Measurement Characteristics of an Automotive LED Driver Based on a Hybrid Controller

Application Note

Products:

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- R&S®RTA4000
- R&S®NGL202
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This application note describes different measurement techniques and methods for an automotive lighting module based on a hybrid controller design. Of course, a lighting module in such an environment has to fulfil requirements according to the automotive standard, which is typically a relatively high-level standard compare to the industry standard. The oscilloscope is a perfect tool for this application to verify the set of requirements because time domain signals (analog and digital) are present in the whole design. Furthermore, measurements in the frequency domain have to be performed, which a modern oscilloscope can fulfil. In addition to the oscilloscope, a programmable power supply supports the measurement in several measurements. The set of requirements are the main reason why a hybrid controller from Microchip is a great choice for this design because it provides tremendous analogue and digital capabilities. The hybrid controller provides beside the analogue functions like an operational amplifier digital functions like analog-to-digital converter and interface functions like UART, CAN or LIN to interact with other systems. The programmable software part is hosted in the digital part. The digital part of the controller implements the communication interface and provides status information to the outer system controller. The light source itself has to avoid any flicker and shall be capable to dim to different lighting levels. Wide input voltage variations and efficiency have to be taken into account during the design of a converter dedicated for automotive applications. Nevertheless, the measurement considerations presented with the design are valid and applicable in other professional lighting industries as well.

Thanks to Mr. Andreas Reiter and Mr. Milan Marjanovic from Microchip who provided us with hardware and software and their great expertise to create this application note.

Note:

Please find the most up-to-date document on our homepage http://www.rohde-schwarz.com/appnote/GFM339.

Application Note

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1 Introduction

1.1 LED Component

The facts, the user should know about how to operate a Light Emitting Diode (LED) in a lighting applications, are described in this chapter.

1.1.1 Characteristics

In general, the LED is a non-linear device with the U-I-Characteristic shown in Fig. 1-1.

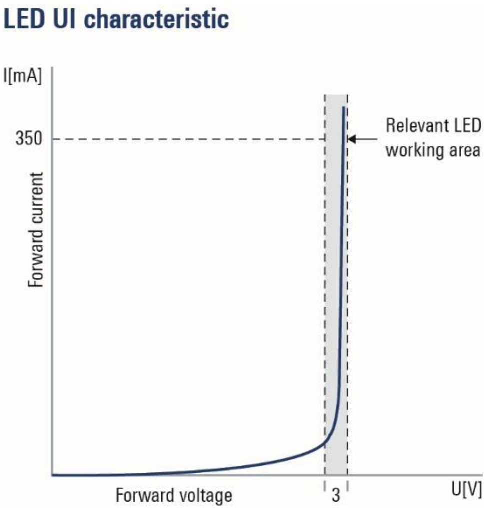

Fig. 1-1: LED U-I-Characteristic

If a low voltage is applied to the LED below the relevant working area, very low current will flow through the LED. As the voltage value is shifted into the relevant LED working area, the forward current will start to increase very sharply. If the applied voltage would be further increased, the current flowing into the LED will become even higher until the LED will be destroyed due to thermal overstress. This electrical characteristic is similar to the well-known semiconductor diode used in almost every electronic circuit with the exception that no photons are emitted.

However, the main purpose of a LED is to emit photons when current is flowing through the semiconductor material of the die. The more current is flowing, the more photons are emitted and the higher the intensity of the emitted light. In addition, with increasing intensity, a change in wavelength of the emitted light can be observed. Hence, changing the forward current of a LED results in two major effects, which are important for the design of a luminaire and its ballast.

The first and most dominant effect is the change in brightness. LED manufacturers have managed to keep the change in brightness sufficiently proportional to changes in forward current. Nevertheless, this proportional area is not linear and is limited to a defined, nominal forward current range specified in the manufacturer's data sheet. As each production lot produces LEDs with wide tolerances of up to 20% and more, manufacturers are separating LEDs of one and the same type in different sub-groups showing similar luminous flux at nominal forward currents. The Brightness Index Number (BIN) identifies these brightness classes. Each LED type may have up to seven different brightness classes, defined by their unique BIN.

The second, often undesired, effect is an observable change in color temperature, which comes with changes in luminous flux. This effect is produced by differences in the number of photons of specific wavelengths emitted. In comparison to a common light bulb, white LEDs do not emit a seamlessly distributed, coherent, white spectrum but show dominant peaks at specific wavelengths. Typical LED light spectrum often shows a wide, dominant distribution across 500 to up to 1000 nm (green to red) and a second, sharper, dominant peak at around 400-450 nm (blue). This dominant, blue peak increases in intensity over-proportionally with the forward current while the wider green-to-red area remains more stable. Hence, an increase in forward current inevitably also results in a change in color temperature. Higher currents will give the emitted light a cooler, blue touch while low forward currents will result in a warmer yellow-red tone. LED manufacturers tune their semiconductor materials and use different coatings such as phosphorous to achieve a wider distribution across certain ranges of the visible spectrum to limit these effects and tune color characteristics for applications like office lighting or convenience lighting. This color characteristic is given in manufacturer's data sheet as color temperature in Kelvin [K] at the given, nominal forward current.

As both parameters are depending on forward current, an adjustable constant current source is the best choice for any LED ballast. First, designers of these ballasts need to carefully choose the LED type with regards to brightness and color temperature over related forward current ranges matching their target application requirements. To ensure every produced luminaire eventually shows the same light characteristic in terms of brightness and color, it is important to keep in mind that both characteristics will change during operation with the temperature of the LED die and need to be dynamically compensated by the LED driver adjusting the forward current accordingly. As the LED also loses luminous flux efficiency over lifetime (aging effect), a compensation method within the LED driver by changing the forward current may ensure a constant brightness over lifetime of the luminaire.

The characteristics of a LED and derived requirements for the ballast described above will later allow us to determine the kinds of measurements we need to conduct to analyze and optimize the performance of the LED ballast under test.

1.1.2 Operating Methods of LEDs

As mentioned previously, an adjustable current source is the best choice to operate a LED with its characteristics properly. Several current source circuits exist which are well known and described within this chapter.

The simplest method of controlling a LED forward current is just a resistor supplied by a constant voltage source and in series to one or more LEDs to keep the current constant. The principle of a current source based on a resistor in series with a LED is shown in Fig. 1-2.

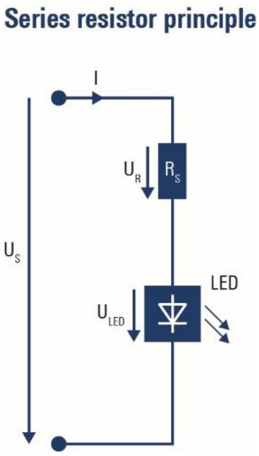

Fig. 1-2: Series Resistor Principle

Of course, this is not an optimized method to have a precise control of the constant current because the LED voltage is not constant and temperature dependent as mentioned earlier. Therefore, this is not a very precise current source and the different light output for different current sources may be noticeable by the human eye. Furthermore, this technique is not very efficient because of the losses in the resistor in the system.

Fortunately, another constant current method exists which is based on a linear constant current regulator. The principle of the linear constant current regulator is shown in Fig. 1-3.

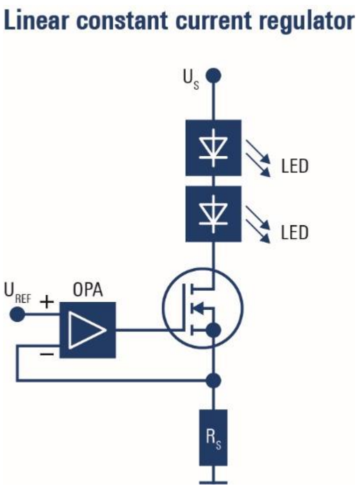

Fig. 1-3: Linear Constant Current Regulator

The linear regulator ensures that the current is constant due to the additional feedback path and therefore suitable to generate a constant light output. This is true also when the LED voltage varies due to temperature effects. Furthermore, the LED current is independent from the input voltage as long as the input voltage is higher than the LED voltage plus the voltage across the field effect transistor. The main reason for the constant current is that the LED current is measured via a series resistor. This small voltage across the resistor is compared to a reference voltage with the help of an operational amplifier. In this case, the MOSFET acts as a changing resistor when the current changes. The disadvantage of this approach is that the regulator (MOSFET element) works in a linear mode. Unless this leads to precise constant current, the efficiency of such a system is not very high. Additional cooling like a heatsink for the MOSFET may be required.

A switched-mode power supply (SMPS) is an approach to have a precise constant current and in addition a high efficiency in the system. This is true even the LED current needs to be in a higher range to increase the brightness. This SMPS approach has also the advantage that it can operate from a wide input voltage and as well as work with flexible output voltages. This SMPS method is described in more detail in the next chapter.

