Application Note

Achieving High-Accuracy Output Below VREF With Space-Grade Multichannel Buck Converters

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ABSTRACT

A typical buck converter application allows regulation of the output voltage as low as the reference voltage of the converter (V_{REF}). Occasionally a circuit requires a highly accurate power supply below a reference of the converter. A modified feedback network can be used in conjunction with an external voltage reference to allow a converter to regulate below the reference voltage, but this design degrades the accuracy of the supply by introducing additional error from the external voltage. Using a single voltage reference for multiple channels allows regulation below the reference voltage while maintaining a high level of accuracy. This application note introduces the concept and analysis of this method and provide an example circuit with results using the TPS7H4104EVM.

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Trademarks

1 Introduction

Electronics such as FPGAs and ASICs used in modern spacecraft usually require voltages at or above current point-of-load buck converter reference voltages, typically 0.6V to 1.2V. As advances continue, lower voltage rails with high accuracy are sometimes required for power or bias in one of these systems. While generating a voltage lower than the reference has previously been accomplished; it is often a challenge to meet the accuracy requirements of sensitive rails while doing so, even if the converter meets such requirements in a typical implementation.

Typical methods wherein an external voltage source is used to extend the output range of a converter can be modified in some buck converters to avoid accuracy losses that normally degrade such a configuration. To be compatible with this method, converters must provide more than one independently configurable output channel, and each channel must share the same internal voltage reference.

This application note describes the theory of operation and requirements for a buck converter to produce a high-accuracy output below the reference voltage, how such an implementation prevents degradation of output accuracy, and provide examples of operation in simulation and hardware.

2 Concept of Operation

Methods to lower a converter's output voltage below the reference are explored in the application notes SLVA216 and SLUAAO0. When these methods are implemented in a feedback divider of the regulator, an external voltage source (V_{EXT}) is connected to the feedback node through a resistor (R_{EXT}). By varying the voltage of V_{EXT} and the values of the feedback resistors, the voltage at the output of the regulator can be set. With set feedback resistor values, when V_{EXT} is raised, V_{OUT} drops, and when V_{EXT} is lowered, V_{OUT} rises.

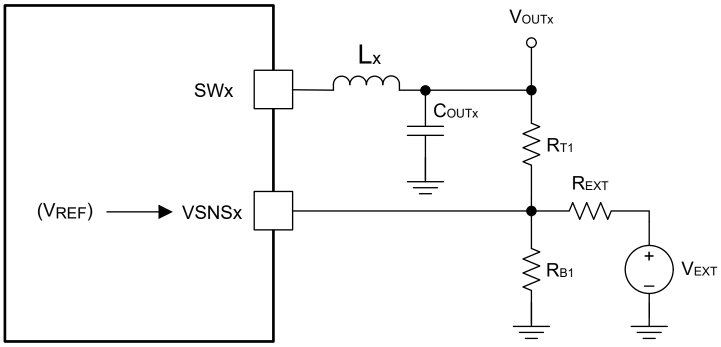

Figure 2-1. Three Resistor Simplified Schematic

When V_{EXT} is greater than V_{REF}, current from V_{EXT} flows to GND through R_{EXT} and R_{B1}. The additional current from V_{EXT} though R_{B1} causes a voltage rise at VSNS. The control loop of the regulator senses this voltage rise and decreases V_{OUT} in response, causing current flow through R_{B1} from R_{T1} to decrease. As the current through R_{B1} decreases, the voltage at VSNS decreases and returns to the reference voltage, but now with V_{OUT} at a lower level. If enough current is allowed to flow through R_{B1} such that the current through the top feedback resistor goes to zero, V_{OUT} is equal to the reference voltage of the regulator. If the current through R_{EXT} is increased beyond this point, then V_{OUT} drops below the reference voltage. During this condition, current no longer flows from V_{OUT} to GND through the feedback divider but rather flows from V_{EXT} to V_{OUT} and to GND through R_{T1} and R_{B1}.

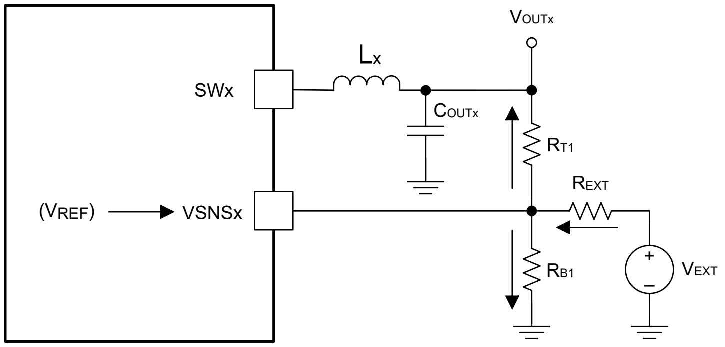

Figure 2-2. Simplified Schematic With Current Flow

In this operating mode R_{B1} is no longer required, as this mode no longer contributes to the feedback functionally and only serves as a source of error. The bottom resistor can then be removed and replaced with R_{EXT} which then becomes the new R_{B1} in the divider.

