High Power Space Grade Point of Load (POL) Voltage Regulator for Distributed Power Architecture (DPA)

By

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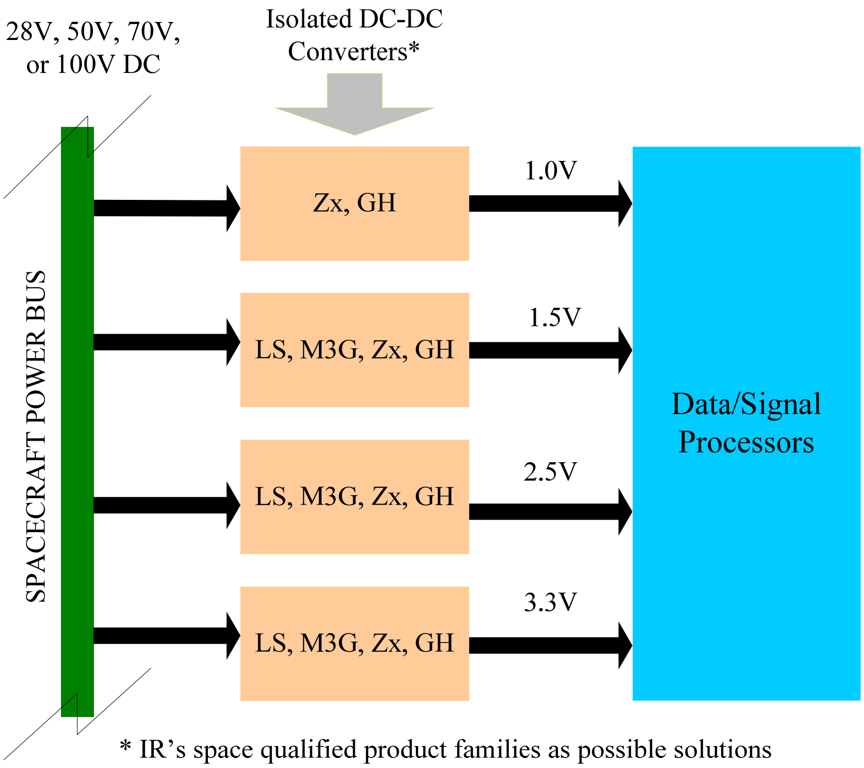
As new generations of space grade FPGAs, DSPs, ASICs, memory, and other digital devices enter the market to meet the growing demand for increased bandwidth and data processing speed of the data processors and signal processors on-board a spacecraft, these new digital devices place unprecedented constraints on power supplies. The new digital devices require lower supply voltages and higher operating currents for a given power demand. For the large data and signal processor designs where the needs for power and/or current become a critical factor (s), the distributed power architecture (DPA) is often the power system of choice to ensure the optimum system performance. This paper presents the key design features and performances of a new point of load (POL) voltage regulator one of the key elements of the DPA power system.

