*Application Note*

# *Output Voltage Clamping Using TPS23521 to Meet NEBS Compliance*

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**ABSTRACT**

Telecommunication systems operate on -48V rail and under harsh environmental conditions. The need for continuous connectivity puts challenging requirements on these systems to avoid system resets during transient events defined in the ATIS-0600315.2018 telecom standard. In particular, the hot-swap protection circuit at the front end needs to handle the transient events reliably. As the system power level increases, the traditional hot-swap circuit becomes complex and bulkier, increasing the system cost. This application note introduces an output voltage clamping design using the industry's advanced featured negative hot-swap controller TPS23521.

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# 1 Introduction

The input power system of the network equipment is composed of a negative -48V DC bus system for the purpose of the protection against harsh environments such as lighting and moisture, thereby achieving a longer lifespan. The normal operating range is generally between -38V and -58V, but a voltage can exceed the normal operating range during the transient condition or system malfunctions. To address this, over-voltage and under-voltage protection functions are typically applied to the hot-swap controller, which turns off the hot-swap unit if the input power is outside the set range, blocking the power path to the downstream circuitry. A system block diagram of a remote radio unit (RRU) is depicted in Figure 1-1.

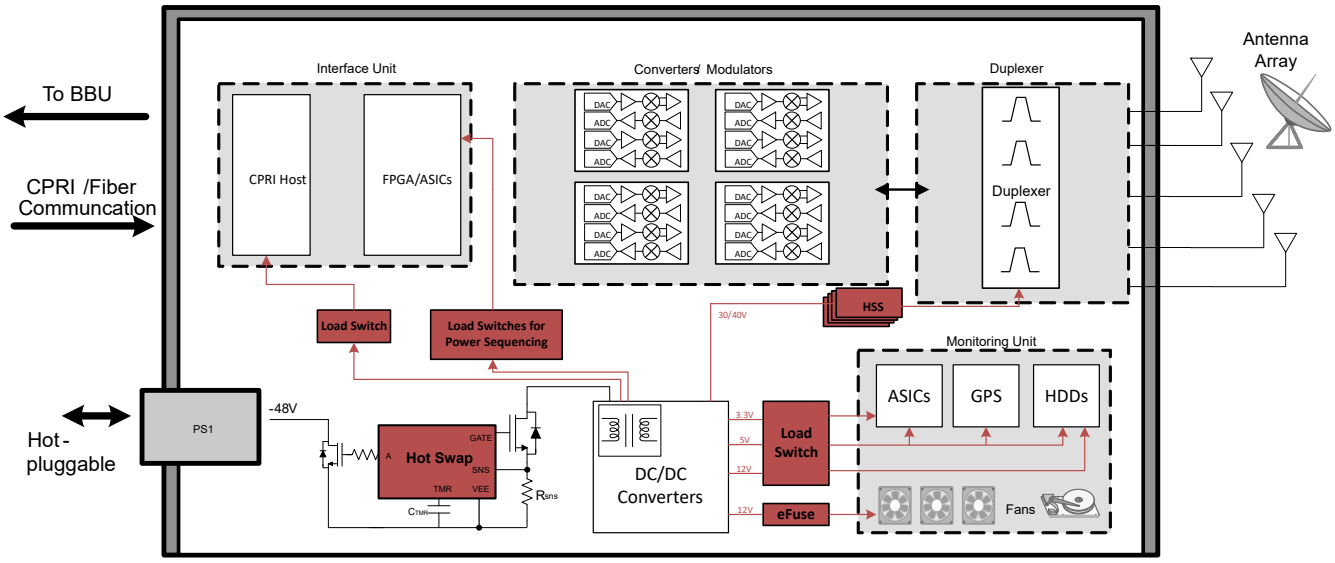


**Figure 1-1. Remote Radio Unit System Block Diagram**

Also, the input voltage range varies depending on the requirements of the operator, and specifically in the case of products aimed at North America, an additional standard for over-voltage transients included in the NEBS (Network Equipment-Building System) specification must be met. The over-voltage standard indicates excessive conditions and noise characteristics outside the normal operating range of the input power device, including an applied input voltage level of 75V (+20%/-0%) for 10ms (+20%/-0%), as shown in the profile in Figure 1-2, in the worst case. Meanwhile, this requires the network equipment to remain in normal operation without a power outage. If the hot-swap is maintained in ON state, the high input voltage of the system determines the voltage rating of the downstream DC-DCs in Figure 1-1, which increases the system cost. Therefore, the recommendation is to limit the output over-voltage resulting in a compact and cost-optimized design with low-voltage downstream components.

