Application Note

Programmable ±HV Power Supply With Low Static Power Consumption for Smart Probe

Matthew Chen, Rayna Feng, and Eric Zhu

ABSTRACT

Smart probes are handheld, highly-integrated, ultrasound imaging equipment. Smart probes are used to obtain the images of internal organs by scanning the human body with ultrasound beams. Compared with traditional portable device, smart probe is stricter in power consumption, thermal performance, size constraint and noise immunity. This application note introduces an efficient and low quiescent loss answer for powering the transmitter in the probe based on TI's reference design PMP40488. This design generates bipolar adjustable high voltage (HV) from ±15 V to ±75 V. The output voltage can be adjusted by FPGA. The continuous average power of each rail is 0.75 W. To meet the size limitation(< 5 mm) of smart probe, a single-ended primary inductor converter (SEPIC) topology with uncoupled inductor is applied. The quiescent power loss is reduced by changing the switching frequency to 100 kHz at standby mode while 250 kHz at normal operation. The deviation of the negative rail is ±2% with the unbalance load at 15-V output and ±1% at 75-V output. The output voltage can be linearly control by an operational amplifier (op amp) with the external signal (0 V to 2.5 V).

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1 Introduction

An ultrasound is one of the most routine examinations in the hospital. Generally, these tests are done by cart-based or portable ultrasound equipment. The advent of the smart probe makes all these processes easier because only a wired or wireless probe connected to a smart phone or tablet is needed. As Figure 1-1 shows, this small-size device integrates the same units as common ultrasound equipment, including a transmitter (TX), receiver, FPGA connection, and power module (high- and low-voltage circuit). The whole device is usually powered by a Li-Ion battery. To extend the battery life, the device requires a highly-efficient power supply, low power consumption, and good thermal performance. This application note provides a new strategy to reduce quiescent dissipation for the power supply of the transmitter.

