VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
BRNO UNIVERSITY OF TECHNOLOGY

FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ
ÚSTAV JAZYKŮ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
DEPARTMENT OF LANGUAGES

Specifications of switched DC/DC converters used for automotive LED applications. Parameters of suitable power MOSFETs, option of partial- damping of their switching operation and their impact on circuit proprieties

Vlastnosti spínaných DC/DC měničů pro automobilové LED aplikace. Parametry vhodných výkonových MOSFETů, možnosti zatlumení, vliv na chování obvodů

BAKALÁŘKÁ PRÁCE
BACHELOR THESIS

AUTOR PRÁCE Lukáš Langer
AUTHOR

VEDOUCÍ PRÁCE Ing. Josef Vochyán, Ph.D.
SUPERVISORS Mgr. Agata Walek

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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

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Ústav jazyků

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Student:	Lukáš Langer	***ID:***	147385
Ročník:	3	***Akademický rok:***	2014/2015

NÁZEV TÉMATU:

Vlastnosti spínaných DC/DC měničů pro automobilové LED aplikace. Parametry vhodných výkonových MOSFETů, možnosti zatlumení, vliv na chování obvodů.

POKYNY PRO VYPRACOVÁNÍ:

Stručně popište typické LED moduly používané v moderních předních světlometech, zaměřte se na druhy a parametry budicích obvodů. Prostudujte parametry výkonových MOSFET tranzistorů a způsoby redukce generovaného šumu. Získané znalosti ověřte měřením na zvoleném vzorku budiče. Okomentujte způsoby a průběhy měření, vyzkoušené úpravy a jejich vlivy na celkové chování obvodu. Práce necílí na technické detaily, ale těžiště je ve zvládnutí jazyka při obecnějším popisu principů a postupu měření.

DOPORUČENÁ LITERATURA:

Small Signal OptiMOS 606 MOSFET in Low Power DC/DC Converters: Application Note AN 2012-12 v2.0 December 2012. 2012-12-06. Infineon Technologies Austria AG 9500 Villach, Austria, 2012

GRAOVAC, Dr. Dušan, Marco PÜRSCHEL a Andreas KIEP. INFINEON TECHNOLOGIES AUSTRIA AG. MOSFET Power Losses Calculation Using the Data-Sheet Parameters: Application Note, V 1.1, July 2006. Infineon Technologies Austria AG 9500 Villach, Austria, 2006.

MAXIM INTEGRATED. 2013. MAX16833/MAX16833B-MAX16833D: High-Voltage HB LED Drivers with Integrated High-Side Current Sense. Maxim Integrated Company. 19-5187; Rev 6; 8/13.

Termín zadání:	9.2.2015	***Termín odevzdání:***	22.5.2015

Vedoucí práce: Mgr. Agata Walek

Konzultanti bakalářské práce: Ing. Josef Vochyán, Ph.D.

doc. PhDr. Milena Krhutová, Ph.D.

Předseda oborové rady

Upozornění:

ABSTRAKT

Tématem bakalářské práce je úvod k využití nových prostředků pro osvětlení automobilů, zejména pak osvětlení pomocí LED. Tato práce bude zaměřena právě na systém LED osvětlení a jejich zapojení a spínacích obvodů. Dále bude práce věnovaná LED budičům pomocí MOSFETů, jejich parametrům a vlivům na jejich obvody. V práci bude také popis samotného měření daných obvodů s rozborem měření i jeho výsledků. Práce necílí na technické detaily, ale těžiště je ve zvládnutí jazyka při obecnějším popisu principů a postupu měření.

KLÍČOVÁ SLOVA

budiče LED, LED, MOSFET, spínání, světlomety, tlumení, transistor, osvětlení, ztráty

ABSTRACT

The main topic of this bachelor thesis is an introduction to the usage of a new device for automotive lights, mainly LED lights. The thesis is focused on the usage of LED lights, their circuits and drivers. Furthermore, the thesis is aimed at power MOSFETs suitable for LED drivers, their parameters and their effect on the circuits. In the thesis will be included also a description of the measurement of given circuits with following comments on the output as well as the comment on the measurement itself. The goal of the thesis is not in technical details, but it is in a usage of English language used for more general description of principles and measurement processes.

KEYWORDS

automotive lights, damping, LED, LED drivers, lighting, losses, MOSFET, switching operation, transistor

LANGER, L. *Vlastnosti spínaných DC/DC měničů pro automobilové LED aplikace. Parametry vhodných výkonových MOSFETů, možnosti zatlumení, vliv na chování obvodů*. Brno: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií. Ústav jazyků, 2015. 38 s., 1 s. příloh. Bakalářská práce. Vedoucí práce: Ing. Josef Vochyán, Ph.D., Mgr. Agata Walek.

PODĚKOVÁNÍ

Děkuji vedoucím bakalářské práce, kterými byli Ing. Josef Vochyán, Ph.D. a Mgr. Agata Walek za účinnou metodickou, pedagogickou a odbornou pomoc a další cenné rady při zpracování mé bakalářské práce.

V Brně dne ....

(podpis autora)

PROHLÁŠENÍ

Prohlašuji, že svoji Bakalářskou práci na téma „Vlastnosti spínaných DC/DC měničů pro automobilové LED aplikace. Parametry vhodných výkonových MOSFETů, možnosti zatlumení, vliv na chování obvodů“ jsem vypracoval samostatně pod vedením vedoucích semestrálního projektu a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.

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V Brně dne ....   ……......................................

(podpis autora)

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LIST OF SYMBOLS AND ABBREVIATIONS

LED – Light Emitting Diode

DRL – Day Running Lights

PCB - Printed Circuit Board

IC – Integrated Circuit

MOSFET - Metal-Oxide-Semiconductor Field-Effect-Transistor

INTRODUCTION

The history of automotive lighting over decades

The beginning

The introduction of motoring in the beginning of the last century brought us a new challenge and that was lighting for cars. It is not possible to finish journey on time with a help of day light every time and artificial light became a must. During first days the solution was usually primitive - drivers used torches and lanterns. In 1912 Carello introduced the first electric head light for cars followed by Bosh in 1913, who upgraded this system with battery and alternator. [2]

This step was sufficient until the early 1930s when the traffic became heavier and a need for fog lamps, brake lights and rear lights was satisfied owing to Bosh. Also, while cars were faster and faster, a need for distance lights came as a must. A driver needed to see further in the distance and that was impossible with a low beam. In those times of 1940s the light equipment was almost the same as we know it today. The main problem was the service life of those lights and bulbs used. The energy consumption, the capacity of the batteries and their size were still slightly bigger than nowadays. [2] In 1957, just 5 years before halogen lights were introduced, Bosh came up with a pack of basic lights, such as low beam, high beam and side markers in one unit. In the next 15 years, alongside with halogen lights, double bulb lights were also introduced and installed into cars.

vehicle type	speed [km/h]	speed [m/s]	reaction time [s]	reaction distance [m]	full stop time [s]	full stop distance [m]	10% of safety distance [m]	**necessary distance for full stop** limited visibility for full stop [m]
horse-drawn carriage	8.00	2.22	1.00	2.22	2.00	4.44	0.44	**7.00**
horse-coach	15.00	4.17	1.00	4.17	2.00	8.33	0.83	**13.00**
vintage car	60.00	16.67	1.00	16.67	2.00	33.33	3.33	**53.00 (low beam)**
modern car - road	90.00	25.00	1.00	25.00	3.00	75.00	7.50	**108.00 (high beam)**
modern car - highway	130.00	36.11	1.00	36.11	4.00	144.44	14.44	**195.00**

Table 1 Car light limits to stop

Halogen lights

The halogen lights were introduced in the early 1960s in Europe as a replacement for old and inadequate sources of lights that had been used before. It took almost 20 years to be implemented in cars in the United States. Unlike their predecessor, they are able to produce more light with a longer bulb service life. Nowadays the halogen lights are still the most used ones such as low-beam, distance lights, fog lights, and parking lights. [1]


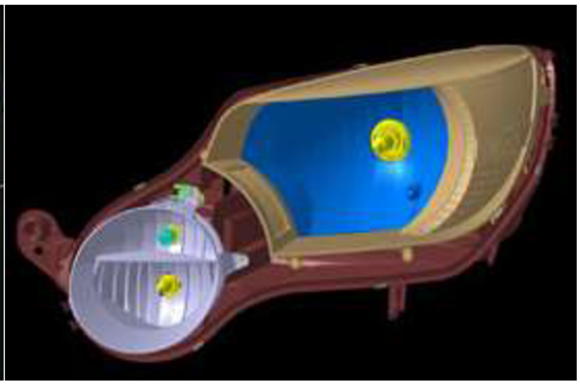

Figure 1 Halogen lights – Škoda Yeti 1 [1]

Figure 2 Halogen lights – Škoda Yeti 2 [1]

Xenon lights

The next big step forwards was made in 1991 when Xenon lights were introduced for a public market. Their big advantage is twice bigger light efficiency with only one third electricity consumption compared to halogen lights. Another advantage is their service life that is almost the same as the one of the car they are installed in. [1]


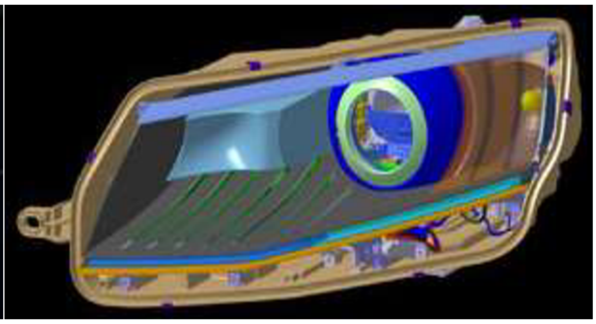

Figure 3 Xenon Lights – Škoda Octavia 1 [1]

Figure 4 Xenon Lights – Škoda Octavia 2 [1]

Basic LED Lights

LED lighting is now common in motorism and it is based on semiconductor technology which gives us plenty of advantages compared to other lighting methods. One of them is a much more space that is available in the head lights area as well as in the rest of the places that had to be used. Due to this, there is a bigger possibility of placing and installing the LED lights in the headlight area. Another big advantage of LED lights in any sphere of interest is its low electricity usage very appreciated these days. Other difference is the quality of produced lightening which is nearly the same as the quality of day light. The future of this lightening principle is not warranted yet and it depends on the future development in this field. [1]

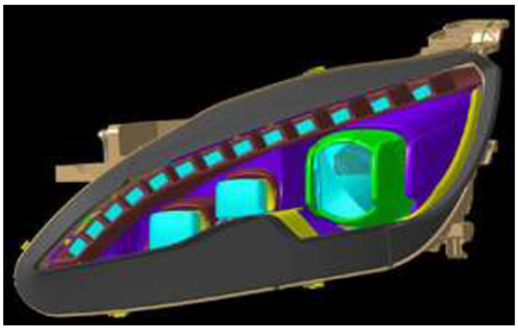

Figure 5 Basic LED 1 [1]

Figure 6 Basic LED 2 [1]

Advance LED

This advanced LED technology gives much more time to the driver during the whole journey so one could focus better. The thing and main difference between Advanced and Basic LED technology is that low-beam and distance lights are controlled by a computer. This works on the principle of full-time cooperation of BiGl and LFX modules that are able to make up to 14 various light modes. These modes are corrected automatically and the process of switching between those modes is smooth, following the signals from sensors taking into account lights in the opposite direction or the speed of the driven car. This is also better for the drivers in the opposite direction as they are not blinded by distance lights. [1]

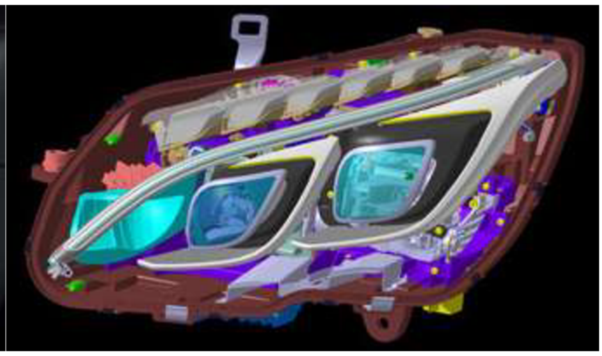

Figure 7 Advanced LED 1 [1]

Figure 8 Advanced LED 2 [1]

LED LIGHTS

Advantages

In order to understand the advantages LED lighting offers us, it is necessary to understand how Light Emitting Diodes work. LED is composed of a semiconductor diode. On account of the properties of this semiconductor material, the diode is able to conduct electricity. And because it works on the principle of conducting the electricity, even solar power can be used to keep LEDs operating, and in this way, it saves the energy that is man-made. And the light produced by LED lights is a cool light. [3]

This cool light feature of LED is also a solution for cooling problems of normal bulbs, which produce more heat than light. Not much space is needed around the diodes. This feature helps designers during projection of lights. It is easier to put smaller LED lights on the right place without any bigger heat precautions and also they could be installed into harder accessible places easier.