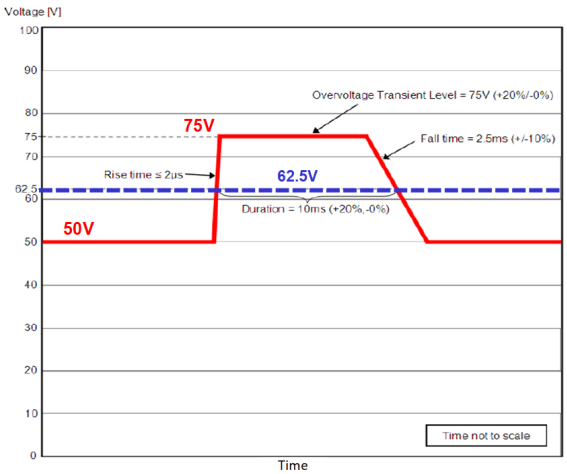


**Figure 1-2. Transient Input Voltage Profile as per NEBS, ATIS-0600315.2018 Standard**

## 2 Existing Design and Challenges

A typical design requirement for a Remote Radio Unit (RRU) is shown in Table 2-1. Traditional hot-swap designs in Figure 2-1 can handle such requirements with the robust protection schemes:

- Inrush current management
- Under-voltage and over-voltage protection
- Reverse current blocking
- Reverse polarity protection
- Fast recovery during line transients
- Over-current and short-circuit protection

However, a challenge comes from a voltage transient event, during which the input voltage rises to 75V (+20%/-0%) for 10ms (+20%/-0%) requiring the system to remain the normal operation without any damage from the over-voltage.

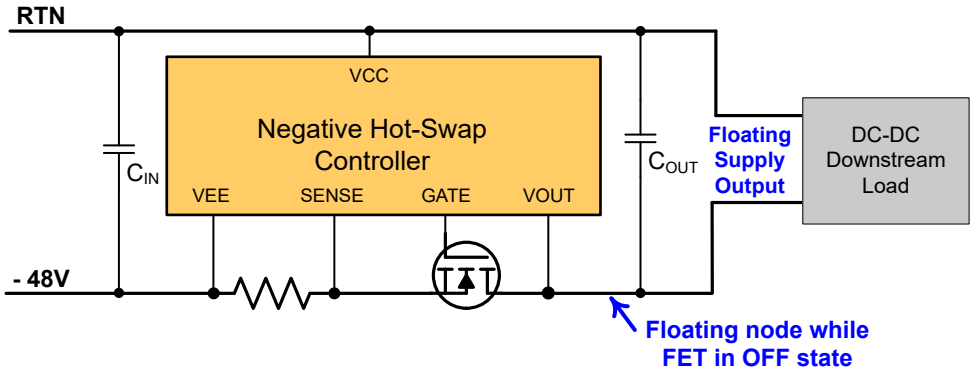


**Figure 2-1. Traditional Negative Hot-Swap Protection Circuit**

**Table 2-1. Typical system specifications**

| DESIGN PARAMETER | VALUE |
|---|---|
| Input Voltage Range | -36V to -60V |
| Nominal Voltage | -50V |
| Maximum Load Power | 700W |
| Maximum Load Current | 700W / 36V = 20A |
| Target Current Limit (12 x maximum load current) | 24A |
| Voltage Transient Event | 75V for 10ms over-voltage as per NEBS/ATIS-0600315.218 |
| Maximum Output Voltage | 62.5V ± 5% |
| Level of IEC61000-4-5 to pass | ± 2kV Line to Line with 2Ω series impedance |
| MOSFET $R_{\Theta JA}$ (Function of layout) | 20°C/W |
| Maximum Ambient Temperature | 85°C |

The existing hot-swap design utilizes the over-voltage protection (OVP) functionality at the input side. Figure 2-2 shows conceptual waveforms during an over-voltage event in the existing hot-swap design where the OVP functionality is utilized at the input side. Once the voltage rises over 62.5V±5%, the voltage turns off the hot-swap FET Q1, and the hold-up capacitor ($C_{OUT}$) powers the load for 10ms. For a 700W load, 4.7mF of the large hold-up capacitor is required to prevent the under-voltage lockout (UVLO) of the downstream system as calculated in Equation 1. In addition, hot-swap FET Q1 can withstand significant power stress during recovery from over-voltage events. The huge voltage gap between the input node and the output node brings a high inrush current hitting the current limit. Due to such limitations, the traditional hot-swap design can be not a viable design for high-power telecom systems, especially Remote Radio Unit (RRU) and Active Antenna System (AAS) which typically requires >500W.

$$C_{out} > \frac{2 \times P_{load} \times T_{hold}}{v\_nom^2 - v\_min^2} = \frac{2 \times (700W) \times (10ms)}{(65V)^2 - (36V)^2} \approx 4.7\ mF \quad (1)$$