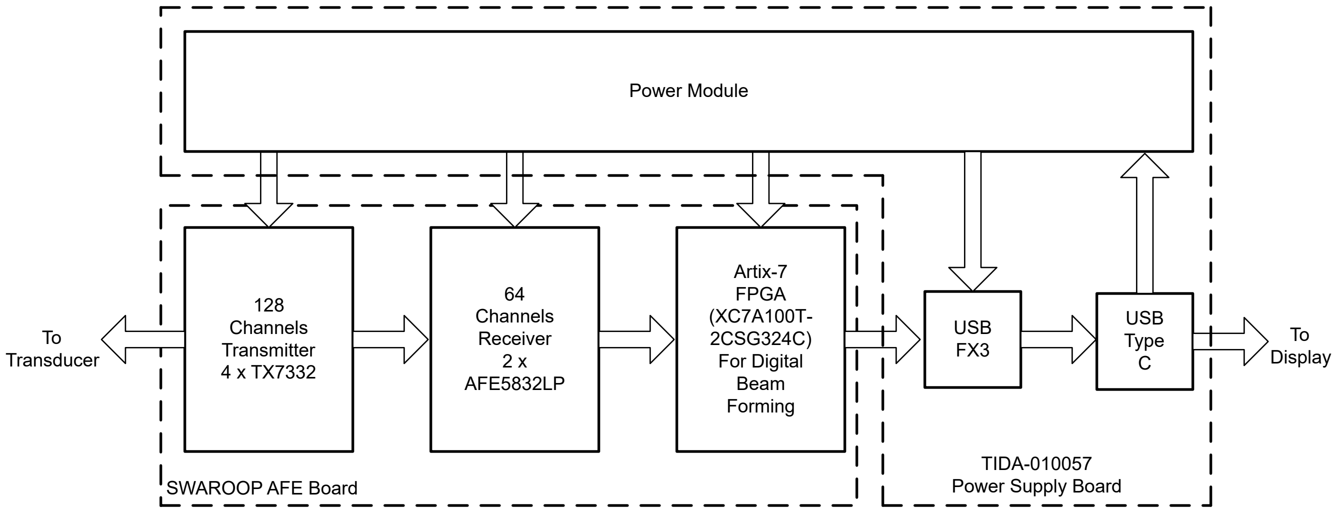


Figure 1-1. Ultrasound Smart Probe System Diagram

For the pulsers in an ultrasound smart probe, high- and low-voltage power supplies are required to transmit the desired voltage pulse for the transducer to generate an ultrasound signal. Generally, there are two modes, Brightness (B) mode and Continuous (CW) mode, which requires bipolar high voltage (+75 V and –75 V) and low voltage (±2.5 to ±15 V), respectively. In the B mode, the whole working period consists of a pulse mode period and a no load mode period as shown in Figure 1-2. During the former period, the high-voltage pulses are transmitted for a short time (several microseconds) with a large current (about 1 A). To meet the power requirement, a switched-mode power supply (SMPS) is applied in most ultrasound systems. However, the switching frequency (Fsw) of SMPS is often fixed by a resistor which causes the power loss during the no-load period. If simply shutting down the SMPS during the no-load period, the device cannot wake up in time before the next pulse. Thus, slowing down the Fsw is a good way to reduce the power consumption. If synchronizing the frequency with an external clock, the change of frequency must be within +25% and –30% of the desired Fsw, which cannot save the power significantly. In this application note, the external GPIO is input to program the switching frequency to 100 kHz at standby mode while 250 kHz at normal operation, achieving the lowest no-load power consumption at the maximum voltage output. This approach can also scale to other applications that need SMPS with low power dissipation.

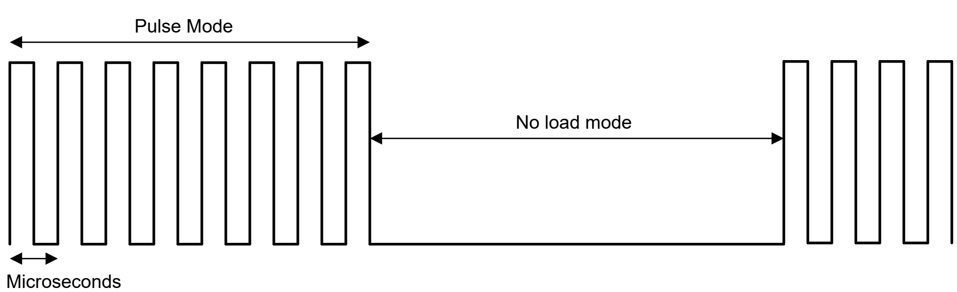


Figure 1-2. Driving Waveform for Pulse Mode

1.1 Design Specification and Key Challenges

Table 1-1 summarizes the design specifications of a high-voltage power supply for an ultrasound smart probe.

Table 1-1. Design Specification of High-Voltage Power Supply

Characteristic	Specification
Input voltage	12 V
Output voltage	Bipolar (from 15 V to 75 V at 10 mA and –15 V to –75 V at –10 mA), total maximum output power 1.5 W
Peak efficiency	88%
Switching frequency	250 kHz
Size (length × width)	15 mm × 45 mm (single layer)
Height	< 5 mm
Output voltage regulation	2%
Voltage symmetry with equal load on both rails	1%
Output ripple	0.1% of the output voltage
Synchronization to external clock frequency	No
Adjustable output voltage	Yes

An ultrasound smart probe has strict requirements on the size, power consumption, and thermal performance to make the device convenient to use. The key design challenges are as follows:

- Bipolar output rail (from 15 V to 75 V at 10 mA and –15 V to –75 V at –10 mA), with deviation of the output rail with ±2%
- Programmable switching frequency from 250 kHz at normal operation to 100 kHz at standby mode
- Adjustable output voltage linearly controlled by external voltage signal

2 High-Voltage Power Supply Design Using SEPIC

The single-ended primary inductance converter is selected to be the topology for a high-voltage power-supply circuit. Figure 2-1 shows the uncoupled inductors reduce the design size and the output voltage can be greater or less than the input with no polarity reversal, which is an excellent choice for an ultrasound transmitter.

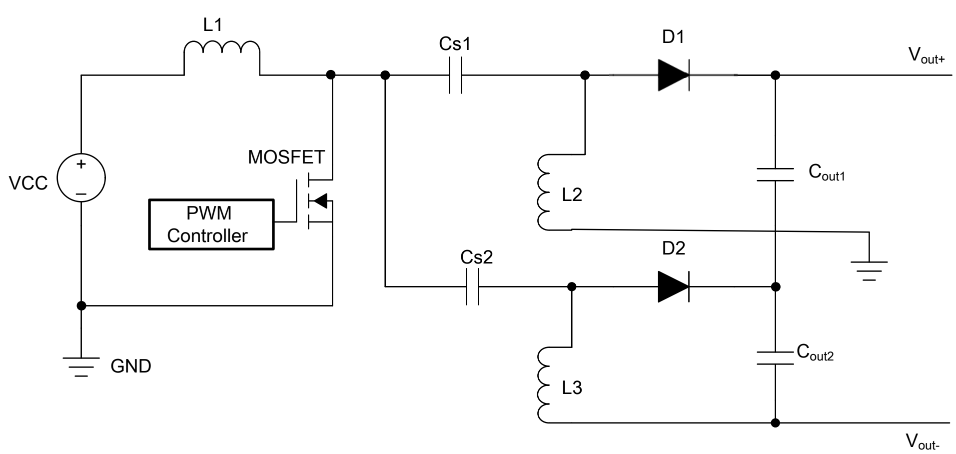


Figure 2-1. SEPIC Circuit Topology

2.1 TI HV Supply Architecture Using SEPIC Topology

Figure 2-2 shows the schematic of this design. The LM51551 device is used as the controller for the SEPIC circuit. To meet the requirements of height, three uncoupled inductors are used. The switching frequency is set by the RT pin and the output voltage is regulated by the FB pin.