The power consumption is reduced drastically. Halogen bulbs use plenty of electrical energy to produce light, but when using the LED technology, only a fraction is needed to produce the same quantity of light. For a low beam, it is usually 2 x 55 Watts for halogen lights and 2 x 10 Watts for LED lights while the same luminance is kept. [6]

Speaking about lower power consumption, another advantage appeared. With lower current and voltage also smaller diameters / cross sections of wires can be used. There is no need for a big and heavy relay then and the circuits can be made smaller, lighter, more compact, and suitable. Also less material is needed to produce these components.

Long life of LED lights is a good and welcome change too. According to the market offer, LED lights last for about 10 up to 20 times longer than halogen bulbs. This feature saves money needed to buy new bulb, but also time needed for maintenance as well. And this working time is extended every day as a result of the progress in research in this technology field. [4] [5]

The light color variety of LED lights is an advantage as well as it is possible to make any color needed for the given use. No extra filters are needed and because they have much lower heat production, it is easier to use them. [6]

It is also much easier with power supply to keep LED lights working longer as less energy is needed to keep them in an operational status. Instead of big battery sources, LED lights are able to work from their own energy source that could be small and placed at the same place as the lights. Or, keeping them connected to the main circuit gives them much more time to operate without major effect on the energy supply. On the other hand, a small power supply can be used in case of emergency which could be small and independent so more security could be guaranteed. [6]

Durability of LEDs is also a step forward compared to halogen bulbs. They are made of plastic instead of glass. That means they are more durable when hit or dropped. Even after this happened, they do not make sharp glass pieces that are dangerous to animals or human beings.

Compact design specifies LED lights in a matter of application. They can be made in almost any shape, design, specification, color or size. That means there is lower need for making changes in the current design or on the other hand they could be made fitting their place perfectly.

Another very important advantage is security. LED lights are usually made of more lights connected together, but independent of each other. It means that if one of them breaks down, there are still other working LEDs. While using a low-beam halogen bulb which breaks down the only available light is the distance one or fog light that should, in case of emergency, at least partly replace the broken bulb. It appears from this that LED lights ensures more safety on the roads and even with a failure, the car is still safe for the driver as well as visible for the others.

Using LED lights as brake lights increase safeness too. Time needed for LED lights to become fully lighted is lower, in the interval of milliseconds and less, than for halogen bulbs. And this time is critical during braking as the driver behind usually reacts to the brake lights of the car in front of him. This is the moment when the time between stepping on the brake and lighting the brake lights is important as it gives more time to the others to react. And during some critical situations, stopping the vehicle depends on a reaction about seconds or less.

Disadvantages

The main disadvantage of LED lighting is the purchase cost of one lumen in comparison with one lumen cost while using halogen lighting. This happens mainly because of the research, which is expensive. Usually more than one LED is needed in the LED bulb due to low luminance, and they are used combined into one light source of different shapes and count of LEDs.

In motorism, car lights have to operate over a wide range of temperatures. Especially warm conditions are problematic as high temperatures are dangerous to LED lights. They could be easily overheated, which lead to their destruction. Mainly the LED head lights are more fault-prone because of their principle of more independent connected lights. [7]

Use

The first use of LED lighting in automotive was a cautious step. The safety factor of this technology has not been known yet and the lights were used as auxiliary lighting or for rear lights. With bigger reliability and luminance, the lights spread more into other systems. The boom and spread of LED lighting came with their use as daytime running lights - DRL. The LED lights prove themselves to be a good source of lighting with no major disadvantages and worth more research and application.

DC/DC CONVERTERS

Low Power converters

A LED power supply is a good example of low power DC/DC converter. As the LED lighting is being more and more used in automotive it is easier to find these types of converters in cars. The most common LED automotive application of these days is a Day Running Lights (DRL) function. But with bigger progress in the field of LED technology, even applications like LED low-beam modules and LED high-beam modules are being mounted into vehicles more often. [8]

MOSFETs

Basic MOSFET Structure and Principle of Operation

The MOSFET as we can see in Figure 9 is an n-type Metal-Oxide-Semiconductor Field-Effect-Transistor (MOSFET). The three main parts it consists are the Gate, the Source and the Drain. The source and the drain are made of highly conducting n-type semiconductor regions. These parts of the MOSFET are isolated from the third one, the gate that is made of metal. The gate is separated from the semiconductor by a gate oxide. The right part of the Figure 9 shows a corresponding circuit to the MOSFET. [10]

The voltage at the gate controls the flow of the electrons from the source to the drain. If the voltage at the gate is positive, it attracts the electrons to the interface between the gate dielectric and the semiconductor. A conducting channel is formed by these electrons between the drain and the source and it is called the inversion layer. Any carrier flow is blocked by the gate oxide. That means that no gate current is required to maintain the inversion layer at the interface. The net result it that the voltage controls the current between the drain and the source. This voltage is applied to the gate. [10]

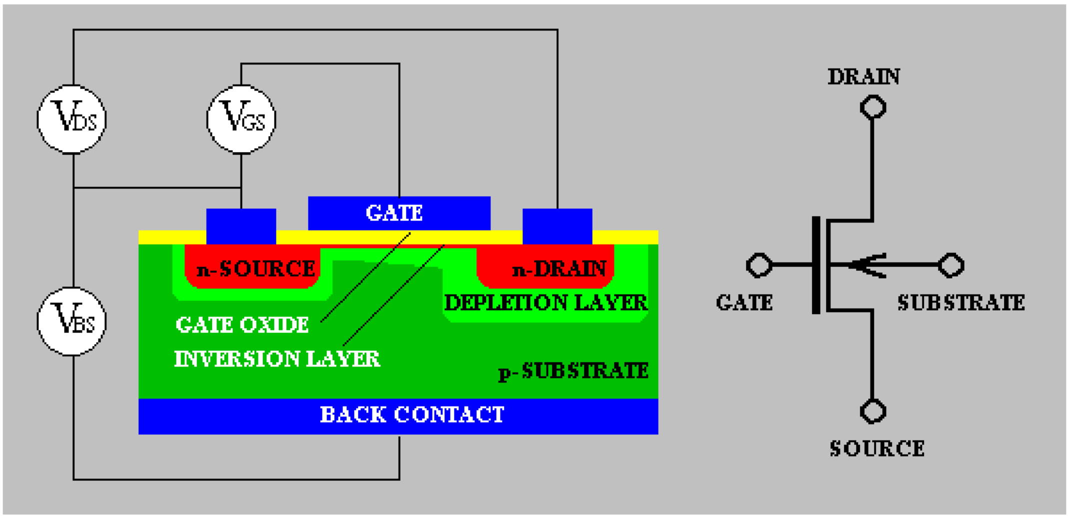

Figure 9 MOSFET structure and circuit [10]

Small Signal OptiMOS^{TM} 606 MOSFET

This particular OptiMOS^{TM} 606 family MOSFETs is qualified to AEC Q101 that makes them ideally suitable for automotive and other high quality demanding applications. The main features show why they are good for automotive use is listed in the Table 2 below. [8]

Parameter	Symbol	Conditions	Value			Unit
Continuous drain current	I_D	$T_A = 25\ °C$	4.5			A
Drain-Source breakdown voltage	$V_{(BR)DSS}$	$V_{GS} = 0\ V$, $I_D = 250\ \mu A$	60	-	-	V
Gate threshold voltage	$V_{GS(th)}$	$V_{DS} = 0\ V$, $I_D = 15\ \mu A$	1.3	1.8	2.3	
Drain-Source on-state resistance	$R_{DS(on)}$	$V_{GS} = 4.5\ V$, $I_D = 3.6\ A$		69	95	mΩ
Gate to source charge	Q_{GS}	$V_{DD} = 48\ V$, $I_D = 4.5\ A$, $V_{GS} = 0$ to $5\ V$		1.9	2.5	nC
Gate to drain charge	Q_{GD}			1.0	1.5	
Gate to charge total	Q_G			4.1	6.1	

Table 2: BSL606SN Main Features [8]

DRL application example

Boundary conditions

An example for DRL function boundary conditions are following as given by official application note AN 2012-12:

- The sum of the LED forward voltage (DC/DC converter output voltage VOUT) is approximately 25 V.
- The supply input voltage VIN is specified in the range of 8 V to 16 V. The nominal value is 12 V.
- The LED current or the output current of the DC/DC converter I OUT should be 400 mA.
- Boost configuration is used with a switching frequency of around 400 kHz operated in continuous conduction mode.

The Boost circuit configuration of a DRL application is presented in the Figure 10 below. [8]

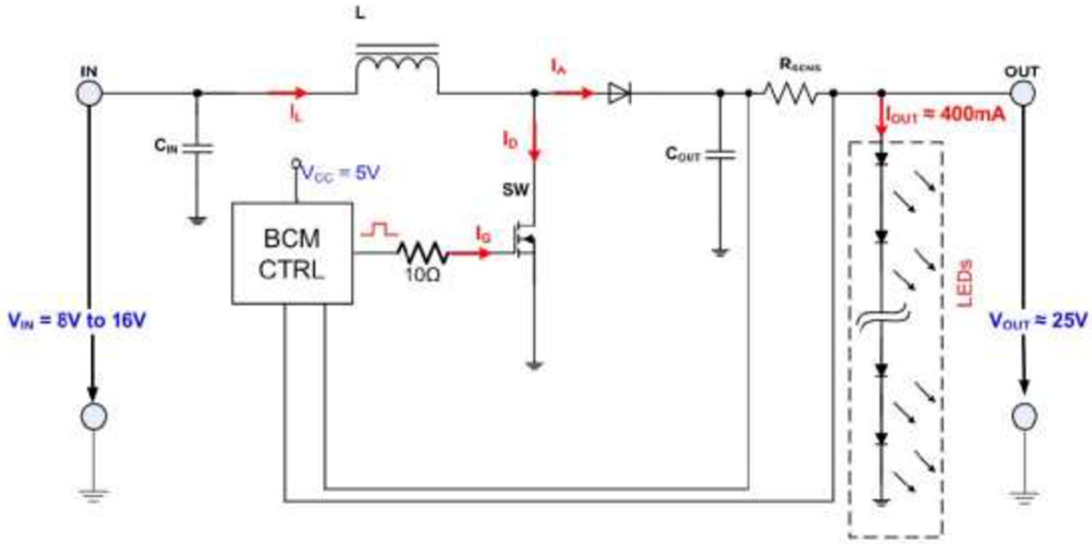

Figure 10: Boost circuit configuration

This is the boundary conditions summary of this DRL application that should be the basis for the calculation of the losses.

Symbol	**Value**	**Unit**	**Name**
V_{IN}	12	V	Nominal input voltage
V_{OUT}	25	V	LED forward voltage
I_{OUT}	0.4	A	LED current
F_S	400	kHz	Switching frequency
ΔV_{OUT}	100	mV	Max. ripple voltage on V_{OUT}
$\Delta I_L\%$	20	%	Pk-Pk inductor ripple current

Table 3: Application boundary conditions [8]

DC/DC converter losses review

The efficiency of a DC/DC converter is a measure of the ratio of the output power supplied to the load with respect to the input power. The load power plus the converter losses are equal to the input power. A DC/DC converter has its losses in its control circuit and magnetics, out of which switching losses are the greatest contributor. [8]

MOSFET Switching losses

The switching losses occur due to the positive product of current through the MOSFET and voltage across it during switching transition. These switching losses occur twice per a switching period. That is during turn-on and during turn-off. The figure below illustrates current and voltage during the turn-on period. The input voltage V_{CC} is represented by the black color while the current at the gate I_G is red. The yellow color is for voltage between the drain and the source V_{DS}. And the last signal in the Figure 11 I_D is represented by the blue color. [8]

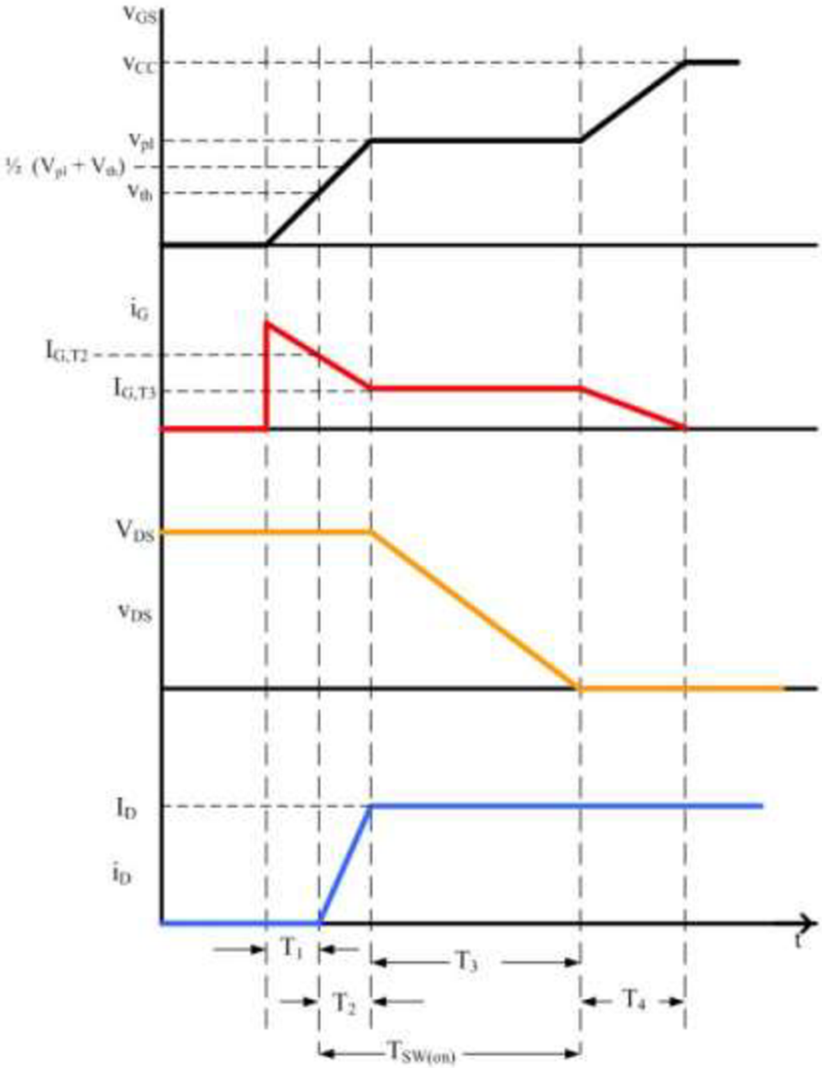

Figure 11: MOSFET turn on waveforms [8]