Power stress on the FET Q1 during recovery from the OVP event is defined in Equation 2.

$$P_{FET}(W) = \frac{1}{2}\left(V_{final} - V_{initial}\right)I_{LIMT} = 0.5 \times (62.5 - 36) \times 24 = 350 \quad (2)$$

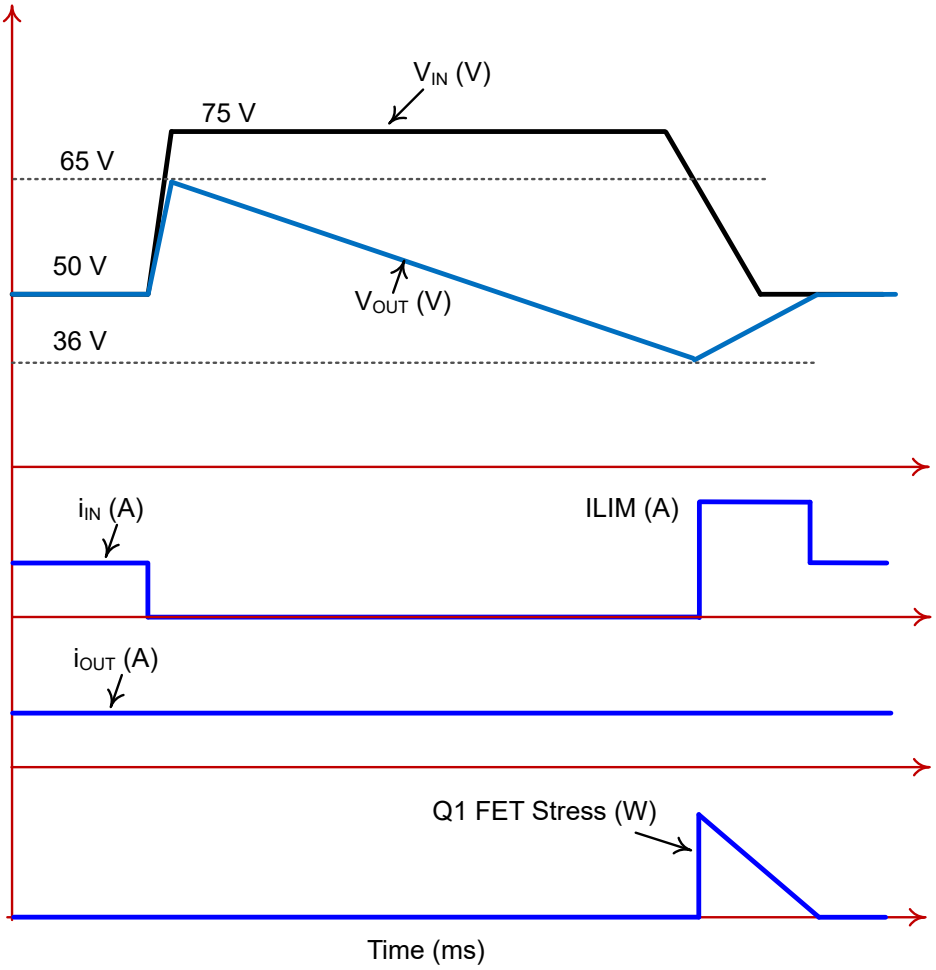


**Figure 2-2. Conceptual Waveforms During 75V/10ms Over-Voltage Event**

# 3 Negative Hot-Swap Controller – TPS2352x

The TPS2352x is an advanced featured integrated hot-swap and OR-ing controller to deal with negative input voltage systems with stringent transient requirements. The TPS2352x provides intelligent control of the power supply connections during the insertion and removal of the systems from a live back-plane. TPS2352x provides in-rush current control to limit system voltage droop and transients, a programmable current limit, input insertion, and fault detection timer, and input over-voltage and under-voltage lockout levels and hysteresis. Additional features described in the following are implemented in the TPS2352x series to tackle common hot-swap design challenges.

- **Dual Current Limit:**
  The device has two current limit levels depending on the drain-to-source voltage (VDS) of the series pass FET. The current limit levels are programmable with the selection of a sense resistor and the VDS threshold for the current-limit switch-over is also programmable with an external resistor.

  Inevitably, the hot-swap design runs into a challenge with FET selection as the pass FET can exceed the safe operating area (SOA) region during startup when the VDS is high. The design requires a larger FET than the need of the normal operating condition. Two different current limit levels can address this conundrum by utilizing the SOA region of pass FET in the high VDS range. With a high VDS sensed from the pins during the startup, TPS2352x applies the lower current limit level, thereby effectively limiting the power across the pass FET. Once the output voltage level is stabilized and VDS becomes low, TPS2352x sets the higher current limit level to provide the power needed during normal operation but still protect the pass FET within the SOA region.
- **Soft Start Disconnect:**
  The device has a disconnection switch implemented between the soft-start capacitor and FET gate pin to make sure an agile operation if transients or short circuits are encountered.

