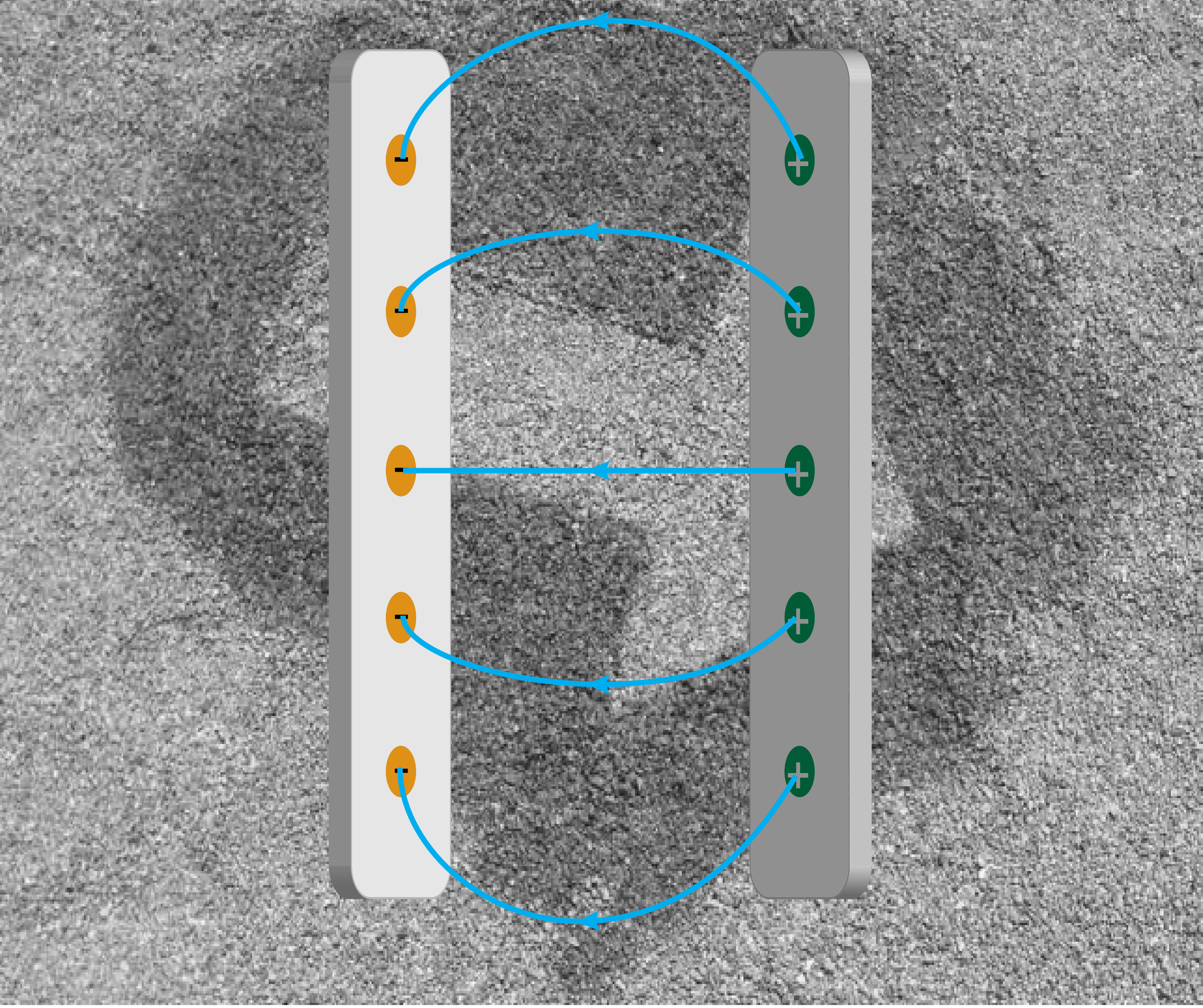


White Paper

Capacitance hazards in e-mobility

Capacitance hazards in e-mobility

Safety Standards

Abstract – In December of 2017, the International Standards Organization (ISO) issued a letter warning designers of electric vehicles (EVs) and charging stations that existing standards were insufficient to fulfill the safety objective of “Protection against electric shock” for all possible combinations of charging stations and vehicles. The relevant standards this letter referred to were the IEC 61851-23:2014 for charging stations and ISO 17409:2015 for connection of EVs to an external power supply. The letter stated that “the approach of limiting the capacity energy will not be sufficient for the safety objective”, but refrained from making specific recommendations. Instead, it strongly recommended to users of the standards to perform a “safety assessment”. Making a safety assessment starts from understanding the potential hazards imposed by stored capacitive energy, and is the subject of this paper.

