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Touch hazards at 800+ V

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Executive Summary

New challenges in the design and safety monitoring of Electric Vehicles and Trucks arise with transition to higher voltages. "Touch energy" is becoming the most prominent potential hazard, as voltages rise from 450 V to 800-1500 V range. Potentially hazardous energy stored in the system's parasitic and Y-capacitances, increases exponentially with the rail voltages, pressuring power systems designers to reduce Y-capacitances and international standard committees to relax their tolerances. In this paper we will explain the dynamics between insulation deterioration and "touch energy" rise and will review the safety standards landscape and evolution as they apply to these higher voltage systems. Finally, we'll review the methods used for safety monitoring of these systems to provide a better understanding of their capabilities and "blind spots" associated with each method.

1 The *touch* hazards

Electric vehicles implement an IT (isolated terra) power system topology. The high voltage battery, associated electronics and motors are "floating" in respect to the chassis. The advantage of this IT topology is that unlike grounded systems, a single short from any power rail to the chassis will not disable the vehicle.

Vehicle designers expend a lot of effort to insulate and double insulate high voltage contact points. In extraordinary conditions though it is possible for humans or personnel to expose themselves to a high voltage conductor. In such an event two things are going to happen. Within the first few milliseconds any charge stored in the Y and parasitic capacitors will discharge through the low resistance of the human body. The amount of energy which will be discharged is referred to as the "touch energy".

The second effect is that a DC current will start flowing through the human body, limited only by the values of the isolation resistances. The amount of this current is referred to as the "touch current".

Excessive values of "touch energy" or "touch current" can be hazardous and they must be timely identified and contained.

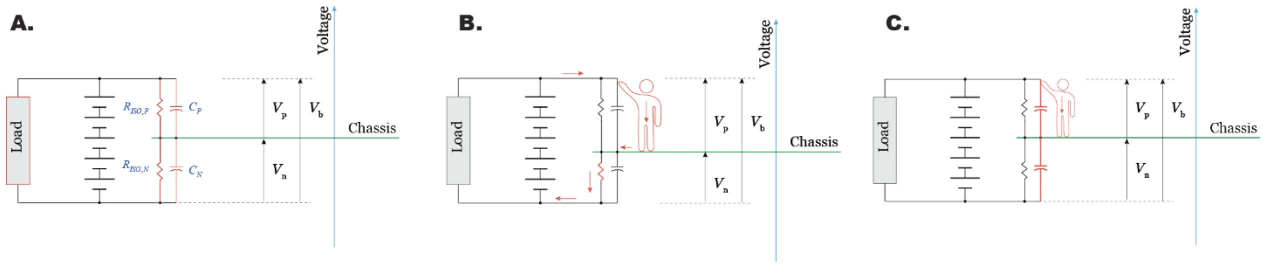


Figure 1: A. The IT system topology. B. Touch current in this example is limited by the isolation resistance between the negative rail and chassis, C. Touch energy depends on the rail voltage and the [1]total capacitance.

For the less than 500V EVs the main concern was *touch current. Touch energy* was not such a big concern as the relatively low battery voltage ensured that in a vehicle designed within Y-capacitance specs, stored energy could be contained within a 0.2 J safety limit[1],[2].

As vehicle batteries approach 1000V the stored energy increases dramatically. Touch energy is provided by:

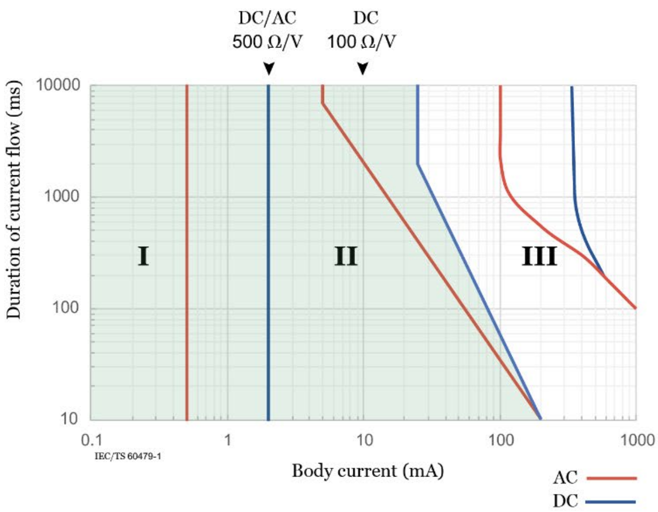
$$E_{MAX} = 0.5 \cdot C_{TOTAL} \cdot U_{MAX}^2 \quad (1)$$

