



Single Event Burnout in DC-DC converters for the LHC experiments

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Abstract— High voltage transistors in DC-DC converters are prone to catastrophic Single Event Burnout in the LHC radiation environment. . This paper presents a systematic methodology to analyze single event effects sensitivity in converters and proposes solutions based on de-rating input voltage and output current or voltage.

I. INTRODUCTION

EXPERIMENTS for the Large Hadron Collider (LHC), the new particle accelerator under construction at the European Center for Nuclear Research (CERN), are facing new challenges in the design of electronics systems. As an example, all the electronics located inside and around the LHC detectors has to operate reliably in a radiation environment during the LHC lifetime of 10 years. Due to the huge size of the detectors and the experimental halls where they are located, power supply systems are preferentially positioned around the detector and as close as possible to the front-end electronics, in a region still exposed to relatively high particle fluxes. In the periphery of the Compact Muon Solenoid (CMS) detector, the Total Ionizing Dose (TID) levels foreseen are negligible, even for commercial-of-the-shelf (COTS) components, typically being below 1 krad (SiO_2). However, the abundance of high-energy neutrons is a serious threat to the reliable operation of high-voltage power devices. Monte-Carlo simulations estimate a total fluence over 10 years of operation of about $1.7 / 3.4 \times 10^8 \text{ n/cm}^2$ with energy above 20 MeV. In fact, the neutron spectrum extends to the GeV region, and peaks at about 60-100 MeV. [1]

A proposed topology for direct-current (DC) low-voltage power distribution consists of AC/DC converters located in the control room that rectify the three phase mains and generate a primary DC voltage of about 200-300V. Each rectifier supplies several DC-DC converters located in the

detector-hall near the front-end electronics. Switching regulators then convert the high voltage into appropriate low voltages that are locally distributed to the detector read-outs. The DC-DC converters are COTS components that have to operate reliably in the neutron environment described above and they have to be tested to validate their operation and ensure their reliability in a representative radiation environment.

One family of converters fulfilling the electrical specifications for this application is produced and commercialized by VICOR [15]. The salient characteristics of these units are a compact design, low cost, high efficiency and wide variety of input and output voltage and power capability. In this work, we have studied the effect of proton irradiation on these devices. In particular, we have identified and characterized the sensitive component determining the observed radiation response of the converters, and defined the appropriate de-rating to be applied for reliable operation of the parts.

II. THE VICOR DC-DC CONVERTER

A. Generalities

The VICOR converter is a Forward Quasi-Resonant converter with secondary-side resonance operating in half-wave mode [2]. Figure 1 depicts the schematic diagram of such topology. The converter transfers energy from the primary side to the secondary side when the switching transistor Q is turned ON during a fixed period of time T_{on} . This energy is coupled through a resonant circuit composed of the inherent series parasitic inductance of the transformer L_r and the capacitor C_r in the secondary. Figure 2 shows the most important converter waveforms. During T_{on} , the switch current follows a half-sinusoidal wave defined mainly by the elements L_r and C_r . This current starts from zero when the transistor is turned ON describing a positive half cycle that ends-up when it turns negative, cutting-off the diode $D1$. This transferred energy is stored in the output filter and consumed by the load circuit. At the end of the time interval T_{on} , the switching transistor Q is turned OFF when current is still flowing through it. This magnetizing current and the magnetic energy still stored in the transformer cannot be reduced to zero too quickly without generating over-voltages. To avoid them, the third coil in the transformer and the reset circuit allows this magnetic energy to be discharged during the time the principal transistor Q is in the OFF state.