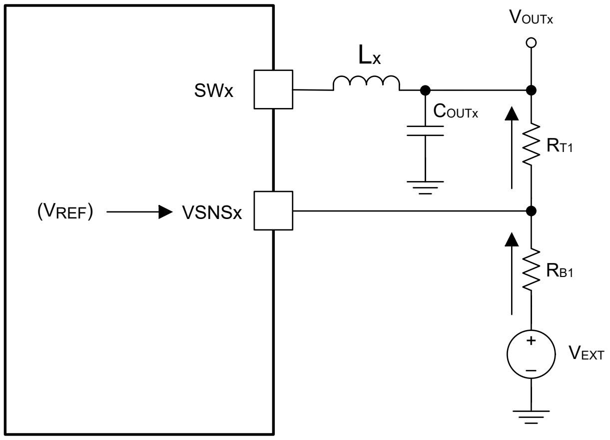

Figure 2-3. Two Resistor Simplified Schematic

In this new configuration, the feedback resistor divider is now formed between V_{EXT}, and V_{OUT}. When the voltage of V_{EXT} is greater than V_{REF}, to maintain VSNS at the reference voltage, V_{OUT} must be lower than V_{REF} to accommodate the voltage drop across R_{T1}. Stable regulation is still maintained, as when V_{OUT} drops or rises, the voltage at VSNS still drops or rises proportionally, as with a standard implementation. V_{OUT} in this configuration is now determined by the values of R_{T1}, R_{B1}, V_{REF}, and V_{EXT}.

$$V_{OUT} = R_{T1} \times \left(\frac{V_{REF} - V_{EXT}}{R_{B1}}\right) + V_{REF} \quad (1)$$

The configuration shown in Figure 2-3 is already useful, as it allows for V_{OUT} to be regulated below the reference with only the addition of an external voltage source. However, the problem it introduces can be seen in the equation for V_{OUT}. Since the output voltage is dependent on both V_{REF} and V_{EXT}, errors in both terms must now be considered when calculating output accuracy of the regulator. Since V_{EXT} is not an accurate voltage source, in this configuration the accuracy of the regulator is permanently degraded by the accuracy of whatever external voltage source is used for V_{EXT}.

3 Maintaining Output Accuracy

Many multichannel regulators use independently generated voltage references to regulate each output. However, the TPS7H410x converters generate only a single internal voltage reference that is shared by all the output channels of the device. This design allows the accuracy degradation of the implementation shown in Section 2 to be bypassed, and device output accuracy to be maintained while regulating below V_{REF}.

Output accuracy degradation can be avoided by using a second output of the device to generate V_{EXT}. This configuration only allows V_{OUT} accuracy to be maintained when a single voltage reference is shared for both channels generating V_{OUT} and V_{EXT}. If the two channels do not use the same voltage reference, no accuracy benefit is gained over simply using an external voltage source. The shared voltage reference enables this possibility due to the way that changes in the reference voltage propagate to V_{OUT}. If V_{REF} is lowered, V_{EXT} is also lower, and therefore V_{OUT} rises. However, since both channels share a common reference, V_{REF} of V_{OUT} has also fallen, so V_{OUT} must fall to compensate, and the additive effects are canceled. The shift in V_{REF} is not canceled but simply reduced to the same magnitude as a single channel in a standard configuration.

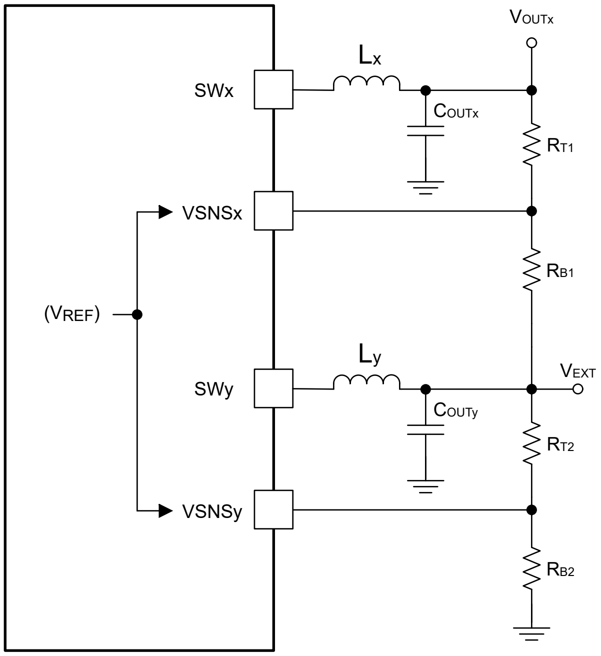

Figure 3-1. Full System Simplified Schematic

$$V_{OUT} = V_{REF} \times \left(1 - \frac{R_{T1} \times R_{T2}}{R_{B1} \times R_{B2}}\right) \tag{2}$$

Equation 2 shows V_{OUT} when V_{EXT} is generated by another channel using the same voltage reference. All four resistors from the two feedback dividers are incorporated to make an equation for V_{OUT} using the full system. Since there is no longer a term from a second voltage reference, all V_{REF} terms can be grouped and factored into a single term. This gives an equation for V_{OUT} that is now only dependent on V_{REF} and a term consisting of feedback divider resistors for both channels. The form is the same as the equation for V_{OUT} in a standard configuration; the difference lies in the addition of R_{T2} and R_{B2} for the second feedback divider. The above simplified schematic shows how the feedback of both channels is connected. V_{OUT} is the desired output that is below V_{REF}.