, where C_{TOTAL} is the sum of all Y and parasitic capacitances and U_{MAX} is $\max\{V_P, V_N\}$.

In a perfectly balanced IT system $U_{MAX} = V_{BAT} / 2$, while in a compromised system in which one of the rails is shorted to chassis $U_{MAX} = V_{BAT}$. In such a compromised system of 800 V and 2 µF , E_{MAX} can become as high as 0.64 J.

2 Human body touch tolerance

The question on how much current the human body can tolerate is addressed in the IEC/TS 60479 standard titled “Effects of current on human beings and livestock”. Part 1 [4]of the standard addresses the body tolerance to AC and DC currents while Part 2 [3] deals with the effect of current impulses, such as the ones originating to a capacitor discharge.



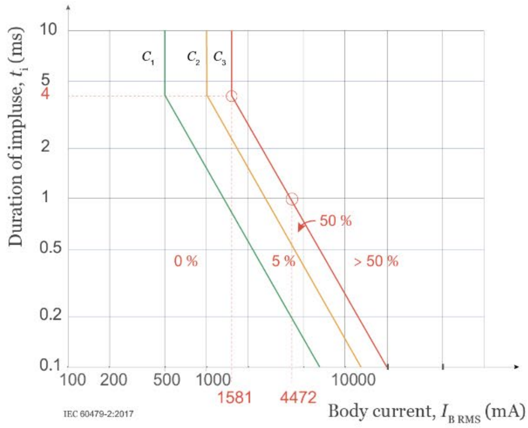


Figure 2: IEC 60479 sets the current tolerance limits for AC, DC and impulses. The percentage figures on the right chart represent the probability of fibrillation. For example, an rms current of 1.581 A passing through the body for 4 ms has 50% probability to cause fatal fibrillation.

Based on these limits, derivative safety standards had so far accepted the limits of 100 Ω/V (or 10 mA) for DC systems, 500 Ω/V (or 2 mA) for AC/DC systems and 0.2 J for maximum stored energy. A detailed explanation of these derivations can be found in [1],[2].

An analysis on how these limits propagate in other standards, such as the SAE 1772 [5], and specifically in the relationship between battery voltage and maximum system capacitance can be found in [1].

3 “Touch energy” presents a bigger danger for 800+ V systems

A simple calculation shows that the maximum capacitance for maintaining the original 0.2 J limit in an 800 V system would be just 0.3 µF. In practice this limit is very hard to achieve, especially since most charging station standards allow the charging station to contribute up to 1 µF on its own, when an EV is connected to them.

Note that in the above calculation the maximum capacitance was determined assuming the worst-case scenario, where one of the power rails is shorted to chassis, forcing the other rail to attain the maximum battery voltage value. This is an extreme situation, which will already have been signaled as “fault” by an

Insulation Monitoring Device, forcing power to cease. The best-case scenario would be the "balanced" case, where each rail rests at the equal potential in reference to chassis of $U_{MAX} = V_{BAT} / 2$.
In this case maximum capacitance for the same 800 V system can be as high as 1.25 μF which is better but still hard to achieve.

4 The "push" for more tolerance in standards

These severe capacitance limits led committees to challenge the previously absolute energy limit of 0.2 J. A view of how different standards rate maximum capacitance vs voltage is shown in Fig 3.