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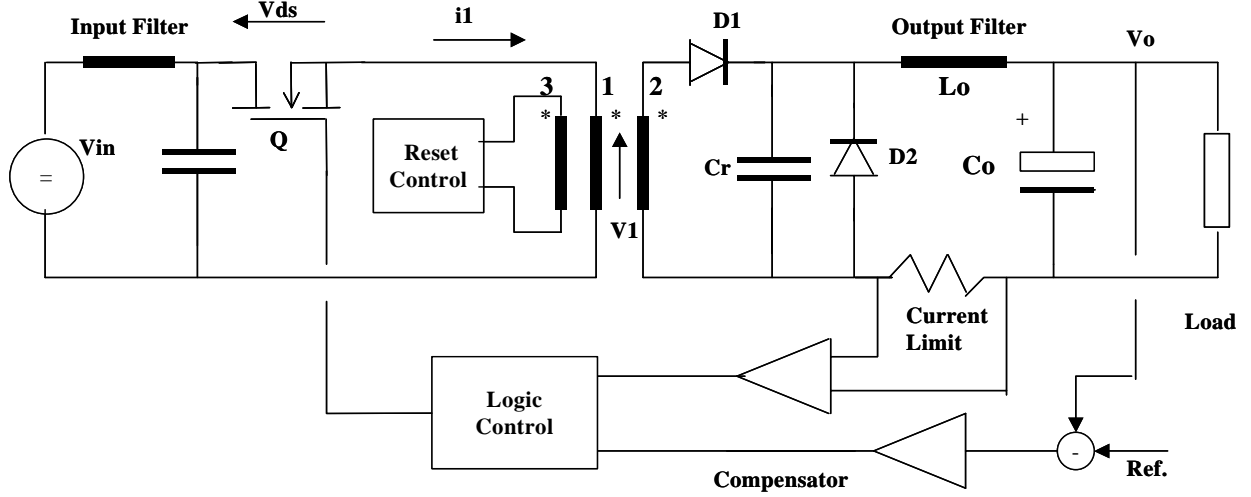


Fig. 1: Schematic diagram of the VICOR regulator

During the time T_{off} , the switching transistor is turned OFF and the primary circuit is disconnected from the secondary side. In this interval, only the energy stored in the output filter is consumed by the load. The complete process is repeated cyclically with a period $T = T_{on} + T_{off}$. The converter output voltage is regulated by balancing the primary energy, transferred when the transistor Q is ON, with the power consumed by the load. The circuit regulates the output voltage via a feedback circuit that adjusts the T_{off} duration. This time interval T_{off} depends mainly on external factors such as the input voltage, output voltage and the load condition.

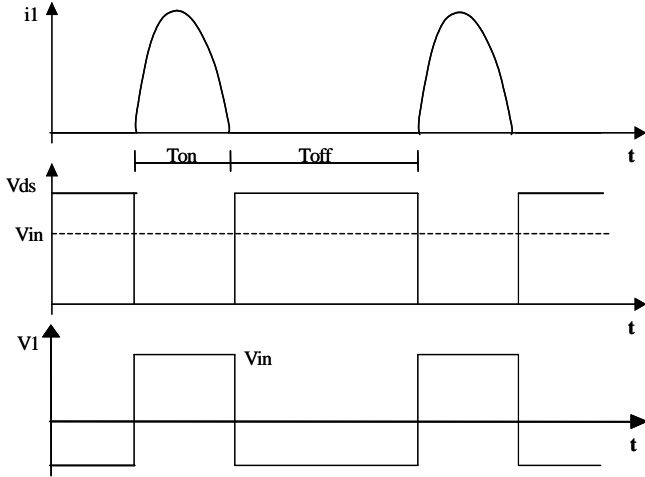


Fig. 2: Current and drain-source voltage waveform of the power transistor. Voltage waveform of the transformer primary winding.

A. Effect of high-energy neutrons on the converter

When exposed to high-energy neutrons, high voltage devices in power converters are susceptible to Single Event Burnout (SEB) and insulated gate power devices are also prone to Single Event Gate Rupture (SEGR). Since SEB is highly dependent on the voltage that the device has to block when it is turned OFF [3][4], the sensitivity of the converter to this effect strongly depends on the external conditions, such as input voltage, output voltage and output current. On the other

hand, SEGR is instead mainly dependent on parameters that are not affected by the magnitude of the external variables of the converter [5][6]. In VICOR step-down converters, it is possible to predict that the critical components to SEB and SEGR are the switching transistor Q and the auxiliary transistor included in the reset circuit. The drain-source voltage (V_{ds}) of both transistors cannot be measured directly because the converter is sealed into the package by a thermal compound. This voltage can nevertheless be estimated for the switching transistor Q on the basis of the conditions imposed by the transformer.

In addition to SEB and SEGR on power devices, high energy neutrons can induce single event effects (SEE) on the control circuitry; which is implemented in an integrated circuit using bipolar technology. Internal devices of this circuit can be affected by single event transients (SET). As a consequence the circuit may induce destructive misfiring on power transistors, transient output voltage dropout, temporary disabling, etc.