Using linear approximations of the waveforms, the power loss components for the respective intervals can be estimated. The estimated power components in intervals T2 and T3 are given by: [8]

$$P_2 = T_2 * V_{DS} * \frac{I_D}{2} * F_S \tag{1}$$

$$P_3 = T_3 * \frac{V_{DS}}{2} * I_D * F_S \tag{2}$$

The total turn-on switching losses are the sum of the two components and are given: [8]

$$P_{ON} = P_2 + P_3 = \frac{1}{2} * (T_2 + T_3) * V_{DS} * I_D * F_S = \frac{1}{2} * T_{SW(ON)} * V_{DS} * I_D * F_S \tag{3}$$

Dynamic losses

Total switching losses are divided into two sub-categories. The dynamic losses and the static losses and they are shown in Figure 12. The dynamic losses are represented in violet color area and they are those ones that happen during the switching operation. Since the signal is switched and until it reaches the opposite state the losses are dynamic.

Static losses

Static losses are called the losses that are present after the signal is switched into the opposite state than it was before the switching happened. These losses are also outcome of the conducted emissions and noise of the signal that are present in the non-ideal real conditions. In the Figure 12 below, they are in the signal bordered by orange color.

The losses are bigger with a higher frequency. These losses are in many cases transformed into heat and due to this, the components are placed on the self-cooling PCBs or external cooler is added to the PCBs.

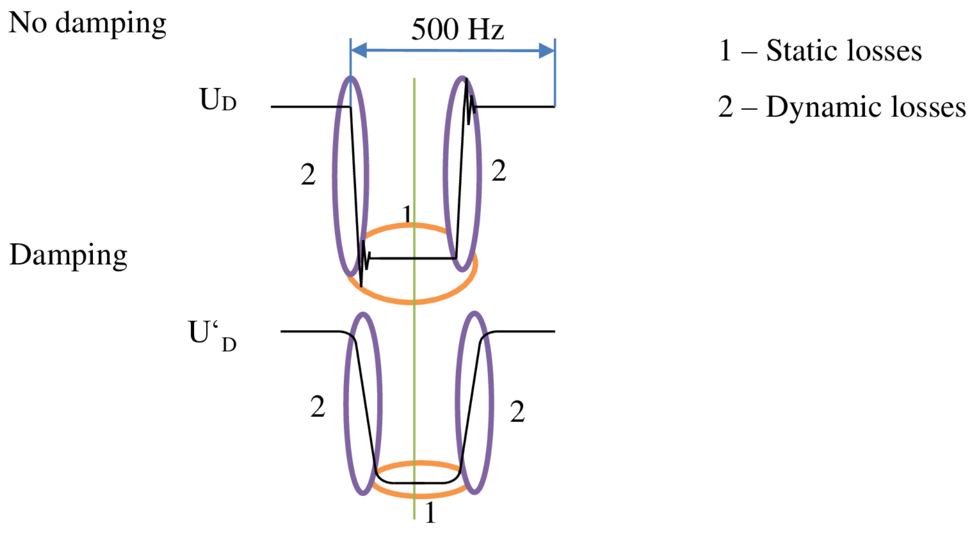

Figure 12 Dynamic vs. Static losses

MAX16833 LED DRIVER FOR DRL

This is the driver used in the measurements. This LED driver is made by Maxim Integrated™ Company and it is widely used for automotive exterior lighting (high-beam, low-beam, signal lights, position lights, daytime running lights 'DRLs'). It is also used for fog lights, adaptive front light assemblies and in commercial, industrial, and architectural lighting. [9]

The features of the LED drivers from MAX16833 series are following as given by the manufacturer:

- Boost, SEPIC, and Buck-Boost Single-Channel LED drivers
- +5V to +65V wide input voltage range with a maximum 65V boost output
- Integrated high-side current-sense amplifier
- ICTRL pin for analog dimming
- Integrated high-side pMOS diming MOSFET drive (allows single wire connection to LEDs)
- Programmable operating frequency (100kHz to 1MHz) with synchronization capability
- Frequency dithering for spread-spectrum applications
- Full-scale, high-side, current-sense voltage of 200mV
- Short-circuit, overvoltage, and thermal protection
- Fault indicator output

- -40°C to +125°C operating temperature range
- Thermally enhanced 5mm x 4.4mm, 16-pin TSSOP package with exposed pad

From the features mentioned above is ensuing that the MAX16833 is a peak current-mode-controlled LED driver for boost, buck-boost, SEPIC, flyback, and high-side buck topologies. The wide-range dimming control is provided by a dimming driver designed to drive an external p-channel in series with the LED string. The frequency from 100 kHz up to 1 MHz is set by a single resistor while the capacitive of a signal from an external clock allows the ICs to synchronize to an external clock. The wide input voltage range from 5 V up to 65 V is also an advantage as under-voltage or over-voltage should not damage the LED driver. The IC also includes a 3 A sink/source gate driver for driving a power MOSFET in high-power LED driver applications. Also some additional protection such as fault-indicator output for short or over-temperature conditions, or an over-voltage is included to protect the LED driver from being damaged due to some signal failures. [9]

MEASUREMENT

Introduction into the measurement

The measurement itself took place in Automotive Lighting Company in Jihlava. A MAX16833 LED driver evaluation kit mentioned above has been used for the measuring tests and a low-beam lights removed from actual vehicle has been used as a load. This LED driver is actually used in automotive nowadays alongside with others LED drivers by other companies. But this one was chosen as it does exist in the automotive applications nowadays. It is also the one, which is used for various tests done by the company for many reasons.

Before the measurement started alternatively anything was assembled and connected, a table for values had to be done. The table sets also the goals and values, which have to be measured. But the table can be done straight in cooperation with a wiring diagram for a given application.

The measurement has been divided into four steps. First two steps were measured in the laboratory by me. The other two steps were measured in the electro-magnetic wave laboratory by a laboratory authorized personnel.

Firstly a resistor and a capacitor, which serves as components to remove damping, from the PCB were removed. This was done by using a soldering machine and a wiring diagram.

After this was done by me it was needed to solder external wires for oscilloscope probes. This was done in more steps as a suitable grounding was found as mentioned below in *Grounding* chapter. After these steps were done, the circuit was ready for the upcoming measurement. After the non-damping measurement was done, the resistor and capacitor were soldered back to their places and the measurement was repeated once again with damping. The simplified operating circuit is shown in Figure 13. Only the simplified circuit diagram is shown because of complete schematic diagram of the measured module is a property of Automotive Lighting and cannot be published.

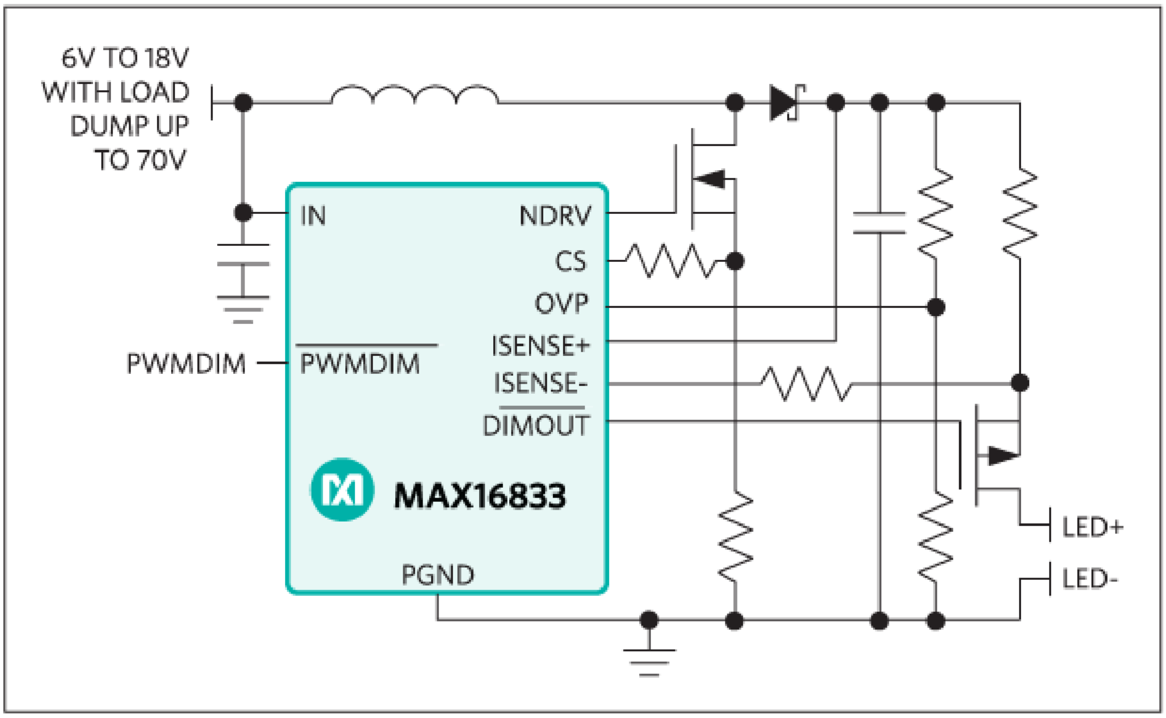

Figure 13 MAX16833 - Simplified operating circuit [9]

Second measurement was done in the electro-magnetic wave laboratory, which is described below. As the measurement was done with and without damping too, it was needed to do the same procedure as it was done during the first measurement. The resistor and the capacitor were removed and put back by using the soldering machine. Also the connection wires for the probes were removed so the circuit was without anything extraneous to the LED driver circuit.

Measuring equipment

Oscilloscope

In this case, a four channel digital oscilloscope has been used. Advantage of an oscilloscope is that it serves as a multi meter, in other words a huge scale of different values can be measured like voltage, current, frequency, time etc. Other advantage is the display where measured values can be seen in real time or if it is needed, a pause can be made so even the signal keeps on going the showed value is not moving. And in case of additional research of already once made measurement a print screen option as available to the user.

Even no oscilloscopes are made the same, the key features are similar for the most of them. For example, a display. It is a part of any oscilloscope and it does not matter if the oscilloscope is digital or analog. But in a case of this measurement, a digital oscilloscope with a color display was used. Usually the display is criss-crossed with horizontal and vertical lines. These lines are called divisions and serves for a better orientation as well as for scale reading. Generally, 8 to 10 vertical lines and 10 to 14 horizontal lines is present on the display.

The trigger option on the oscilloscope makes the measurement better and easier. By this option can be set what signal and signal parts to "trigger" on and start the measuring. Otherwise the signal will be shaking and running over the place and sometimes it makes the self-measurement unable.

For a connection to a signal were used probes. One of the probe was provided with a grounding connector. These probes were connected to the external wires that were added to make the measurement possible.

V-meter

Because of the used oscilloscope, which has only 4 channels, one Voltmeter has been in need to measure the output voltage U_{LEDS}. For this purpose, a non-portable multi-meter was used. It was set to measure voltage with an auto scale option on.

Power supply

As an input signal, an external power supply was used to imitate the possible conditions that could happen with a car battery connected. The output voltage was set manually by a rotary rheostat. It also had a display with the output voltage displayed on it. However, it was used as a visualization only as the real value was at the input was different and it was measured by the oscilloscope right at the input to the LED driver and not at the power supply output.

Electro-magnetic wave laboratory

The last test has been done in a special laboratory in Automotive Lighting Company in Jihlava, which is normally used for testing out-going products as well as products in on-going research.

In this laboratory that is a special room built-in in a normal room in the factory where the electro-magnetic resistance is tested. It is a room made out of a special metal to keep the inside un-reachable by electro-magnetic waves from outside. Under these conditions the tests are undisturbed and they are also done without any environment errors. Inside the room are small metal plates mounted on the sides' surface and foam in a specific shape. The foam serves to absorb the overflowing waves li it does in the light laboratories.

During these tests, variable antennas are used for variable tests that are done. However, these tests are done to show if the product is able to keep its characteristic, which are needed to be kept, during different simulated cases. Mainly, above mentioned electro-magnetic resistance is important for products made by Automotive Lighting. Sensors, drivers, LED drivers and almost any electrical device which are used in a vehicle have to be tested for these characteristics.