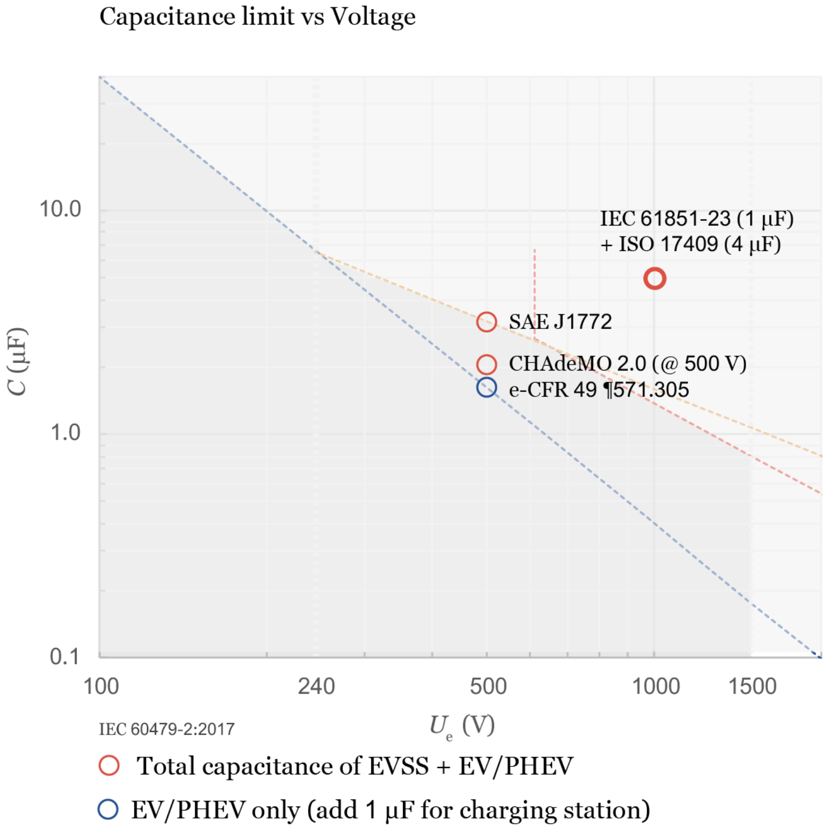


Figure 3: Total capacitance limits vs Voltage in different standards.

An interesting approach on how to minimize the risk of touch energy standards is taken by CHAdeMO who dictates the placement of "balancing" resistors between each rail and chassis. In CHAdeMO 2.0 these resistors already violate the 10 mA (100 Ω/V) limit. In v3.0 the resistance values have increased but they would still under specific conditions violate the "touch current" limits.
As a result of such pressures, ISO 17409:2020, "Electrically propelled road vehicles — Conductive power transfer — Safety requirements" [6] published in 2020, states "The total insulation resistance of the complete vehicle power supply circuit may be below 100 Ω/V when the vehicle is connected to a DC charging station". In addition, with this edition "the limitation of y-capacitance for protection against electric shock under single failure conditions is no longer applicable as a fault protection provision when the vehicle has a conductive DC connection to an external electric circuit".
Since our knowledge for the body tolerance to electricity has not changed the last couple of years, the only way to interpret these new tolerances, is the willingness of the industry to undertake more risks to keep pace with the automotive electrification momentum.

5 Touch Energy and Touch Current

A well designed and balanced IT system ensures that both leakage currents and stored energy are within the safety limits defined by the standards. In such system leakage currents are limited and touch energy is limited to the design specifications. Any asymmetrical deterioration in the isolation resistances will raise the potential between a power rail and chassis, increasing the stored energy by:

$$E_{UNBAL} = 0.5 \cdot C_{TOTAL} \cdot \left(U_{UNBAL}^2 - U_{BAL}^2\right)$$

Where, E_{UNBAL} is the energy difference between the unbalanced state and the balanced one. A symmetrical deterioration of isolation resistances on the other hand will not alter the energy stored in the IT system. For monitoring the touch energy one can conclude that it would be sufficient to know the total capacitance of the system C_{TOTAL} and the maximum voltage between each power rail and chassis $\max\{|V_P|, |V_N|\}$.

