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Cosmic Ray Failures in Power Electronics

1. General 1
   1.1 Cosmic rays on earth 1
   1.2 Cosmic rays and power electronics 2
2. Measuring Single Device Cosmic Ray Failure Rates 3
   2.1 Measuring cosmic ray failure rates under typical radiation conditions 3
   2.2 Accelerated measurements of cosmic ray failure rates 4
3. Calculation of Module and Application Failure Rate 4
   3.1 Module failure rate 4
   3.2 Cosmic ray failure rates of applications 5
      3.2.1 Voltage 6
      3.2.2 Temperature 6
      3.2.3 Elevation 6
      3.2.4 Other dependencies 7
   3.3 Examples 7
      3.3.1 Uninterruptible power supply (UPS) 7
      3.3.2 1000 V solar inverter 8
4. 2-Level (2L) vs. 3-Level (3L) topologies under the aspect of cosmic ray failures 9
   4.1 2L vs. 3L NPC 9
   4.2 2L vs. 3L TNPC 10

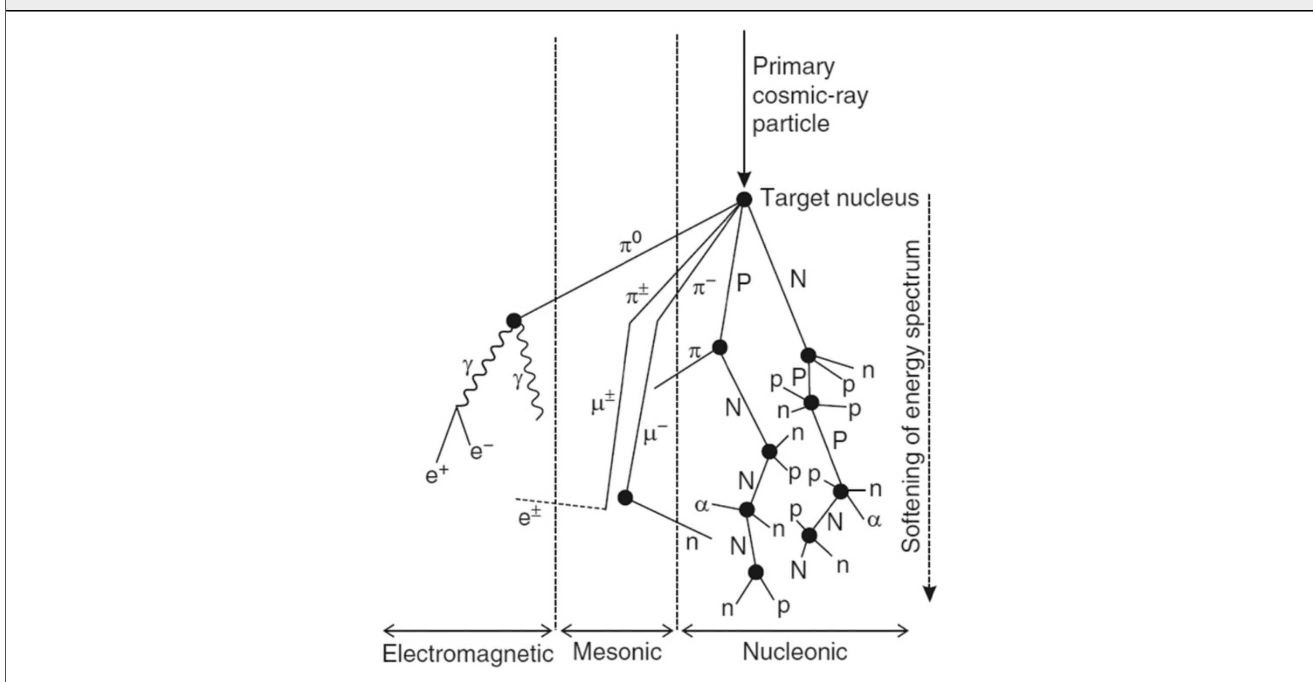
1. General

The useful life of a power electronic component is generally considered to be delimited by early-life failures and end-of-life failures. However, random failures must not be neglected when considering the reliability of a power electronic system. Single event burnouts (SEB) due to cosmic rays are a typical contribution to the random failure rate. While the single event is random, the probability of occurrence, that is, the failure rate of an inverter can be predicted from the application conditions of the inverter. This application note presents the basic approach of how to estimate the cosmic ray failure rate of an application, whether under design or already existing. More details on the failure mechanism, related reliability testing and literature can be found in [3].

1.1 Cosmic rays on earth

High-energy particles are ubiquitous in space. They constantly reach the earth from all directions. On their path towards the surface, they eventually collide with an atomic nucleus in the outer atmosphere. This collision creates a multitude of secondary particles which carry away the energy of the primary particle. Generally, these secondary particles have sufficient energy to create even more particles in subsequent collisions (Figure 1). Consequently, avalanche multiplication takes place while at the same time the particle intensity is reduced by absorption in the atmosphere. The description already implies that the number of secondary particles (generally called “secondary”, even if created in a multi-stage process) arriving at the earth’s surface depends on the elevation of a certain location. A comprehensive account of the process can be found in [4].

