Application Note

Highly Scalable Space Motor Control Platform based on TI’s Space Enhanced Products (-SEP) and Space Products (-SP)

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ABSTRACT

This application note presents a complete space-grade motor control platform for satellite and spacecraft actuator systems, targeting aerospace system designers and power electronics engineers. Built around TI's radiation-tolerant F28377D-SEP MCU and TPS7H6101-SEP GaN half-bridge power stages, alongside radiation-hardened monitoring and power management devices including the INA901-SP, TMP9R00-SP, TPS7H5020-SEP/SP, and TPS7H1121-SEP/SP, this solution addresses the SWaP+C challenges of LEO through GEO space missions. The platform supports single 2- and 3-phase stepper or dual motor configurations with trapezoidal or Field-Oriented Control (FOC), and scales across radiation hardness levels through pin-compatible components. MATLAB®/Simulink® model-based design accelerates software development, while GaN technology and high device integration minimize board area and thermal overhead. Engineers benefit from a single, scalable R&D investment that meets the reliability and size demands of both high-volume and deep space applications.

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1 Introduction

Next-generation space missions demand high-performance, compact motor control systems that deliver exceptional reliability while minimizing size, weight, power, and cost (SWaP+C). This application note showcases a complete space-grade motor drive platform, featuring breakthrough GaN-based power stage devices controlled by a radiation-tolerant high-performance MCU running model based designed software.

Key highlights include:

- First device in a family of designs, up-to 200V rated rad-tolerant TPS7H6101-SEP, self-protected GaN half-bridge power stages delivering superior power density and efficiency
- Rad tolerant F28377D-SEP real-time MCU:
  - Providing up-to 800 MIPS with superior analog integration such as four 16-bit ADCs or eight windowed comparators with integrated 12-bit DACs.
  - Comprehensive self-diagnostic and monitoring capabilities
  - Enabled for Model-Based Systems Engineering (MBSE) with MATLAB® and Simulink®
- Radiation hardened INA901-SP current-sense amplifier withstanding common-mode voltages from –15 V to 65 V
- Radiation hardened TMP9R00-SP provides up to eight remote and one local temperature monitoring capabilities with high-accuracy.
- PMP23546 2.4W PSR flyback bias supply based on rad-tolerant TPS7H5020-SEP or rad-hard TPS7H5020-SP with input range from 22V to 36V, generating two 12V output rails with less than 1% ripple. The rad-hard precision programmable reference TL1431-SP provides the required up-to-36V input regulator for the start-up supply.
- Rad-tolerant TPS7H1121-SEP or rad-hard TPS7H1121-SP low dropout linear regulator (LDO) devices provide the 3.3V and 5V rails.
- Rad-hard TPS7A4501-SP low dropout linear regulator (LDO) provides the 2V rail for the TMP9R00-SP.
- Radiation-tolerant SN54SLC8T245-SEP eight-bit, 0.65-V to 3.3-V, direction-controlled level translator assures PWM signal integrity and provides an additional level of protection.

All of the above have been implemented in a highly scalable reference design platform supporting single 2- and 3-phase stepper, or dual motor control configuration for trapezoidal, or field-oriented control (FOC). Pin-compatible mounting options enable for LEO or up-to GEO mission requirements, addressing the unique challenges of high-volume LEO deployments and deep space missions from a single R&D investment.

The goal of this application note is to demonstrate the following value propositions of this solution:

Fast and easy to design with, yet highly reliable:

- Matlab Simulink model-based coding enables very fast adaptation of custom motor drive application with very high software integrity level.
- The components suggested offer a very high level of protection and monitoring capabilities, keeping the hardware design overhead to a very minimum.

Small form factor:

- The usage of GaN FET technology, high integration level and use of space-grade plastic packaging enables very small board area requirement, high efficiency and compelling thermal performance.

Economies of scale:

- High scalability in terms of radiation hardness, numbers and types of motors and motor control options, and voltage and power levels.

2 Detailed Description

2.1 Design Concept

The described space-grade motor control platform leverages the comprehensive design development ecosystem of the C2000 MCU family. The hardware is based on the C2000 MCU Launchpad EVM LAUNCHXL-F28379D which allows to connect to various so-called application specific booster packs such as the BOOSTXL-3PHGANINV, a 48V Three-Phase Inverter With Shunt-Based In-Line Motor Phase Current Sensing Evaluation Module (Figure 2-1).

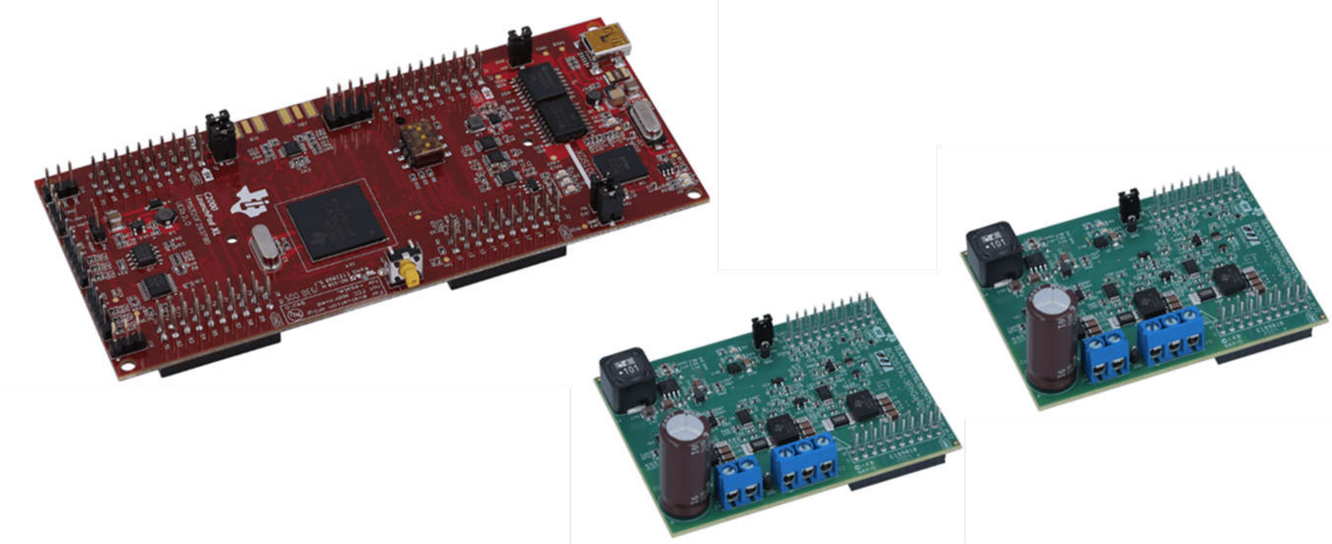


Figure 2-1. The Commercially Available Evaluation Kit of One LAUNCHXL-F28379D and Two BOOSTXL-3PHGANINV Form the Basis for this Space-Grade Design

The launchpad provides a great evaluation platform for all devices of the TMS320F2837x family, including its space-grade member, F28377D-SEP, due to their software and pin-compatibility to each other. The BOOSTXL-3PHGANINV booster pack however is a pure commercial grade implementation and needs to be re-designed to host the mentioned space-grade devices. Never-the-less, the existing motor control software for the combination of LAUNCHXL-F28379D and BOOSTXL-3PHGANINV can be completely re-used for space-grade applications.

