High Temperature DC to DC converter operates in +215 ^{0}C environment, meeting demands of down-hole oil exploration market

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1. PROLOGUE:

Just about all downhole exploratory and operational tools employ a large number of analog and digital electronics sub-systems and different sensors, gauges etc. - all of which need stable and reliable D.C. power supplies. There exists a geothermal gradient of 25 to 30 ^{0}C/km (40-48 ^{0}C/mile) and at depth of 5 kms, temperature can be as high as 170 ^{0}C and pressure up to 900 bars. But with increasing demand for oil and fast depleting crude oil reserves, almost all companies are now digging deeper and wider, with requirements for downhole tools to be rated at 200ºC. Its implications are that all electronics should not only survive but function at these higher temperatures and pressures. Leading companies, making oil exploration tools and equipment, in both "Logging while drilling" and "continuous logging" applications, need electronics for motion control, instrumentation, computation and telemetry and, to power them, require D.C. power supplies. In order to guarantee operations at 200ºC, manufacturers look for components rated about 10ºC-15^{0}C higher or 215ºC to provide design margin. When oil exploration tools and equipment operate, the electronics contained therein also experience shock & vibrations. To ensure reliable operation, therefore, design efforts for all electronics sub-systems and power supplies should take all these into account.

Oil exploration tools are cylindrical in nature and require electronic assemblies to be as narrow as 1" wide. Therefore these assemblies do extend in length to deliver the functions, features and power needed. However the length is also limited due to the cost of the pipe and the need to accommodate reasonable radius for directional drilling. Designing electronic assembly with such form factor constraints require special design attention and sometimes unique technologies.

Operating environments and required reliability pose challenges and influences the design process. Just to give an example, magnetic feedback is used instead of opto-couplers, because opto-couplers pose reliability issues at high temperatures and in downhole environment. Similarly choice of all components, materials, processes and manufacturing techniques also are influenced by the end use in downhole applications.

To address the above needs, International Rectifier Hirel Products, an Infineon Technologies Company, has developed a High Temperature DC to DC converter, which features high efficiency, tight regulation, low ripple and low noise and operate in harsh environment of -35 ^{0}C to +215 ^{0}C concomitant with shock & vibrations. The VHB converter use standard 28VDC input bus, with a wide range from 17V to 34V, and provides a regulated 5.0 VDC output voltage at 5W with > 78% efficiency. Other output voltages, such as 3.3V, 12V, 15V are also available. The VHB converter comes in a hermetic hybrid package, which yields the small size of 1.0" W x 0.4" H x 3.5" L (plus flange) and weighs 85 grams. This is in line with the industry requirements of size, shape and weight. Quality assurance includes environment screening, using temperature cycling, shock, vibration and burn-in.

This paper describes design, selection of components, materials and processes, development of manufacturing techniques & implementation of tools & methods for quality assurance. The paper also briefly describes applications of these converters in the down-hole industry for oil exploration, drilling and production.

2. TOPOLOGY, CONTROL TECHNIQUES & FEATURES:

Block Diagram in Fig. (1) depicts major building blocks of VHB DC to DC converters. It uses classical forward converter with active clamp topology, having two MOSFETs in the primary side, a high frequency transformer and a PWM controller IC to control output voltage in conjunction with synchronous rectification to enhance operating efficiency. The selected topology provides high line rejection. Under Voltage lock out and output overload and short circuit protection greatly enhance the converter's survivability due to line and load faults. Electrical (Galvanic) isolation and tight output voltage regulation are achieved through the use of a patented magnetically coupled feedback, while closed loop control is afforded by employing IR's proprietary custom-built, feature-rich PWM IC. This PWM controller IC was developed by IR to operate reliably at high temperatures, proved by life tests done at 240 ^{0}C for 1200 hours in biased condition. To mitigate noise, simple internal EMI filter was conceived, designed and implemented.

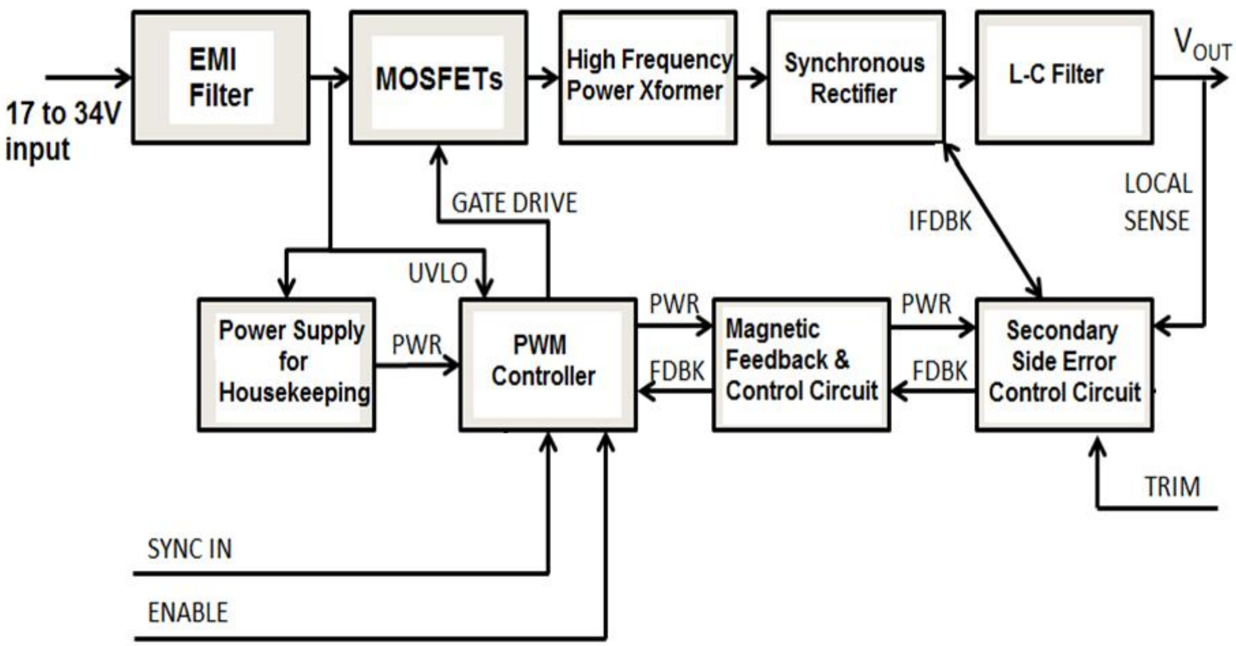


Fig. (1) Block Diagram showing Topology of VHB DC to DC Converters

Additional features include inhibit/enable, external synchronization, Voltage adjust facility, line feed forward with ramp generator, soft-start at power-on, enable-on and fault-shutdown release. Pulse-by-pulse current limit at 1.2 A, and fault shutdown at 1.5 A protects the converter against common load faults such as overload or short circuit. Facilities such as Synch In, Remote Enable, and Voltage Adjust are provided for user convenience.

VHB employs specially selected active & passive components, materials & process technologies, during manufacturing that not only survive 215 ^{0}C environments with vibrations, but perform creditably during mission life. Electrical stress analysis and thermal analysis have been performed on each component.

In the Block Diagram of Fig. (1), blocks on the top represent flow of power and the blocks on the bottom represent control circuitry. Fig. (2) Shows basic circuit elements with their functions.

