APPLICATION NOTE

Negative input resistance of switching regulators

ANP008c by Ranjith Bramanpalli

Developers of switching regulators and switch mode power supplies attach great importance to the efficiency of their circuits. However, at the end of their development phase, they encounter unpleasant effects such as unwanted oscillations at the input of the switching regulator and these although the switching regulator produces a constant output voltage under all conditions. However, why does the input of the switching regulator tend to oscillation under certain circumstances?

A switching regulator can achieve efficiency of more than 90%; however, the efficiency for conventional switching regulators is usually a lot lower. For high efficiency, we can assume almost loss-free power conversion so that the following approximately applies:

$$P_{In} \approx P_{Out}$$

However, let us assume that a switching regulator does not produce any power loss and the input power equals the output power, the following applies for the performance ratio:

$$P_{In} = P_{Out}$$

Any switching regulator design requires that the output voltage is constant in every operating mode and, even in the event of abrupt load change, quickly regains its setpoint without being set in oscillation. Thus, only any change of the voltage on the input side is permitted. However, a constant power ratio between input and output results in the input current of the switching regulator dropping in the event of any rise of the input voltage; ergo, the input current rises when the input voltage drops. This effect is based on the so-called **"Negative input resistance"**. Figure 1 illustrates this effect.

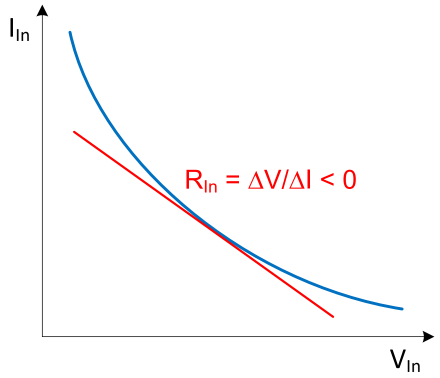

Figure 1: Voltage / current curve at the input of the switching regulator

This effect is not initially apparent. It is also not expected because the current usually rises proportionally with the voltage.

$$I \sim V \qquad \text{(if R is constant)}$$

In any case, Ohm's Law describes the behaviour of a linear resistance. If a simple voltage divider made of ideal resistors is considered, its output voltage rises when its input voltage is increased. This is illustrated in Figure 2.

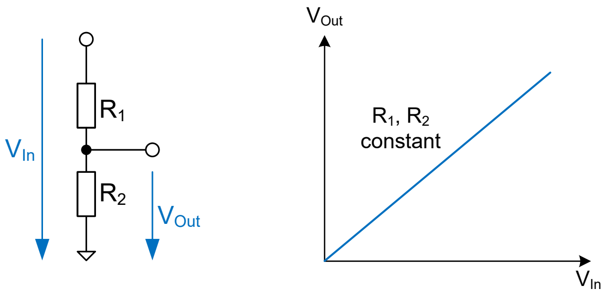

Figure 2: Voltage divider with ideal resistors

However, in our case, the input resistance of a switching regulator is not linear but very **non-linear** and also negative. Figure 1 makes this clear. For further illustration, we would like to consider a voltage divider which is not constructed from two ideal resistors but from one voltage source with defined internal resistance and a switching regulator with negative resistance. Figure 3 shows such a voltage divider. A basic design of the switching regulator and its components is not further required here for the closer consideration.

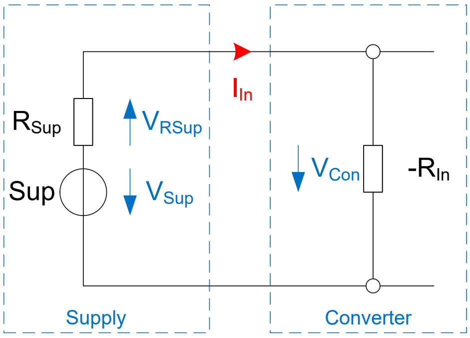

Figure 3: Voltage divider consisting of voltage source and negative resistance.

