A Simple Method to Determine ESR Requirements for Stable Regulators

Many engineers seem to have trouble with the stability of linear regulators. Given how little stability information is published by the manufacturers of these devices, this is not surprising. In most linear regulators, the output capacitor ESR provides the control loop zero, stabilizing the regulator. The datasheet generally offers little information regarding the stability of the regulator as a function of the load current, output capacitance and output capacitor ESR, which are the external parameters which impact the stability of the regulator.

Since many of my articles and lectures focus on the criticality and impact of phase margin and overall stability, as well as how to measure the stability using either invasive or non-invasive techniques, this article will take a different perspective. This article will provide a method for the determination of capacitor ESR required to achieve a particular phase margin for any output capacitance value, based on a single, simple measurement.

The general representation of a linear regulator

The majority of linear regulators, regardless of topology, reflect output impedance that provides all of the information necessary to determine the ESR required to achieve a particular degree of stability.

Without performing an analysis or derivation of the shape of the impedance response, which is beyond the scope of this article, it is possible to measure the output impedance of the voltage regulator without any output capacitors connected to it. Not all regulators are stable in this condition, though most are. The impedance result can be segmented into three distinctive regions. At DC and low frequencies, the output impedance is resistive, with the resistance being related to the load regulation of the regulator and circuit trace resistances. In the second region, the impedance is inductive, with the inductance being dependent on the load current and the bandwidth of the regulator. In the third region, it is possible that the output impedance is again resistive or not, depending on the regulator.

Measuring the Output Impedance

Since this method is based on the output impedance, the first step to defining the required ESR is to measure the wideband output impedance, using the OMICRON Lab Bode 100 and the Picotest J2111A current injector. The selection of these two devices is due to their wide bandwidth and their ability to directly measure both the phase margin and effective Q from the output impedance measurement. The measurement should be made at the lowest expected operating current, since this condition generally results in the poorest phase margin. In fact, the minimum load requirement is often the limit to the achievable performance of the regulator.

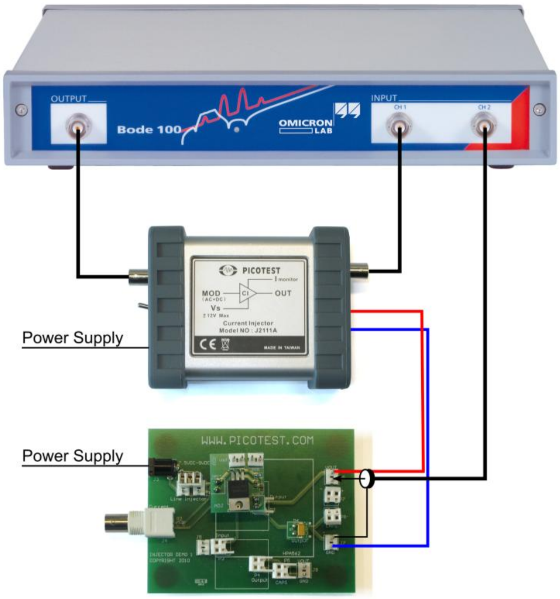

Figure 1: Test setup to measure output impedance using a Bode 100 and J2111A. The Picotest VRTS provides a simple method for the mounting of the regulator and connecting the equipment.

The output impedance of an LM317 voltage regulator operating at 25mA and at 50mA is shown in figure 2. This impedance measurement clearly shows the three regions, as well as confirming that these impedances are dependent on load current. In addition to load current, the output impedance is also affected by the output voltage of the regulator and by the internal compensation of the regulator, so different regulators will yield different results.