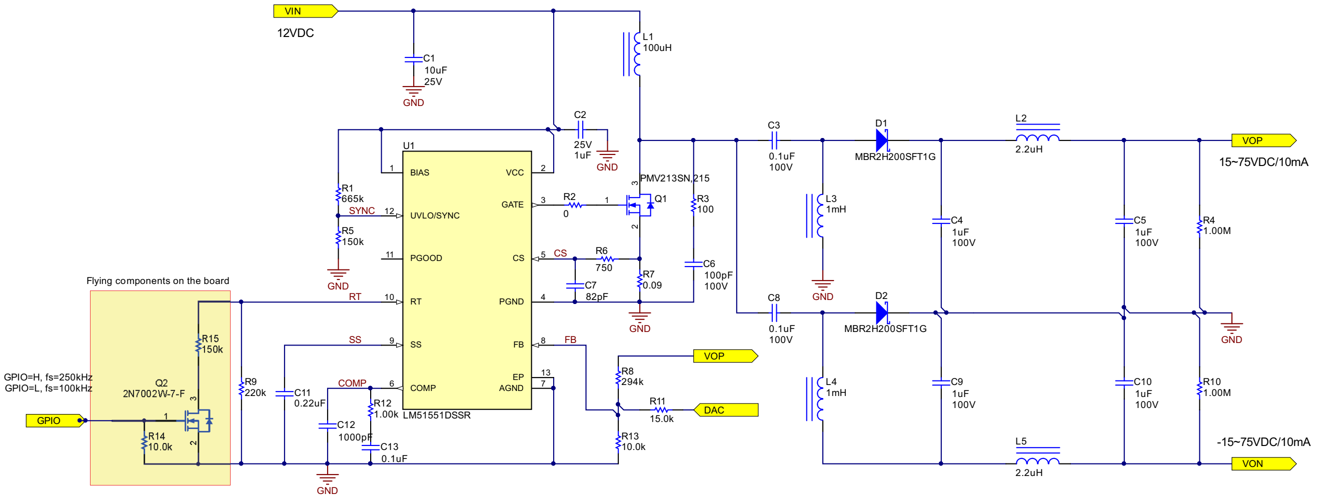


Figure 2-2. High-Voltage Circuit Design Schematic

For the detailed components selection in SEPIC designs, see the *Designing Bipolar High Voltage SEPIC Supply for Ultrasound Smart Probe* and *AN-1484 Designing A SEPIC Converter* application notes. These documents explain how to choose the value of each component based on the design specifications. Also TI has Microsoft® Excel® calculation tools for most DC/DC Converter and *Webench*, which helps with the power design.

2.2 Switching Frequency Shift

As previously mentioned, the switching frequency for SMPS is set by the resistor. The frequency stays constant during all the transmitting period which forces the MOSFET working at a high frequency. That leads to the high-quiescent dissipation of the control chip. In this application note, a MOSFET combined with two additional resistors are used to change the switching frequency at the no-load period. The signal from GPIO can set the Fsw from 250 kHz to 100 kHz, which is only 46 mW at the maximum output voltage.

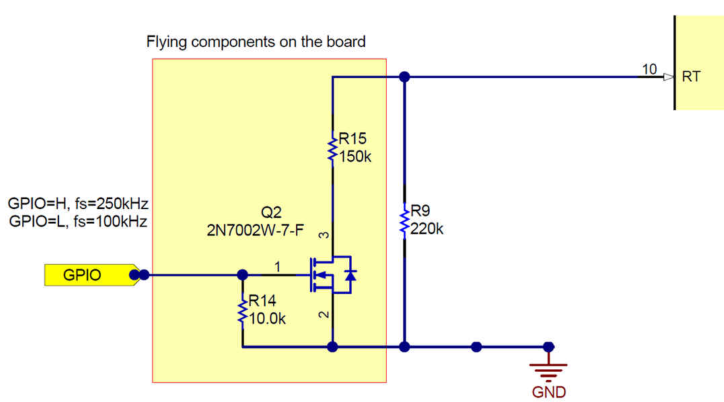


Figure 2-3. Switching Frequency Control by GPIO

2.3 Voltage Control by External Signal

Adjustable outputs can meet the requirement from different customers and make it easy to power the transmitter since the design may need several voltage rails. In this design, a signal (0 V to 2.5 V) from FPGA is used to control the output voltage by comparing the feedback voltage captured from the positive output. The output of the op amp is connected to the FB pin of the LM51551 device to regulate the V_{OUT}.