This method does have drawbacks. To achieve the maximum accuracy of the low-voltage output, the channel that is used to generate V_{EXT} must not be used to power any external loads. While voltage ripple on V_{EXT} is not a concern, as any ripple must have a frequency at least a decade higher than the device control loop, load-steps from an external load on V_{EXT} cause perturbations at V_{OUT}. Therefore, the number of usable channels on the device is effectively reduced by one. Efficiency is reduced due to the need for a channel running that is not providing any power to the load. Sequencing requirements are also introduced, as V_{EXT}

must start up concurrently or before V_{OUT} to avoid a temporarily higher than desired voltage at V_{OUT}. Since the TPS7H4104 provides integrated channel sequencing, this is simply resolved by making use of the internal channel sequencing, and selecting a channel for V_{EXT} that starts up before the channel selected for V_{OUT}.

4 Simulation Results

A simulation was configured and run using the TPS7H4104-SEP SIMPLIS model provided on ti.com. CH2 was used as V_{EXT} and CH3 as V_{OUT}. Channels 1 and 4 are unused in the simulation and are therefore disabled and not shown in Figure 4-1. CH2 was not modified from the original configuration and is set to output 1.2V. CH3 was modified to output a voltage below V_{REF}, in this case 0.5V was selected. 10.02kΩ was selected for the top resistance of the V_{OUT} (CH3) feedback divider to match the default values on the TPS7H4104EVM. Equation 3 calculates the bottom resistor value.

$$R_{B1} = R_{T1}\left(\frac{V_{EXT} - V_{REF}}{V_{REF} - V_{OUT}}\right) \tag{3}$$

Using the following inputs results in RB1 = 61.24kΩ:

- R_{T1} = 10.02kΩ
- V_{EXT} = 1.207V
- V_{REF} = 0.59948V
- V_{OUT} = 0.5V

61.9kΩ was selected for the resistor in the simulation as the closest E96 series value to the calculation result. A switching frequency of approximately 300kHz was also configured for this simulation to avoid violating the minimum on-time specification of the device in the data sheet. RT, COMP and RSC for CH3 were also configured using the equations found in the TPS7H4104 data sheet.

