LOW-NOISE SWITCHING POWER SUPPLY CONSIDERATIONS FOR TELEMETRY ENCODER APPLICATIONS

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KEYWORDS

ABSTRACT

Modern telemetry systems using state of the art field programmable gate arrays (FPGAs) and signal processing components require lower voltage supplies to support various CMOS core geometries while still needing multiple higher voltage rails to support legacy interfaces. Addressing these power supply requirements efficiently requires switching power supply topologies that if left unchecked can generate high input surge currents and high levels of detrimental noise for both the sensitive analog signal processing circuitry and the power supply input source.

This paper focuses on the design considerations and tradeoffs associated with implementing an efficient telemetry encoder power supply while mitigating the resulting noise effects typically associated with switching power supplies. This noise can negatively affect the power supply input source and the linear signal processing circuitry within the telemetry encoder.

INTRODUCTION

The continuing evolution of modern telemetry systems places many demands that drive the need for the development of a new multi-output power supply. Customer driven system level telemetry encoder requirements specifying functionality and power consumption influence and guide the possible power supply implementation options that may help satisfy the overall power constraints. Manufacturing processes and thus parts availability then direct the specific voltage output requirements for telemetry encoder's power supply subsystem.

As with any evolving product the trend is usually to expand functionality, add new features and capabilities, while support for maintaining the legacy functionality is slow to wither away albeit with the same or lower power requirements. For example, one key aspect of telemetry encoder systems that complicates the design as compared to many commercial and consumer applications is the requirement to provide higher voltage analog interfaces for legacy sensors, while also providing multiple voltages for the numerous silicon geometries of modern digital and mixed-signal electronic components that are required due to added functionality or parts obsolescence issues.

GENERAL DESIGN REQUIREMENTS

Many of the requirements for a telemetry encoder power supply are industry driven and have specific standards written to address the normal requirements, such as the nominal input voltage range (MIL-STD-704). Many other aspects are also standards driven such as, input EMI filtering (MIL-STD-461) and over/reverse voltage protection (MIL-STD-704). Examples of requirements the customer may impose might be related to environmental conditions, or inrush current limitations. Some indirect requirements affecting the power supply design are the total encoder size, weight restrictions, and of course overall system functionality given the power constraints. Finally, there may be specific manufacturer driven requirements like the supply rails required, sequencing constraints, load regulation, ripple and noise limitations. Table 1 summarizes some key requirements for a telemetry encoder power supply.

Source	Requirement
Industry Standards	• Input voltage range • Input EMI filtering • Surge voltage protection • Transient voltage protection • Reverse voltage protection
Customer	• Under voltage protection • Input surge current/soft-start needs • Power stabilization time • Input dropout characteristics • Isolation levels • Back voltage • Environmental constraints • Excitation requirements – indirect implications • Size and weight restrictions - indirect implications • Maximum allowed input power – indirect implications
Manufacturer	• Supply voltages required • Maximum and minimum current per supply • Peak power output • Continuous power output • Thermal mounting methods • Supply sequencing constraints • Input regulation • Load regulation • Load short and over voltage protection • Ripple and noise limitations

Table 1: Telemetry Encoder Power Supply Requirements

IMPLEMENTATION

The availability of small, multiple output MIL-STD-704/461 compliant power supplies and DC-DC converters are limited and while the voltages supplied address the needs of older telemetry encoder systems they provide a far from complete power supply solution for a modern telemetry encoder. The efficiency of the standard DC-DC converter available is well beneath the capabilities of modern technologies (~75% typical). A custom design may attain better (~85%) efficiency under high load conditions.

On the other hand, building the complete power supply subsystem from scratch requires additional development cost and time for hardware development and standard compliance testing. Therefore, the L-3 Communications PCM330E telemetry encoder's power supply module (PSM310) development focused on utilizing an off the shelf isolated multiple output DC-DC converter while efficiently generating the additional required supply rails using effective noise mitigation techniques to counteract the negative aspects of switching regulation methods.

Architecture

At the input side of the power supply subsystem, soft-start, under voltage and reverse input protection must be present since the DC-DC converter doesn't include these functions. Additionally, the surge voltage and transient suppression must be added for the additional circuitry required for the soft-start and under voltage functions. EMI filtering is included in the DC-DC converter, but additional filtering is included at the input of the DC-DC converter to help with switching transients from the post secondary switching regulators.