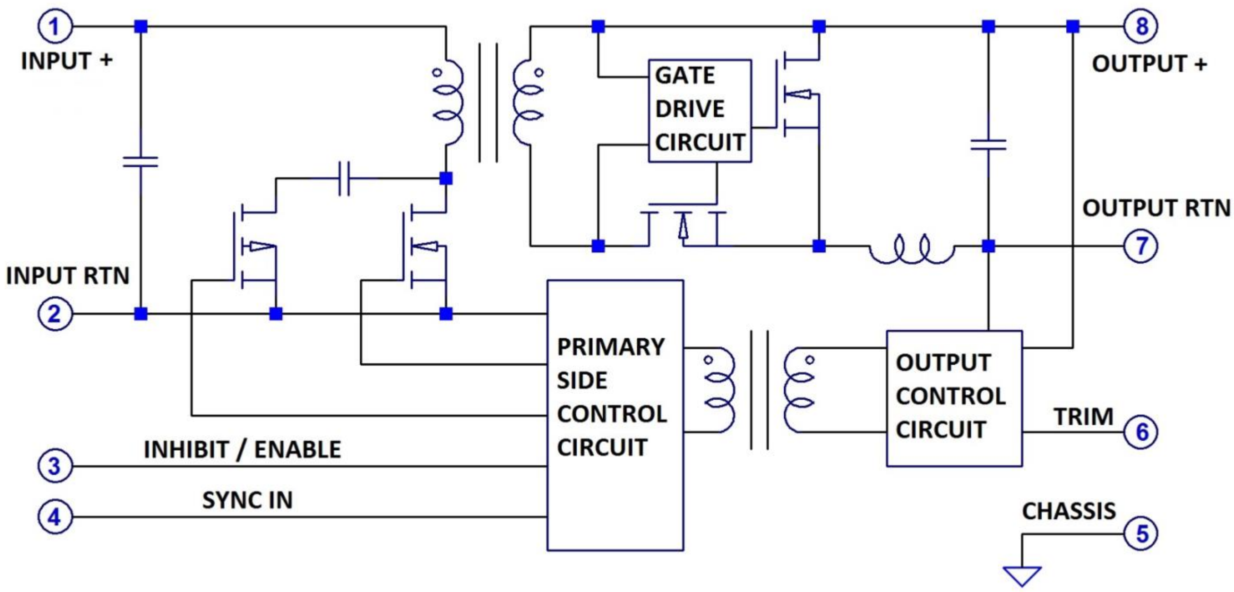


Fig (2) – Functional Block Diagram of VHB Converter

3. CHALLENGES FACED:

Selecting the proper materials and securing large components such as substrates, magnetics need special design focus to survive the shock test. For example, choice of substrate, choosing methods to attach semiconductor die onto this substrate, choosing right solder materials, interconnections and thermal dissipation were the challenges. The methods and techniques used are described below in section 4.0 on packaging

Projects involving designing, manufacturing and qualifying high temperature DC to DC Converters for 215 ^{0}C ambient can naturally be challenging. Component selection, developing optimum design and then implementing such a design, within constraints imposed by the down hole industry were all daunting tasks. Just to give one example, Schottky didoes become too leaky above 200 ^{0}C, and so MOSFETs can be used instead as synchronous rectifiers, giving one added benefit of lowest forward voltage drop so that higher efficiency can be achieved for low output voltages. For higher output voltages, SiC rectifiers are used in place of Schottky rectifiers.

Developing a qual plan to ensure performance at 215 ^{0}C without over stressing the part was also a challenge. At each stage lessons were learned. It was a group effort, involving departments of engineering, quality control, planning and management. Developing manufacturing techniques using the right materials that perform at 215 ^{0}C posed the greatest challenge. All these efforts contributed towards products, which now work satisfactorily from -35 ^{0}C to 215 ^{0}C.

4.0 PACKAGING:

Fig. (3) shows VHB2805S converter, which is a Thick Film Hybrid implementation. As can be seen and appreciated it is shaped to meet dual goals of accommodating all hardware, while meeting requirement of 1” width for the downhole industry. With such a width, the aspect ratio of the hermetically sealed package is unusual. IR has developed techniques to successfully seal the package with such an aspect ratio.

There are two substrates used in building VHB. Primary substrate, which houses all circuits that are connected to the input bus of 28VDC nominal, and, secondary substrate, which houses circuitry that are connected to the output.

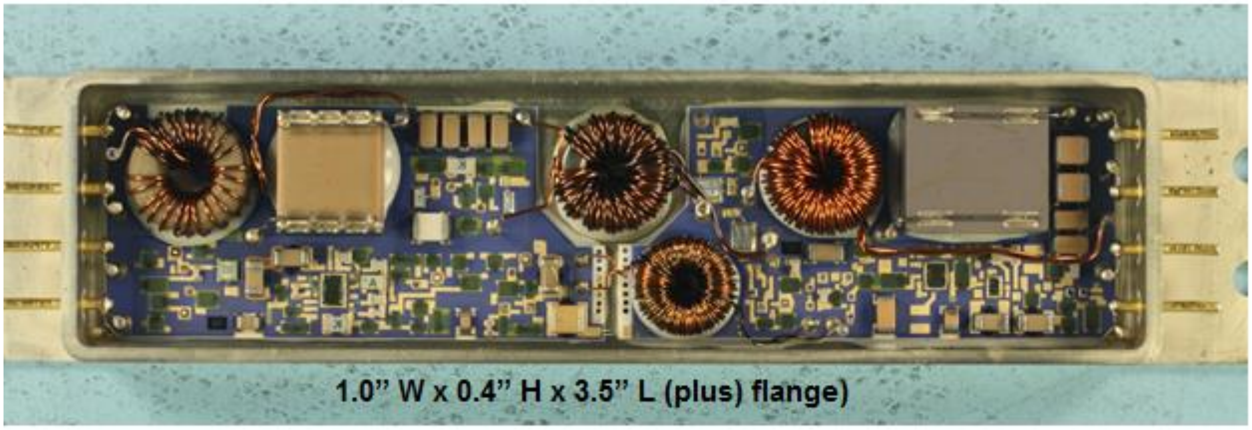


Fig (3) – Photo of Open Assembly of VHB Converter

VHB uses thick film hybrid technology, which is explained by the drawing in Fig. (4) below : Substrate is made up of alumina having multiple layers with screen printed ink resistors. All semiconductor die are attached to the substrate using special epoxy that has good thermal conductivity and which can withstand high temperature. Interconnections amongst electronic components are done using wire bonds.

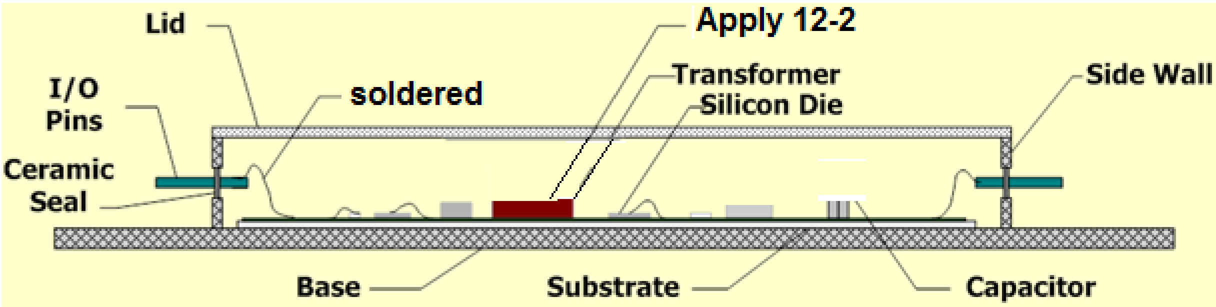


Fig. (4) Assembly, Design and Construction of Hybrid

1. Thick film hybrid is typically used for RF designs and in space for HiRel electronics
2. Package is made of machined, Cold Rolled Steel (CRS) unibody base, side wall and Kovar Lid. Upon completion of the assembly, the lid is sealed to create a hermetically sealed package filled with nitrogen.
3. Substrate is alumina with screen printed resistors.
4. I/O pins are copper core Alloy 52 and are ceramic sealed to the side wall.
5. High Temperature conductive Epoxy is used to attach die of all semiconductor components. This facilitates rework and replacement of any component.

