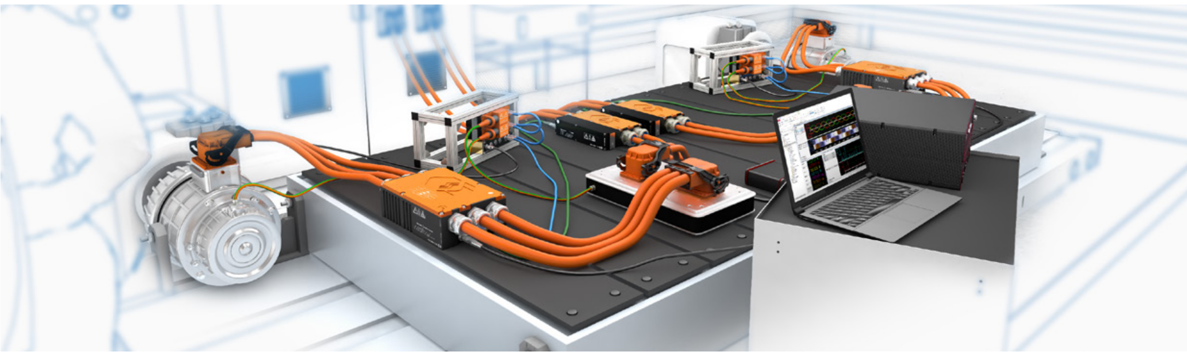
Power and Efficiency Analysis of an Electric Powertrain

HV Power Measurement

High performance cars and heavy duty trucks often utilize multiple electric motors. This architecture results in the power and performance tests on test benches to be particularly challenging. Even early in the development process the individual components and their interactions are tested with real-time simulations of actual driving maneuvers on test benches and the performance parameters are verified. For this purpose, the power and efficiencies of the components are analyzed in real time and the raw data is recorded.



Background

On the test bench, all relevant characteristic values of the powertrain components are verified by measurements using various individual tests. Fine-tuning of the power electronics and e-motors with performance analyses is carried out right at the start.

Functional tests, fatigue tests and durability tests then show whether all the selected system parameters are effective from the overall vehicle point of view. One example is to assure that compliance with limits of electrical current overloads is met to protect the high-voltage battery, since electric motors can quickly be turned up to very high power.

Special tests check the motor management of the Motor Control Unit (MCU) during rapid changes of acceleration, braking, regeneration and reactions during load jumps or full load curves.

The development and range targets are verified by recording the efficiency maps of the individual components as well as the entire powertrain. All thermal parameters are also measured to record the temperature dependencies that influence efficiency, or to determine if there is excessive heat generated as a result of electrical inefficiency.

Performance data and the integration of the powertrainin the overall vehicle are verified on dynamic vehicle and roller dynamometers using different, pre-defined driving cycles. The measurement technology (sensors, cables, DAQ measurement modules) must be installed in the vehicle, and ideally with the modules close to the measurement location. The entire measurement system must be able to operate independently with automatic data logging, as well as being integrated it into the automation of test benches.

Challenge

The goal of test bench measurement instrumentation is to have a unified system which can measure all physical parameters along with the simultaneous acquisition of ECU data. The measurement system must include multi-channel, synchronized, electrical and mechanical power analysis and also meet high-voltage safety requirements. The measurement results must be recorded in real time so that direct failure reactions and interdependencies of the components can be observed online at the control room or in the vehicle by the test engineer.

In addition, the raw data must be recorded so that more detailed analyses can be carried out later in the event of transient processes, failures, and detected anomalies. Then problems can be analyzed in detail, the causes can be identified, and design improvements implemented.

For electric vehicles, additional and special requirements are placed on the power analysis: Especially on the Alternating Current (AC) connections to the electric motors, the effective power of the individual motor windings must be determined in order to validate the wheel-specific control of the inverters. Classical measurement methods with star point adapters or Aron circuits are therefore not applicable.

The inverter efficiency must also be calculated in real time in order to verify the design of the power electronics. Even small changes in the efficiency curves indicate weaknesses. The same applies to the efficiency curves of the electric motors, which provide evidence of the design of the e-machine. At the same time, the temperatures inside both components must be measured in order to record the temperature dependence. Measurement modules must be placed as close as possible to the sensor to eliminate interferences that affects the data traveling on long sensor lines. The best scenario is to convert the sensor's analog data into digital data on the measurement bus as quickly as possible.