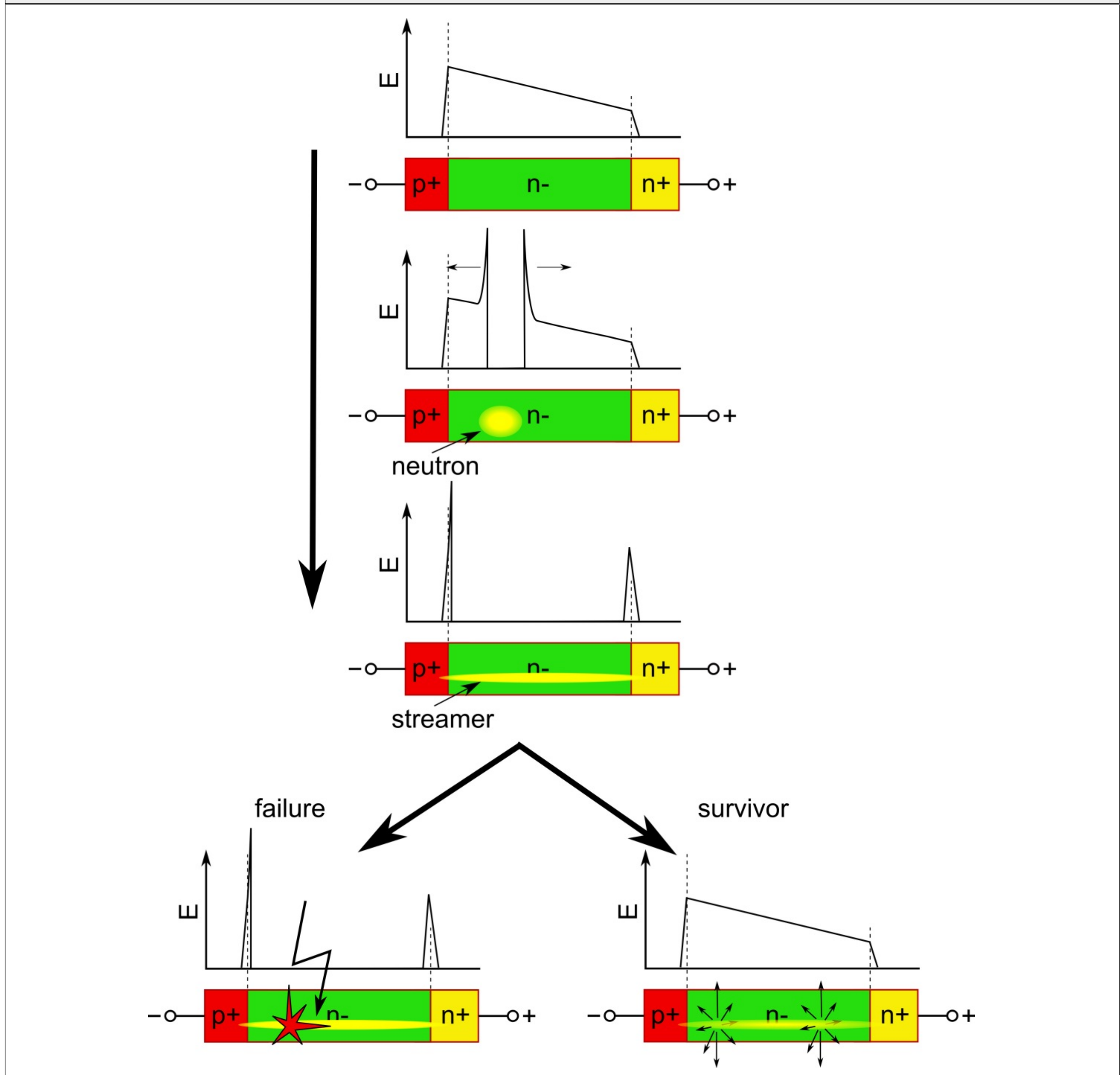
Figure 1: Avalanche generation of particles from primary cosmic rays (picture from [5])