The space-grade power stage design was therefore held compatible as much as possible to the BOOSTXL-3PHGANINV. For the space-grade power stage PCB it was decided to double the number of individual power stages to six to enable dual three-phase motor control or a single 2-phase or 3-phase stepper implementation (Figure 2-2.)

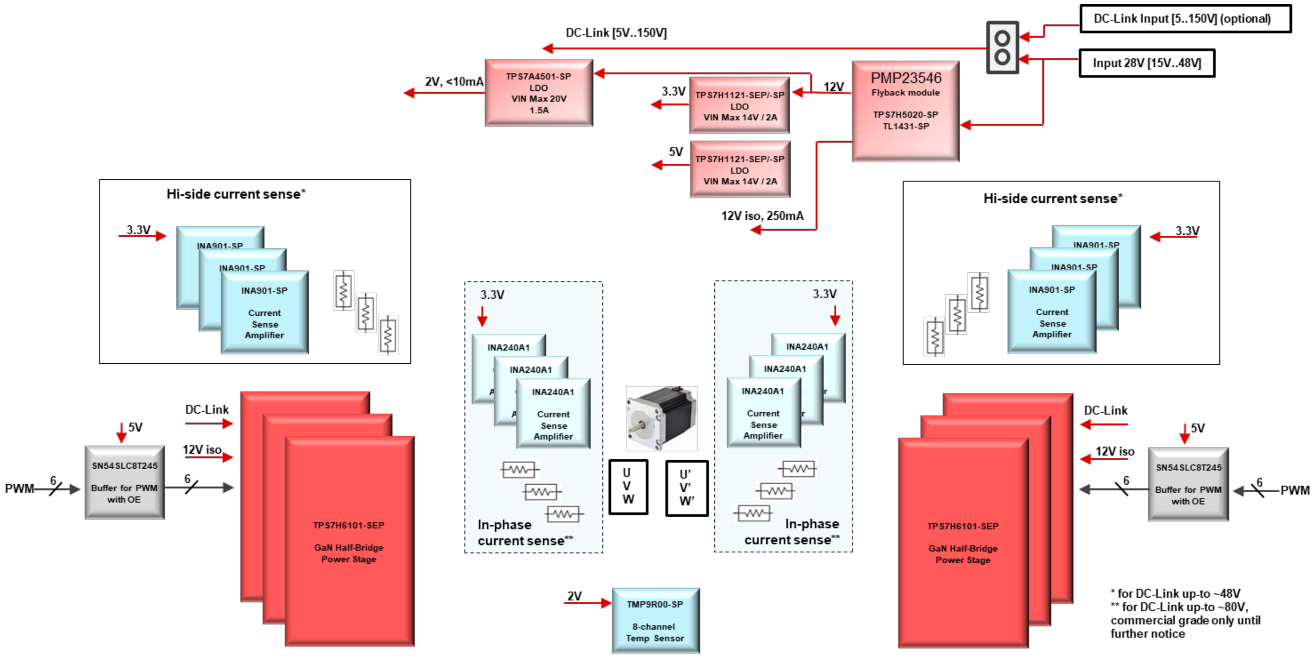


Figure 2-2. System Block Diagram of the Space-Grade Motor Drive Booster Pack

3 Hardware Design Details

3.1 Power Stage

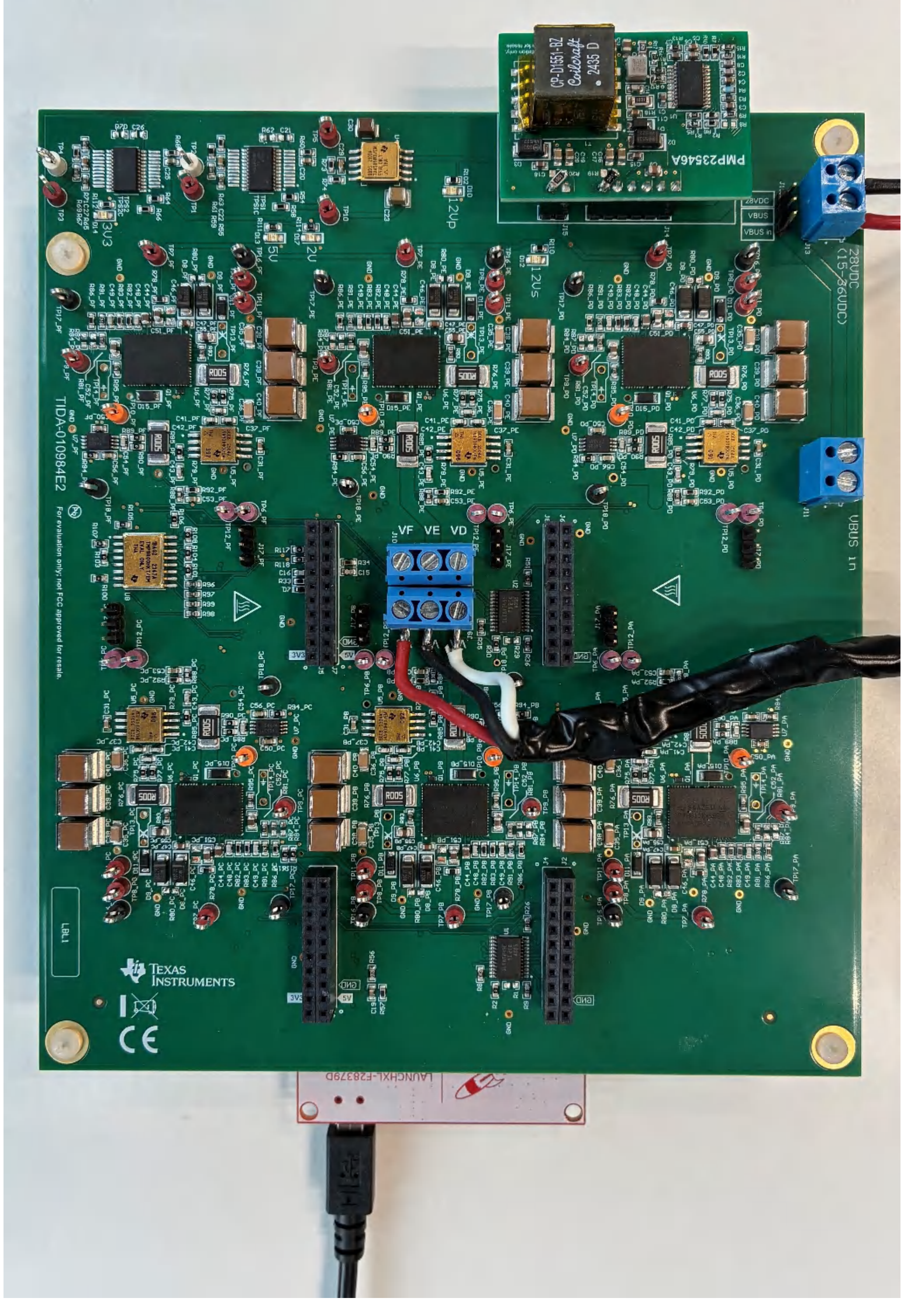


Figure 3-1. TIDA-010984 Design with 2.4W PSR Flyback Bias Supply (Top Right Corner) and LAUNCHXL-F28379D (Underneath)