If more components that are producing electro-magnetic waves are placed close to each other makes an possibility of affect not only each other but also all the components around them. And the goal of these tests is to make sure that individual components will work correctly in any case and under any influence that could happen while already placed in a vehicle.

Assumed values

Before the measurement is started, it is good to set the values that are expected at the measurement output. For this particular measurement there are two expected values. They are the voltage and the current at the output that leads to the LEDs. Because the 8 LED panel has been used with the LEDs of input voltage 3 Volts each, the output voltage from the LED driver should be 24 Volts as it is calculated in equation 4. The current value for this application has been assumed 30 mA as that is normal value while using this LED driver. The start voltage value wasn't set in advance but it was raised until the LEDs lighted up. The maximum value of 18 Volts was set as a maximum to see how the LEDs react with higher voltage.

$$U_{BAT} \doteq 3 * 8 \doteq 24\,V \qquad 4$$

$$I_{LED} \doteq 350\ mA \quad 5$$

Grounding

A selection of grounding is important. Even the LED driver component is small in size, however, the connection routes have its length and in weak current equipment it does make changes in measuring output. When the oscilloscope channel for ground was connected to the position no. 1, which was easily accessible for us on the printed circuit board, it had great impact on the measured output values. The main reason for this is that the signal has to go through bigger distance and more components. Due to this, conducted emissions are bigger and bigger and at the end, the measurement has bigger distortion. This problem can be easily avoided by choosing better grounding for oscilloscope channel.

A tester with some experience can find the right place on the PCB at the first try, but it took me three attempts before the measured values had distortion that can be used and which is within accepted limits.

Scales

The selection of suitable scales is crucial for right measuring. When the scales do not correspondent with each other or they don't fit the display, it could happen that the whole measuring is done unnecessarily or it is not possible to use the measurement records afterwards. It also makes it easier to work with the display during the measuring. For example, when values of quantities have to be written down they can be easily read and written down from what is visible on the display of the oscilloscope, or a comparison between measured signals could be done right on the display of the oscilloscope in a real time, or small signals can be shown in a bigger scale for a better work with them. When a scale is set bigger, the signal is still the same in the circuit so the work with even weak signal is possible without any changes in the circuit signals, or any unneeded values changes are done. When the scale is set the same for two signals, it makes the comparison easier.

Power

The power tells us how the input power is changed at the output. What are the losses and how much is the circuit overloaded. The basic computation for power is shown in equation 7. How the power was computed from the measured values is shown in equation 8. The numbers are taken from Table 4. The same principle is used for P_{LEDS}. The computation of the total power is shown in equation 9 and the equation 10 shows the example of equation from the values in Table 4

$$P = U * I\ [W] \tag{6}$$

$$P_{BATS} = U_{BAT_{14}} * I_{BAT_{14}} = 13.97 * 0.74 = 10.34\ W \tag{7}$$

$$P = P_{BAT} - P_{LED}\ [-] \tag{8}$$

$$P = P_{BAT\_14} - P_{LED_{14}} = 10.34 - 8.01 = 2.33[-] \tag{9}$$

Non-Damping circuit for DRL measurement #1

As it was already mentioned above, before the first measurement itself, all the preparations had to be done. All the measuring apparatuses like multi-meter, oscilloscope, power supply, or measured components LED light component and the LED driver were set and ready. Extra preparations were done for the non-damping method, for example the resistor and capacitor were removed, extra wires were soldered on place, and table was ready too. The component itself is visible in the Figure 14 and the Figure 15 below.

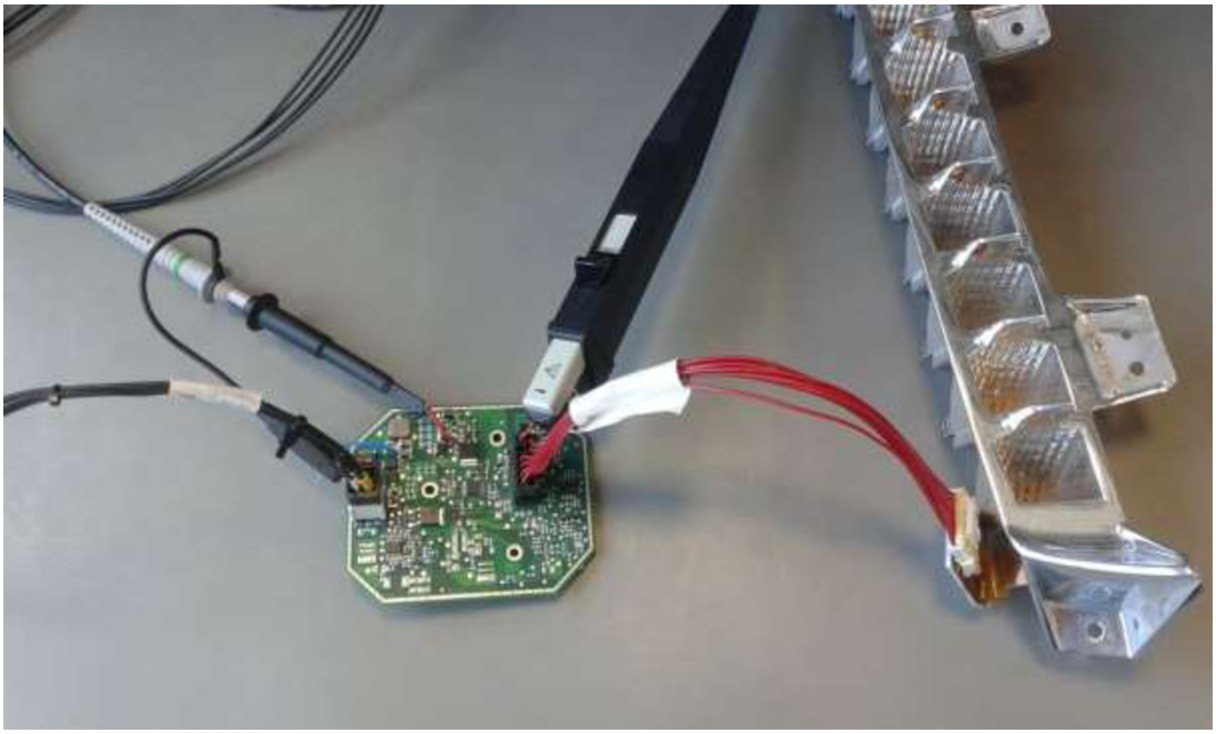

Figure 14 Measured component for DRL - illustration of connection 1

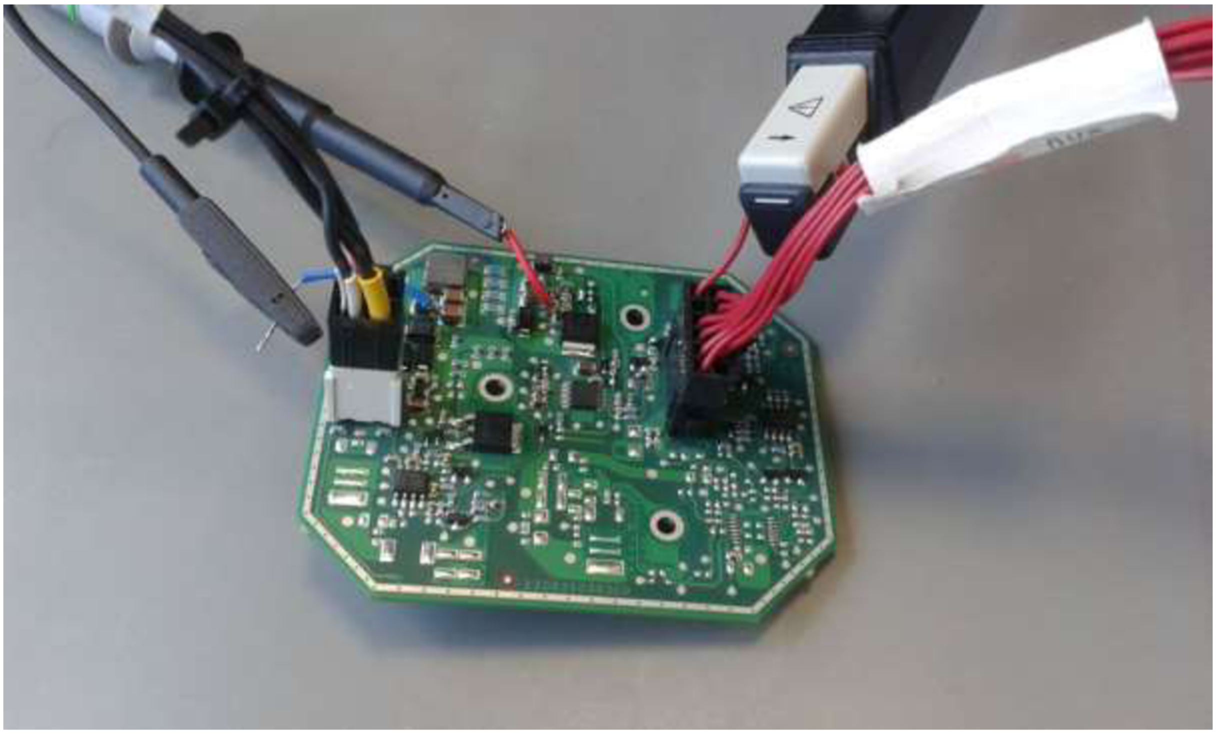

Figure 15 Measured component for DRL - illustration of connection 2

The non-damping method was done for a comparable reason and also to show why the damping is used in general. The Table 4 Non-damping measurement results – shortened shown below is just a part of the whole table that is listed in the enclosures. It shows anyway the important values of the measurement needed for this description of the measurement. In this case, it was mainly 4 values that can show the difference.

The values at start voltage, then values at 10 V, 14 V, and 18 V are picked up for comparison as the difference is clearly visible. Especially in the case of input current and output power. These values are also from all three parts of the table representing under-voltage, operational voltage and over-voltage. Under-voltage and over-voltage is divided into category B, whereas operational voltage is in category A. The input Voltage was increased manually and the real value was displayed on the oscilloscope display and in Table 4 and Table 4 is given by U_{BAT}. A fast raise with a slightly decreasing tendency of input current I_{BAT} can be also read from the Table 4. While the output current I_{LED} increased very rapidly until the voltage reached 8 Volts, then the current stayed at the same level of 340 mA for the whole measurement. Output voltage was measured not by the oscilloscope, but by the external multi-meter at the same output wires that lead to the LED lights component. It is clearly visible that the output voltage U_{LEDS} stayed at the same value of 23.6 V. The only exception is the start value of 4.87 V when the input voltage was that small that it could not been amplified enough to reach the wanted value. The value of power was then calculated from the measured values of voltage and current as it is shown in equation 7 and 9.

No Damping	Under-voltage											Over-voltage
Nominal configuration	Start	6.00	7.00	8.00	10.00	11.00	12.00	13.00	**14.00**	15.00	16.00	18.00
U_{BAT} [V]	**4.87**	**6.08**	**7.01**	**8.05**	**10.09**	**11.02**	**12.02**	**13.03**	**13.97**	**15.01**	**16.01**	**18.04**
I_{BAT} [A]	0.27	1.60	1.46	1.36	1.04	0.94	0.86	0.79	**0.74**	0.69	0.65	0.58
I_{LED} [mA]	26.10	261.00	307.56	339.93	339.91	340.13	340.19	340.25	**339.00**	339.88	340.13	340.19
U_{LEDS} [V]	21.14	23.46	23.67	23.72	23.66	23.64	23.63	23.62	**23.62**	23.62	23.61	23.61
P_{BAT} [W]	1.31	9.73	10.23	10.95	10.49	10.36	10.34	10.29	**10.34**	10.36	10.41	10.46
P_{LEDS} [W]	0.55	6.12	7.28	8.06	8.04	8.04	8.04	8.04	**8.01**	8.03	8.03	8.03
P[-]	0.76	3.60	2.95	2.88	2.45	2.32	2.30	2.26	**2.33**	2.33	2.38	2.43

Table 4 Non-damping measurement results – shortened

The start voltage is the value measured right at the moment when LED lights turned on. The assumed value was under 5 V. The real value is, referring to Tab. 3 4.87 V. This measurement confirms our assumption of the lowest input voltage value very well. But because of the low input voltage as well as low input current, the light was very glimmering and the circuit cannot work under these circumstances for a longer time due to its overload. This situation was captured as a screenshot and it is visible in the Figure 16. Also the opening and closing time can be reproached from Figure 16 as well. The opening time is represented in almost a straight line with opening time of mili-seconds while the closing time has a behavior of a smooth curve and after some time passed it changes into an almost straight line too. It is clearly visible that the closing time is longer than the opening time.