Measurement data must be acquired synchronously in real time to interpret correlations of events. In particular, current and voltage measurements must be phase synchronous to accurately calculate electrical power in real time. Phase offsets between current and voltage would otherwise have to be laboriously corrected for the subsequent power calculation. Typical time alignment of measurement data is not sufficient for this application. Precise synchronization is required for accurate results.

The fast connection of the instrumented test components to the measurement technology is desired in order to optimize the changeover to new development patterns and to minimize test bench downtimes.

The CSM Measurement Solution

For power analysis and efficiency measurement, CSM's **High-voltage Breakout Modules** (HV BM) are inserted directly into the high-voltage power cables (Fig. 1). One **HV BM 1.2** measures the Direct Current (DC) input power to the powertrain and is connected via EtherCAT® with one HV BM 3.3 as well as synchronized in time. Two **HV BM 3.3** synchronously measure the voltage and current on all 3 phases of AC power between the inverters and the pair of e-motors. The Breakout Modules measure currents and voltages up to ±2.000 V and ±1.400 A respectively. All of the voltage and current measurements are synchronized to better than 1 µ second.

A CSM counter module (**CNT4 evo**) acquires speed and torque at each of the motor shafts for mechanical performance analysis. Temperature measurements are performed with CSM's high voltage safe Minimodules **(HV TH)** using K-Type thermal modules within a special safety sensor cable. The CNT4 evo and HV THMM modules are integrated into the measurement chain via CAN-bus. The CAN-bus is connected to one of the HV BM 3.3 which also functions as a gateway for all connected EtherCAT® and CAN measurement modules' data to be converted into XCP-on-Ethernet for the DAQ software.

Both of the HV BM 3.3 send the measurement data directly via XCP-on-Ethernet to the measurement computer or the Vector Smart Logger. With the PTP option (Grandmaster Clock), the measurement modules are synchronized better than 1 µs (utilizing the PTP: Precision Time Protocol according to IEEE1588 standard) with the Vector Smart Logger.

On the Vector Smart Logger (**VP6400 or VP7400**), data is acquired and recorded in real time. The CANape log or vMeasure log software contains the eMobilityAnalyzer function library, which performs all power calculations in real time with the data acquisition.

The data from the embedded control units for the power electronics and e-motors are recorded via a Vector Interface VX1000. The measurement data from the **VX1000** and CSM measurement modules are synchronized with the Vector Smart Logger via PTP (again, per IEEE 1588).