5.0 ADVANTAGES OF THICK FILM HYBRID OVER PRINTED CIRCUIT BOARD

When implementation of high temperature or space grade electronic modules is considered, thick film hybrids offer many advantages, as enlisted below:

1. Hybrids use all semiconductors in die form, which are less than 10% of packaged semiconductor by volume. Hybrid is typically more compact than PCB implementation. With the 1" width form factor, you'll note that the hybrid VHB is only 3.5" long.
2. As placement of these die can be close to each other, signals are less prone to noise pick-up. Rise and fall times of switched semiconductors are reduced, enabling adaptation of higher frequency in designs, resulting in reduced size & volume of transformers, inductors and capacitors.
3. In the hermetically sealed hybrid package, the components are impervious to outside moisture or other ionic, liquid or gaseous contaminants thus ensuring total immunity from corrosion. This results in long life and reliable performance.
4. Power semiconductor die are attached, directly to the substrate, which provides enhanced thermal conductivity. This improved heat transfer from die to substrate and then to base of package helps overall performance & reliability, when handling power conversion.
5. Ink resistors used in hybrid are amenable to laser trimming, thus facilitating precise adjustments and calibration during manufacturing & testing.

6.0 MEASUREMENT RESULTS AND EXPLANATION:

Fig. (5) shows the % efficiency of VHB2805S at 25 ^{0}C. Efficiency is nearly 85% at rated power. Fig. (6) shows % efficiency of VHB2805S at 215 ^{0}C.

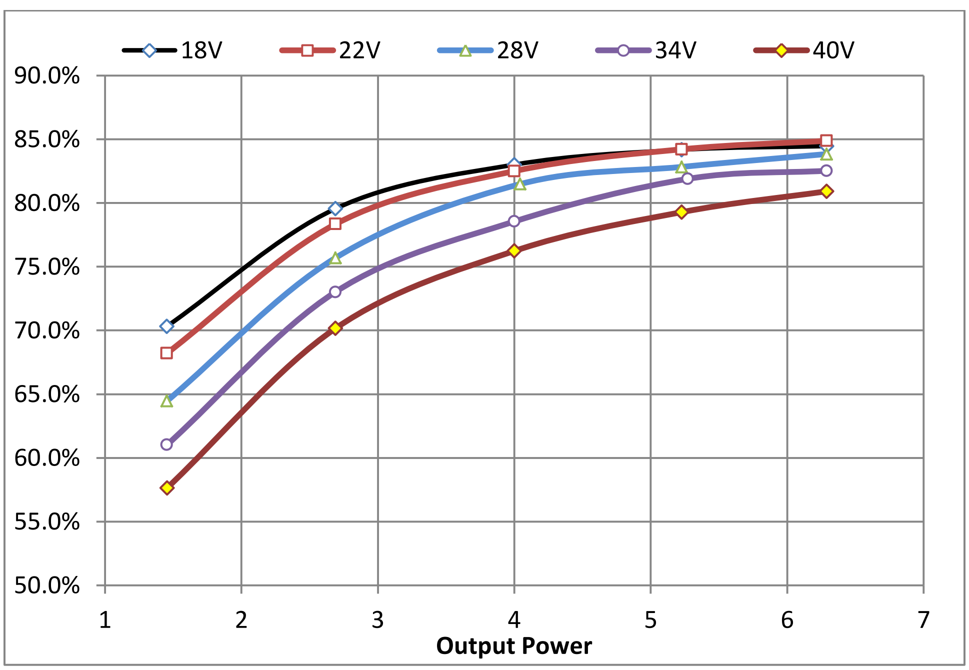


Fig. (5) VHB % Efficiency vs. output power in watts at 25 ^{0}C

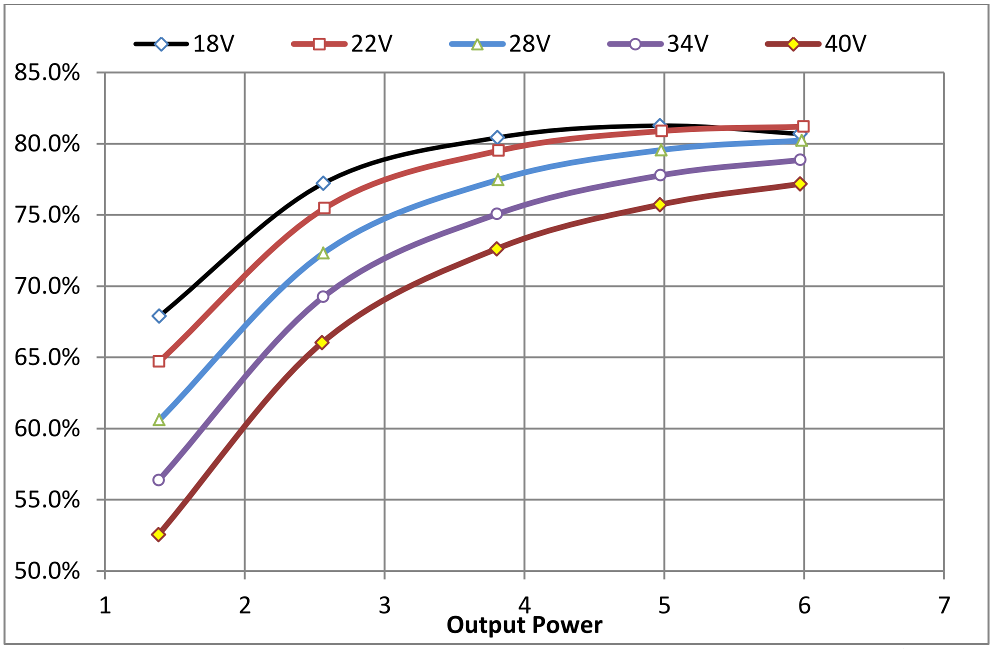


Fig. (6) VHB2805A % Efficiency vs. output power in watts at 215 ^{0}C

Vi (Volt)	Io (Amp)	Phase Margin	Gain Margin
17	0.0	71.0	22.0
17	0.5	72.5	19.8
17	1.0	74.2	18.5
28	0.0	68.8	23.5
28	0.5	73.5	20.5
28	1.0	76.2	20.0
34	0.0	75.2	24.3
34	0.5	73.6	22.3
34	1.0	76.4	20.3

Fig. (7) Measurement data of Phase and Gain Margins of VHB at different line inputs