1.2 Converter Topology

There are different SMPS topologies existing, which would fit for driving a LED load with constant current. In general, the buck converter or step-down converter is one of the topologies, which would fit but has some disadvantages especially in automotive applications. As mentioned previously, the input voltage is highly variable in the automotive industry. The main disadvantage of selecting the buck principle for this environment is that the input voltage has to be always higher than the output voltage because of the converter topology. This would limit the maximum numbers of LEDs connected in series when you do not have a relative constant input voltage.

Beside the advantages of using switching converters, there is also a drawback, which has to be considered during the design of the converter. The fact that we have a switching converter principle, undesired harmonics will be generated by the system. These harmonics needs to be filtered accordingly. Especially in lighting applications, ac current at certain frequencies might be visible in light and noticeable to the human eye.

The LED ballast reference design analyzed in this application note is specified to operate at input voltages between 6 and 20 V including short-term peaks of up to 45V while being capable of driving LED strings from one to up to twelve series connected LEDs. Hence, input and output voltages may overlap eventually during operation, which requires a power converter topology capable of stepping the input voltage up and down seamlessly to provide a stable output voltage level for any number of the specified range.

The converter used in this design is a so-called single-ended primary inductance converter (SEPIC) and is described in more detail in the next chapter.

1.2.1 SEPIC Converter Topology

As mentioned previously, the SEPIC converter is able to generate a positive constant output voltage and current even working from a wide range input voltage supply. The main parts of a SEPIC power stage are shown in Fig. 1-4.

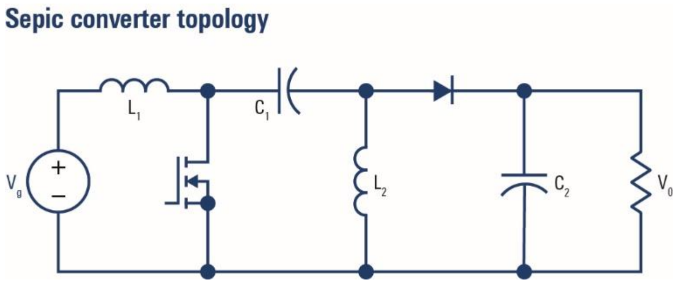

Fig. 1-4: SEPIC Converter Topology

The SEPIC topology consists of a boost stage (step up converter), followed by a buck stage (step down converter). The coupling capacitor connects the two stages together. The energy transfers from the input to the output in two cycles or states because of the structure of two stages and the coupling capacitor. However, the topology has also the advantage that the coupling capacitor provides an inherent short circuit protection in case of a shorted output. This capacitor isolates the input from the output when the switch is not actively operating. Furthermore, filtering at the input of the converter stage is easier because the input current is a continuously flowing current while the input current of the buck topology is discontinuous. The continuously flowing current may also improve the results of the EMI conducted emissions.

2 Driver Design Based on Hybrid Controller

The hybrid controller combines the best of the analogue and digital world in one physical part or device. The idea of Microchip's PIC16F1769 is to provide excellent performance of independent analog circuits, which can be extended, altered and tailored to match application specific requirements.

The structure of the LED driver including the main parts is shown in the Fig. 2-1 below.

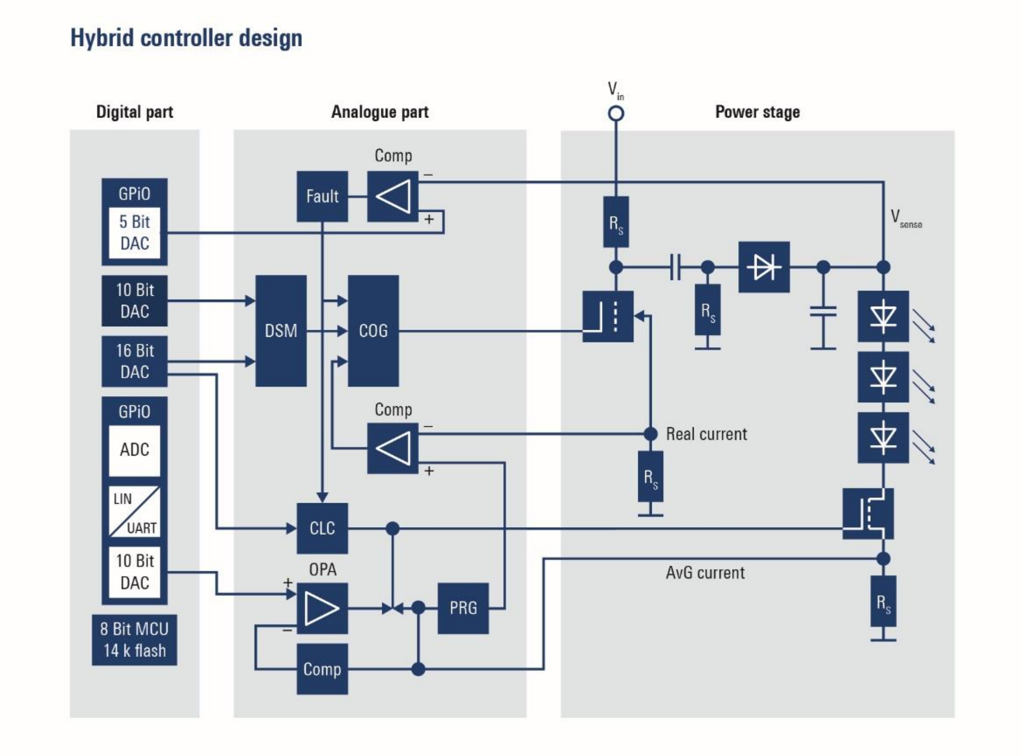

Fig. 2-1: Hybrid Controller Design

The design consists of the hybrid controller including analogue and digital part in one chip and the power stage including the LED load. The hybrid controller controls the whole circuit using its on-chip peripherals.

2.1 Features of the Design

The LED driver is able to maintain constant current and provides enhanced dimming technique with a single hybrid controller with few external components. However, the controller uses core independent peripherals like operational amplifier and comparator to operate the power stage in a fixed frequency continuous conduction mode and controls the LED current by a peak current mode control (PCMC) with no interaction of the software. A programmable ramp generator module is provided to apply a slope compensation, which is typically needed above 50% duty cycle for the peak current control method. This provision allows the user to develop the regulation feedback loop including the compensation network with high performance and to use established design methods from the analogue world.

The analogue output current control is enhanced with digital functions. For example, the switching frequency is configured in the 10Bit PWM module by setting the registers. Furthermore, the dimming frequency of the driver is generated by the 16Bit PWM module. Different digital to analogue converter modules (5Bit and 10Bit) are used to support reference voltages, which can be changed at runtime by the software executed by the MCU core.

Analogue to digital converter are used to measure external analogue voltages. In the design, the temperature and binning information of the LEDs are derived from external measurements. Protection or diagnostic functionalities like under voltage lockout or over voltage lockout are implemented in the digital part by software and operate independently from the analogue part.

In addition to the peak current mode control, an enhanced dimming technique is provided. With this enhanced technique, side effects like color shifting or lifetime reduction of LEDs during conventional PWM dimming can be eliminated. Therefore, a combinatorial logic cell (CLC) for switching an external switch and the possibility of setting the operational amplifier into a tristate are provided. This functionality will be discussed in further details in the dimming chapter.

Furthermore, the user can select different dimming curves like linear or logarithmic type at runtime. The dimming mode can be changed via the digital interface, UART or LIN.

The hybrid design is very flexible for the user and provides the capability to obtain a great performance of the design. Due to the core independent peripherals, the analogue part of the controller is able to regulate the output current completely with no interaction of software parts. However, the flexibility needs also some validation techniques to ensure and release a proper design for production. The most important validation methods will be presented in more detail in the following chapters.

2.2 Controlling software features

An external GUI provided by Microchip is used to control the driver. The main control window of the GUI is shown in the Fig. 2-2 below.

