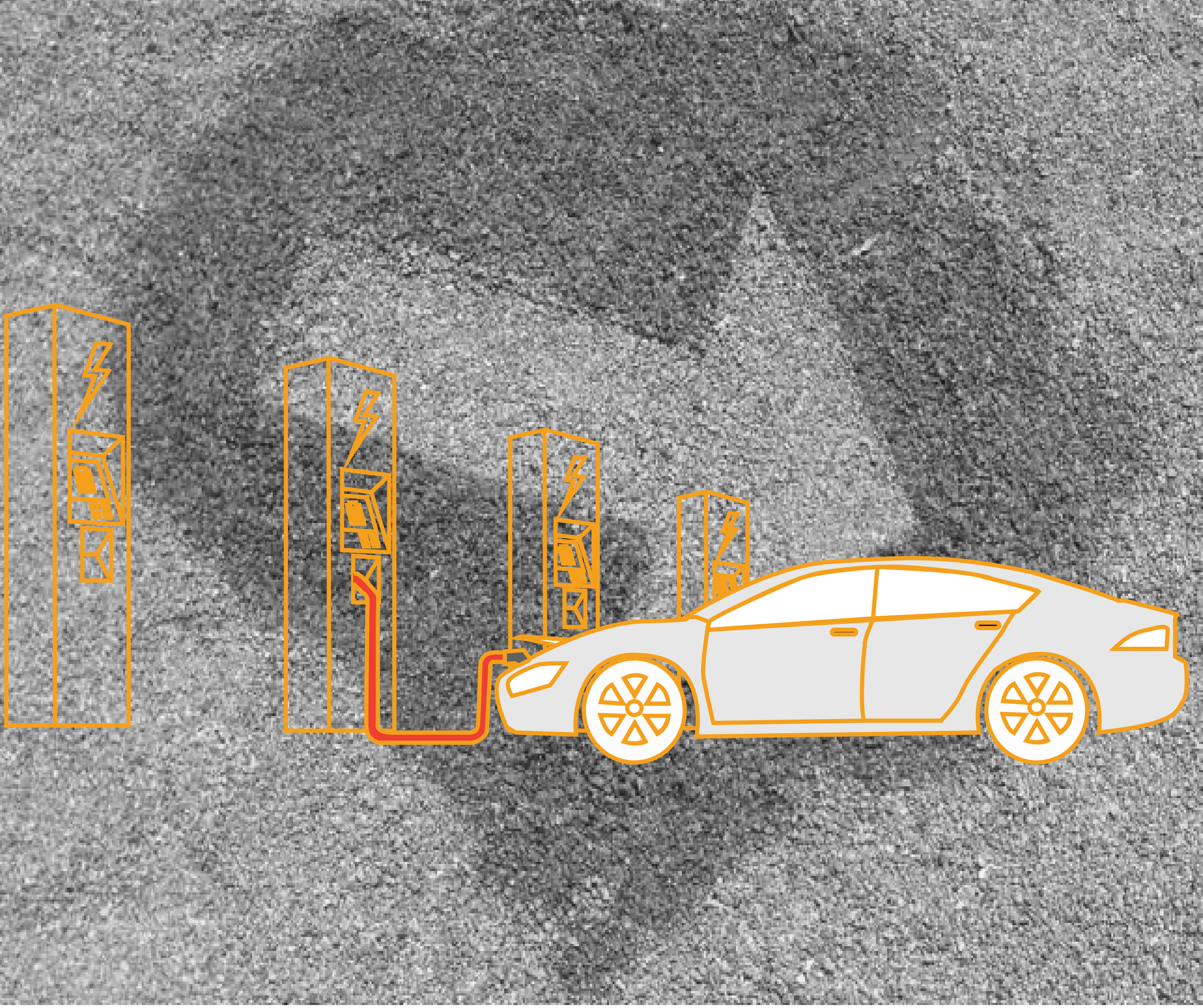


Sendyne®

White Paper

Safety of unearthed (IT) DC power systems

Safety of unearthed (IT) DC power systems

Abstract --- Ungrounded, unearthed, “floating” or IT (Isolé-terré or 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. It is essential for the safety of such systems to continuously monitor their isolation state as even a single fault can generate hazards to personnel in contact with these systems. “Isolation monitors” are the devices required by several international standards to perform this function. This paper reviews the potential hazards in an IT system and the most common methods employed today for detection of isolation faults. It identifies safety related shortcomings inherent to each method and illustrates some of the unique features of Sendyne’s SIM100 designed to overcome them.