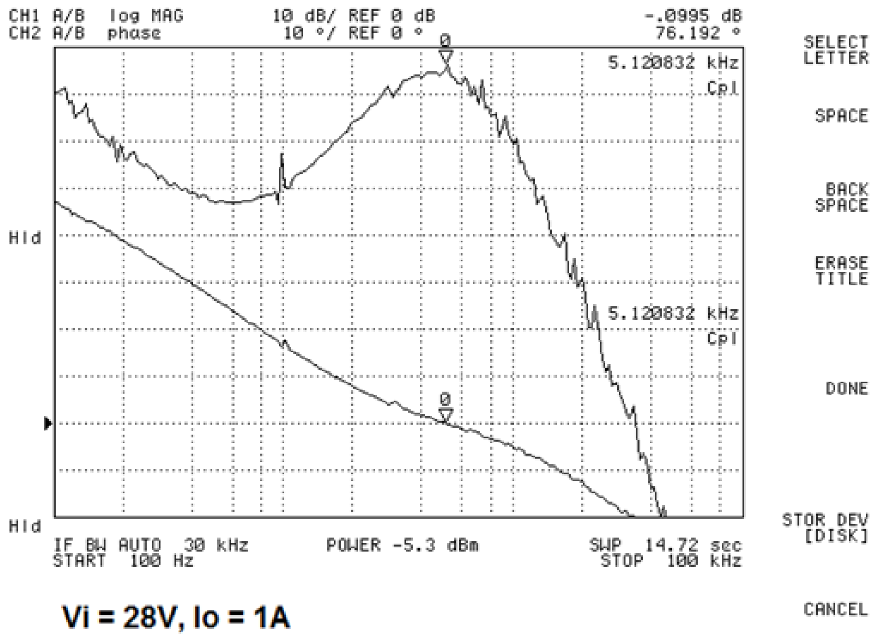


Fig. (8) Bode plot showing adequate Phase Margin

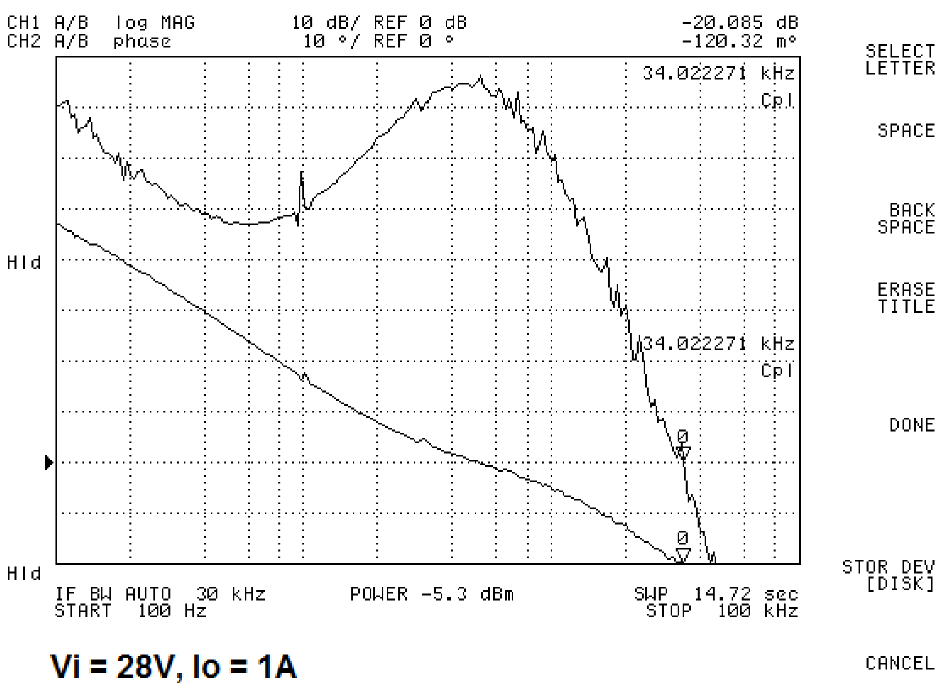


Fig. (9) Bode plot indicating adequate Gain Margin

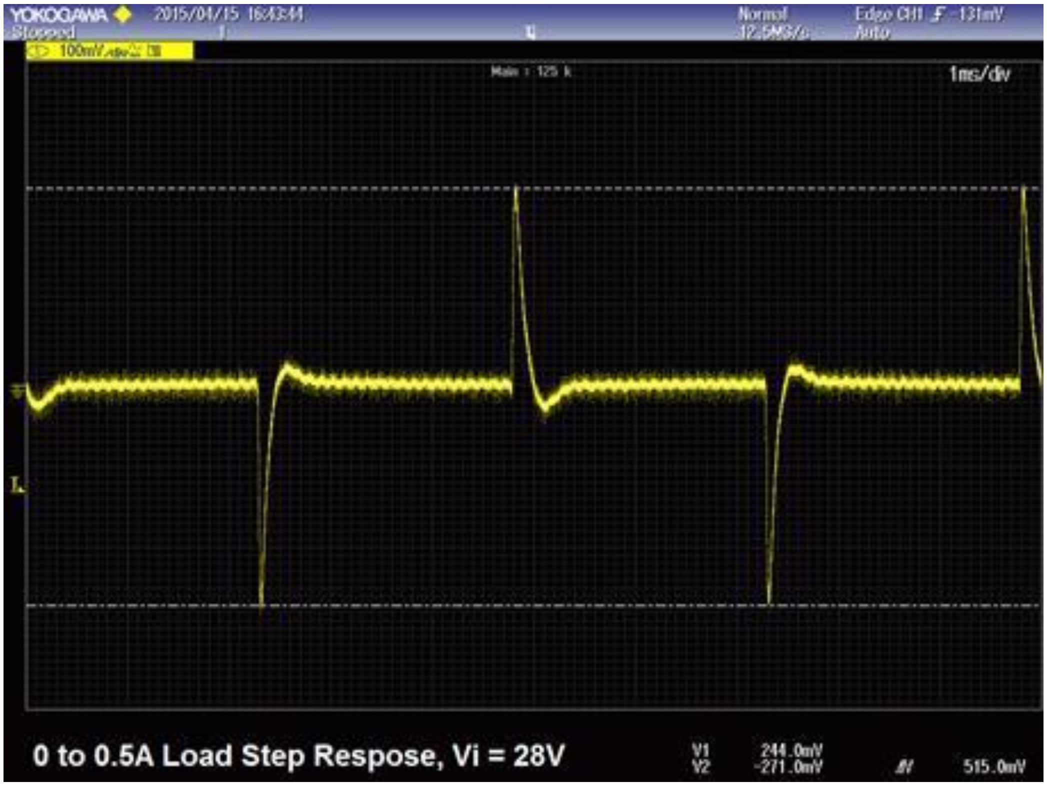


Fig. (10) Dynamic Response of output when input=28VDC and output load is switched from 0.0 to 50% at 25 ^{0}C