1.0 Introduction:

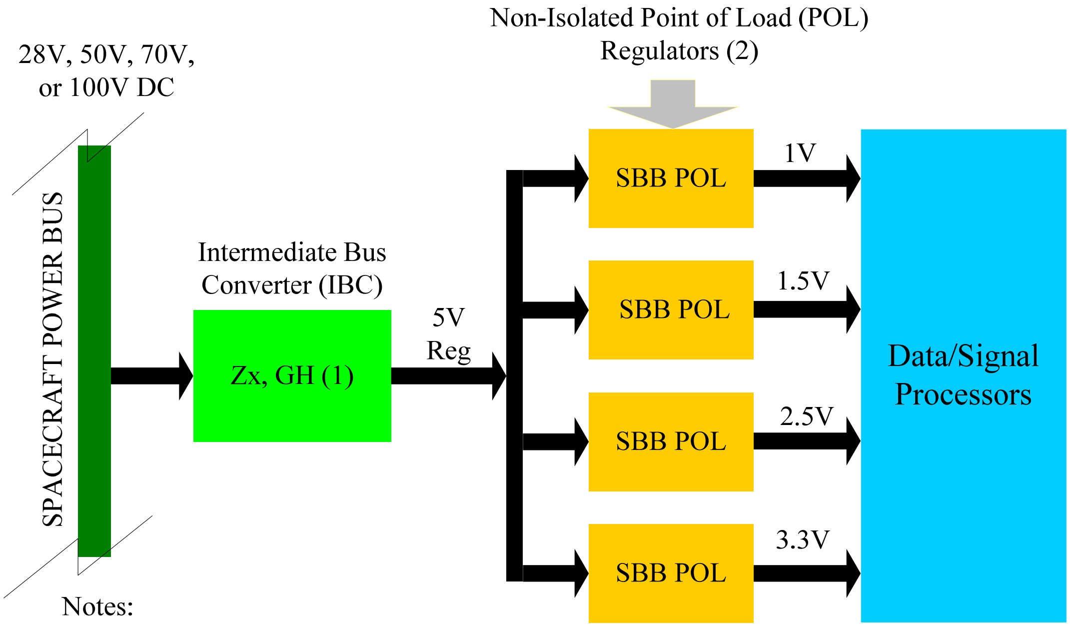
New generations of the digital devices require low supply voltage. For large or multiple data/signal processors this means the required operating current can be quite high in the order of 5 to 10A or more, and in some cases up to several tens of amperes. Traditionally, there are at least two basic design approaches being deployed for most power design solutions. One common solution as depicted in Figure 1 is a decentralized approach where several isolated DC-DC converters operating directly off a space craft power bus, are used to provide the regulated supply voltages, 1V, 1.5V, 2.5V, 3.3V, 5V, etc., as required by the digital loads. The other popular approach is known as distributed power architecture (DPA) of Figure 2. A basic DPA system typically uses one isolated DC-DC converter operating directly off a spacecraft power bus and two or more POLs. The isolated converter provides an intermediate regulated or unregulated voltage that powers the down-stream non-isolated point of load (POL) voltage regulators which provide regulated supply voltages to the digital loads. One POL is typically required for each unique output voltage. Two or more output voltages are commonly required. Each voltage may range from 0.8 to 3.3V though the trend is moving toward 1V and lower. Redundancy and other system design considerations will add complexity and may require additional DC-DC converters and POLs to satisfy the system design requirements.

IR’s product offerings support both and similar system design approaches. In fact, IR offers product solutions suitable for most power system designs. The block diagrams list the family names of IR’s building block DC-DC converters (i.e., LS, M3G, Zx, and GH) designed for modern digital devices targeted for a wide range of radiation environments including designs for extended mission life of 15 years or more.



* IR's space qualified product families as possible solutions

Figure 1 – A simplified De-centralized Power System Diagram



Notes:
1. IR's product families as an IBC
2. The newly released standard off the shelf SBB series as the POLs

Figure 2 – A simplified Distributed Power Architecture (DPA) Block Diagram

Each of the two basic design approaches has its respective merits and drawbacks. Detailed analysis and a trade-off study are generally performed to insure that the specific design and program objectives are met. The design system approach selected is generally dependent on, but not limited to, the following factors.

- System efficiency
- Dynamic performance due to parasitic impedances
- Size and weight
- Heat distribution
- Mechanical layout design
- System redundancy requirements
- Availability of the power conversion elements
- Costs

2.0 SBB Series POLs Description and Key Features

The SBB series POLs are hermetically sealed, thick film based microelectronic hybrids. The SBB series uses the assembly design and manufacturing processes with which IR has successfully served the world's space community for almost 20 years. IR's SBB series is the first space qualified, standard off-the-shelf point of load (POL) voltage regulator in the industry. The SBB POLs are class K screened per MIL-PRF-38534. The product design drivers are efficiency, compact form factor, ease of system integration, and space flight worthiness. It offers excellent efficiency and performance capable of meeting the power demand of today's digital loads. An SBB is a self-contained POL, ready for system integration as external filtering is not required for most typical applications but the load may require decoupling capacitors depending on actual physical implementation. All internal components have been carefully evaluated and characterized to insure reliable operation under the intended operating environments. Design analyses including electrical stress, thermal, failure modes and effects (FMEA), reliability (MTBF), and worst case analysis (WCA) including end-of-life (EOL) performance, are standards and available upon request. Following are the key features of the SBB POL.

