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Safety of electric vehicle high voltage systems

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Summary

Safety of high voltage batteries along with their chargers extends beyond battery cell safety. Failures in these high voltage ungrounded systems can expose users to hazardous effects if not diagnosed and remedied timely. In this presentation we will discuss sources of isolation and capacitive faults and the methods for actively monitoring them for functional safety. We'll compare monitoring methods for coverage and efficiency and we'll discuss the new safety challenges moving into higher voltage systems.

Keywords: safety, insulation monitoring, ground fault, IMD (insulation monitoring device), standards

1 Hazards in the ungrounded power system

Ungrounded, unerthead, floating or IT (isolated terra) are all terms used to describe power systems that have no intentional conductive connection to earth's or chassis ground. The main advantage of the IT power system is that a single "short" will not disable its ability to continue delivering power. Fig. 1 illustrates the basic topology of such a system.

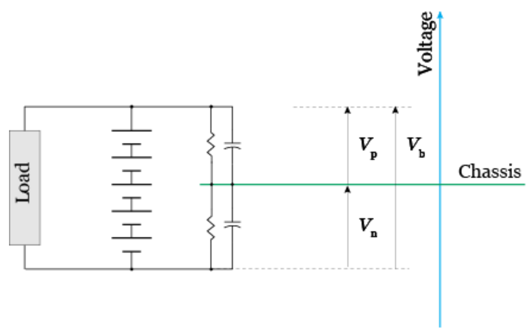


Figure1: IT power system topology

Resistances and capacitances shown represent the parallel combination of all elements present in the system. In a fault-free and balanced system the voltages V_p and V_n , between each power rail and the chassis, will be equal.

1.1 Isolation faults

If either of the isolation resistances decreases below the threshold of 100 Ohms/Volt a hazard occurs if a person makes contact with the terminal "opposite" to the leaking resistor. The isolation resistance may fail in one side (single fault), on both sides (symmetrical fault) or in any part inside the battery or power supply system. These hazardous situations [1] are illustrated in Figure 2.

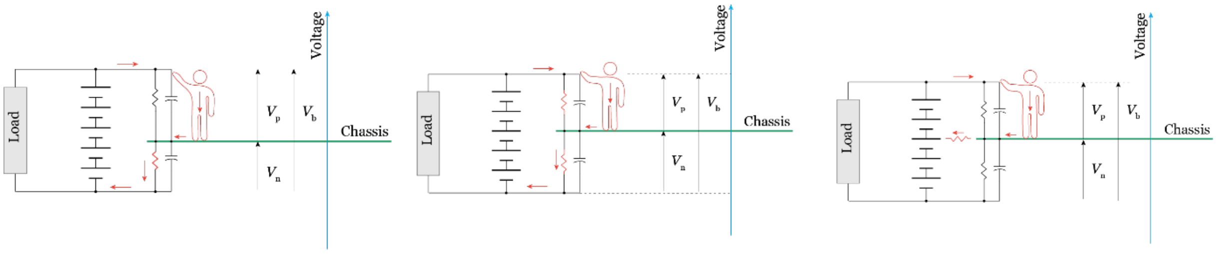
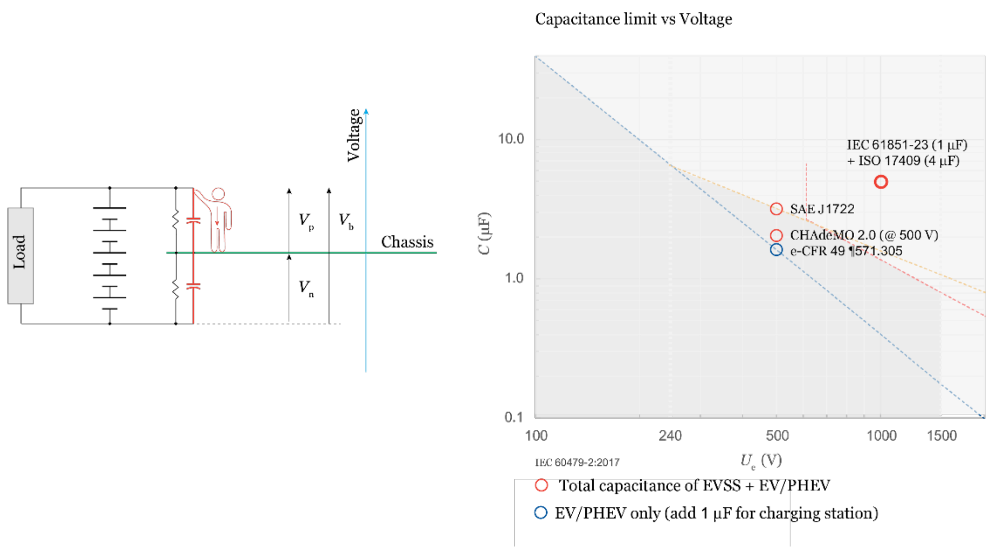