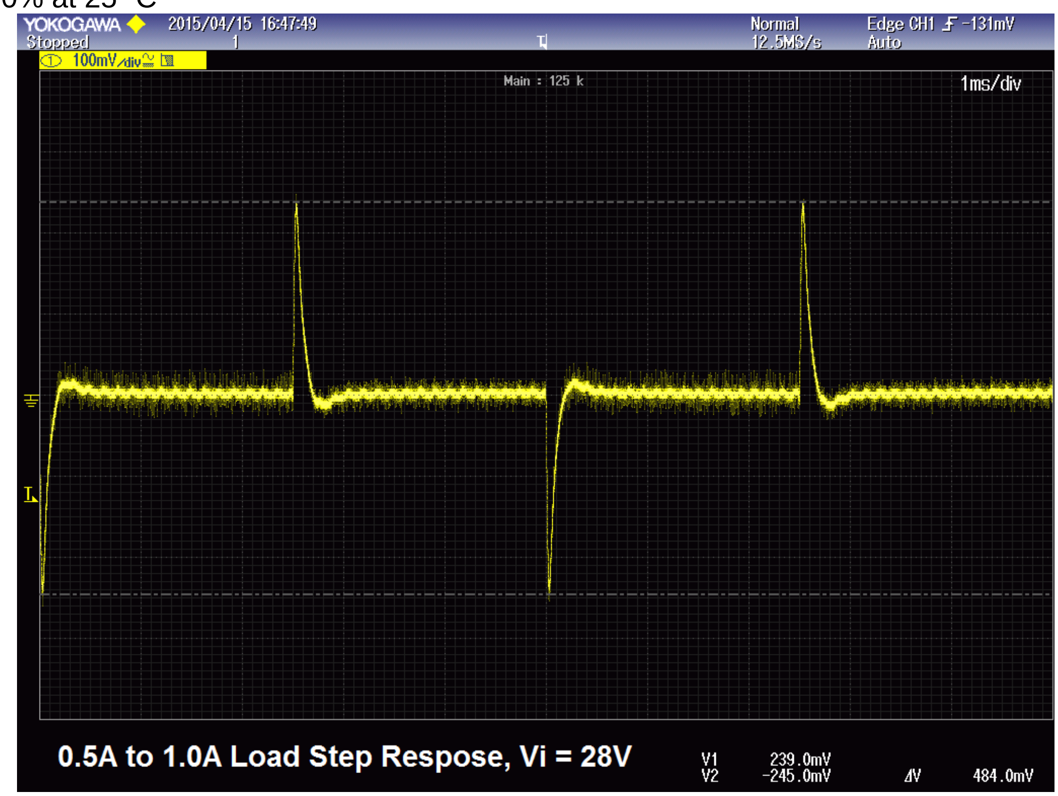


Fig. (11) Dynamic response of output voltage when load is switched from 50% to 100% with input=28VDC at 25 ^{0}C

Fig. Fig. (12) Turn ON output voltage transient at no load and maximum line input voltage of 40 VDC at 25 ^{0}C

Fig. (13) Healthy Voltage waveform across MOSFET without any high Voltage spikes caused by the leakage inductance at 25 ^{0}C

