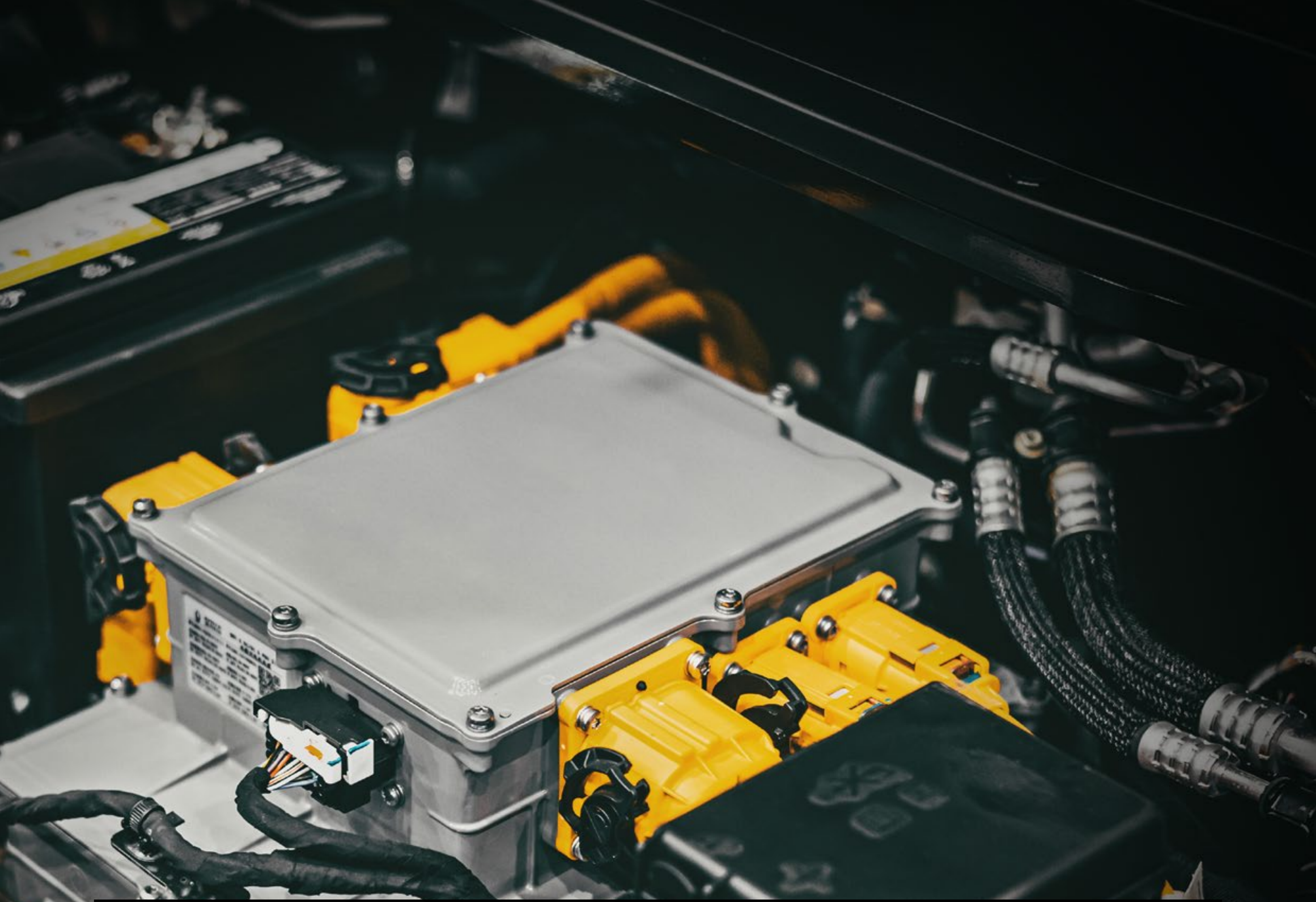
After each test, the ohmic resistance of the terminal was measured. A crack in a tab reduces the conductive cross-section, causing the resistance to rise. Under constant current load, this leads to increased local power dissipation and thus to accelerated thermal stress on the component. Regardless of this, a tab crack carries the risk of an electrical short circuit. This is because broken tab ends can mechanically detach from the composite and protrude. If such a fragment comes into contact with the motor housing or adjacent conductors, a direct electrical short circuit occurs, immediately putting the motor out of operation. Both types of damage were documented after each test through visual inspection of the fracture site and represent key evaluation criteria for the service life of AC connection terminals in the high-voltage range.