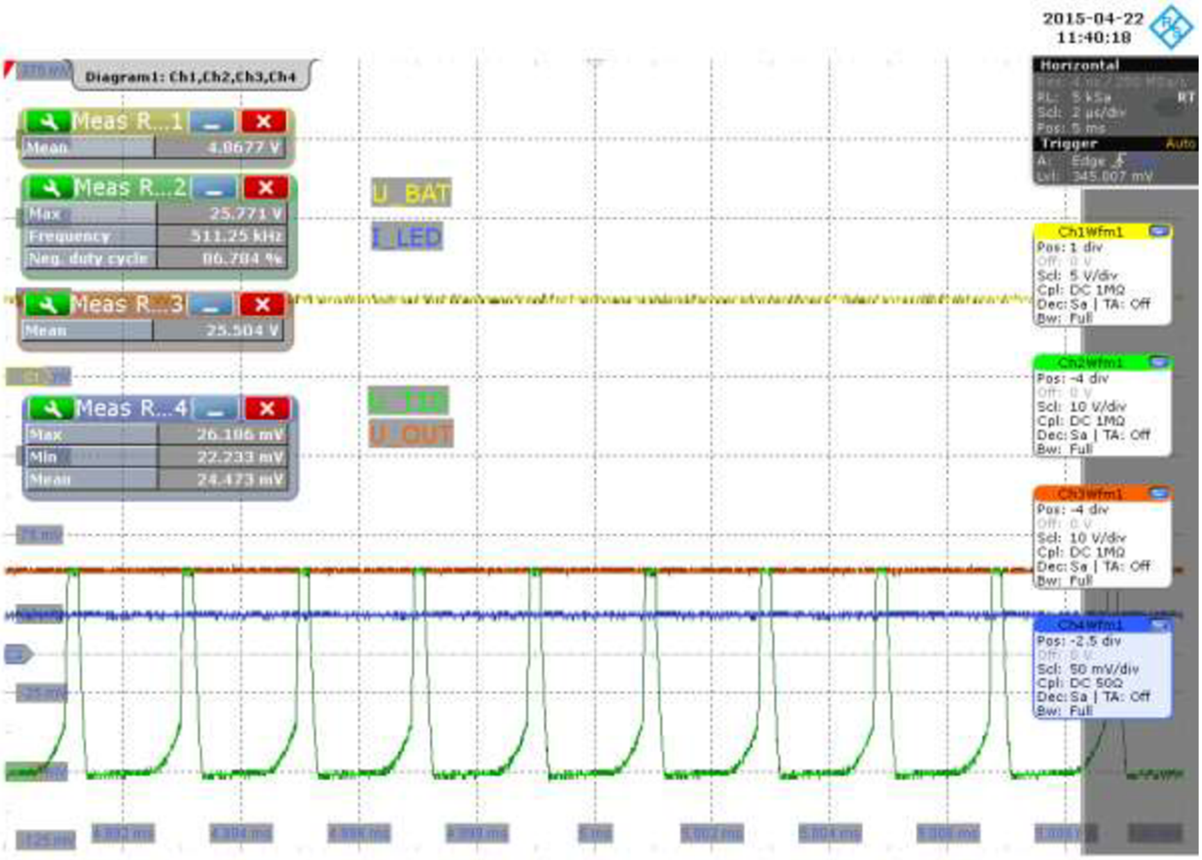

Figure 16 Non-damping Start

The opening and closing time is almost of the same time in the case of bigger input voltage U_{BAT}. It is clearly visible from Figure 17 that the signal switches very fast during both, the opening and the closing without any curve visible. But what is visible are conducted emissions after opening and also after closing of the transistor. The signal needs some time to set. This is done by the lack of resistor and capacitor components that were removed. The signal is a straight line and the time of the change is really low. But it results into bigger conducted emission. These conducted emissions and their impact to the circuit and signal is described more in the *Why the damping is used* chapter. The output current I_{LED} is raising since it reaches the voltage boundary of 10 V. When the input signal is strong enough, the input current I_{BAT} stays at the level around mean value of 340 mA. This signal is not a straight line as visible in Figure 17 and it is represented by blue solid line. The maximal and minimal value changes during opening and closing of the transistor.

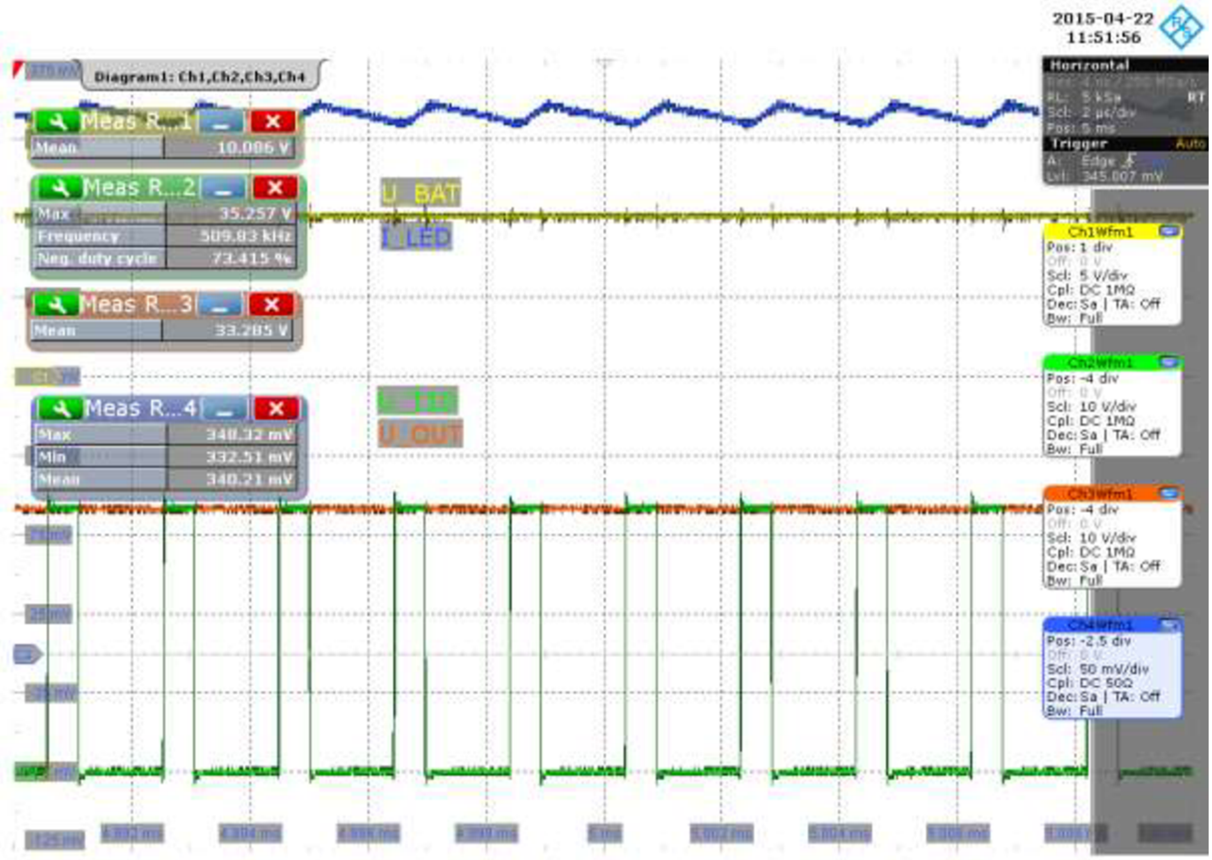

Figure 17 Non-damping 10V

Figure 18 represents the whole operation of the LED driver under the conditions it should be working if no errors influence the circuit. Conducted emissions are still a part of the signal and their oscillation is the same as during other input voltage values. What changed is the time of signal in opened and closed state before switching to the other state. Compared to the signal in Figure 16 the signal showed in Figure 18 is in opened state and in the closed state getting closer to each other in way of time. The opening and closing of the transistor has also bigger impact on the input voltage U_{BAT} as it is visible in the yellow line, which is representing the input voltage. Also the output current I_{LEDS}, which is represented by blue color has its shape more like an identical waves than it was during the signal of input voltage of 10 V. However, all components work as they could under these conditions that were reached. The circuit is not over-loaded. These circumstances make the components in an efficiently working status without, for example, over-heating problems that should not come up.

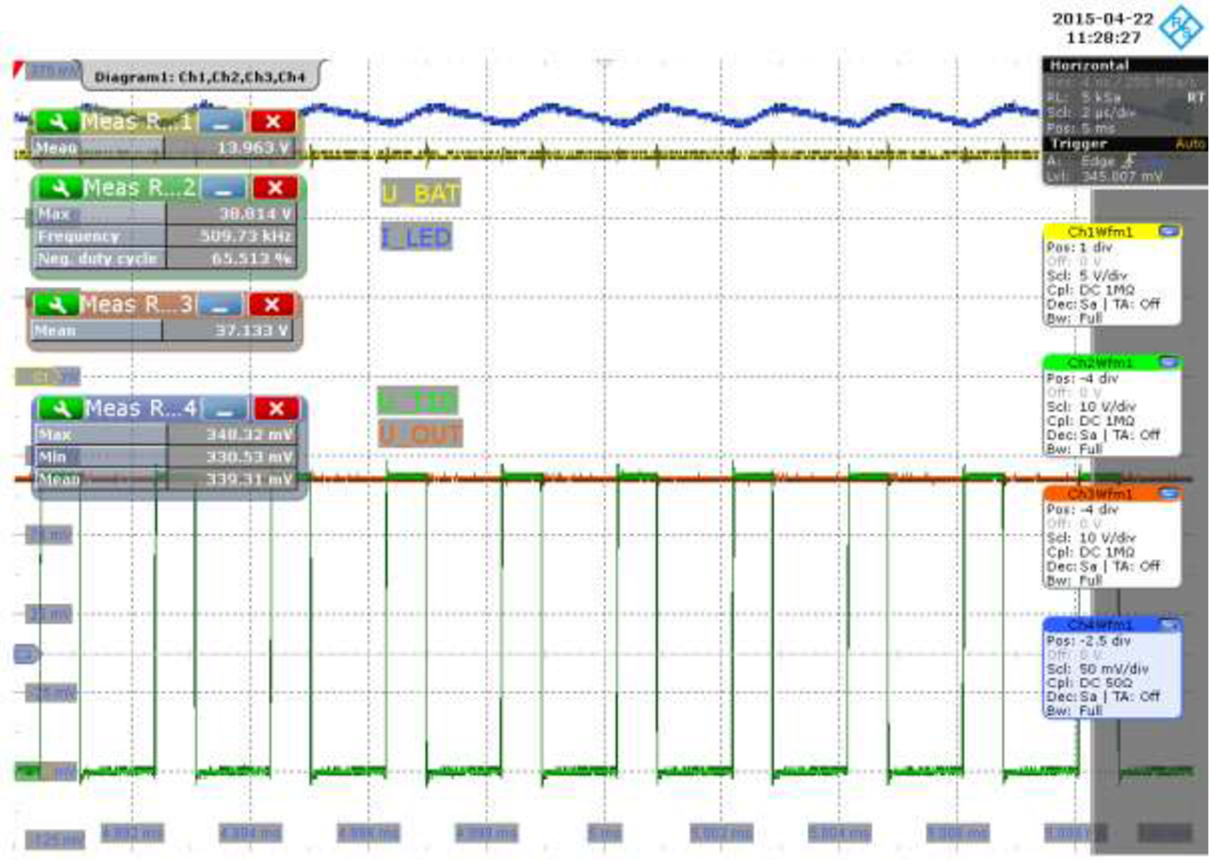

Figure 18 Non-damping 14V

The signal going through the circuit of input voltage U_{BAT} of 18 V is shown in Figure 19. When the data from the measurement are taken and the Power is computed it shows that the circuit itself still works fine but it is over-loaded for no reason. The input voltage is unnecessarily high. The values of opened and closed time are getting even closer to each other. The difference between the peak and the low point of output current I_{LEDS} is around 18 mA. This value is almost the same since the input voltage U_{BAT} reached the value of 7 V and raised. This computation is shown below.

$$\Delta I_{LEDS\_18} = \Delta I_{LEDS\_18\_MAX} - \Delta I_{LEDS\_18\_MIN} \doteq 348 - 330 = 18 \text{ mA} \qquad 10$$

