FAILURE MECHANISMS OF POWER SYSTEMS IN PARTICLE ACCELERATOR ENVIRONMENTS & STRATEGIES FOR PREVENTION

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Abstract

Many challenges must be overcome when designing power systems for use in particle accelerator-based projects. To succeed, a detailed understanding of the environment, the potential component and functional failure modes and insight into the performance degradation of the components is mandatory. This paper presents some of these challenges and also recounts the success of such a power supply project.

THE ACCELERATOR ENVIRONMENT

The environment created by a particle accelerator presents several specific challenges to a power supply's operation. First, there is severe radiation exposure, both in accumulated Total Dose (TID) and in neutron fluence. There are many components designed specifically for such environments, but most such components are designed for use in space-based projects, where, unlike commercial projects, cost is much less of a consideration.

In addition, there can be a strong magnetic field present that induces a large flux bias in the magnetic elements within the power system (particularly the large power transformers) and can easily saturate magnetic devices causing failures.

Moreover, accelerators have long periods of operation with repeated power up and power down events, often at no load [1]. This operational profile is in direct opposition to the high reliability system goals.

Radiation environments can easily exceed 45kRAD(Si) and 7.7E12 n/cm^2. This environment adversely affects many electronic components [2].

Magnetic fields exceeding 300 Gauss in any orientation are not an uncommon environmental requirement. Many power systems are designed using air core magnetics in order to eliminate the issues associated with magnetic fields. This is not generally feasible due to performance considerations, not to mention size and weight limitations. Most power systems are designed using ferrite, powdered cores or tape cores. The core materials have significant permeability and are, therefore, significantly affected by magnetic fields. In order to prevent the saturation of these cores, shielding must be a primary design and manufacturing consideration.

The operational profile is one of the most often overlooked aspects of high reliability systems. Most electronic systems have the highest probability of failure at either the application of input power or the removal of input power. In particular, the tendency is toward failure at removal of the system bus power.

COMPONENTS

As designers of space-based power electronics for long-life (>18 years) satellites and for harsh radiation environments, we have applied much of what we have learned on space-based projects to our design of power systems for particle accelerator environments.

The design of space-based electronics leans heavily on previous, successful heritage designs and testing of components. Many of these components have not, until very recently, been available in "radiation hardened" technologies. Specific examples include devices such as voltage references, opto-couplers and Pulse Width Modulators (PWMs). Many of these devices are now available in "rad-hard" versions; however this upgrade is not always beneficial because:

1. These new devices do not have the long-term proven heritage of their counterparts.
2. While pitched as replacements or improved versions, in many cases these devices are not identical performance replacements. Manufacturers are rarely clear about the differences, many of which are critical to circuit operation.
3. These devices are generally designed for space programs and are cost prohibitive for commercial programs; a typical rad-hard Mosfet or IC easily costs more than $500 (USD).

On the other hand, many components that have been proven in space-based radiation environments are also available as commercial products. Texas Instruments Hi-Rel pioneered the EP initiative. With over 700 EP devices released in the analog, data converter, power management, DSP and logic product lines, Texas Instruments is committed to meeting the needs for ruggedized COTS devices. Many of these common space heritage components are available from Texas Instruments as EP devices released to a DSCC Vendor Item Drawing (VID) and can be found at www.ti.com/ep.

FAILURE MECHANISMS

Many of the typical failure mechanisms of power supplies are well documented. This paper concentrates on failures that are associated with power Mosfets and magnetic fields, as these are not as well documented.

Mosfet Related Failures

Mosfet characteristics have three common reactions to the radiation environment. Single Event Effects (SEE) failures occur which are exacerbated by higher operating drain-source voltage. The sensitivity to SEE is evaluated in relation to the effective die area for a given neutron flux. The results of this damage can be permanent, resulting in total power system failure.

A second failure mechanism of the Mosfet is SEGR. This is a condition where heavy ions cause a Mosfet, which is biased in the off state, to conduct current, which may only be limited by the short circuit current available.

This effect is generally exacerbated by negative gate voltages (for N Channel Mosfets) often produced by various driver topologies [3].

A third and less documented degradation is related to the shift in the gate threshold voltage of the Mosfet as shown in Fig. 1. At 100kRad, the gate threshold voltage, Vgsth reduces by approximately 1.5V. This threshold shift is accompanied by an induced shift in the timing with respect to the gate drive voltage. This timing shift extends the gate drive signal, increasing the operating duty cycle of the Mosfet.

