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ABSTRACT

The efficient design of a power delivery network PDN is a challenging task because all the segments of PDN are linked with each other. Changes in one component can have a significant influence on all the other components. This application note focuses on designing of filters and also discusses the stability problems caused by adding the input filter or the second stage of output LC filter if they are not designed properly by keeping a look on certain important parameters. Furthermore, the application note also explains the damping methods for resolving the stability issues caused by the addition of filters with step-down converter.

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1 Overview

The second-order low-pass LC filter is the most commonly used filter type with DC/DC converters. The filter is used to suppress high-frequency noise or minimize the output voltage ripple. After the addition of the filters on the input and the output sides, the overall output impedance of the DC/DC converter shows high resonance peaks if the filters are undamped. When the load draws current, the voltage at the output can vary due to these resonance peaks in the impedance curve. One other concern is that if the resonant frequency of the filter is in the range of the crossover frequency of the control loop, it affects the control loop stability which further affects the transient behavior of the device. DC/DC converter acts as a load for the input filter which provides negative variable resistance. When this negative dynamic resistance is connected to the input filter, it acts as a negative oscillator circuit. It causes system instability in the case of an undamped system.

This application note discusses in detail how one can design the input and second order LC filter for DC/DC converter and which parameters are important to keep in mind while designing them. [TPS6281x-Q1](#) is used as an example in this application note.

2 Detailed Description

The configuration of connecting the input filter and second stage output filter with DC/DC step down converter [TPS6281x-Q1 2.75-V to 6-V Adjustable-Frequency Step-Down Converter](#) data sheet is shown in [Figure 2-1](#).

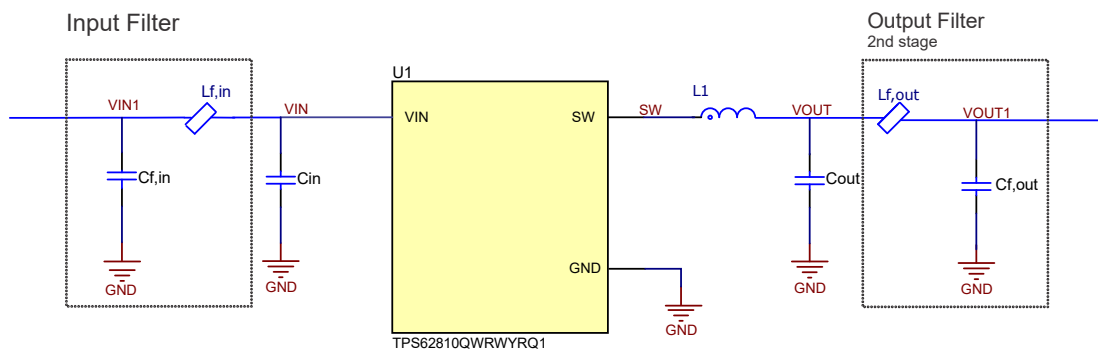


Figure 2-1. Modified Schematic of the TPS62810-Q1 Step-Down Converter with the Input and Second-Stage Output Filters

2.1 Input Filter Design

Gain and Output Impedance are two important parameters that are considered for designing the input filter. The maximum impedance of the whole circuit needs to remain under the target impedance limit of the converter. This target impedance Z_{target} for the DC/DC converter can be calculated [Equation 1](#).

$$Z_{target} = \frac{2 \cdot V_{dd} \cdot \Delta V}{I_{max}} \quad (1)$$

In this equation, V_{dd} is the supply voltage of the power rail, I_{max} is the worst case maximum current from the chip and ΔV is the maximum allowed variation in the voltage level of power rail. In the target impedance calculation, transient current is used because the slope of this current can trigger the high resonant frequencies of PDN impedance, resulting in significant output voltage variations.