B. Estimation of the drain-source voltage of the switching transistor

Analyzing the voltage waveforms from figure 2, during the interval T_{on} when Q is conducting, the voltage $V_{ds_{on}} = 0$ and the voltage across the transformer's primary coil $V_{I_{on}} = V_{in}$. During T_{off} , the voltage across the transistor is $V_{ds_{off}} = V_{I_{off}} + V_{in}$, where $V_{I_{off}}$ is the reflected equivalent voltage in the primary coil due to the reset circuit. The transformer's magnetic circuit imposes the condition that in steady-state the time average voltage across any transformer's coil should be approximately zero. Assuming a square wave voltage across the transformer primary coil, the voltage magnitude must satisfy the condition:

$$V_{I_{on}} \cdot T_{on} - V_{I_{off}} \cdot T_{off} = 0 \quad (1)$$

Inserting this boundary condition into $V_{ds_{off}}$, we obtain

$$V_{ds_{off}} = V_{in} \cdot (T_{on} + T_{off}) / T_{off} \quad (2)$$

This expression allows to calculate how the voltage drop across the OFF power transistor depends of the input voltage

and on the load conditions. A similar analysis is valid to estimate the drain-source voltage V_{ds} of the transistor in the reset circuit. For both devices, V_{ds} increases for both higher V_{in} and increasing load conditions (reduction of T_{off}).

From equation (2), it is possible to estimate the V_{ds} of the switching transistor by measuring the input voltage, the overall period T and the time T_{on} . The first two parameters are easily measured from the converter terminals, while T_{on} can be measured from the output ripple. VICOR converters with nominal input voltage of 300V (V300B12C250AL, V300B5C200A) and 375V (V375B5C200A, V375B12C250A) use similar transistors and have been used for these tests. The values calculated from equation (2) are shown in figure 3. It depicts the drain-source voltage V_{ds} for different converters under different operating conditions. V_{ds} clearly decreases when the input voltage, output voltage and output current are de-rated from their nominal values.

C. Characteristic of the converters tested

The converters used during these tests belong to the VICOR family known as *MINI*. The total power transferred by those converters is in the range of 200-250W. Table 1 lists the nominal characteristics of the converters.

TABLE 1: NOMINAL CHARACTERISTICS OF THE CONVERTERS USED IN THE RADIATION TESTS.

Converter model	Nominal V_{in}	V_{in} Range	V_{out}	Nominal I_{out}
V300B5C200A	300V	180V-375V	5V	40A
V300B12C250AL	300V	180V-375V	12V	21A
V375B5C200A	375V	250V-425V	5V	40A
V375B12C250AL	375V	250V-425V	12V	21A

III. SEB, SEGR IN POWER MOSFET TRANSISTORS

Destructive SEB effects on n-channel power MOSFETs were first reported in 1986 by Waskiewicz, *et al.* [7] after testing those power devices with heavy ions. Since then, extensive studies on SEB and SEGR have been conducted. A review paper by Titus and Wheatley presents a comprehensive bibliography on these topics [8]. At the beginning of these studies, tests, based on a non-destructive technique, were performed using heavy ions to measure the SEB cross section. In parallel, extensive analysis and modeling of these destructive events have been conducted to characterize the phenomena involved and develop design techniques to produce SEB tolerant devices [9][10][11]. Studies with heavy ions also showed a non-negligible SEB cross section at low linear energy transfers (LET). Based on this measurement, it was possible to predict that recoils induced by high-energy protons and neutrons can induce SEB. Some reports of tests performed on high voltage power MOSFETs have shown SEB during irradiation with high-energy protons. Oberg *et al.* [4] and Normand *et al.* [3] reported SEB in n-MOSFET using high-energy neutrons. In general, tests performed with high energy neutrons and protons gave similar SEB cross section for the same device. When compared to heavy ions, the SEB cross section for nucleons are several orders of magnitude lower. Normally devices operating in an environment with high-energy neutrons or protons require a de-rating in the

operating voltage to perform reliably. The higher the rated voltage of the device, the higher the fractional de-rating required. In general, p-channel MOSFETs are much less sensitive to burnout than equivalent n-channel devices.