The six half-bridge power stages are based on the TPS7H6101-SEP. It is a radiation-tolerant 200V GaN power-FET half bridge with integrated grounds-up radiation hardened gate driver design. The same gate drive technology is also available as a family of discrete half-bridge drivers: TPS7H6003-SP, TPS7H6013-SP,TPS7H6023-SP, TPS7H6005-SP, TPS7H6015-SP, TPS7H6025-SP, TPS7H6005-SEP, TPS7H6015-SEP, TPS7H6025-SEP. This provides split output with high source and sink current capability, dedicated hi-lo & lo-hi dead band configuration and low delay matching between hi- & lo-side switching for optimal turn-on & turn-off switching behavior. Further, it demonstrates a very compelling SEE performance (SET, SEFI, SEL) and is validated for zero cross conduction events up-to 75 MeV•cm^2/mg. With the TPS7H6101-SEP all these capabilities are available as a fully integrated half-bridge power stage with the power GaN FETs included that makes it very easy for designers to come to a highly optimized space-grade motor drive power stage design. The integration of the FETs naturally assures lowest possible traces between driver and FETs to minimize any parasitic impedances for ideal switching characteristics. The optimal slew rate and dead times are already resolved by the vendor to the greatest extent. The motor control power stage design discussed in this application note does further take advantage of the single PWM control mode. Only a single PWM signal is provided to the power stage. The complement signal is generated inside the power stage device with adjustable dead times and the assurance that any issues in PWM signal generation cannot lead to a shoot through event. The implemented dead time follows TI's recommendation in the data sheet of the TPS7H6101-SEP.

The only additional protection external to the power stage device is a Schottky diode between the FETs' source and drain pins. Unlike IGBTs or Silicon MOSFETs there is no reverse diode in a GaN FET. In case of a sudden power loss or an unexpected shut-off of both FETs of the power switch while there is still energy in motor this diode allows for a controlled path of the current without excessive peak voltages.

Please note that in the design generated for this application note the Schottky diodes have been only added for the low sides in support of test and debug ideas. For an actual product implementation it is recommended to add such diode to all the FETs.

The TPS7H6101-SEP grants two bootstrap charging options: direct charging from VIN and charging via its internal bootstrap switch. The PCB used for this application note has provision for both options. Actual test results were taken with direct charging option as shown in Figure 3-2 and Figure 3-3: R78 and D8 are mounted, R80 and C46 are depopulated to verify *direct charging* only.