- Total dose >100K Rads (Si)
- SEE hardness rated, SEL/SEB/SET with LET >82 MeV-cm2/mg
- Operates from 4.5V to 5.5V DC supply
- Fixed output voltage: 1V, 1.2V, 1.5V, 1.8V, 2.5V, and 3.3V are standards
- Output power up to 30W or 14A maximum without power de-rating
- High efficiency to 89%
- -55 to +85ºC operating case temperature without output power de-ration
- Remote sense compensation
- Fixed 400 KHz operating frequency
- Output adjustable to ±10% of nominal output with external resistors
- Enable functional pin for remote on/off control
- Under voltage lockout (UVLO)/input under-voltage protection
- Overload and short circuit protection
- Low noise with integrated input and output filters

- No external filter capacitors required
- Soft start
- Synchronization, input and output
- Logic high signal power OK (POK) for output status
- End-of-life (EOL) worst case analysis (WCA)
- MIL-PRF-38534 element evaluated components
- Derating per MIL-STD-1547 for space flight
- MTBF > 2.8 million hours for space flight environments
- Size: 1.9"L x 1.5"W x 0.335"H excluding I/O pins and mounting tabs
- Weight: 60 grams maximum
- Custom versions available

3.0 Design Topology

Block diagram of an SBB is shown in Figure 3.

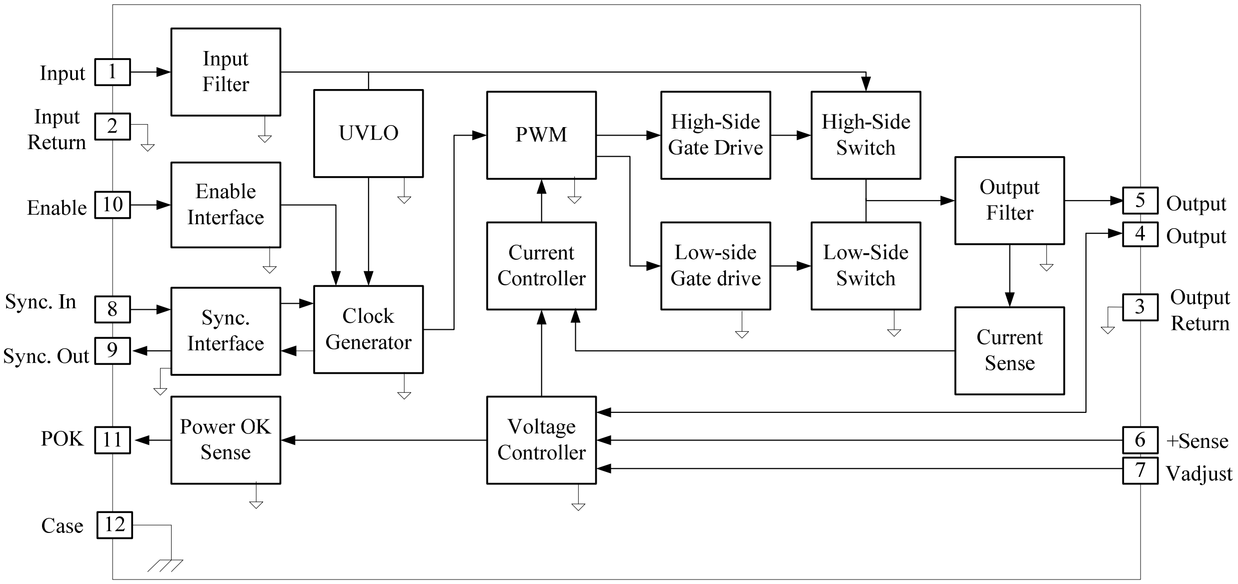


Figure 3 - SBB Series POL Block Diagram

The SBB uses a non-isolated synchronous buck topology to step down a nominal input voltage of 5V to an output as low as 1.0V. As depicted in Figure 2, IR's Zx and GH series can be used to provide a 5V power source for the SBB POLs. The power train consists of an input filter, high side and low side switches, and an output filter. The output regulation is achieved using an average current mode control operating at a fixed frequency of approximately 400 KHz. The discrete devices that make up the PWM controller includes LM124 (quad operational amplifier), 54AC14 (hex inverter Schmitt Trigger), and AD8042 (high speed Op Amp). The power switches are IR's rad-hard IRHC57Z30 MOSFETs. IR's R7 rad-hard logic MOSFETs are used as the pre-drivers and are used throughout the design for general signal processing purposes. All semiconductor devices are selected for their known performance under the intended radiation environments.

Since the internal circuits must operate from an input source of 5V, all components are selected based on the available supply voltage. However, a charge-pump circuit is added to raise the supply voltage to 6.5V for some of the semiconductor devices. Additionally, small signal transformers are deployed to raise the drive voltage as required by the rad-hard power MOSFET switches which require a 10V gate drive to fully enhance the switching functions.