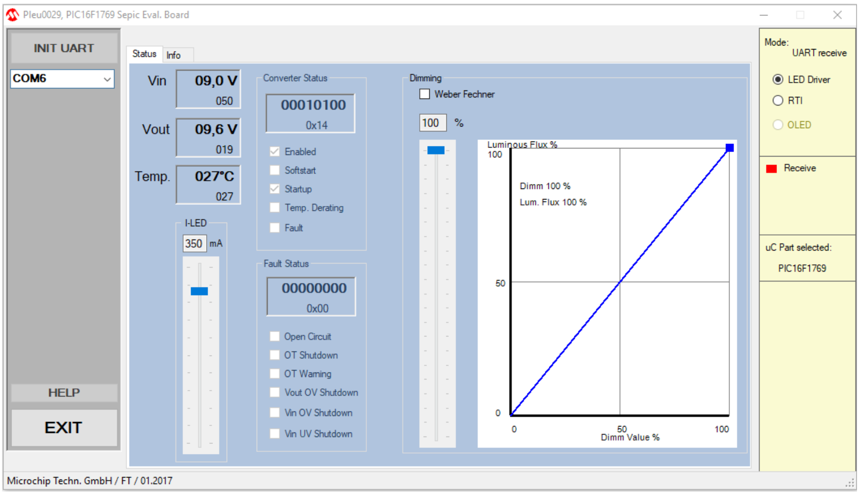

Fig. 2-2: Software GUI tool

This software is able to receive status information like temperature and LED voltage information or to select programmed features in the hybrid controller. For example, the user is able to select between the linear or the logarithmic dimming curves capability. Furthermore, the maximum LED current value can be set via this graphical user interface. The GUI tool is easy to use and is connected via the UART channel of the DUT.

2.3 Development tools

For programming the PIC-Controller, the MPLAB X IDE was used to change any lines of code in the software like constants or configuration settings. Please refer to Microchip's website in order to obtain more information about development tools.

https://www.microchip.com/mplab/mplab-x-ide

2.4 Design Data

The device under test is provided by Microchip and the design data, more detailed information and all relevant software packages can be downloaded by using the following link:

https://www.microchip.com/wwwAppNotes/AppNotes.aspx?appnote=en575383

3 Validation of the LED Driver Functionalities

3.1 Startup and Tracking the Behavior

The measurement of a start-up sequence is an important task to perform in this application because the designer has to validate functional parts like the LED output current ramp-up. This current ramp-up validates the control loop partly and the user can ensure that the ramp-up function is fast enough and the ramp-up slope has no overshoot. An overshoot may cause undesired light outputs, which are typically observable by the user. The best method to track the output current is actually at the input of the power stage. In other words, the duty-cycle of the PWM output is the best input for the track function of the oscilloscope. In this case, the user is able to analyze that the control loop behaves correct or it has to be optimized accordingly.

The start-up sequence measurement is shown in Fig. 3-1

Fig. 3-1: Startup Sequence

The sequence starts with triggering at the gate of the main switch on channel four. This channel shows the gate voltage and is used to track the duty-cycle later on. As mentioned, the duty-cycle is shown as a track and is defined in the math channel to show the behavior of the start-up in more detail. The voltage across the current sense resistor represents the LED average current and is shown in the trace of channel three. In the LED current, a small part of the switching frequency of the converter (350 kHz) is visible. However, the human eye is not able to see this high frequency content in the light output.

The start-up details are shown in an additional zoom window, because during the first part after the input voltage (channel 1) is applied, no switching is visible. During this time, the controller gets initialized. This has to be done before the controller can start with transferring energy from the input to the output. In this case, the size of the memory within the oscilloscope plays a big role to obtain a suitable record length.

After the initialization of the controller, the switching of the element has started and the duty-cycle is visible in the track functionality and start to increase. The slope of the duty-cycle is reasonable flat and has not overshoot. This is how an ideal slope has to look like. However, after reaching the steady-state current, there is a small dip visible in the output current probably caused by some noise effects. This is shown in Fig. 3-2 in a more detail view.

Fig. 3-2: Duty-Cycle drop

It is clearly visible that the duty-cycle drops significantly for a short period. Therefore, the output current drops after some switching cycles because the delay is caused by the power stage. However, it is important to mention that the information of the duty-cycle may help to understand the system behavior in more detail.

3.2 Fault Detection and Protection

In the LED driver design, several fault detection and protection mechanisms are implemented because of functional safety reasons, which are required in automotive applications. Most of them are implemented in software and that is the reason why it is very important to validate after implementation by means of a measurement. Due to the time correlation between the fault event and the detection, an oscilloscope is the perfect choice for the validation process. The protection methods consists of the following:

- Input under voltage lockout

It is used to prevent excessive currents in case of a small input voltage event. This method is described in the following paragraph in more detail.

- Input overvoltage lockout detection

This method is very similar to the under voltage lockout except that the limit is set to the maximum input voltage. The limit is set and can be changed in the software part.

- Output overvoltage detection

It is implemented to detect any over voltage at the output LED string. This protection method is based on hardware comparators shutting down the switching PWM immediately to prevent damages of the LED load. The threshold reference voltage is set in software at runtime and continuously adjusted to account for changes in forward voltage due to temperature changes.

- Short circuit protection at the output of the driver

Due to the peak current mode control (PCMC) mechanism where the current is controlled cycle by cycle, it is very easy to recognize any short circuit at the output terminal. As in PCMC the inductor current is automatically truncated by the peak current comparator, any over-current or short circuit condition will immediately result in a hard current limit, preventing electrical overstress at the load.

- Input voltage protection

It is required to prevent damage to the hardware in case of reverse polarity input voltage. This method is implemented in hardware and is not further discussed.

- Over temperature protection

It is necessary to prevent any thermal runaway of the design and is required due to safety reasons. This feature is implemented in software as part of the temperature compensation of the forward current and power derating scheme as soon as the design approaches its maximum allowed temperature.

3.2.1 Input Undervoltage Lockout

3.2.1.1 Motivation

Typical automotive power distribution networks (PDN) specify a wide variety of input voltage transients. Some of them may be temporary short-term hiccups others may be caused by more severe system failures. Carmakers release detailed specifications such as Volkswagen's VW80000 defining the expected transient waveform and test condition. An additional application specification will define the expected device response referenced to each transient specification. Hence, automotive LED drivers require an advanced delay adjustment capability of under-/over voltage level detection versus the point where an actual fault response is tripped. These adjustable delays are required to allow fast line-dropouts to pass while being buffered by on-board hold-up capacities, while other, long-term drop-outs will eventually lead to a converter shut-down. As specifications may differ between different converters and applications, the fault response is adjusted in software.

These delays need to be known when running measurements to be able to distinguish between voltage threshold accuracy and delay period accuracy.

3.2.1.2 Validation

The input under voltage lockout is implemented in a way that the converter shuts down the power stage in case of an input voltage event of less than 6V. For a validation, an input variation of the input is needed. This can be provided by any DC supply but in case of a programmable DC supply like the NGL202, it is much faster and easier to measure such an event in combination with an oscilloscope.

In the Fig. 3-3 The input voltage was measured on channel 1 while at the same time the output current was measured on channel 3 to analyze the behavior of the functionality. In addition, the usage of the cursor of the oscilloscope can help to measure the input voltage threshold voltage. In the measurement, the threshold of the input voltage is about 6V, which was the limit definition in the software. In this case, many software programming and setting failures (wrong scaling of AD converter, calculation within the software, AD-configuration) can be excluded by this validation method.

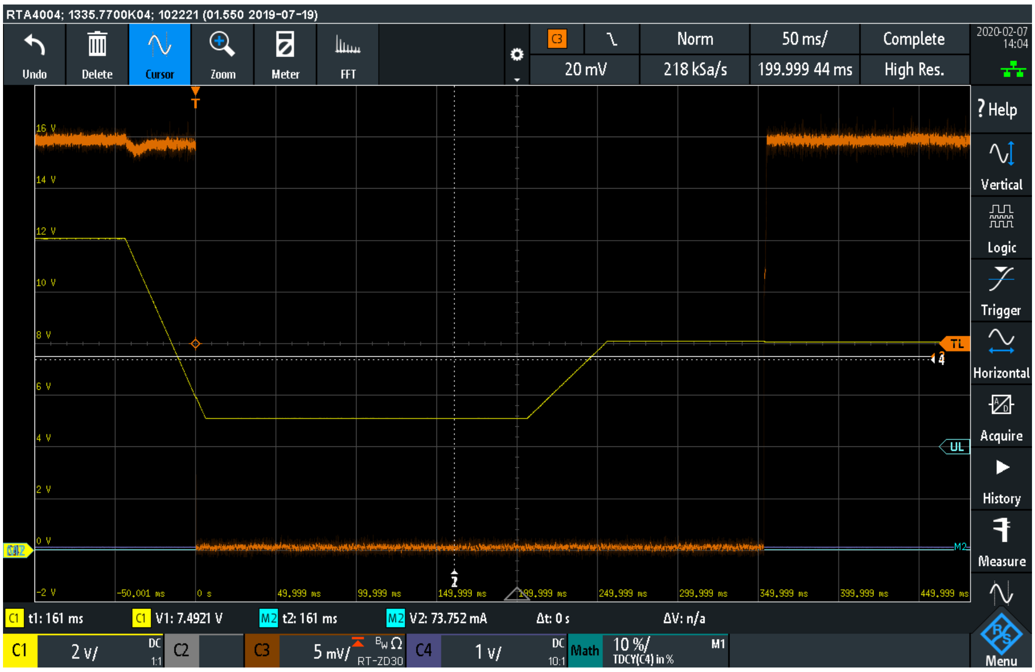

Fig. 3-3: Restart of Converter after Under Voltage Event

Beside the switch off in case of under voltage, a hysteresis has to be applied because oscillation may occur instead. In our application, a hysteresis of 1.5V was defined. This means the point where the controller switches the converter in on state after switch off is at 7.5V.