  The use of a soft-start capacitor in hot-swap is to limit the inrush current into the output capacitor. The capacitor is tied to the gate of pass FET to limit the slew rate of gate voltage. However, the capacitor can interfere with the normal operation during transients, deteriorating the fast charge and discharge of gate voltage.
- **Secondary Gate Drive:**
  The device features a second hot-swap gate drive, which can save the boll of material (BOM) cost and size when multiple pass FETs are designed. The device drives the FET only during normal operating conditions where the main FET is enhanced, reducing the SOA requirement of the secondary FET.
- **OR-ing:**
  The device features integrated OR-ing that controls the external MOSFET in a way to emulates an ideal diode. TPS2352x regulates the forward drop across the OR-ing FET to 25mV by controlling the gate-to-source (VGS) voltage of the FET. The device blocks the reverse current if any system disorder happens and provides advantages in BOM cost and size as the design can save external OR-ing control devices.

For more detail and specific design examples, please refer *Protecting Radio, Baseband and Active Antenna Systems with TPS2352x Hot Swaps.*

# 4 Output Voltage Clamping with TPS2352x

Traditional hot-swap design has a limitation of excessive SOA stress on the hot-swap FET in case output needs to be powered under over-voltage conditions.

The proposed design uses TPS2352x to address the SOA problems. As shown in Figure 4-1, the voltage clamp design adds one feedback loop using an op-amp to the traditional hot-swap design and uses the over-voltage lockout (OVLO). OVLO is typically set by the input voltage node, however, in the proposed design the OVLO signal is fed back from the floating supply output node. Once the OVLO signal trips, the hot-swap controller can turn off the pass-FET immediately and limit the output voltage at the target to 62.5V. With the floating supply output powering the downstream system, $C_{OUT}$ is discharged and the OVLO signal also goes below the threshold turning back the pass-FET ON again. This repetitive process clamps the output voltage as shown in Figure 4-2. This brings system benefits by lowering $C_{OUT}$ by 80% and reducing SOA stress by 55% compared to the traditional hot-swap design.