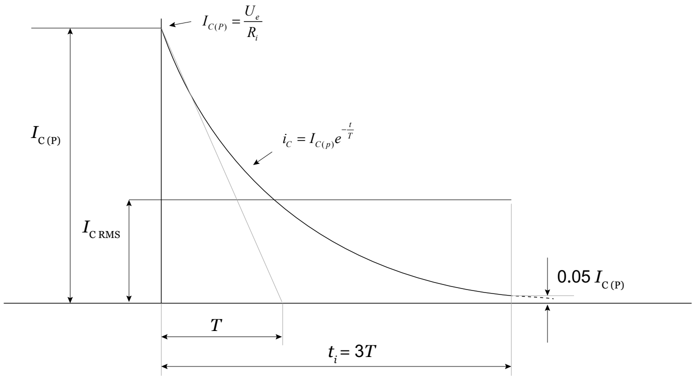
Keywords: isolation monitor, isolation monitoring device, IMD, insulation monitor, ground fault, earth fault

WARNING: *Information presented in this paper expresses the opinions and interpretations of the authors and shall not be used for design as substitute for the international and national standards which specify safety requirements for DC charging stations.*

Introduction

High voltage IT (isolated terra) systems employ Y capacitors. The purpose of Y capacitors is to suppress EMI (electromagnetic interference) and RFI (radio frequency interference) noise. They are typically connected between each power rail and the chassis ground. EMI is created by the high frequency switching components of the power supply which, as a byproduct, produce high frequency disturbances on the power rails. Methods appearing in the literature to improve the power factor of switching power supplies use ubiquitously low order harmonic reduction, which in turn transfers the energy to the higher end of the frequency spectrum in the Radio Frequency Range, thus exasperating the problem. Y-capacitors provide a low reactance path to the ground for these unwanted byproducts of power conversion, so devices and systems can meet the relevant EMI limits imposed by standards, ensuring non-interference between devices and systems.

Since capacitive reactance is defined as $X_C = \frac{1}{\omega C}$, it makes sense that the larger the capacitance the smaller the reactance and the better job will be done in suppressing unwanted noise. Taking into consideration that addressing EMI problems in



IEC 60479-2:2017

Figure 1: Discharge of a capacitor through the human body for an interval of three time constants. The value of I C RMS corresponds to the value of direct current that would produce during the same interval the same average power dissipation in a resistive load.

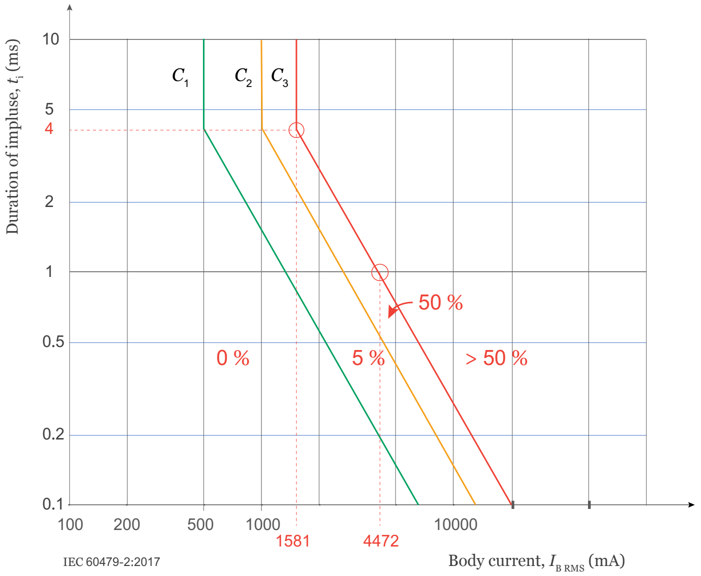
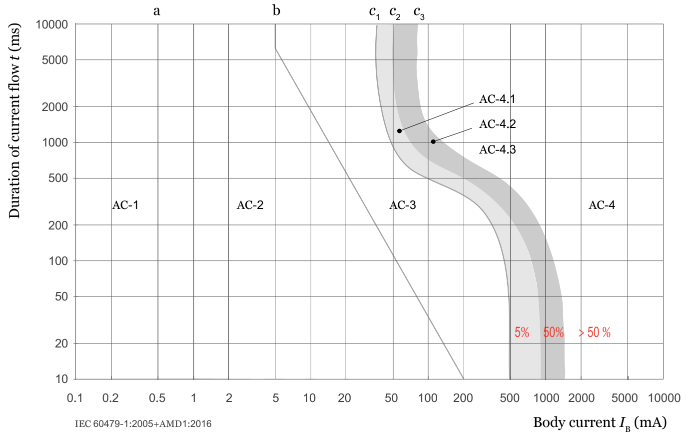