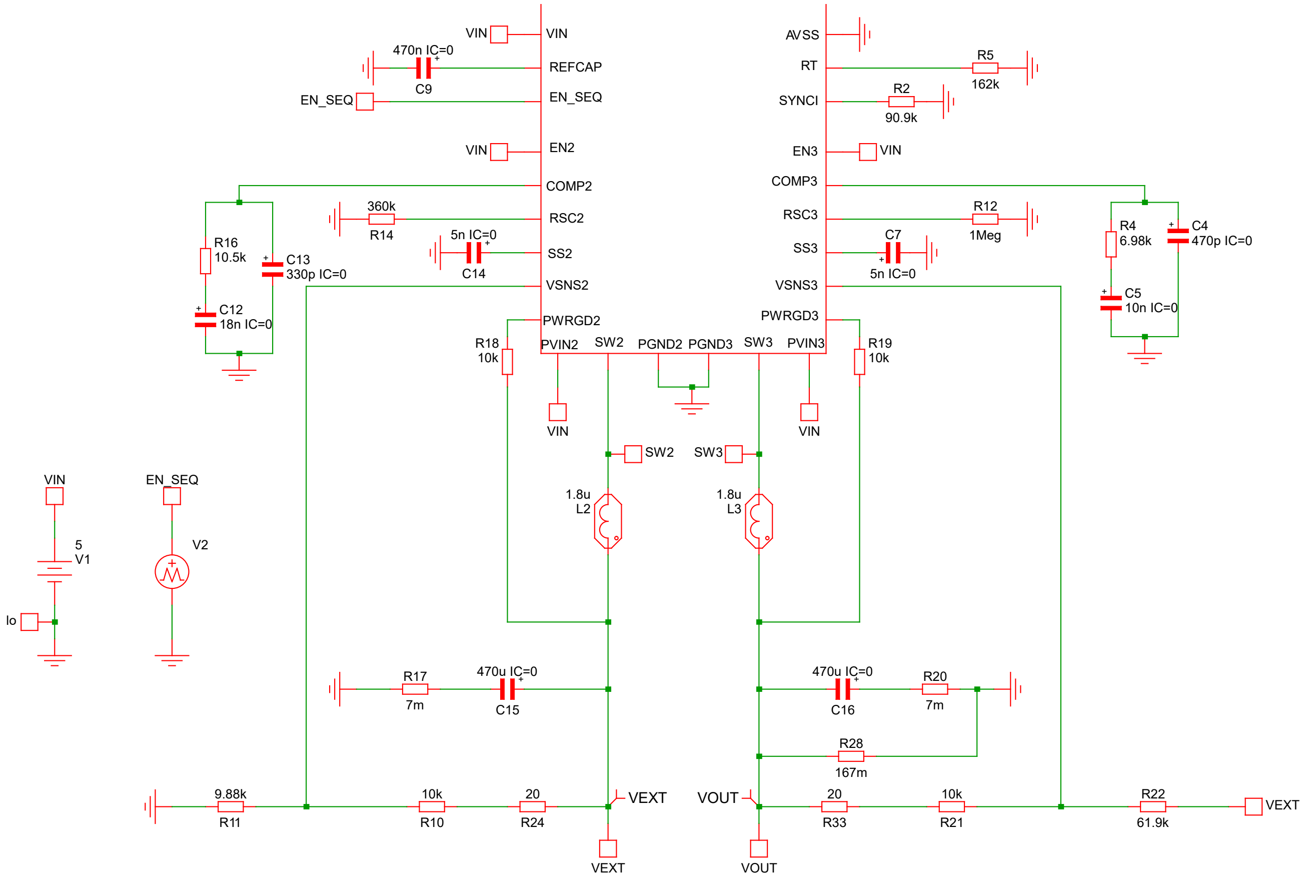

Figure 4-1. Simulation Schematic

Startup was simulated with the internal channel sequencing enabled. Since the internal sequencer of the TPS7H4104 brings up channels in numbered order, and CH2 was used for V_{REF} while CH3 was used for V_{OUT}, the sequencer enables V_{OUT} only after V_{EXT} has finished the soft startup sequence. The plot below shows V_{OUT} and V_{EXT} during startup and steady-state operation with a load of 3A applied to V_{OUT}. As expected, V_{OUT} regulates to 0.5V, which is 100mV below V_{REF} as shown in Figure 4-2.

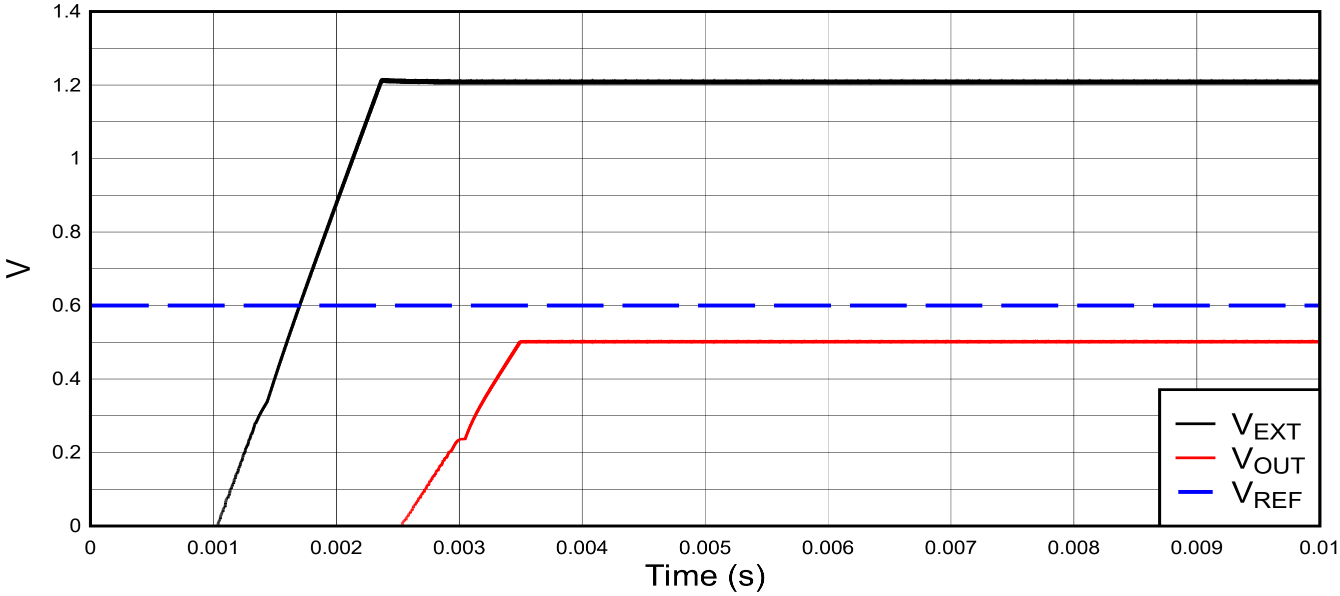

Figure 4-2. Simulation Startup Results

Using a simulation allows the ability to vary the internal voltage reference between simulation runs. V_{REF} was set to the Min, Typ, and Max values shown in the TPS7H4104 data sheet, and the RMS value of V_{OUT} from 6ms to 10ms of the simulation was recorded. The RMS values for V_{OUT} along with the corresponding V_{REF} values are shown in Table 4-1. The percentage shift from the typical value is also calculated for V_{REF} and for V_{OUT}.

Table 4-1. V_{REF} To V_{OUT} Error Propagation

Value	V_{REF} (mV)	V_{REF} Change (%)	V_{OUT} (mV)	V_{OUT} Change (%)
Typ	599.48	-	501.04	-
Min	591.50	-1.33%	494.38	-1.33%
Max	603.50	0.67%	504.40	0.67%

Table 4-1 shows that V_{REF} changes are propagated to V_{OUT} without adding extra error. So, a 1% change in V_{REF} results in a 1% change in V_{OUT}. This behavior is consistent with the equation for V_{OUT} that was shown in Section 3, as there is only a single V_{REF} term to contribute error to V_{OUT}. This is the same error propagation from V_{REF} that is seen in a single-channel setup regulating at or above V_{REF}, so the goal of creating a channel that regulates below V_{REF} while maintaining the same accuracy has been achieved.