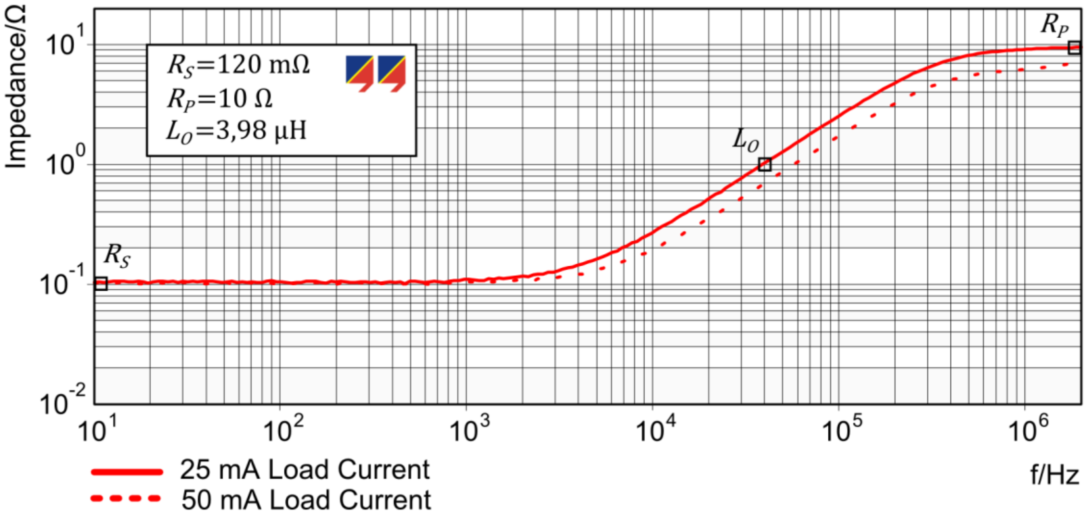

Figure 2: LM317 output impedance at 25mA (solid line) and 50mA (dashed line) load current

The equivalent circuit representing the regulator at 3.3V and 25mA is shown in figure 3

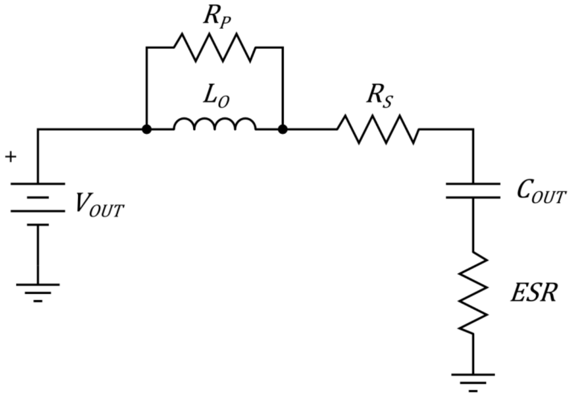

Figure 3: General representation of a voltage regulator with an output capacitor and the capacitor ESR. Note that the value of L is operating current dependent. RS and RP may also be operating current dependent

The equivalent circuit inductance is determined by selecting a point in the inductive region. Selecting 1 Ohm at 40 kHz at 25mA operating current, Lo can be calculated as

$$L_O = \frac{1}{2\pi \cdot 40\ \mathrm{kHz} \cdot 1\ \Omega} = 3{,}98\ \mu\mathrm{H}$$

Next, the values of Rs and Rp are taken directly from the impedance measurement as 120 milliOhms and 10 Ohms respectively. Much of this resistance is from contact resistance of the connections on the VRTS.

The derivation of the ESR requirement is beyond the scope of this article, however it can be directly calculated as a function of the equivalent parameters, desired output capacitance and desired phase margin (PM).

$$ESR(PM; C_{OUT}; L_O; R_S; R_P) = 2\sin\left(\frac{PM}{2}\right)\sqrt{\frac{L_O}{C_{OUT}} - \frac{R_P L_O}{R_P^2 C_{OUT} + L_O}} - R_S$$

The bandwidth of the regulator can be calculated from the equivalent inductance and the output capacitance.

An Example

Using the LM317 at an output voltage of 3.3V and an operating load current of 25mA, the values of Lo, Rp and Rs can be determined from figure 2. A 22uF capacitor is selected as the output capacitor. Arbitrarily choosing a desired phase margin of 38 degrees, the required ESR is calculated to be 139 milliOhms.

$$ESR(38\,°;\ 22\ \mu\mathrm{F};\ 3{,}98\ \mu\mathrm{H};\ 0{,}12\ \Omega;\ 10\ \Omega) = 139\ \mathrm{m}\Omega$$

The expected bandwidth of the regulator is calculated from the equivalent inductance and the output capacitance, using the well known resonant frequency relationship for an inductor and capacitor.

$$BW = \frac{1}{2\pi\sqrt{L_O C_{OUT}}} = 16{,}18\ \mathrm{kHz}$$

A 22uF tantalum capacitor sample is selected and measured, using an OMICRON Lab Bode 100 and B-SMC adapter. A detailed application note describing this method can be found at http://www.omicron-lab.com/application-notes/capacitor-esr-measurement.html . The capacitance and ESR results are shown in figure 4.