1.2 Cosmic rays and power electronics

As secondary cosmic particles arrive at the earth's surface, they interact with the dense matter on the ground. For a power electronic device, this means that there is a certain probability of being hit by such a particle in the blocking region, as depicted in Figure 2. If it does so, it eventually deposits its energy of typically several ten to several hundred MeV (100MeV ≈ 16pJ) in the device by creating electron-hole pairs (that is, charge carriers) over a distance of some micrometers. An in-depth analysis of the spectrum and composition of the secondary cosmic radiation shows that neutrons are by far the most harmful component of cosmic radiation, since they are the only ones present in sufficient numbers and at the same time capable of depositing all their energy in one single spot [6]. In a device in conduction state, some extra charge carriers will do no harm; however, in the blocking state, a plasma of charge carriers in the field zone shields its interior from the electric field. The voltage drop will occur at pronounced field spikes at the edge of the plasma instead. These field spikes might exceed the critical field strength of the semiconductor and thus create more charge carriers via impact ionization, thereby extending the plasma. In this self-sustaining process, a so-called streamer develops which locally shorts the device. All this happens within less than one nanosecond. Afterwards, the charge carriers might diffuse away radially quickly enough such that the shorted region returns into its blocking state. However, if the diffusion process is too slow, sufficient energy is deposited in the device to melt the device locally and the device permanently loses its blocking capability. In an application, this leads to a permanently damaged chip and, in case of no sufficiently fast short circuit protection, to an explosion. In cosmic ray failure rate measurements, the devices are usually protected by a fuse and a molten channel through the semiconductor material can be found in a post mortem analysis.
From this description, it is clear that the rate at which mortal hits happen is directly proportional to the area (more exactly volume, but this is in turn proportional to the area in vertical devices) over which a certain electric field extends: twice the area has twice the failure rate. Furthermore, it can be understood that cosmic ray failures only occur in the region of a chip were an intense electric field is present. This is not only the active area, but can also be the edge termination [7]. For simplicity, failure rates are thus usually specified per total chip area. This will introduce a certain (usually acceptable) inaccuracy, as failure rates for of the edge termination and the active area generally differ. We have not observed edge termination failures of SEMIKRON CAL diodes in any of our experiments. Yet, we will adhere to the convention of specifying failure rates per total chip area.

Figure 2: Cosmic ray failure mechanism



2. Measuring Single Device Cosmic Ray Failure Rates

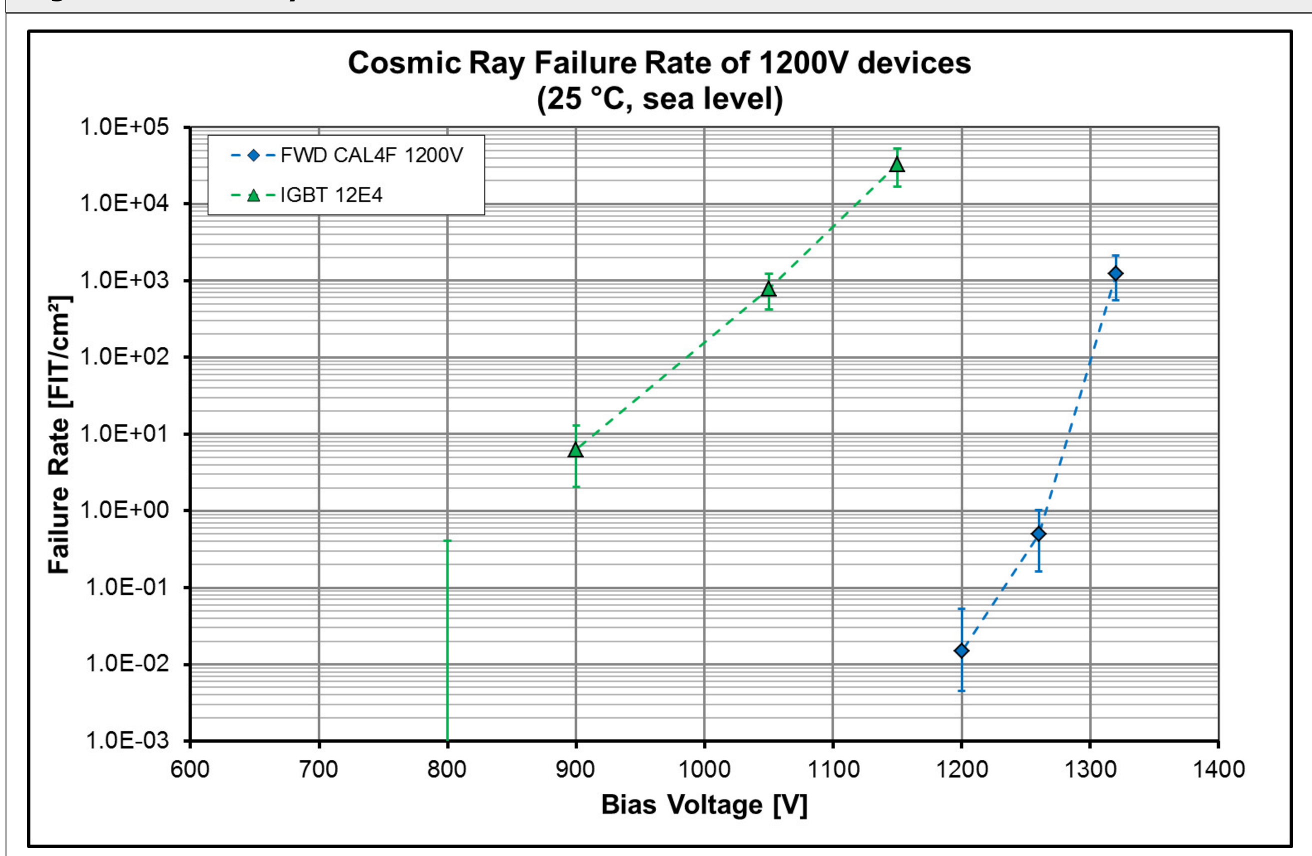
2.1 Measuring cosmic ray failure rates under typical radiation conditions