Keywords --- isolation monitor; ground fault detection; symmetrical faults; EV safety; charging station safety

Ungrounded, unearthed, “floating” or IT (Isolé-terré or 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. Figure 1 illustrates the basic topology of such a system.

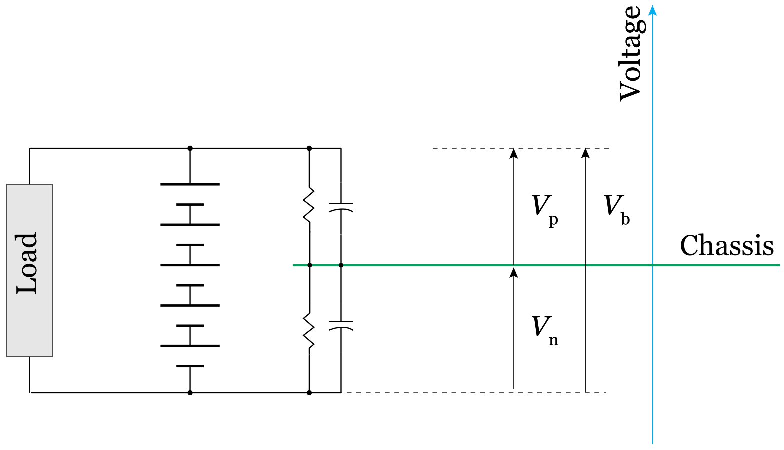


Figure 1: The IT power system topology

The resistive connections, shown in Fig 1, between the terminals of the power source and the chassis are referred to as the “isolation resistances” ($R_{ISO,P}$ and $R_{ISO,N}$) and they represent the parallel combination of all resistive paths from the power source terminals to the chassis (including the ones the isolation monitor introduces). The values of isolation resistances are desirable to be high so leakage currents that travel through them are kept to a harmless minimum. The capacitors shown represent the parallel combination of all capacitances present, including the Y-capacitors