The design steps to select the inductor and capacitor values for the input filter are discussed further. Gain value is calculated as the first step in designing the input filter. The maximum input current amplitude I_{in_max} without a filter and the desired amplitude of input current I_{req} are important to calculate the gain of the filter. The maximum input ripple current is calculated with [Equation 2](#). The operating conditions are input voltage V_{in} of 5-V, output voltage V_o of 3.3-V, switching frequency f_{sw} of 2.25 MHz and maximum load current I_o of 1-A.

$$I_{in_max} = I_o \cdot \sqrt{D(1-D) + \frac{1}{12} \cdot \left(\frac{V_o}{L \cdot f_{sw} \cdot I_o}\right)^2 \cdot (1-D)^2 \cdot D} \quad (2)$$

In Equation 2, I_o is the maximum load current, D is the duty cycle, V_o is the output voltage and L is the inductor value. Then gain can be calculated with Equation 3 with desired amplitude of input current I of 1 mA and calculated maximum input ripple current value I_{in_max} .

$$Gain = \sqrt{\frac{I_{req}}{I_{in_max}}} \quad (3)$$

In next step, cut-off frequency $f_{c/o}$ can be determined based on the gain and switching frequency f_{sw} with Equation 4.

$$Gain = \frac{f_{c/o}}{f_{sw}} \quad (4)$$

Further, the third step involves calculating the input impedance of the converter. All of these values are derived from the efficiency vs. output current graphs plotted in the [TPS6281x-Q1 2.75-V to 6-V Adjustable-Frequency Step-Down Converter](#) data sheet for the operating conditions of the device.

$$Z_{in,c} = \frac{V_{in}^2 \cdot \eta}{P_{out}} \quad (5)$$

The output impedance $Z_{out,f}$ of the filter needs to be less than the input impedance $Z_{in,c}$ of the converter for stability of an overall system. One-eighth of input impedance of converter seems reasonable limit for output impedance of filter.

$$Z_{out,f} < \frac{1}{8} \cdot Z_{in,c} \quad (6)$$

After computing all the data in above equations, it gives gain value of 0.030, crossover frequency of 69.5 kHz and output impedance of filter is 1.2 Ω . Keeping these values as base parameters, the values of $L_{f,in}$ and $C_{f,in}$ are chosen. The AC impedance equations can help to give the minimum filter capacitance and maximum filter inductor value to maintain the calculated impedance limit.

$$Z_R = R \quad , \quad Z_L = j\omega L \quad , \quad Z_C = \frac{j}{\omega C} \quad (7)$$

After inserting the maximum impedance value and cut-off frequency of the filter in Equation 7, it gives maximum filter inductance of 2.7 μ H and minimum filter capacitance of 1.9 μ F. The filter components used for further analysis from the available range are inductor $L_{f,in}$ value of 530 nH and a capacitor $C_{f,in}$ value of 10 μ F to check its impact on the stability of the overall step-down converter.

2.2 Output Filter Design (Second Stage)

Second stage of the output filter is used in general to improve the ripple performance of the device for applications which are more sensitive to variations in an output voltage. The maximum impedance limit $Z_{out,max}$ of the second stage of filter can be determined with Equation 8.

$$Z_{out,max} = \frac{\Delta V_{out}}{\Delta I} \quad (8)$$

In Equation 8, ΔV_{out} is the maximum allowed variation in output voltage which is taken five percent of the output voltage for this design and ΔI is the maximum change in output current which is 1-A. The cut-off frequency chosen for the second stage of an output filter is 79 kHz and calculated maximum impedance limit is 0.17 Ω . After inserting these values in Equation 7, it gives the minimum capacitance limit of 12 μ F and maximum inductance of 340 nH. These values are selected for the second stage of the output filter as $L_{f,out}$ and $C_{f,out}$.

3 Measurement and Analysis

The designed filters on the input side and the output side of the DC-DC step down converter [TPS6281x-Q1 2.75-V to 6-V Adjustable-Frequency Step-Down Converter](#) data sheet are connected in the configuration shown

in [Figure 3-1](#). After adding the designed filters on the input side and output side of the converter, the measured output impedance, load transient response and bode plot response are shown next.