The cosmic ray failure rate of a certain device technology can be measured by reverse biasing a number of devices in this technology and waiting for failures to happen. The condition of the devices can be monitored with a data logger, for example, by measuring the reverse current. Variations of parameters like the reverse voltage and the temperature require separate runs, one for each combination of parameters. This approach is feasible for sufficiently high failure rates usually only obtained close to avalanche breakdown voltage V_{BR}. However, one cannot define a "voltage acceleration factor" to determine the device failure rate at application-relevant voltage levels from measurements close to V_{BR} of the device; instead, the failure rates also have to be measured at lower levels. Here accelerated testing becomes a necessity to avoid years of measurement time on excessively large numbers of devices. For instance, to measure a failure rate of 10FIT/cm² without acceleration would require 100 000 chips with 1cm² area to be measured for 1 year to obtain a certain statistical confidence in the result (~8-9 failures).

2.2 Accelerated measurements of cosmic ray failure rates

At high elevation, the flux of cosmic radiation increases. Therefore, high altitude testing offers an acceleration compared to (close to) sea level testing. The advantage of this approach is the constant presence of a realistic spectrum of cosmic neutrons, and several manufacturers use this approach by testing, e.g., at the German mountain Zugspitze (2962m above sea level (a.s.l.)) or at the Jungfraujoch (3466m a.s.l.) in Switzerland. However, the drawback is a tedious accessibility and an acceleration factor hardly above 10 (see also Figure 5).
Therefore, testing with high energy proton or neutron beams has been established. The available fluxes offer acceleration factors of up to 10^{10}. These enable the experimenter to conduct single runs in half an hour and sweep a certain range of parameters of bias voltage and junction temperature within one measurement campaign. The results for an IGBT 12E4 and a CAL4F free-wheeling diode (FWD) are depicted in Figure 3 below. These chip technologies are typically combined in latest generation SEMIKRON power modules.
Please note that the FWD was measured at and above the specified blocking voltage to obtain failures. By contrast, the failure rate of the IGBT close to 1200V is six to seven orders of magnitude higher and it will therefore determine the failure rate of modules with this chip set. This is, however, not the case for all combinations of IGBTs and FWDs; consequently, the failure rate of both IGBT and FWD must be known to determine module failure rates.

Figure 3: Cosmic ray failure rate of a 1200V IGBT and FWD



3. Calculation of Module and Application Failure Rate

3.1 Module failure rate

Failure rates of chip technologies are usually specified per cm² chip area for a certain blocking voltage and temperature. Let us consider a hypothetical 1200V/300A power module in half bridge configuration with 10cm² IGBT area and 6cm² FWD area in total. Assuming further the specific failure rates shown in Figure 3 to apply, one could try to calculate the module failure rate at 900V DC link voltage from the individual failure rates of the IGBT (6FIT/cm²) and the FWD (<0.02FIT/cm²) by simply multiplying the area with the specific failure rate: (10*6+4*0.02)FIT = 60FIT. Here, the contribution of the FWD is neglected, as the remaining error in the IGBT failure rate is much larger than the total contribution of the FWD. However, this approach is misleading. During operation of the half bridge, each switch will block 900V for half the

time, while the other one is conducting. Since at every point in time, only one switch (with half the total area) is in blocking mode, also the total failure rate will only be half as much, i.e., 30FIT. In the off-state, with both switches turned off, the total area is in blocking mode, but the voltage drop is divided (roughly) evenly among the two switches, so that every switch blocks only 450V; at this voltage level, the failure rate will usually be negligible.
In addition to the discussed half bridge configuration, other module topologies are also common, e.g. modules for multilevel inverters, boost operation, etc. Therefore, SEMIKRON decided not to specify failure rates on a module level. Rather, SEMIKRON can provide product information sheets as shown in Figure 4 on request in which the failure rates are given for each logic electric unit (usually a switch consisting of an IGBT and antiparallel FWD) within the module.

Figure 4: Product information sheet for the cosmic ray failure rate of the SEMiX603GB12E4p

SEMiX603GB12E4p

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Cosmic ray failure rates of the module — Date: 2016-04-20

Conditions	
Elevation above sea level	0 m
Junction Temperature	25 °C
Duty Cycle	50 %

1200V Switch					
Voltage	800 V	900 V	1000 V	1100 V	
Failure rate / switch	0.91 FIT	7.3 FIT	640 FIT	14000 FIT	

Failure rates are given per switch. Failure rates need to be corrected for actual duty cycle and DC link voltage.

Data interpolation

There is no general physical model to interpolate between the measured failure rates λ_1 and λ_2 at voltages V_1 and V_2, respectively. Based on experience, we use and recommend the following interpolation: $\lambda(V) = \lambda_1 \left(\frac{\lambda_2}{\lambda_1}\right)^{\frac{V-V_1}{V_2-V_1}}$ for $V_1 \leq V \leq V_2$.
Extrapolation is deprecated.