To verify the hysteresis, it is necessary to change the input voltage of the DC supply. In Fig. 3-4 the level of the input voltage was reduced to 6.6V to check that the hysteresis of 1.5V is not set. In this case, the converter will not switch on after applying the new input voltage profile. However, due to the flexible and programmable DC supply, this process can be automated and validated very easy.

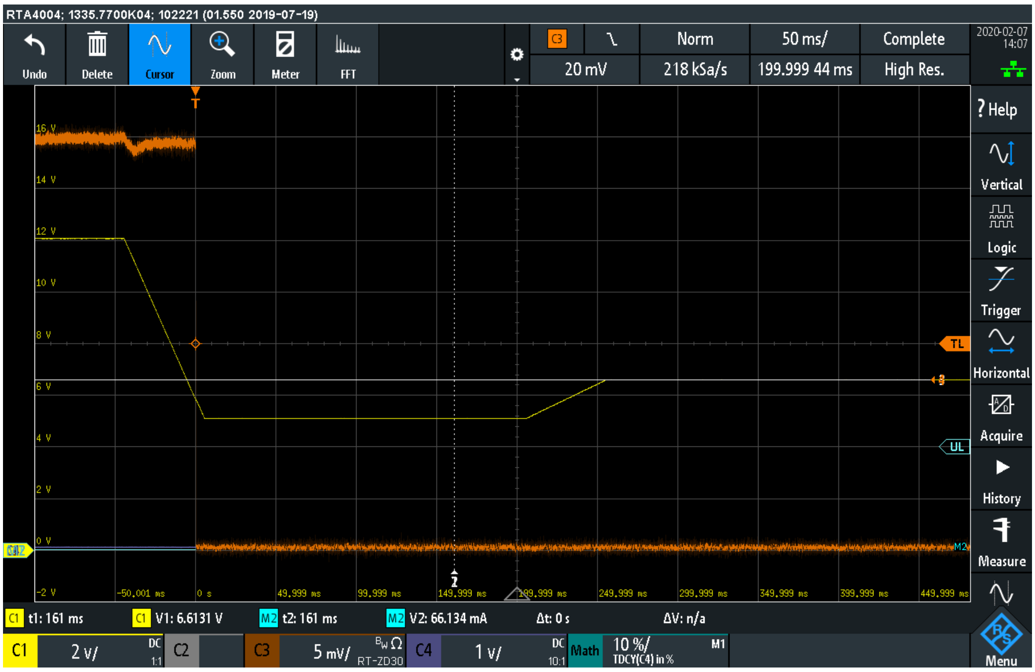

Fig. 3-4: Restart Fail of Converter after Under Voltage Event

3.2.2 Output Overvoltage Shutdown

An output overvoltage protection is always required because the design has to be always cost efficient. In this case, the components of the converter are limited to certain values and therefore also to the size. For example, the output capacitor size depends also on the maximum output voltage and therefore some precaution are required to limit the output voltage. In the software part, there is an overvoltage detection and implementation, which has to be validated. Again, this is a perfect application for an oscilloscope with sufficient capabilities.

To validate the overvoltage shutdown sequence, an open circuit was caused by hand to create an output overvoltage. This is a typical failure mechanism when a single LED is in a failure mode "Open Circuit". This behavior and its related signals is shown in Fig. 3-5.

Fig. 3-5: Output overvoltage shutdown sequence

The result shows, that the converter shuts down the system after reaching the output voltage of about 37V. The defined value in the software part is at 34V. Of course, due to the fast rise time it exceeds the limits slightly. However, the protection mechanism implemented by software can be validated easily by means of an oscilloscope.

3.3 Dimming Techniques

3.3.1 Common Diming Methods

LED lighting applications in the automotive environment require often a dimming functionality implemented in the device. However, two common dimming techniques are typically used in lighting applications:

- Analogue dimming
- PWM dimming

Which technique is preferred, depends on the dedicated lighting application. In some cases, also a combination of analogue and PWM dimming technique is applied.

3.3.1.1 Analog Dimming

This dimming method is practically not introducing any noise and thus do not require any additional hardware components other than an adjustable control loop reference voltage. However, as described in chapter 1 of this application note, the impact on LED brightness always comes with a significant impact on color temperature when the forward current is changed. Thus, this dimming technique is only applicable to applications where color temperature does not matter or brightness variations are small enough to keep the effects on color temperature negligible.

3.3.1.2 PWM Dimming

In applications where the adjustable brightness range is wide and color temperature is important, linear or analog dimming becomes insufficient. The method used to achive both, exact constant color temperature at an exact luminous flux (brightness), is to adjust the forward current to the desired level by turning the luminaire on and off at frequencies beyond the point where the human eye can distinguish between on- and off-states. The human brain then starts to filter the information to a perceived, continuous illumination at a seemingly lower brightness level even if each emitted light pulse produces light at full intensity. It is commonly perceived that most humans cannot consciously detect light frequencies above 200 Hz. However, this only applies to static lighting and while a test person is not moving.

In automotive applications, higher frequencies are required as luminaires are moved with high speed across roads to which the human eye is much more sensitive while multiple luminaires are operated close to each other potentially producing optical interferences. Camera systems with attached image processing capabilities are very sensitive to PWM dimming frequencies. Therefore, the DUT provides dimming frequencies at 1 kHz while providing options to increase the dimming frequency up to 5 kHz.

The PWM dimming approach implemented in a DC-DC Converter is illustrated in Fig. 3-6.

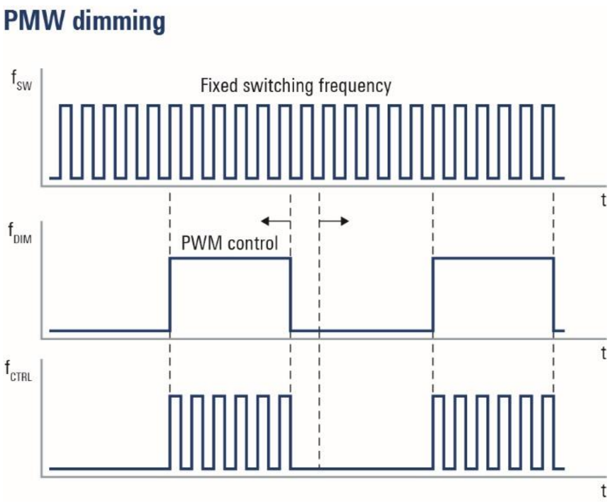

Fig. 3-6: PWM Dimming

It shows the switching frequency of 350 kHz, which is required for the converter to operate the switches to transfer energy to the output. The PWM dimming frequency is much lower than the switching frequency and is superimposed on the switching frequency of the converter. The resulting switching input for the power stage is the control frequency. In case of a desired change in the output light level, the PWM dimming duty-cycle ratio has to be changed.

However, the PWM dimming has the advantage that there is no color shift when the system is driven to small current levels because the dimming is performed by reducing the average current by changing the dimming control duty cycle ratio. In this case, the current remains at the peak current during on time.

In our application, the PWM dimming technique is highlighted. Some additional precautions or design consideration have to be taken into account to avoid any undesired behavior. These behaviors are described in the next paragraph.

3.3.2 Challenges of the PWM Dimming

What is required to apply a PWM to our converter topology? You need to control your current regarding the peak current during the on time of the PWM and you have to reduce the current down to zero during the off time. When you do not spend additional hardware this is a challenging task to do.

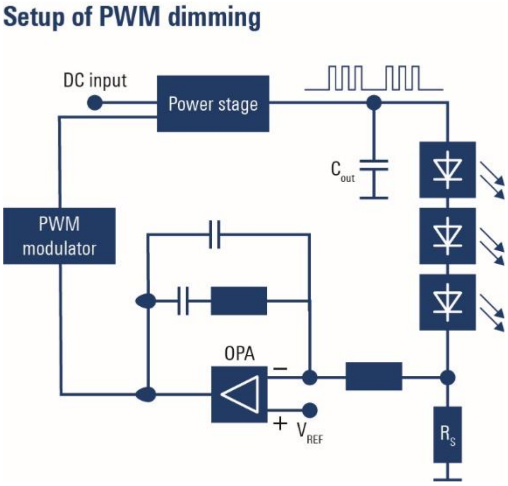

Fig. 3-7: Setup of PWM dimming

The setup how to dim the current with the PWM approach is shown in Fig. 3-7. The problem with this setup is actually that the PWM modulated control signal generates big load steps in the LED output current. This behavior is a challenge to for the feedback circuit including the compensation components to be fast and stable at the same time.

