GOSSEN METRAWATT

TESTING HYBRID AND ELECTRIC VEHICLES

SAFETY AND FUNCTIONS DIAGNOSIS FOR VEHICLES WITH ELECTRIC OR SEMI-ELECTRIC DRIVES

HIGH-VOLTAGE TECHNOLOGY IN ELECTRIC VEHICLES

Today's high-voltage systems in hybrid and electric vehicles (passenger cars) are supplied by energy storage units with up to 500 V. Voltage levels are expected to increase by a factor of roughly two in the future.
Commercial vehicles are already using technologies with operating voltages of up to 1000 V. However, only voltage values of less than 60 V DC and 30 V AC are considered safe where electrical hazards to human health and life are concerned. Due to the fact that voltages occurring in electric vehicle systems are far above these safety limits, extensive hazard analyses have been conducted in recent years. Amongst other things, the EU has issued directives which are binding for the manufacturers, who in turn have prepared operating and work instructions in order to eliminate, to the greatest possible extent, hazards due to electrical energy during use, as well as during production, development, maintenance and repair. Occupational health and safety guidelines stipulate an acceptable residual risk, roughly comparable to the risk associated with using an intact household appliance.

DANGERS FOR USERS AND INSPECTORS

The hazards involved with the use of electrical equipment and systems always result from dangers associated with the flow of electric current through the body, electric arcs, electromagnetic interference and static electrical charges. Other potential, but nevertheless avoidable hazards can be caused by improperly executed electrical work performed on the vehicle by inadequately qualified personnel, as well as technical defects in the vehicle.

According to the VDE (German Association for Electrical, Electronic & Information Technologies), an alternating voltage of 50 V or a direct voltage of 120 V is already deemed a life threatening touch voltage for healthy adults. Technical rules for safety during operation of electrical systems, published by the German Federal Office for Occupational Safety and Health (BAUA), specify maximum values of 25 V AC and 60 V DC.

The IUE (German institute for the examination of electrical accidents) has determined that roughly 40% of all electrical accidents involving up to 1000 V occur during troubleshooting and repair work.

