SMART®
Modular Technologies

Power Failure Protection

Application Note AN003

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1 Introduction

Enterprise storage system power supplies are designed with the highest reliability in mind, and subsystem designers are careful in selecting the most reliable regulation components. However, the reality is that power to data storage drives does occasionally fail. Since Enterprise-class SSDs maintain mission-critical data, it is unacceptable for previously stored data to be lost or for data in flight to nonvolatile storage to be corrupted.

It is vital that Enterprise-class SSDs are designed to survive power reductions and outages without risk to the data itself.

Power loss events range from momentary loss of regulation (transient brown-out condition) to loss of all power for an extended period of time. Such events can be caused by failure of the facility's supply grid or UPS unit, failure of the system's power supply (including fusing and cabling), failure of the SSD's voltage regulation components, or mechanical failure of PCBs or connectors due to vibration, heat, or impact. Power failure risk at the SSD level depends only partly on the power delivery redundancy measures in place; power failure can cause system latency (when the drive needs to rebuild mapping tables) or permanent data loss.

This application note discusses the multiple methods of addressing power failure risk and the superior approach employed by SMART Modular XceedIOPS and Xcel-100 SSDs.

2 Data Loss in Power Failure Scenarios

When programming a NAND flash page, the program operation must complete to ensure the data is stored reliably within the page. Data is at risk if flash memory cells are in the process of being programmed when power to the drive is lost. The risk is compounded for MLC NAND flash memory, which uses the same physical page of memory cells to store two logical pages of data. When power is lost during program operation of the upper page, valid data already stored in the lower page cells can be damaged. This is typically referred to as lower-page data corruption.

Solid state drives have three areas of potential data loss or corruption when system power fails:

- **Loss of data:** This can occur due to the implementation of write caching (also called "write back" or "write behind") to achieve peak performance. In this case, the host system is informed that a write operation has completed when in fact it is still in process. If power fails while the controller is "catching up" with the write operation, the data in the write buffer is not yet hardened and can be lost. When the data is requested later by the host, the controller can either report the data irrecoverable or (depending on the controller design) it can deliver a previous "stale" version of those sectors to the host. In the latter case, this translates to silent data corruption, since the host system is not informed that the data delivered is incorrect.
- **Loss of mapping information:** Every SSD controller uses mapping information to translate from the host's logical LBA addresses to physical flash memory locations. Mapping information must be created and maintained if the data is to be later retrieved from the drive, and must be updated whenever new data is written to a previously written LBA. If the mapping information is lost when power fails, the drive may

show data corruption, deliver stale (corrupted) data or may not be capable of supporting logical I/O on the next power up.

- **Lower page corruption:** MLC or E-MLC NAND flash uses each physical page to store the data of two logical pages; each memory cell represents two bits. The lower page (the logical page addressed by the lower of the two addresses) is programmed first, followed by the upper page. When programming the upper page, programming voltages are applied to the same cells already storing valid data in the lower page. If power fails while the upper page is being programmed, data in that page is lost, and already-stored data in the lower page is corrupted as well. When that lower page data is requested later by the host, the SSD will report the data irrecoverable.

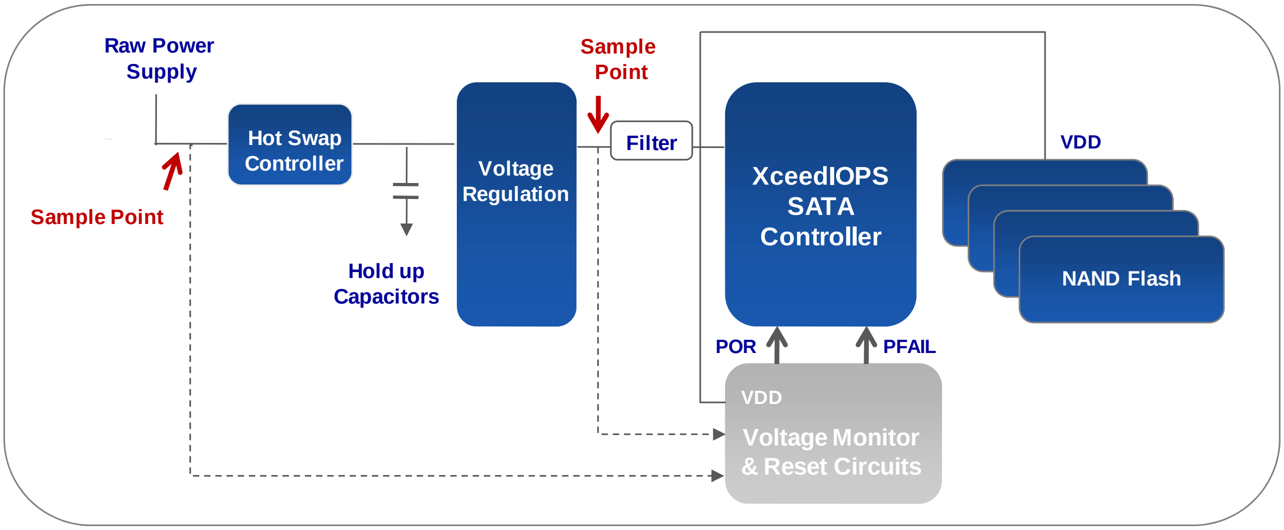
The Unrecoverable Bit Error Rate (UBER) for an enterprise-class SSD is specified to be $\leq 10^{-16}$, according to the JEDEC JESD218[1] specification. To achieve this error rate, an enterprise-class SSD must employ power failure protection circuitry to ensure that that loss of data and mapping information will not occur when power is lost.