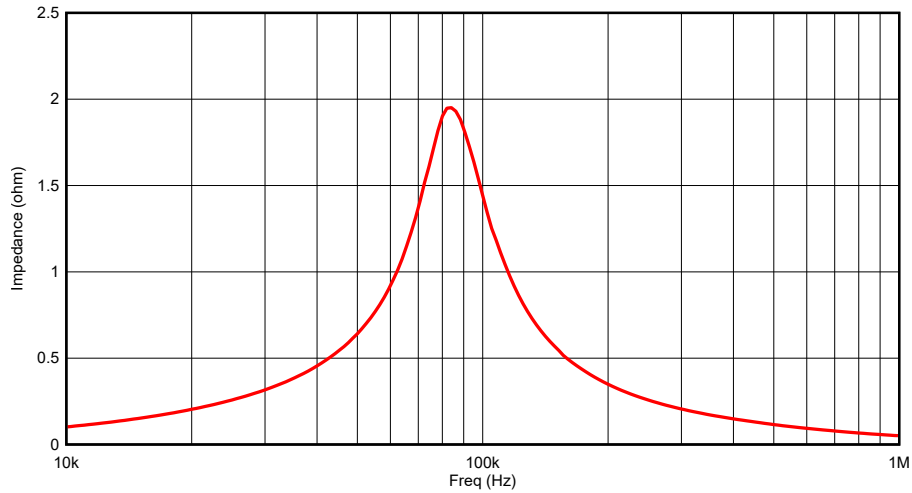


Figure 3-1. Output Impedance of the Step-Down Converter with Undamped Filters

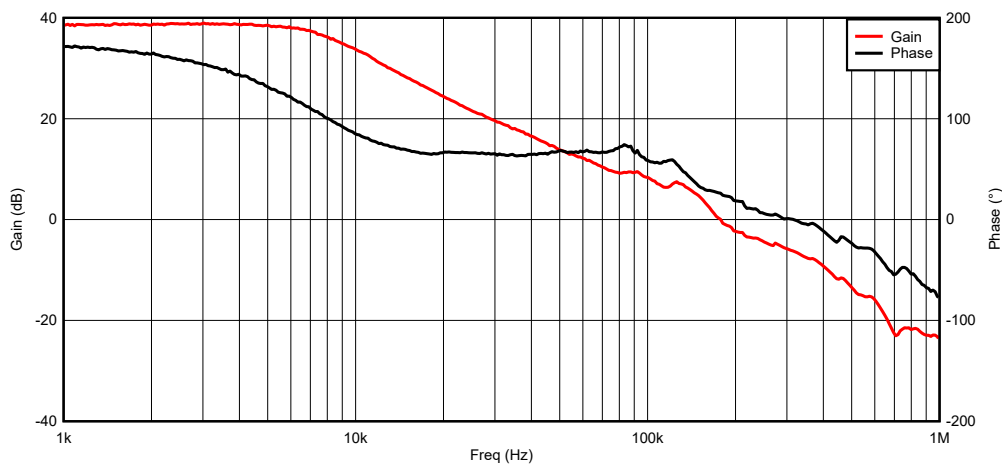


Figure 3-2. Gain Magnitude and Phase Plot of the Step-Down Converter with Undamped Filters

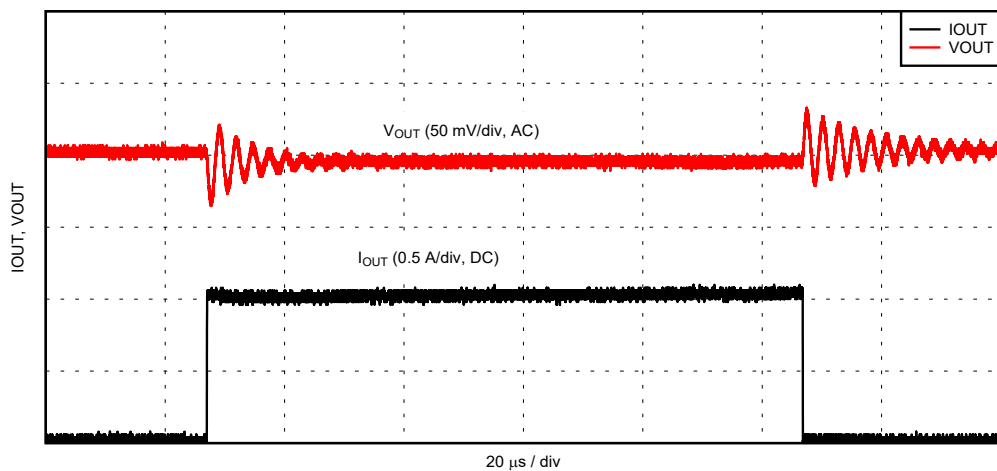


Figure 3-3. Time-Domain Response of an Output Voltage of the Step-Down Converter Model with Undamped Filters

The output impedance can be measured by the [How to Measure Impedance of a Power Distribution Network of a DC-DC Converter](#) application note. In the output impedance plot in [Figure 3-1](#), the first resonance peak can

be seen at the frequency of 83.4 kHz, near to resonant frequency of the connected second stage of the output filter that is 79 kHz. At the same time, the gain and phase response of control loop is also measured, as shown in Figure 3-2, which gives us the phase margin of around 26°. This low phase margin can cause unwanted oscillations in the output voltage, which can badly affect the operation of voltage-sensitive applications. The transient output voltage response becomes oscillatory as the phase margin decreases which is also noticeable in the transient output voltage response in Figure 3-3.

