Tips and Tricks on how to verify control loop stability

Application Note

Products:

- R&S®RTB2000
- R&S®RTM3000
- R&S®RTA4000

This application note describes how to measure the control loop stability of switch-mode power supplies to get the best performance and confidence of the design. It will explain the main measurement concept and will guide the user during the measurements and mention the main topics in a practical manner. Wherever possible, a hint is given where the user should pay attention to it to avoid weak measurements. The Rohde & Schwarz buck converter reference board was designed in collaboration with Texas Instruments and is used to illustrate the closed loop measurement in a practical manner.

Note:

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Application Note
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1 Introduction

1.1 Measurement methods in modern SMPS.

In a design of a modern switch-mode power supplies (SMPS), the designer has to ensure that the converter is operating in its specified values over all circumstances. Therefore, some specific tests for SMPS have been established to get the confidence of a well-designed power supply. For example, some of these tests to ensure proper performance are output voltage deviation test, load transient test, output voltage ripple, input voltage ripple, start-up and shutdown sequences. Although most of the tests convince the designer to have a proper operation over all circumstances, some of them do not cover all situations. If you are relying on the load transient test method to ensure system stability, you will not cover all operating conditions of the power supply.

Due to parasitic effects or temperature effects, the designer needs to consider these effects to ensure a proper performance of the SMPS. Unfortunately, it is not easy at all to calculate these parasitic and their effects. Therefore, an additional measurement method should provide confidence.

Fortunately, there is already an additional method introduced called “Closed Loop Response” test (CLR) to overcome this weakness of the previous mentioned load transient test method. Usually a network analyzer is needed to measure the CLR, which is an additional device for the power supply designer in the device pool. Typically, a network analyzer is also an expensive device. Therefore, Rohde & Schwarz provides an option in their Oscilloscopes to make an investment of an additional device unnecessary, because the oscilloscope is a standard device in the equipment of a power supply designer. This option will be discussed in the following chapters.

1.2 Feedback loop principle of a SMPS

Power supplies can be divided in two parts:

- Modulator and power stage including the output filter. This is the forward path of the system.
- Error amplifier and its compensation network. This is the feedback path of the system.

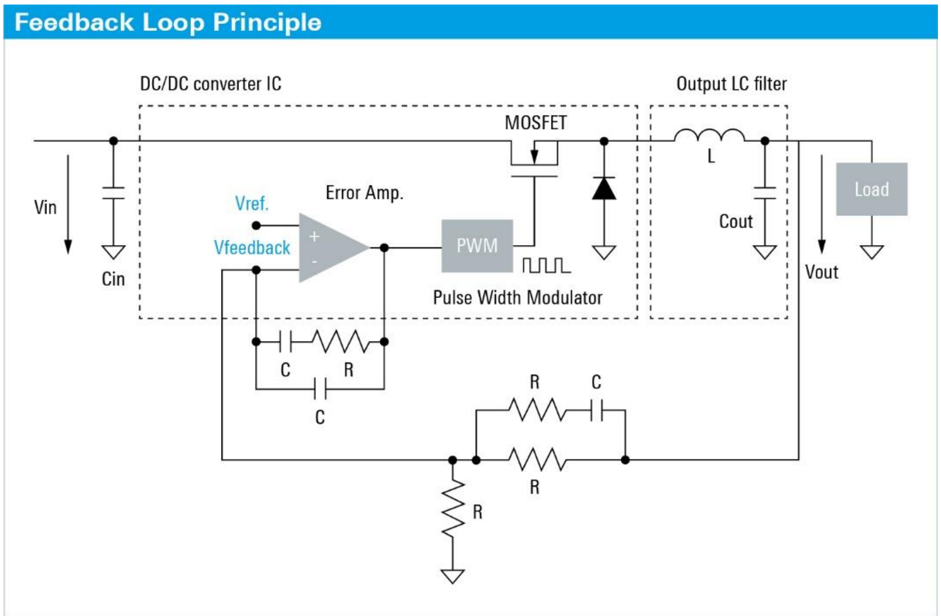

Fig. 1-1: Regulation principle of a switch-mode power supply

All these components are mandatory to regulate the output voltage by sensing the output voltage and feeding a portion back and compare this with a reference value. Eventually, the difference is amplified and this signal is transferred to a PWM modulator, which drives the power switch. The output LC filter stage filters the high frequency content caused by the switching of the MOSFET to a DC output voltage.

When the output voltage drops due to a load step, the output of the error amplifier will increase. Therefore, the duty cycle will temporarily increase and thereby increasing the output voltage back to the target value. This is the basic control mechanism of the buck converter and its control loop.

For this control loop, two main requirements during the design process should be taken into consideration:

- The power supply has to operate fast enough to minimize the effects on load variations and input variations.
- The power supply has to operate stable enough to avoid any oscillation in the system.

In addition, also some non-electrical parameters like cost and size exists. Therefore, it is not an easy task to fulfil the requirements above to reach an optimized stability of a power supply. This evidence is usually done with calculations but also measurements are used to verify this design.

1.3 Frequency loop response analysis

In the analysis of the frequency loop response, we want to estimate or analyze the gain and the phase of the control loop. The definition of gain and phase can be describes as follows:

- Gain is the portion of the magnitude of the output towards the magnitude of the input.

- Phase is the shift of the signal measured in an angle. This means how the input signal is shifted compare to an output signal.

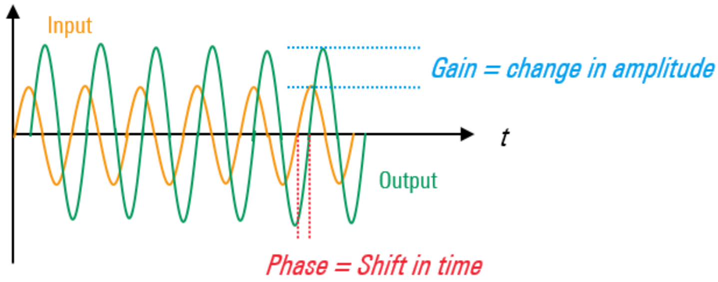

Fig. 1-2: Gain and phase definition

In summary, the output of a single input frequency is a combination of gain and phase shift. In fact, the gain and phase of a control loop are dependent over the frequency. The bode plot allows frequency response information to be displayed graphically on two separate plots. This is the best method two illustrate this behavior of the control loop.