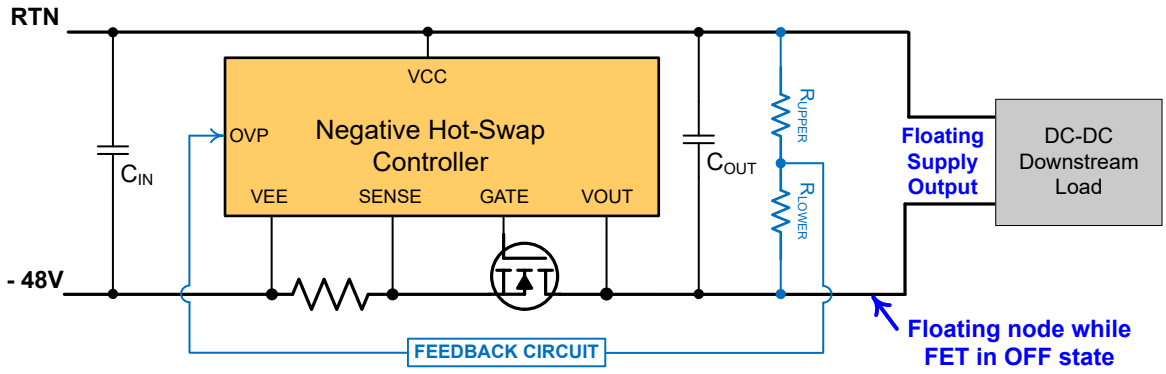


**Figure 4-1. Hot-Swap Circuit with Clamping Scheme on Floating Supply Output**

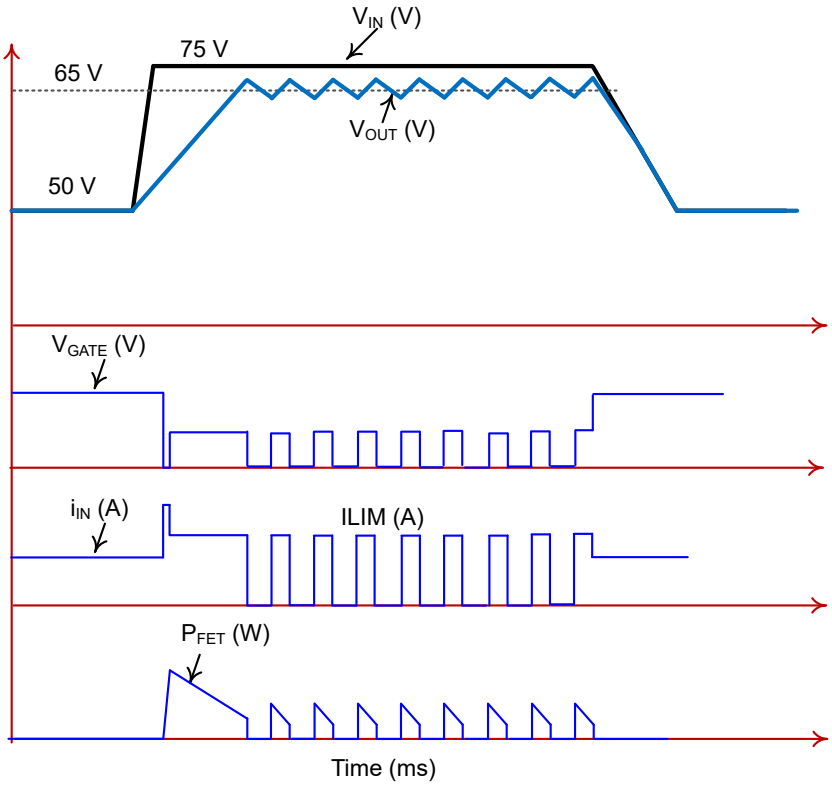


**Figure 4-2. Conceptual Waveforms During 75V/10ms Over-Voltage Event in the Proposed Design**

# 5 Design Procedure and Implementation

The proposed output voltage clamping technique uses negative hot-swap controller TPS2352x and op-amp for output voltage feedback control. Proper selection of TPS2352x configuration and associated components is critical to achieve desired results.

## 5.1 Configuring the Current Limit Switch-Over Threshold for TPS2352x

TPS2352x has two current limit thresholds as shown in Figure 5-1. This dual-level protection scheme makes sure that the part has a higher chance of riding out voltage steps and other transients due to the higher current limit at low VDS, while protecting the MOSFET during the start into short and hot-short events, by setting a lower current limit threshold for conditions with high VDS. The transition threshold is programmed with a resistor $R_D$ that is connected from the drain of the hot-swap FET to the D pin of the TPS23521.

Based on the region of operation, the GATE source capability of TPS23521 varies. In high current limit mode for example, where VDS < VDS,SW, the GATE sourcing current is 400µA vs 20µA at high VDS region. This high GATE current helps to quickly switch ON/OF the external FET to reliably operate in hysteric mode during over-voltage conditions. Considering a peak of 75V input transient from the NEBS standard (Figure 1-2) and the requirement that the voltage to the downstream load does not exceed 62.5V, we have set the VDS,SW to be greater than 12.5V for example, 75V – 62.5V). Accordingly, resistor $R_D$ can be selected using Equation 3.

$$V_{DS,SW} = \frac{1.5V \times (30k\Omega + R_D)}{30k\Omega} \quad (3)$$

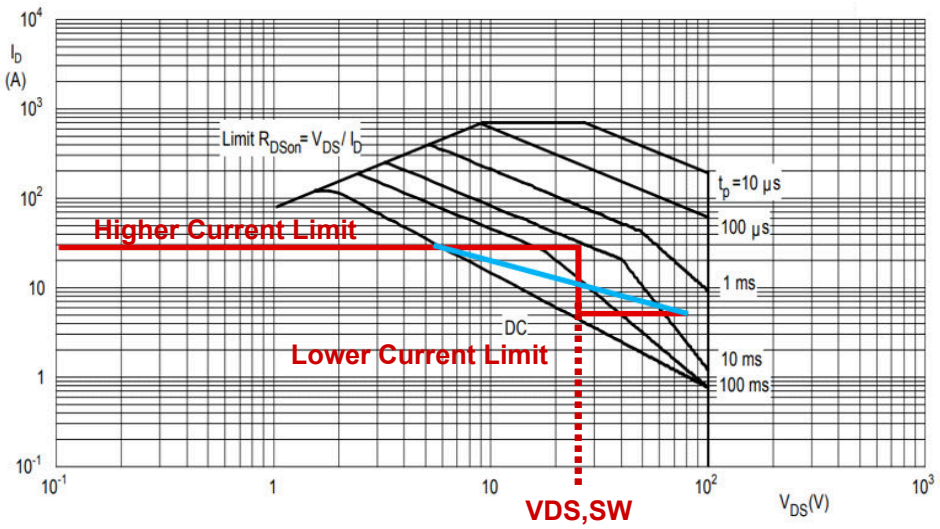


**Figure 5-1. Dual Current Limit in TPS2352x**

## 5.2 Feedback and Control Loop Response

The feedback loop of the system decides when to cut off the circuit when a transient event occurs and when to turn the system on once the event has been surpassed. To perform this task effectively, the feedback loop needs to have a fast response to the transient events. If the response is delayed, the system can become unstable and lead to turning off the output voltage.