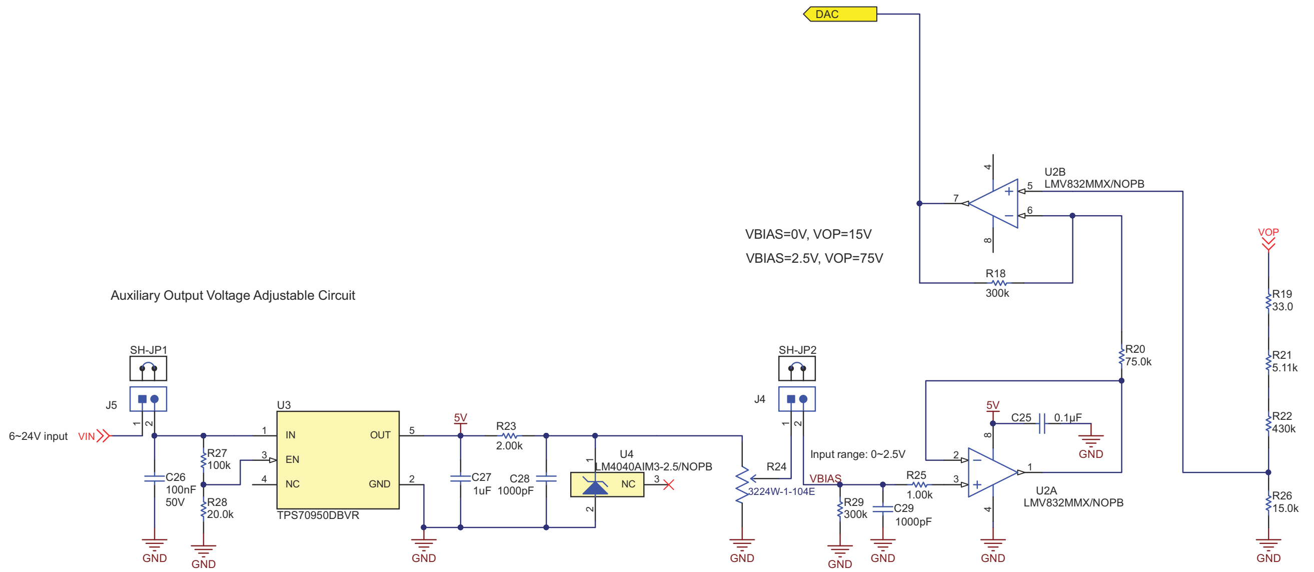


Figure 2-4. Output Voltage Control by External Signal

Figure 2-5 shows the diagram of the voltage control circuit. To select the proper value of R18, R19, R20, R21, R22, and R26, see the following equations.

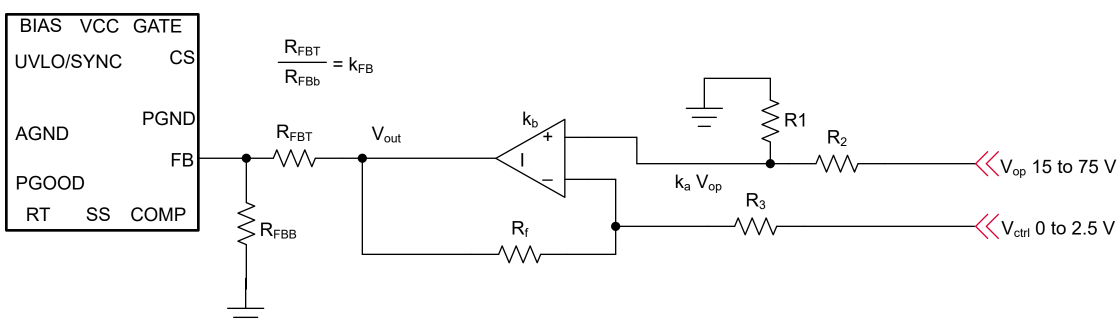


Figure 2-5. Voltage Control Circuit Diagram

$$V_{out} = V_{ref}\left(k_{FB} + 1\right) \tag{1}$$

$$\frac{R_1}{R_1 + R_2} = k_a \ldots, \frac{R_f}{R_3} = k_b \tag{2}$$

$$k_{FB} + 1 = k_a \times V_{op}(k_b + 1) - k_b V_{ctrl} \tag{3}$$

$$k_{FB} + 1 = k_a \times V_{op}(k_b + 1) - k_b V_{ctrl} \tag{4}$$

where

- V_{ref} is the reference voltage of the FB pin in LM51551
- V_{ctrl} is the desired control voltage range of the customers
- k_{FB} , k_a , and k_b are the ratio of the resistors which helps to define the value