Elevation dependence

The failure rate at a certain elevation h (in meters) can be estimated by the following formula introduced by ABB:

$$\lambda(h) = \lambda_0 \cdot \exp(7 - 7 \cdot (1 - h/44300)^{5.26})$$

with λ0 the failure rate at sea level. This formula applies to ground-based installations only and must not be applied for avionic or space applications.

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3.2 Cosmic ray failure rates of applications

The cosmic ray failure rate depends mainly on three parameters: voltage, temperature, and elevation.

3.2.1 Voltage

In general, the failure rates are specified for certain voltages. If the failure rates λ_1 and λ_2 are specified for the voltages V_1 and V_2, respectively, then we recommend an interpolation which corresponds to a straight line in a log scale plot:

$$\lambda(V) = \lambda_1 \left(\frac{\lambda_2}{\lambda_1}\right)^{\frac{V - V_1}{V_2 - V_1}}$$

for $V_1 < V < V_2$. Extrapolation is deprecated, as it is principally unknown how the curvature of the failure rate plot changes and errors can quickly amount to more than three orders of magnitude because of the quasi-exponential voltage dependence of the failure rate.

Switching overvoltage

In an actual inverter operation, voltage overshoots above the DC voltage occur at the silicon dies during each turn-off event due to the stray inductance of the DC link connection. However, the local electric field strength during turn-off (as relevant parameter for the cosmic ray failure rate) differs from the local electric field strength if the same voltage is applied statically. In a first approximation, one can try to estimate the cosmic ray failure rate of a device during turn-off by assuming the voltages to act like static voltages and integrate the failure rate over the time of the switching event. It was shown for 6.5kV devices that this estimate can be too low, as the failure probability depends on the electric field inside the device, which is dynamically enhanced during turn-off [9]. However, this effect is most pronounced in high voltage devices, and even there the contribution was not dominant. Consequently, we recommend to use abovementioned approximation for our devices up to 1700V nominal blocking voltage.

3.2.2 Temperature

With rising temperature, the dielectric strength of silicon increases. According to the description of the cosmic ray failure mechanism in the first section, one would therefore expect a lower failure rate at elevated temperatures, because the avalanche mechanism generating a streamer is shifted to higher electric fields. However, other effects can counteract this increasing voltage stability. For example, the sensitivity to latch-up is generally higher at higher temperatures, so that a streamer which is not destructive at low temperatures can become so at elevated temperatures. Dedicated measurements show no universal behavior, rather it seems that the temperature dependence is different for each device technology. Unfortunately, data on the real temperature dependence is still sparse. Therefore, we recommend to use ABB's "temperature factor" ([8]) given by

$$F(T) = e^{-\frac{T_j - 25°\text{C}}{47.6°\text{C}}}$$

which estimates the temperature dependent failure rate of each device by simply multiplying the failure rate at room temperature with $F(T)$, keeping in mind its limited accuracy.

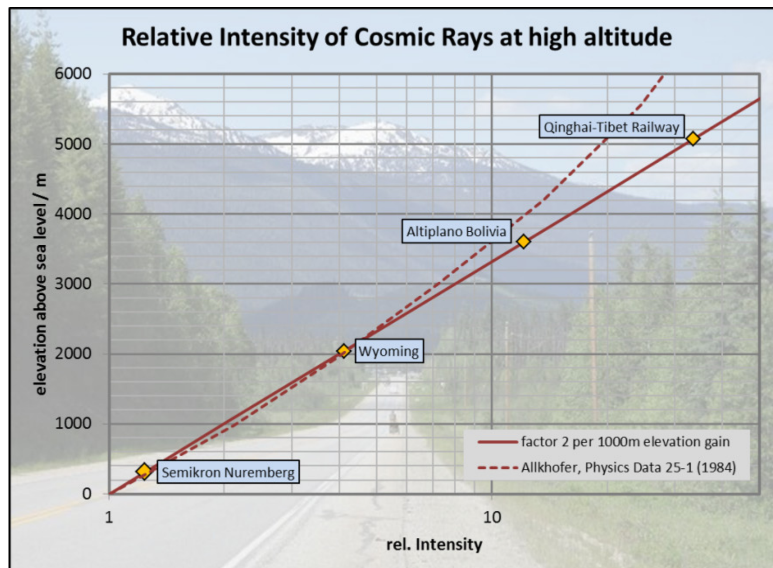
3.2.3 Elevation

As already mentioned in the first section, the intensity of the cosmic rays increases with increasing altitude because there is less residual atmosphere to shield the radiation. At even higher altitudes, the intensity decreases again because the avalanches have not grown to full size yet. For non-airborne applications only the first effect of less shielding is relevant and the intensity approximately doubles for a gain of 1000m in altitude. Therefore, a failure rate given for sea level can simply be rescaled with a factor A to obtain the failure rate at a given elevation h above sea level (a.s.l.):

$$A = 2^{h/1000\text{m}}$$

Compared to measurement data [10], this approximation induces less than 10% error up to 3000m a.s.l. and overestimates (that is, gives a conservative estimate) the failure rate at 5000m a.s.l. by a factor of two (Figure 5).