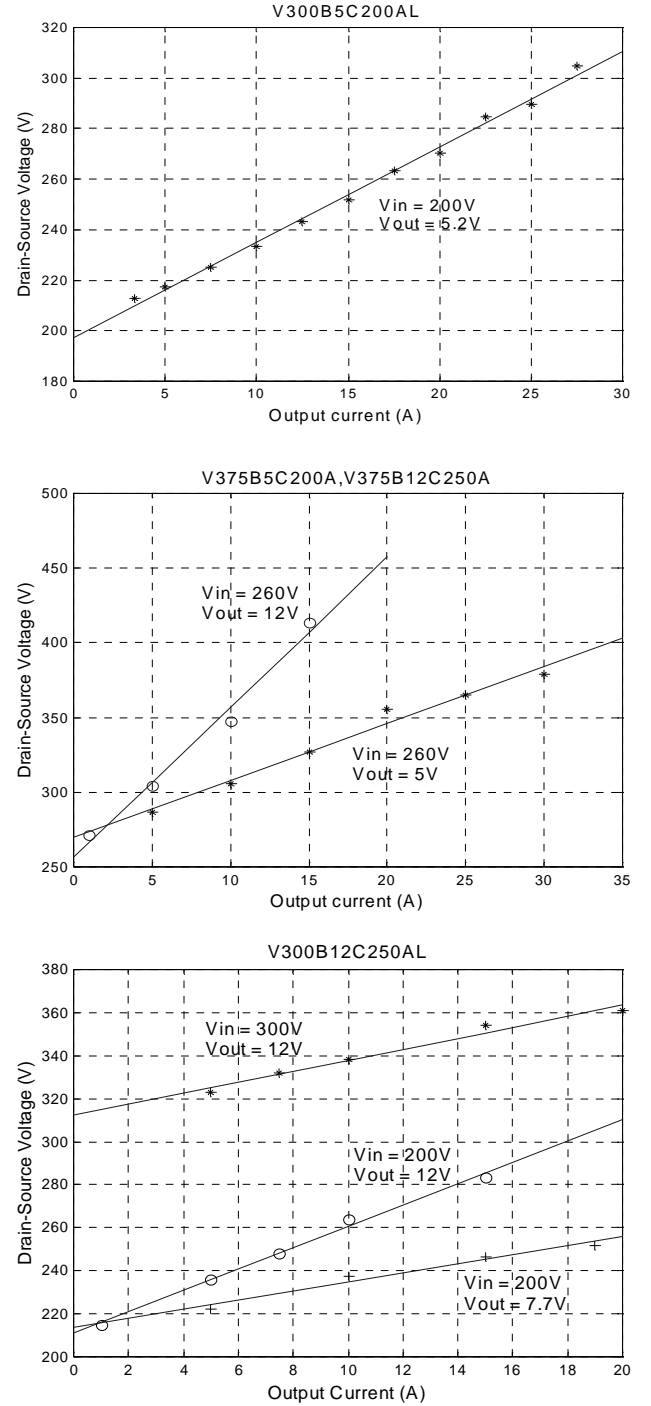


Fig. 3: Power Transistor V_{ds} as function of the converter output current for different input and output voltage combinations

The SEB mechanism is associated with a second breakdown of the parasitic bipolar transistor intrinsic to the power MOSFET structure. Due to the extremely low LET of high-energy neutrons and protons charge carrier multiplication is necessary to induce SEB. Si recoils, product of hadron-Si

inelastic collisions, have LET of the order of 10-15 MeVcm²/mg and can induce SEB. The mechanism of this destructive event can be explained by the Kuboyama model [3][12]. For MOSFETs operating at low V_{ds}, heavy ion strikes only induce current filaments due to the direct charge deposition of the ion. Increasing the voltage V_{ds}, produces two effects. One is an avalanche in the reverse biased epitaxial region and the other is the activation of the parasitic transistor. These two effects induce a regenerative process where more electrons are injected by the transistor in the depletion region and more holes from the avalanche directly bias the parasitic transistor. This effect rapidly drives the parasitic bipolar transistor to breakdown. The end result is a sudden collapse of the drain-source impedance and, if the current is not controlled by the external circuit, the MOSFET is destroyed.

SEGR in power MOSFETs was not recognized as a serious problem until manufacturers started developing SEB-hardened MOSFETs. Standard MOSFET devices are more susceptible to SEB effects than SEGR. The later is a destructive effect that can be described as the result of the energy released through the insulator by a heavy ion strike when the gate is biased by a voltage higher than a critical value [8]. However, this type of effect has been observed during proton radiation [13].

IV. IRRADIATION TESTS

Several irradiation tests have been performed on different samples of VICOR converters. When exposed to low-energy neutrons (mean energy around 0.75 MeV), the performance of the converter has shown no appreciable degradation up to a fluence of 10¹² neutrons/cm². This test was performed to explore possible displacement damage sensitivity of the control electronics, which is in bipolar technology. The total fluence achieved in the test is almost an order of magnitude higher than the one expected in the application and gives us a good confidence that displacement damage will not be a problem.