3 Power Failure Circuitry in SSDs

Most Enterprise-class solid state drives rely on power failure circuitry that monitors the supply voltage and generates an “early warning” signal to the SSD controller if voltage drops below a predefined threshold. They implement a secondary voltage hold-up-circuit to ensure the drive has power for a sufficient time to harden data whenever that warning is received.

As an example of an Enterprise-class implementation, Figure 1 below illustrates the power failure circuit block diagram of the XceedIOPS SSD.

Figure 1: Power Failure Circuit Block Diagram of XceedIOPS SSD



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[1] JEDEC JESD218 specification is available for download http://www.jedec.org/

The secondary voltage source can be either a high capacity supercapacitor, a bank of discrete capacitors or even a battery (although no known SSD on the market uses this approach). These different implementations are not the same from a performance and reliability standpoint; some are better suited for usage in Enterprise-class SSDs than others.

Descriptions and relevant tradeoffs of a supercapacitor solution and a bank of discrete capacitors in an Enterprise-class SSD design are presented below.

3.1 Supercapacitor

A supercapacitor is an electrolytic capacitive charge storage device. It is capable of storing a large amount of energy in a comparatively small three-dimensional space. A generic supercapacitor-based voltage hold-up circuit is consistent with the block diagram shown in Figure 1.

Designing a supercapacitor-based power failure protection circuit is easy to do, and many SSDs employ the approach for this reason. Unfortunately, there are a number of concerns related to long term supercapacitor reliability that makes this component type questionable for Enterprise-class SSDs.

Supercapacitors are typically Aluminum Electrolytic Capacitors. This type of capacitor is known for a high capacitance-to-size ratio, and is an attractive choice for applications requiring large bulk capacitance like a solid state drive. However, like all electrolytic capacitors, supercapacitors suffer from a well known set of deficiencies with regard to long term reliability. Supercapacitors “wear out”, resulting in reduced capacitance over time. They use a wet electrolyte, and the packaging is subject to ongoing losses via leakage and diffusion.

The performance of the supercapacitor degrades slowly with electrolyte loss, until the onset of total failure occurs with little or no warning. In addition, loss rate increases with higher operating voltage, and in higher operating and non-operating temperature environments. For every 10°C of ambient operating temperature rise, the life expectancy of a supercapacitor can be cut approximately in half.

A thorough analysis done by SMART Modular has shown that supercapacitors are not reliable enough to meet the required reliability standards for the high-performance enterprise and industrial computing markets served by SMART’s XceedIOPS and Xcel-100 product line.

Figure 2 shows an example of a supercapacitor reliability projection, based on component life test data.