Figure 5: Elevation dependence of the cosmic ray intensity



3.2.4 Other dependencies

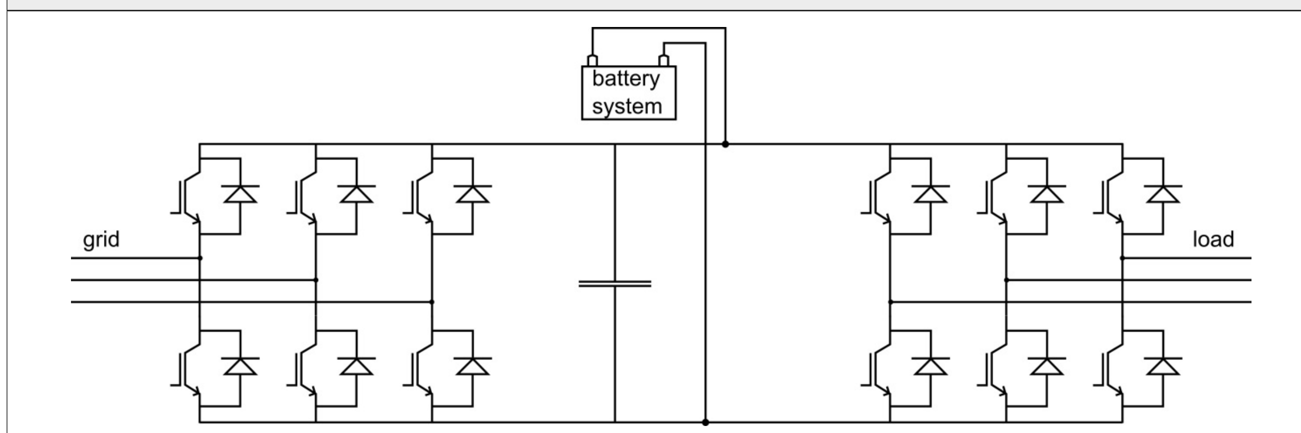
In addition to the factors discussed above, there are several other parameters that the cosmic ray failure rate depends on to a lesser degree. One is the 11 year solar cycle: while the sun is not a source of harmful cosmic rays itself, the solar wind changes within this cycle. This influences the magnetic field of the earth, which in turn determines how well charged primary cosmic rays are deflected. The intensity varies countercyclically by about 20% from minimum to maximum within a solar cycle, that is to say, maximal solar activity corresponds to a minimum in the cosmic ray flux. For similar reasons, the intensity also depends on magnetic longitude and latitude of a location on earth. For example, the neutron flux in Tokyo (25°N geomagnetic latitude) is about 40% lower than the neutron flux in New York (52°N geomagnetic latitude); this is already close to maximal obtainable difference of about 50%. Finally, the shielding can also play an important role, in particular if the installations are typically found in basements of high rise buildings, in mines, etc. For more details, refer to [4]. Lastly, a common question asks about a diurnal cycle in the cosmic ray intensity and consequently the failure rate. As mentioned above, the sun is not the source of the primary cosmic rays which generate high energy neutrons, therefore such a cycle does not exist.
The dependencies discussed in this paragraph are often neglected, as the calculation of cosmic ray failure rates is usually only an order-of-magnitude estimate

3.3 Examples

3.3.1 Uninterruptible power supply (UPS)

Assume a simple case of a three-phase online UPS with an inverter and a converter and a battery voltage of 900 V. Assume further that the inverter and the converter both consist of three half bridge modules SEMiX603GB12E4p each. The cosmic ray failure rate for a switch in this module at 900V and room temperature can be found in Figure 4: 7.3FIT. This failure rate is already given for a duty cycle of 50%, which corresponds to normal half bridge operation. Therefore, the total failure rate of this inverter due to cosmic rays is expected to be 6 modules * 2 switches/module * 7.3FIT/switch = 87.6FIT.

Figure 6: Circuit diagram of a simple UPS system



3.3.2 1000 V solar inverter

Solar inverter manufacturers would like to implement inverters with a rating of 1000V DC with components with 1200V nominal semiconductor blocking voltage. This is electrically feasible, as the highest DC voltages occur only at low currents, so that the switching overvoltage remains low. As soon as the current increases, the DC voltage from the photovoltaic cells drops and normal operation is far below 1000V. We will assume a simplified voltage profile shown in Table 1 (for profiles from real applications, see e.g. [11]).

Table 1: Hypothetical distribution of DC voltages in a photovoltaic system with maximum 1000V DC voltage

Voltage [V]	Time [h/y]	Time percentage
1000	2	0.023%
950	20	0.228%
900	200	2.283%
850	2000	22.831%
800 and less	2158	24.635%
Turned off at night	4380	50.000%

With such a table, one can estimate the cosmic ray failure rate of a photovoltaic inverter. Assuming an inverter consisting of 12 modules SEMiX603GB12E4p, the failure rates can again be found in Figure 4. By summing up the failure rates weighted with their share of operation time results in the total failure rate of the inverter of roughly 30FIT as shown in Table 2.