For example, the following equations show that if k_{FB} = 1.5 , desired control voltage is 0 V to 2.5 V and the output voltage is 15 V to 75 V:

$$1.5 + 1 = k_a \times 15 \times (k_b + 1) \tag{5}$$

$$1.5 + 1 = k_a \times 75 \times (k_b + 1) - 2.5\, k_b \tag{6}$$

$$k_a = 0.033, k_b = 4 \tag{7}$$

3 Test Result

Figure 2-2 and Figure 2-4 show the entire circuit which is characterized for performance with a 5-V input supply. Test results are presented in the Section 3.1 through Section 3.6.

3.1 Efficiency and Power Consumption (100 kHz vs 250 kHz)

Figure 3-1 shows the efficiency graphs under different output voltages. As illustrated, the peak efficiency reaches to approximately 83% at 75-V outputs. Figure 3-2 demonstrates the power consumption at different switching frequency. The power loss is lower at 100 kHz and decreases to 46 mW at maximum output voltage.

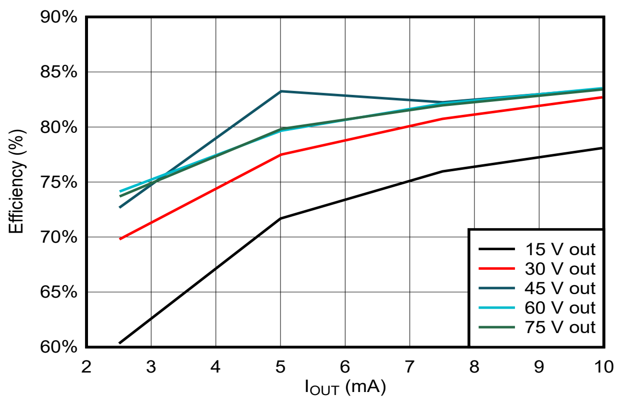


Figure 3-1. Efficiency Curve of SEPIC HV Power Supply

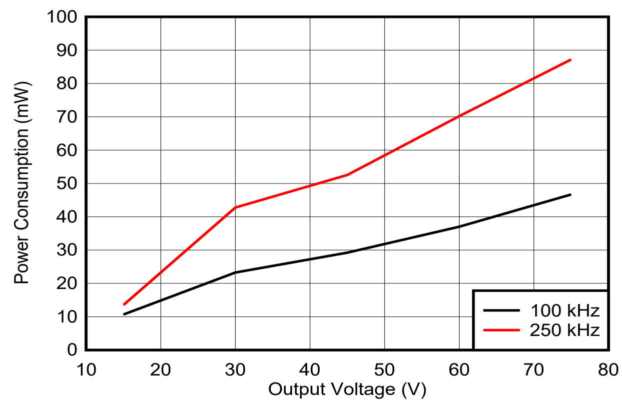


Figure 3-2. Power Consumption of Different F_{SW}

3.2 Linearity of Output Voltages vs V_{BIAS}

Figure 3-3 and Figure 3-4 show the linearity of output voltages at full load, half load, and no load. The curve shows a good correlation and matches the designed equation.