Figure 2: An isolation fault may occur in one side, two sides or in any place in the power system. Resistors in red represent leakage resistors.

1.2 Capacitive faults

Of equal importance to personal safety is the hazard that can be caused by excessive energy stored in the IT power system capacitors [2]. Sub-system failures, such as a coolant leakage or personnel interventions, may alter the originally designed capacitance values. In this case energy discharged through a person's body can create a hazardous event as shown in Figure 3.

Figure 3: Capacitive faults and the limits set by international standards



2. Fault detection methods

There are several methods traditionally used in the field for the implementation of an isolation monitoring function which can be broadly grouped in the categories described in the following sections.

2.1 Voltage method

This method is the simplest one and relies exclusively on voltage measurements between each power pole and the chassis. It depends on the observation that a single isolation fault will create an imbalance between the two voltages V_p and V_n. If the initial values of isolation resistances are known, the voltage ratio between V_p and V_n can be used to estimate the value of a single faulty isolation resistance. Besides the requirement that voltages have to be stable in order to be measured accurately, this method fails to detect "symmetrical" or any type of concurrent faults, where both isolation resistances change, and it is not acceptable in any product that intends to be safe.

2.2 Resistance insertion method

The method involves two steps [3]:

STEP 1: Measure V_p and V_n and determine the lower of the two.

STEP 2: Connect a known resistance R_0 in parallel to the isolation resistance of the higher voltage and measure again the two new voltage values $V_p^{'}$ and $V_n^{'}$. If $V_p > V_n$ $R_{ISO,n}$ can be shown to equal:

$$R_{ISO,n} = R_0 \frac{V_p - V_p^{'}}{V_p^{'}} \left[1 + \frac{V_n}{V_p} \right] \tag{1}$$

For this method to be accurate, R_0 has to be selected in the range of 100 to 500 Ω/V. This is exactly the range in which the isolation system becomes hazardous, which means that during the measurement period the system becomes deliberately unsafe. A second issue is that during the measurement the voltage should be stable. A third issue is related to cost, size and reliability, as inserting and de-inserting the test resistor in the high voltage system requires expensive and bulky relays. For these reasons the method is not favored in active IT systems.

2.3 Signal injection method

In this method a known current signal is injected, as shown in Fig. 4, forcing a change in the voltages between the power rails and chassis. In the incarnation of the method of Fig. 4 the value of the parallel combination of the isolation resistances R_{ISO} can be shown to be equal:

$$R_{ISO} = \frac{\Delta V}{i_X} \tag{2}$$

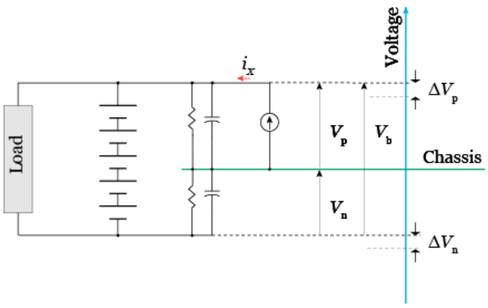


Figure 4: Signal injection method

Some of the problems associated with this method is the inability to discriminate between the positive and negative resistance isolation values, susceptibility to noise and long times required to determine isolation state.

2.4 A stochastic method for determining isolation resistances & capacitance

A novel method is presented that overcomes several of the limitations from previously engaged methods for isolation monitoring and which relies on stochastic methods for determining the IT system parameters. The new method takes into consideration all the system parameters, including unknown capacitances and loads and is utilizing stochastic methods for finding optimal solutions in a system characterized by more unknowns than measurements.