This gives an idea about the relationship between output impedance of the converter and stability of a control loop. A high-quality factor of the resonance peak in the output impedance curve can cause the lower phase margin when the resonance peak is triggered by load current, which in result turns into poor transient response of a system. Next section discusses the damping methods for the filters that can help in solving the device stability issue by damping the resonance peaks, which are caused by addition of the filters.

4 Damping of the Filters

There are two different ways of damping the filter which can help in reducing the quality factor of filter resonance. Figure 4-1(a) is the filter model without damping. Figure 4-1(b) is the damping technique with series damping resistor R_d and Figure 4-1(c) is the damping method with parallel R_d - C_d branch with filter.

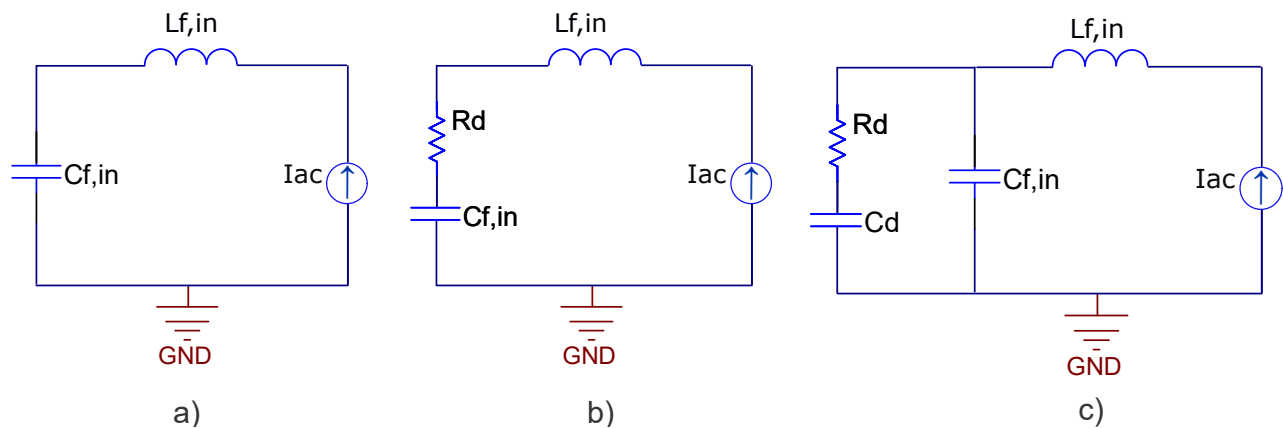


Figure 4-1. Models of an Input Filter Without Damping, as Well as With Two Different Damping Techniques

Quality factor Q is the parameter which determines the damping of any resonance. High quality factor gives sharper resonance peak. Equation 9 helps to determine the quality factor of series RLC circuit.

$$Q = \frac{1}{R_d} \sqrt{\frac{L}{C}} \tag{9}$$

R_d is the damping resistor which can be calculated for particular value of Q which is chosen according to the damping required in the system. Q is taken as 1 for critically damped system. After inserting the Q value in Equation 9, it transforms the equation to Equation 10.

$$R_d = \sqrt{\frac{L}{C}} \tag{10}$$

Here the input filter is taken as an example. With the help of $L_{f,in}$ and $C_{f,in}$, R_d is determined with Equation 11 which is 0.23 Ω . In the second method, parallel R_d - C_d is used with the filter to dampen the resonance of the filter. Damping resistor R_d value is already calculated. To avoid affecting the filter cut-off frequency, the damping capacitor C_d needs to be larger than the filter capacitor. At least five times of filter capacitor seems a reasonable value.