If the voltage "V_{Sup}" of the source increases, the current "I_{In}" drops and consequently the voltage drop "V_{RSup}" at the internal resistance of the voltage source. However, the voltage at the switching regulator input increases. The input voltage of the switching regulator is reduced by the voltage drop at the internal resistance of the voltage source. The following approximately applies:

$$V_{Con} = V_{Sup} - V_{RSup}$$

Electronic components such as electrical resistors do not occur in real life with negative values. The real input resistance of a switching regulator is also not negative, but **its behaviour during change of the input voltage**. Accordingly, this behaviour shows a negative resistance which is based on a mathematical origin.

If a tangent is applied to the voltage-current curve in Figure 1, its increase of the negative resistance can be determined at any operating point. This is "generally" defined by:

$$R_{IN} = \frac{\Delta V_{IN}}{\Delta I_{IN}}$$

As the slope of the tangent is **negative in this case**, the input resistance of the switching regulator is negative!

$$R_{IN} = \frac{\Delta V_{IN}}{\Delta I_{IN}} < 0$$

There is dynamic behaviour with negative slope whose differential quotient can theoretically be used as base to determine the negative resistance as numeric value. The following example shows a calculation example for this.

$$R_{IN} = \frac{\Delta V_{IN}}{\Delta I_{IN}} = \frac{10\ \text{V} - 8\ \text{V}}{0.5\ \text{A} - 0.625\ \text{A}} = -16\ \Omega$$

However, in practice and diverse literature, the differential quotient is not determined but the stationary input resistance is considered. Dynamic behaviour is present and thus a different resistance value at each operating point. From a pure mathematical consideration, the stationary resistance is not negative. **It is now based on the fact that its dynamic behaviour is negative and it is calculated using a negative sign**. Using large signal analysis, the stationary resistance can be approximated with the following assumption and calculated as shown in Example 2.

$$P_{IN} = V_{IN} \cdot I_{IN}$$

$$5\ \text{W} = 8\ \text{V} \cdot 0.625\ \text{A}$$

$$R_{IN} = \frac{-V_{IN}}{I_{IN}} = \frac{-8\ \text{V}}{0.625\ \text{A}} = -12.8\ \Omega$$

If the input voltage is further increased, the negative resistance rises. This should be illustrated by the following example.

$$P_{IN} = V_{IN} \cdot I_{IN}$$

$$5\ \text{W} = 10\ \text{V} \cdot 0.5\ \text{A}$$

$$R_{IN} = \frac{-V_{IN}}{I_{IN}} = \frac{-10\ \text{V}}{0.5\ \text{A}} = -20\ \Omega$$

However, the negative resistance is not a persistent state, but only occurs during a short-term change – a transient – at the input of the switching regulator. Once the original operating state is reached again, the negative resistance is no longer representative. However, a transient, in combination with the negative input resistance, is sufficient to put the input of a switching regulator in oscillation.

A pulsed current flows in the input circuit of the switching regulator; this current should be suppressed to prevent conducted emission interference. Therefore, an additional input filter is placed before the switching regulator input in practice. Figure 4 shows such an arrangement.

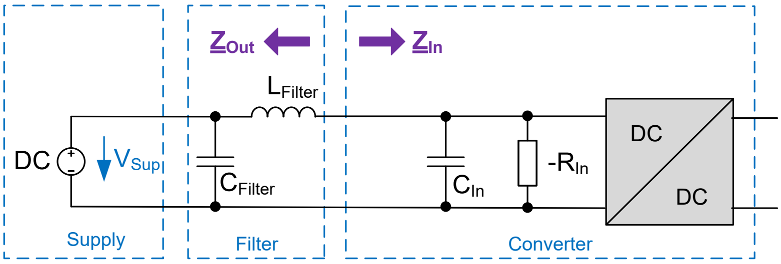

Figure 4: Simplified arrangement of a switching regulator with input filter

Figure 4 should show the input impedance $\underline{Z}_{In}$ of the switching regulator which is formed by the input capacitor C_{In} and the negative input resistance $-R_{In}$. The input filter, which can be realised for example using a WE-PD2 or WE-TI filter coil from Würth Elektronik, forms a series resonant circuit with the output impedance $\underline{Z}_{Out}$ in the direction of the switching regulator input. The input filter is parallel to the input capacitor C_{In} and the negative input resistance $-R_{In}$ and can result in oscillation of the input circuit at resonance frequency. However, if a small signal analysis is performed, the voltage source at high frequencies presents a short circuit whereby the filter capacitor is short-circuited resulting in only the filter coil still being considered. A high quality coil is usually selected as filter coil. Figure 5 shows the impedance curve of the inductance and the resulting output impedance of the filter, which clearly shows its maximum impedance at its natural resonance.