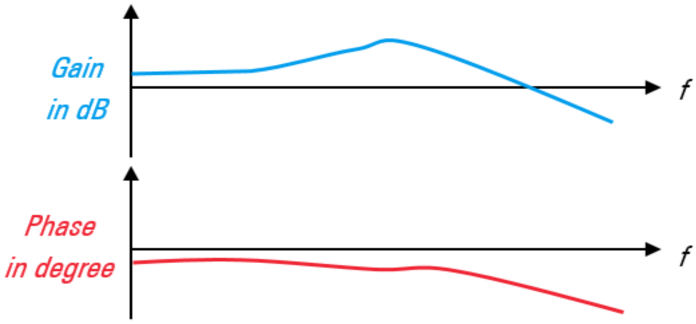

Fig. 1-3: Bode plot of a control loop

The gain and the phase can be used to estimate whether a SMPS is stable or some oscillation exist. In addition it can be estimated how much margin we have in the system. There are several key parameters in the bode plot which you have to identify to evaluate the stability of the system.

The first parameter is the crossover frequency. The crossover frequency is at the point where the gain crosses 0dB. At this point, the system shows how much phase margin is left before the system gets into unstable behavior.

The second parameter is the gain margin. The gain margin is at the point where the phase crosses -180° phase. The gain margin is the gain we can add before we reach -180° phase.

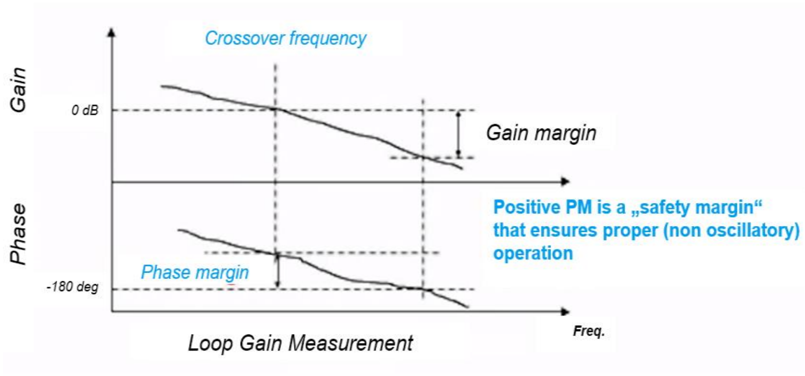

Fig. 1-4: Loop Gain Measurement

Regarding the gain and phase margin measurement, the following statements may help to analyze the closed loop response.

- Higher 0 dB cross-over frequency = Faster response to load changes
- Higher phase margin (>45°) at 0 dB cross-over frequency = More stability
- Lower gain at higher frequencies = Better noise immunity (output ripple)

When analyzing the stability of a power supply, we measure the open loop gain in a closed loop system. Therefore, the phase margin must be measured relatively to the 0° line. This is noticeable in all measurements performed later on.

Assumed we have to measure the close loop response on a feedback system we need a physical break, which would lead to an open loop measurement. Anyway, in an open loop the dc operating point is not easy to maintain. Therefore, this is not a practical approach. Fortunately, an alternative exists to break the loop. This alternative approach to measure the open loop gain on a closed system is described in the next chapter.

2 Selecting the right injection point

2.1 Injection method

To measure the CLR we have to break the loop at a suitable point and inject a perturbation signal at this point. Furthermore, it is required to reconnect the loop to maintain the DC operation point while injecting the signal. This can be done with an additional resistor at a suitable point. The influence of the additional resistor can be neglected, if the value is small enough and the point where the resistor is added, is carefully selected. However, the method to find a suitable point to break the loop and to add a small resistor is explained in more detail in the next paragraph.

The voltage injection method is an appropriate injection method to inject a small signal level into the feedback loop. For the voltage injection method, we need to find a point where the impedance in the direction of the feedback loop is much larger than the impedance looking backwards.

In our reference design, the impedance at the output (Z_O) is relative low due to the output capacitance and the load resistor. The error amplifier represents the input impedance (Z_I) into the feedback loop, which is typically in the range of several MΩ. Usually you also have a resistor divider in front of the error amplifier. This will reduce the input impedance of the feedback loop to a range of 10kΩ - 100kΩ. Anyway, the rule from voltage injection ($Z_I >> Z_O$) is still valid and we are able to apply the voltage injection method to our reference design.

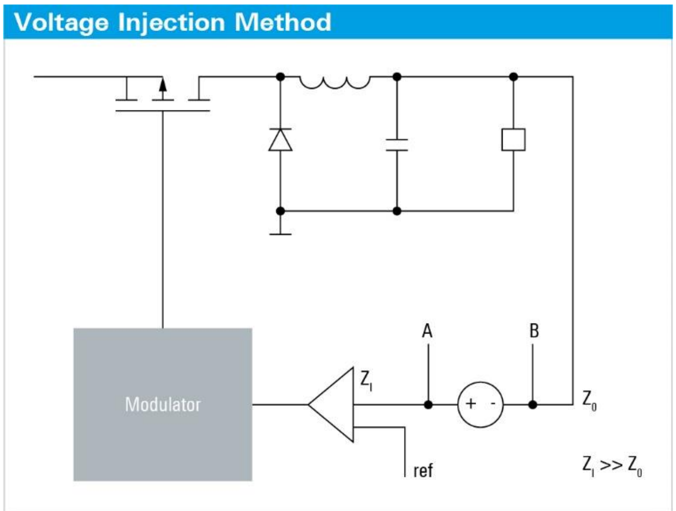

Fig. 2-1: Voltage injection method

2.2 Measurement setup

Supposed you have decided to use the voltage method to inject some perturbation signal. In our reference design, it is exactly the case where we use the voltage injection method. All what you have to build up is the following measurement setup.

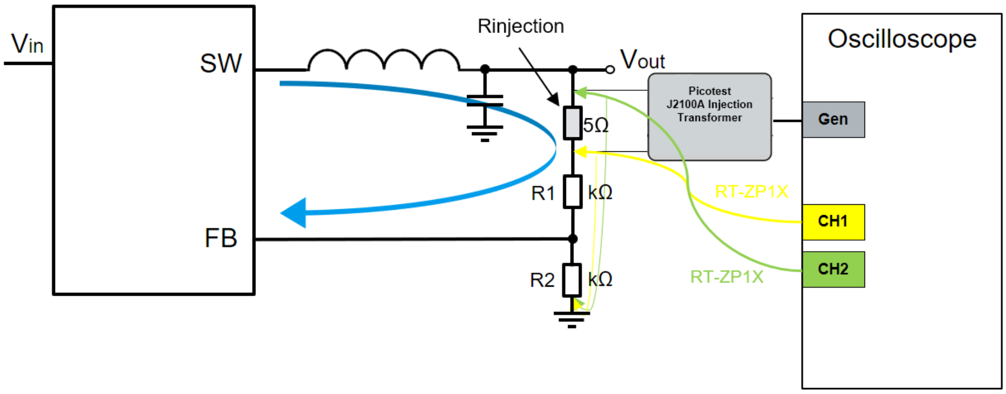

Fig. 2-2: Setup of closed loop response measurement

It consists of an R&S Oscilloscope including a signal generator and bode plot option, an injection transformer and the device under test.