The result of the output current is shown in Fig. 3-8. Due to the big load steps, the continuously running integrator tends to generate a current overshoot because the integrator may be saturated during off time. This overshoot leads to a reduced LED lifetime. In addition to the current overshoot, the output capacitor is discharged with a long time constant during off time because the differential resistor of the LED becomes a big value. The resulting low current will generate a color shift in the LED string.

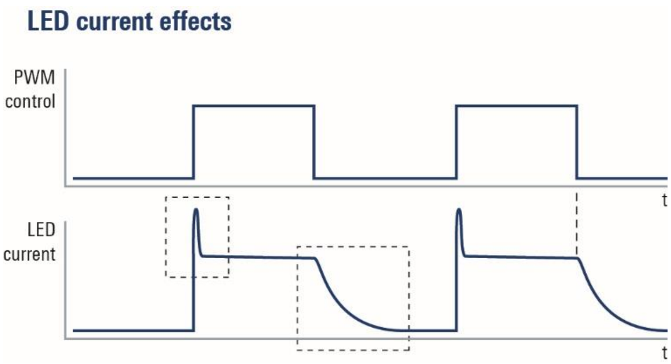

Fig. 3-8: LED current effects

However, the PWM dimming is typically selected to avoid color shift in the LED's. Therefore, additional hardware and enhanced control methods have to be implemented to avoid the undesired behavior. These options help to optimize the PWM dimming. The options are described in more detail in the next paragraph.

3.3.3 Enhanced Dimming with Hybrid Controller

Due to the fact, that the integrator is running continuously it saturates during the off-time period when applying a PWM dimming method. The hybrid controller provides a functionality to set the output of the error amplifier from an active condition into a tristate condition. This great flexibility will help to avoid the saturation of the feedback regulator and its compensation network. Furthermore, an additional switch is used and is triggered by the controller to interrupt the LED current completely. The setup of the enhanced dimming is shown in Fig. 3-9.

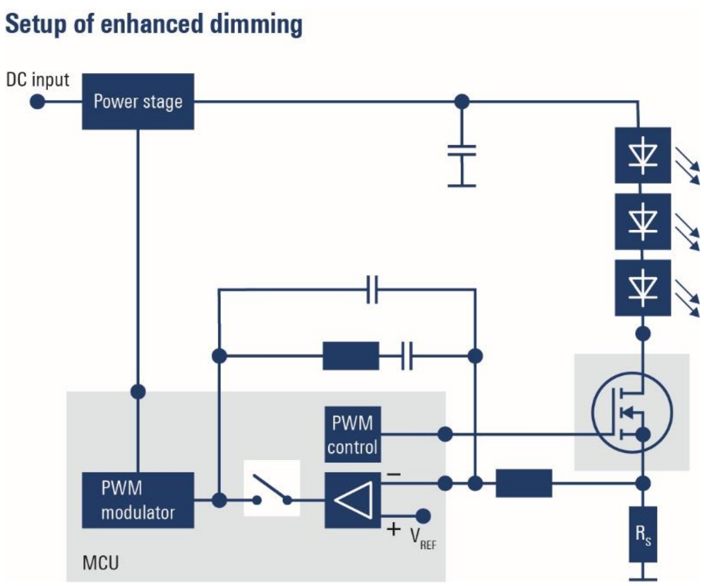

Fig. 3-9: Setup of Enhanced Dimming

The usage of the tristate logic works in the following manner: During the tristate condition, the compensation network is completely disconnected from the feedback loop and holds the last point of the stable feedback. The charged compensation capacitor do not change because of the tristate condition. When the next on time of the duty cycle appears, the compensation network is reconnected and the control loop can work directly from the last stored values. This helps that the output current jumps immediately to the previous output current value and no overshoot will occur.

The discharge effect caused by the output capacitor is avoided by the use of an additional switching element to interrupt the LED current. The switch is connected in series with the LED output current and is synchronized with the PWM dimming control circuit. In this case, the switch ensures that there is no current flowing from the output capacitor into the LED during the off state of the duty cycle. Therefore, the color shift due to very low current during of time does not exist anymore.

The result of the enhanced dimming technique is shown in Fig. 3-10

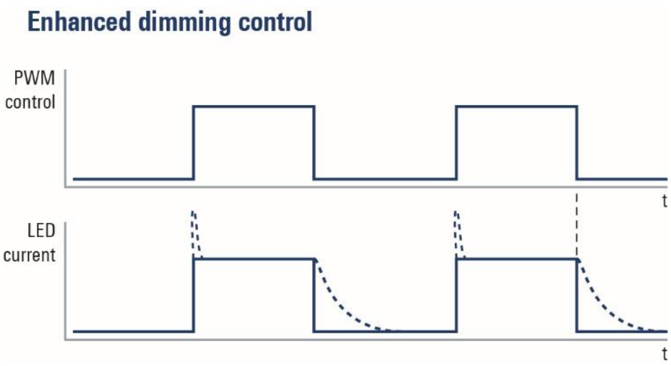

Fig. 3-10: Enhanced Dimming Control

In this case, the current waveform is represented rectangular. This ideal rectangular waveform should be visible in our time domain measurements. Even this is not controlled by software, the configuration of the tristate and control of the external switch is done by setting the register in the digital part. Therefore, these functionalities must be validated and this is done with the oscilloscope. The result of the enhanced dimming technique is shown in Fig. 3-11.

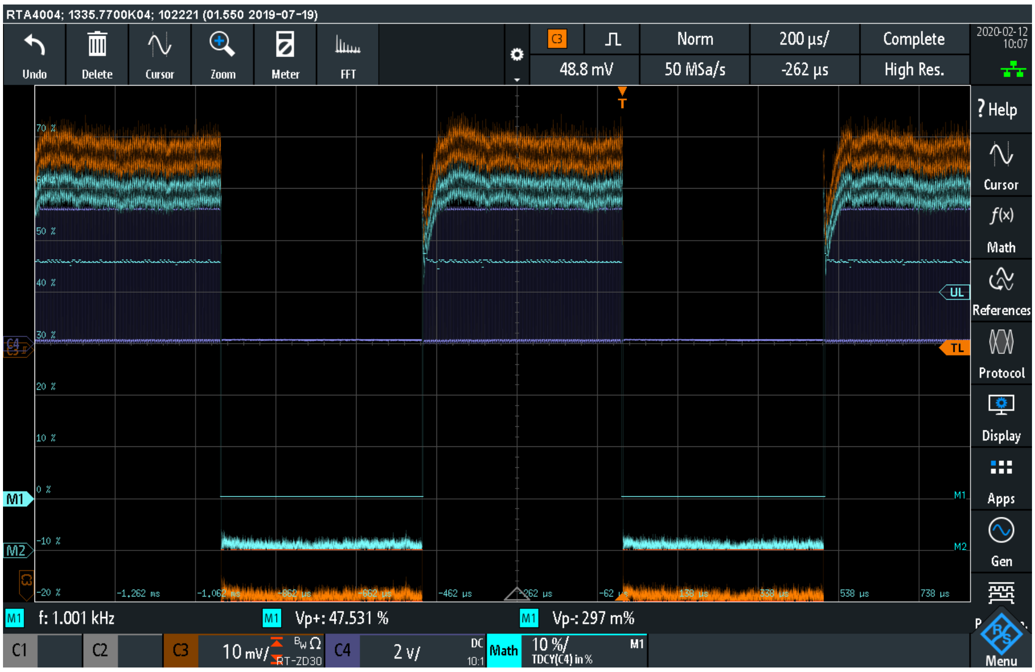

Fig. 3-11: Enhanced Dimming Measurement

The output current is measured with a differential voltage probe and is shown at channel 3. The light blue M2 represents the calculated current from channel 3. In this measurement, also the duty-cycle track function of the oscilloscope is activated used to analyze the control signal of the PWM modulator (M1). The information of the duty-cycle indicates that the integrator is not saturated. It starts with almost the same duty-cycle value during the on-to-off transition and the off-to-on transition. In addition, the LED current does not exceed the average current during the on time. In other words, no current peaks appear at the beginning of the switch on period. However, the usage of PWM track function helps to analyze the performance of the enhanced dimming technique. Due to the PWM, a suitable trigger technique has to be defined.