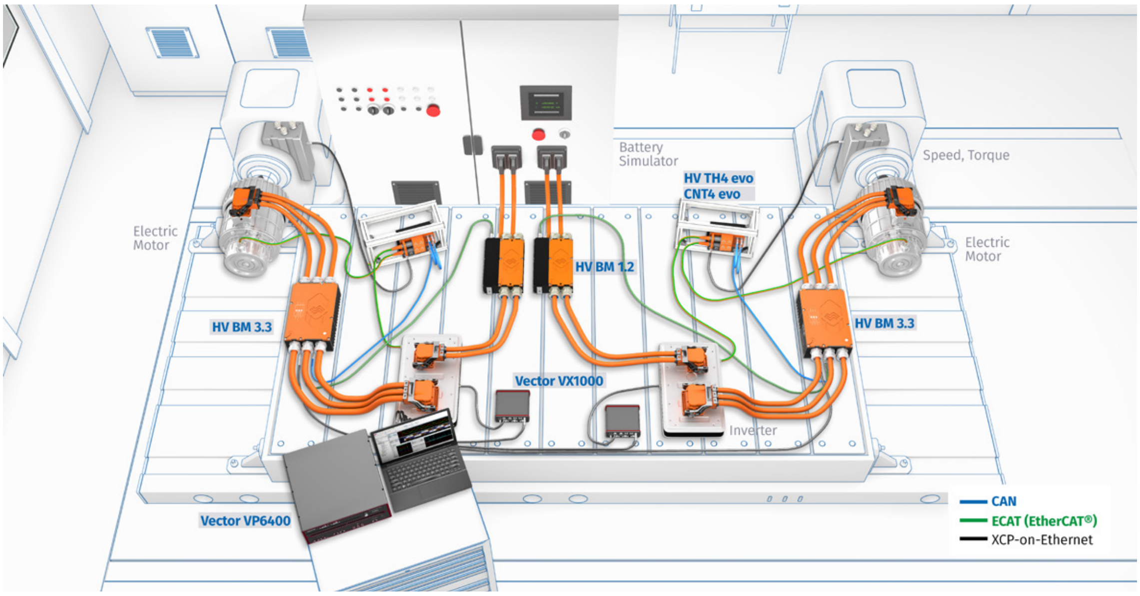


Fig. 1: Performance analysis with the Vector-CSM-E-Mobility Measurement System on an electric powertrain with two axle motors and simultaneous acquisition of ECU data. One counter module each acquires torques and speeds of the axle shafts and two temperature measurement modules each measure temperatures inside the motors and inverters. The measurement system is synchronized via PTP.

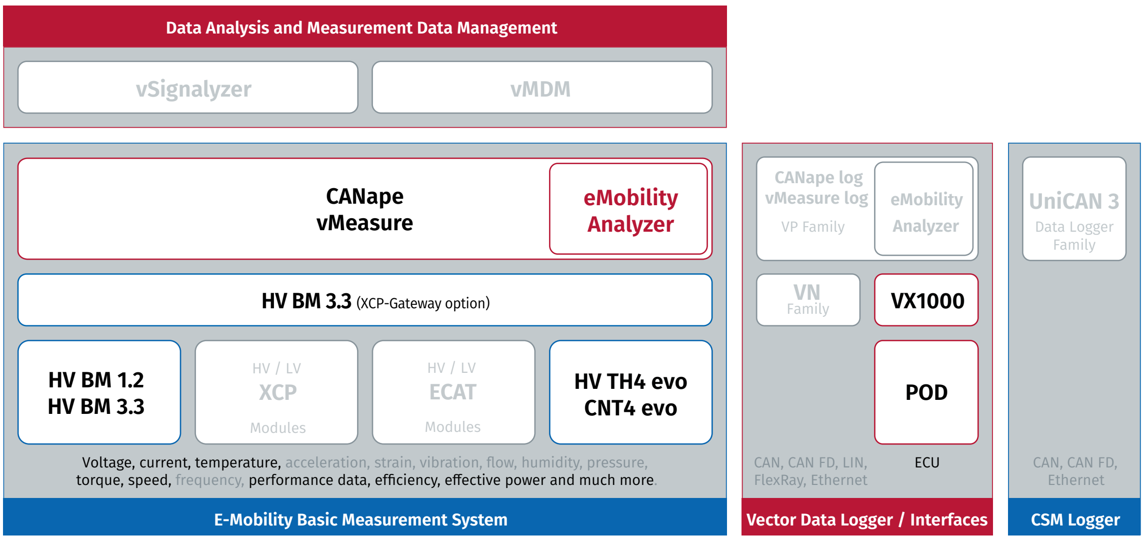


Fig. 2: The power and efficiency analysis of an electric powertrain in the systematics of the Vector CSM E-Mobility Measurement System

Vector eMobilityAnnalyzer

The eMobilityAnalyzer is a standard library of pre-defined functions available in the popular software packages CANape and vMeasure from Vector Infomatik.

The measurement configuration is easily done by selecting the desired function and the measurement channels to be used as the input to that function.

The individual functions calculate all parameters for an application:

E-motor power analysis
Inverter efficiency
Harmonic or harmonics E-motor
Mechanical power of the motor shaft
Mechanical axis performance parameters
Analysis of a DC signal
Ripple of a DC signal
Efficiency charging system
PWM power analysis
DC/DC converter efficiency