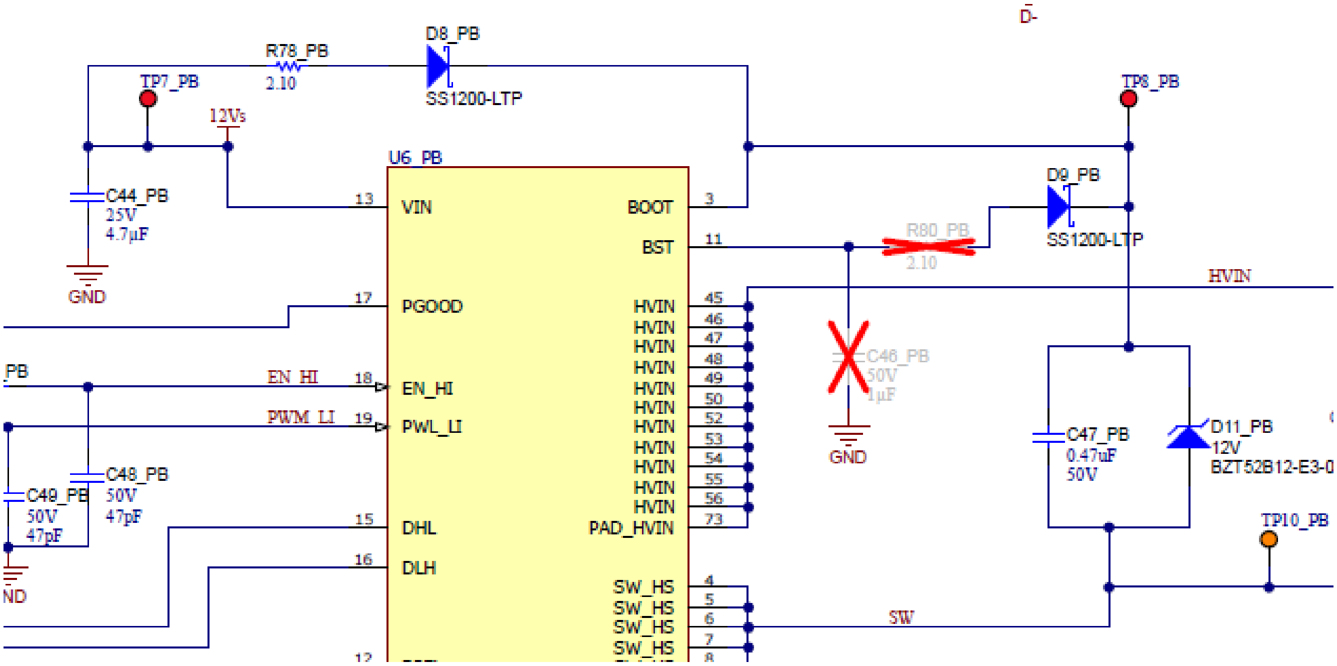


Figure 3-2. Only Direct Charging From VIN Bootstrap Option is Mounted

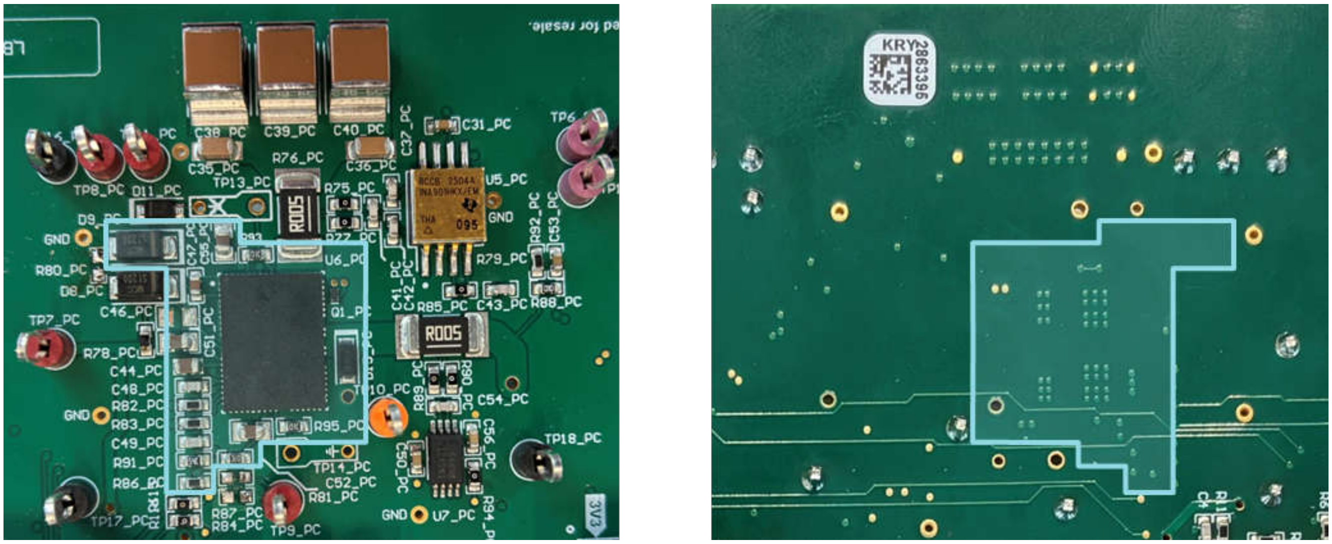


Figure 3-3. Left picture: Top Side View of TPS7H6101-SEP Layout. Only very Limited Number of External Components Needed. No Components on Bottom Side (Right Picture).

3.2 Current Sense

The in-phase current sensing circuitry based on the commercial-grade INA240A1 was carried forward from BOOSTXL-3PHGANINV to keep the space-grade power stage as close as possible to its parenting design configuration for easy board bring-up with minimal software changes.

A high-side current sense option based on INA901-SP was added as it is typically used in stepper drives and in some cases also in three-phase motor applications for the benefit of a ground-fault detection capability (Figure 3-4). INA951-SEP would be recommended if lower radiation hardness is required such as in LEO constellations.

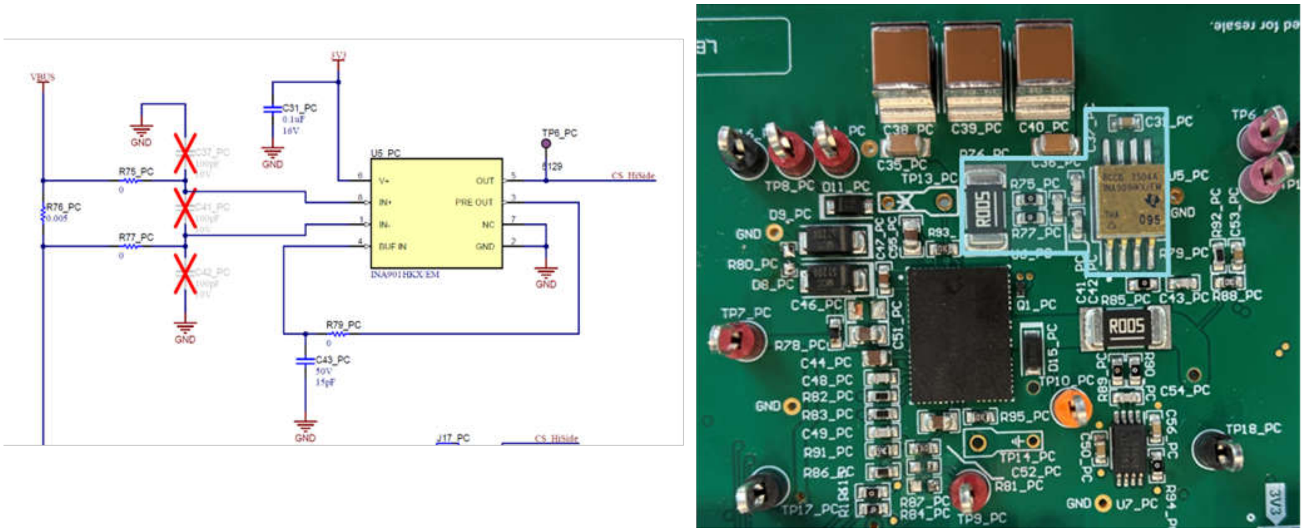


Figure 3-4. High-Side Current Sense Option Based on INA901-SP

Alternative space-grade in-phase current sensing solutions from TI are available based on INA951-SEP or INA901-SP with a constant current source added (Bidirectional Topologies for the INA901-SP), OPA4H199-SEP/-SP for up-to 40V common mode input voltage, or INA1H94-SEP/-SP combined with OPA4H199-SEP/-SP or OPA4H014-SEP for common mode input voltages from -150V to +150V.

3.3 Temperature Monitoring

TMP9R00-SP enables the temperature monitoring of all six power stages from a single component. The actual temperature sensors positioned in close proximity to each of the power stage devices are implemented by small and cost effective BJT transistors in diode configuration (Figure 3-5). Excitation current generation, several signal conditioning features, voltage reference and analog-to-digital conversion are all integrated into TMP9R00-SP. Temperature values from all remote sensors and the local sensor inside the device are transferred to the MCU via I2C bus. Two programmable alarm signals THERM and THERM2 do also connect to the MCU's GPIOs for external interrupt generation.

Figure 3-5. Small and Cost Effective Implementation of Temperature Monitor with a BJT in Diode Configuration in Close Proximity to Each of the TPS7H6101-SEP Power Stage Devices

3.4 Area Estimate Per Power Stage

- TPS7H6101-SEP' package alone is 12 mm × 9 mm = 110 mm^2. The external passive components (protective Schottky diodes, Zener bootstrap diode, configuration resistors, capacitors, temperature sensing transistor, etc.) sum up to 120mm^2. In total 230 mm^2 for each of the power stage blocks.
- For the high-side current sensing option the INA901-SP itself contributes 85 mm^2, Shunt resistor and passives roughly the same amount again: 170 mm^2
- The generous amount of bulk capacitors add 200 mm^2
- A single TMP9R00-SP device supports all six power stages of a dual three-phase motor implementation and adds 70 mm^2 by itself. Its surrounding passives contribute another ~100 mm^2, the LDO to provide the required supply voltage of 2V another 140 mm^2 (center of Figure 3-6). In total ~50 mm^2 per power stage.

In sum approximately 550 mm^2 per power stage for a layout with all components mounted only on one side of the PCB and a fairly high amount of bulk capacitors. For the common voltage rails of 12V, 5V and 3.3V (Figure 3-6) the design shows the following board area requirements:

- The module PMP23546 for the DC/DC conversion from the unregulated 28V bus to 12V contributes 1640 mm^2.
- The two TPS7H1121-SEP/-SP LDOs for the 5V and 3.3V supplies 130 mm^2 each.