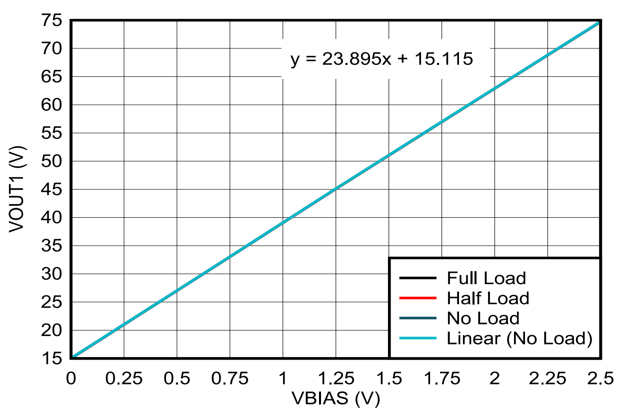


Figure 3-3. Linearity V_{OUT+} vs V_{BIAS}

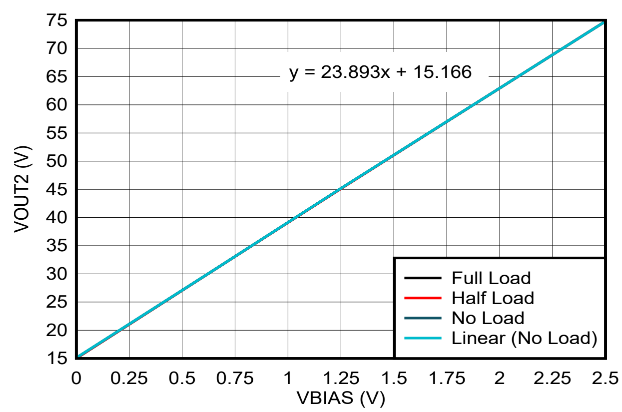
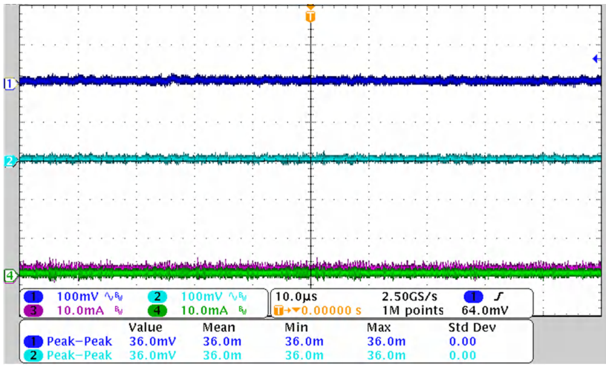


Figure 3-4. Linearity V_{OUT-} vs V_{BIAS}

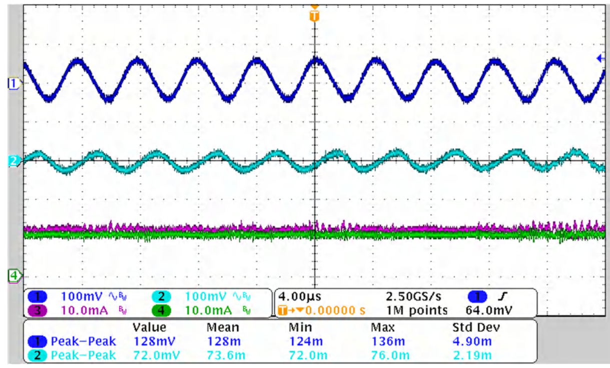
3.3 Output Ripple Measurement

Figure 3-5 through Figure 3-8 show the output voltage ripple at 15-V and 7-V output voltage during no load and full load.



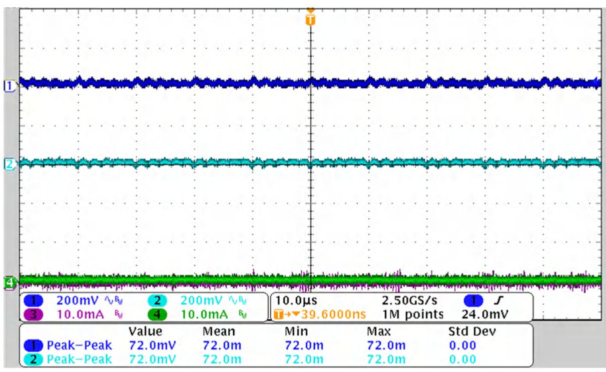
CH1: V_{OUT1}, CH2: V_{OUT2}, CH3: I_{OUT1}, CH4: I_{OUT2}

Figure 3-5. 12-V Input, ±15-V No Load



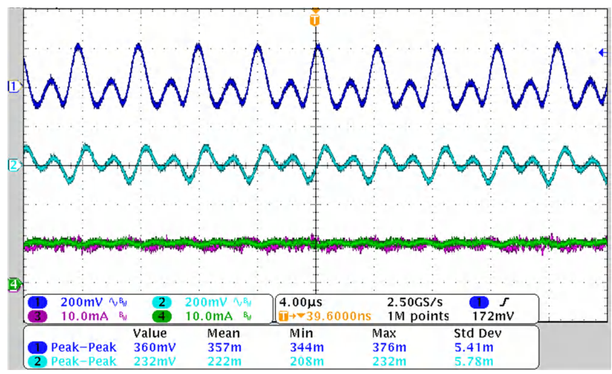
CH1: V_{OUT1}, CH2: V_{OUT2}, CH3: I_{OUT1}, CH4: I_{OUT2}