Tab. 1: Functional packages included in the eMobilityAnalyzer

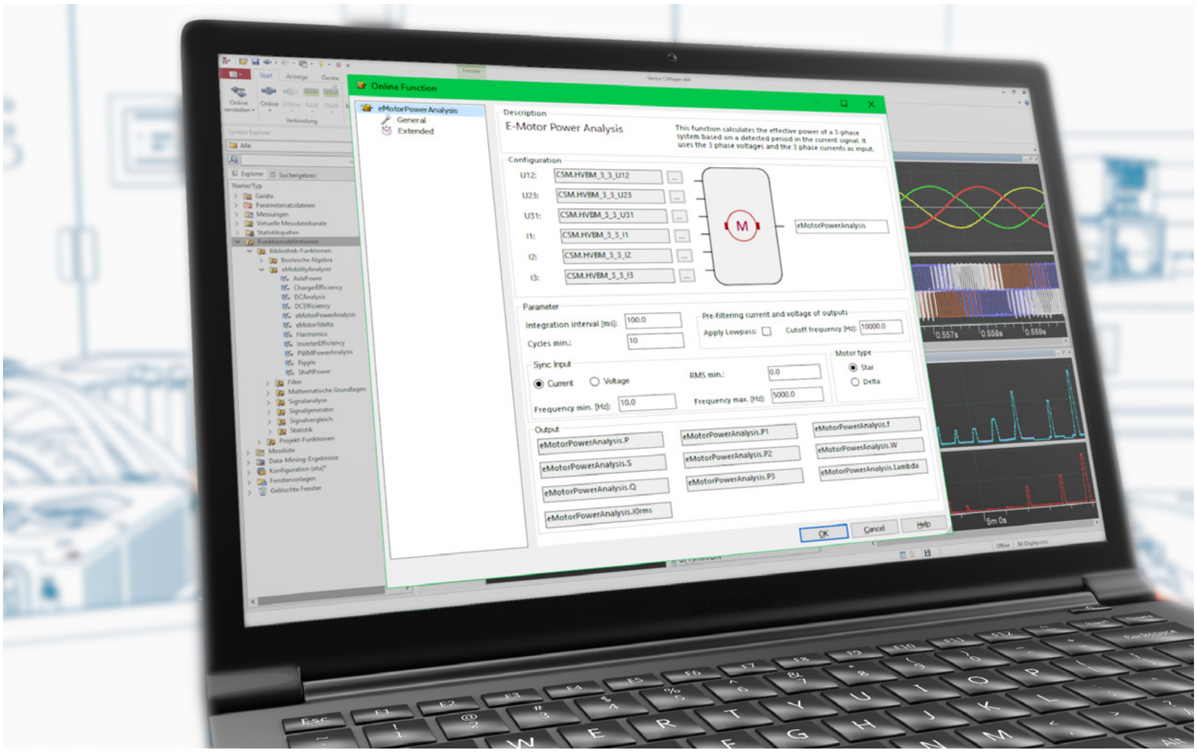


Fig. 3: eMotorPowerAnalysis configuration

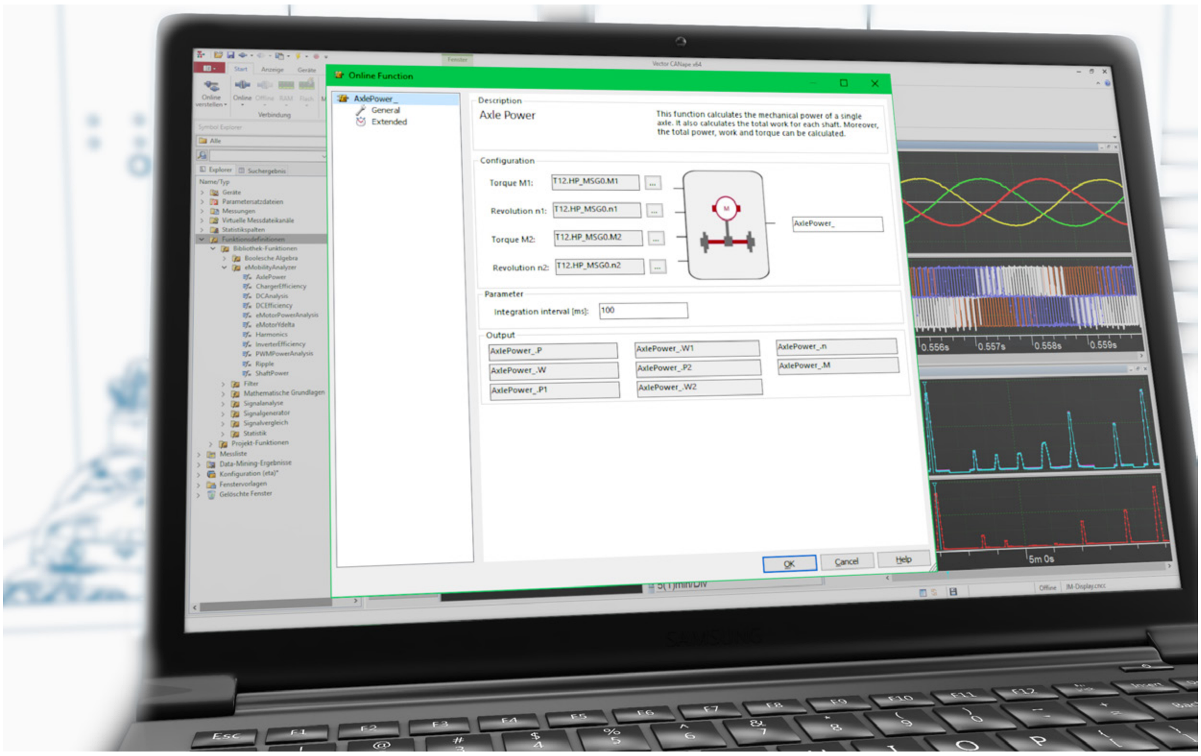


Fig. 4: Axle power configuration

Fig. 5: Performance analysis of a ten-minute test run on the test bench with CANape. The raw values of the phase-to-phase voltages and string currents are shown in the upper area. The electrical values calculated in the process, such as active, reactive and apparent power, and the calculated mechanical power are listed numerically at the bottom left. The three calculated effective values of the motor currents are shown at the bottom right.

Power measurement on the powertrain

In both of the HV BM 3.3 modules, the power measurement circuit is already applied. The phase currents (I1, I2, I3) are measured directly and the voltages between the phases (U12, U23, U31) are measured phase-synchronously. Sampling is performed at 2 MS/s in each case to assure that all spikes and fast transient ripples are not aliased. This assures that all relevant data is captured. The eMobilityAnalyzer calculates all e-motor power values such as active, apparent and reactive power, the power factor or the effective power of the motor windings in real time.

The eMobilityAnalyzer can perform power analyses simultaneously, allowing multiple motors to be analyzed in parallel. This gives test engineers the ability to closely examine traction control tuning.

In addition, DC power is measured via HV BM 1.2 modules at the inverter inputs.

With the high-speed data capture of both power into and out of the inverter, the eMobilityAnalyzer thus simultaneously calculates the inverter efficiency as well as the working efficiency of the e-motors. This allows the load spectrum of the inverter and e-motor to be examined in detail. For example the inverter efficiency in the various driving situations in the transition between acceleration, braking and recuperation, when the efficiency drops at low currents can be studied.