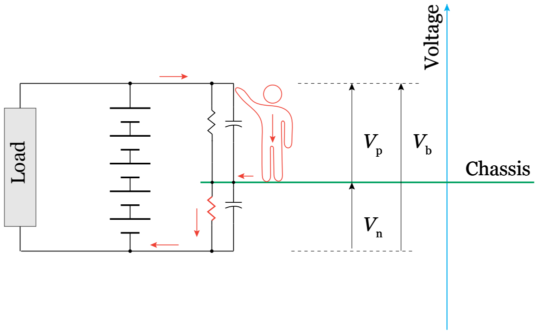


Figure 2: Single isolation fault

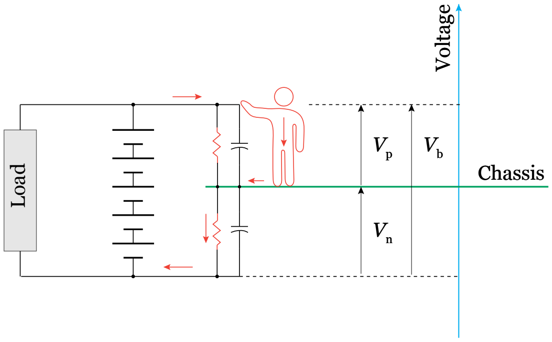


Figure 3: In a "symmetrical" isolation fault Vn = Vp

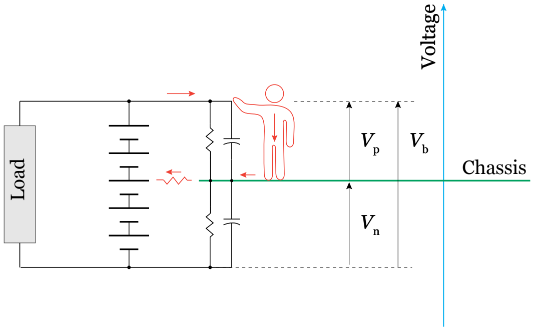


Figure 4: An isolation fault may originate from any point within a battery pack

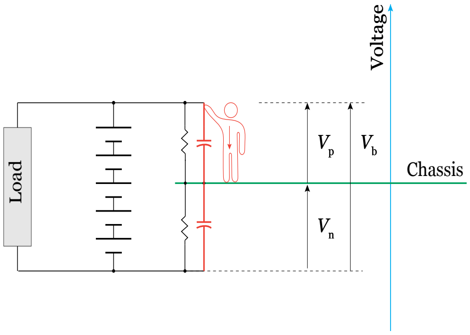


Figure 5: A capacitive fault will lead to excessive energy stored

typically used in DC IT systems to suppress EMI. The values of Y-capacitors are kept within limits in order to avoid hazardous accumulation of energy. The voltages Vp and Vn are shown each to be equal with half the battery voltage, which will be the case if the values of $R_{ISO,P}$ and $R_{ISO,N}$ are equal.

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. This hazardous situation is illustrated in Figure 2.

This contact closes the circuit and current flows through a person's body. Note that although it is shown that Vn < Vp in this example, an isolation fault cannot be detected based solely on voltage readings. The following illustrations show two examples where an isolation fault may be present while Vn = Vp .

A "symmetrical" or "double" isolation fault may occur through insulation failures in power connectors or other environmental and intrusion reasons and, depending on the value of leakage currents, may cause power loss, overheating and even fire. Detection of these types of faults is an absolute requirement for the safety of IT power systems.

Capacitive faults

Of equal importance to personal safety is another type of hazard. While international standards do not yet require it to be monitored, it is the hazard that can be caused by excessive energy stored in the IT power system capacitors. IT system designers ensure that design values of Y-capacitors prevent energy storage beyond the safety limit of 0.2 J. 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 Fig. 5.

Note that the stored energy limits are set for the parallel combination of all capacitances between the power terminals and chassis.

Sendyne's SIM100 is the only isolation monitor today that tracks dynamically IT system's capacitances and reports the maximum energy that can be potentially stored in them.

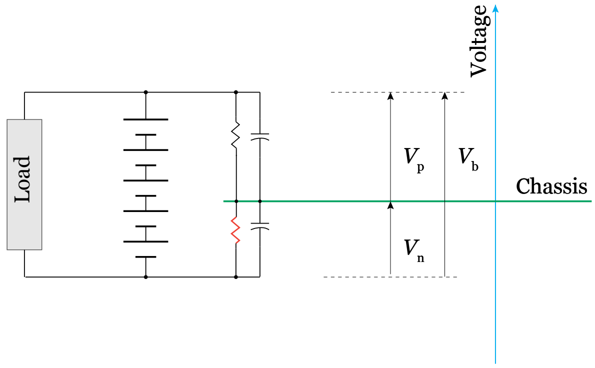


Figure 6: Determine which voltage between Vp and Vn is smaller

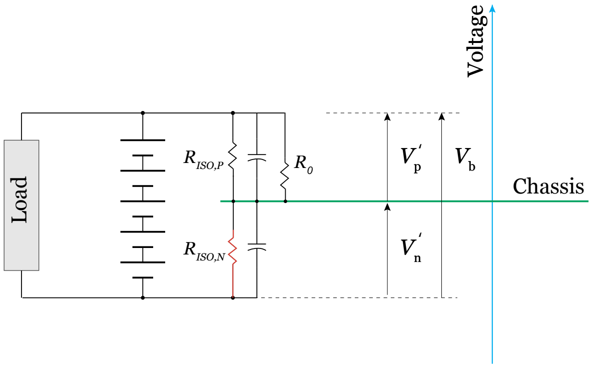


Figure 7: Known resistance insertion method

Fault detection methods

While there are several methods traditionally used in the field for the implementation of an isolation monitoring function, they can be broadly grouped in three main categories that will be described in the following sections.

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 Vp and Vn. If the initial values of isolation resistances are known by some method, the voltage ratio between Vp and Vn can be used to estimate the value of a single faulty isolation resistance. As it was illustrated in the previous sections, this method completely 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.

Resistance insertion method

Specific safety related standards such as the ISO 6469-1, SAE J1766 and CFR 571.305, specify a method for estimating isolation resistances through insertion of a known value resistor. The method 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 ($V_P > V_N$) as shown in Figure 7 and measure again the two new voltage values V_P' and V_N'.