4.1 V_{EXT} Output Deviation Effects

During operation, it is possible for V_{EXT} to deviate from the nominal DC value due to external factors such as line transients, load transients (if V_{EXT} is loaded), and single-event transients caused by radiation. The SEE report for the TPS7H4104-SEP, Single-Event Effects (SEE) Radiation Report of the TPS7H4104-SEP shows and discusses the results of testing the TPS7H4104-SEP under a heavy-ion beam. While no SET events 3% or greater in magnitude were observed, a theoretical 3% transient can be induced on V_{EXT} in simulation to observe the effects on V_{OUT} with different nominal levels of V_{EXT}.

In the simulation, a -3% transient was injected directly onto the V_{EXT} rail with rise and fall times of 10µs. Three different nominal V_{EXT} levels were tested, and transient magnitude was adjusted for each V_{EXT} condition to -3% of nominal. Figure 4-3 shows the results for all three V_{EXT} levels displayed on a single plot.

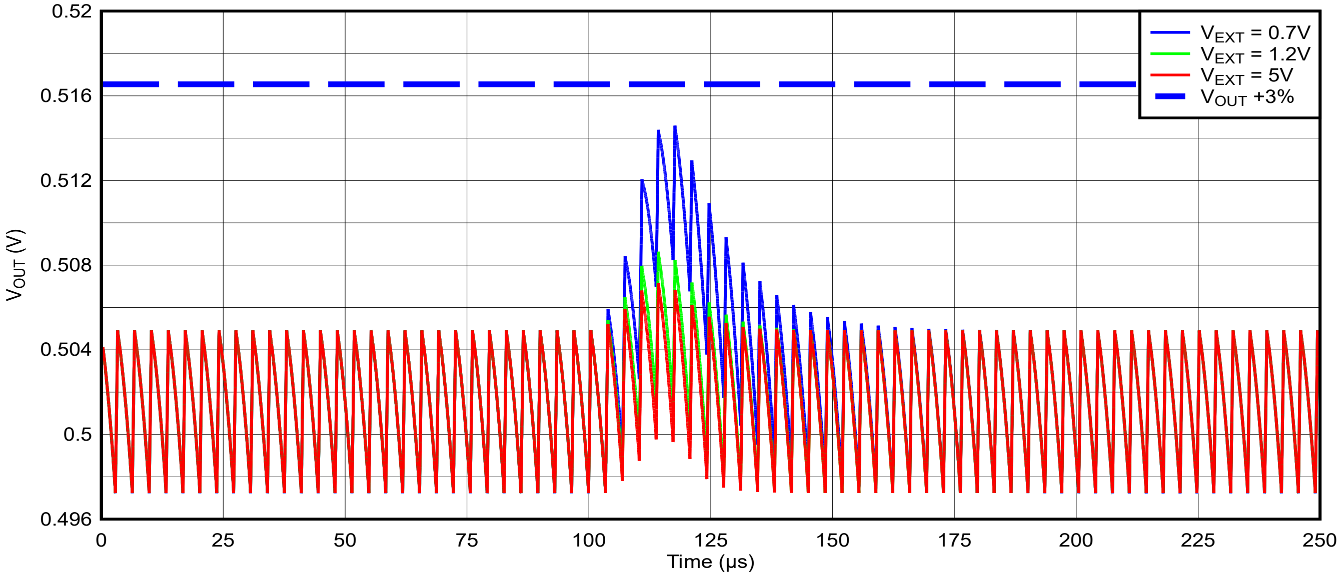

Figure 4-3. Simulation Result of VEXT Transient on VOUT

The plot above shows that for larger values of V_{EXT}, the same percentage deviation from the nominal voltage will produce a smaller disturbance on V_{OUT}. The cause of this unintuitive relationship is the voltage drop across R_{B1}, and the V_{REF} voltage. The current flowing through R_{B1} is not determined by the total potential between GND and V_{EXT}, but rather between V_{EXT} and V_{REF}. Since the magnitude of the upset on V_{EXT} was determined by the V_{EXT} to GND voltage, after V_{REF} is subtracted from V_{EXT}, smaller values of V_{EXT} will end up with larger percentage upsets because V_{REF} is a larger portion of the value.

In addition, a modified TPS7H4104EVM with V_{EXT} and a low-voltage output channel in a similar configuration as described in section 3 and simulated in section 4 was exposed to a heavy ion beam with an LET of 75MeV. No SET events with a magnitude greater than 2.5% were observed on V_{OUT}.

5 Test Results With TPS7H4104EVM

To verify this configuration outside of simulation, a TPS7H4104EVM evaluation module was modified to output 0.5V on CH3. Similarly to the previous simulation, the 1.2V output generated by CH2 was used as V_{EXT} for the CH3 feedback divider. To implement this configuration, four modifications are required to the EVM which are circled in red in Figure 5-1.