Input Filter

The input filter is a second order resistively damped filter. It is designed to provide sufficient damping of the ripple current for the 5V bus and low ripple voltage towards the POL. The ripple current is kept below 100dBµArms at the first harmonic, and the input ripple voltage of less than 0.5mVrms is another design objective. These objectives establish the baseline under which the system design is based, to insure system stability when selecting an intermediate bus converter (IBC) and the POLs. Refer to item 4 of the listed references for the compatibility analysis of the IBC and the point of load (POL) regulators. The article examines the compatibility of IR's ZB series as an IBC and the SBB series POLs, to insure the stability of the power converters and the power system under various static and dynamic loading conditions.

Main Power Stage

IR's R5 generation advanced rad-hard power MOSFETs IRHC57Z30 with the V_{DS} rating of 30V are used for the high-side and low-side switches, one for the high-side and two power MOSFETs in parallel for the low-side. Furthermore, a low V_F Schottky diode is placed in parallel with the lower switch to ensure noise free transition of the output current from the upper to the lower switch. The Schottky diode also provides a fast discharge path during a reverse recovery transition to minimize recovery losses and to further improve the efficiency.

Regulation of the POL and Overload Protection

As mentioned an average current mode control is selected for the output regulation. The voltage regulation is realized with the use of an LM124, a quad operational amplifier. The output signal is sensed, processed and pulse width modulated (PWM) through a chain of discrete devices that make up the PWM controller. The PWM operating at a fixed frequency of approximately 400 KHz, through the sequence of signal processing steps, the discrete PWM controller generates the duty cycle controlled gate drive voltages that switch the low-side and high-side switches which in turn provide a tightly regulated and stable voltage output.

The average current mode control, where the output current is sensed across the output choke, also offers the inherent benefits of a constant current limitation for the output overload and short circuit protection. This forgoes the need for a current sense resistor as the resistance of the output inductor element is readily available to provide the sensing function. However, temperature has a considerable effect on the resistance of the copper wires used for the output inductor. This effect is kept under control to within ±20% of a preset threshold with an inclusion of a temperature compensating diode and the inherent positive temperature coefficient of the copper resistance. The over-current threshold is inherently lower under a higher temperature condition than at a lower operating temperature thus lessening the electrical stresses on the power devices and other components in the power train.

Output Filter

The output filter circuit is a two-stage L-C filter that minimizes both the fundamental and high frequency ripple and noise. The two-stage filter also meets the needs for low output impedance ensuring an acceptable overshoot and undershoot excursions of the output voltage when the load is transitioned to and from half-load and full-load. A typical step load output response and the output ripple/noise waveforms are included in the typical performance section of this paper.

Input Under-Voltage Protection (UVP)

The SBB series POL is protected against an input undervoltage condition when the input power source drops below the low line limit of 4.5V. It is a non-latching class with an automatic restart when the input voltage returns to the normal operating range. The input UVP circuit senses the 5V supply and compares it to the input UVP reference. If the input voltage is below the limit (approximately 3.9V), the POL will not operate, there will not be any voltage at the output. When the input rises above the preset threshold (approximately 4.3V) the POL will begin to operate and provide a regulated output. The turn-on and turn-off threshold levels vary slightly with temperature. The UVP includes an on-off hysteresis preventing the POL from turning on and turning off in the event the input power source does not rise monotonically.

4.0 Functional Features

The SBB POLs include several key functional features that benefit the typical design applications. They are output on/off control, frequency synchronization of multiple converters, remote output sensing compensation, precise output voltage setting, and output status signal (POK).

On/Off Control - The SBB POL can be commanded on and off via the Enable pin (Pin 10). The POL will turn off when the Enable pin is pulled low with the signal of 0.4V or lower with respect to the Input Return pin (Pin 2) and a 5V power source is present at the Input pin. The POL will turn on when the Enable pin is left open or with a signal of greater than 2.5V is applied to this pin. The typical turn-on threshold is 2.5V with respect to Input Return. The Enable pin can also be used to control multiple SBB POL modules for output sequencing. Please refer to the SBB data sheet to size the power requirements of the control signal.

Synchronization – Multiple SBB POL modules can be synchronized to a common operating frequency with an external signal source with the frequency range of 400±40 KHz. Specific requirements of the synchronization input signal can be found in the SBB data sheet. Each SBB can also source and accept a signal from another SBB in a daisy chain style, i.e., Sync Out A to Sync In B, Sync Out B to Sync In C, and so on. This way, each synchronization output (Sync Out) is driving only one synchronization input (Sync In), and the oscillators of the converters are slightly out of phase with one another, which reduces the combined input ripple/noise.