Figure 2: Probability of fibrillation, RMS current vs time. Red numbers indicate the probability in each chart area.



Conventional time/current zones of effects of a.c. currents (15 Hz to 100 Hz) on persons for a current path corresponding to left hand to feet

Figure 3: For larger than 10 ms impulses the standard refers to the a.c. time current zones of effects. Curves c1, c2, c3 define zones of probability 5%, 50% and >50 % for ventricular fibrillation.

the initial design stage is not an exact art and that trial and error is often employed to find the proper EMI suppression solution, one can understand the tendency of trying to solve these problems in the final stage by adding more capacitances. Unfortunately, there is no such thing as a free lunch. The energy stored in these capacitors, presents a potential hazard to anyone who comes in contact with them. The stored energy and, subsequently, the severity of the hazard increases exponentially with the voltage of the IT system. Going from a 400 V to an 800 V battery quadruples the energy stored in its Y-capacitors. The question is what is the maximum capacitance for an intrinsically safe IT system?

Ventricular fibrillation through capacitor discharge

IEC 60479-2:2019 “Effects of current on human beings and livestock – Part: Special aspects” was published to be used by technical committees in preparation of standards. It lists among other thing the effects of current passing through the human body in the form of impulses resulting from capacitor discharges.

The IEC 60479-2 uses the value for setting the various limits. The value can be derived from the peak value according to the relationship:

$$I_{CRMS} = \sqrt{\frac{I_{C(p)}^2}{3T} \int_0^{3T} e^{-\frac{2t}{T}}} \simeq \frac{I_{C(p)}}{\sqrt{6}}$$

(refer to the section “Notations & definitions” at the end of this paper for

The limits specified are deemed to be applicable for impulse durations from 0.1 ms up to and including 10 ms. Assuming a worst case body resistance of 500 Ω, an impulse of three time constants totaling 10 ms, sets the upper capacitance limit at 6.66 μF.

For larger duration pulses the standard refers to IEC 60479-1 which provides a chart for a.c. currents (15 Hz to 100 Hz).