It is important to mention that the insertion resistor is much smaller compare to the following voltage divider. This is the precondition to measure your loop gain. All the things you have to do is to inject a small error signal by means of an injection transformer and a signal generator. This signal generator has to sweep the signal over the whole frequency range. Of course, you have to measure the error signal at the input and the output of the resistor during the sweep.

The inputs of the oscilloscope are connected to either side of the injection transformer. CH1 measures the disturbance signal that is applied to the feedback divider and CH2 measures the signal that appears at the output of the converter. By dividing the voltage at CH2 by the voltage at CH1, we get the loop gain of the system. Of course, the phase shift is also measured.

2.3 Additional selection requirements

For the right injection point, you need to fulfill a couple of requirements beside the condition $Z_I >> Z_O$. It is also important to find an injection point where the loop is restricted to one single path to make sure that there are no parallel signal paths. In our reference design, it is clear that there is no additional parallel path. In more complex feedback loops e.g. when optocoupler devices are used it might be more difficult to identify a point where the condition is fulfilled.

The connection length between the resistor and the transformer should be as short as possible for minimizing noise pickup effects. In addition, a twisted pair connection can improve the measurement quality.

3 Injection Transformer

3.1 Introduction

An injection transformer is a specific transformer that is connected between the signal generator and the power supply converter in order to inject a small error signal into the control loop and is primarily used for CLR measurements.

The measurement concept requires a connection to the DUT, but it must be clear that beside the additional resistor, the transformer must not change the behavior of the loop.

3.2 Galvanic isolation

Isolation specifications are often overlooked but this requirement is still needed in many applications for different reasons. In fact, isolation is needed in case of CLR measurement for three reasons: Safety, Signal Integrity and Instrument Protection.

3.2.1 Safety

The transformer has to ensure that there is not a galvanic connection between the signal generator incorporated in the oscilloscope and the device under test. This isolation provides the possibility to have a floating high voltage connection to the transformer. In PFC applications, often a floating 400V DC is used and therefore the isolation of the transformer is mandatory to protect the user from an electrical shock.

3.2.2 Instrument Protection

In general, expensive measurement devices like oscilloscope and network analyzer are used to measure the CLR of the power supply. These devices are typically very sensitive against overvoltage at the terminals. In this case, an isolated connection to the DUT helps a lot to keep the higher voltage away from the terminals. In detail, the signal generator output is connected via the transformer to the circuit. Due to the isolation of the transformer, the generator is protected against any common mode high voltage.

Keep in mind that you have to double check the capability of the probes you are using. The probes are connected directly at the DUT and are not protected by the isolation of the transformer. Consider using the right probes in your application. It is described in more detail in the probe selection chapter.

3.2.3 Signal integrity

The injection transformer can also play a big role regarding signal integrity. Usually SMPS have often issues with common mode noise. When unwanted signals occur on a pair of conductors, it is referred to as common mode noise and it adds to both lines in the same direction. This common mode noise might be generated due to parasitic components in the power supply design. Therefore, the isolation helps a lot to attenuate this common mode noise from the system. Of course, this attenuation level of the transformer is limited due to the existing coupling capacitance (typically some hundred pF) between the primary and the secondary winding of the transformer.

Anyway, supposed no isolation barrier exist, an existing ground noise coming from the DUT can couple to the measurement device without any damping. This could influence the measurement in an unwanted way.

3.3 Injection of a DC free small error signal

In fact, we have a requirement not to inject any DC portion from the signal generator to the tested power supply. This ensures that we do not shift the DC operating point while we inject a small error signal.

In theory, a transformer is not able to transfer any DC signal from primary to secondary. That is exactly the reason why we use also a transformer to inject the AC error signal.

3.4 Attenuation of the transformer

In order to inject the same magnitude of the injected signal over the frequency, we need a transformer, which provides a relative flat gain/damping. In other words, we need gain flatness over the whole frequency range ideally. This ensures that you have an injection signal, which is independent from the transformer over frequency. When sweeping the frequency automatically this could be beneficial. Anyway, if you have not a flat gain response over the whole frequency range, this could be corrected by profiling. In fact, profiling to correct the transformers frequency response is not the preferred approach because it is not easy to track.

3.5 High permeability core

It is recommended to use a transformer with a high permeability core. This would provide a large saturation current capability. In addition, you will have a very good low frequency limit This would be beneficial when measuring the CLR of a PFC circuit where you have to inject very low frequencies signals (0,1Hz f <10Hz).

The drawback of this high permeability core is that you will have a reduced high frequency limit. Therefore, you get injection transformer with focus either on the lower frequency range or with focus on higher frequency range.

3.6 Consider parasitic capacitance between primary and secondary

Due to the construction of the transformer and the mentioned core property, there is always a portion of parasitic capacitance. This may influence the measurement of the

CLR in a negative way because it can couple some signals from the primary to the secondary. If you compare different injection transformer you should check this capacitance as well. If you want to design your own transformer, keep the coupling capacitance as small as possible.

3.7 Conclusion

The injection transformer is a key device of the CLR measurement technique. Therefore, the selection of a suitable injection transformer should be done carefully to fulfil the requirements and recommendations mentioned in the previous paragraph. Recommendation for CLR measurement with our reference design is the Picotest J2100A Line Injection Transformer for lower frequency (1 Hz -5 MHz). If you need to measure at higher frequency, the Picotest J2101A Line Injection Transformer is the right choice.

4 Amplitude Profiling

4.1 Introduction

This article illustrates the impact of the size of the injected signal on a closed loop measurement, which is one important part of measurements of switch-mode power supplies. This measurement verifies the stability of the power supply during load switches or input voltage variations. In addition to the generic bode plot option, the R&S oscilloscopes (RTB2000, RTM3000 and RTA4000) provide also a profile setting of the injected signal. In the profile setting, the amplitude of the injected signal can be determined at different frequencies. A profile setting may help to overcome the impact of system effects described in this article.

As a precondition for this chapter, an optimized setup in terms of probe selection and wiring length for the closed loop measurement is assumed, to minimize the effect of noise in general. These effects are not in the focus of this chapter but of course have to be considered. In this chapter, the focus is to point out, why some adaptation of the signal size over the frequency is needed.

4.2 Motivation of signal injection profiling

Usually the signal needs to be injected over the whole frequency range with a certain magnitude. This magnitude may be different at lower, mid and high frequencies dependent of the power supply circuit. This is where a profiling of the injected signal can help to overcome some natural properties of the system.