Remote Sense and Output Voltage Adjustment - The +Sense pin must be connected to the Output pins (pins 4 and 5) or to the output line at the load where the load is some distance away from the POL for a proper operation. In the latter case, the SBB POL is capable of compensating for a voltage drop in the positive output line. This can be accomplished by connecting the +Sense pin (Pin 6) to the high potential point at the load. The maximum compensated voltage can be as high as 10% of a nominal output voltage of the POL if the Output Voltage Adjustment feature is not used. The Input Return and Output Return are internally connected. To enhance the output regulation, the Input Return (Pin 2) may be connected externally to Output Return (Pin 3).

The SBB POL also includes an output voltage adjustment capability for a precise output voltage setting. Output voltage of each SBB POL is pre trimmed to a standard voltage at the factory. The standard voltages are 1.0V, 1.2V, 1.5V, 1.8V, 2.5V, and 3.3V. However, if the output voltage needs to be set to a slightly lower or higher than a given standard, the output of the SBB POL can be reset to a different voltage with the addition of an external resistor. The combined voltage of the increased output voltage and the voltage drop in the output line (by way of remote sense compensation) is limited to ±10% of a nominal output voltage. If the remote sense feature is not used, the maximum adjustable output voltage is 10% above the nominal output. The formula for a desired output voltage and a corresponding application note can be found in the SBB data sheet.

Output Status (POK) – The POK circuit (Pin 11) supplies a logic high output whenever the converter's output voltage is greater than approximately 95% of the nominal. The POK signal does not go low in case of output over-voltage.

5.0 Assembly Design and Construction

Similar to most of IR’s DC-DC converter products, the SBB series POL is a thick film hybrid hermetically sealed assembly. The assembly design and constructions offer many distinct benefits. The hybrid assembly with its inherent iso-thermal plane offers the shortest thermal paths from the components to the base for cooling yielding the lowest possible junction thermal impedances. Along with the use of high thermal conductivity materials throughout the design, the best possible thermal performance is achieved. The assembly design insures the minimization of the temperature rise on the internal components, thus enhancing the product reliability.

The package’s base and side wall are welded. The package material is cold rolled steel offering assembly ruggedness. The lid is Kovar. It is seam sealed to the package for the air-tight construction which promotes long term reliability. The basic cross sectional view of the SBB assembly design is shown in Figure 3.

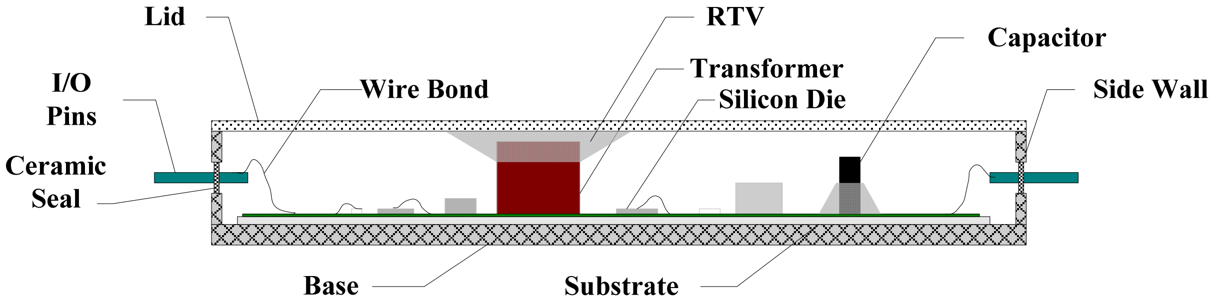


Figure 4 – Basic Cross Sectional View of the SBB POL Regulator Assembly

Assembly begins with attachment of electrical components by way of solder reflow or adhesive epoxy to bare beryllium oxide (BeO) thick film substrates with screen printed resistors.

Transformers and other magnetic parts are attached to substrates and base of the assembly with thermally conductive epoxy. The assembled substrates are then solder reflowed to the base. Lead frames and wire bonds are attached from the substrate to substrate and substrates to the I/O pins. The assembly is then inspected for acceptable workmanship and tested to insure proper functionality. High profile components are secured with silicone based gap filler to enhance mechanical stability for the intended shock and vibration environments. The assembly is completed with laser sealing the lid. A completed assembly is retested to insure proper functionality and is subjected to additional reliability screening as required.