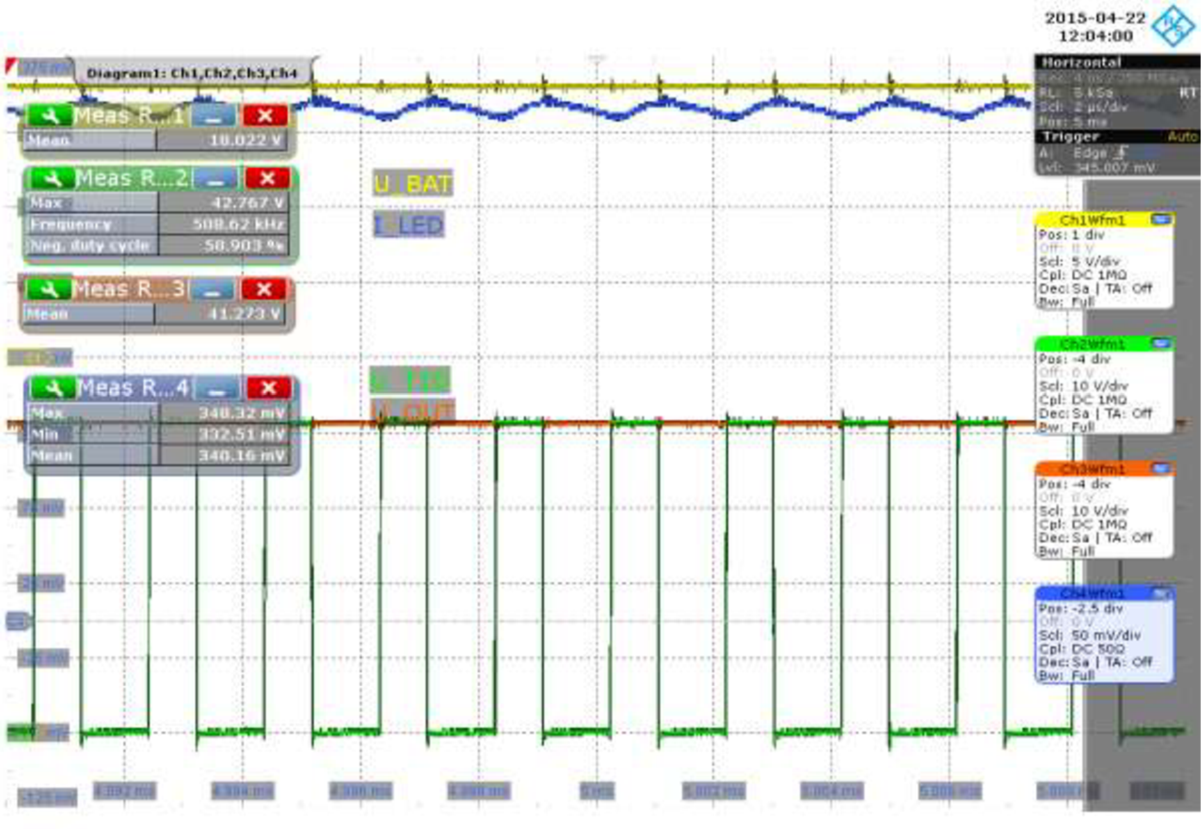

Figure 19 Non-damping 18V

From the examples that are shown above is appreciably visible that the signal is strong and all the components works as they should work. The time of switching between the opened and closed state of the transistor is very fast. But the thing which makes the non-damping method problematic is the conducted emissions. They are clearly visible and present since the circuit started to work. The signal needs some time to settle down into an undisturbed one. And this is not needed nor wanted in this particular case.

Damping circuit for DRL measurement #1

The second measurement was done with the LED driver and with all the components on their places, such as a resistor and a capacitor that were removed before the first measurement was done. The external probe wires that were soldered on their places are left as they were during the first measurement, and no other changes were done to keep the measurement under the same conditions as in the first case. No extra preparations had to be done before the measurement itself started as everything was already done before the first measurement and ready for the second one. The table was prepared and the instruments were set and calibrated.

The only thing that was done was with the oscilloscope where the signals were moved by using triggers and scales to fit the display as wanted.

For a comparison were chosen the same four values thus it comes to this, that the values of chosen input signal were picked up and they are shown for the value at the start, that was a bit lower than 5 V, next one is for 10 V followed by 14 V and ended with the measurement for 18 V.

Damping Under-voltage Over-voltage

Nominal configuration	Start	6.00	7.00	8.00	10.00	11.00	12.00	13.00	**14.00**	15.00	16.00	18.00
U_{BAT} [V]	**4.90**	**5.99**	**7.02**	**8.00**	**10.05**	**11.00**	**12.01**	**13.00**	**14.02**	**15.02**	**16.00**	**18.01**
I_{BAT} [A]	0.13	1.07	1.62	1.47	1.10	0.99	0.91	0.83	**0.77**	0.72	0.68	0.61
I_{LED} [mA]	15.40	156.92	304.68	340.13	340.52	340.76	340.68	340.58	**340.62**	340.52	340.66	340.67
U_{LEDS} [V]	20.77	22.72	23.58	23.68	23.64	23.61	23.61	23.60	**23.59**	23.59	23.58	23.58
P_{BAT} [W]	0.64	6.41	11.37	11.76	11.06	10.89	10.93	10.79	**10.80**	10.81	10.88	10.99
P_{LEDS} [W]	0.32	3.57	7.18	8.05	8.05	8.05	8.04	8.04	**8.04**	8.03	8.03	8.03
P[-]	0.32	2.84	4.19	3.71	3.01	2.84	2.89	2.75	**2.76**	2.78	2.85	2.95

Table 5 Damping measurement results – shortened

In the Figure 20 is the difference between damping and non-damping circuits shown. As it is visible from Figure 16 and has been mentioned above, the switching is without any curve. The output voltage U_{LEDS} is represented by a green color and the opening and closing of the transistor is done almost directly. Also although the signal is low, it is clearly visible that there are no conducted emissions as the noise is emitted. The opening and closing takes some more time than in the non-damping circuit. The reason why this effect is happening is described more in detail in the chapter called *Why the damping is used*. The input current I_{BAT} is represented by blue color and it is shown that the current is still low enough to see any abnormalities of the signal.

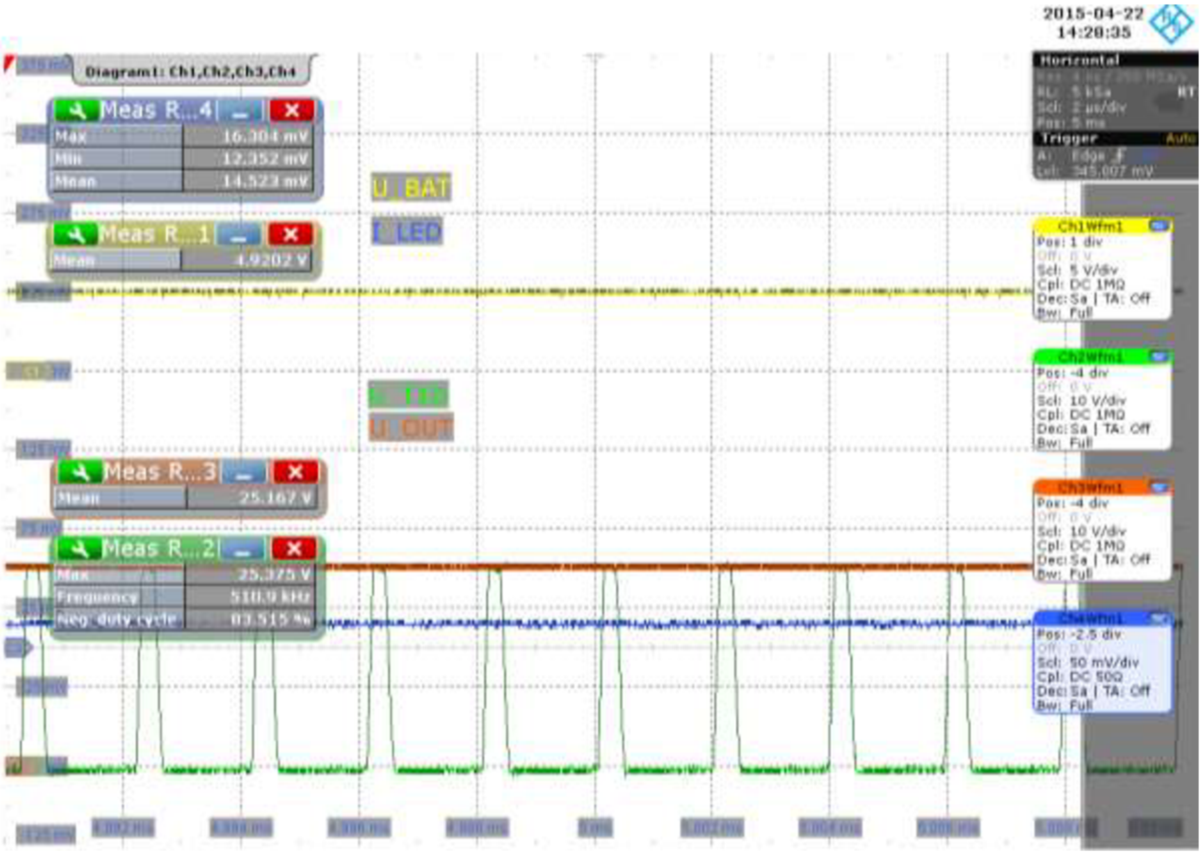

Figure 20 Damping Start

The next figure, Figure 21 represents the circuit still in the under-voltage category but already in the working state. The circuit is overloaded even more than in the non-damping method as the Table 5 shows compared to the values of power in the Table 4. Also, the noise is shown in the Figure 21 during the opening and closing operation of the transistor. The difference in this case is the different and lower time needed for the signal to set. The same way as the noise lasts for a shorter time, the peak of the noise is not that big is it is in the non-damping setup. The wave form of the output current I_{LEDS}, which is represented by the blue color, is again visible in this screenshot. The differences between the peaks and low points are almost the same as in non-damping measurement as the resistor and capacitor have no influence on the transistor amplification so the output signal has the same value in both configurations.

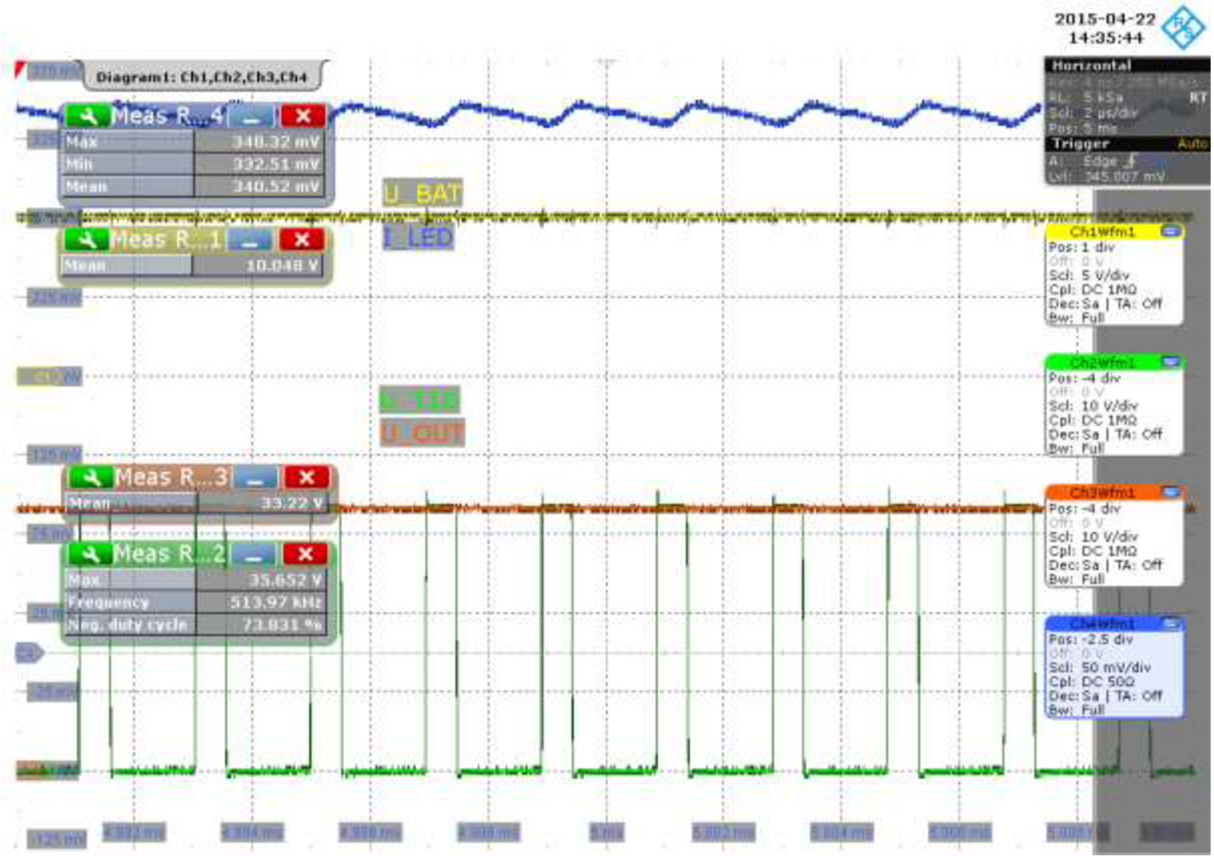

Figure 21 Damping 10V

The nominal configuration under the normal working conditions are represented and shown in the Figure 22. The difference between the open state and the close state is about twice as big. The difference between the non-damping setup and this setup with damping is the power, which is bigger in the case of the damping circuit. Again, the noise is present even in the damping setup, but it is not as big as in the non-damping circuit when these signals are compared. These peaks are however normal when the signal changes its status from one value into another during a very short time and they does not have any important influence on the components nor the circuit operation.