In this system, the loop response depends on op-amp response time, OVP response of hot-swap, and FET ON/OFF response time.

The FET ON/OFF response time depends on the gate drive of TPS23521 which has a strong source current of 400µA and a strong sink current of 1A, resulting in a fast ON/OFF response. The OV response time of TPS23521 is 4µs which is also very small. So, the op-amp response is very critical. An op-amp needs to be chosen which can respond within sub µs. OPA863 is chosen in this application which has a slew rate of 105V/µs.

## 5.3 Powering the Feedback Amplifier

When the MOSFET is OFF, the negative input to the op-amp is floating which causes the op-amp to saturate due to common mode voltage as shown in Figure 5-2. Independent high-voltage linear regulators such as TPS7A4001 can be a good option to power op-amp at 12V.

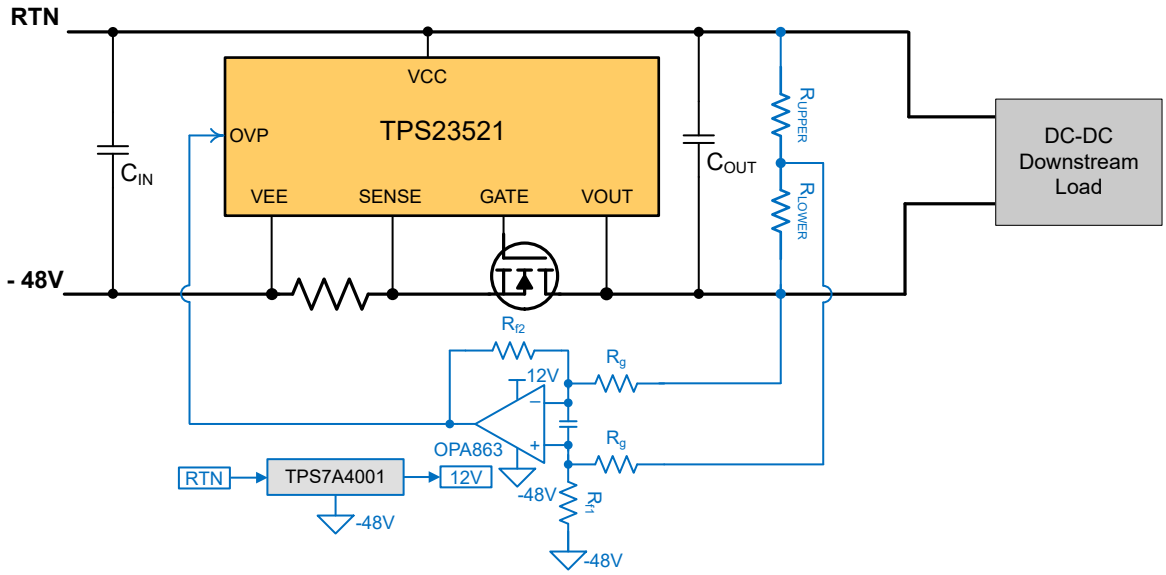


**Figure 5-2. Implementation Using OPA863 Op-amp and TPS7A4001 Regulator**

## 5.4 Noise Immunity

Owing to the harsh and noisy environment of the telecom system, the recommendation is to add a small filter capacitor (approximately 1nF) between the input pins of the op-amp OPA863.

# 6 Test Results

Considering the previous design guidelines, the test setup was made using TPS23521, OPA863, and TPS7A4001 EVMs and configured the circuit in Figure 5-2 with the following component values.

$R_1$ = 54kΩ, $R_2$= 2kΩ, $R_f$= 100kΩ, $R_g$= 237kΩ, and $C_{OUT}$ = 500µF.

## 6.1 Startup

Figure 6-1 shows a successful startup of the system at NO LOAD condition. A voltage of 48V is applied across the system input. The voltage at the GATE of the FET starts to rise after an insertion delay of 32ms. The $V_{gs-th}$ of the selected FET is 2.6V post which we can see that the $V_{ds}$ starts to come down and the $V_{out}$ starts to rise and follows the input.