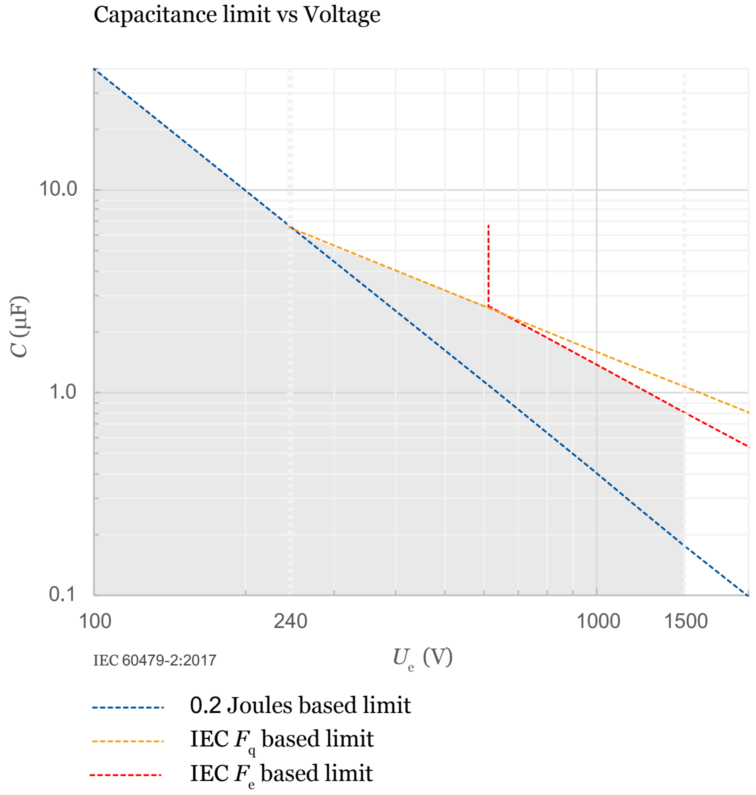


Figure 4: Capacitance limit vs Voltage. The blue line corresponds to the 0.2 Joules limit imposed by several standards. The range of applicability of the Fq based limit starts at 240 V.

Maximum Capacitance vs Voltage

A more practical chart would be one to relate maximum allowable capacitance for 0% fibrillation risk vs voltage. A chart like this can be derived by noting that:

$I_{CRMS} \simeq \frac{I_{C(p)}}{\sqrt{6}}$, and $I_{C(p)} = \frac{U_e}{R_i}$, where U_e is the voltage of the capacitor at the beginning of discharge through the human body and R_i is the initial body resistance. Combining these two relationships and setting $R_i = 500\Omega$ we get

$$I_{CRMS} = \frac{U_e}{500 \cdot \sqrt{6}},$$

which relates the RMS current to the initial capacitor voltage.

From $t_i = 3T = 3RC$ we can derive the second relationship we need between capacitance and time:

$$C = t_i / 3 \cdot 500 \quad .$$

The slope of C_1 curve of Fig. 2 can be deducted from a numerical example given in IEC 60479-2 (values are shown on Fig 2) and is derived in detail in SAE J1772:2016 "SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler" standard. Using a second numerical example in IEC 60479-2, which appears without any reference to a chart, the authors of SAE J1772:2016 infer a second curve relating maximum capacitance limit to total capacitance charge

$$F_q = \int_0^\infty i \cdot dt \quad .$$

We have included also this limit in Fig. 4 and using the same methodology we extended the original SAE J1772 chart up to 1500 V systems.

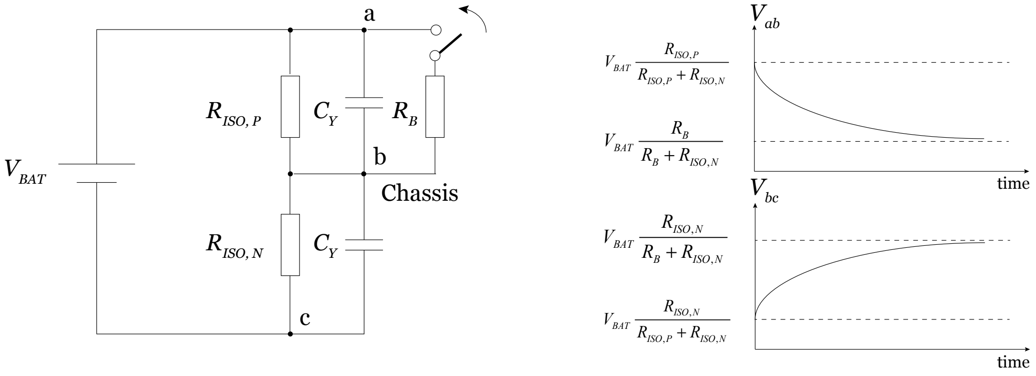
How do these limits apply to an IT system

Figure 5 illustrates the equivalent circuit of an IT system. R_B is the body resistance. The voltages V_{ab} and V_{bc} are set by the voltage divider resistor network formed initially ($t = 0$)by $R_{ISO,P}$ and $R_{ISO,N}$, and finally ($t = \infty$) by the parallel combination of $R_B // R_{ISO,P}$ and $R_{ISO,N}$. Because $R_B << R_{ISO,P}$, we substitute $R_B // R_{ISO,P}$ with R_B .