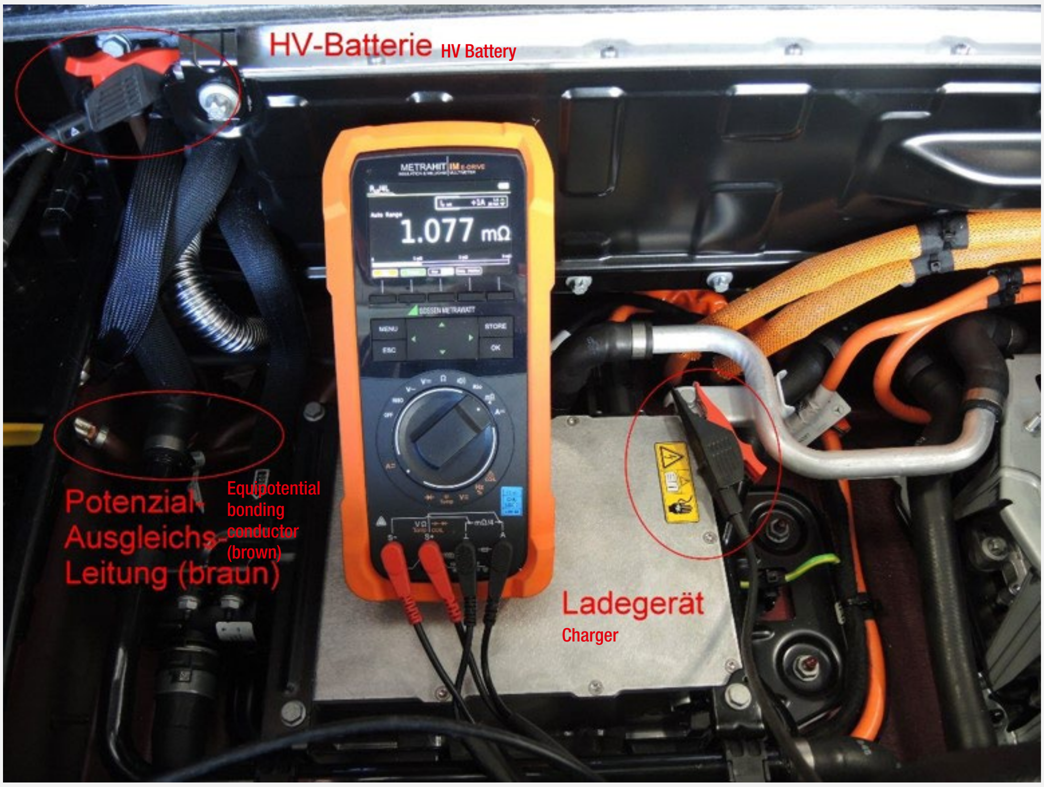


Figure 1: High-Voltage Components Identified in Orange

ELECTRICAL HAZARDS DUE TO HIGH-VOLTAGE SYSTEMS IN MOTOR VEHICLES

A certain amount of residual risk remains for personnel who work on hybrid and electric vehicles in research, development, production and service. Although extremely high levels of intrinsic vehicle safety are required by the legal guidelines and are achieved by means of technical design measures implemented by the vehicle manufacturers, this residual risk cannot be entirely eliminated, even with all due care (above-mentioned example of household appliances).

Touching high-voltage components which are energized due to an internal fault can conceivably cause current to flow through the human body. Even in the case of direct current as of roughly 30 to 50 mA, the respiratory musculature may be subject to contraction if contact is made in proximity to the ribcage, resulting in respiratory standstill for a long as current flows. Alternating current at 50 Hz can cause ventricular fibrillation or even cardiac arrest with a current of only 10 mA and an exposure time of greater than 2 seconds.

Which electrical hazards need to be taken into consideration where hybrid and electric vehicles are concerned?

- ➔ Arcing which can lead to burns and even death
- ➔ Residual voltages or uninsulated cables
- ➔ Insulation faults which result in uncontrolled fault currents

VEHICLE TYPES

Differentiation is made amongst battery electric vehicles (BEVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs).

Strictly electric vehicles use only electrical energy for drive power. The required energy is either stored within the vehicle, for example in a rechargeable battery, or fed from an external source as needed, for example with the help of an overhead contact line or contact rail, or by means of induction. Less frequently, electrical energy is also generated on board the electric vehicle.

Hybrid vehicles are equipped with two different drive systems, each with its own energy storage system. As a rule, this involves an electric drive (electric motor with high-voltage battery) in addition to the conventional drive system (internal combustion engine with associated fuel tank). Differentiation is made amongst plug-in, mild and micro hybrid vehicles.