In order to analyze the robustness to SEEs and define a safe de-rating for the input voltage, output voltage and output current, we have performed a series of irradiation tests on VICOR converters using proton beams. For their capability to induce Single Event Effects, protons and neutrons can be considered practically equivalent at any energy above about 20 MeV [14]. Since proton beams are much easier to access, we performed our tests using 60, 200 and 300 MeV proton beams. The maximum fluence during the test for each individual converter was limited by the maximum total dose these commercial devices could tolerate without any appreciable change in their electrical characteristics.

Since the sensitive device in the converter is the power transistor, we started by performing a non-destructive test on such a device. We were able to identify the power transistor actually used in the converter thanks to the collaboration of the manufacturer. Two different but electrically very similar power MOSFET transistors (rated 600V/6A) are used for the converters produced by VICOR. In the following, we will refer to them as Q1 and Q2.

A. Non-destructive SEB tests

A 60 MeV proton beam has been used to measure the SEB cross-section of the transistors as a function of the applied drain-source voltage with the transistor in OFF state. During this non-destructive test, transistors are biased at different voltages through a protection resistor connected to the drain. Current spikes due to SEB induced by the proton beam are measured and counted during the irradiation. Test cards, containing four power MOSFETs each were irradiated, keeping the device bias at the same potential during the test. The cross section was calculated as the ratio between the average SEB measured and the integrated fluence. The maximum fluence applied was limited by total dose effects induced into the device up to 1.0x10¹¹ protons/cm². Results of the radiation tests are depicted in figure 4. Based on the foreseen accumulated fluence in 10 years of operation and the results shown in figure 4, one can predict that transistor Q1 operating at V_{ds}=350V will have, in average, 6.8x10⁻³ failures/10 year. This value is equal to 77.62 failures / 10⁹ hrs. or a mean-time-to-failure (MTTF) = 12.8x10⁶ hrs. This value can even further reduced operating Q1 at V_{ds} below 300V and, in the case of Q2, below 350V. Since it is unknown which one is mounted in each DC-DC converter, it is assumed for safety that the most sensitive one (Q1) is used.

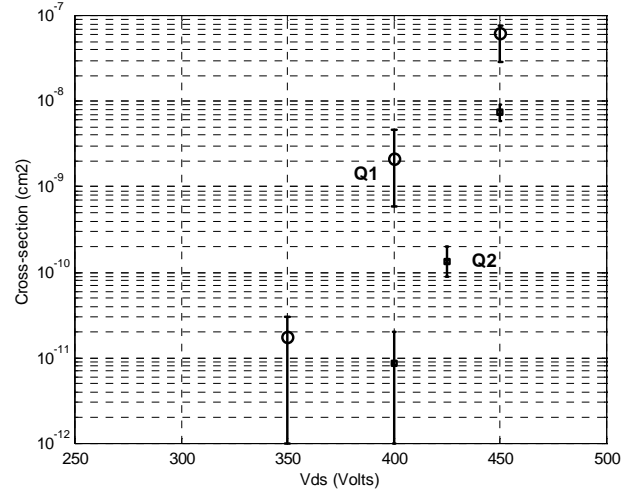


Fig. 4: 60MeV protons cross-section of 2 different power transistors types, both rated 600V/6A. Bar-errors depicts the minimum and maximum cross sections

Combining these results with the estimate of V_{ds} in figure 3, it is possible to predict that the converter V375B5C200A (V_{in}=375V / V_o=5V) can operate under high-energy neutron radiation if the input voltage is de-rated to 260V and the output current is lower than 10A. The converter V300B5C200A (V_{in}=300V / V_o=5V) can tolerate high-energy neutron radiation if the input voltage is de-rated to 200V and the output current limited to 25A. For the converter V300B12C250AL (V_{in}=300V / V_o=12V) a reliable operation is only possible if the input voltage is de-rated to 200V. Nevertheless, as it will be shown later, this might not be sufficient.

B. Destructive tests

Several destructive tests on the complete DC-DC converters have been performed to test those conclusions. During the tests, the input voltage and the output current was continuously monitored and the temperature of the converter and heat sink was kept at about 40-45°C using forced air. Since the beam was larger than the whole converter, we could actually test the complete system, including the control circuitry, at the same time as the power transistor. The control circuit was free of latch-ups, destructive misfiring, etc and the complete converter proved robust under high-energy proton environments.