The $R_{ISO,N}$ can be shown to equal:

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

There are several issues with this method. In order to be accurate, R0 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. This requirement severely limits the utility of the method in systems that have active loads most of the time. 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 utilized in active IT systems.

Current measurement method

A variation of the voltage method that is referenced frequently, especially in quick charger specifications, is the current measurement method. It appears in international standards like IEC 61851-23, IEEE 2030.1.1 and in CHAdeMO specifications. An illustration of this method is shown in Figure 8. Two equal value resistors R along with a current measuring device are simultaneously connected to the power rails as shown in the illustration. The current measurement device measures the current that goes through it and determines the value of the fault isolation resistor R_F according to the relationship:

$$i_g = \frac{V_b}{2R_F + R}$$

where:

i_g	is the measured current
R	is the grounding resistor
R_F	is the insulation resistance

This method has all the drawbacks of the voltage method described previously, such as that it cannot detect symmetric isolation faults. Worse, the resistors R have to have a low resistance value in order to provide measurement accuracy around the isolation fault values and at the same time settle capacitances quickly. In a 500 V IT system the Rs used are specified to only 40 kΩ, while the fault isolation value calculated by the 100 Ω/V rule is 50 kΩ. It is obvious that while these resistances remain connected the system is not safe. This is the reason that all of the mentioned international standards specify a "Maximum detection time" to be less than 1 s. What these specifications mean (although they do not state it explicitely) is that if the current measurement method is used, it is unsafe for the circuit to remain connected for more than a second.

In addition, the measurement sensitivity of this method is optimized around the fault values of the isolation resistances thus it cannot provide accurate estimates for the actual values outside this range. This is the reason that some standards require a self check to be implemented by insertion of a fault resistor in the IT system. For a 500 V system , the insertion of a "fault resistor" of 50 kΩ will create a potential hazard by allowing more than 20 mA -twice the limit - fault current.

Because the current measurement method was utilized in the early days of quick charging, many standards still reference it.

In the end of 2017 the International Organization for Standardization (ISO) issued a letter regarding IEC 61851-23 stating:

"*It is, as always, strongly recommended that users of standards additionally perform a risk assessment. Specifically in this case, standards users shall select proper means to fulfill safety requirements in the system of charging station and electric vehicle.*"

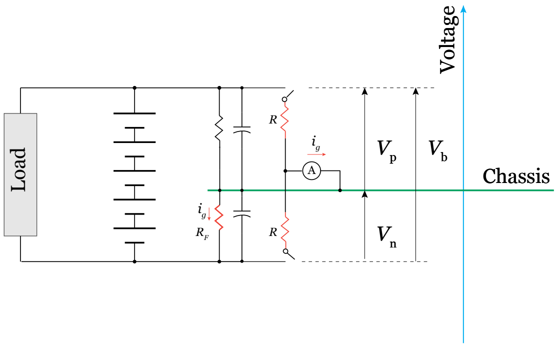


Figure 8: Current measurement method

Signal injection method

To overcome the limitations of the previously described methods, a signal injection method is utilized in most of today's isolation monitoring devices. While there are many variations in the method, in principle the implementation is the same and is illustrated in Figure 9.

A known current i_X is injected in a branch of the isolation circuit, forcing a change in the respective voltage. In the example shown in Figure 9 the value of the parallel combination of the isolation resistances R_{ISO} will be:

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

Implementations of this method vary in the way the signal is injected, the method utilized for calculating its value, the signal shape, duration and amplitude and other details.

One variation (Nissan US Pat. 6,906,525 B2) relies on the injection of a pulsed signal through a coupling capacitor and then detecting the attenuation of the original signal due to the presence of an isolation resistance.

Some of the issues with the signal injection method include:

- An active IT power system (or battery) will interfere with the signal used to identify isolation resistance. Therefore this method can be effective only when there is no interfering load activity.
- The DC injection method can take a long time to make a determination depending on the time constant of the RC isolation circuits.
- The AC injection method by design cannot be accurate in the whole range of possible isolation resistance values. It is optimized for the range of fault resistance (100 Ohms/V or 500 Ohm/V) and provides only an estimate of the parallel combination of isolation resistances.