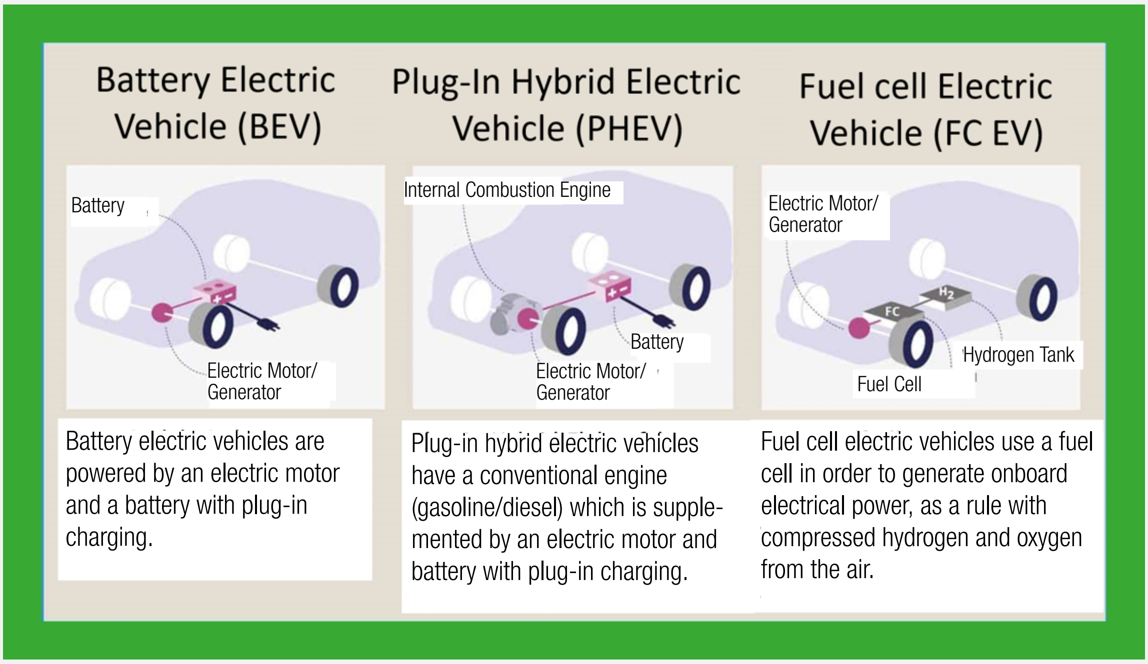


Figure 2: Types of Electric Vehicles

HIGH-VOLTAGE BATTERY AND MAINTENANCE/SERVICE PLUG AS MEANS OF SAFETY

Maintenance/service plugs (see figure 3) are/were used in various high-voltage systems. They function as a main fuse and a master switch such as those found in industrial electrical installations.

The circuit is interrupted between the high-voltage battery's modules, thus de-energizing the entire high-voltage system. Their layout is always similar regardless of manufacturer.

Service switches (see figure 4), jointly developed by several OEMs, are now being used to an ever greater extent. Manufactured under license, they're purchased and used by other OEMs. The disconnectors interrupt control current to the contactors in the high-voltage battery, so that no voltage is applied to the external battery terminals.

Figure 3: Source: DGUV I 200-005, previously BGI/GUV-I 8686

High-Voltage Cable Strand / High-Voltage Cable Harness

High-voltage cables and lines in the high-voltage cable harness must be identified with orange sheathing (see figure 5). One positive and one negative lead connect the battery's poles to the high-voltage components.

Figure 4: Archive IB-HJ

Converter

The converter (also commonly called an inverter) transforms 3-phase current from the output of the high-voltage generator into direct current during deceleration (high-voltage battery charging), and into 3-phase alternating current (usually pulsating direct current) when the electric motor is being used for propulsion.

High-voltage components must be identified with special safety labels.

Figure 5: Archive IB-HJ

Figure 7: Archive IB-HJ

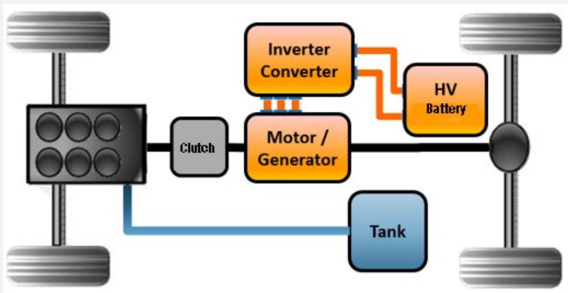
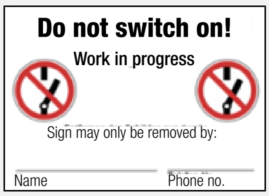


Figure 6: Schematic Design of a P2 Parallel Hybrid Vehicle (source: archive IB-HJ)

FIVE SAFETY RULES FOR WORKING ON HIGH-VOLTAGE SYSTEMS IN VEHICLES

1) De-energize

- ➔ Ignition off
- ➔ Pull the service disconnect plug
- ➔ Remove the fuse



2) Secure against restart.

- ➔ Remove the ignition key and store in a secure location
- ➔ Disconnect the service/maintenance plug or remove the master battery switch and keep it in a safe place. Secure both against reactivation.
- ➔ If necessary, replace the service disconnect switch with a dummy plug.

3) Verify absence of voltage with a 2-pole voltage tester (in accordance with DIN EN 61243-3).

Observe the procedure specified by the manufacturer! This is important because residual charges may still be present in the high-voltage components even after the high-voltage battery has been electrically disconnected.

The system must be considered live until absence of voltage has been substantiated.