The multiple output DC-DC converters provide three outputs, two of which are high voltage bipolar supplies of +/-15V supporting the analog interfaces at lower currents and one is a relatively high current +5V supply. With the need to generate multiple additional lower voltage supplies, switching regulation methods must be utilized for the higher power outputs in order to maintain reasonable power efficiency.

For example, with the 90nm silicon geometries the core voltage required is 1.2V which would translate to an ideal efficiency of 24% if using linear regulation methods, while switching regulation methods can typically achieve better than 85% efficiency. Since the field programmable gate arrays (FPGAs) core voltage typically requires a relatively high current and a telemetry encoder may include several FPGAs it would be unthinkable to use linear regulators for this supply rail. Similarly, the other digital supplies should use switching regulators to maximize the efficiency since the loading is generally significant. Figure 1 below shows the block diagram of the developed telemetry encoder power supply module.
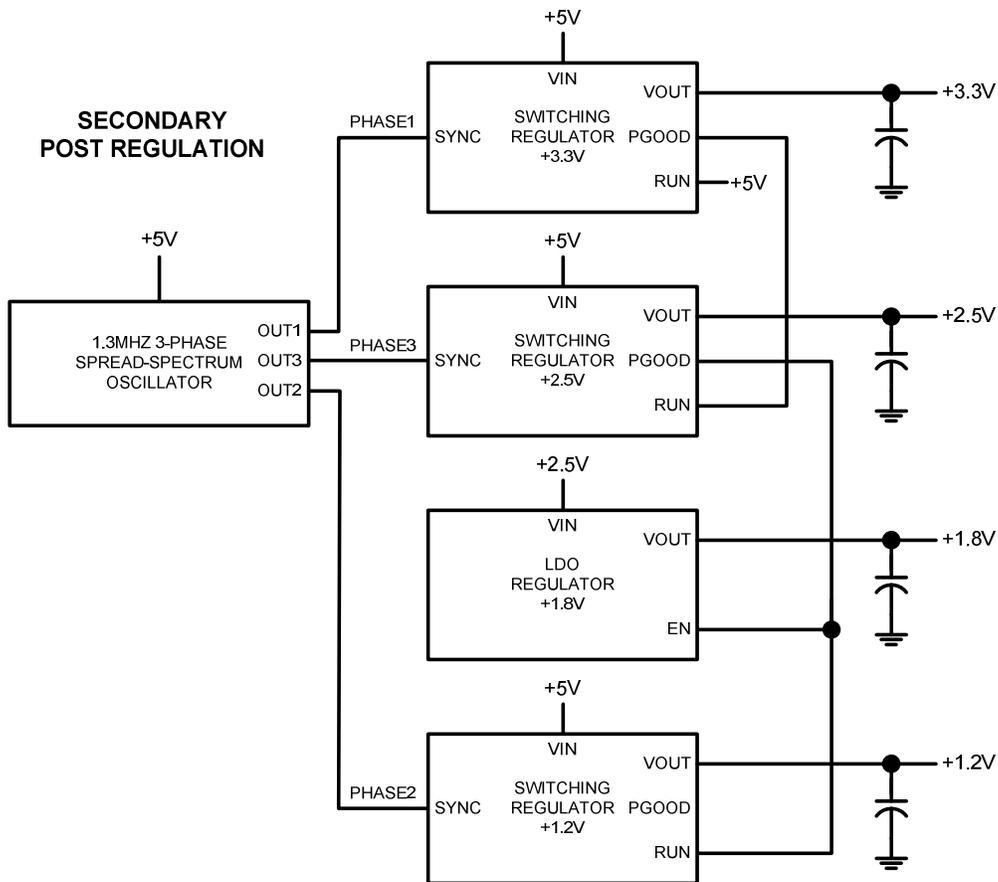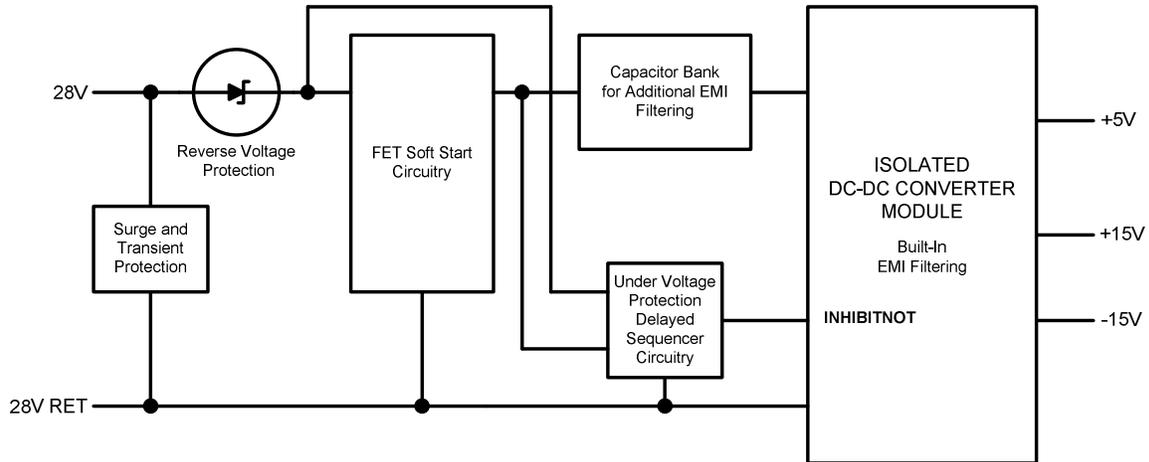
Figure 1: Telemetry Encoder Power Supply Module (PSM310)