$$C_d = 5C_{in} = 75 \mu F \tag{11}$$

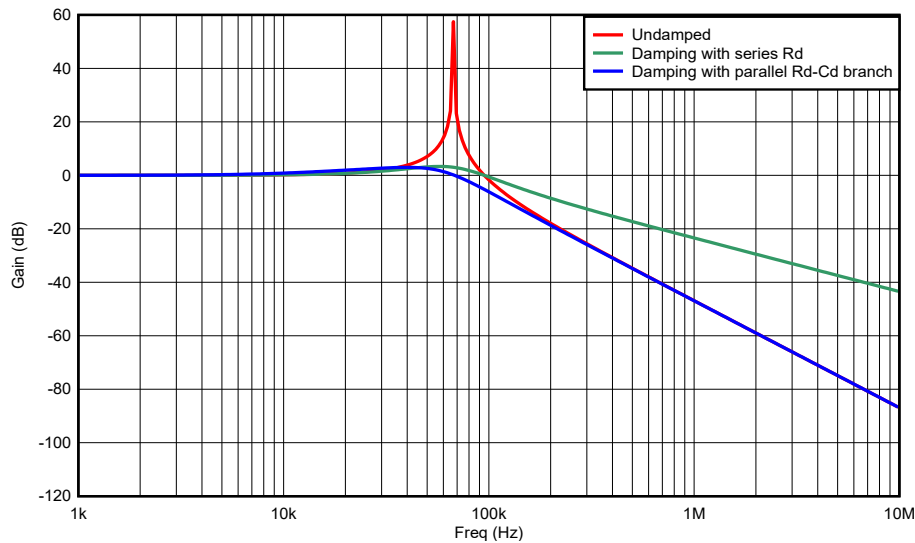


Figure 4-2. Frequency Plots of Filter Model with Different Damping Techniques

It can be observed in the gain-frequency plot in [Figure 4-2](#) that extra series damping capacitor and resistor in parallel to the filter capacitor helps to damp the resonance peak without impacting the attenuation level of the designed filter while technique (b) in [Figure 4-1](#) dampens the resonance peak but it also affects the attenuation level after the cutoff frequency of the filter. After adding the damping branch with the input and output filter, all measurement results are observed again in next section.

5 Further Analysis with Damped Filters

The output impedance, bode plot and load transient response of the converter are again measured after adding the parallel damping branch (R_d-C_d) with the filters.

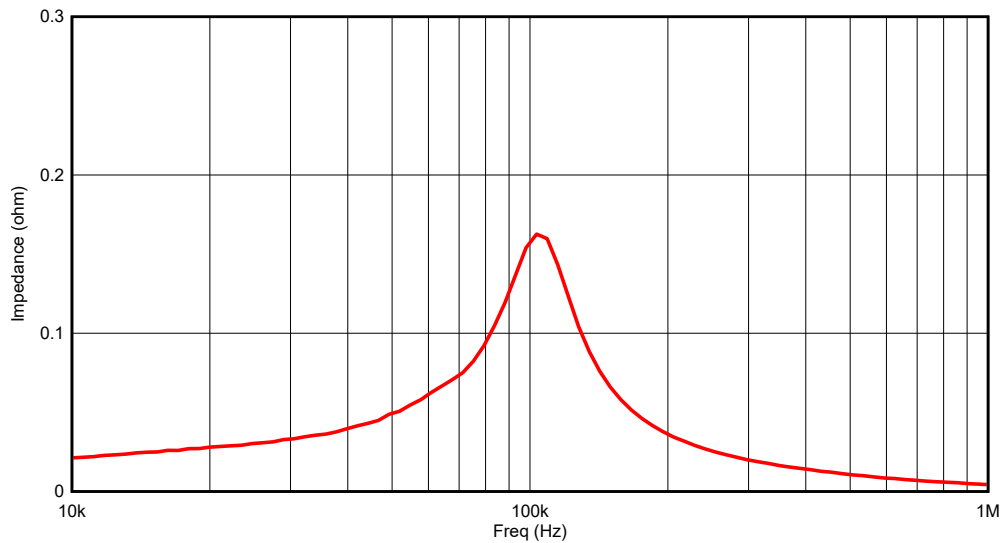


Figure 5-1. Output Impedance Curve of the Step-Down Converter with Damped Filters