Figure 3-6. 12-V Input, ±15 V, 10-mA Load



CH1: V_{OUT1}, CH2: V_{OUT2}, CH3: I_{OUT1}, CH4: I_{OUT2}

Figure 3-7. 12-V Input, ±75-V No Load

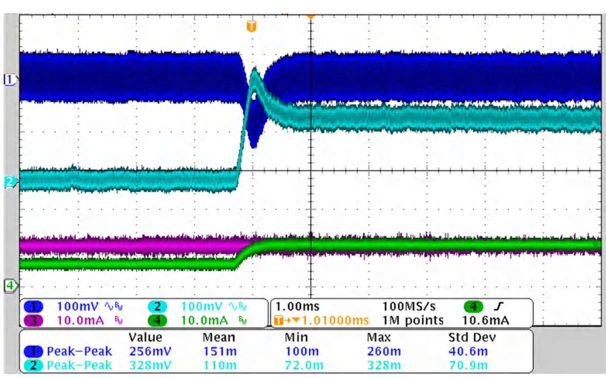


CH1: V_{OUT1}, CH2: V_{OUT2}, CH3: I_{OUT1}, CH4: I_{OUT2}

Figure 3-8. 12-V Input, ±75 V, 10-mA Load

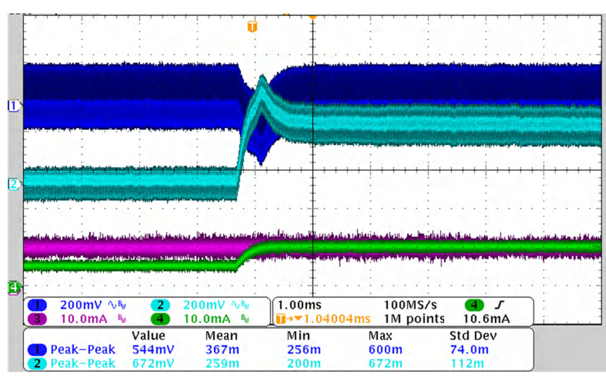
3.4 Load Transient Test

Figure 3-9 and Figure 3-10 show the waveforms of output AC ripples at load transient. The high current level is full load for 10 ms; the low current level is half load for 10 ms, with a slew rate of 0.1 A/µs. As the load on the positive output remains stable, the load on the negative increases from 5 mA to 10 mA, the voltage drops are 151 mV and 367 mV with the output 15 V and 75 V, respectively.



CH1: V_{OUT1}, CH2: V_{OUT2}, CH3: I_{OUT1}, CH4: $-I_{OUT2}$

Figure 3-9. 12-V Input, 15 V, 10 mA, –15 V, 5 mA to 10 mA

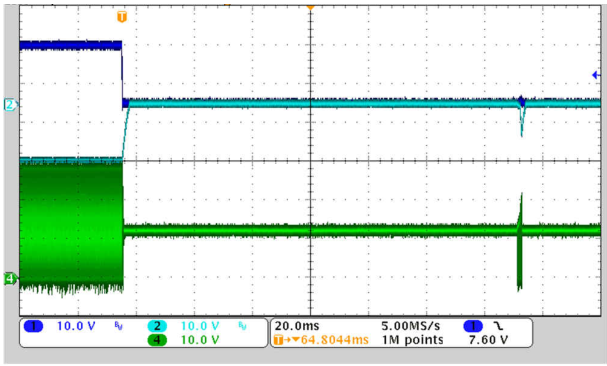


CH1: V_{OUT1}, CH2: V_{OUT2}, CH3: I_{OUT1}, CH4: $-I_{OUT2}$

Figure 3-10. 12-V Input, 75 V, 10 mA, –75 V, 5 mA to 10 mA

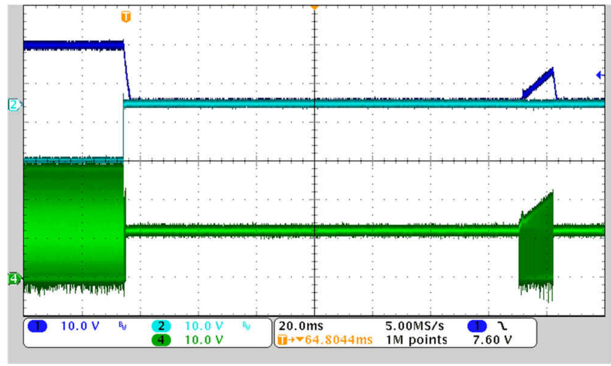
3.5 Overload Protection

Figure 3-11 through Figure 3-14 show the output overload protection when one of the outputs goes overload.