The details of the transition from off-to-on state is shown in Fig. 3-12. In this measurement, the start of the LED current is shown. Also in this zoomed view, no peaking of the current occurs. The duty-cycle is the same because the loop compensation is stored from the previous on time. In addition, the measurement shows a slight drop in forward current at the beginning of each new dimming PWM pulse. The small dip in forward current lasts for approx. five to six switching cycles (~15 µsec). This dip is caused by the leakage discharge of the output capacitor during the dimming off time but is so small and short, that it does not show any measurable optical effects and can safely be neglected.

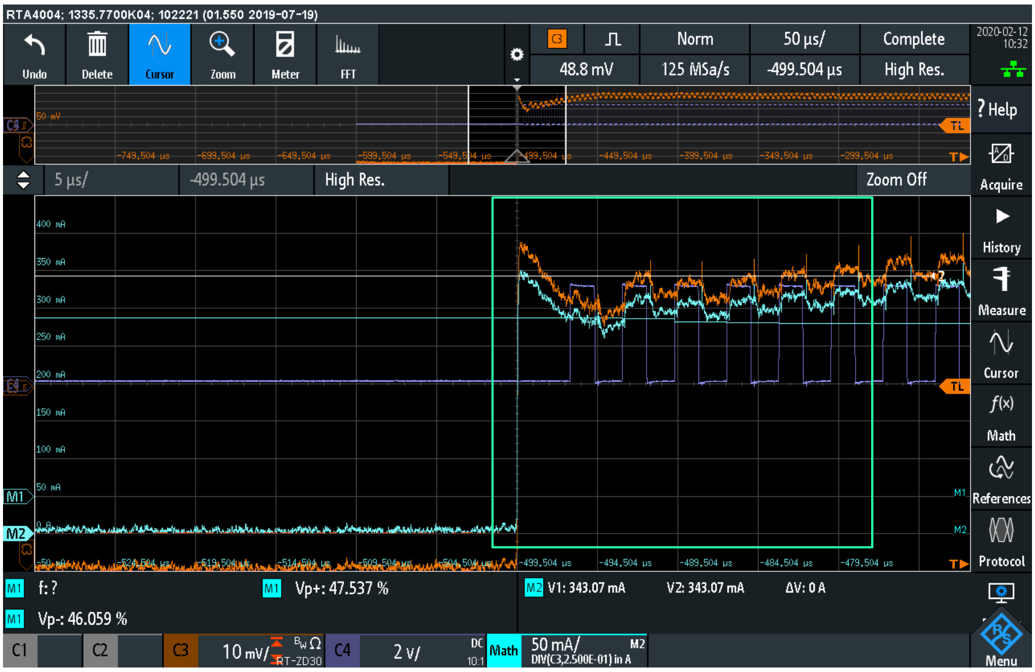

Fig. 3-12: Start of PWM on time

The details of the transition from on-to-off state is shown in in Fig. 3-13. The small current discharged via the output capacitor described in the previous chapter do not appear. This is a good indication that the external switch, controlled by the controller works properly.

Fig. 3-13: Start of PWM off time

The user does not program the control of the enhanced dimming technique. However, a validation with an oscilloscope can ensure that the configuration of the registers is implemented correct. The configuration has to be implemented in the software part by the user.

3.4 Frequency domain measurements and considerations

Typically, the designer calculates the compensation network to obtain the best response of the feedback loop in the system. In this case, the designer can be sure that the driver operates not only in a stable condition, but also in a condition that the driver acts fast enough on load changes. However, the calculation of gain margin and phase margin has to be validated by a real measurement. Typically, this would require a vector network analyzer, which is a dedicated device for this purpose. Rohde & Schwarz oscilloscopes integrate frequency response measurements as part of the common software environment making this additional, rather high investment obsolete.

With common DC-DC converters, the setup of the compensator is a very structured, straightforward process. In this process, poles and zeros of the power plant are derived from a model and compensated by adding poles and zeros to the compensation filter. For each pole found in the plant transfer function, a zero to the compensation filter needs to be added. For each zero found in the plant transfer function, a pole needs to be added to the compensation filter. For a proper loop compensation, zero and pole locations should match. It is safe to assume that applying this practice will sufficiently stabilize the power supply and influences introduced by attaching a load to the power supply may be minor. A common feedback loop tuning procedure is performed, where pole and zero locations of the compensation filter are adjusted to meet certain, application-specific performance criteria.

In current source applications such as battery chargers or LED drivers, however, this approach is different as the load is an additional circuit of the closed current loop, connected in series to the power plant. Therefore, its influence is dominant and needs to be taken into consideration when calculating the compensation network filter components.

3.4.1 Setup of a Closed Loop Response Measurement

3.4.1.1 Motivation

Due to the fact, that the humans should not perceive any flicker while the LED driver is in operation, a sufficient damping factor of the gain in the system at lower frequency has to be determined. In this reference design, -20 dB @150 Hz was determined to assume that no flicker is noticeable by any human observer. This defined damping factor might be different in other applications.

Knowing the slope of -20dB/decade of the transfer function, a cross over frequency of 1.5 kHz in the outer current loop is determined. The outer current loop measurement including the led load is required to validate the flicker behavior of the system.

This measurement is definitely not sufficient to evaluate the converter stability because the LED load influence dominates the loop response of the system.

3.4.1.2 Measurement Setup

The setup of a closed loop measurement for a current source converter is shown in Fig. 3-14.

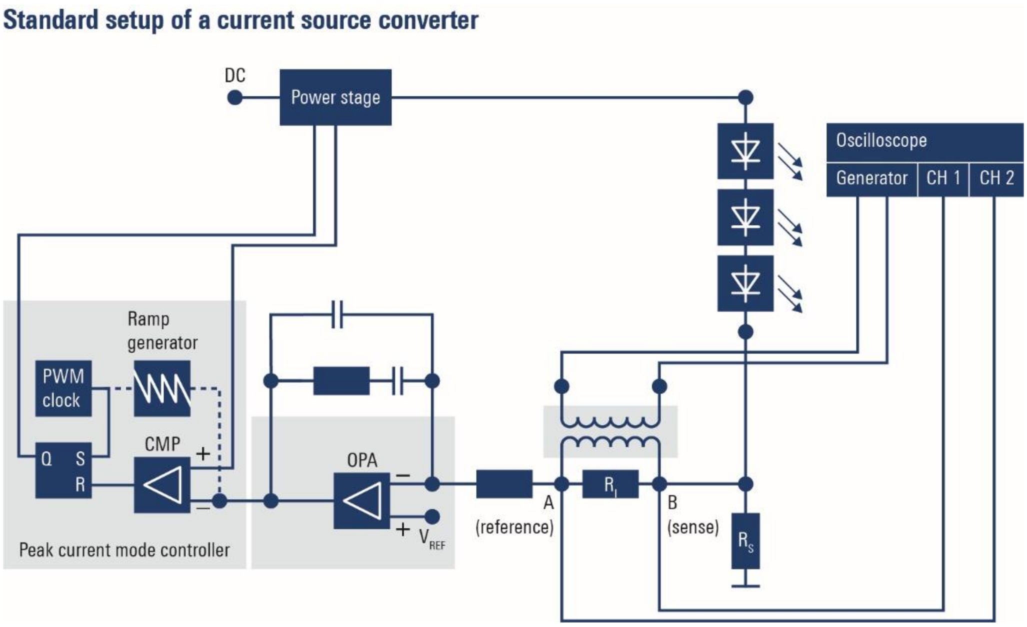

Fig. 3-14: Standard Setup of a Current Source Converter

This is the standard setup to measure the frequency response of a DC-DC converter working as a current source converter. It consist of an oscilloscope, the injection transformer and a small injection resistor. Two probes are used to measure the voltages at the injection point (Sense) and reference point (Reference). Eventually gain and phase can be calculated from the measured voltages. This closed loop measurement can be performed with an oscilloscope from Rohde & Schwarz.

The result of the loop measurement is shown in Fig. 3-15.

Fig. 3-15: Standard Loop Response

The result of the gain and phase margins indicate that the loop is stable and should not cause any trouble. The phase margin is at 86 degree. Phase margin values, which are higher than 60 degree, indicate than the system is very stable. The result of the gain margin is at -32 dB. Gain margin values, which are above -15 dB, indicate that the system is very stable. The cross over frequency of this outer current loop measurement is at 1.1 kHz, which is slightly below the desired 1.5 kHz.

However, as mentioned previously, the LED load influences these conservative margin values tremendously. In reality, these values are different when only the converter stability is the focus of the measurement. Therefore, an additional measurement technique is required where the converter stability can be measured to analyze the converter according to the stability criteria.

Therefore, the setup is changed to exclude the LED load from the existing closed loop measurement setup. This topic is described in more detail in the next chapter.