The time constant of the V_{ab} discharge is $T = R_{eq} C_{eq}$. From circuit theory we can find R_{eq} by shorting V_{BAT} and calculating the resistance seen between points a and b. In this case $R_{eq} = R_B // R_{ISO,P} // R_{ISO,N}$, which is approximately R_B . Utilizing the same method we can calculate C_{eq} , which is equal to the parallel combination of the two C_Y capacitances or $C_{eq} = 2C_Y$ (assuming they are of equal value). The conclusion is that the capacitance limits should be calculated based on the parallel combination of all capacitances in the IT system. We can verify this intuitively as while the top capacitor is discharging the bottom capacitor is charging at the same speed. A lower capacitance value on the lower capacitor for example will have the effect of increasing its voltage faster, affecting the time constant also of the top capacitor, until the whole circuit reaches its final state determined by the formed resistor network.

Which voltage to use

The next question is what voltage to assume for determining maximum capacitances limit. In an IT system with no leakages $V_{ab} = V_{BAT} / 2$. The worst case voltage conditions would be if $R_{ISO,N} = 0$, in which case $V_{ab} = V_{BAT}$. This situation is unlikely to happen in a system engaging an Insulation Monitoring Device (IMD), as the IMD would already have signaled an isolation fault. In a system with an IMD the worst case scenario would be for $R_{ISO,N} = 500\Omega \cdot V_{BAT} + \Delta R$, which for $R_{ISO,N}$ is to be a little bit larger than the IMD "Warning" value for the isolation resistance. In a 500 V system with $R_{ISO,N} = 2.7M\Omega$, the worst case (no isolation warning) voltage V_{ab} could be 458 V (92% of V_{BAT}) in which case the maximum capacitance from Fig. 4 is determined to be approximately 3.5 µF. In a 1000 V system worst case V_{ab} could be 844 V (84% of V_{BAT}) and maximum total capacitance, according to the same chart, should be less than approximately 1.6 µF.



$$T = R_{eq} C_{eq} \text{ where } R_{eq} = \frac{R_B \cdot R_{ISO,N}}{R_B + R_{ISO,N}} \approx R_B \text{ , } C_{eq} = C_P + C_N = 2C_Y$$

Figure 5: IT system equivalent circuit

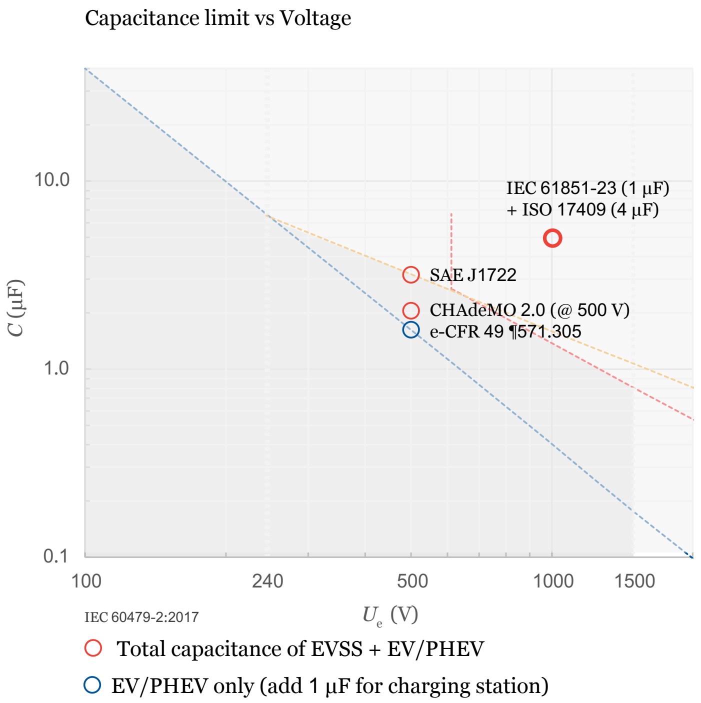


Figure 6: Total capacitance limits vs Voltage in different standards

Conflicting standards?

When an EV/PHEV connects to a quick charging station the Y-capacitances of the charging station add to the Y-capacitances of the vehicle. This is the situation described in the December 2017 ISO letter regarding "Protection against electric shock". Fig. 6 illustrates the maximum combined capacitance limits imposed by different standards.