In general, the power supply loop gain itself determines the size of the injected input signals. From the theory, the injected signal is smaller at the input injection point (towards the high impedance of the feedback) at low frequencies (gain > 0) and larger at the output injection point (towards the low impedance output capacitor). Therefore, in low frequency region, a higher injection signal is needed to make the higher gain visible in the bode plot. At higher frequencies (beyond the cross over frequency), the voltage at the input injection point is larger and the voltage at output injection point is smaller. This system property requires a reduction of the injection signal to avoid distortion of any active components within the circuit.

Two main rules exist which determine the amount of the signal. These rules apply over the whole frequency range.

- The input signal level must be low enough that it provides only a small signal perturbation. This is necessary to avoid overdriving the active components.
- The input signal level must be high enough to provide a measurement, which is above the noise level.

In addition, a profiling may help to compensate damping effects of the injection transformer. Refer to chapter Injection Transformer.

4.3 Realizations of an optimized profile setting

In every power supply, active components are used which are frequency dependent and this is hard or even impossible to calculate the correct magnitude of the injected signal at a specific frequency by given formulas.

The possibility to measure some signals around the loop e.g. output of the error amplifier to identify a not optimized signal injection is not recommended. The reason is that you may have several stages with gain and not all of them are easy to verify. Furthermore, the probe connection may introduce an additional noise source to the measurement.

The ideal solution would be to look at the measured loop gain and compare the result the predicted loop gain. Unfortunately, many power supplies are not easy to model and the prediction is not an easy option.

Beside all of the mentioned approaches, the practical solution is to verify the loop gain while changing the profile of the injected input signal. The profile you need is typically a large signal at low frequencies and a small signal at high frequencies as described in the previous chapter. Actually, a good starting point to record the first CLR is a measurement with a constant smaller signal level.

4.3.1 Injection of a constant small injection signal (Constant profiling)

The measurement is shown in Fig. 4-1 and it was performed to demonstrate the results when no profiling is determined. This measured loop gain was performed with constant signal injection level of 100 mV from 100 Hz up to 150 kHz. It shows a noisy signal up to 10 kHz. In the frequency region beyond this point, the signal looks reasonable and we probably do not have to change the signal level.

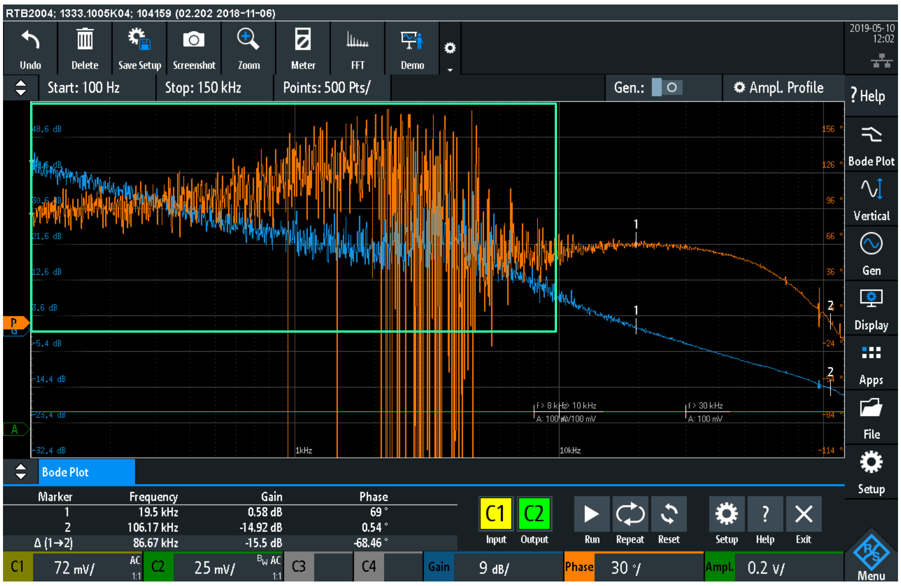

Fig. 4-1: A small injection level constantly injected

The noisy signal is clearly visible in the gain but also in the phase signal. We can assume that the signal to noise ratio is not large enough. This is at least true for the lower frequencies (less than 10 kHz). The result shows that a new injection level is needed for the lower frequency range. The higher frequency range looks reasonable and therefore no change in the amplitude is applied so far.

4.3.2 Improved profiling at low frequency

In this measurement, the injected signal amplitude was increased to 750mV between 100 Hz and 10 kHz. From the theory, this should drastically reduce the noise, which was visible in the previous measurement. The result is shown in Fig. 4-2.

Fig. 4-2: Improved amplitude at lower frequency (Version 1)

It shows an improved CLR measurement in the lower frequency range. Noise reduced a lot but there is still some room of improvement. In detail at the 10 kHz edge, the noise is still visible and this indicates that the injected signal is still too small.

In the next measurement shown in Fig. 4-3, we will change the profiling again to reduce the noisy part of the signal. An additional range from 10 kHz up to 50 kHz was introduced and the amplitude was set to 250 mV.

Fig. 4-3: Improved profile (Version 2)

In this result, there is an improvement in the noise level of the phase signal at 10 kHz. Anyway, there is still a part of noisy signal visible at 10 kHz. This means that the amplitude of 250mV is still too small at this point.

The next measurement shown in Fig. 4-4 was performed with an increased amplitude (400 mV) between 10 kHz and 50 kHz.

Fig. 4-4: Optimized amplitude profile

Finally, this measurement is already a CLR with an optimized profile setting. We do not have any noticeable noise in the signal. It shows that a profiling is a helpful feature to increase the quality of the CLR measurement.

4.3.3 Distortion due to larger signal

This measurement was done to clearly show the behavior of the circuit when the user apply an injection signal level which is to large. As we know from theory, the circuit is overdriven and some distortion should be visible in the measurement.

Well known that at high frequency it is easy to overdrive some active part, the profile was adopted to apply a constant level of 750mV over the whole frequency range.

Fig. 4-5: Constant large amplitude profile

Fig. 4-6: Optimized amplitude profile

In the measurement shown in Fig. 4-5, it is visible that due to the new profile the gain and the phase dropped significantly at 30 kHz. This is caused by injecting a large signal at these higher frequencies. This sudden drop in the gain or phase is typically an indication, that distortion of the circuit is present and this behavior should be avoided. The reference measurement shown in Fig. 4-6 illustrates an optimized profile measurement.

The measurement shown in Fig. 4-7 illustrates the effect of distortion due to a large injection level in the time domain window. However, the time domain window of the oscilloscope visualize the injected signal in addition to the bode plot and the user is able to obtain additional information about input and output signal. The profile of the measurement is the same as it is for the previous measurement.