Note that C_{TOTAL} can change from the system design specifications, either through environmental factors or by usage modes, such as in the case of charging stations which connect to vehicles with unknown capacitances. An active safety monitor must be capable besides determining the leakage currents to estimate the system total capacitance.

6 Intrusive isolation monitoring methods

In 2004 the US Code of Federal Regulations published the "§ 571.305 Standard No. 305; "Electric-powered vehicles: electrolyte spillage and electrical shock protection"[7]". Section S7.6.6 of the standard describes a method of detecting the isolation state of a fully charged vehicle, at rest, by taking two voltage measurements and subsequently inserting a known value resistor R_0 between a power rail and the chassis. The method is described in [2] and involves two steps:

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 ($V_P > V_N$) and measure again the two new voltage values V_P' and V_N'. The $R_{ISO,N}$ can be shown to be equal with:

$$R_{ISO,N} = R_0 \frac{V_P - V_P'}{V_P'}\left[1 + \frac{V_N}{V_P}\right]$$

While it was clear by the standard that the described measurement was intended to be performed at a service station, some implementations adapted some variation of it, in onboard electrical isolation monitoring systems. All these implementations, while they may differ in the level of sophistication, share one inherent common characteristic. In order to make the assessment of the isolation state, they either make the system unsafe, or they compromise the availability of the monitored IT system.

The resistor insertion, like other IMD methods, changes the value of the current circulating in the isolation circuit and determines the state by observing the voltage response.

Unlike other methods though, it does so by significantly unbalancing the isolation state of the IT system. The impact on touch current can be small if the insertion resistance value is relatively high, but the impact on stored energy is significant as is shown in Fig. 4.

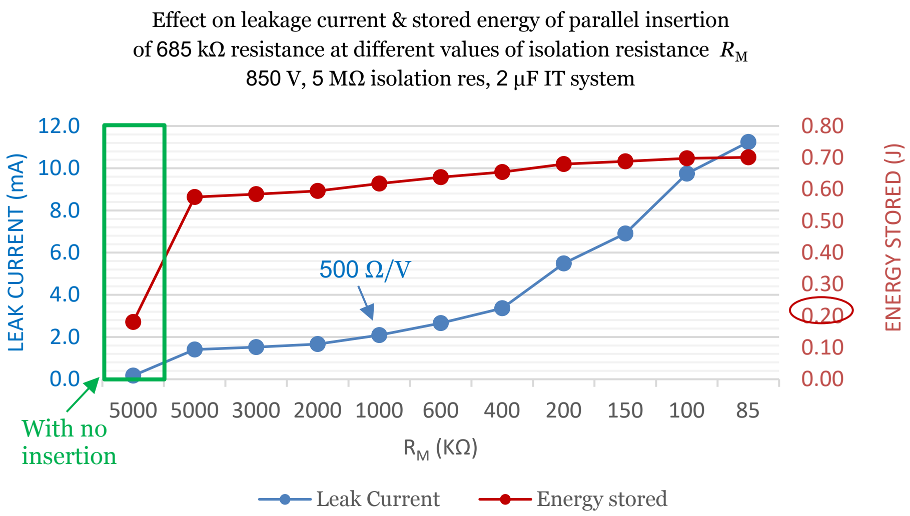


Figure 4: The impact of resistor insertion on touch current and touch energy. On each measurement cycle the stored energy gets out of safety bounds.

7 Conclusions

As “touch energy” becomes the main potential hazard in the newer high voltage systems (800+), the importance of keeping Y-capacitances to a minimum becomes a safety goal for power component designers. Y-capacitances are added to systems as an after-thought to eliminate EMC interferences and can be minimized by proper planning and design effort.

In the new environment, where the probability of hazardous touch events increases, it is important to upgrade the role of Insulation Monitoring Devices, not only to monitor for isolation resistances, but also for total stored energy to at least warn users and personnel for highly risky situations.

8 References

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[7] § 571.305 Standard No. 305; Electric-powered vehicles: electrolyte spillage and electrical shock protection: https://www.ecfr.gov/current/title-49/subtitle-B/chapter-V/part-571/subpart-B/section-571.305. Accessed: 2021-12–21.

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