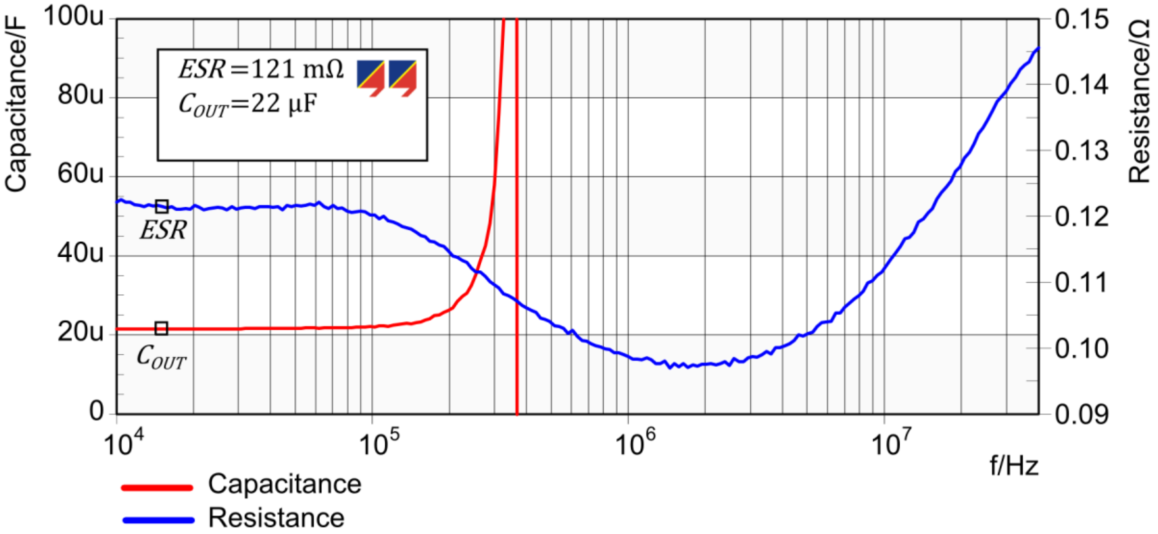

Figure 4 A tantalum capacitor sample measures 22 uF with an ESR of 121 milliOhms at 16kHz

Finally, using the Bode 100 and J2111A in a non-invasive phase margin measurement, the phase margin is measured at 25mA. The results, shown in figure 5, indicate a phase margin of 38 degrees and a bandwidth of approximately 16kHz, confirming the mathematical result.

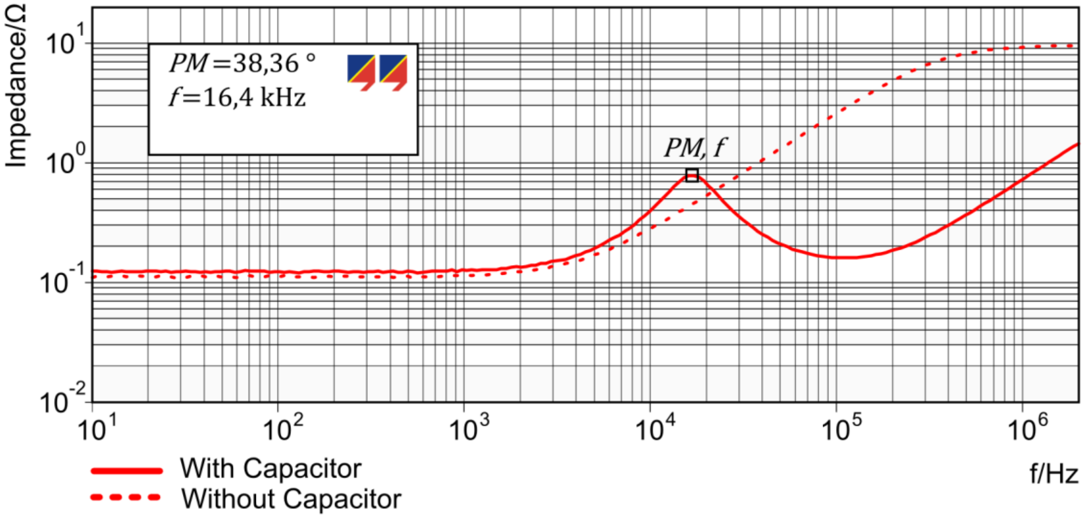

Figure 5 LM317 25mA with 22uF Tantalum capacitor confirms the phase margin of 38 Degrees with 0.12 Ohm ESR. The measurement also confirms the regulator bandwidth of 16kHz.

Conclusion

A single, simple measurement has been described which allows the determination of the ESR required to achieve a desired phase margin, using a particular value of output capacitor. Solving the ESR requirement at the lowest operating current provides a stable solution for higher operating currents as well. The non-invasive phase margin support, offered by the Bode 100 and J2111A allows this method to be used even with fixed voltage regulators, where there is not control loop access. The stability improvements that can be realized in the regulator may improve many system level performance characteristics, such as improved output impedance and dynamic step load response, PSRR, reverse transfer and crosstalk.

References:

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