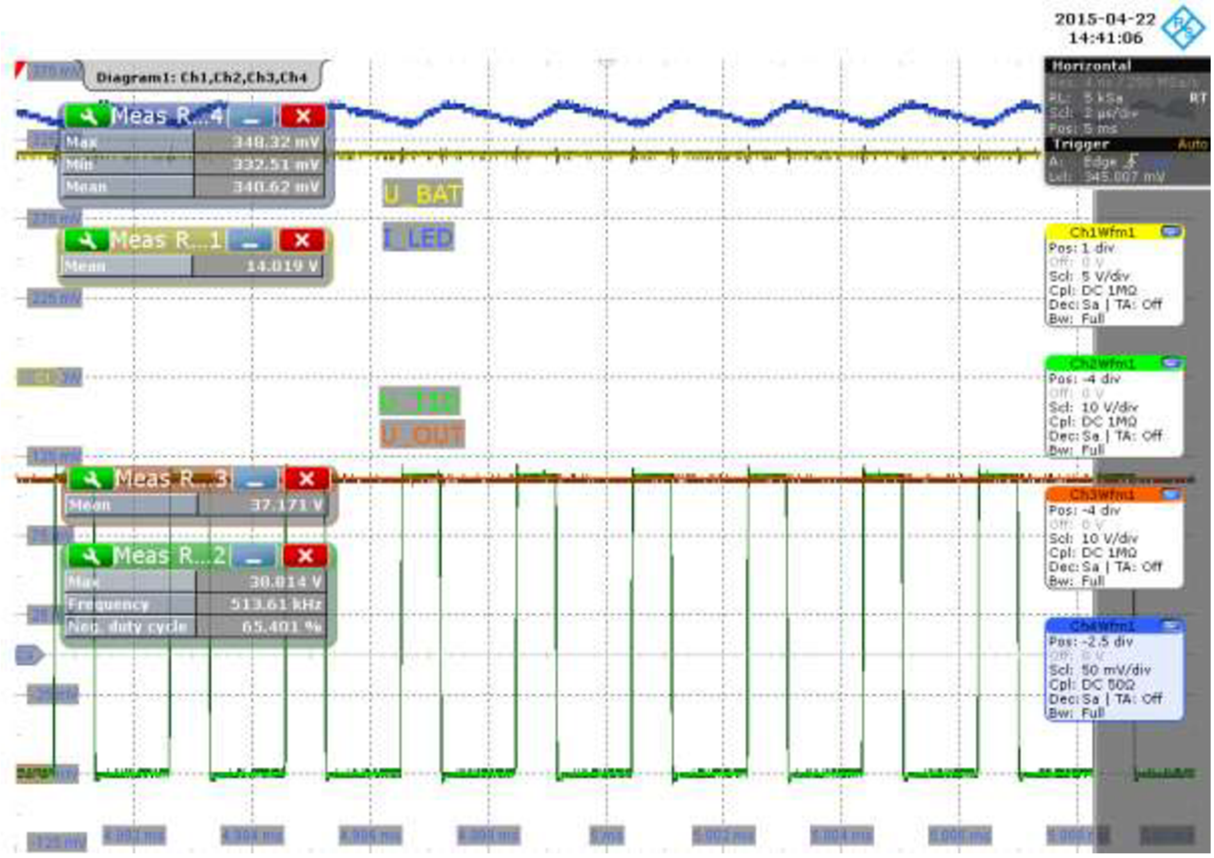

Figure 22 Damping 14V

The last example of the first set of measurements that is represented by Figure 23 of the measurement with a damping configuration is shown below. This example is picked up from the over-voltage category, the same category as the one from non-damping configuration is. It tells us that the circuit works very well even when the voltage is bigger than needed but, the power is also bigger and that could leads into some errors or other problems that are not welcomed during the operation especially when the circuits are in operation for a longer time.

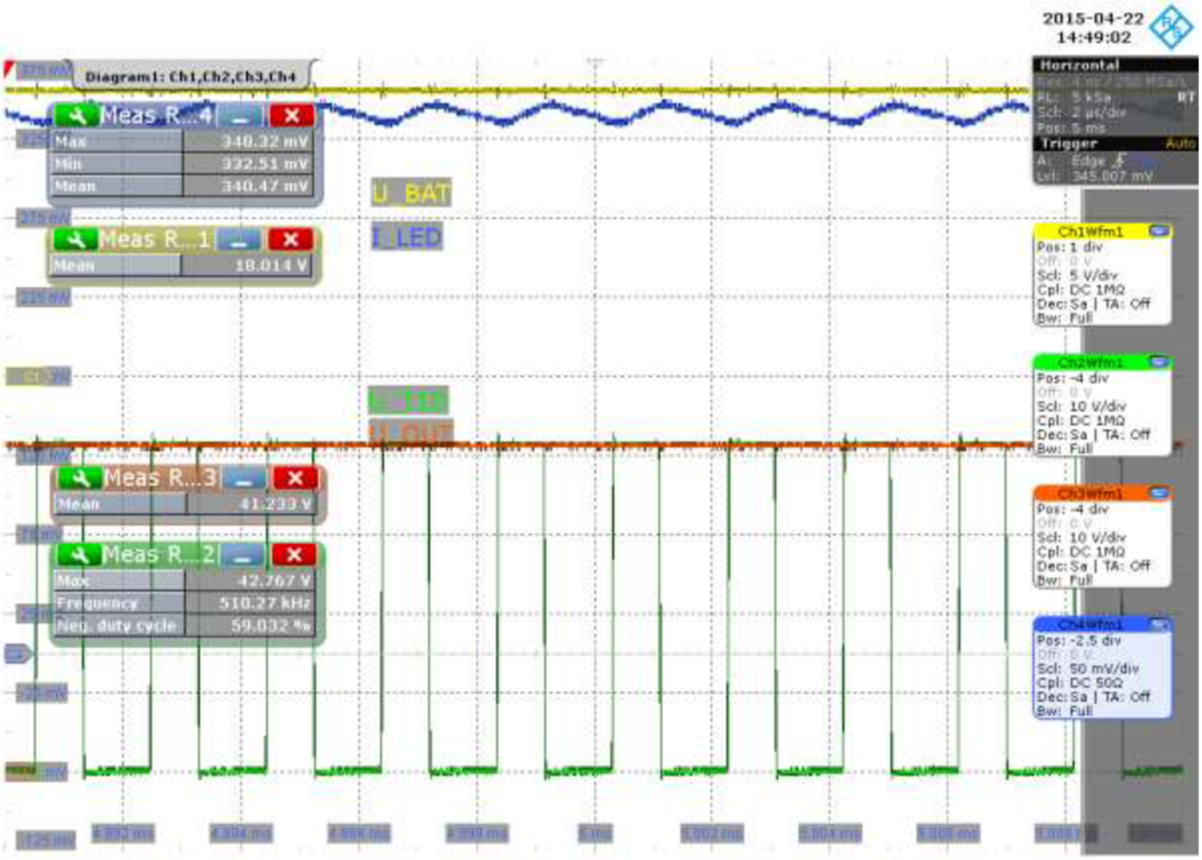

Figure 23 Damping 18V

The result of the damping circuit configuration compared with the non-damping circuit configuration can be mainly seen in the comparisons of total power. The total power is lower while the non-damping configuration is used. The difference between these two values of the same total power in different configurations is not that large and the results of a damping are still more useful than a loss of a part of the signal.

Why the damping is used

Conducted emissions are the reason why the duping circuit is a part of the LED drivers. And not only in this LED drivers as it is an effect that appears in any electrical circuits. But let us have a better look at this problem.

The main differences that are also visible on the oscilloscope are shown in the Figure 24. The input signal is meant to be an ideal and it is represented as U_D. The example is shown during one period of the signal. Also the example shown below is the example of an ideal state and that is why there is no noise while damping configuration is used, and no others negative forces influence the signal. Let us say that the input of the signal is in the open state and it is firstly switched into the closed state and then it is switched back to the opened state.

In the first case of the non-damping configuration are the conducted emissions and noise clearly visible in the chart. The amount of the conducted emissions and noise depend on the value of the input signal. If the input signal is bigger and stronger then also the conducted emissions and noise will be bigger and they will last for a longer time. In the case of the non-damping configuration the time needed to switch from one state into the other is shorter and the signal is more a straight line. When the value of a closed state is reached the signal tries to set but because of the lack of the resistor and capacitor the noise and conducted emissions makes the signal shake over the value of the closed state until it is stabilized. This reaction takes some time but the change itself is done faster. The same effect is repeated once the signal is switched back to the open state. The change from one to another state is however done straight and without almost any loss of time. The signal runs in the straight lines with a minimal or none curves at the points of direction change.

The behavior of the signal under the damping configuration is slightly different. Once again, this is the ideal state, where no noise is present. When the signal is switched into the opposite state, in this example it is the closed state, the change is not done directly, but the signal goes into a smooth curve firstly and then in a straight line down into another curve. The line itself is more sloped than it is within the non-damping configuration. The behavior of the signal is the same during switching from the closed state into the opened state, but it is reversed on the display of 180°.

This comparison shows us the main difference between the damping and non-damping configuration of circuits. And even the non-damping configuration switches faster than the damping configuration, the conducted emissions and noise are bigger disadvantage than the time lost during the switching operation. The clearance of the signal is more important. And as the first two measurements show, the difference of switching time is almost indistinguishable while the difference in the conducted emissions and noise is shown clearly and very well.

In real application, the noise and conducted emissions are not suppressed from the switching signal totally, but they are only reduced. And because of the curves during the switching operation the switching losses are also bigger and the MOSFET is more heated. That leads to another steps of heat reduction that is needed to be taken in consideration during the design of a product.

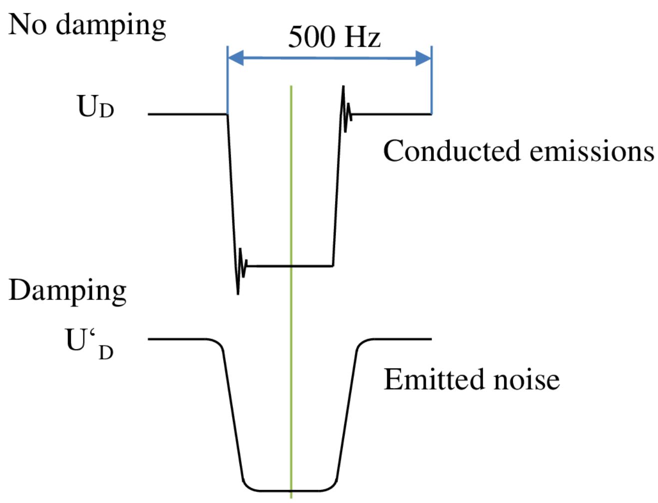

Figure 24 Damping vs. non-damping - signal example

Non-Damping and damping circuits for DRL measurement #2

The last two measurements were done in the electro-magnetic wave laboratory mainly to show the differences between the two circuits under external electro-magnetic influence simulated by an antenna placed in the laboratory.

The boundary conditions are set by a norm. The measurement was done with the same LED driver as the previous measurements. The resistor and capacitor were removed or placed back for each individual measurement as needed. The only difference is the lack of external wires that were removed as they were not needed for this kind of measurement. The Figure 25 shows the connections and conditions for the second set of measurements.

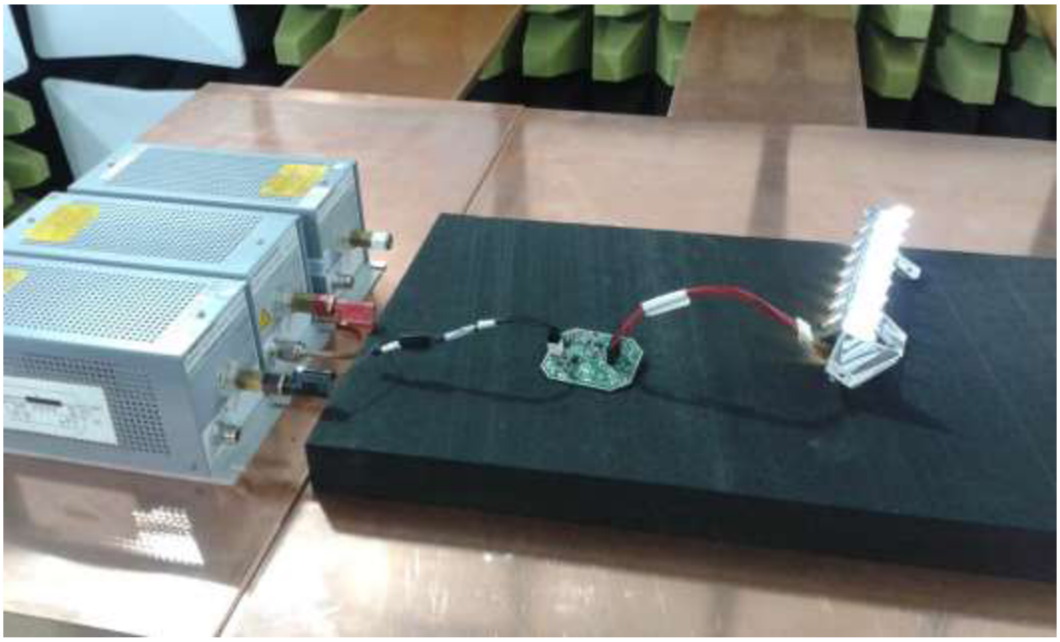

Figure 25 Measured component - illustration of connection 3

Figure 26 represents the first measurement of the second set. During this measurement the average values of the signal were measured and compared in special software. The green line represents the average value with damping while the black color represents the average value without damping. The pink color then represents the boundary conditions. From the Figure 26 it is clearly visible that both values crossed the boundary conditions. But the figure also shows that the average value with damping is not that much over the border as the average value without damping. The average value with damping has also a tendency to decrease faster than the configuration without damping.