6.0 Package Outline and Heatsink (Cooling) Consideration

The overall package outline of the SBB measures 2.4"L x 2.0"W x 0.335"H. The length and width dimensions include protrusion of the input/output pins and the mounting tabs. The package foot print measures 1.9"L x 1.5"W. The mounting tabs layout design is such that it allows multiple SBB units to be placed side by side where the mounting tabs of one unit can be placed in line with the other unit to minimize the board space. Adequate cooling must be provided for an SBB. An SBB POL must be attached to a thermally conductive surface for cooling. A thermally conductive pad similar to a SIL-PAD is recommended to fill the voids between the base of the package and the surface to which the SBB is mounted. Contact the factory for mounting procedure which includes the recommended mounting screws, SIL-PAD material, mounting sequence, and mounting torque requirements.

7.0 Product Qualification

Flight hardware of the SBB series POLs is now available with a standard lead time for a space qualified product from IR. The product is internally qualified to Class K in accordance with MIL-PRF-38534. Representatives of SBB qualification model were subjected to and successfully passed both the total ionizing dose (TID) and single event effects (SEE) radiation tests. Class K qualification report including life test and radiation tests reports are available. Also available are design analysis reports which include electrical stress, thermal analysis, failure mode and effects, reliability (MTBF), and worst case analysis (WCA). Please contact the factory for these reports. DSCC qualified SMDs are in process.

8.0 Samples of Actual Test Data and Performances

Following are samples of the typical performance of the SBB series POLs.

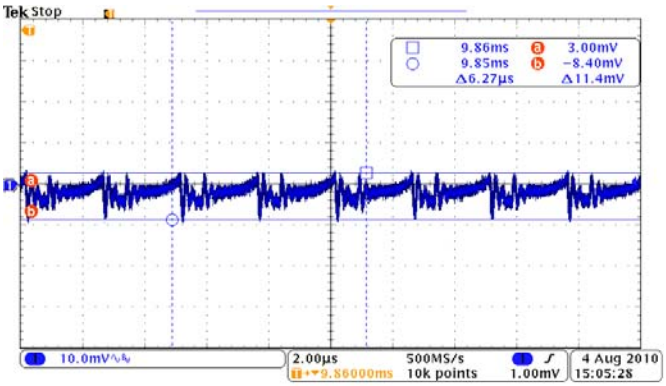


Figure 5 – Output Ripple/Noise at 5V Input and Rated Load, SBB503R3S (3.3V Output)

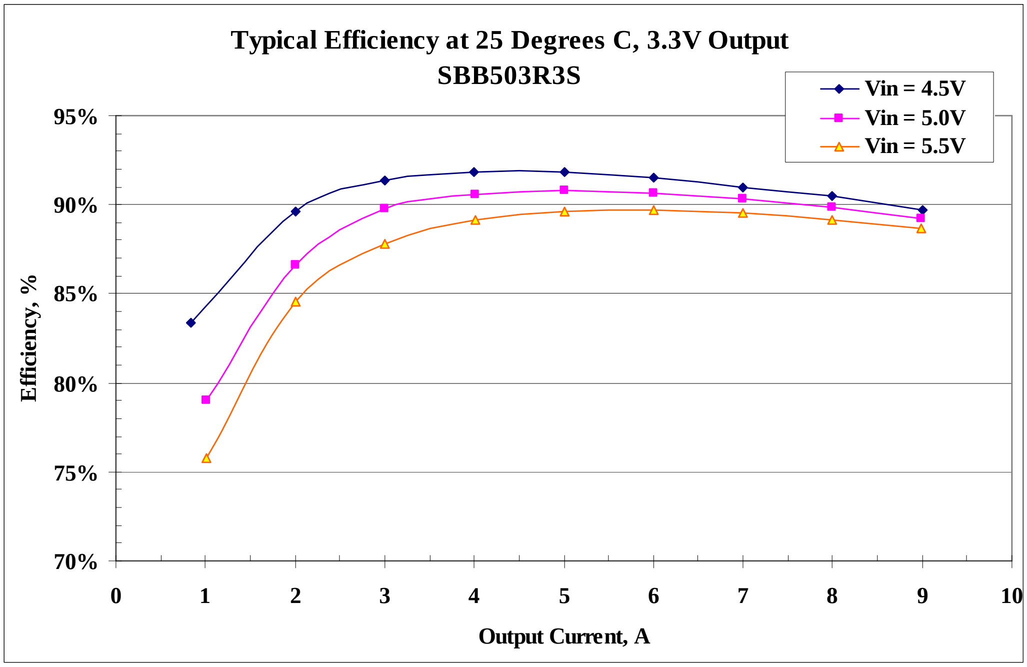


Figure 6 – Typical Efficiency Performance with Respect to Output Load and Input Voltage at 25ºC, SBB503R3S (3.3V Output)