Fig. 4-7:Constant large amplitude profile in time domain

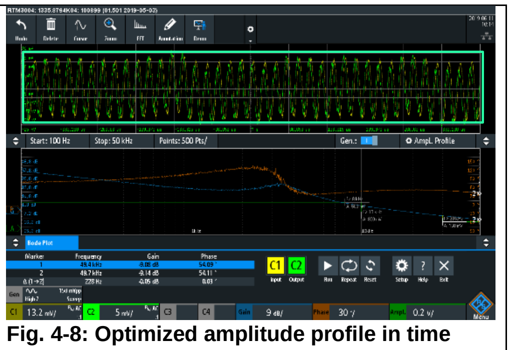

Fig. 4-8: Optimized amplitude profile in time domain

In the time window, it is very easy to analyze the injected signal whether the signal is injected in a way that the circuit under test is driven in non-linear behavior or not. Furthermore, it is also easy to detect a signal, which is too low and may cause an incorrect measurement in the frequency domain. In the measurement shown in Fig. 4-7, it is easy to observe the distorted signal over time in the time window. In the measurement shown in Fig. 4-8, the input and output signal is stable over time and therefore the injected signal is in the optimum.

4.4 Conclusion

The profiling feature of the Rohde & Schwarz Oscilloscope Series is a helpful option to perform high quality CLR measurements. In most cases, the size of the injected signal must be varied to get an optimized CLR measurement. In this case, neither distortion due to injection of too large signals nor noise due to injection of too small signals will be existing. The use of the time domain window of the oscilloscope is a very good possibility to adjust the amplitude profile to the optimum.

5 Probing

5.1 Motivation

In general, it must be clear that for any measurement it is crucial to apply an optimized probing. Probing is also part of the CLR measurement and should not be underestimated. In the CLR measurement small signal needs to be measured and probing becomes an issue.

5.2 Probe selection

5.2.1 Probe Type

As you already know, we have to measure voltages in the range of several hundred millivolts or even less at a frequency of several hundred kHz. This means we have already two main parameters, which need to be evaluated.

- Low Attenuation Factor
- Bandwidth of the probe

Two main category of probe type exists which would fit to our application, the active and the passive probes. The focus of the active probes is more on applications where you need very high bandwidth, high voltage capability and high input impedance. The high input impedance would help not to load the circuit under test too much. In our application, high impedance and the very high bandwidth is not required. The high voltage probes may help in PFC application where you typically have output voltages up to 400VDC. Anyway, the active probes are relative expensive and are therefore not used as a standard probe.

The passive probes are a good choice in our reference design but you have to choose the right type of passive probe. The limited bandwidth of some probes is usually not critical but we need a passive probe with a small attenuation factor because of the small signal we want to measure. This is usually a probe with 1:1 attenuation factor. The input impedance of 1MΩ is large enough that the signal in the circuit is not attenuated too much. The bandwidth of these probes are typically around 50 MHz, which is sufficient for our application.

5.2.2 Attenuation

As describes in the previous chapter, a passive probe with lower attenuation factor is the best choice for our application. Anyway, the oscilloscopes are usually delivered including passive probes with 10:1 attenuation. In our application, this high attenuation factor leads to a measurement with less fidelity.

However, due to a large attenuation factor, the extension of the voltage range of the scope is extended to be capable to measure higher voltages. This is what most of the people know about the purpose of an attenuation factor. Unfortunately, there is also a drawback of introducing this attenuation factor. As we introduce the attenuation factor, we also extend the noise at the oscilloscope input. The definition of the SNR of the system can be described as follows:

Equation 5-1: $SNR = \frac{V_{in}}{Attenuation * V_{noise}}$

This formula shows that the attenuation will reduce the signal to noise ratio of your system when you will use a 10:1 probe instead of using a 1:1 probe. This does not have a big influence when you measure relatively higher voltage signals but in our application, we have small signals to measure. In other words, we would reduce the signal to noise ration when we try to measure a small signal with a high voltage probe.

As we have to use two probes in our measurement, another important topic to mention is that you should use only identical probes in terms of attenuation, bandwidth and input capacitance to avoid any undesirable measurements. A good practice would be to use the same probe type and are even provided by the same vendor.

5.2.3 Measurements

In this chapter, a comparison between a good and a bad selection of probe types is illustrated. In all measurements, a passive probe 1:1 was used for both channels to avoid any misunderstanding. Only in this paragraph, a passive probe 10:1 was used to demonstrate the big difference in the result.

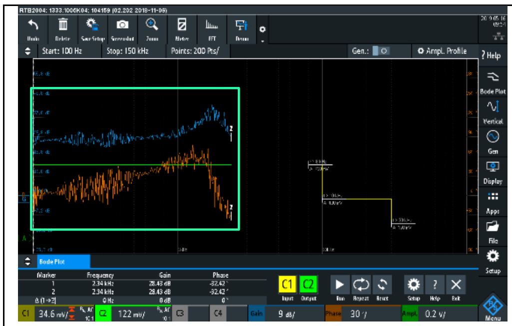

Fig. 5-1:High attenuation passive probes (10:1)

Fig. 5-2: Low attenuation passive probes (1:1)

In the measurement shown in Fig. 5-1, it is clearly visible, that the gain and the phase of measurement in the low frequency range drops a lot compare to the correct measurement on the right. This measurement is not a reasonable measurement at all. This result shows that due to the higher attenuation factor, the measured signals we want to measure are close to the noise level of the measurement system.

The measurement shown in Fig. 5-2 is the reference measurement performed with a low attenuation factor.

Remark: The measurement with the 10:1 Probe was interrupted because the sweep function of the system became very slow and it is clearly visible that this kind of probe is not useful at all. The signal to noise ratio is not large enough.

5.3 Identification of a probing point

In the concept of a SMPS, you will have noise due to the switching elements. This noise is dependent on few parameters of the converter, like switching frequency and switching speed of the switching element. This is very important to keep in mind that you may have some noise generator on the DUT.

If you keep this information in mind, you can imagine that probing may become an issue. For example if you are using the ground lead of your probe, you may have some additional noise introduced via the ground wire. Be careful using long ground leads especially when you have inductive elements like a transformer or switching elements nearby. These elements typically generate EMI and the ground lead acts as an antenna and may introduce this noise into the circuit. In this case, it would be better to use a ground spring instead of using the ground lead. In this case, the loop of the ground is reduced to a minimum.

Fig. 5-3: Standard ground connection

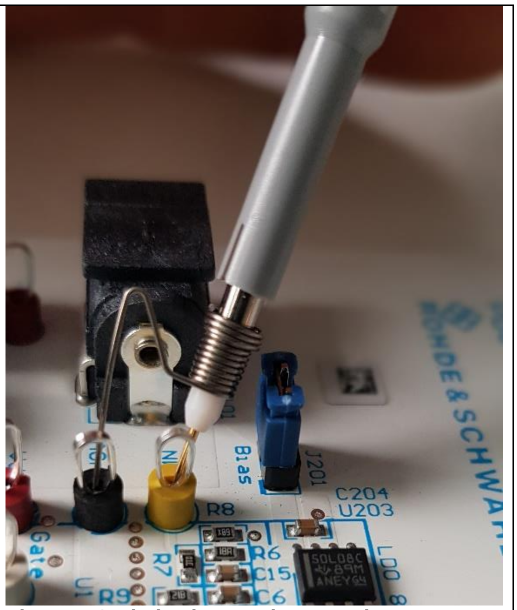

Fig. 5-4: Optimized ground connection

The pictures above show the two possibilities to make a ground connection at the injection point. Due to the long ground lead shown in Fig. 5-3, noise can easy couple into the circuit due to the loop of the wire. In the setup shown in Fig. 5-4, this effect is minimized and it will result in a higher fidelity of the measurement.