It can be seen clearly on the upper right corner of the chart that the lax limits of 4 μF allowed by the ISO 17409:2015 standard allows a total capacitance value, between the EVSS and EV/PHEVs, which is inherently unsafe for rail voltages above approximately 280 V. ISO 17409 from this perspective is in direct conflict with e-CFR 49 §571.305, which requires capacitively stored energy not to exceed 0.2 Joules. Any vehicle with a battery of more than 280 V would be violating e-CFR 49 §571.305 if the Y-capacitors are totaling 4 μF. Given the trend for higher voltages in charging stations and electrically powered heavy vehicles it seems that some of the standards producing organizations are are facing some challenges in trying to keep systems intrinsically safe.

What are the safety measures for inherently unsafe IT systems? Unfortunately, the only measures that are suggested are passive systems, like implementing double or reinforced insulation, more layers of insulation, barriers and/or enclosures with mechanical robustness, etc.

IEC 61850:2010 "Functional safety of electrical/electronic/programmable electronic safety-related systems" states clearly that safety achieved by measures that rely on passive systems is not functional safety. The same way a fire resistant door is not an instance of functional safety – the same way enclosures and barriers come short of providing functional safety.

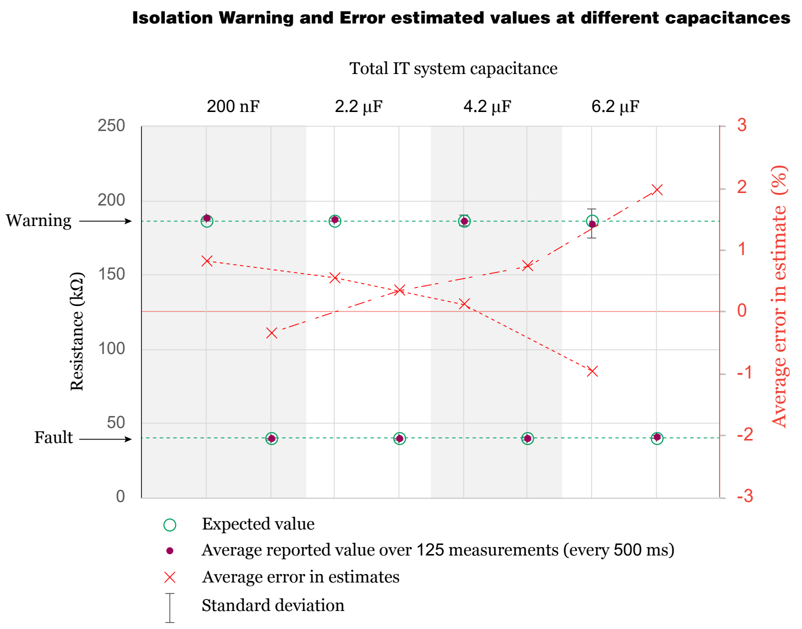


Figure 7: SIM100MOD performance in detecting "Warning" and "Fault" isolation resistance values under different system capacitances. Red crosses represent the average error in each estimate and vertical bars the standard deviation, in a sample of

Capacitance side effects to IMD operation

Charging stations work with unpredictable system capacitances. To the known Y-capacitance of the charging station adds the unknown capacitance of the charging vehicle, which can be as high as 4 µF according to ISO 17409. A side effect of dealing with large capacitances is that they introduce large time constants that may interfere with specific IMD's fault detection method.