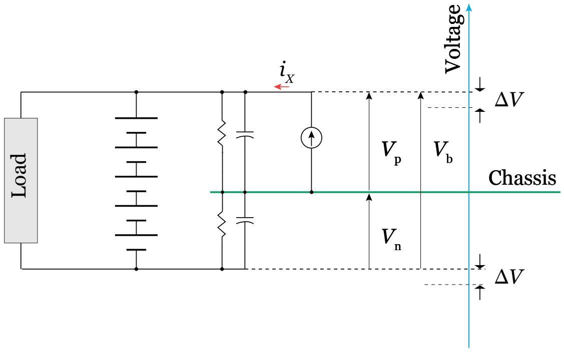


Figure 9: Signal injection method

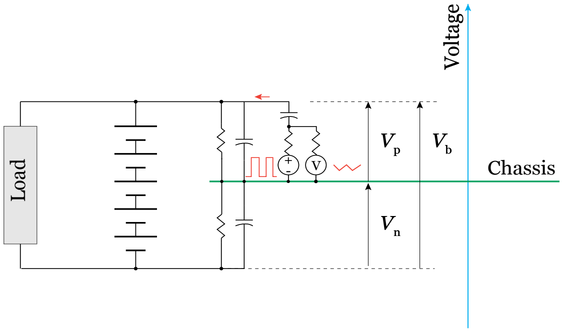


Figure 10: A variation of the injection method is applying a known square pulse through a coupling capacitor and detecting the attenuation of the signal by the isolation resistances/capacitors.

Sendyne’s SIM100

Sendyne’s patent pending method for monitoring the isolation state of the IT power system overcomes all shortcoming of the methods described in the previous section. Specifically, the SIM100 is capable of estimating accurately the state of the isolation system when the load is active and the battery voltage is continuously varying. This unique feature, while important for the safety of every IT electrical system, is especially important for the safety of systems that are engaged in commercial activities with very little down time, such as commercial vehicles and equipment.

The SIM100 is the only product in the market today that provides estimates for the isolation system capacitances. Besides the added safety provided by estimating the energy stored in them, capacitances estimation is necessary to be able to analyze the isolation system behavior dynamically and during transitions. Sendyne utilizes state-of-the-art stochastic filtering and numerical methods to evaluate the isolation state dynamically and accurately. The SIM100 provides individual estimates for each isolation resistance and capacitance along with the uncertainty in their calculation. Typical accuracy of SIM100’s estimates is better than ±5%.

SIM100 response time

The SIM100 refreshes its estimates every 500 ms. Slow changes in the system isolation state can be tracked and updated within this interval. For large changes, such as the ones described in the UL 2231 tests, the response time of the SIM100 is less than 5 s.

As can be seen in Figure 13, SIM100 provides stable and accurate results within 5 sec of the transition. Response time is well below the 10 s requirement by different standards. Subsequent estimates are updated every 500 ms. In the same chart, highlighted in grey, are the ±15% accuracy levels specified by UL 2231-1 and 2. SIM100 estimate errors are below ±3%. During the transition and while SIM100 is estimating the new isolation state, it will indicate a high level of uncertainty, so the host ECU can ignore those transition results. Similar results were obtained when operating the SIM100 of the positive side of the battery.

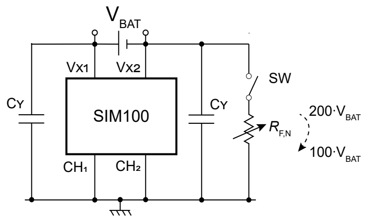


Figure 12: Circuit for testing SIM100 response time and accuracy in the successive insertion of a 200 Ohm/V and 100 Ohm/V resistor ($R_{F,N}$)

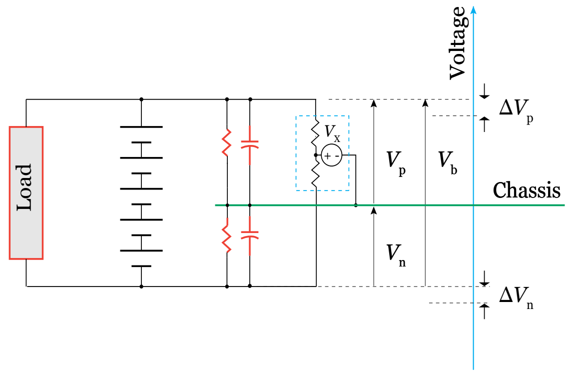


Figure 11: Sendyne’s SIM100 estimates dynamically the isolation state taking into consideration the varying battery voltage and the Y-capacitances.