Figure 8: Checking for Absence of Voltage with a Voltage Tester

4) Ground and short circuit

Exception: If rules 1 through 3 have been reliably complied with, rules 4 and 5 can be omitted for electrical systems with nominal voltages of less than 1000 V AC or 1500 V DC.

5) Cover neighboring live components, or make them inaccessible.

As opposed to reports to the contrary which can occasionally be found in the literature, this is also indispensable when working on high-voltage-systems in vehicles because:

- ➔ Under certain circumstances, the intrinsic safety of an early prototype vehicle may not yet be assured.
- ➔ The high-voltage system may be in an unknown state in the case of a vehicle which has been involved in an accident.

Example of possible safety precautions issued by an automobile manufacturer for working on high-voltage systems:

- ➔ Ignition off
- ➔ Disconnect the 12 V battery's minus pole.
- ➔ Inspect high-voltage safety gloves and put them on.
- ➔ Open maintenance switch / remove the maintenance plug and keep it in a safe place.
- ➔ Wait for 5 minutes until capacitance in the inverters/converters has been discharged
- ➔ Verify the absence of voltage at the HV connection (use the manufacturer's test adapter if necessary).
- ➔ Always isolate the pulled HV plug

PERSONAL SAFETY EQUIPMENT

Personal safety equipment consists of the following items:

- ➔ Suitable tools for working on live components
- ➔ Safety gloves, helmet with face shield (visor), arc flash protective clothing
- ➔ Voltage tester in accordance with EN 61243-3 (DIN VDE 0682-401)
- ➔ Safe test equipment and measuring instrument with adequate accessories

Note:
Only electricians with special training are permitted to work with live voltages of greater than 25 V AC / 60 V DC!

RESPONSIBILITY

The fact must always be taken into consideration that business enterprises and operating companies are liable for the safety of their employees during product manufacturing, and are also responsible for the safety of the buyer (user) of a product when it's being correctly used. These two areas of responsibility are known as work safety and product safety. Within the framework of product safety, we also speak of operational safety. In some respects, the rules for assuring operational safety coincide with work safety rules targeted at accident prevention. However, the difference lies in the fact that accident prevention rules are of a legal nature.

The operating company is responsible for accident prevention at its facility. In particular, it's required to assure that electrical systems and operating equipment are only set up, modified and/or maintained by qualified electricians or under their supervision.

Certain entrepreneurial obligations can be assigned to authorized personnel in the spirit of TRBS 1203. This is only possible by means of written assignment of responsibility in accordance with paragraph 13.2 of German occupational safety legislation (ArbSchG) and paragraph 9.2 of the German regulatory offences act (OwiG).

The operating company and the person to whom responsibility has been delegated must ensure that work on high-voltage systems in vehicles is only carried out by persons qualified to do so. The required qualifications depend on the degree of electrical danger associated with the respective work. In this respect, German statutory accident insurance (trade association), which functions in this case as, amongst other things, the normative institution, specifies the following in bulletin DGUV-I 200-0052 (previously BGI / GUV-I 8686) as a supplement to general accident prevention regulation DGUV regulation 1 and specific accident prevention regulation DGUV regulation 3 for the handling of electrical systems and equipment:

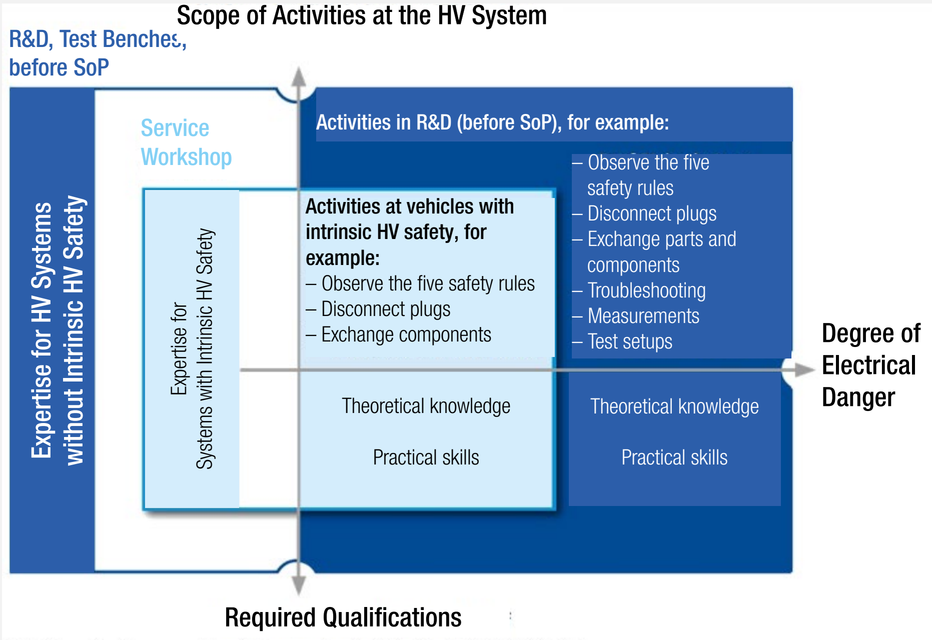


Figure 9: Qualification Requirements Diagram (source: DGUV I 200-005)

3-STAGE QUALIFICATION FOR WORKING ON HIGH-VOLTAGE SYSTEMS

Stage 1 – non-electrical work:
(Requirement: properly instructed person, EuP1.) Safe operation of HV components. Knowledge of the design, mode of operation and identification of HV components, but no execution of technical electrical work on these components.

Stage 2 – work in the absence of voltage:
(Requirement: person qualified to work on high-voltage systems in the de-energized state, FHV).

Stage 3 – work on live components:
(Requirement: person qualified to work on high-voltage systems in the energized state). Taking stage 2 one step further, theoretical and practical knowledge is required for working on live components.

SAFETY REGULATIONS AND TEST DIRECTIVES

The International Organization for Standardization (ISO) develops international standards in all areas except electrical and electronics engineering, for which the International Electrotechnical Commission (IEC) is responsible, with the exception of telecommunications which is the responsibility of the International Telecommunication Union (ITU). All three organizations comprise the World Standards Cooperation (WSC).

ISO TC22 (technical committee) SC21 is involved with the standardization of electric vehicles in general, and IEC TC69 with the associated electrical components in particular.

UN Economic Commission for Europe (UN-ECE). ECE regulations are a collection of internationally agreed upon, uniform technical regulations for vehicles, as well as components and equipment included in motor vehicles. As of 1997, non-European countries are also able to adopt this agreement. ECE regulations are decisive with regard to the approval of vehicles and components.

UNECE R100 – regulation no. 100 of the United Nations Economic Commission for Europe: uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train, first version dated 23 August 1996, last series (02) of amendments dated 15 July 2013, most recently [2015/505]. This regulation defines safety requirements for electric vehicles with electric propulsion during operation and decoupled from any charging device, and is decisive for the testing of high-voltage safety.

ECE R100 is the valid regulation for type testing of vehicles with high-voltage systems in Europe and other countries who have adopted this regulation (all non-European successor states of the Soviet Union, the USA, Canada and Israel). To some extent, the safety requirements specified in IEC standards go above and beyond those of ECE R100, in which not all high-voltage safety concerns are addressed. For this reason, manufacturers should in any case take the IEC standards into account as well.

ELECTRICAL SAFETY REQUIREMENTS IN ACCORDANCE WITH UNECE R100

1) All active components in the passenger compartment and the trunk must fulfill protection category IPXXD, and in all other areas IPXXB.

2) All exposed, conductive parts – such as the conductive barrier and the conductive housing – must be reliably grounded in order to assure protection against electrical shock due to indirect contact, so that no dangerous potential can occur. In this respect, the accident prevention regulations and UNECE R100 both stipulate a maximum resistance between any two touchable, conductive parts of less than 100 mΩ at 0.2 A.

3) Identification of high-voltage components with the high-voltage symbol

4) Cables for high-voltage busbars must be equipped with an orange outer jacket.