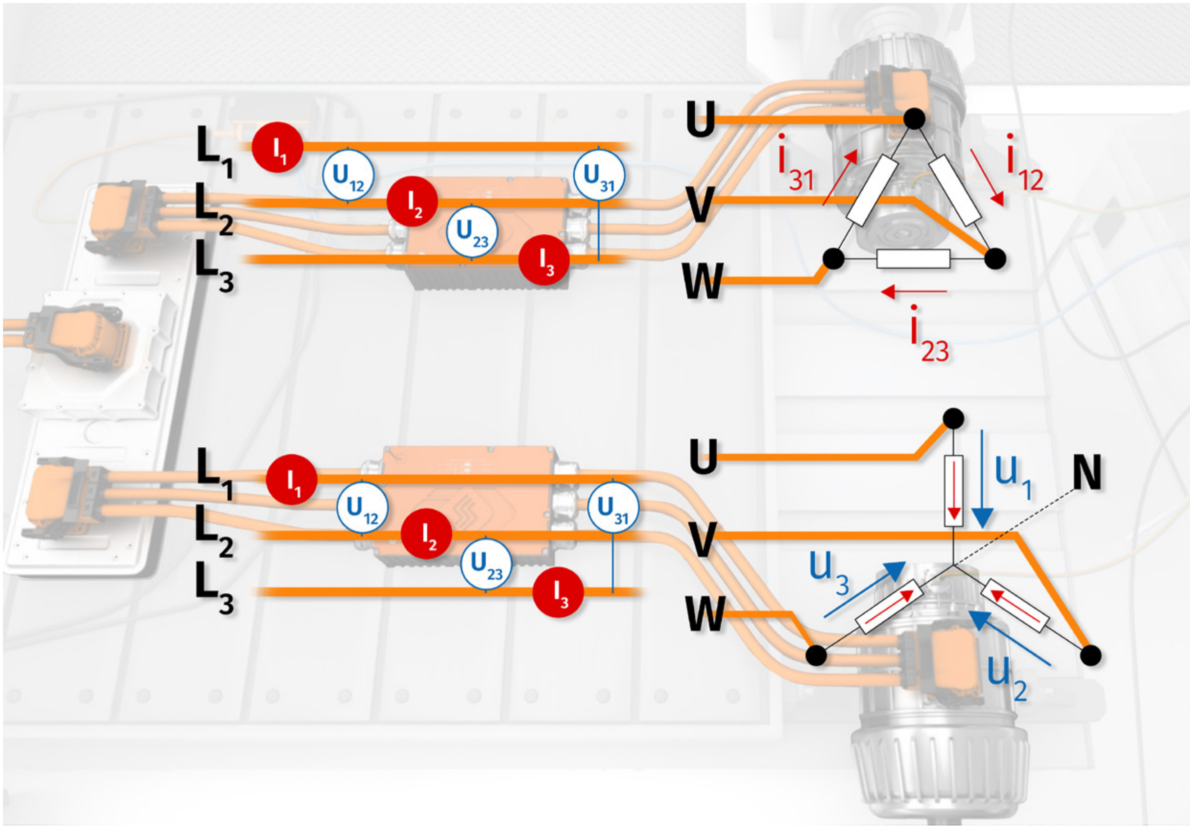


Fig. 6: Measurement circuit in the HV BM 3.3 for real-time power analysis with the Vector eMobilityAnalyzer. The star-triangle transformation is used to calculate the directly measurable conductor-to-conductor current strengths I12, I23, I31 and star voltages U1, U2 and U3.

Fig. 7: HV Breakout Module 3.3.: The measurement system can be extended with further measurement modules via an EtherCAT and CAN interface. Via a Gbit Ethernet interface the data are sent to the measuring computer. Via the cable glands (shielded) HV cables up to 95 mm2 are connected inside the housing.

E-motor power analysis

The 3-phase power measurement is carried out time-synchronously with the measurement circuit in the HV BM 3.3 (Fig 5).

The eMobilityAnalyzer calculates the winding currents via the star-delta transformation. The instantaneous values (samples) of the phase currents (I1, I2, I3) and phase voltages (U12, U23, U31) are converted to the delta currents (I12, I23, I31) and star voltages (U1, U2, U3). From this, the effective powers of the three motor windings and the total active power of the electric motor are determined. For the calculation of interval-related quantities, the eMobilityAnalyzer uses a sophisticated algorithm that calculates all power parameters.

This method of power calculation offers several advantages:

- The real conditions in the engine and all asymmetries can be seen at a glance.
- No artificial star point is required, which has nothing to do with the motor design.
- The test specimen is not loaded by an artificial star point.
- There are no sources of error, as in otherwise common measuring circuits, for example in the Aron circuit due to leakage currents.
- Wiring errors, which are usually common in the complicated power measurement circuits to a measurement rack, are excluded.

HV BM PowerLok plug-in system

The PowerLok connector system (from Amphenol) is provided for flexibility in the test bench and easy adaptation of test bench systems. This allows individual DUTs to be connected quickly and without errors on the test bench, for example replacing the universal inverter with the inverter intended for later use in the vehicle. Complete powertrain components can also be connected easily in this way: If another complex component such as a fuel cell drive, is to be integrated into the powertrain, both components can also be tested independently of each other when plugged together.