3.4.2 Measurement Setup of Plant & Compensator

3.4.2.1 Motivation

As described previously, the LED load influences the measurement of the converter and the stability criteria of the plant and the feedback loop cannot be evaluated correctly. Therefore, the measurement setup has to be changed in a way that the LED load is still connected to the plant but the probing is done in way that the feedback loop and the plant is measured and the LED load is excluded. Only the inner loop (plant and compensator) shall be measured to evaluate the stability criteria correctly.

3.4.2.2 Measurement Setup

To exclude the LED load in the loop response measurement, the user has to change the probing of the measurement setup. The required measurement points are shown in Fig. 3-16. The injection resistor and the injection point remains the same as shown previously.

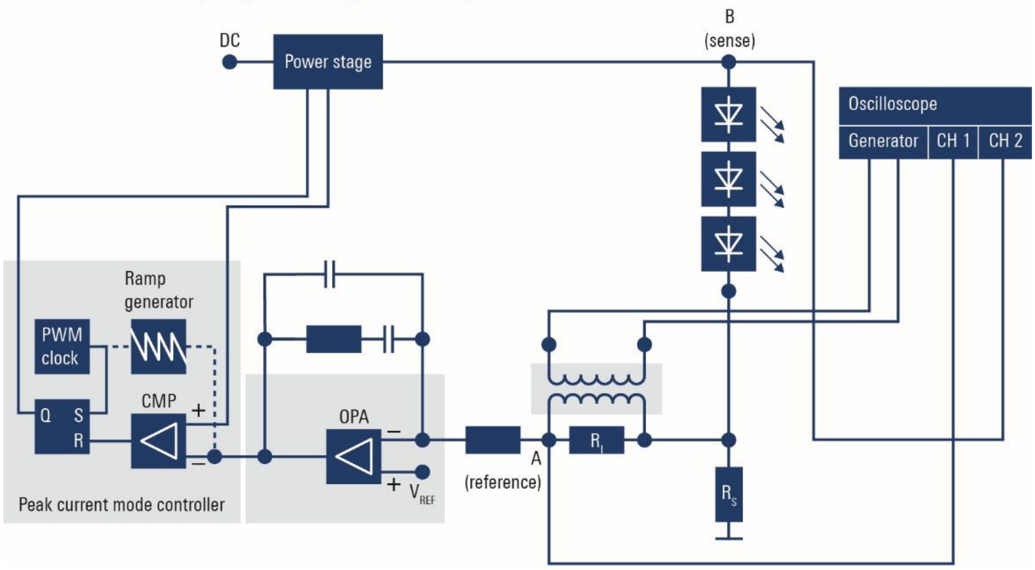

Fig. 3-16: Measurement Setup of Power Stage and Compensator

The result of the measurement is shown in Fig. 3-17. The result of the measurement shows different values of the stability criteria. The margins for the gain and phase changed completely compare to the previous measurement setup. The phase margin is at 38 degree while the gain margin is at -7 dB. The cross over frequency has changed to approximately 14 kHz.

Compare to the values measured including the LED load, the margins dropped tremendously. However, these new measured values are the correct values to evaluate the margin criteria of the converter design. Therefore, the developer has to change the measurement setup slightly if he wants to use the gain and phase margin values to evaluate, optimize and validate the converter design and its compensation filter.

However, the phase margin of 38 degree obtained during the measurement does not give a lot of confidence to have a proper and stable design. At least 45 degree is required. In addition the gain margin of -7dB is a low value. If the converter tends to oscillate in some cases, it can have an impact on the reliability or even functionality of the design.

Fig. 3-17: Plant and Compensator Loop Response

In DC-DC converter design, the capability of the oscilloscope to measure the frequency loop response gives the user already a great benefit. However, in case of an LED application, this can support the user to analyze the control loop in a very detailed way. Proper loop validation is an essential design validation step and vital to keep most expensive field failures and related damages to a minimum.

3.4.3 Measurement Setup of the LED Load

3.4.3.1 Motivation

In addition to the measurements described in the two previous chapters, a different measurement setup is also required to measure the frequency response of the LED load. Only with this additional information, the designer is able to specify the required converter design and to design the required compensator components accordingly. To obtain a cross over frequency of the outer current loop of 1.5 kHz (required for flicker prevention), a cross over frequency of 15 kHz of the inner current loop is required. However, the relation between the outer current loop and inner current loop cross over frequency depends on the result of the LED frequency response measurement. Therefore, a single measurement of the LED load loop response is mandatory to obtain a proper overall system design.

3.4.3.2 Measurement Setup

The required setup to measure the CLR of an LED load is shown in Fig. 3-18

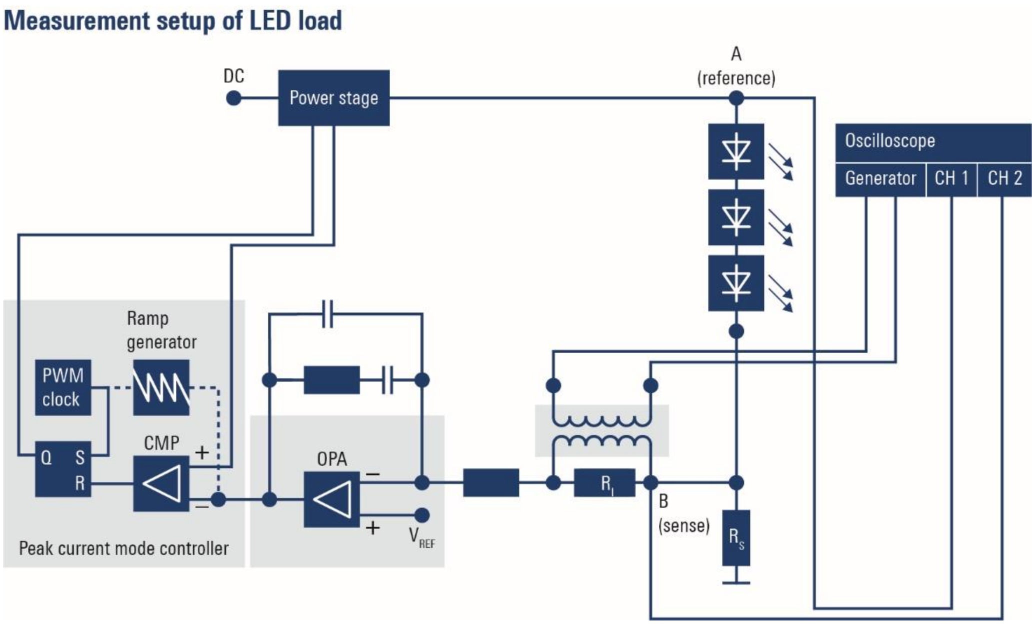

Fig. 3-18: Measurement Setup of LED Load

With this setup, the user is able to measure only the LED load frequency response. The power stage and the compensator are excluded in this measurement setup by changing the probe connections only.

The result of the measurement is shown in Fig. 3-19.

Fig. 3-19: LED load response

It is remarkable that there is a constant gain over the relevant frequency range of about -25dB. If you consider subtracting this value from the previous measurement (plant and compensator), this will result in less gain and phase margin what was measured during the first measurement setup where the LED load was included in the setup.

It is clear that this LED load gain value hides the response result of the converter. However, the loop response of the LED load has to be performed to be able to design the converter and its compensator properly.

3.4.4 Conclusion

All different measurement methods and setups are required to obtain a proper validation of the whole design regarding converter stability and flicker prevention.

3.5 Light Stability

3.5.1 Power Supply Rejection Ratio (PSRR)

In lighting application, it is always the case that light stability is required. This is an optical measurement, which is not easy to measure for each designer during development. Typically, special optical equipment like a flicker meter according to the standard is needed to measure the light stability. However, applying a modulated signal with different frequencies at the input while measuring the reaction of the LED output current is a good method to validate the driver in terms of light stability. Of course, this measurement does not cover the light stability of the complete luminaire with regards to electrical perturbation. Further measurements are needed to fulfil the complete standard of the light stability. The setup of the light stability measurement based on PSRR is shown in Fig. 3-20.

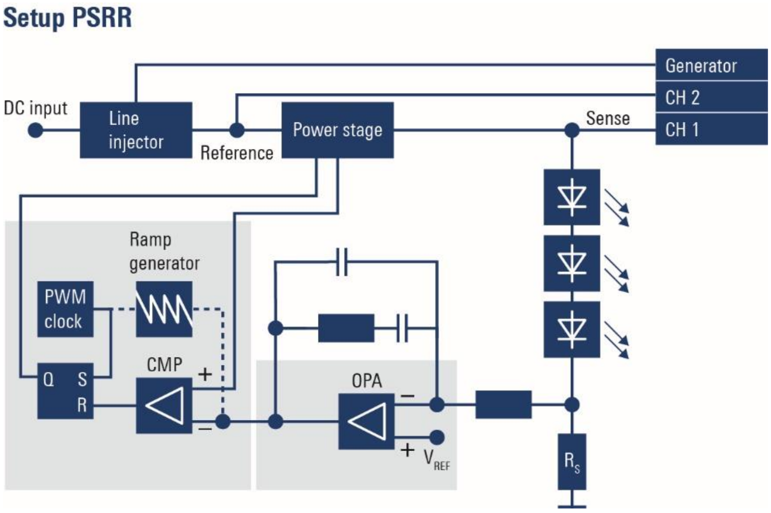

Fig. 3-20: Setup for Light Stability

This setup requires a line injector device to inject the error signal at the input of the converter. The oscilloscope generates the error signal with the bode plot application, which was used already for the closed loop response measurement in the previous chapter. A voltage probe at the input and output with the oscilloscope has to be connected, while injecting the signal at the input via the generator and line injector. The result of the PSRR measurement is shown in Fig. 3-21.