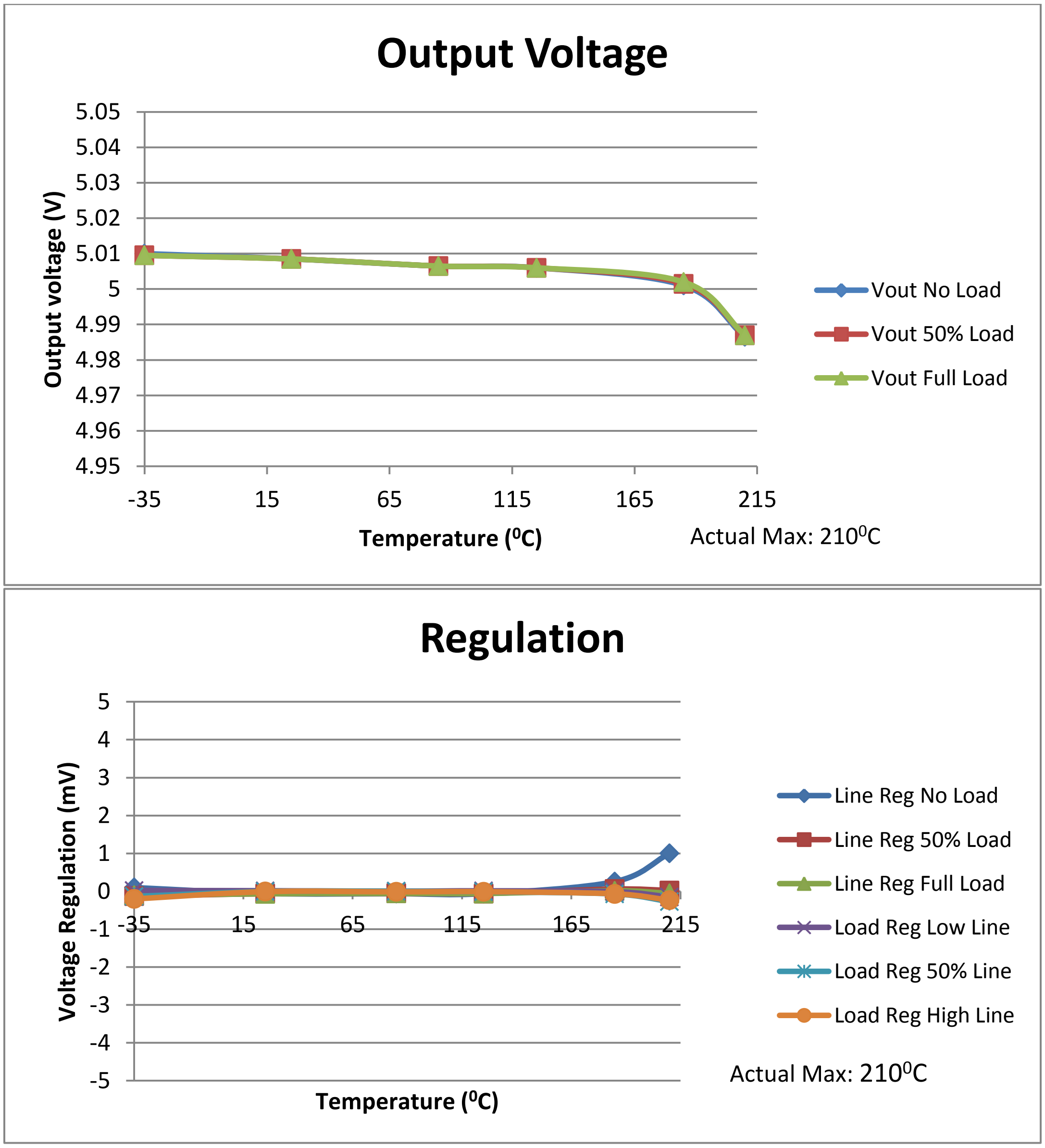


Fig. (14) Output Voltage and Regulation vs. Temperature of VHB2805S

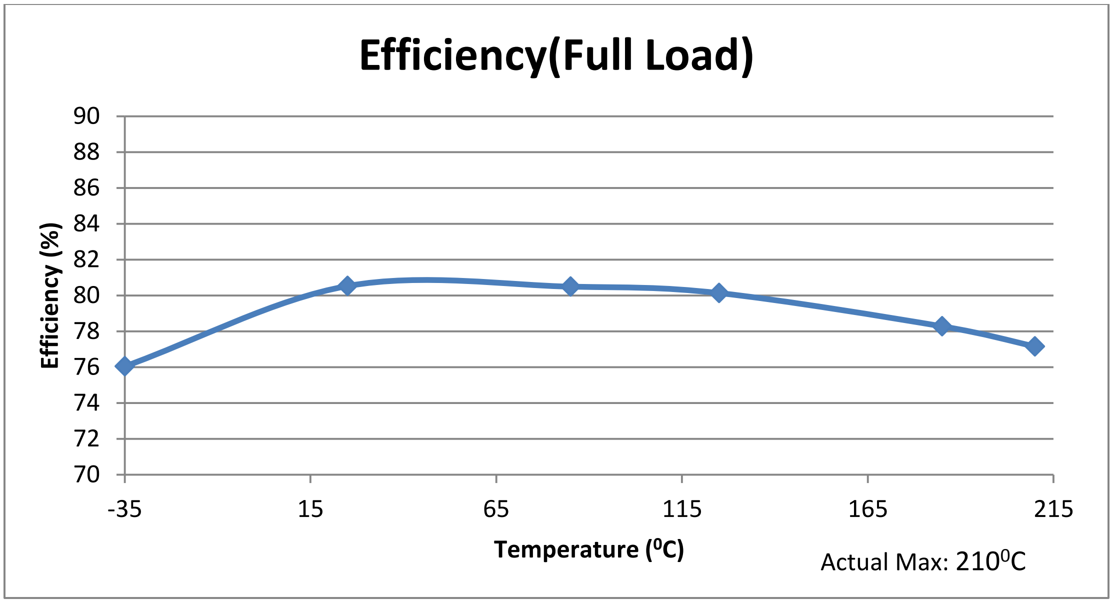


Fig. (15) Efficiency at full load vs. Temperature of VHB2805S

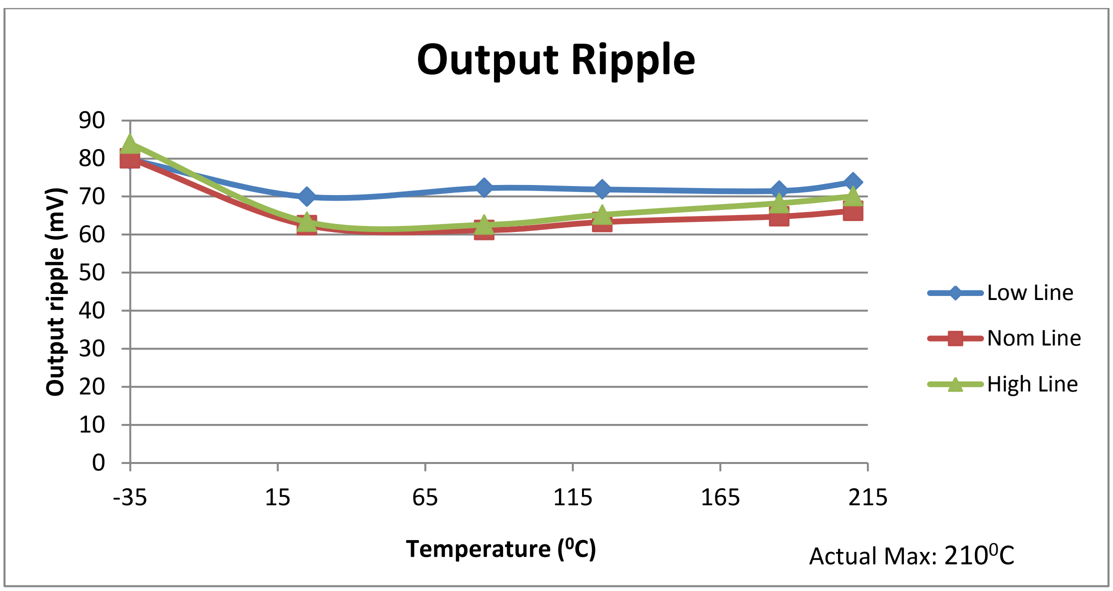


Fig. (16) Output ripple vs. temperature of VHB2805S at three line voltages

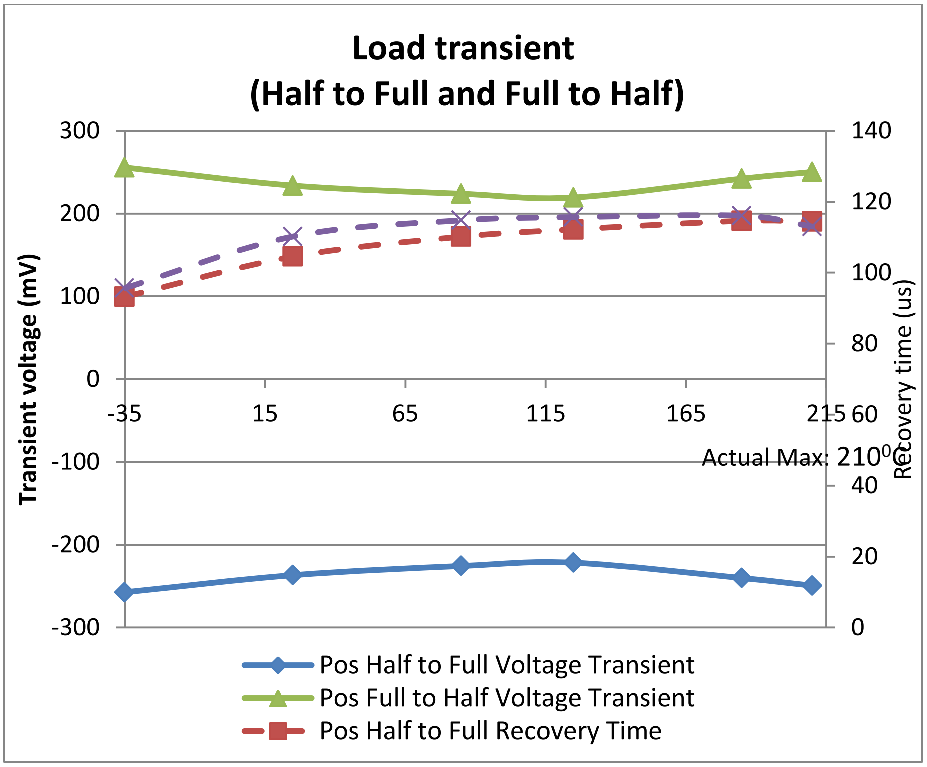


Fig. (17) Load transient response in amplitude and time for different changes in loads

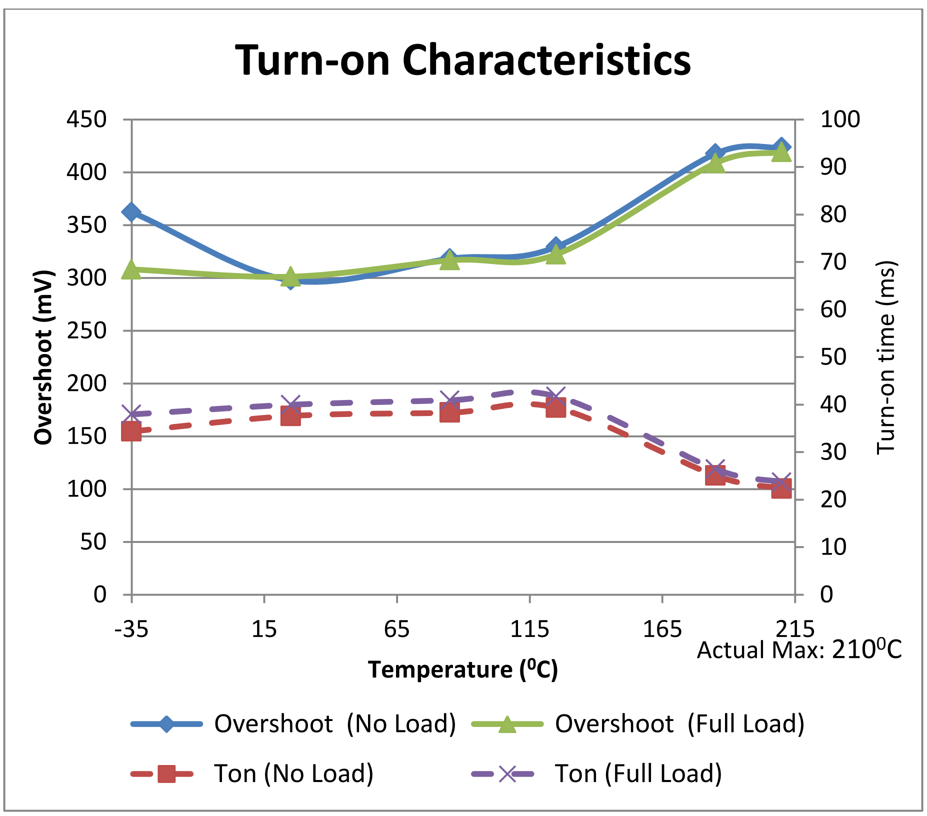


Fig. (18) Turn on characteristics with overshoot amplitude and time duration vs. Temperature.