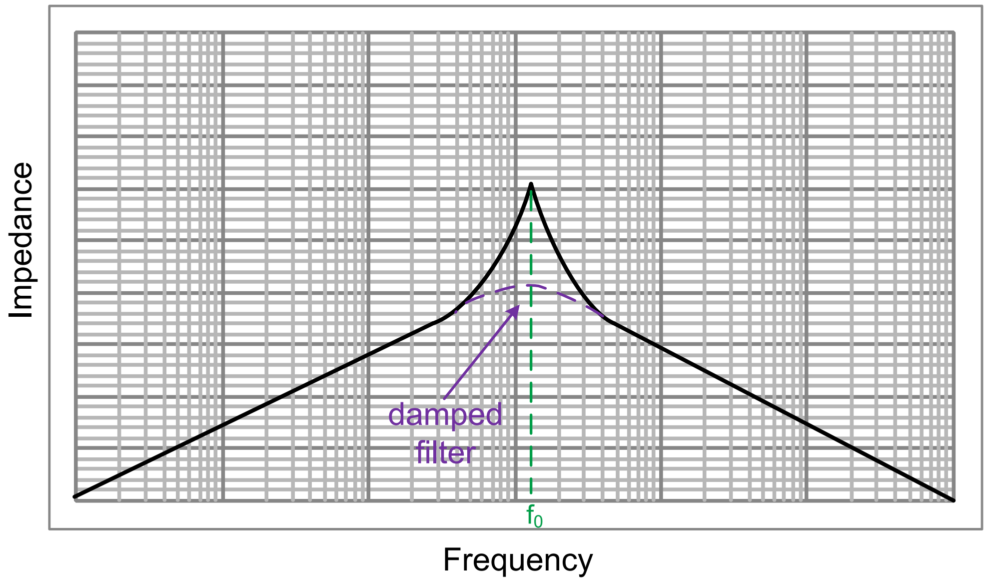

Figure 5: Impedance curve of the input filter at resonance frequency

The output impedance of the filter is at its highest at resonance frequency and conflicts with the input impedance $\underline{Z}_{In}$ of the switching regulator. To prevent any oscillation, it is recommended to attenuate the filter as shown in Figure 5 to reduce the impedance during resonance. Therefore, a design tip is to keep the output impedance of the filter much lower than the input impedance of the switching regulator.

$$\underline{Z}_{Out} \ll \underline{Z}_{In}$$

Ceramic capacitors are often used in the input circuit; however this results all the more in oscillation of the filter as ceramic capacitors have negligibly small ESR. This increases the quality of the filter. Reduction of the quality could theoretically be realised by a parallel circuit of resistors; however this is not a practical solution. It is therefore recommended as a design tip to use electrolyte capacitors here which have relatively large ESR. A large ESR can sufficiently reduce the quality of the input filter whereby the input filter is attenuated and oscillation at the switching controller input is prevented.

After extensive examination of the "negative" resistance, we come to the understanding that the sign is based on a behaviour which can be attributed to the drop of the input current during increase of the input voltage of a switching regulator – transients. Due to the conducted interference, an input filter is absolutely required; however it should be attenuated so that the negative resistance is overcompensated and further prevents any oscillation. Finally, it is recommended not to use ceramic capacitors and to use electrolyte capacitors to prevent unwanted oscillations at the switching regulator input.

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CONTACT INFORMATION

Würth Elektronik eiSos GmbH & Co. KG
Max-Eyth-Str. 1, 74638 Waldenburg, Germany
Tel.: +49 (0) 7942 / 945 – 0
Email: appnotes@we-online.de
Web: http://www.we-online.com