A Simplistic Example

Rg:=20 Effective gate resistance,
Ciss: = $5\cdot10^{-9}$, Vgsth := 3, Freq := $2.55\cdot10^{-5}$, ID := 5, KP:=5, Qgd := $30\cdot10^{-9}$ and the Mosfet Gate signal voltage Vdrive_hi := 12.
The Mosfet Turn-On delay 40.55ns.

$$\mathrm{Tdon} := -\ln\left(1-\frac{\sqrt{\frac{\mathrm{ID}}{\mathrm{KP}}}+\mathrm{Vgsth}}{\mathrm{Vdrive\_hi}}\right)\cdot\mathrm{Rg}\cdot\mathrm{Ciss} \tag{1}$$

The Mosfet Turn-Off delay occurs from the falling edge of the driver signal to the on-state gate voltage, Vgson.

$$\mathrm{Tdoff} := \left(-\ln\left(\frac{\sqrt{\frac{\mathrm{ID}}{\mathrm{KP}}}+\mathrm{Vgsth}}{\mathrm{Vdrive\_hi}}\right)\right)\cdot\mathrm{Rg}\cdot\mathrm{Ciss} \tag{2}$$

Then, there is the time that it takes to discharge the Gate-Drain (Miller) capacitance. The average net gain (or loss) of the two edges is determined as:

$$\mathrm{Duty\_gain} := (-\mathrm{Tdon} + \mathrm{Tdoff} + \mathrm{Tmiller})\cdot\mathrm{Freq} \tag{3}$$

Duty_gain = 5.483%, Substituting for Tdon, Tdoff and Tmiller:

$$\mathrm{Duty\_gain} = \left[\ln\left[1-\frac{\left(\frac{\mathrm{ID}}{\mathrm{KP}}\right)^{\frac{1}{2}}+\mathrm{Vgsth}}{\mathrm{Vdrive\_hi}}\right]\cdot\mathrm{Rg}\cdot\mathrm{Ciss} - \left[\ln\left[\frac{\left(\frac{\mathrm{ID}}{\mathrm{KP}}\right)^{\frac{1}{2}}+\mathrm{Vgsth}}{\mathrm{Vdrive\_hi}}\right]\cdot\mathrm{Rg}\cdot\mathrm{Ciss}\right] + \frac{\mathrm{Qgd}\cdot\mathrm{Rg}}{\left(\sqrt{\frac{\mathrm{ID}}{\mathrm{KP}}}+\mathrm{Vgsth}\right)}\right]\cdot\mathrm{Freq} \tag{4}$$

And differentiating with respect to the Mosfet Gate threshold voltage we get dVgsth = -1.875%.

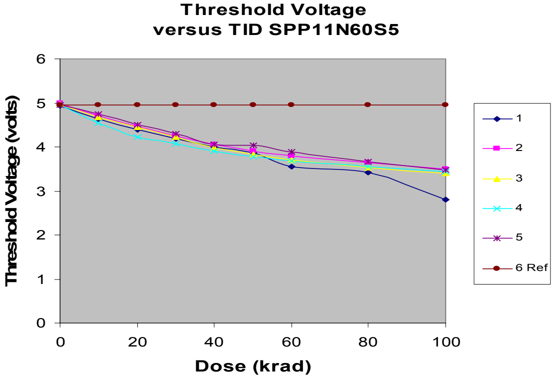

Figure 1 The traces show Vgsth vs. Total Dose for a high initial gate threshold (5V) device. The commercial FET shows approximately 1.5V of reduction at 100krad.

And so the duty cycle of the Mosfet is nominally 5.5% greater than the drive signal and will increase by an additional 1.9% for each Volt of reduction of the Vgsth value. This means that the duty cycle will increase by almost 3% due to radiation effects (assuming a 1.5V shift) and potentially an additional 3% due to temperature and initial tolerances as shown in Fig. 2.

While the power system is operating normally, the control loop will reduce the drive signal duty cycle to the Mosfet in order to maintain the system regulation, and so there are generally no ill effects from this timing shift, other than an increase in power dissipation due to slower turn-off switching. However, if the power system is turned off by turning off the input power source, the duty cycle of the converter will increase as the input voltage falls, attempting to maintain regulation. At some time during this discharge it is possible that the duty cycle will increase beyond the allowed dead-time or reset condition, which is often 50% of the duty cycle. If this point is reached, it is possible to saturate the power transformer and the current in the Mosfet will reach permanently destructive levels.

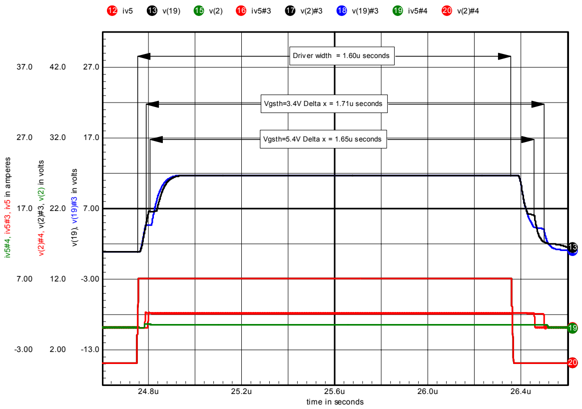

Figure 2 SPICE shows the increase in gate drive pulse width (turn-off delay time) as a function of Vgsth.