NOISE AND RIPPLE MITIGATION TECHNIQUES

Switching power supplies are notorious for generating conducted and radiated noise. A power supply subsystem responsible for powering sensitive analog sensor interfaces must take all

reasonable steps to minimize the noise from the switching supplies. The PSM310 power supply module utilizes six key methods for mitigating switching power supply noise.

Synchronized Multi-Phase Switching

Synchronized multi-phase switching power supply regulators were utilized to reduce input current ripple loading. By strictly offsetting each switching regulator by 120 degrees, the peak-to-peak ripple current loading is greatly reduced. For example, if three switchers had equivalent efficiencies, power loading and were running asynchronously the ideal input current would range from 0 amps to 3 times the peak input current required for any single switcher. But when synchronized on non-overlapping phases the peak input current is reduced to that of a single switcher. Reducing the peak-to-peak ripple current not only minimizes switching induced noise, but also lowers the size of required input capacitor for equivalent filtering.

Optimized Load Balancing

In order to gain the most benefit from synchronized multi-phase switching methods, careful attention to load power balancing should be considered. It is important to remember that it is the power to the post secondary switching regulators that must be optimized and not the load currents.

Spread Spectrum Modulation

Spread spectrum modulation of switcher synchronizing clock is also helpful in reducing the observed noise from a switching power supply. Neglecting the change in input current requirements verses switching frequency, the peak instantaneous current inputs will not change. But the since measurements are integrated over a limited resolution bandwidth the spectral spreading will reduce the measured level of the noise proportionately as given in equation (1) below.

Attenuation (dB) = $10 \cdot \text{Log10} \left(F_{spreadbw} / F_{mbw} \right)$ (1)

where $F_{spreadbw}$ = bandwidth of the spectral spreading in Hz
        F_{mbw} = measurement bandwidth in Hz

High Frequency Switching

Spectral occupancy telemetry sensor information is typically limited to frequencies below 100kHz; therefore, high frequency switchers that put noise components out of the regular signal processing areas of interest enable direct filtering of the signal to remove any switching power supply noise components. For example, if the switching frequency is 1MHz and the highest signal of interest is 100kHz, there is full decade of spectrum separation between the signal of interest and the main switching noise component which allows for easy filtering of the sensor signal should it become significantly corrupted. Additionally, keeping the switching frequency high eases the filtering because smaller capacitances and inductances and thus smaller footprints provide effective filtering.

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Components

A step-down regulator's ripple current is inversely proportional to the value of the inductance and having lower ripple current lowers core losses of the inductor and equivalent series resistance (ESR) losses in the regulators output capacitors. Therefore, it is important to optimize this inductor value given the size restrictions to maximize the supply's efficiency. The inductor ripple current is given by formula (2) below.

$$\Delta I_L = [\ V_{out} / (\ F_{sw} \cdot L\ )\ ] \cdot [\ 1 - (\ V_{out} / V_{in}\ )\ ] \quad (2)$$

where V_{out} = regulator output voltage
$\quad\quad$ F_{sw} = switching frequency in Hz
$\quad\quad$ L = step-down regulator inductance
$\quad\quad$ V_{in} = regulator input voltage

The inductor optimization also reduces the power supply ripple because the current through the output capacitors ESR is converted directly into a ripple voltage. Having a lower ripple current also allows for a smaller load capacitance for the same level of ripple. Care must be taken to not just use the largest value and size of inductor the design will tolerate because larger valued inductors in the same family and size package from a vendor will have larger ESR losses that may nullify and even degrade the benefits from lowering the inductors core losses and the output capacitors ESR losses. Another issue with increasing the inductor value relates the method of regulation the switching regulator uses. Some switching regulators require a minimal amount of ripple current in order to maintain stability. Even if the output voltage seems stable, care must be taken to look closely at the output because this instability may manifest itself as a low level oscillation.