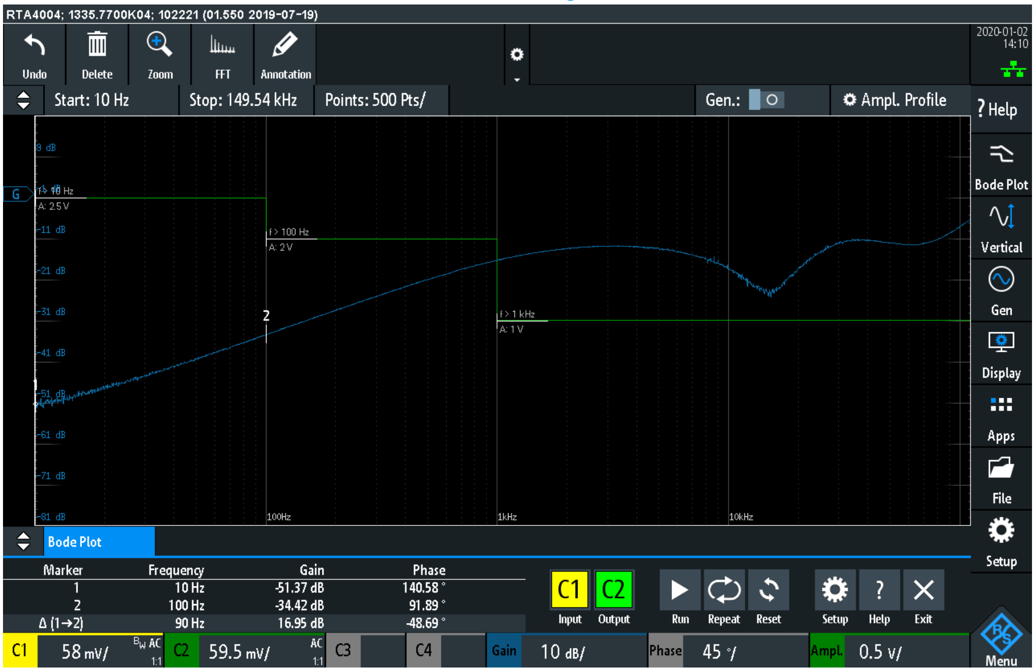

Fig. 3-21: Power Supply Rejection Ratio measurement

The blue trace shows the result of the gain over the frequency. The critical frequency range is between 10Hz and 1000Hz because the human eye is more sensitive in this range. The damping at 10Hz is about -51dB and at 100Hz about -34dB, which are reasonable values. Of course, this is a kind of pre-compliance measurement because no direct light measurements were performed. However this gives already a good indication whether the light might be perceived to be stable or not by a human observer.

3.5.2 FFT

The FFT functionality of the Rohde & Schwarz oscilloscope may also help to identify instabilities in the light output. At least this is a suitable method when the waveforms appear periodic. The FFT of the output current at full brightness is shown in Fig. 3-22.

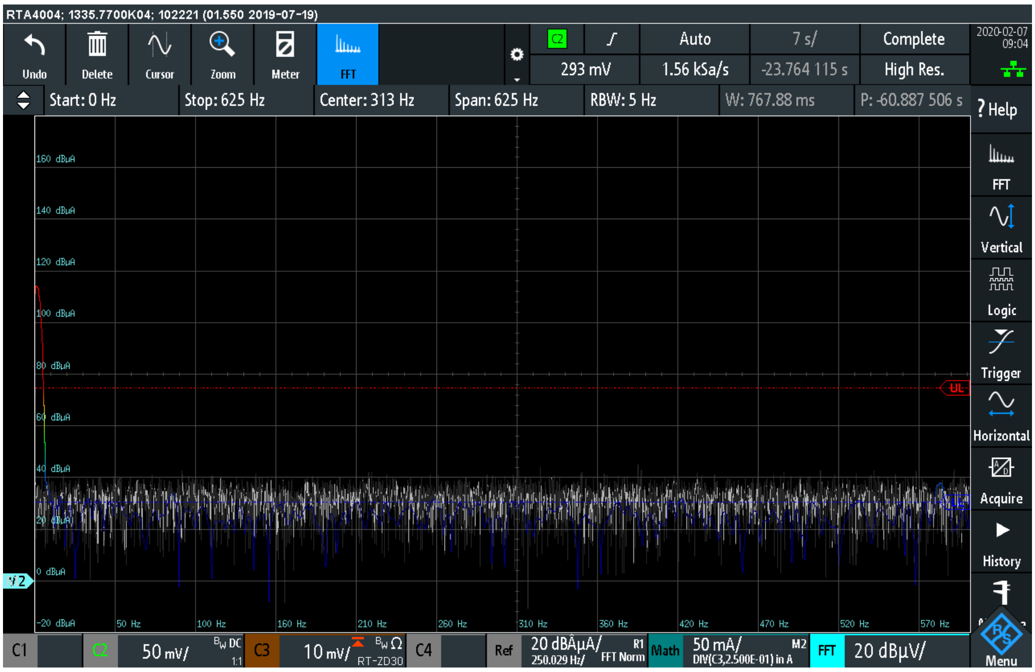

Fig. 3-22: Full Light Output

In the critical frequency range between 1Hz and 500Hz, there is no harmonic visible, which would imply some flicker at a certain frequency. The noise level at zero current is shown in the reference channel (white trace).

To demonstrate a real visible flicker, a measurement was performed at 10mA but this dimming level is set with analog dimming. However, a flicker is visible by the human eye so the expectation is that it is visible also in the FFT. The measurement is shown in Fig. 3-23.

Fig. 3-23: Analog Dimming at Low Current (8mA)

The result of this FFT indicates that the output current content has some harmonics at lower frequencies. Especially the frequency range between 1Hz and 100Hz shows some harmonics, which have critical amplitudes.

The difference in the FFT when the PWM dimming method is used is shown in Fig. 3-24.

Fig. 3-24: PWM Dimming at Medium Current (160mA)

It is clear that the PWM frequency is the main part of the frequency spectrum. The fundamental frequency is visible at the defined frequency of 1 kHz. Of course, the visible peaks in the spectrum are not affecting the light stability because they are all far beyond the critical low frequency region.

The FFT capability of the oscilloscope is a great method to analyze the flicker trend of the design in an early state of the development phase. This measurement can ensure that problems with flicker will not occur right before the product launch.

4 Conclusion

The validation process of a hybrid controller design requires extensive measurements to release a product during and after the development phase. Of course, several different methods exists but they require in some cases additional measurement equipment. A dedicated vector network analyzer is needed to perform the closed loop response measurement or to perform the power supply rejection ratio (PSRR). Furthermore, an external power supply combined with an arbitrary generator is required to validate protection functions implemented in the software of the system.

The Rohde & Schwarz proposal may help to reduce the amount of different equipment needed for the validation process. The capability of the oscilloscope to measure the closed loop response test or to perform a PSRR measurement to evaluate the light stability is a great benefit. Furthermore, beside the time-correlated analog or digital signal measurement, the decoding option for LIN or CAN may help to validate or analyze any information within the data stream.

The Rohde & Schwarz programmable power supply with its built-in capability to generate freely programmable waveforms will support the designer to validate different voltage variation scenarios defined in the automotive standard.

The Rohde & Schwarz solution is a perfect measurement setup to cover most of the design requirements or even requirements of the automotive standard.

5 Literature

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6 Ordering Information

Designation	Type	Order No.
R&S®NGL200 Power supply series	R&S®NGL202	3638.3376.03
Oscilloscope, 200MHz bandwidth, 4 channels	R&S®RTA4004	1335.7700P04
Frequency Response Analysis option for R&S®RTA-series Oscilloscopes	R&S®RTM-K36	1335.7975.02
Passive Probe, 38MHz, 1:1	R&S®RT-ZP1X	1333.1370.02
Active Differential Probe	R&S®RT-ZD30	1410.4609.02

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