5) Relative to operating voltage, the following requirements apply to insulation resistance of the electric power train's busbars to ground:
   - $>$ 100 Ω / V for the DC busbar, if it's electrically isolated from the AC busbar
   - $>$ 100 Ω / V for the AC busbar if it's protected by:
     - a) Two or more layers of solid insulation, isolating barriers or housing

b) Mechanically rugged protection devices with appropriate durability for the duration of the service life, e.g. motor housing

> 500 Ω / V for the AC busbar and any DC busbar connected to it

SUITABLE MEASURING METHODS AND INSTRUMENTS FOR TESTING FOR COMPLIANCE WITH SAFETY REQUIREMENTS IN ACCORDANCE WITH UNECE R100

Checking the Resistance of the Ground Connection – Requirement: < 100 mΩ at 0.2A

At 0.2 A, ground connection resistance must be less than 100 mΩ. And thus a measuring instrument must be used for the resistance measurement which generates a measuring current of at least 0.2 A, and is also capable of measuring resistance in the milliohm range.

The accident prevention regulations and UNECE R100 specify a measuring current of at least 0.2 A. Due to the fact that resistance increases along with amperage, vehicle manufacturers also specify testing with higher current values, for example 1 A.

Adequately precise measurement of small resistance values is not possible with the common 2-wire measuring method. This method measures the voltage drop of a known current source I over resistance to be measured Rt. Resistance is then calculated using Ohm's law: R = U / I. However, voltage is not measured over resistance Rt, but rather over the sum of resistances or at the current source, namely over Rt + Rcbl where Rcbl = Σ (cables, screw or plug connector).

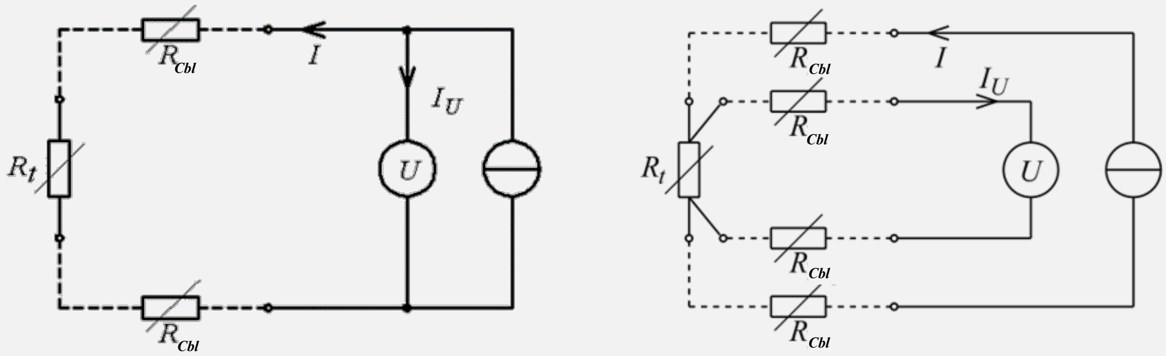


Figure 10: 2 and 4-Wire Measurement

4-wire measurement, also known as Kelvin measurement, is a suitable measuring method. In this case, measuring current is applied to the device under test with two wires, and voltage drop is measured with two separate wires directly at the device under test.

Relative to measuring current I, current IU, flowing though the voltmeter with high resistance, is negligible. Voltage drop over the measurement cables is also negligible as opposed to voltage drop over the device under test. Furthermore, current source I is independent of Rt. And thus only voltage over resistance Rt is measured. Resistance is then calculated as Rt = U / I.

PROCEDURE FOR MEASURING INSULATION RESISTANCE

Protection against direct contact while working on the high-voltage system during operation of the EV is assured by means of adequate resistance of the insulation used on active components (high-voltage cable and high-voltage plug connector if applicable). Beyond this, an integrated insulation monitoring device monitors the high-voltage system during operation. This is intended to detect any fault currents and prevent possible hazards for the user.

Insulation resistance must be measured or determined by means of calculation. Measured values for each part or section of any given high-voltage busbar must be used for calculation; this is designated "separate measurement".

1) Measuring method with direct current from external sources:

A measuring instrument is used to which a direct voltage can be applied, which is higher than the busbar's operating voltage. Measurement is performed between active components and ground with at least 50% operating voltage. These measuring instruments are known as insulation resistance measuring or test instruments.

2) Measuring method with direct current from the vehicle's battery:

A voltmeter with Ri ≥ 10 MΩ is used for this measurement.