- R22 was replaced to set the device switching frequency to approximately 300kHz.
- R17 was depopulated to remove the connection to GND of the feedback divider.
- R33 was populated to be used as R_{B1}
- V_{EXT} was connected to R_{B1}.

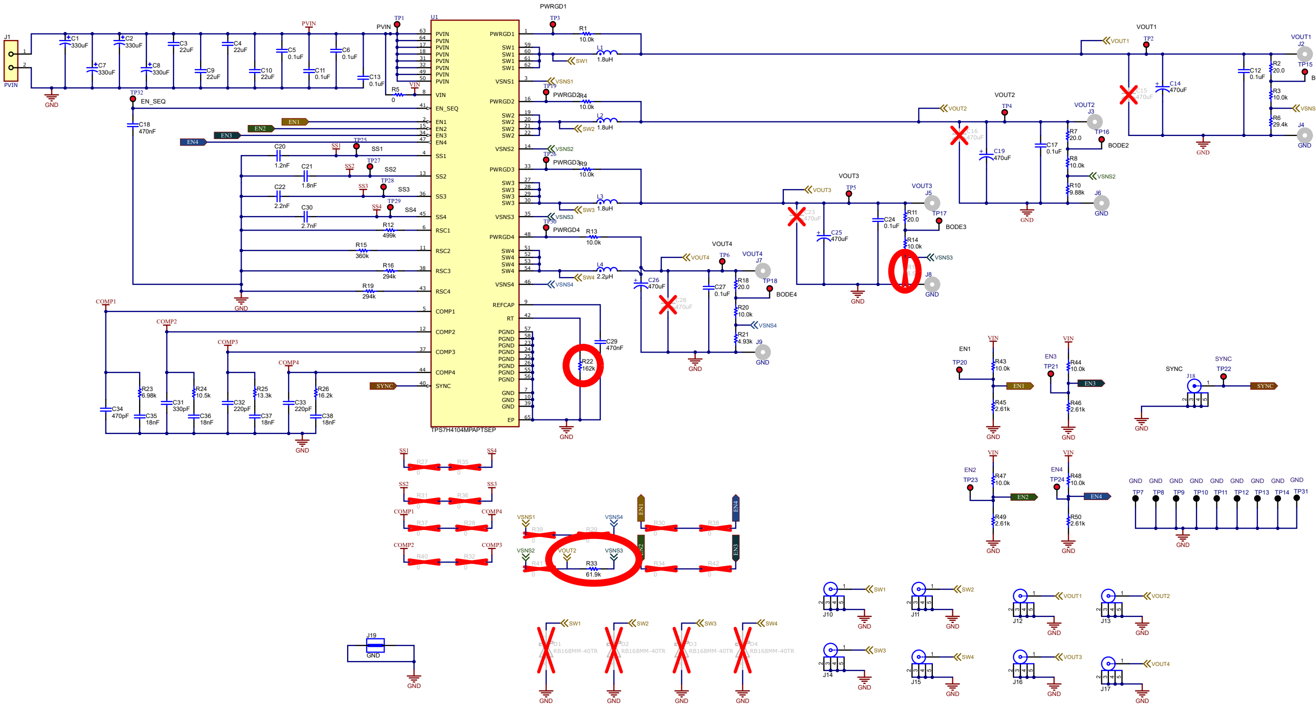

Figure 5-1. Modified EVM Schematic

The location of R17 is shown in Figure 5-2.