Parameter with description		Measured Value	Measured Value	Lower Limit	Upper Limit
STEP.1 : Initial Setup					
STEP.3 : Output Voltage Accuracy DMM(Nom Line Vout Full Load)	Output (V)	4.839	4.755	4.850	5.150
STEP.4 : UV Release and UV Lockout(No load)	UV Release (V)	16.129	14.917	12.000	16.000
	UV LockOut (V)	15.372	14.216	14.000	16.000
STEP.5 : Overload Single(Nom Line)	STATUS	OLP Working	OLP Working		
	Trip Point (A)	1.279	1.224	1.050	1.500
	Power Diss. (W)	1.510	1.540	1.000	3.000
STEP.6 : Voltage Regulation Single(Line Reg No Load)	Regulation (mV)	-1.891	-2.310	-25.000	25.000
STEP.7 : Voltage Regulation Single(Line Reg Nom Load)	Regulation (mV)	-1.648	-2.285	-25.000	25.000
STEP.8 : Voltage Regulation Single(Line Reg Full Load)	Regulation (mV)	-1.736	1.847	-25.000	25.000
STEP.9 : Voltage Regulation Single(Load Reg Low Line)	Regulation (mV)	-26.085	-22.350	-50.000	50.000
STEP.10 : Voltage Regulation Single(Load Reg Nom Line)	Regulation (mV)	-26.304	-21.659	-50.000	50.000
STEP.11 : Voltage Regulation Single(Load Reg High Line)	Regulation (mV)	-27.307	-19.665	-50.000	50.000
STEP.12 : Efficiency(Nom Line Full Load)	Efficiency (%)	79.106	77.581	75.000	90.000
STEP.13 : Input Current(Nom Line No Load)	Input Current (mA)	31.750	34.461	5.000	50.000
STEP.14 : Input Current(Nom Line Inhibit)	Input Current (mA)	3.955	4.194	1.000	5.000
STEP.16 : Short Circuit(Nom Line)	Power Diss. (W)	1.875	1.808	1.000	3.000
STEP.18 : Switching Frequency(Nom Line)	Frequency (KHz)	434.120	435.630	400.000	500.000
STEP.19 : Output Ripple(Low Line Full Load)	Output Vpp (mV)	5.406	6.488	0.000	50.000
STEP.20 : Output Ripple(Nom Line Full Load)	Output Vpp (mV)	6.619	8.813	0.000	50.000
STEP.21 : Output Ripple(High Line Full Load)	Output Vpp (mV)	6.988	8.894	0.000	50.000
STEP.22 : Input_Ripple(Nom Line Full Load)	Input Ripple (mA)	7.870	7.430	3.000	25.000
STEP.24 : Load Transient Test(Nom Line Pos Half to Full)	Transient (mV)	-248.150	-190.460	-500.000	500.000
	Recovery Time (us)	118.400	97.800	0.000	200.000
STEP.25 : Load Transient Test(Nom Line Pos Full to Half)	Transient (mV)	249.220	190.600	-500.000	500.000
	Recovery Time (us)	125.200	86.800	0.000	200.000
STEP.26 : Load Transient Test(Nom Line Pos 10% to Half)	Transient (mV)	-205.500	-164.130	-500.000	500.000
	Recovery Time (us)	117.200	116.000	0.000	200.000
STEP.27 : Load Transient Test(Nom Line Pos Half to 10%)	Transient (mV)	203.990	155.620	-500.000	500.000
	Recovery Time (us)	124.000	87.800	0.000	300.000
STEP.29 : TurnOnSingle(Nom Line No Load)	Overshoot (mV)	321.430	208.550	0.000	500.000
	Ton (ms)	23.860	23.400	3.000	75.000
STEP.30 : TurnOnSingle(Nom Line Full Load)	Overshoot (mV)	306.150	204.420	0.000	500.000
	Ton (ms)	25.190	24.710	3.000	75.000

Fig.(19) Actual measurement values of all important parameters. Min and Max values are shown for comparison.

Fig. (7) shows measurement data in tabulated form of Phase and Gain Margins of VHB at different line inputs, while Fig. (8) and Fig. (9) show actual Bode plots of phase margin and gain margin, which enable one to study how both parameters vary w.r.t. frequency.

The wave forms of dynamic response of VHB are shown in Fig. (10) and Fig. (11). Fig. (12) shows start-up waveform with soft start of output voltage. Fig. (13) shows the voltage across MOSFETs, indicating clean waveform without any undue voltage spikes, indicating healthy waveform. All these waveforms are taken at 25 ^{0}C.

Fig. (14) shows two plots. The upper plot shows variation of output Voltage vs. Temperature, while the lower plot shows Regulation vs. Temperature of VHB2805S.

Fig. (15) shows variation of % Efficiency at full load vs. Temperature of VHB2805S. This enables one to understand how the % efficiency varies w.r.t. temperature.

Likewise, Fig. (16) shows variation in output ripple vs. temperature of VHB2805S at three line voltages. Fig. (17) shows load transient response in amplitude and time for different changes in loads, from half to full anf from full to half. Fig. (18) shows turn on characteristics with overshoot amplitude and time duration vs. Temperature.

An EXCEL spread sheet in Fig. (19) shows all pertinent Data Sheet parameters at +215 ^{0}C and the results tabulated for five serial numbers and statistically studied. The calculated sigma (not shown in table) is 0.005 in critical parameters such as output voltage regulation. That means the output voltage is very tightly regulated vs. load and line and throughout the temperature range. This is important for critical digital, Instrumentation and signal processing type of loads. As can be seen in table of Fig.(19), at nominal line and full load, the regulation is ±2 mV.

Other critical parameter for sensitive loads such as instrumentation amplifiers, sensors, signal conditioner and digitals loads is ripple and noise of power supply. Measurement of ripple ranges from 5 mV p-p to 9 mV p-p as compared to Data Sheet limit of 50 mV p-p. Additionally the dynamic response of the DC to DC converter to line and load changes is also important and here too the VHB fares very well. The maximum amplitude change in output voltage is ± 250 mv recovering in 125 us, when output load current abruptly changes from half to full (or vice versa). Thus it can be seen that the actual performance of VHB converter is much better than the Data Sheet specifications.

7.0 QUALITY CONTROL:

Fig. (20) shows qual flow. As can be appreciated very elaborate scheme has been implemented to ensure that the finished part meets or exceeds data sheet specifications. Here in Sub group 1, unbiased temperature cycle testing is done on 5 samples for 10 cycles from -35 ^{0}C to +215 ^{0}C with ramp rate of 3 ^{0}C per minute maximum. In subgroup 3, fresh set of 5 samples are tested for temperature cycling unbiased 1hour at 215 ^{0}C and then -35 ^{0}C for 1 hour using 50 cycles. In addition, qual flow performs other tests as well.