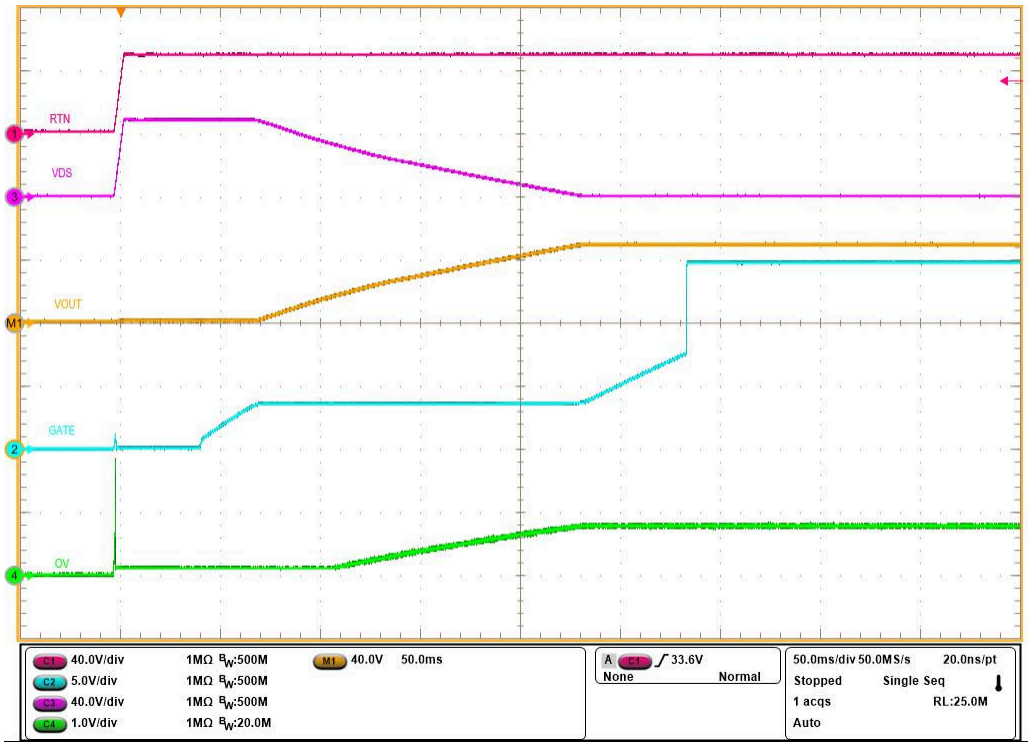


**Figure 6-1. Startup Waveform in the Proposed Design**

## 6.2 NEBS Transient Response

The NEBS standard requires passing 75V transient for 10ms to the system as illustrated in Figure 1-2 during which the output voltage needs to be clamped to 62.5V. In Figure 6-2, the RTN voltage is at 48V and then a transient of 75V is applied at the input for 10ms with a load of 10A.

As soon as the transient is applied, the device enters into over-current protection turns off the FET, and then immediately turns back ON in current limiting mode. During this time, the output voltage ($V_{OUT}$) slowly ramps up to RTN. Once $V_{OUT}$ reaches 62.5V, the output of the op-amp feedback circuit reaches over-voltage protection threshold of 1V, the TPS23521 turns the FET off. Then, the $C_{OUT}$ discharges, and as soon as the $V_{OUT}$ goes below 62.5V, the TPS23521 comes out of OVP mode and switches ON the FET again. This cycle continues, operating the FET in hysteretic mode to clamp the output voltage around 62.5V. Figure 6-2 and Figure 6-3 show the over-voltage response of the proposed design. Due to the fast response of the TPS23521 device and the feedback circuit, the ripple on the output voltage is less than 10%.