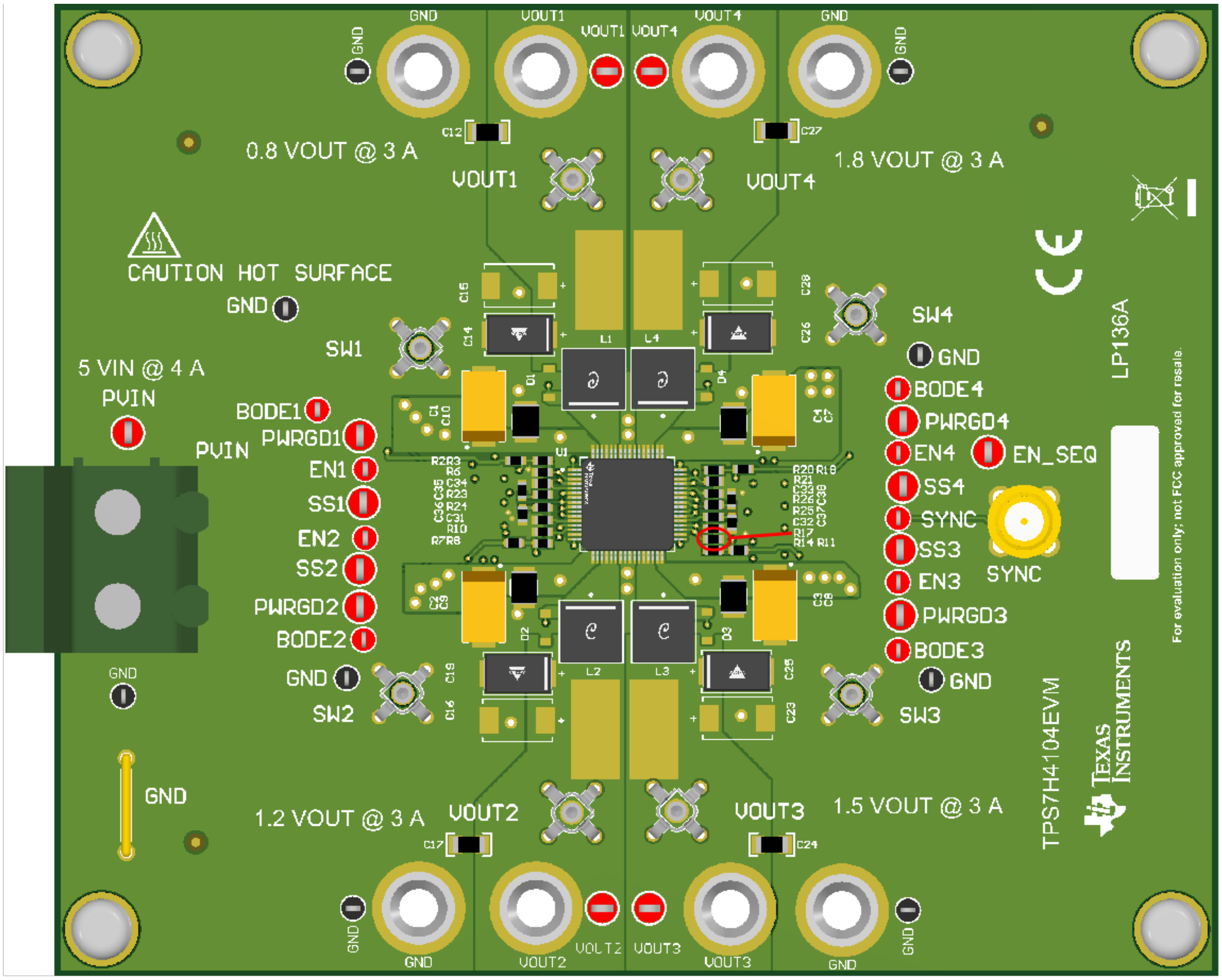

Figure 5-2. Top-side EVM Board Render

Modifications to the bottom of the EVM are shown in Figure 5-3. When R33 (RB1) is populated, one pad is connected through a via to VSNS3, while the other pad is connected to a trace that leads to R41. Since R41 is not populated, the left-side pad of R41 can be connected through an external wire to VOUT2 (V_{EXT}), this was done by connecting to the bottom side of the VOUT2 test point. The trace connecting R33 to R41 now provides V_{EXT} to R_{B1}, completing the modified feedback circuit.