First of all, voltage is measured at the battery outlet (Vb), as well as the plus and minus poles of the HV busbar (V1 and V2 respectively). If V1 ≥ V2, a known reference resistance is connected between HV minus and ground, and V1' is measured.

Internal resistance is calculated as follows.

Ri = Ro * (Vb/V1' – Vb/V1) or Ri = Ro * Vb * (1/V1' – 1/V1)

Insulation resistance is then calculated as follows: Rins = Ri/Vb

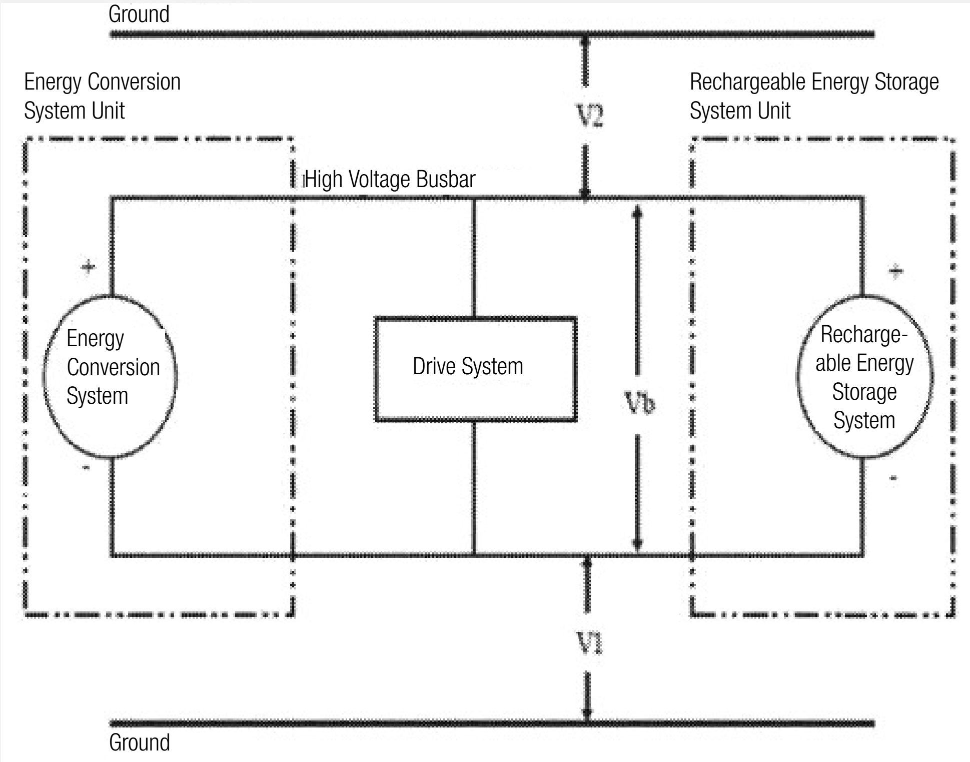


Figure 11: Measuring Method with Direct Current From the Vehicle's Battery

If V2 > V1, measurement and calculation are analogous but with the reference resistance between HV plus and ground: Ri = Ro * Vb * (1/V2' – 1/V2)

The second measuring method doesn't require any external voltage source, but several measurements, a determination regarding which case has occurred and calculation are necessary. Consequently, it's not very practical for use in the field and it's more of a makeshift solution in the event that no measuring instrument with its own voltage source is available for measuring insulation resistance.

THE METRAHIT IM E-DRIVE ALL-IN-ONE INSTRUMENT

An example of a suitable measuring instrument is the METRAHIT IM E-Drive from Gossen Metrawatt. It unites four instruments into one: a multimeter, a milliohmmeter for testing the ground connection, an insulation tester for measuring insulation resistance and an inter-turn short circuit tester with an additional COIL Adapter XTRA.
The milliohm measurement can be performed with the minimum requirement of 200 mA as specified by UNECE R100, as well as with a considerably higher measuring current of 1 A, thus increasing measurement reliability. Thermovoltages which occur as a result of material and temperature differences at the connections may influence measurement results. It's equipped with automatic thermovoltage compensation for the relevant measuring ranges.
4-wire or Kelvin measurement with the METRAHIT H+E CAR is performed by means of measurement cables with alligator clips or probes with spring-loaded test tips, which allow reliable contacting even through non-conducting surfaces. Insulation resistance measurement is conducted with the help of a mega-ohm function using selectable test voltages of 50, 100, 250, 500 and 1000 V. Any interference voltages are automatically detected and displayed. Measurement is conveniently started and stopped with a START/STOP key on the test probe. The additional STORE key on the test probe is used to store individual measured values (very user-friendly).