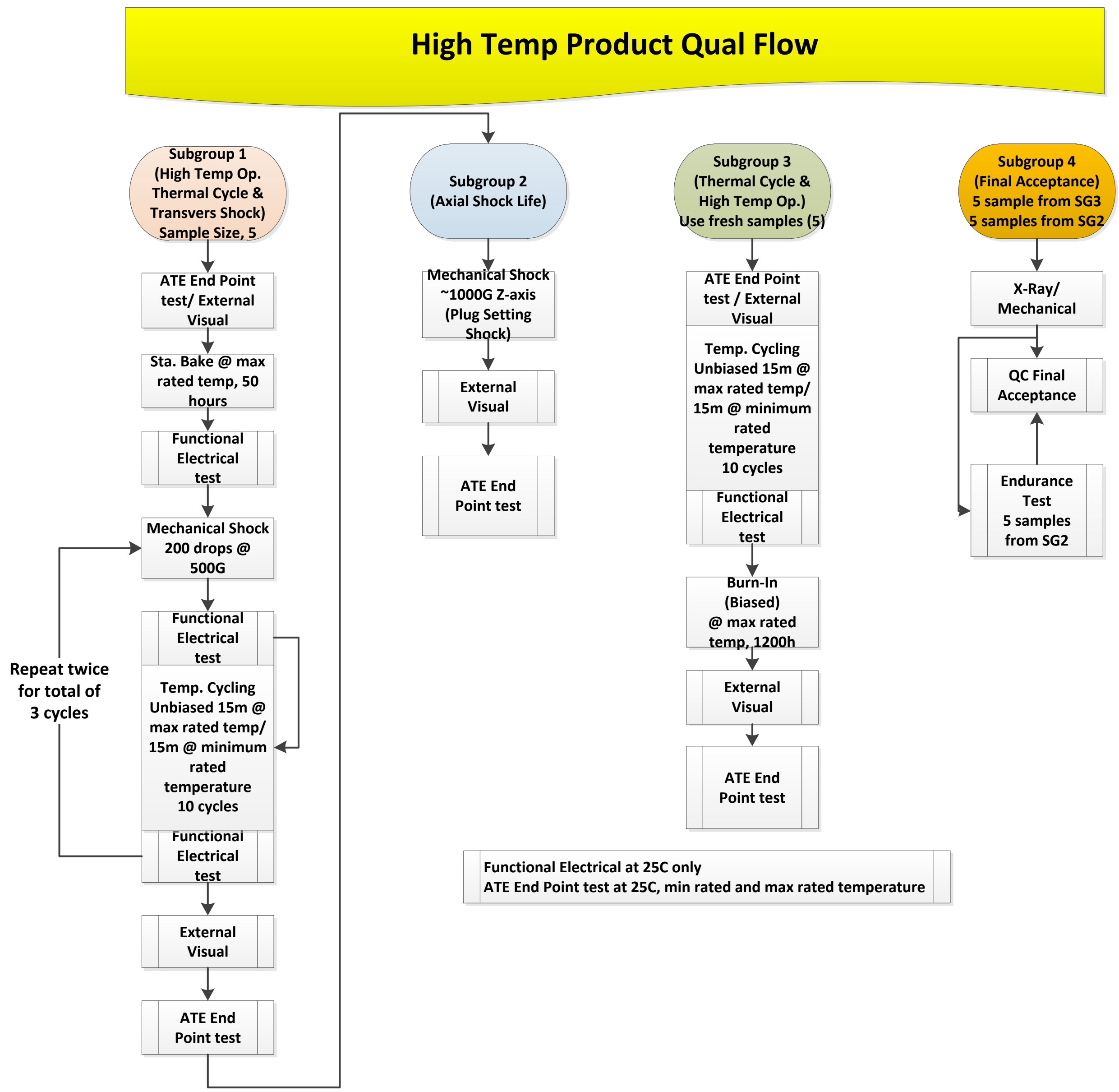


Fig. (20) High Temp product Qual Flow.

8.0 APPLICATION OF VHB CONVERTERS IN DOWNHOLE EXPLORATION:

To enable optimization of the production from advanced oil and gas wells, measurement and control systems are being developed for permanent use downhole. These systems will facilitate measurement and control of individual production streams coming from different areas of production zones in a single reservoir or from different adjacent reservoirs.

These employ sensors, sensor conditioners, A/D converters and data preprocessors - all of which require collocated stable, reliable DC to DC Converters that operate in extreme environments. VHB DC to DC Converters are destined to perform this role. They are compact, lightweight and reliable and have performance specs that meet or exceed requirements of sensors as well as analog and digital electronics used as described above.

Another trend, which has implications on such DC to DC Converters, is a trend namely "digitization of everything". This necessitates gradual trend to lower regulated bus voltages in order of its need of occurrence in future: 3.3V, 2.5V, 1.8V, 1.2V, 1.0V and even 0.8V. This definitely would require synchronous rectification and higher operating efficiency at these lower voltages. Here too the VHB series when adapted, or reconfigured with some modifications, can shine out.

9.0 ACKNOLEDGEMENT:

Tasks involved in development of such High Temperature DC to DC converters that can operate in +215 ^{0}C environment naturally involve team efforts of engineers with multi-disciplinary background and skilled & experienced staff for manufacturing & quality control. It also needs an infra-structure with special facilities and full support and guidance of management team that monitors progress. So I would like to give the credit for this paper to the High Temperature team at International Rectifier, An Infineon Technologies Company, San Jose, CA, U.S.A.

For diligently editing the paper, I thank Ms. Odile Ronat and Mr. Lorentz Ou of International Rectifier, An Infineon Technologies Company, For providing needed measurement data, I thank Joseph Alexander and Ms. Esther Lee of International Rectifier, An Infineon Technologies Company, I want to express my thanks and appreciation to all at International Rectifier, An Infineon Technologies Company, who have helped me by providing me necessary data and information for preparing this paper.

Petromar Technologies inc. collaborated in the initial design and development of this converter under contract with International Rectifier and I gratefully acknowledge my reference to their documentation, while preparing this paper.

10.0 CONCLUSION:

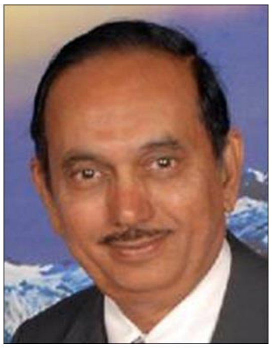
The deep waters of the Gulf of Mexico & North Sea, the cold regions of Russia or Alaska and the hot, dusty deserts of the Middle East are merely the geographic challenges facing today's oil and gas exploration and production industry. But other challenges emanate from designing and building exploration and drilling systems that help gather data and help reliable and continuous operations. It also needs optimization and dissemination of accurate data obtained from exploration & drilling. Sensors, Analog & Digital hardware, associated power supplies, digital data preprocessors and software do play their due roles. Also important is data handling that happens underground to minimize high amount of raw data being transmitted above ground.

Looking at the totality of these systems, hardware's consistent and reliable functioning is a prerequisite.

The advances made in high temperature analog and digital electronics, including generation and regulation of electrical power, play their key roles. A major trend is in employing more compact and yet more reliable electronics modules, which make it convenient in deployment and replacement. Also evident is the move towards more and more digitization.

Towards these lofty goals, VHB series of DC to DC Converters are making their modest contribution in providing regulated D.C. power at popular bus voltages that can work up to 215 ^{0}C and as they are built using Thick Film Hybrid technology, they are compact, lightweight and provide required performance and reliability at reasonable costs.

About the Author:



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