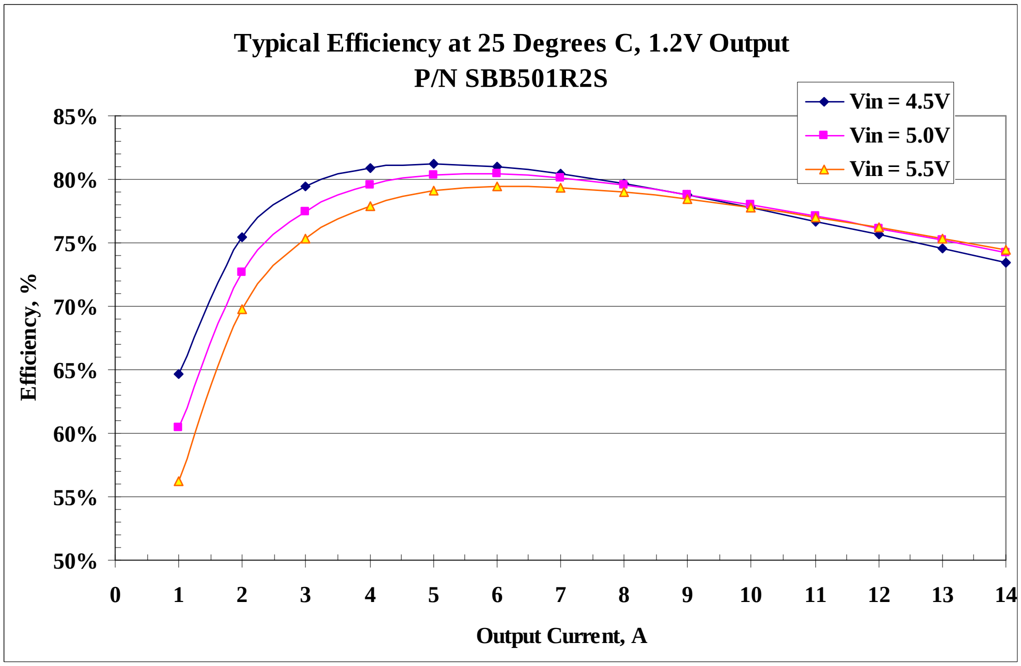


Figure 7 – Typical Efficiency Performance with Respect to Output Load and Input Voltage at 25ºC, SBB501R2S (1.2V Output)

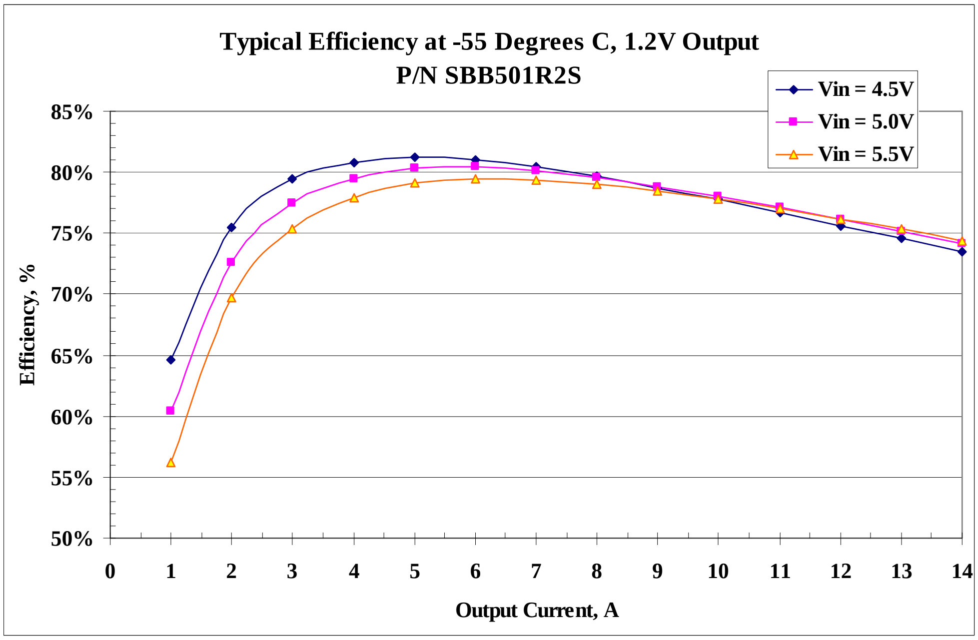


Figure 8 – Typical Efficiency Performance with Respect to Output Load and Input Voltage at -55°C, SBB501R2S (1.2V Output)