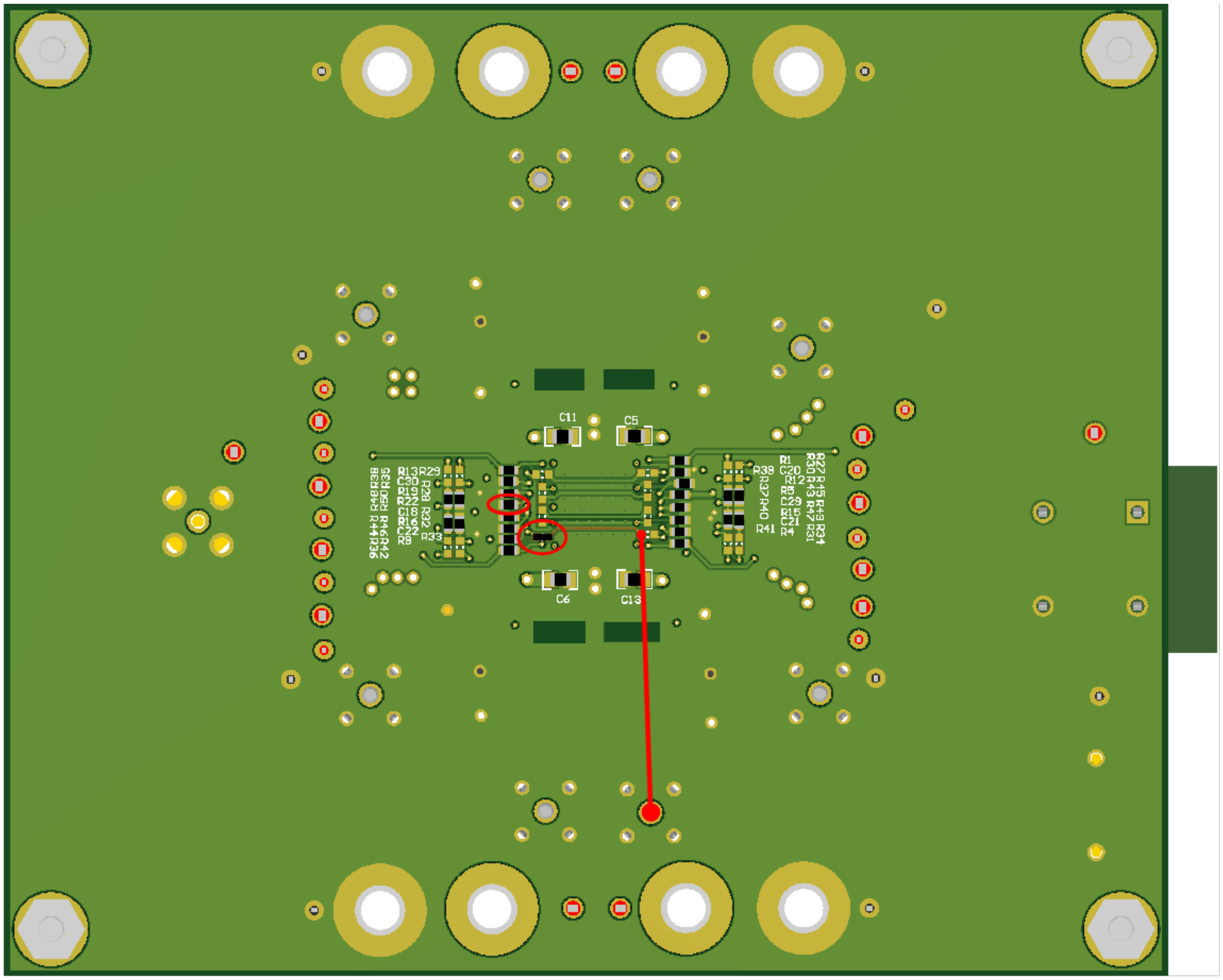

Figure 5-3. Bottom-Side EVM Board Render

The modified EVM was powered on with the internal sequencer enabled, and the startup was recorded with a 3A load on V_{OUT}.

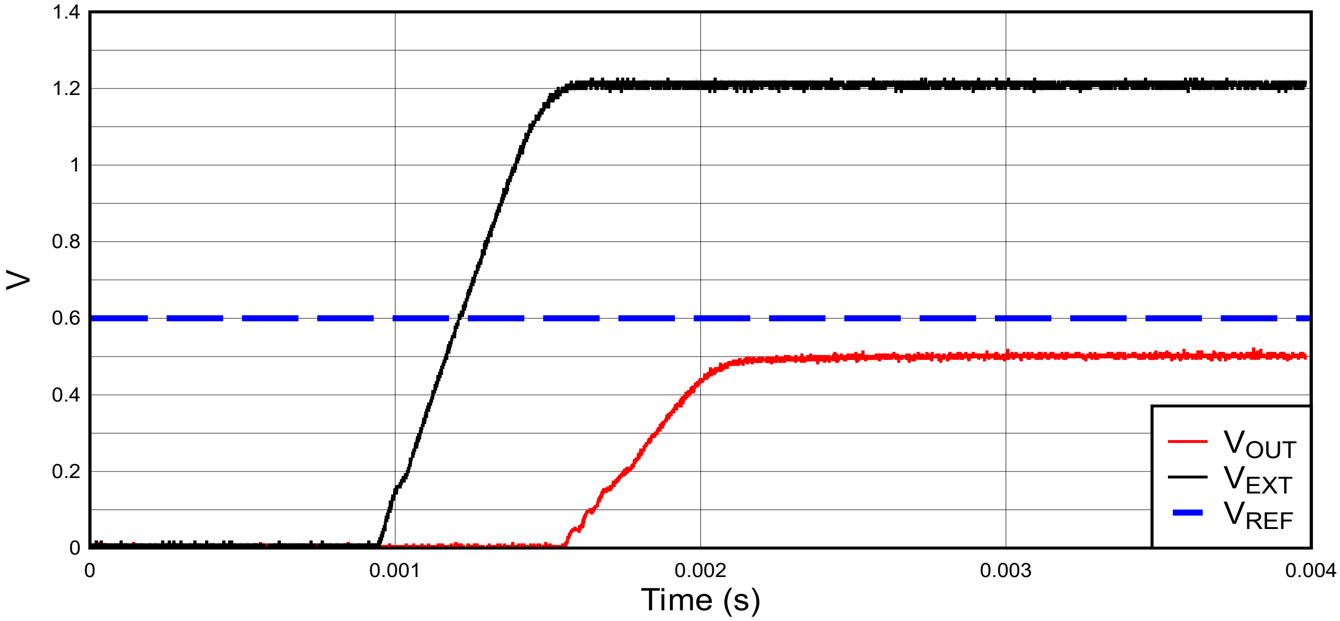

Figure 5-4. EVM Startup Result

As expected, the output from the modified EVM matches closely with the simulation results in Figure 4-2, providing a 0.5V output on CH3 using the 1.2V V_{EXT} generated from CH2.

6 Summary

For applications requiring voltage rails at lower voltages than the reference voltage of a buck converter, the demonstrated circuit can be implemented with an external reference to regulate to lower voltages. When maintaining accuracy is also critical for a below-reference rail, multichannel regulators that use a single internal reference, such as the TPS7H4104, can be configured to use one of their outputs to generate the external reference voltage. In doing so, no extra error is introduced from an external reference, and output accuracy is maintained with minimal additional component count. This application note provides details on the theory of operation of such a system, provides simulation results using the TPS7H4104, and details the modification of a TPS7H4104EVM to produce the described high-accuracy sub-reference output.

7 References

- Texas Instruments, Regulating V_{OUT} Below 1.2 V Using an External Reference, application note.
- Texas Instruments, How to Receive a Lower Output Voltage Than Reference Voltage, application note.

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