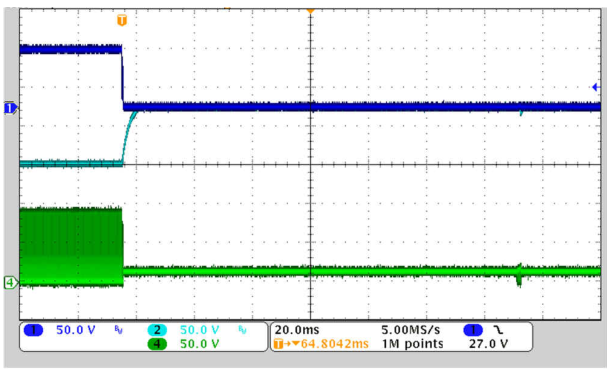
CH1: V_{OUT1}, CH2: V_{OUT2}, CH4: V_{SW}

Figure 3-11. 12-V Input, ±15 V, 10 mA, Output1 Overload



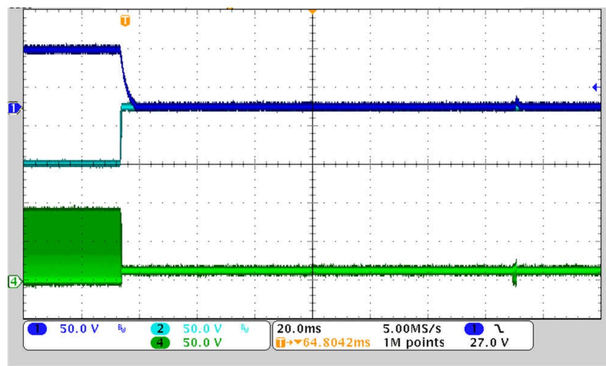
CH1: V_{OUT1}, CH2: V_{OUT2}, CH4: V_{SW}

Figure 3-12. 12-V Input, ±75 V, 10 mA, Output2 Overload



CH1: V_{OUT1}, CH2: V_{OUT2}, CH3: I_{OUT2}, CH4: V_{SW}

Figure 3-13. 12-V Input, ±75 V, 10 mA, Output1 Overload



CH1: V_{OUT1}, CH2: V_{OUT2}, CH3: I_{OUT2}, CH4: V_{SW}

Figure 3-14. 12-V Input, ±75 V, 10 mA, Output2 Overload

3.6 Thermal Image

Figure 3-15 shows the thermal image of the high-voltage power supply board after testing for 20 minutes. With the 12-V input, ±75 V/1.5 W output operation, the maximum temperature is 42.7°C in the top side at an ambient temperature of 22°C.

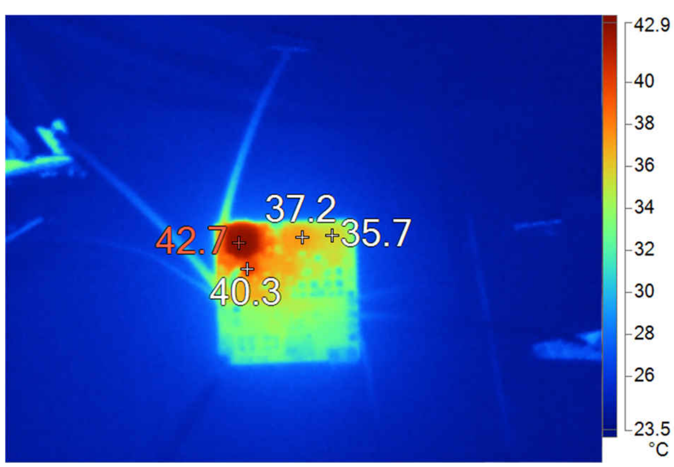


Figure 3-15. Thermal Performance of the Design

4 Summary

The smart probe is a new trend for the next generation of portable ultrasound equipment. The handheld size of a smart probe provides convenience for doctors, but consumes more power. Due to the working process of the transmitter, the controller of the power supply does not always need to switch fast. By slowing down the switching frequency during the no load period, the quiescent loss decreases significantly. This decrease extends the battery life and improves the thermal performance. The adjustable output helps meet a variety of requirements of the customer and eases the methods for powering the transmitter. These features help simplify the system design.

5 References

1. Texas Instruments, *Designing Bipolar High Voltage SEPIC Supply for Ultrasound Smart Probe* application note
2. Texas Instruments, *Programmable ±100-V, High-Current, Floating Linear Regulator Reference Design for Ultrasound Systems* tool page
3. Texas Instruments, *Programmable ±100-V, High-Current, Floating Linear Regulator Reference Design for Ultrasound Systems* design guide