Figure 12: Testing Insulation Resistance with a 500 V Test Voltage Between Inverter and Ground with a Measuring Adapter on the Rosenberger Plug using the Mercedes GLC 350 e as an Example

Insulation aging status can be checked with the help of the polarization index (PI) and the dielectric absorption rate (DAR). Beyond this, the **METRAHIT IM E-DRIVE** also includes multimeter functions for the measurement of voltage, current, resistance, capacitance, continuity, diodes, frequency, rotational speed and duty cycle, as well as temperature measurement with TC or PT100/1000 sensors. Current and voltage are measured for AC, CD and AC+DC with bandwidths of 10 and 100 kHz TRMS, respectively.
Individual measured values are stored quickly and reliably to the instrument by pressing the **STORE** key, or automatically by means of the DATA Hold function. The measured values are transmitted live or measurement data memory is read out via the integrated Bluetooth port. Windows IZYTRONIQ software and the METRALOG app are available for storage, visualization and further processing of measurement data, as well as for the generation of test reports.
The instrument is mains-independent and mobile thanks to the unique quick-change battery with a lithium polymer cell, and can thus be used at any location. The battery is charged externally with the included 2 A USB plug-in power pack or any other standard USB power pack. The option of operating the instrument with a mains module instead of the battery pack permits continuous operation. Gossen Metrawatt has always placed great importance on safety for users and the instrument itself. The instrument complies with measuring category CAT IV 600 V / CAT III 1000 V in accordance with IEC 61010. Overload protection for up to 600 V and a high-quality fuse for the milliohm measuring ranges protect the instrument and the user.

INTER-TURN SHORT CIRCUIT TESTING

Problems occurring in electric machines, regardless of whether motors or generators are involved, may result from electrical or mechanical causes. Electrical causes include faults in the windings, in the controller or in the electronics. The insulation resistance measurement detects insulation faults between the windings and to the housing. Inter-turn short circuits are readily detected within the coil by comparing the electrical characteristics of the windings in multi-phase motors with each other. The METRAHIT IM E-DRIVE with the optional COIL Adapter XTRA conducts testing with a 1 kV surge voltage (surge test). In this way, defects are detected which only occur when operating voltage is applied.

Figure 13: METRAHIT IM E-DRIVE with Accessories

Figure 14: METRAHIT IM XTRA with COIL Adapter XTRA

The rubber holster included with the **IM E-DRIVE** and its rugged hard case are orange, like the insulation of the high-voltage cabling in the vehicle. The case accommodates the instrument and all included accessories:
a probe, one each Kelvin clip and probe, a pair of measurement cables, a rechargeable battery and a plug-in power pack with USB charging cable. The case also has practical storage compartments for optional accessories such as an additional battery or power pack.

The **METRAHIT IM E-DRIVE** is equipped with an integrated Bluetooth port for connection to data processing systems. Future plans include the addition of a WiFi port and a network module with USB data interface. Selected customers will also be provided with the interface protocol for integration into proprietary applications and systems.

The instrument's scope of delivery also includes **IZYTRONIQ** database software with a license for the Business Starter version. The software makes it possible to manage equipment, machines, systems and medical devices in combination with locations using a double tree structure, as well as inspectors, test instruments, catalogs and sequences.
Data exchange with test/measuring instruments is bidirectional. Transmission of measured values from the instrument to the software via Bluetooth is also supported by means of the push-print function. The report editor can be used to individualize test report templates, save reports as Word and PDF files, insert a company logo and signatures and freely edit reports with Microsoft Word.

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GMC INSTRUMENTS

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