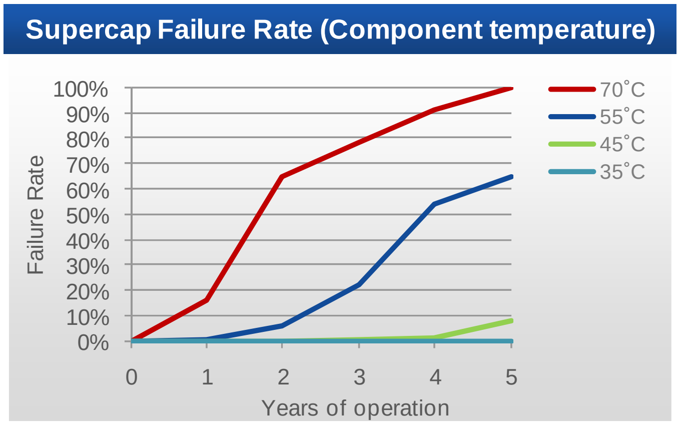


Figure 2: Supercapacitor Failure Rate by Temperature

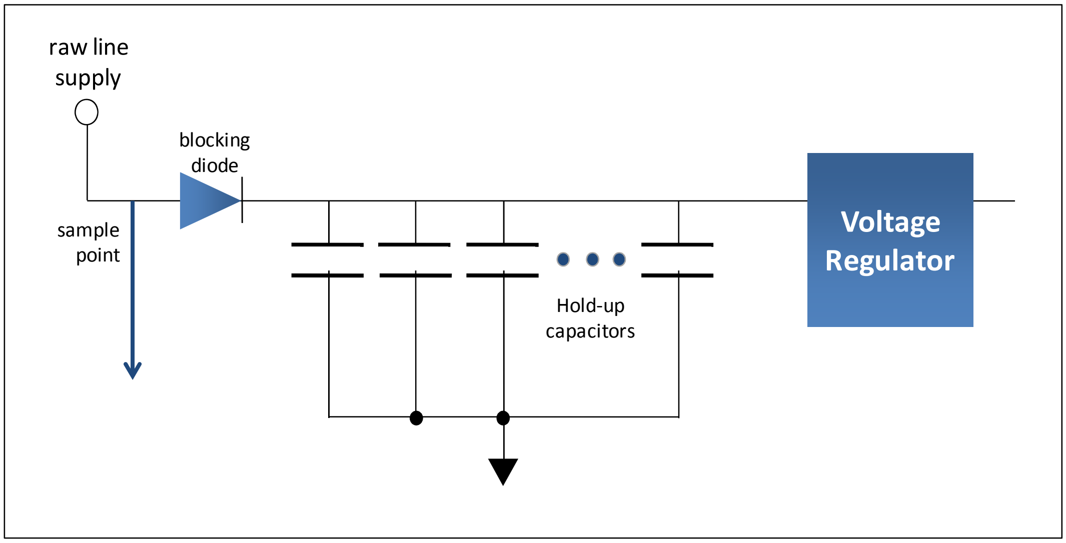
Due to the reliability concerns associated with this capacitor type, it is imperative **t**hat the SSD constantly monitor the capacitor's operating capabilities to ensure continued reliable operation as the SSD ages. This is done by periodically measuring the supercapacitor's charge/discharge ("Hold Up") time under a controlled load.

The challenges associated with performing this test seamlessly and transparently to the host system are many. Because the secondary power system is under a "live test" during hold up time measurements, the SSD must harden data prior to testing (in case the test fails). This operation and the test time itself almost always result in extended latencies (as much as 100ms or more) for host commands issued during the test interval.

3.2 Discrete Capacitors

This approach requires more design expertise, but overcomes the supercapacitor limitations. A discrete capacitor-based voltage hold-up circuit employs a bank of discrete capacitors connected in parallel, shown in Figure 3 below. This is the approach employed by SMART Modular's XceedIOPS and Xcel-100 SSDs.

Figure 3: Discrete Capacitor Rail Hold-Up Sub-Circuit



XceedIOPS and Xcel-100 SSDs utilize Niobium Oxide capacitors[2]. These capacitors are similar to Tantalum in terms of their electrical characteristics, but address the two most common Tantalum failure modes: dead-short and combustive failure.

Niobium is a well-proven technology. They do not employ a "wet" electrolyte and are not susceptible to the leakage related issues that plague supercapacitor technology. Niobium capacitors are rated to 85ºC, providing considerably more temperature operating range than is typical for a supercapacitor (70ºC). As a result of these factors, a discrete component Niobium based hold up circuit is better able to meet the demands of the enterprise and industrial computing environments.

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[2] XceedIOPS 1.8" SATA uses Polymer Tantalum capacitors.

The advantages of discrete capacitors over supercapacitors are:

- **Consistent Capacity:** Discrete capacitor energy storage capability is highly predictable and reliable. Provisioning can be selected so that it is optimal for the SSD's needs over its lifetime. Derating and significant over provisioning is not required. SMART Modular's discrete capacitor circuit has been carefully optimized to meet the XceedIOPS and Xcel-100 holdup requirements, and includes design margin in the form of extra capacitance (N+1).
- **Predictable Failure Mode:** The discrete capacitors used by SMART Modular exhibit an open circuit (rather than short circuit) failure mode. SMART Modular's design ensures a sufficient amount of reserve power to guarantee reliable drive operation under all circumstances over the life of the drive, and employs an extra capacitor component (N+1) such that failure of any single discrete capacitor does not erode operating margins.

Discrete capacitor implementations require more careful design. Lacking the compactness of supercapacitors, the capacitance-to-size ratio of a discrete solution is less space-efficient. To provision sufficient capacitance with a discrete capacitor solution requires packing components as densely as possible onto the PCBA board.

Tradeoffs are necessary to achieve a balance between cost, reliability and operating margin. Not all SSD manufacturers have the knowledge and experience to navigate these tradeoffs correctly.

4 Summary

The Early Warning / Rail Hold-Up approach is the most reliable solution for a backup power circuitry in an Enterprise-class SSD design. SMART Modular's SSD design team has in excess of 1000 man-years of experience in the design of memory storage and data storage devices. SMART's expertise has allowed us to identify the risks associated with supercapacitor reliability, and implement a discrete capacitor circuitry which is superior in every regard. Discrete capacitors do not degrade over time or with elevated temperatures and can operate reliably in environments up to 85ºC. They exhibit an open circuit failure mode and through the implementation of an extra (N+1) component a failure of a single capacitor will not impact the overall reliability of the solid state storage device.

Implementing a discrete capacitor backup power circuitry into the design differentiates SMART SSD products from their competitors in a way that provides meaningful advantage to our customers.

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