5.4 Conclusion

The CLR measurement is a small signal measurement and therefore it is important to look carefully at the attenuation factor of the probes. Unless suitable active probes are available in the market, a good economical choice would be the RT-ZP1X with has an attenuation factor of 1:1 and a bandwidth of 38MHz.

Furthermore, it is highly recommended to optimize the ground connection of the probes during the measurement to obtain the best fidelity of the measurements.

6 Stability measurements over all conditions

6.1 Motivation

In SMPS circuits, changes in line, load and temperature tend to degrade phase margin markedly from the nominal value. This is exactly the reason why it is always a good idea to perform a stability measurement with different load and line conditions. For example at low output loads power supplies go into discontinuous current conduction mode, which will change the loop characteristics. Also in converters without input voltage feed forward, the loop characteristics will change with input voltage. In our reference board, the voltage feed-forward compensation is provided.

6.2 Input voltage variations

Due to the fact, having an input voltage feed forward regulation in the control IC, no big change in the closed loop response will exist. In the following measurements, the input voltage was set to 8V and 16V. Expectations are that unless the SMPS does not change the control mechanism, the CLR should not change. Refer to the measurement results below.

Fig. 6-1: CLR measurement @ Vin = 8V, Pout = 2,5W

Fig. 6-2: CLR measurement @ Vin = 16V, Pout = 2,5W

In fact, no bigger changes occurred when input voltage variations are performed. Only a small difference in terms of noise, shown in Fig. 6-2, is visible in phase and gain when the converter works from 16V input voltage. This may be caused by switching of the switching element of higher voltages, which generates typically more EMI.

6.3 Output current variations

In this paragraph, a comparison is illustrated between different output load conditions and a stable input voltage at 12V.

6.3.1 Higher current load

In the following measurements, the results are very similar between two load conditions. This means no issues about stability can be identified.

Fig. 6-3: CLR measurement @ Pout = 2,5W

Fig. 6-4: CLR measurement @ Pout = 2W

6.3.2 Lower output current load

After a further reduction of the output current, some drops are visible which indicates an erroneous applied amplitude profile. These drops are shown in Fig. 6-5.Therefore, some adoption of the amplitude profile was necessary. The reduced amplitude from 400 mV down to 300mV in the mid frequency range helps to get a reasonable result. The result is shown in Fig. 6-6.

Fig. 6-5: CLR measurement @ Pout = 1,5W

Fig. 6-6: CLR measurement @ Pout = 1,5W Improved Profile

A new profiling was necessary because output impedance of the loop was changed and therefore the injected signal may influence the DC bias operation point.

6.3.3 Lowest output current load

Further reduction down to 200 mA and 100mA (Pout =1W / 0,5W) showed results which are not useful anymore. At 200 mA, the converter is still in the same regulation method, which is the continuous mode. Anyway, the reduced load current shifted the output impedance to a higher value. This means the requirement $Z_I >> Z_O$ to maintain the closed loop measurement criteria is not fulfilled anymore especially at lower frequency. The result is shown in Fig. 6-7.

Fig. 6-7: CLR measurement @ Pout = 1W

It is clearly visible that at low frequencies the measurement was not reasonable anymore. The system was stopped due to very low speed of the signal sweep. This effect becomes even more relevant at Pout = 0,5W.

6.4 Output filter effects

The output filter consists of an inductor but also an output filter capacitor. These two components are part of the power stage and determine the loop characteristics of the system. This changed characteristic is illustrated in the following measurements.

The gain and phase was measured with the standard value (approximately 80µF) and in addition, the gain and phase margin was measured with an increased output capacitance of 180µF.

Fig. 6-8: CLR reference with standard output filter capacitance

Fig. 6-9: CLR with additional output filter capacitance of 100µF

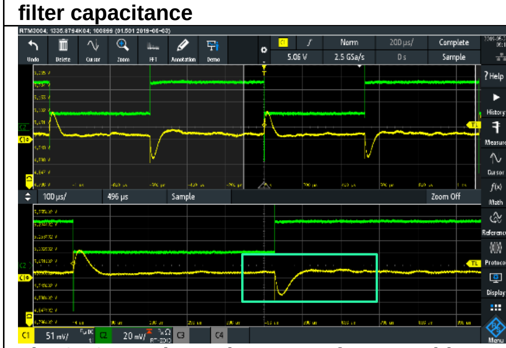

Fig. 6-10: Load transient test reference with standard output filter capacitance

Fig. 6-11: Load transient test with additional output filter capacitance of 100µF

In the CLR measurement shown in Fig. 6-9, it can be seen that that the cross over frequency at 0dB shifted from 15 kHz down to 5 kHz. This will reduce the speed of regulation. In addition, a load transient test shown in Fig. 6-11 was performed to show the reduced regulation speed. The system is still stable but the time the system needs to regulate to the output voltage is longer than it was before the additional capacitance.

6.5 Temperature variations

To perform temperature variations with the DUT is usually a challenging task.

Firstly, most of the probes do not have a temperature range which matches e.g. to the industry temperature rang which is -40 to +85 Celsius.

Secondly, it is usually the case that the DUT has to be placed in a temperature chamber in order to fulfil the required temperature profile. The measurement equipment is usually outside the chamber because its specification is limited. Anyway, this requires a longer cable connection and precautions should be taken into account to avoid any kind of electromagnetic interference. This can influence your measurements quiet drastically.

7 Simulation of the converter design

7.1 Motivation

Nowadays, the PC-Hardware and software simulation tools become more powerful which may support the designer to simulate parts of the design before testing the real hardware. This may reduce development time and cost. Companies like Texas Instruments or Analog Devices provide spice simulation tools for free to accelerate the design process. In addition, the designer may obtain more confidence of the design. Especially the spice circuit simulator in the time domain is widely used in the market. In addition to that, companies have developed software tools to simulate the gain and phase of a switching mode power supply where different topologies can be simulated.

In this chapter, a simulation result performed in the time domain and frequency domain of the used converter is shown and is compared to the real measurement of the design.