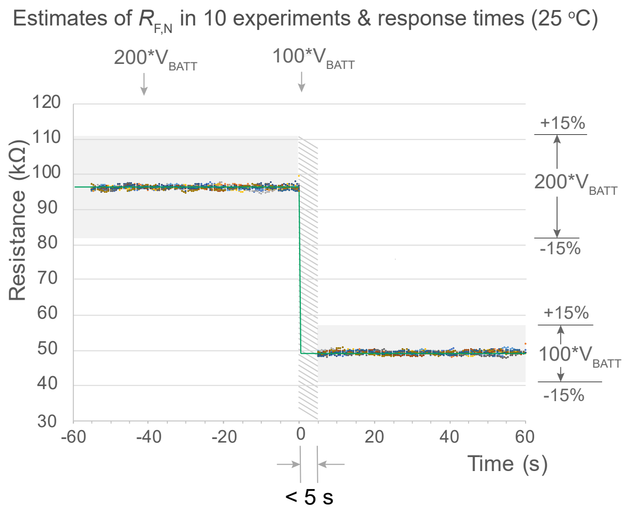


Figure 13: Estimates of $R_{F,N}$ provided in 10 successive experiments at room temperature. The green line represents the actual value of the inserted resistor. Greyed areas show UL2231-2 accuracy requirements.

Thermal stability

Per UL 2231-2, the SIM100 was tested using the test apparatus of Figure 12 at different environmental temperatures. In the following illustrations the colored dots indicate the average error at each temperature obtained through approximately 1100 reports. The experiments were repeated for different Y-capacitor values (2 x 100 nF and 2 x 1 uF). The greyed areas show the spread of error in the reports indicating the max and min error for each experiment. We illustrate the worst case errors that occur at the smaller insertion resistance $R_{F,x}$. As can be seen all errors are well below the ±15% of the UL requirements.

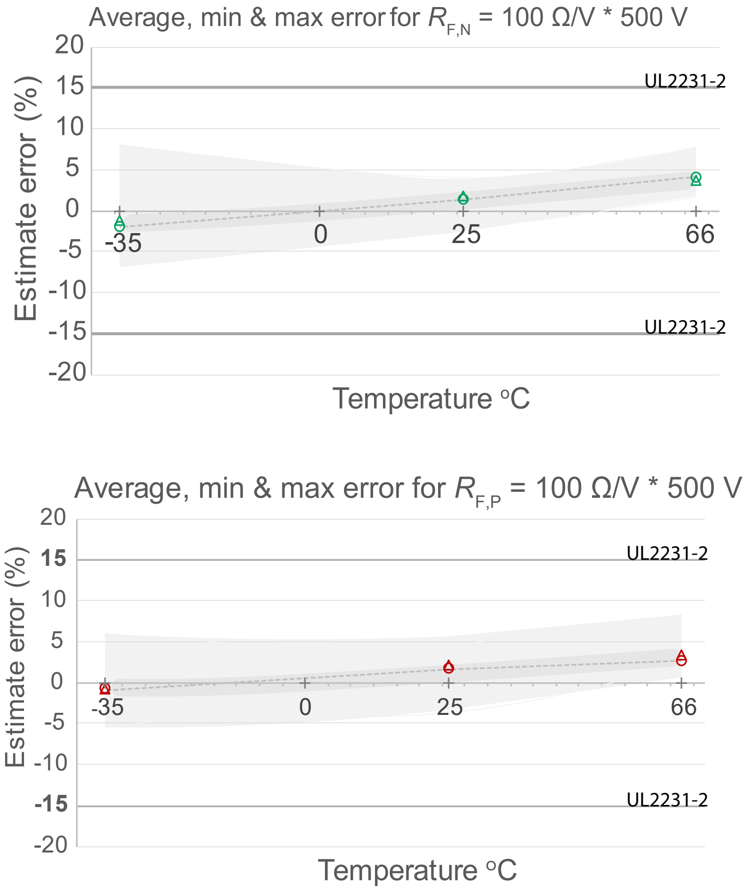


Figure 14: Inserted resistance estimate error at different temperatures

Uncertainty

The SIM100 submits along with each report an estimate of the uncertainty associated with the estimates. The uncertainty is reported as a percentage of the estimated values and takes into consideration both the measurement and processing uncertainties. Uncertainty is derived in the interval of two standard deviations (95.45% of samples) and rounded to the next higher absolute value. For example, if the uncertainty calculated is ±1.4 % it will be rounded to ±2%. The SIM100 then adds to this value another ±3% to accommodate for factors that cannot be calculated, such as part values shifting over age, etc. As a result, the uncertainty value provided is a conservative one.