When choosing the inductor it is also of the utmost importance to insure that inductor will not come close to saturating. As an inductor approaches saturation, the effective inductance can decrease rapidly which causes spikes in the switching current. These higher transient current levels increase both conducted and radiated noise. Whether the inductor is saturating or not, the radiated noise can be reduced by using a magnetically shielded inductor.

As mentioned previously the output voltage ripple of the switcher is directly proportional to the ripple current times the ESR of the output capacitors; therefore, type of capacitor is a critical choice when minimizing the output ripple. For buck or step-down switching regulators using capacitor dielectric formulation such as X5R and X7R will minimize the ESR, but still maintain relatively good value stability over temperature. The output ripple is also inversely proportional to the value of the output capacitor as given in formula (3) below.

$$\Delta V_{out} \leq \Delta I_L \cdot [\ ESR + 1 / (\ 8 \cdot F_{sw} \cdot C_{out}\ )\ ] \quad (3)$$

where ΔI_L = inductor ripple current in amps
$\quad\quad$ ESR = equivalent series resistance of the total output capacitance
$\quad\quad$ F_{sw} = switching frequency in Hz
$\quad\quad$ C_{out} = total output capacitance

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The step-down regulator also requires a low ESR input capacitor rated for the maximum RMS current in order to filter the trapezoidal wave current input waveform. Without this local input capacitance it is possible to generate very high levels of switching noise induced by this current waveform which eludes to the importance of the switching power supplies layout.

Layout

The circuit topology, operating parameters and every component can be optimized correctly, but if the layout is poor the performance and even stability can be destroyed. There are numerous books, application notes and articles written that deal with the subject of noise reduction techniques relating to a circuit's layout, but a short list of some key guidelines are given below for quick reference. Generally, a good step-down switching regulator layout will optimize the following given their application constraints:

- Utilize ground and power planes if possible
  – Using a ground plane will reduce radiated noise, ground loop errors

- Minimize parasitic inductance of capacitors
  – Using multiple vias connecting to planes with the shortest current loop and connecting the ground terminals to same layer floods

- Minimize the additional routing inductance when connecting the inductor
  – Use as wide and short of traces possible when routing to and from the inductor, the parasitic inductance is inversely proportional to the width and thickness of the trace

- Make copper planes and traces as thick as possible
  – 1 ounce copper will help reduce resistive losses and provide better thermal management compared to utilizing ½ ounce copper

- Minimize routing areas of all circuitry especially the synchronous switch, inductor and output capacitor loop and place the input capacitor close to the power switch sourcing current to the inductor
  – Placing the related components tightly and in the correct orientation to minimize area and conduction loops will reduce both external noise pick-up and radiation outside the circuit

- Isolate and minimize coupling to the sensitive feedback voltage and compensation nodes from the inductor and other high current traces
  – Noise coupling on the feedback voltage and compensation nodes can ruin the regulation characteristics, routing the traces on the opposite side of the board as the inductor will help isolate these sensitive nodes by having a ground plane for improved isolation., If signals must overlap without a ground plane, route at right angles to minimize magnetic field pick-up. Low impedance guard traces around high impedance sensitive nodes may reduce noise pick-up.

- Shield switching elements
  – Electrostatic and magnetic shielding reduce radiated noise, for example using a copper shield box over a circuit to reduce high frequency radiation or using a high-permeability

magnetic material like Mumetal to constrain low frequency magnetic fields. Magnetically shielded inductors are localized example of magnetic shielding.