7.2 Simulation of closed loop response and load transient response

The simulated closed loop response was performed with the Power Stage Designer Tool provided by Texas Instruments. As it is always with simulated results, you have to keep in mind that some parasitic components are not included during simulation and the result will not fully match the result of the measurement. The power stage designer is able to simulate the closed loop response including all power stage and feedback components but the input EMI filter components are not considered in the calculation.

If the noise in the loop measurement curve is not considered, the result of the closed loop response calculation shown in Fig. 7-2 is very close to the reality. The gain of the loop has a calculated cross over frequency of about 14,4kHz, which is very close to the measured value of 14,9kHz. The measured phase margin of 64 degree is also close the calculated value of 68 degree. The difference between measured and calculated gain margin of about -12dB is relatively high due to parasitic components. This mismatch indicates, that even after a calculation of the key parameters, a measurement must be performed after the simulation to validate the key parameters of the closed loop response.

Fig. 7-1: CLR with standard output filter capacitance

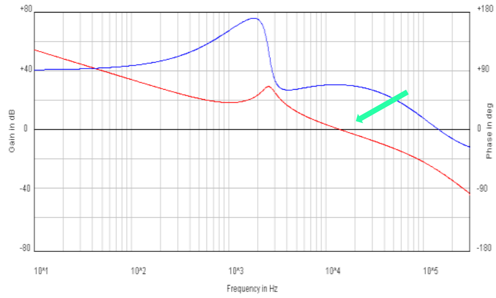

Fig. 7-2: CLR Simulation with the Power Stage Designer Tool

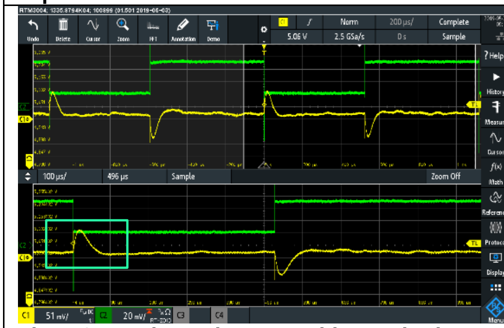

Fig. 7-3: Load transient test with standard output filter capacitance

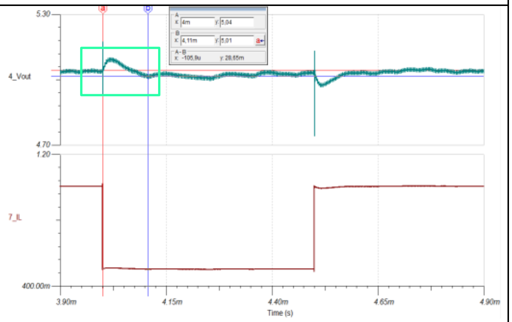

Fig. 7-4: Load transient test simulation with TINA

The load transient test simulation was performed with the TINA Spice simulation tool provided by Texas Instruments. In this simulation, the load was switched in the same manner (timing and current load values) as it was the case for the real measurement. In this simulation also most of the parasitic components like ESR of the capacitors were defined to get as close as possible to the real measurement.

The comparison between the measured results shown in Fig. 7-3 and the simulation results shown in Fig. 7-4 are very close together and this is very impressive. The response time of about 100us after the load switches is true for the simulation and for the measured value as well. This shows clearly that the simulation model is very close to the real circuit. The gap of the voltage overshoot between real world and simulation is about 20mV, which is a good match between the two methods. The curve itself shows a good regulation in simulation and in real measurement as well.

7.3 Simulation of output filter effects

The output filter consists of an inductor but also an output filter capacitor. These two components are part of the power stage and contribute to the loop characteristic of the system. To demonstrate the influence of the output filter on the loop response, the output capacitance was increased with an additional 100uF capacitance. This characteristic was already illustrated in chapter 6.4.

The changed characteristic of the output capacitance was also simulated with the simulation tools to demonstrate the different performance.

Fig. 7-5: Measured CLR with additional output filter capacitance of 100µF

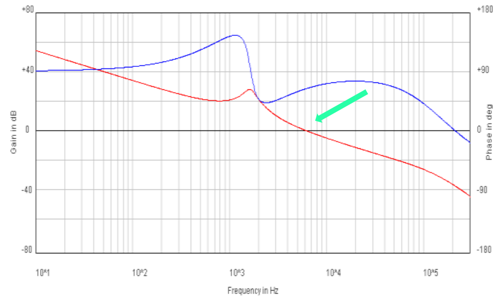

Fig. 7-6: Simulated CLR with additional output filter capacitance of 100µF

Fig. 7-7: Load transient test with additional output filter capacitance of 100µF

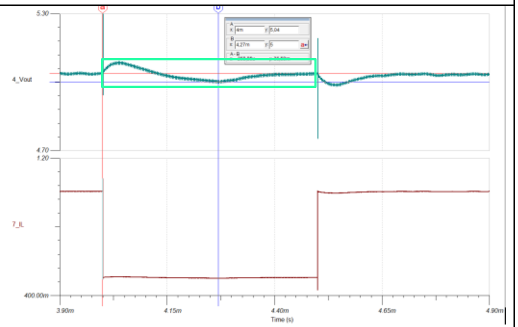

Fig. 7-8: Simulated load transient test with additional output filter capacitance of 100µF

In the CLR measurement, it can be observed that that the cross over frequency at 0 dB shifted from 15 kHz down to 5 kHz. This will reduce the regulation speed. In the simulation with the power stage designer the cross over frequency dropped from 14 kHz down to 6 kHz. This result is shown in Fig. 7-6 and is very similar what we evaluated in the measurement shown in Fig. 7-5. The expectation is that the simulation of the load transient test will show a very similar result as well. If you check the curve in the simulation shown in Fig. 7-8, you will notice that the regulation speed is reduced. In the measured curve, the regulation speed is reduced as well. The system is still stable but the time the system needs to regulate to the output voltage is longer than it was before the additional capacitance.

7.4 Conclusion

All simulated results for the closed loop response and for the load transient test showed more or less results, which are very close to the real measurements. Main reason for different results are parasitic components, which are not considered during modelling the design. If the user is aware of how the circuit functions and is able to include most of the parasitic components e.g. equivalent series resistor (ESR), a simulation is a suitable method to be performed before the first hardware model is available. This will provide the designer with better knowledge about the design and the designer will be able to apply changes much quicker as it would be the case with a real hardware. Anyway in some cases, it is very hard and a lot of effort to consider all parasitic components in the design. Therefore, a real measurement should be performed in any case when the first hardware model is available.

8 Effect of input filter on loop stability

8.1 Motivation

A PI filter circuit is often used to optimize the EMI during the switch-mode power supply design, but improper design of the input filter may cause instabilities in the system. This chapter discusses the influence of the input filter on the closed-loop gain, and explains how to solve instabilities in the closed loop by changing the input filter components. The CLR measurement is an adequate approach to verify the stability of the SMPS including the EMI input filter circuit.