An illustration of the relationship between measurements distribution and uncertainties reported is shown in Figure 15. The green vertical line shows the actual value of the isolation resistance of the test circuit. Its value is the parallel combination of the 250 kΩ inserted resistance with the 2.7 MΩ resistance of the SIM100. The red vertical line shows the average value of SIM100 reports; the actual estimate error is 1.8%. Uncertainty is estimated to ±2% and then augmented by ±3% to provide the final estimate of ±5%. As can be seen in this experiment, uncertainty provides a very conservative estimate of the reported value.

How to use the uncertainty

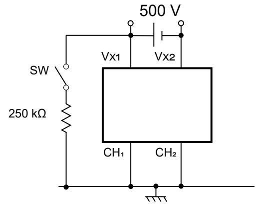
Uncertainties should be used in the most conservative way to calculate worst case scenarios. If, for example, the SIM100 reports a value of 100 kΩ with uncertainty of ±5%, the host should assume the worst case possibility that the actual isolation resistance is (100 – 5) kΩ.

Very high uncertainties

There may be instances that the SIM100 reports very high uncertainties. This may happen when there is no voltage present and there is a lot of noise in the IT system or during a large and rapid transition of isolation resistance values. During these instances, the SIM100 will flag the "High Uncertainty" bit to notify the host that these reports may be discarded.

Uncertainties in capacitance estimates

When there is no activity on the IT power system it is expected that individual capacitance estimates will have a high level of uncertainty. Nevertheless, the total value of isolation capacitance (the parallel combination of all capacitances) and the estimates for maximum energy that can be stored on them would be accurate. The uncertainty in capacitance estimation will become small (less than ±5%) as soon as there is activity on the IT power bus.



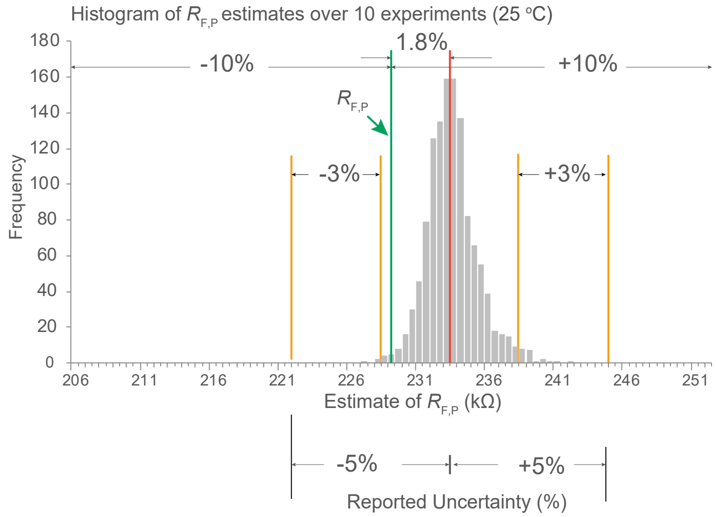


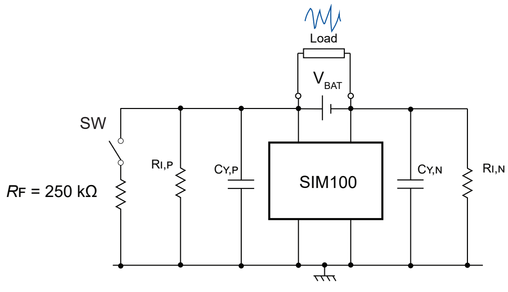
Figure 15: Distribution of reports over 1200 measurements and illustration of uncertainty reported by SIM100