Table 2 describes the results obtained using 60MeV, 200MeV & 300MeV proton beams. Converter failures were traced back to SEB of the switching transistor. Vds conditions for the switching transistor are specified for each test. In case

of failure, the maximum fluence specified in the table corresponds to the occurrence of the SEB.

From all the data presented, it appears that converters can operate safely in the foreseen high-energy neutron environment up to a fluence of $1.0\text{-}3.0 \times 10^{11} \text{ p/cm}^2$ only if Vds is in the range of 255÷300V. However, reducing the input voltage is not enough for safe operation. In addition to such de-rating, converters have to operate either at reduced output voltage (and nominal output current) or at reduced output current (and nominal output voltage).

TABLE 2: RESULTS OF THE DESTRUCTIVE TESTS PERFORMED WITH 60, 200 AND 300 MeV PROTONS ON THE DC-DC CONVERTERS

Converter model	Proton Energy	Vin [V]	Vout [V]	Iout [A]	Max. fluence [p/cm ²]	Test result and Vds conditions
V375B5C200A	60MeV	260	5	1	1.0×10^{11}	No failure (Vds = 275V)
	300MeV	260	5	1	1.0×10^{11}	No failure (Vds = 275V)
	300MeV	260	5	5	0.5×10^{11}	No failure (Vds = 290V)
	300MeV	260	5	10	0.5×10^{11}	No failure (Vds = 310V)
	300MeV	260	5	15	0.45×10^{11}	Fail SEB (Vds = 330V)
V375B12C250A	60MeV	260	12	5	1.59×10^{11}	No failure (Vds = 310V)
V300B12C250AL	60MeV	207	12	1	1.0×10^{11}	No failure (Vds = 210V)
	200MeV	200	7.5	20	2.0×10^{11}	No failure (Vds = 255V)
	300MeV	200	7.7	19.77	3.0×10^{11}	No failure (Vds = 255V)
	300MeV	200	12	19.77	1.6×10^{10}	Fail SEB (Vds = 310V)
V300B5C200A	200MeV	200	5.2	25	2.0×10^{11}	No failure (Vds = 290V)

For our application, de-rating both the input and output variables is still a valid solution. Two converters are necessary to deliver to the front-end electronics 7.5V/20A and 5.2V/25A. Using the V300B12C250AL unit with an input voltage of 200V and the output voltage equal to 7.5V, table 2 shows that no failure occurred up to a fluence of $3.0 \times 10^{11} \text{ p/cm}^2$ when the converter operates at maximum output current. Similarly, no failures occurred up to a fluence of $2.0 \times 10^{11} \text{ p/cm}^2$ when the V300B5C200A operate with 200V input voltage, nominal output voltage and a maximum output current equal to 25A. De-rating the converter affects the efficiency but the penalty is tolerable: in the both cases the efficiency decreases to about 76%, while in nominal conditions it is 82%.

Radiation tests are performed to evaluate the reliability of the unit tested operating under a new foreseen environment. A distinction needs to be drawn between the interpretation of tests which measure the change in characteristics of the device

as function of the dose and tests which induce catastrophic failures. Tests inducing displacement damage and total dose effects can be considered as a measure of either the new life-time or variation of the principal characteristics for an estimated level of radiation. Test inducing destructive effects are more related with statistically random failures of the unit during its life-time. The results from table 2 only give a probabilistic measure of the future behavior of converters operating under a neutron environment. It is not possible to guarantee that if a sample tolerates a given fluence, another sample will work for the same fluence. The results in table 2 in conjunction with the SEB cross section measured for the power transistor can give a better indication of the unit reliability operating under the foreseen environment. The measurement of the transistor cross section allows a better definition of a threshold Vds voltage for safe operation of the critical device.

I. CONCLUSIONS

This work has presented results of proton irradiation tests to validate the operation of VICOR converters in an environment with high-energy neutrons. We developed a methodology to predict the de-rating necessary for the input/output variables of the converter. This methodology is based on the analysis of the power converter to estimate the blocking-voltage across the critical devices and the measure of the SEB cross-section of such devices. Further analysis and test are necessary to predict the reliability of a high number of converters in the foreseen environment, in particular their mean-time-to-failure. Our future work is oriented in that direction.

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