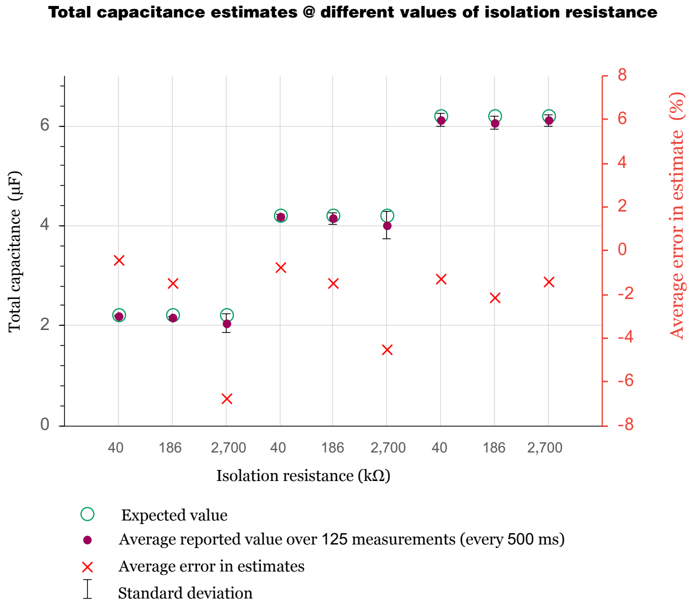


Figure 8: Total capacitance estimation by SIM100MOD at different values of isolation resistance. Average values over 125 measurements performed every 500 ms, along with average errors and standard deviations.

Sendyne's SIM100MOD has been tested for its efficiency in detecting Warning and Fault level isolation resistances with up to 6.2 µF total system capacitance. The accuracy of Warning and Fault predictions of SIM100MOD are shown in Fig. 7.

Functional safety with the assistance of SIM100MOD

While it is clear that inherently safe high voltage IT systems can only be achieved by limiting the total system capacitance to safe limits, a fact pointing to the necessity of better designs of power supplies, there are things that can be accomplished in functional safety with the assistance of the IMD.

Know your total system capacitance

The Sendyne SIM100MOD is the only IMD in the market that provides estimates of the total system capacitance. This feature is useful not only in charging stations where the total capacitance changes with each new vehicle connected, but also as a system health monitoring function for any battery powered vehicle.

Total capacitance in an electric vehicle is determined by both the intentionally designed Y-capacitors and the parasitic capacitance formed by metal housings, cooling and related structures. Changes in the value of these parasitic capacitances can be used as one of the indications for the status of operating conditions of such systems including those related to cooling and electronics measurement (US 9696384B2). Other reasons that may cause a change in total capacitance include:

- The Y-capacitance values can change as a result of user intervention (accessories, modifications, etc.)
- Y-capacitors may fail. Depending on their type they may either produce a short (it will be detected via monitoring) or become open (also detected)
- An accident may result in change of the isolation capacitance

Monitor the rail voltages

As we have shown before, in order to determine the safe operating range of an IT system we need to know not only the total capacitance but also the voltage these capacitors operate on. For example, a 480 V car charging at a station with 5 μF total capacitance can be safe for as long as the isolation system is balanced and each capacitor experiences 240 V at its terminals. The same system will be unsafe if one of the isolation paths deteriorates causing the potential of one rail to chassis to exceed approximately 300 V (SAE J1772 limit). Monitoring total capacitance and individual rail to chassis potentials can provide an active functional safety feature by facilitating the warning of personnel for the potential hazardous situation. Sendyne's SIM100MOD provides information on both of these safety critical quantities.

Notations & definitions

I_{CRMS} - RMS value of current of the capacitor discharge for a duration of 3T . It is defined as the equivalent DC current value that would produce the same average power dissipation in a resistive load.

T – time constant (equal to RC)

$I_{C(p)}$ - peak value (or initial value) of capacitor discharge

F_e - Specific fibrillating energy. Capacitor energy that could be discharged through the human body divided by the resistance of the human body.

$I_{C(p)} = \frac{U_e}{R_i}$, where U_e is the voltage of the capacitor at the beginning of discharge through the human body and R_i is the initial body resistance.

$$t_i = 3T$$

$$i_C = I_{C(p)} e^{-\frac{t}{T}}$$

$$F_e = \int_0^\infty I^2_{C(p)} e^{-\frac{2t}{T}} dt = I^2_{C(p)} \frac{T}{2} = I^2_{CRMS} t_i$$

$$I_{CRMS} = \sqrt{\frac{I^2_{C(p)}}{3T} \int_0^{3T} e^{-\frac{2t}{T}}} \simeq \frac{I_{C(p)}}{\sqrt{6}}$$

$$T = R_{eq} C_{eq} \text{ where } R_{eq} = \frac{R_B \cdot R_{ISO,N}}{R_B + R_{ISO,N}} \approx R_B \text{ , } C_{eq} = C_P + C_N = 2C_Y$$

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