All the area truly required for the design with six power stages sums up to a total of 5810 mm2. For example, such a design fits on a 85mm × 70 mm PCB

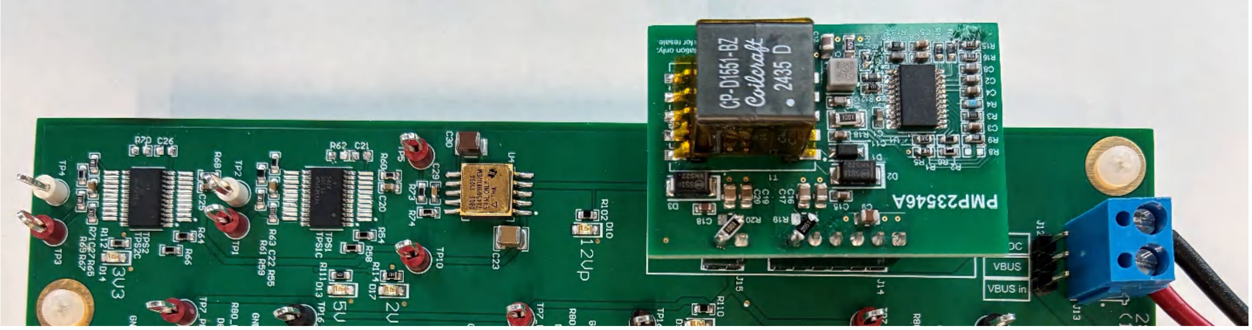


Figure 3-6. Power Tree Design from Left to Right: PMP23546 (15V-36V Input, 12V Output), TPS7A4501-SP (12V Input, 2V Output), Two Times TPS7H1121-SEP/-SP (12V Input, 5V and 3.3V Output)

3.5 Connecting the F28379D LaunchPad

The F28379D Launchpad is connected to the backside of the power stage PCB (Figure 3-7) and is powered via the USB debugging interface to the PC with corresponding jumper headers mounted (Figure 3-8):

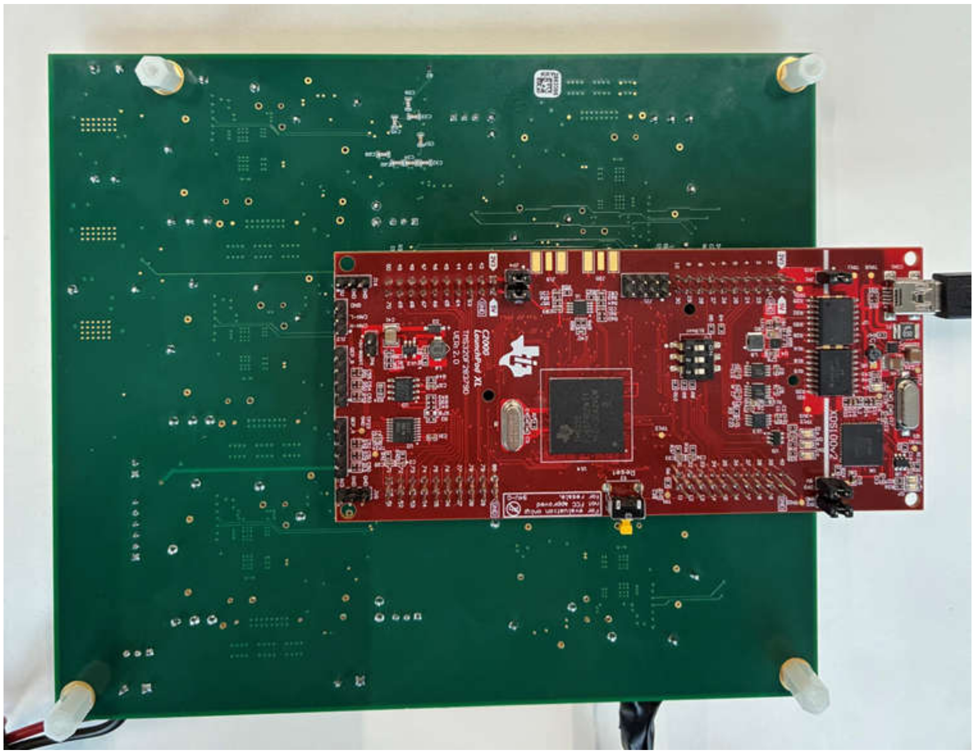


Figure 3-7. F28379D Launchpad is Connected to the Backside of the Power Stage PCB

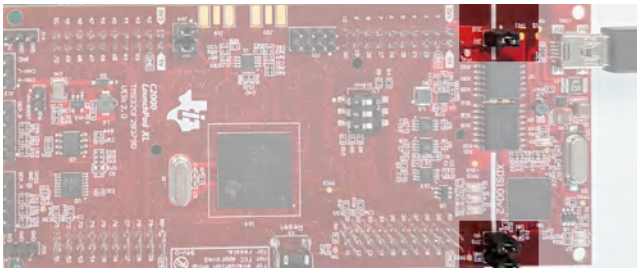


Figure 3-8. By Applying the Jumpers J1, J2 and J3 the MCU Board is Powered via USB Port, Independent of the Power Stage Design