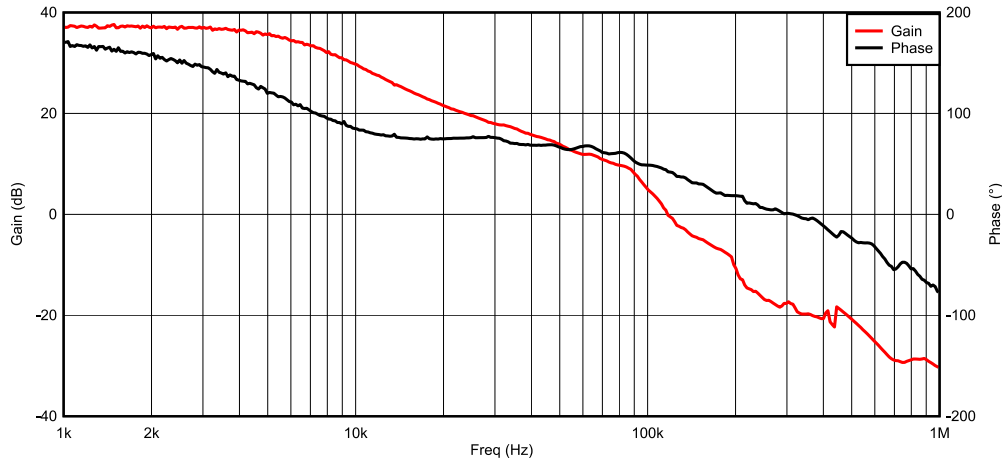


Figure 5-2. Gain Magnitude and Phase Plot of the Step-Down Converter with Damped Filters

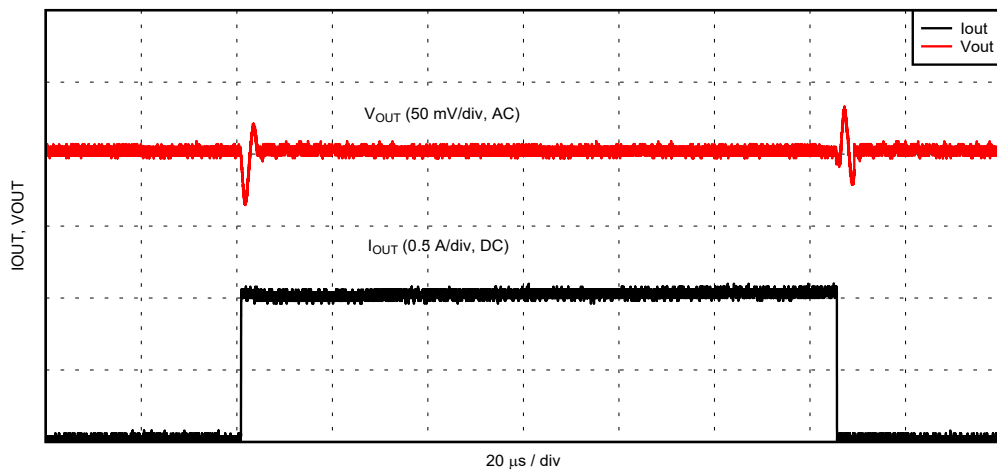


Figure 5-3. Time-Domain Response of an Output Voltage of the Step-Down Converter Model with Damped Filters

In [Figure 5-1](#), it can be seen that addition of the damping with the filters has helped to reduce the peak in the output impedance curve and reduces the maximum impedance value to 0.15Ω . This damping method helps to reduce the excessive power loss also as compared to series R_d with filter as shown in [Figure 4-1\(b\)](#). In [Figure 5-2](#), phase margin is also improved to 45.9° from 26° by damping the filters. [Figure 5-3](#) shows the transient response of the device in which oscillations are properly damped. Therefore, it can be observed that the addition of the damping branch to the filters helps to dampen the filter resonance, which improves the phase margin. Furthermore, the load transient response also appears to be reasonable as compared to the transient response of the system with undamped filters.

6 Conclusion

This analysis concludes that integrating input and output filters into the step-down converter circuit reduces input and output voltage ripple while filtering out high-frequency noise. The difficulty comes when the output impedance of the filters influences the closed-loop transfer function of the converter. However, it can be carefully designed so that resonances caused by these elements are appropriately damped and have a low-quality factor. If the load is excited at any resonance frequency of the impedance curve, it should not stimulate voltage noise in the power delivery network in the worst case.

7 Reference

1. Texas Instruments, [TPS6281x-Q1 2.75-V to 6-V Adjustable-Frequency Step-Down Converter](#), data sheet.
2. Texas Instruments, [How to Measure Impedance of a Power Distribution Network of a DC-DC Converter](#), application note.

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