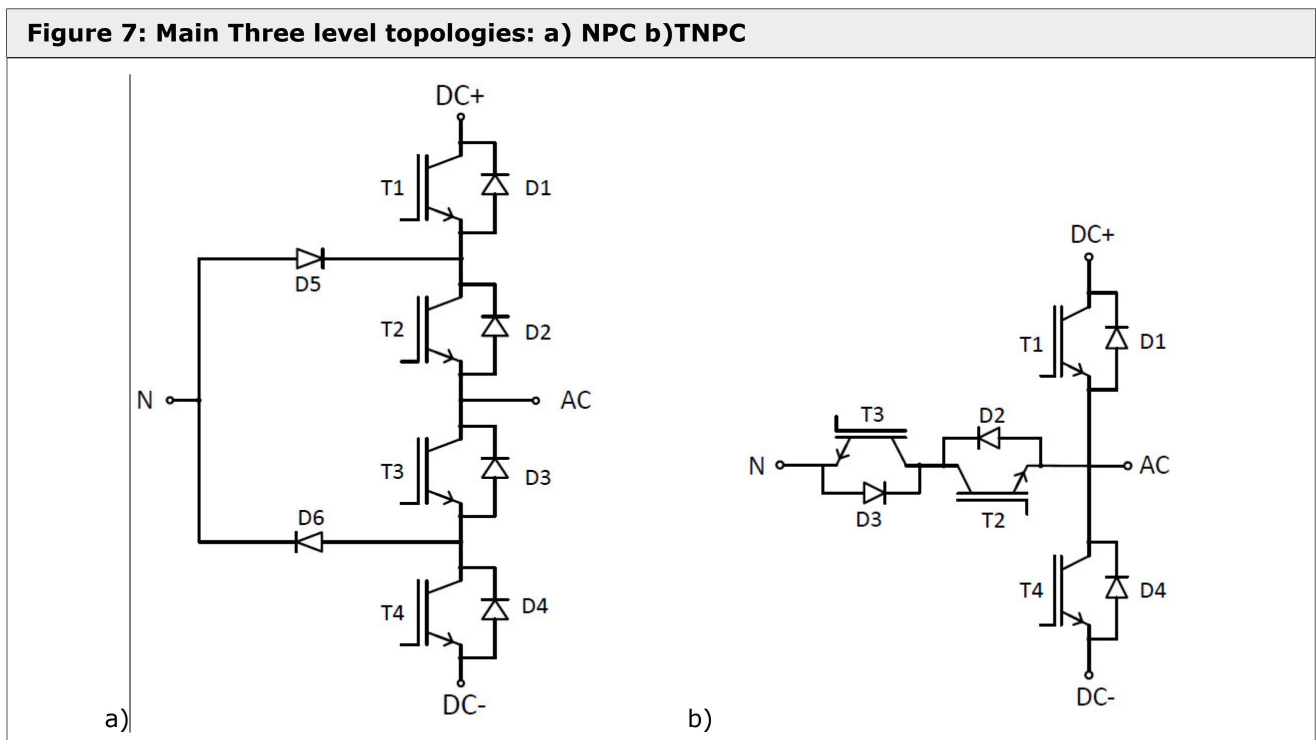
Table 2: Resulting failure rates for the system from Table 1

Voltage [V]	Failure rate [FIT]	Time percentage	Weighted failure rate [FIT]
1000	15360	0.023%	3.51
950	1640	0.228%	3.74
900	175.2	2.283%	4.00
850	61.8	22.831%	14.11
800 and less	21.8	24.635%	5.37
Turned off at night	0	50.000%	0.00
		Total failure rate:	**30.73**

4. 2-Level (2L) vs. 3-Level (3L) topologies under the aspect of cosmic ray failures

Recently, 3L topologies have gained increasing attention, in particular in applications with high DC voltage, which are also most critical with respect to cosmic ray failures. So how does the cosmic ray failure rate of a three-level inverter compare to the cosmic ray failure rate of a two-level inverter? The two most common topologies for 3L inverters are shown in Figure 7, the neutral point clamped (NPC) and the T-type neutral point clamped (TNPC). (A detailed description of both topologies and their respective advantages can be found in [12].) In addition, semiconductors are available in three main voltage classes: 650V, 1200V, and 1700V. Two-level modules as well as three-level modules are generally equipped with switches from these voltage classes.

Figure 7: Main Three level topologies: a) NPC b)TNPC



4.1 2L vs. 3L NPC

In the NPC topology, all semiconductors have the same blocking voltage rating and, as always two semiconductors block the full DC voltage, a module nominally can have up to twice the blocking voltage rating as the used semiconductors.