3.6 Software Design

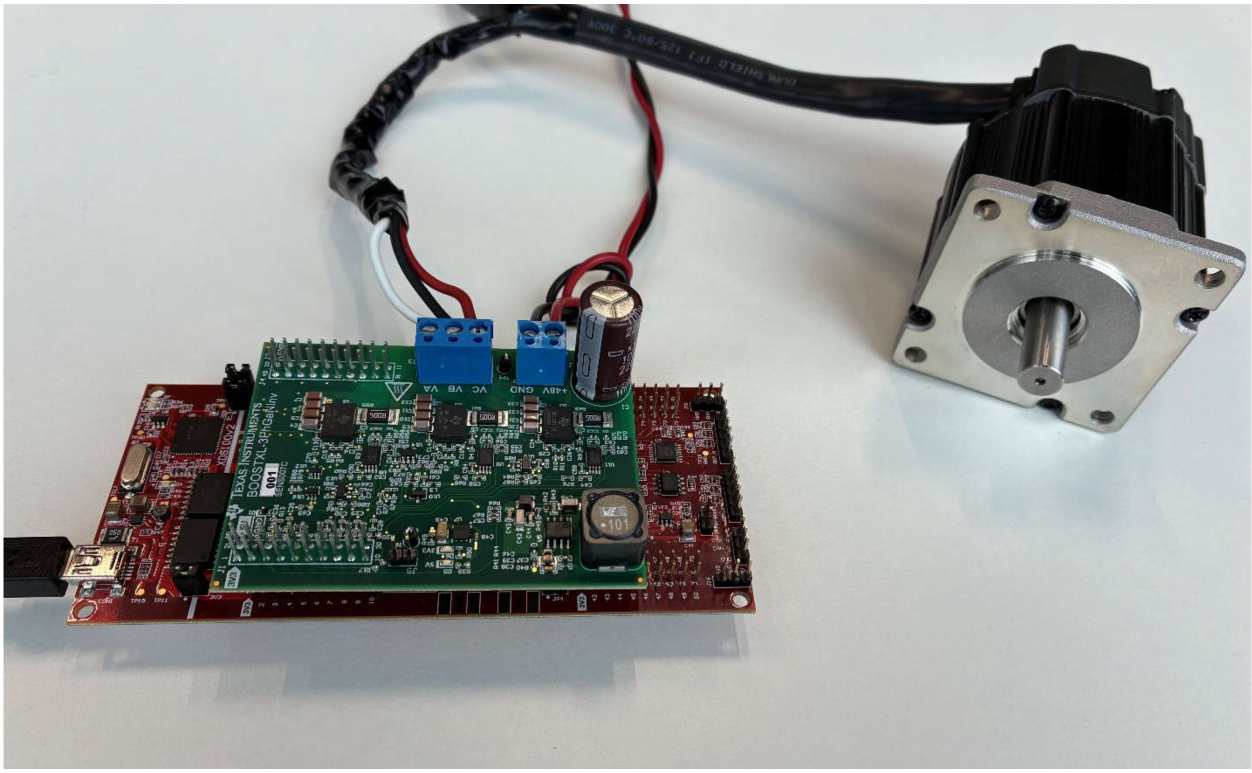


Figure 3-9. LAUNCHXL-F28379D , BOOSTXL-3PHGANINV,and LVSERVOMTR, Supported by Mathworks' Simulink Model-Based Implementation of Sensorless FOC

The design is based on the commercially available hardware setup based on LAUNCHXL-F28379D , BOOSTXL-3PHGANINV, and LVSERVOMTR (Figure 3-9), fully supported by Mathworks' Simulink model-based implementation of sensorless FOC available on Mathwork's web page: Sensorless Field-Oriented Control of PMSM Using C2000 Processors - MATLAB and Simulink. The goal of the space-grade design was to take as much advantage as possible of this existing and well-proven setup. However, for best robustness the TPS7H6101-SEP power stages are set to single PWM mode. Therefore, two small modifications to the model are necessary. TPS7H6101-SEP expects the single PWM signal on its "low-side" input PWM pin. The *hi-side* PWM input pin turns into a general enable pin for both of the FET drivers. This results into the need that the hi-side PWM signal in the original configuration for the BOOSTXL-3PHGANINV with two independent PWM signals per half-bridge power stage must be connected to the *low-side* connection for the space-grade design. For the enable signals for each of the power stage devices three additional GPIOs are activated together with the already implemented general inverter enable logic (Figure 3-10).

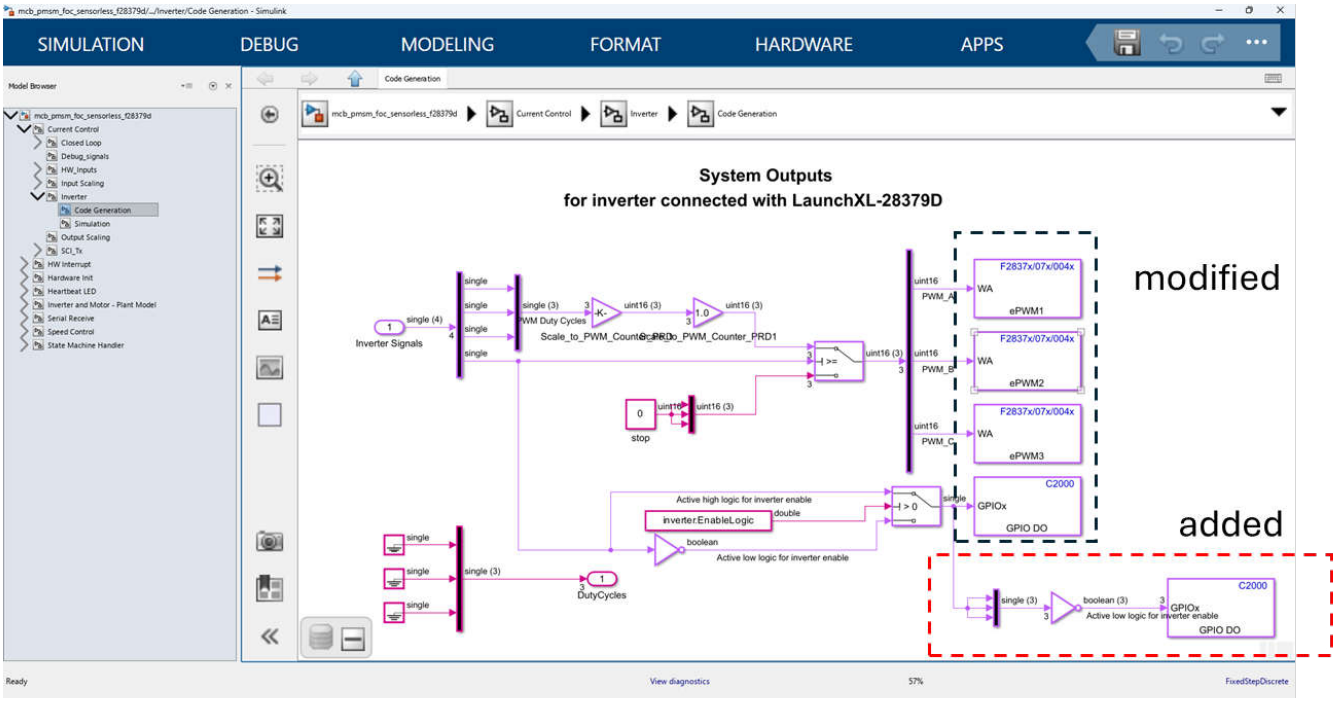


Figure 3-10. Only Minor Modifications Needed in the Simulink Model to Enable Single PWM Mode

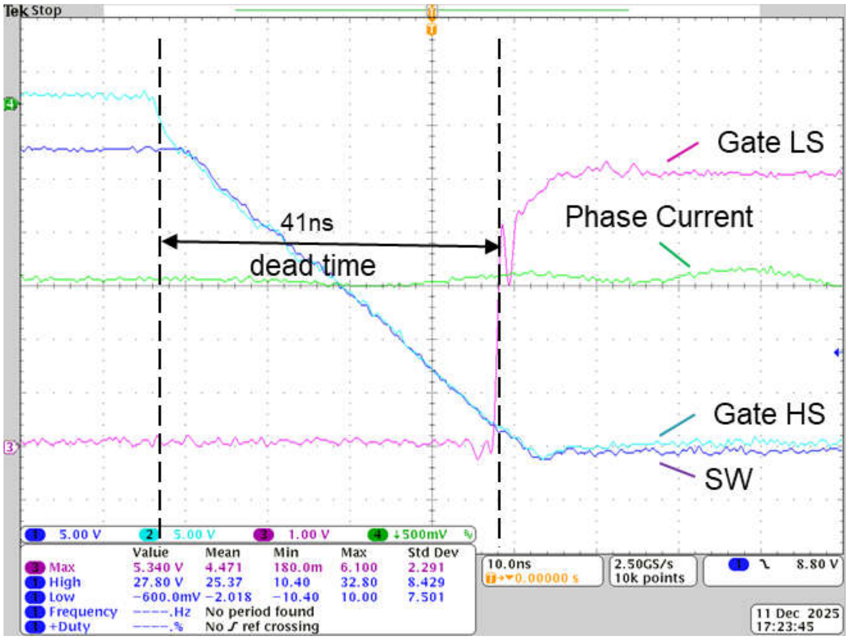
With these few changes applied the model can be compiled, built and loaded into the MCU. There is no need for changes to the host model running on the PC to allow for the control of the motor via the GUI with this updated code running on the MCU.