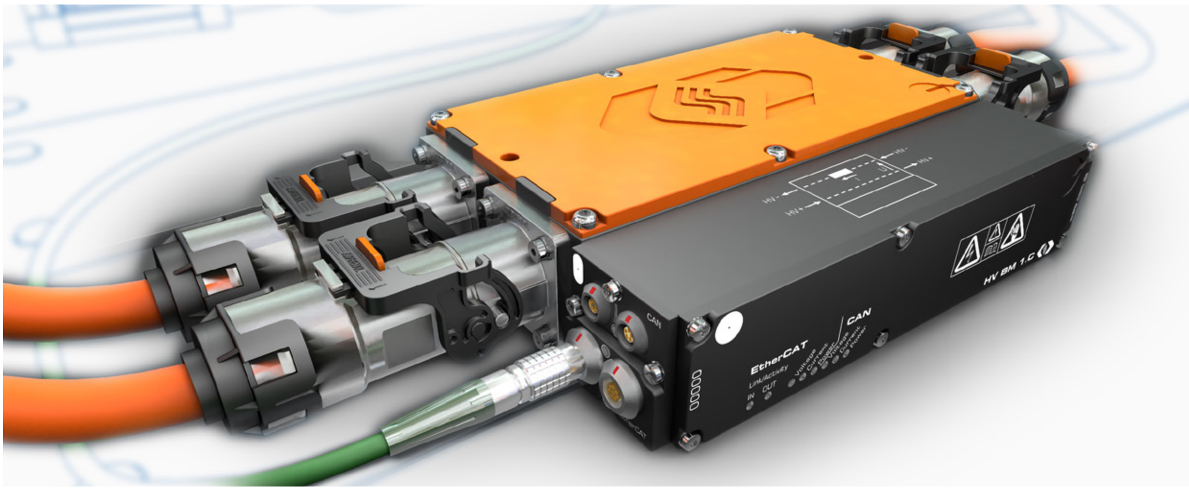


Fig. 8: The cables can also be easily connected to the HV Breakout Modules via PL plug-in systems. This simplifies instrumentation when the components to be tested change.

Benefits

With the distributed design of the measurement modules, any test bench can be easily instrumented with measurement technology. Direct measurement in the high-voltage lines and directly at the sensors ensures interference-free acquisition of the measurement data. The measurement chain is short at all measurement points and the A/D conversion takes place in the interference-proof encapsulated module housing at the measuring point.

Due to the power measurement being done directly in the HV DC and AC inner conductor of the cable, the measurement setup can be instrumented consistently in both the test benches and the test vehicles. Measurements in component and powertrain test benches are identical to those in test vehicles on vehicle, and chassis dynamometers provide a consistent measurement toolchain throughout the development process

Multi-channel power analysis is easy and time-saving to install in powertrains even with multiple electric motors, for example in all-wheel drive or utility vehicles.

The measurement circuit for electrical power measurement is already laid out in the HV BM 3.3. Complex wiring between current sensors and power analyzers installed in measurement racks is no longer necessary, and the installation time of the measurement system is significantly reduced. Sources of error in the wiring of the measurement circuit are eliminated. Long sensor cables from typical current transformers to the power meter, which are susceptible to interference, no longer exist. Phase correction for power measurement is now eliminated.

Integration of the Vector CSM E-Mobility Measurement System into test bench automation is also easy thanks to modern and standard bus systems and protocols (CAN, EtherCAT®, and XCP).

Electrical power measurements, mechanical power measurements, efficiency measurements and temperature measurements are performed with a single, scalable measurement system. They can be used to perform temperature-accurate power and efficiency analyses at operating points. Examples are the effect of the cooling jacket of the electric motors, the heat dissipation of the power electronics or the temperature dependence of magnetic flux and torque accuracy of the motors.

In the case of multi-motor electric drive trains, measurement data of 100 Mbytes per second and more can easily accumulate, which are recorded with the high-performance smart loggers from Vector Informatik. The data from the measurement technology and the control units are recorded synchronously in time.

Featured Products

HV Breakout Module - Type 1.2

CSM's HV Breakout Module (BM) Type 1.2 was designed for single-phase measurements of current, voltage and power. It is ideal for measurement on large consumers such as electric motors equipped with separate HV+ and HV- cables.

The HV Breakout Module 1.2 is available in two versions for connection via cable glands or PL500 plug-in system (HV BM 1.2C).

HV Breakout Module - Type 3.3

The HV Breakout Module (BM) 3.3 has been specially designed for safe and precise three-phase measurement in HV cables. The inner conductor currents and outer conductor voltages are directly acquired and output 100% synchronously and phase-accurately via XCP-on-Ethernet.

The connection is made either via cable glands through which the HV cables are led into the module (HV BM 3.3) or via a PL300 plug-in system (HV BM 3.3C).

HV TH4 evo

CSM's HV TH4 evo measurement module allows safe temperature measurements with thermocouples on high-voltage components. Thanks to its compact design and reinforced insulation up to 1,000 V RMS, it is particularly suitable for decentralised use in road tests.

CNT4 evo

CSM's CNT4 evo is a high-precision measurement module for measuring frequencies up to 300 kHz, for determining duty cycles or PWM signals, for determining period and pulse duration as well as up and down counting. Speeds can be recorded directly in the module and output as a value on the CAN bus. In addition, the time offset between adjacent channels can be measured.

Complete solutions from a single source:

CSM provides you with comprehensive complete packages consisting of measurement modules, sensors, connecting cables and software - customized to your individual needs.

Further information on our products are available on our website at www.csm.de or via e-mail sales@csm.de.

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