Magnetic Field Failures

Magnetic field induced saturation of transformers can be a difficult problem to quantify. The field may be ill-defined with questions about its direction, worst case amplitude, and frequency fluctuations. Without a well-defined signal software tools are hard-pressed to go beyond static field approximations.

Commonly available materials and planar structures do not handle magnetics fields of significant amplitude gracefully, especially when the fluctuations are unknown.

Shielding is the predominant method for reducing magnetic field impact, though case and cooling structures can inhibit the possible implementations.

ATLAS Low Voltage Power Supply for the CERN Large Hadron Collider Calorimeter

In 2007, AEi Systems, LLC and Algen Design Services undertook a redesign of the existing low voltage power supply (LVPS) used in the colorimeter detector section of the LHC. The specification defined a 3kW unit consisting of +6.0, +4.0, +11.0, +7.0, -7.0, and -4.25V output voltages. The environment included requirements as previously mentioned; 45kRAD(Si) and 7.7E12 n/cm^2 with a 300 gauss magnetic field. The architecture included an N+1 modular approach, with failure redundancy.

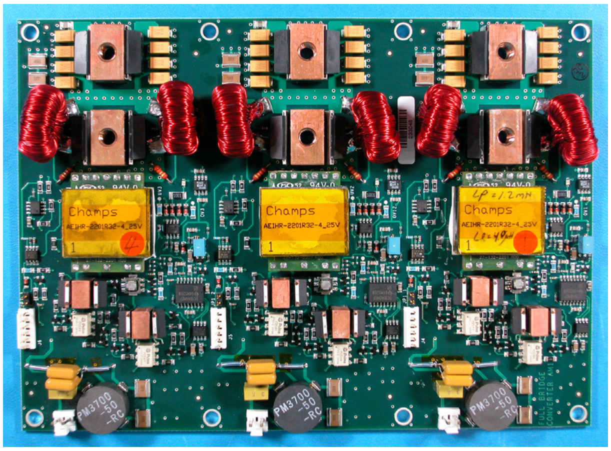

Figure 3 Three +6V 90A (N+1 redundant) prototype modules manufactured for the LVPS.

At this time, prototype modules of the 4.0V, 6.0V, and 11.0V have been constructed and tested with successful results that meet or exceed specifications (Fig. 3).

Radiation Results

Various components, as well as, an entire module were radiation tested. The environment, while not identical to the actual environment that the unit will see, provided insight into potential issues. The module functioned with exposure to a proton beam up to 5x10^{12} p/cm^2. Issues were found with the existing opto-couplers and Mosfet drivers.

The proton bombardment possibly masked low dose rate effects due to the high accumulated dose rates so it was not always discernable whether the degradations were due to dose rates or to displacement damage.

The degradation in the Mosfet Vgsth proved to be just slightly greater than that achieved by much more expensive “rad-hard” FETs. With the selection of high initial gate threshold devices we were successfully able to construct a viable power stage with COTS devices.

Magnetic Field Shielding Results

Shielding proved to be an interesting problem with no clear solution previously conceived given the topology and the unknown magnetic field paths and strengths. Various materials were considered including mu-metal, netic, and co-netic [4].

Finite element analysis was performed using Ansoft’s Maxwell 3-D tool. Results indicated that the closer the netic-based shield is to the power transformer the greater the reduction in the induced field (Fig. 4). Do to various constraints, including board space, and given that the unit sits on a cooling plate, it was not possible to shield each individual magnetic. Module level shielding was implemented and found to enable operation up to 543 Gauss before induced transformer saturation caused module instabilities. Subsequent units will be shielded with thicker netic material at the box level with the hopes that the available margin will prove sufficient to meet the 300 gauss requirement.

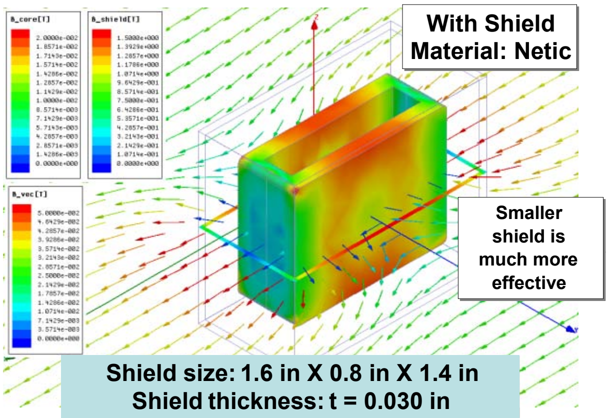

Figure 4 Ansoft 3D Maxwell simulations show the magnetic flux density in the core in response to the 300G external static field with a netic material shield.

FUTURE EFFORTS

Prototype units are in production and will utilize the radiation and magnetic field test results obtained previously. Replacement components for those that had marginal radiation performance have been selected and, in some cases, retested with improved margins. The prototype units will be retested and the results reported in a future publication. Ultimately, it is planned that a production set of power supplies, very similar to those described herein, will be deployed in the LHC to replace the current set of LVPS units.

REFERENCES

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