4 Results

With the changes above the full system implementation proofs to run smoothly as expected in open and closed loop sensorless FOC.

The implementation runs in open loop for speed levels below 300rpm. For inspection of the power stage signal wave forms, current sense accuracy and verification of the dead time configuration the DC-Link voltage was set to 28V and the speed to 100rpm (open loop).

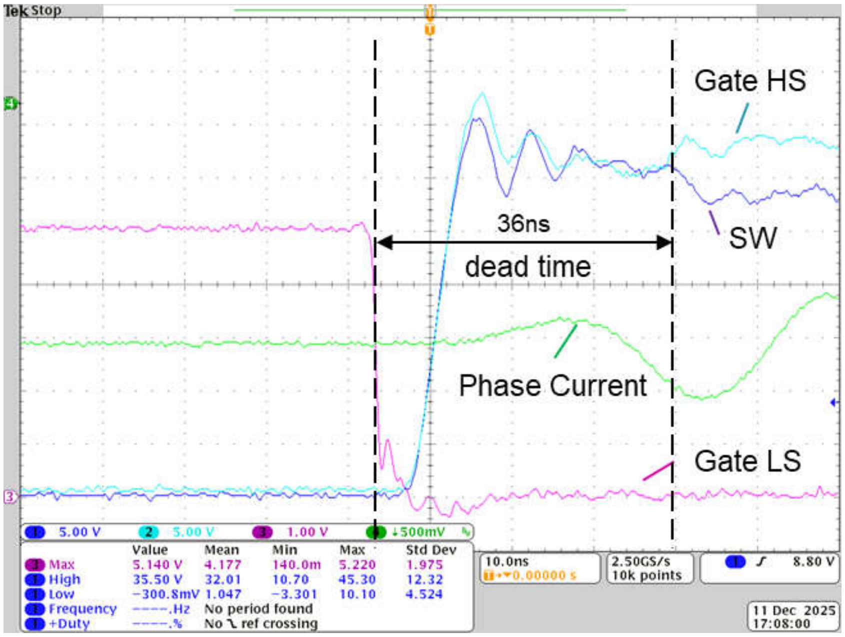
Figure 4-1 shows a representative waveform for turning off the high-side switch and enabling the low-side switch. The phase current corresponds to the output voltage of the INA240A1 current sensor. Please note that the current sensor provides an inverted representation of the actual current into the motor phase since IN+ and IN- have been swapped in the design for optimized layout. The input for the current measurement signal into the oscilloscope has been inverted and its offset has been adjusted to show zero phase current at the central horizontal line. Figure 4-1 shows a small positive current into the motor. During dead time the switch node voltage slowly declines to ground as the small winding current discharges the switch node. When the low side gate turns on to pull the switch node actively to ground it has already depleted to almost zero Volt and one could call this almost a soft switching event. The dead time has been configured with an external resistor connected to RHL = 57.6kΩ as recommended in the datasheet. The observed 41ns is in line with the range of 36ns to 53ns with 44ns typical specified in the datasheet.



	Value	Mean	Min	Max	Std Dev
3 Max	5.340 V	4.471	180.0m	6.100	2.291
1 High	27.80 V	25.37	10.40	32.80	8.429
1 Low	−600.0mV	−2.018	−10.40	10.00	7.501
1 Frequency	-----.Hz	No period found			
1 +Duty	-----.%	No ∫ ref crossing			

Figure 4-1. Dead Time Verification *High-to-Low* Transition

Figure 4-2 shows the opposite scenario with low to high switching. The dead time has been configured with an external resistor connected to RLH = 35.7kΩ as recommended in the datasheet. The observed 36ns is in line with the range of 20ns to 37ns with 30ns typical specified in the datasheet.



	Value	Mean	Min	Max	Std Dev
3 Max	5.140 V	4.177	140.0m	5.220	1.975
1 High	35.50 V	32.01	10.70	45.30	12.32
1 Low	−300.8mV	1.047	−3.301	10.10	4.524
1 Frequency	----.Hz	No period found			
1 +Duty	----.%	No ⌁ ref crossing			

Figure 4-2. Dead Time Verification *Low to High* Transition

4.1 Thermal Performance

Running the motor control in open loop allows for injection of high currents into the motor despite the absence of any load to it.

Running the Teknic M-2310P-LN-04K motor at 100rpm in open loop with a DC-Link voltage of 28V causes a phase current of 4Arms. This can be measured with the help of a current clamp or by reading the INA240A1 current sensor output.

Figure 4-3 shows that at a continuous (>15min) 4A rms phase current there is only very little warming of the power stage under the condition of 24°C room temperature and no forced ventilation.