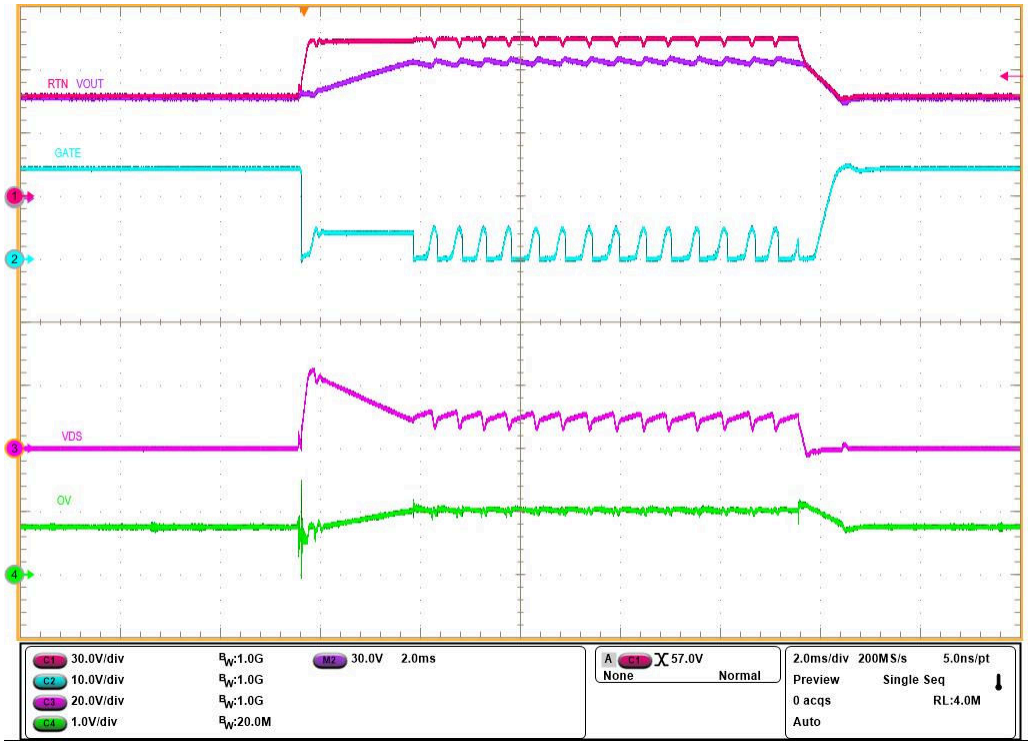


**Figure 6-2. Test Waveforms During 75V/10ms Over-voltage Event**

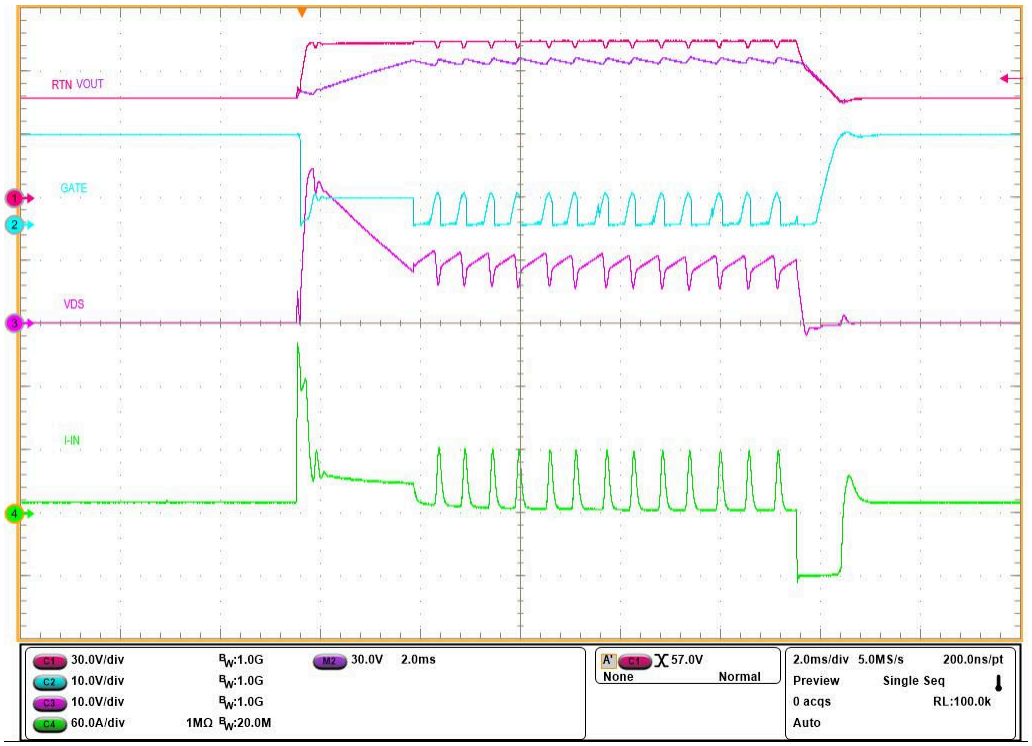


**Figure 6-3. Test Waveforms of Input Current During 75V/10ms Over-voltage Event**

## 7 Summary

The proposed output voltage clamping scheme helps to reduce system hold-up capacitor and FET SOA stress resulting in a robust, cost-effective, and smaller design. The design is highly scalable and can reliably address system transients in high power base band unit (BBU) and Active antenna end-equipment.

## 8 References


- Texas Instruments, *TPS23521: –48-V High Performance Hot Swap Controller,* data sheet.
- Texas Instruments, *TPS7A4001 100-V Input Voltage, 50-mA, Very High Voltage Linear Regulator,* data sheet.
- Texas Instruments, *OPAx863A High-Precision, 105MHz, Rail-to-Rail Input/Output Amplifiers,* data sheet.
- Texas Instruments, Protecting Radio, Baseband and Active Antenna Systems with TPS2352x Hot Swaps, application note.
- Telecom industry-standard, ATIS-0600315.2018

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