Table 3: Blocking voltage of the semiconductors in 2L modules and their 3L NPC counterparts

Typical upper limit DC voltage	2L module		3L NPC module	
	Voltage class	Expemplary module	Voltage class	Exemplary module
480V	650V	SKiiP38GB07E3V1	650V (hypothetical)	none
1000V	1200V	SKiiP38GB12E4V1	650V	SKiiP39MLI07E3V1
1500V	1700V	SKiiP38GB17E4V1	1200V	SKiiP 39MLI12T4V1

A replacement of the 650V 2L module will not be discussed as much of the benefit of a 3L solution is lost if the semiconductor blocking voltage is not adapted. Generally, the maximum DC voltages considered for 1200V modules and 1700V modules are 1000V and 1500V, respectively. In particular in photovoltaic applications, these voltage levels are under discussion. This means that in a 3L module, the 650V dies and the 1200V dies have to block half the DC voltage, i.e., a maximum of 500V and 750V (not taking into account the switching overvoltage), respectively. At these voltage levels, the failure rate of all

semiconductors used by SEMIKRON is below 1FIT/cm², which is usually negligible. Consequently, 3L NPC modules can be considered immune to cosmic ray failures, in contrast to their 2L counterparts. For instance, at 1000V and normal conditions (room temperature, sea level, 50% duty cycle), the SKiiP38GB12E4V1 has a failure rate of 310FIT per switch, while that of the SKiiP39MLI07E3V1 is below the measurement limit of ~1FIT per switch at 500V blocking voltage.

4.2 2L vs. 3L TNPC

The TNPC topology presents a different situation. Here, the semiconductors in the vertical leg have to block the full DC voltage. Therefore, the blocking voltage rating of those semiconductors is equivalent to the blocking voltage rating of the whole module. By contrast, the semiconductors of the horizontal leg have to withstand only half the DC voltage and can therefore have a lower blocking voltage rating. The equivalence classes are:

Table 4: Blocking voltage of semiconductors in 2L modules and their 3L TNPC counterparts

Typical upper limit DC voltage	2L module		3L TNPC module		
	voltage class	Exemplary module	Vertical leg voltage class	Horizontal leg voltage class	Exemplary module
480V	650V	SEMiX305GD07E4	650V (hypothetical)	650V (hypothetical)	none
1000V	1200V	SEMiX453GB12E4p	1200V	650V	SEMiX405TMLI 12E4B
1500V	1700V	SEMiX453GB17E4p	1700V	1200V	SEMiX305TMLI 17E4C

In these configurations, the voltages applied to the horizontal leg correspond to the voltages in an NPC semiconductor module. As detailed above, these are negligible for all voltages encountered in typical applications. Therefore, the cosmic ray failure rate of the 3L TNPC module is determined solely by the failure rate of the semiconductors in the vertical leg. Even though their blocking voltage class and the applied voltage are identical to the 2L module, there are differences in the failure rate for two reasons:

a) At typical switching frequencies, a TNPC module usually delivers roughly 75% of its nominal current as RMS current, while a 2L module only delivers roughly 50%. Therefore, for the same power rating of the inverter, only 65% of the chip area is required in the vertical leg of a 3L module compared to a 2L module. As the cosmic ray failure rate depends linearly on the chip area, the failure rate of the 3L TNPC module will also be only 65% of that of a corresponding 2L module.
b) In a normal half bridge configuration, each switch has to block the full DC voltage half the time. By contrast, in a TNPC module each switch in the vertical leg has to block the full DC voltage only during 25% of the full operation time (+/-5%, depending on the modulation ratio). In the remaining 50% of the time, both switches of the vertical leg are in blocking mode and share the DC voltage drop. During that time, failure rates are even lower than in the horizontal leg (same blocking voltage, but higher voltage rating in the vertical leg). Thus, the relevant blocking time in a 3L TNPC is about half of that in a 2L module; consequently, this effect reduces the failure rate is by a factor of 2.

Combining these two effects, one can say that as a rule of thumb, an inverter designed with 3L TNPC modules has about 33% of the cosmic ray failure rate compared to an inverter of the same power rating designed with a 2L module with the same semiconductor technology. For instance, if the solar inverter discussed in section 3.3.2 was realized as a three-level solution with the same chip technology, its cosmic ray failure rate would drop from approx. 19FIT to approx. 6FIT.

Figure 1: Avalanche generation of particles from primary cosmic rays....2
Figure 2: Cosmic ray failure mechanism 3
Figure 3: Cosmic ray failure rate of a 1200V IGBT and FWD 4
Figure 4: Product information sheet for the cosmic ray failure rate of the SEMiX603GB12E4p....5
Figure 5: Elevation dependence of the cosmic ray intensity 7
Figure 6: Circuit diagram of a simple UPS system 8
Figure 7: Main Three level topologies: a) NPC b)TNPC 9

Table 1: Hypothetical distribution of DC voltages in a photovoltaic system with maximum 1000V DC voltage ....
Table 2: Resulting failure rates for the system from Table 1 8
Table 3: blocking voltage of the semiconductors in 2L modules and their 3L NPC counterparts 9
Table 4: blocking voltage of semiconductors in 2L modules and their 3L TNPC counterparts 10

Symbols and Terms

Letter Symbol	Term
FIT	"Failures in Time": 1FIT corresponds to one device failure in 10^9h of operation
Switch	IGBT + antiparallel FWD
V_{BR}	Avalanche breakdown voltage
SEB	Single Event Burnout

A detailed explanation of the terms and symbols can be found in the "Application Manual Power Semiconductors" [2]

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