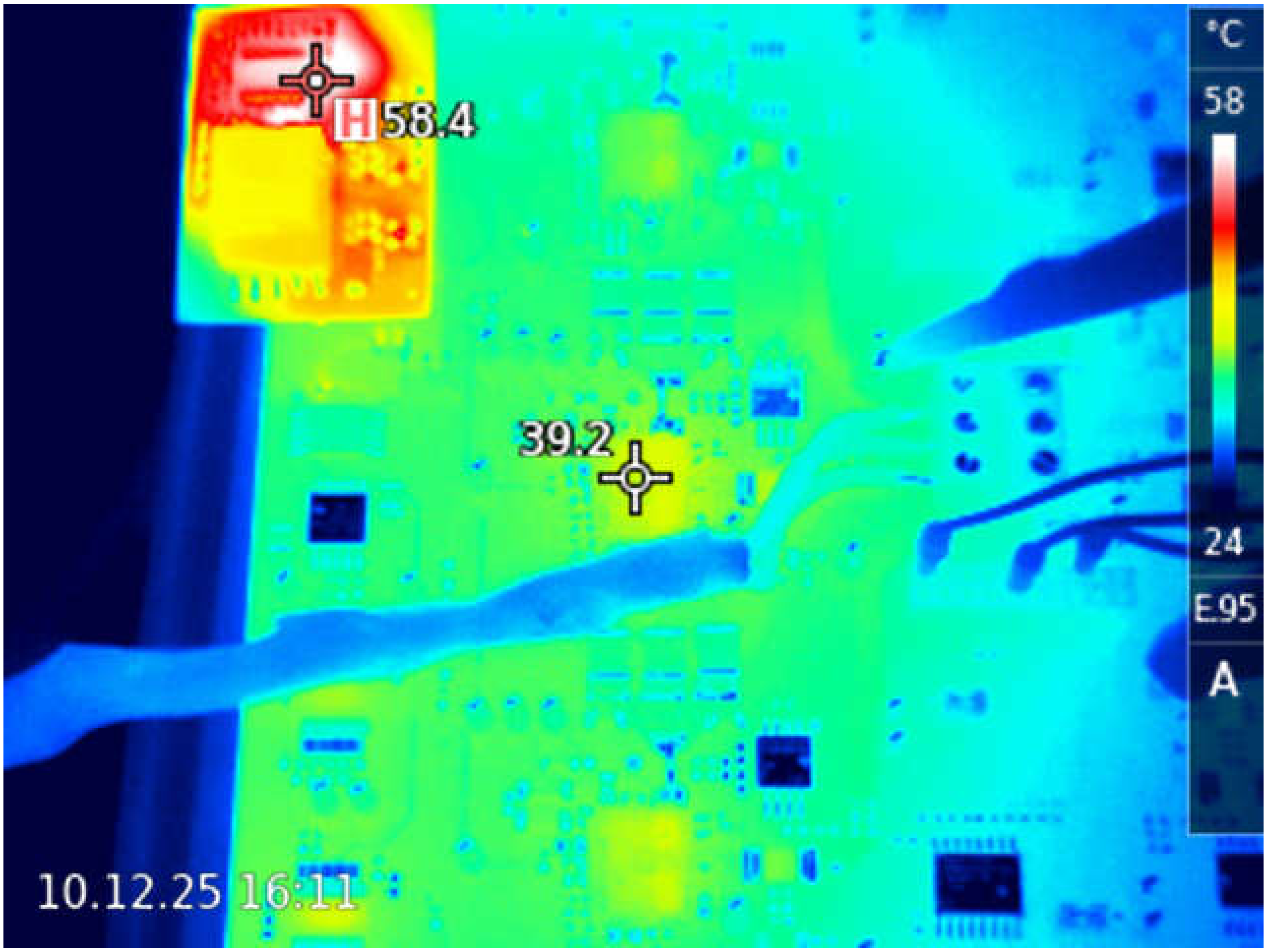


Figure 4-3. Heat Plot of the Power Stage Design at 4A RMS Phase Current Continuous (>15min)

For a stress test a more powerful motor with lower winding resistance was selected: Moons AC Servo Motor – SM0803DE2-KCF-NNV. By raising the DC-Link voltage to 33.1V at 50rpm (open loop) a phase current of 11Arms got established. Figure 4-4 shows the heat plot for 11Arms continuous after 15min. Temperatures do rise as expected but stabilize below 120°C under the condition of 24°C room temperature and no forced ventilation.

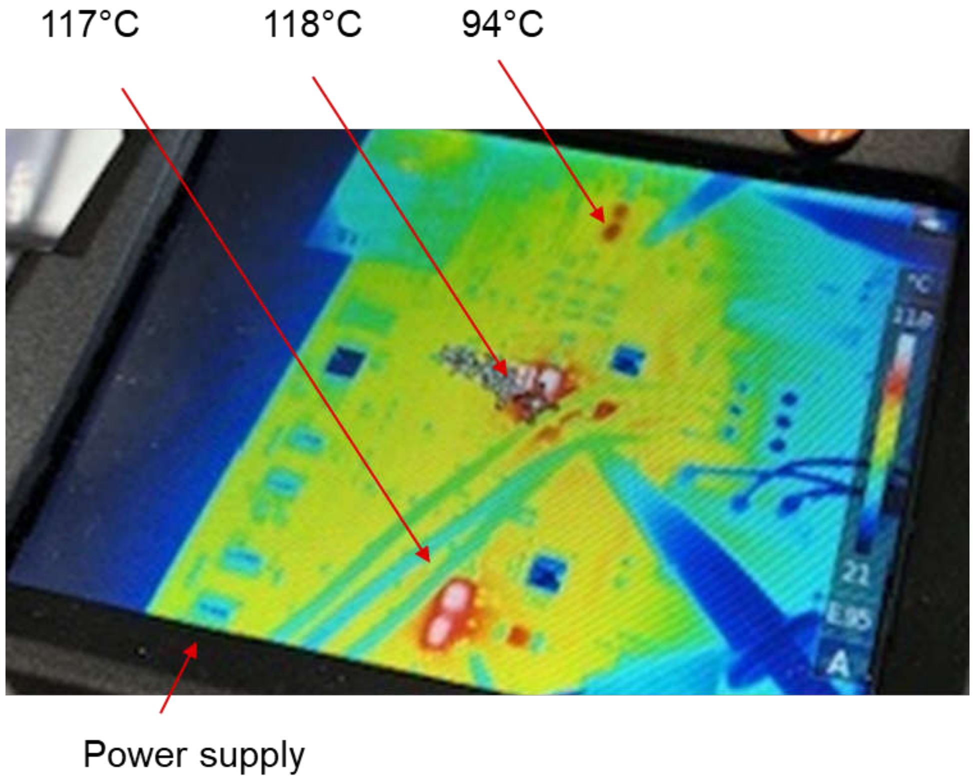


Figure 4-4. Heat Plot of the Power Stage Design at 11A RMS Phase Current Continuous (>15min)

5 Summary

The shown design validates the system capabilities with three independent GaN power stages and MATLAB/Simulink integration running on TMS320F28377D-SEP. The design includes a comprehensive power management solution from an unregulated 28V rail, featuring the PMP23546 flyback design and point-of-load regulation via TPS7Hxxxx-SEP-series components to ensure reliable power delivery to all system components.

The system is based on space-grade components and various monitoring and protection features, including temperature monitoring based on TMP9R00-SP. Thanks to the availability of pin-compatible device options in many cases the design can be easily scaled from more cost sensitive LEO constellation implementations to MEO, GEO or deep space missions with highest radiation hardness and reliability requirements.

The hardware configuration allows for dual three-phase motor, single 2-phase stepper or single 3-phase stepper support.

Matlab Simulink support enabled a very fast implementation of the software but with a very high integrity level as it is mandatory for high-reliability systems such as satellite motor drivers and actuators.

The GaN-based integrated power stages enable very small board area. The low RDSON shows that even up-to continuous phase current of 11Arms the heat development was still very much within reason. For smaller current requirements where heat dissipation will not be the primary concern there is quite some opportunity to reduce the size of the power stage by mounting devices on either side of the PCB and possibly reduce the amount of bulk capacitance.

The results provide confidence that most if not all motor control applications in a satellite can be based on these GaN power-stage devices.

6 References

1. Texas Instruments, *TIDA-010936 48V, 16A Small Form Factor Three-Phase GaN Inverter Reference Design for Integrated Motor Drives:*, design guide.

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Last updated 10/2025