Variable loads

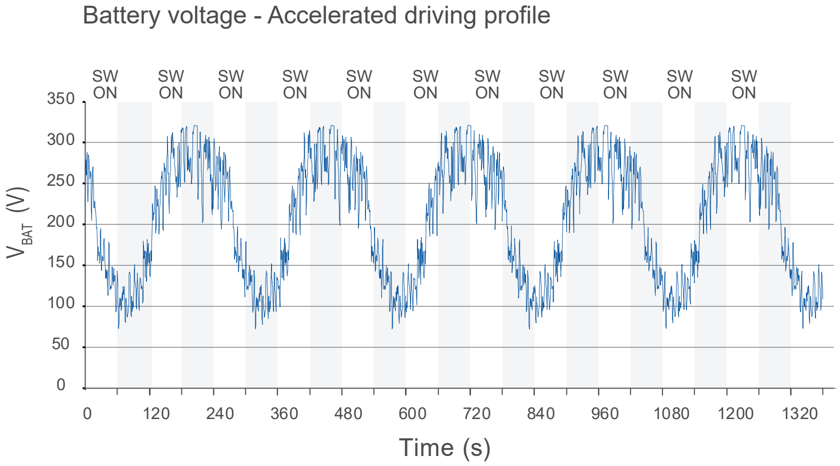
The SIM100 is the only product today that can operate flawlessly in extremely noisy environments when the load of the IT power system is active. This is an important safety feature especially in commercial environments where the electrical equipment is in use most of the time. The SIM100 will provide accurate estimates even while the power system experiences violent swings of 10s or 100s of Volts.

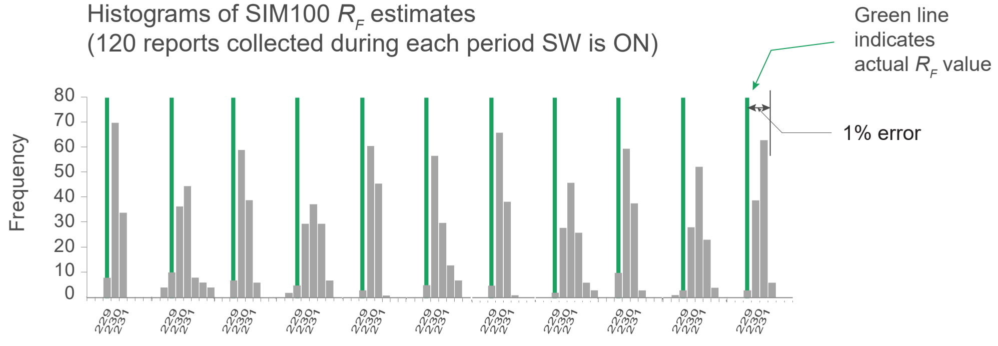
Figure16 shows the test setup and SIM100 responses under a battery load corresponding to an accelerated driving profile. In the test circuit a 250 kΩ resistor is connected and disconnected every 60 s. At the battery terminals an accelerated driving profile load is simulated. The resulting battery voltage is shown in the Battery voltage chart. The greyed areas indicate the 60 s intervals when the resistor is disconnected. The histogram shows the distribution of SIM100 reports in the periods when the resistor is connected.

The green vertical lines in the histogram show the actual isolation resistance when the 250 kΩ resistor is connected. As can be seen in the histograms, the error between the average reported value and the actual value is less than 1%.



Test Circuit


Battery voltage - Accelerated driving profile


Histograms of SIM100 R_F estimates
(120 reports collected during each period SW is ON)

Green line indicates actual R_F value

1% error

Figure 16: Distribution of reports over 1200 measurements and illustration of uncertainty reported by SIM100

SIM100 Self-testing

The SIM100 performs a continuous self-testing process. During the self-test, the SIM100 checks the validity of all connections and the integrity of all references and critical hardware components. Details on the self-test process can be found in the "SIM100 Safety Manual"

Field upgradeable

The SIM100 comes equipped with Sendyne's proprietary boot-loader. The boot-loader relies on AES128 cryptographic standard to ensure that firmware updates are not compromised. It can be accessed through CAN -bus and allows field upgrades of the SIM100 software.

CAN communications

The SIM100 CAN protocol description can be found in the "SIM100 CAN 2.0B Protocol Document" and the "SIM100.dbc" files. The SIM100 can be ordered with CAN running at 250 kb/s or 500 kb/s. The SIM100MOD can be ordered with or without CAN bus termination resistors. For information on ordering see the "Ordering information" section of the SIM100MOD datasheet.

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