8.2 Theory of instability caused by input filter design

In general, a switch-mode power supply input impedance can be described as a negative resistor. In case of a constant output power in a closed loop operation and assumed 100% efficiency, the input current drops if the input voltage increases. The negative resistor curve is shown in Fig. 8-1.

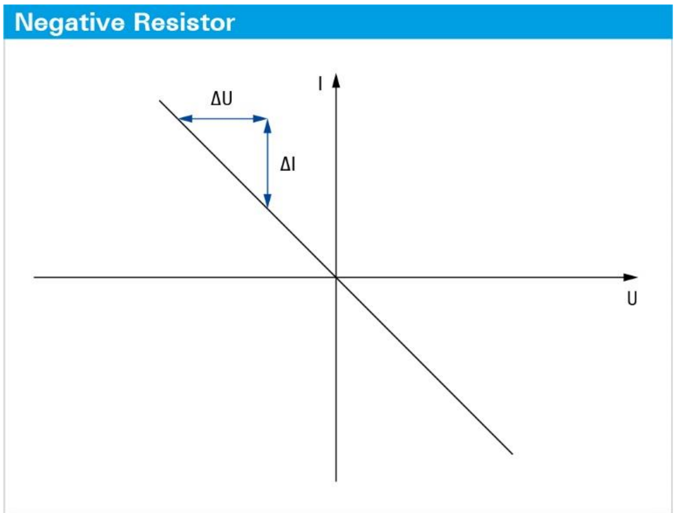

Fig. 8-1: Negative Resistor

This is in contrast to an ordinary resistor, which is positive. In this case, if the input voltage increases, the input current increases proportional. The curve of a positive resistor is shown in Fig. 8-2.

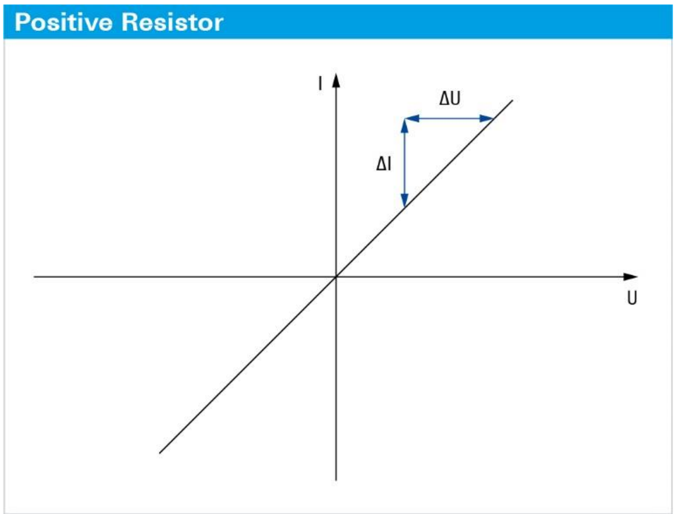

Fig. 8-2: Positive Resistor

In the context of input impedance, the SMPS input represents an active resistor. The filter inductor forms a series resonant circuit with the switching regulator input. Assumed that the losses of the input filter are very low this resonant circuit can result in oscillations at resonance frequency. Of course, this may influence the measurement of the CLR. In this case, it is important to modify the input filter instead of changing the compensation network to improve the CLR of the system.

To prevent the input circuit from this oscillation, a proper damping of the input filter is required. Anyway, the option to put a parallel additional resistor into the circuit for damping purpose is not practical solution. A better solution to reduce the quality of the filter components is to use electrolytic capacitors in the filter design. These kind of capacitors have a relative high equivalent series resistance, which will damp the resonance circuit and prevent the circuit from oscillations.

8.3 Conclusion

This chapter clearly mentioned the influence of the input EMI filter on the transfer function and thus on the control loop. The filter is mandatory in a SMPS due to conducted emissions and audio susceptibility requirements. Fortunately, there are some mechanisms to adapt the filter design to the power supply and its control loop. This adaption can be verified by performing a load transient test and the CLR measurement gives the designer confidence of a good power supply design in all circumstances.

9 Conclusion

The CLR measurement technique offers a great enhancement of already existing SMPS test like line and load transient test. The CLR measurement is not only a substitution of the well-known line and load test. Moreover, it offers the designer additional information and possibilities to verify the design. It is possible to avoid any field failures of the power supplies in its applications because the designer is capable to estimate the worst-case stability margins. Therefore, the risk of a re-design in a product stage where the power supply is already in the field is minimized.

Anyway, a problem with the load transient test we have is that you do not cover all circumstances of stability. Typically, the capacitors have big value in terms of tolerances. Imagine you get a new production lot of output capacitors. This will shift your crossover frequency and instability may occur.

In any measurement, some precautions have to be considered to get the highest fidelity of the measurements. For the CLR especially the correct probing is key for a proper measurement. The selection of the injection transformer is also part of the system considerations. Although, the profiling feature of the oscilloscope may help to compensate some weaknesses of the injection transformer.

Furthermore, it is much easier for the designer to debug or find the root cause when an instability of the power supply occurred. For instance, bad performance of the converter regulation is not necessarily associated with loop bandwidth or phase margin. A common pitfall in the input filter design of a power supply is that the filter damping is not efficient and oscillation may occur. This oscillation effect can be identified when there is no phase margin anymore before crossover frequency is reached. In this case, to modify the compensation loop does not solve the problem because the root cause is the input filter circuit.

In addition to the performed measurements, a simulation in the time and frequency domain may support the design process but it is not intended to substitute a real measurement during the design process.

With the means of an R&S oscilloscope with signal generator incorporated, a line injection transformer, the CLR measurement can be performed easy without any expensive real network analyzer. With this basic equipment, the designer will significantly increase the confidence level of the design.

10 Literature

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11 Ordering Information

Designation	Type	Order No.
Frequency Response Analysis option for R&S®RTB-series Oscilloscopes	R&S®RTB-K36	1335.8007.02
Oscilloscope, 70MHz bandwidth, 4 channels	R&S®RTB2004	1333.1005.04
Frequency Response Analysis option for R&S®RTM-series Oscilloscopes	R&S®RTM-K36	1335.9178.02
Oscilloscope, 100MHz bandwidth, 4 channels	R&S®RTM3004	1335.8794.04
Frequency Response Analysis option for R&S®RTA-series Oscilloscopes	R&S®RTM-K36	1335.7975.02
Oscilloscope, 200MHz bandwidth, 4 channels	R&S®RTA4004	1335.7700P04
Passive Probe, 38MHz, 1:1	R&S®RT-ZP1X	1333.1370.02

Appendix

A The reference board

http://www.ti.com/tool/pmp30595

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