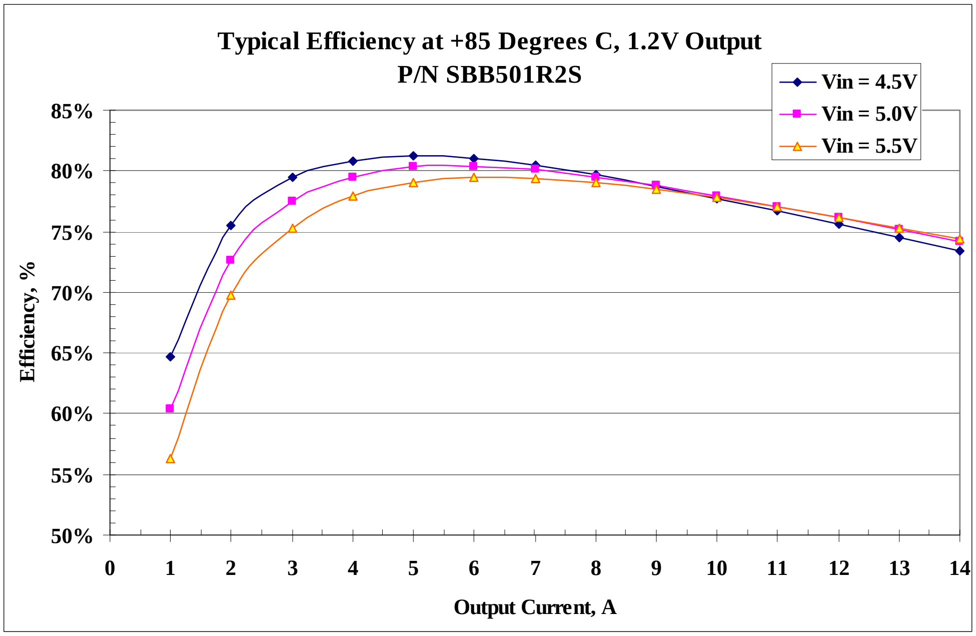


Figure 9 – Typical Efficiency Performance with Respect to Output Load and Input Voltage at +85°C, SBB501R2S (1.2V Output)

It should be noted that the efficiencies for both 3.3V and 1.2V output models peak near half-load. And that the operating temperature has a very little effect on the efficiency performance for the 1.2V output model. A similar conclusion may be drawn for other SBB models in both instances. Please contact the factory for actual performance data of a specific model for your design needs.

Future Developments:

Other platforms in development in support of the market demand and design trends include the GH series IBC, a 50W, single output, high efficiency isolated DC-DC converter, ZA series (a 100W version of the Zx design platform) IBC, single output, high efficiency isolated DC-DC converter and the SBA series POL, 10W/6A, non-isolated point of load regulator, a lower output power version of the SBB. Both the GH and SBA series target the lower power DPA power system designs. Whereas the ZA series is intended to support the medium power DPA design applications. Please contact IR for the latest status for new developments.

Conclusion:

After years of extensive design and engineering, IR has successfully met the challenges in design and development of the first non-isolated point-of-load (POL) voltage regulator for high power space design applications. Key factors in the successful development include the components selection for the challenging radiation environments, materials selection, proven design topology, conservative components de-rating, assembly design, and process development. The SBB POL offers immediate benefits in reduced program costs, short lead time and ease of system integration. With its high efficiency performance and a compact foot print, the SBB series POLs are ideal for the DPA design systems solutions for the modern day digital devices.

References:

1. “Military Satellites Pose Engineering Challenges in DC-DC Converter Development”, Tiva Bussarakons, Defense Electronics, A Primedia Publication, May 2004.
2. “Thick Film Hybrid DC-DC Converters are Standard ‘Brick’ for Satellite Power Systems’, Tiva Bussarakons, Defense Electronics, RF Design, June 2006.
3. International Rectifier SBB Series POL Data Sheet
4. “Compatibility Analysis of Space Qualified Intermediate Bus Converter and Point of Load Regulators for Digital Loads” by Bjarne Soderberg and Tiva Bussarakons, European Space Power Conference, August 2008

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