Reliable tests enable better designs //

The challenges of the test setup stem from the terminals' sensitivity to external masses and the poor reproducibility of the bonding of conventional sensors. The measurement results are distorted by the mass loading of the terminals and by the coupling of an accelerometer. These complicating factors are effectively countered by the use of an LDV. The measurements are comparable across different test specimens, which facilitates the exchange of test specimens and increases the scalability and comparability of the tests.

If unexpectedly high variations in the results occur during measurement, it must be checked whether additional structural factors, such as material homogeneity, geometry, or manufacturing stresses, are influencing the results.



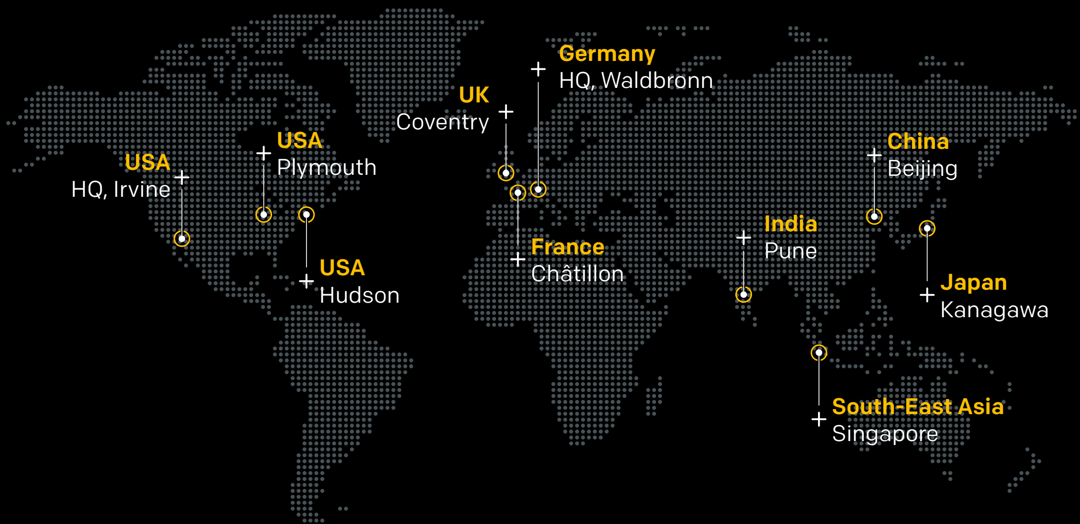
For safe and meaningful test operations, attention should be paid to the following parameters //

- Careful optical alignment of the LDV for maximum signal level
- Lock-in to the resonance point with automated tracking function for early detection of frequency drops
- Documentation and linking of electronic test bench data with visual inspection of the lamellae for cracks and delamination
- Regular calibration of the measurement systems according to DIN standards

Summary //

The methodology presented here enables the vibration behavior, failure risk, and service life of AC connection terminals to be evaluated in a practical manner under realistic load conditions. Measurements with the Polytec LDV system not only deliver reproducible and unbiased results but also offer a clear technical advantage over traditional sensors due to their non-contact measurement. This is particularly advantageous for lightweight structures and facilitates consistent measurement series.

For the optimization of material and geometry, as well as for troubleshooting when unexpectedly high variations in service life behavior occur, further analyses regarding material quality, dimensional accuracy, and manufacturing parameters are recommended. Experience from the application examples conducted shows: The consistent use of high-resolution, non-destructive measurement methods and structured analysis processes makes it possible to economically test reliable and durable connection components for high-voltage electric drives and to obtain data for improved design. Measurement service providers can offer valuable support in establishing these methods through their experience and contribute their expertise.



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