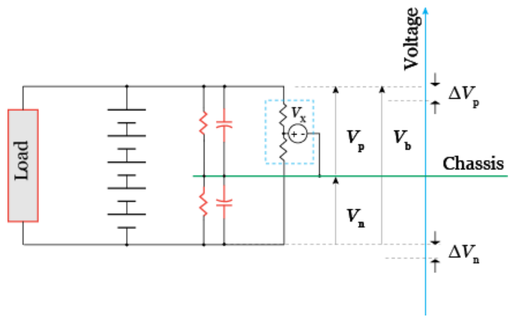


Figure 5: “Stochastic” method

As can be seen in Fig. 5, load voltage, Y-capacitances and isolation resistances are all treated as unknowns that have to be optimized in order to fit the observed values of V_p and V_n. In this method load variations instead of interfering with measurements are contributing information for quick convergence of the solution. The method is fast and it is already employed in electric vehicles and quick charging stations. Since it is not based on static measurements it requires load activity and for this reason it is complemented by signal injection when the system is idle.

A more detailed description of insulation monitoring methods can be found in references [4] and [5]

3. The standards landscape

The main standard addressing specifically the requirements for insulation monitoring devices is the IEC 61557-8 “Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. - Part 8: Insulation monitoring devices for IT systems” [1]. This standard covers all the functional requirements of IMDs as well specifies testing methods and production testing necessary for compliance. Other specific standards for EV/PHEVs and charging stations either refer directly or they are covered by IEC 61557-8. UL publishes 2232-2 “Standard for Safety for Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits: Particular Requirements for Protection Devices for Use in Charging Systems”, which also provides specific testing guidelines for compliance.

A chart showing the dependence of IMD related standards for charging stations is shown in Fig. 6.

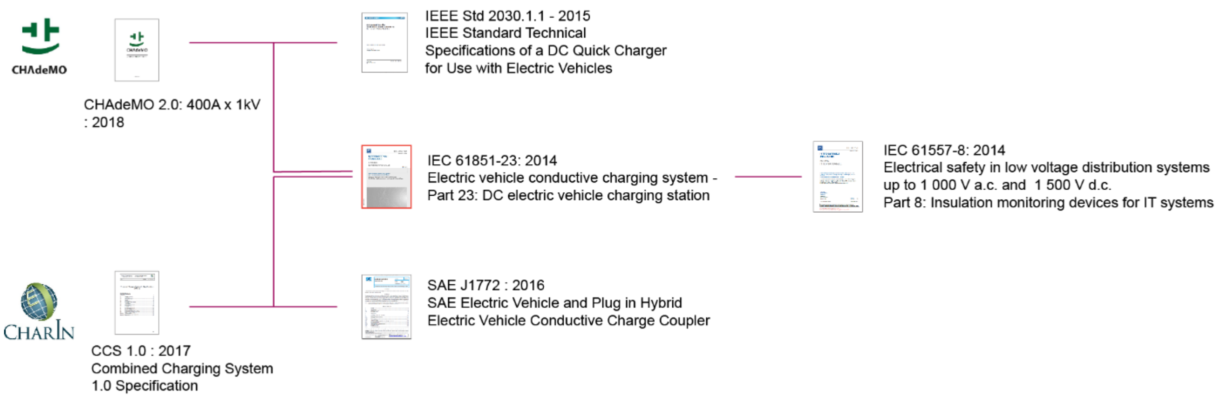


Figure 6: Relationship between charging stations protocols and international standards.

4. Challenges moving to higher voltage systems

Higher voltage systems (800 V, 1000 V, 1500V) present new challenges [4] for active isolation monitoring. Fault and warning isolation levels increase proportionally to the voltage value. The value of total system capacitance decreases, posing challenges to power supply designers who utilize Y-capacitances for EMI suppression. International standards have yet to issue new limits for these systems.

References

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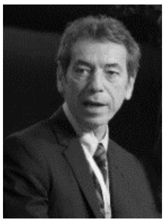

John Milios is a Senior IEEE member. He holds a B.Sc in Physics and an M.Sc in Electronic Automation from the National University of Athens and a Ph.M degree from Columbia University. He has participated in the committees for the creation of several industry standards, including the Smart Battery System, SMBus, USB HID and Bluetooth. He has served as the CTO of Semtech and he is currently the CEO of Sendyne Corp. He holds 13 US patents.

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