- Flood all unused areas with ground connected copper
  – After routing flood the open areas with ground connected copper insuring that the flooded areas have multiple via connections to the ground plane at a reasonable spacing to insure good high frequency bypassing operation

- Place the components so that the direction of the current loops are common for the two switching states to eliminate magnetic field reversal
  – A switching regulator maintains two operating states, one where the a synchronous switch or diode switch conducts energy stored in the inductor and one when energy is delivered from the input source to inductor through another switch. The components comprising these two current loops should be placed so the conduction directions are the same during each of their on states. For example, layout 1 on the left in Figure 2 shows a placement where both states have clockwise current loops, while layout 2 on the right would cause an opposing counter-clockwise current loop when energy is supplied by the inductor. Magnetic field reversal will change the polarity of the induced noise during each state making the peak-to-peak noise larger.
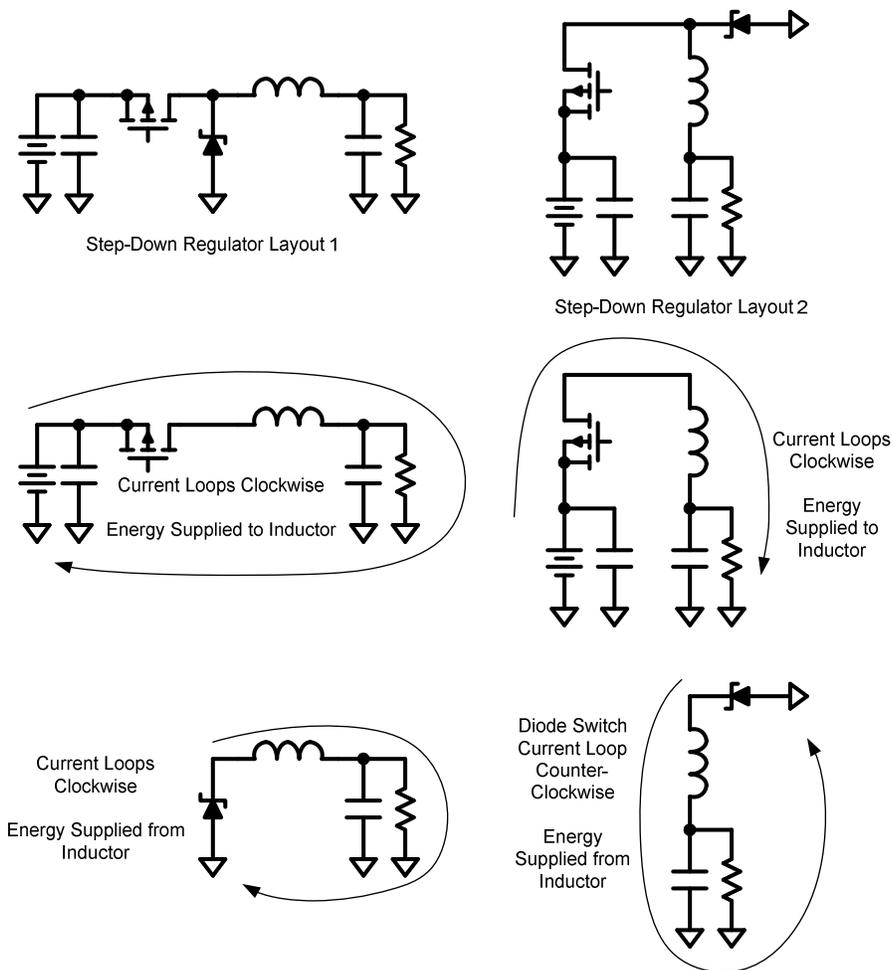

Figure 2: Functionally Illustrative Example Layouts

CONCLUSIONS

Telemetry encoder power subsystems have many industry, customer and manufacturer driven requirements that guide the basic design, but the need for a power efficient telemetry encoder has several implications that require special considerations that could previously be ignored when linear regulation methods dominated telemetry encoder power supply subsystems.

Power efficiency requirements generally rule out the use of linear regulation methods for supplying digital processing components, especially those voltages required for modern 90nm silicon geometries. Therefore, switching power supply topologies must be utilized and their noise implications dealt with accordingly. Several power supply noise mitigation methods were presented, such as multi-phase staggered synchronous clocking that have been effectively implemented in the L-3 Communications PCM330E telemetry encoder.

New power supply options are continually developing that may favor new or previously rejected implementation methods or at least ease the implementation with higher levels of integration. For example, miniature modularized point-of-load converters or multiple output low voltage DC-DC converter solutions tailored for digital requirements.

Future research may be directed toward the development of a more efficient isolated DC-DC converter solution that meets the strict space limitations and environmental conditions needed in telemetry encoder applications. Currently available DC-DC converters that meet the size constraints typically only exhibit ~75% efficiency while commercial DC-DC converters exhibit efficiencies above 90%. Furthermore, there is ample opportunity for additional functional integration and optimization if the isolated DC-DC converter function is taken out of its black box.

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