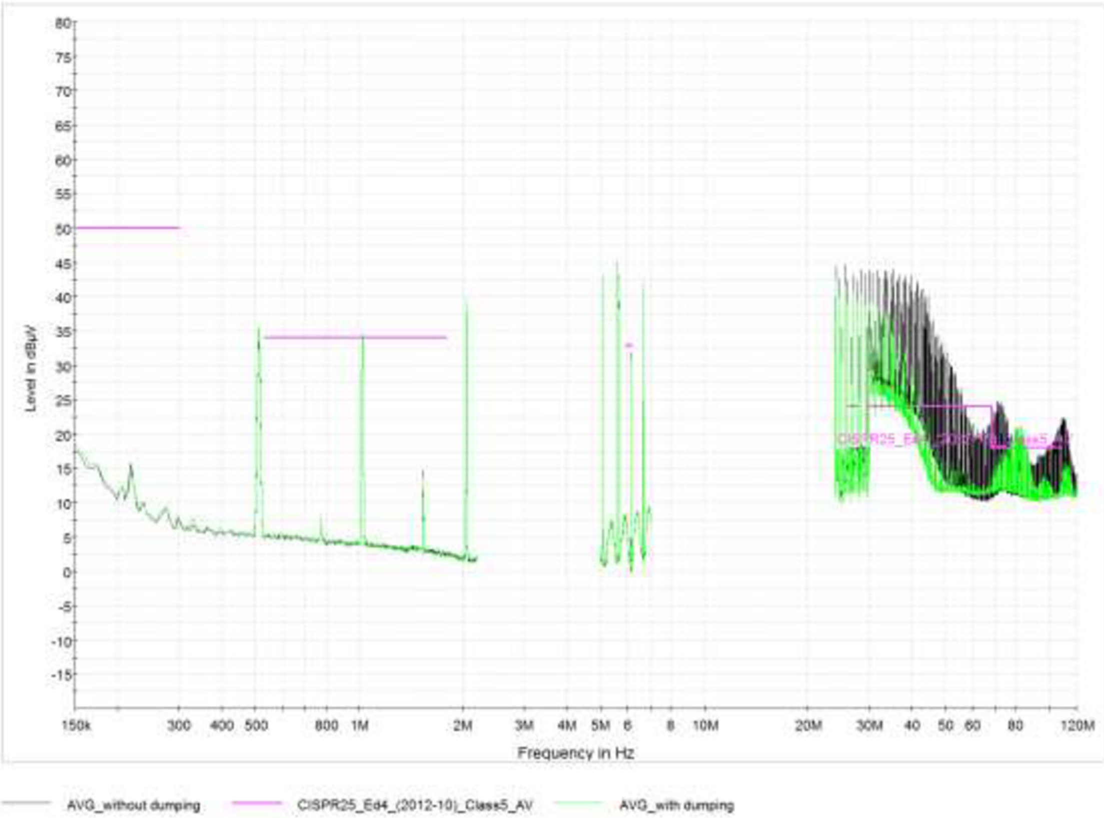

Figure 26 Wave test - Average values comparison

The next Figure 27 shows the comparison between the peak value and the average value both without damping. The average value is represented by the green color and the peak value is represented by the blue color. Because we have two different values, two boundary conditions are needed to be set. The pink color is a boundary condition for an average value, while the red color represents a boundary condition for a peak value. As Figure 26 shows, even if the average value is close or over the border line, there is still a margin for the peak value.

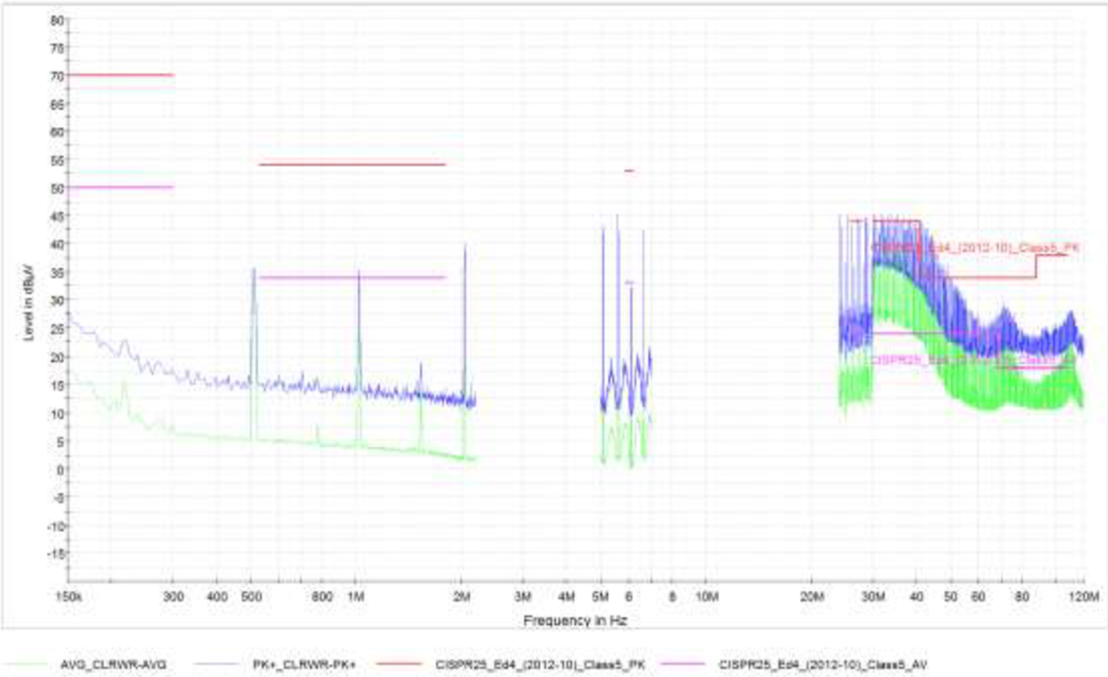

Figure 27 Wave test - Average vs Peak values comparison without damping

As for the next measurement, only peak values, with damping and without damping, were tested and compared in Figure 28. The peak value with damping is represented by the black color and the peak value is represented by the blue color. The red color is for boundary conditions. While the peak value without damping is slightly over the boundary condition, the peak value with damping is not over in any case even during high frequency.

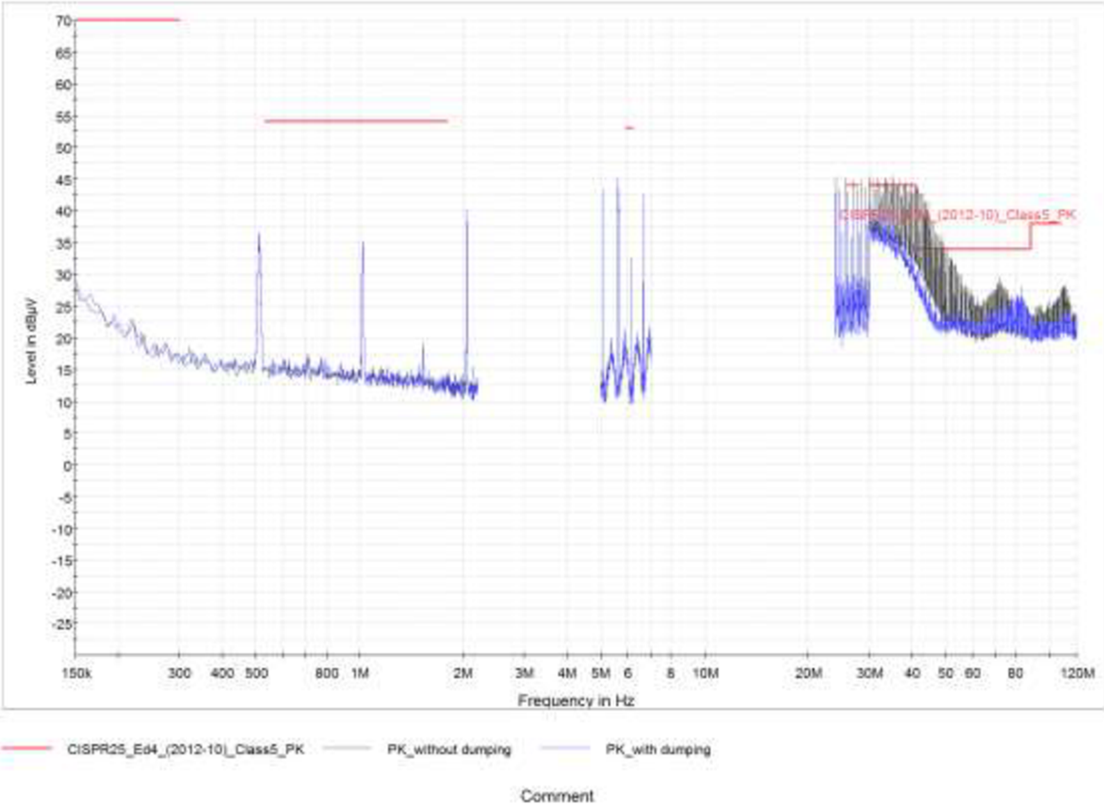

Figure 28 Wave test - peak values with and without damping comparison

The last measurement that is represented by Figure 29 is a comparison of a peak value with damping with an average value with damping. The green color is for the average value and the peak value is represented by the blue color. As it has to be, two boundary conditions are represented by the pink color for an average value and by the red color for a peak value. What is clearly visible from the screenshot is that the peak value is under the boundary condition even during high frequency. _The boundary condition during high frequency is crossed by the average value two times. But compared to the same measurement shown in Figure 27 where both values were over the boundary conditions, in this case the peak value is acceptable and as I was told, the average value is over but still within accepted limits.

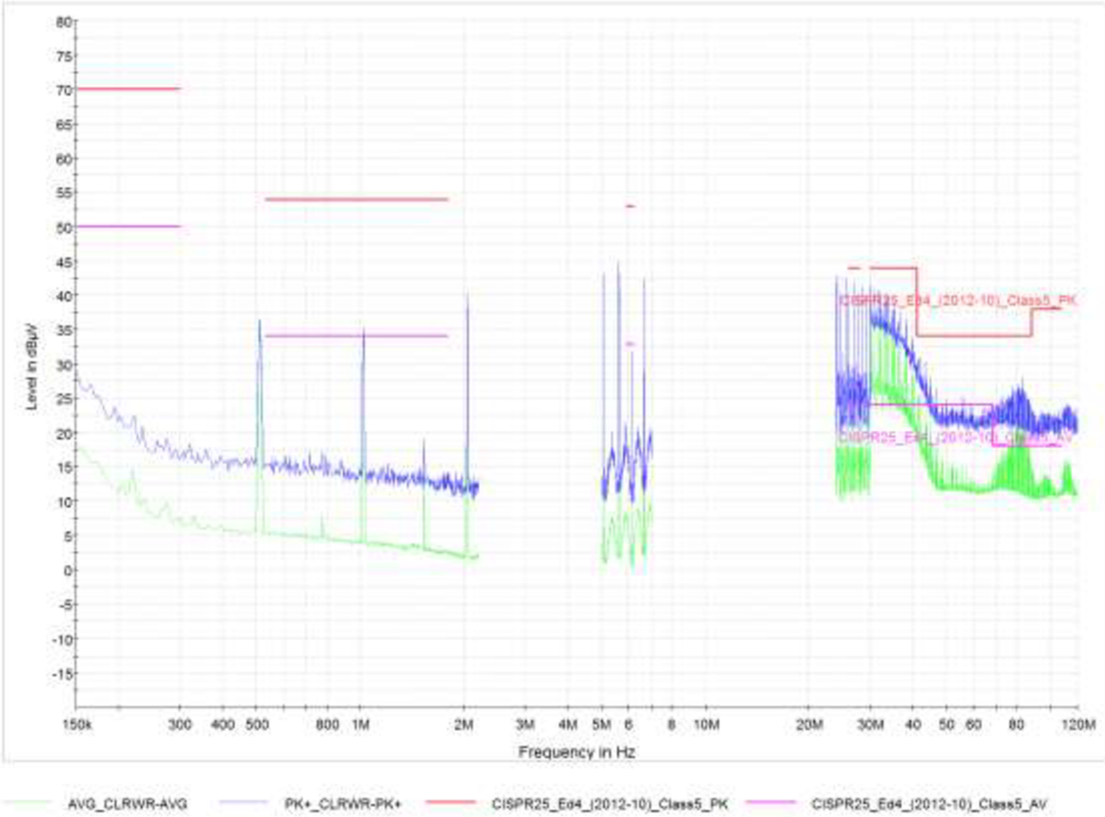

Figure 29 Wave test - Average vs Peak values comparison with damping

The result of the second set of the measurement justifies the reason why the damping is used. Both the peak values with damping as well as the average values with damping have better measuring outcomes than the signal without damping. It is also visible that the influence of the component is not critical until the frequency exceeds 20 MHz and more.

CONCLUSION

The topic of the thesis is LED light applications. These applications include LED drivers for LED lights of any used kind, damping and non-damping circuits, DC/DC convertors, and power MOSFETs. The second part of the thesis includes the measurement of a specific LED driver and h a comment on it.

A brief initial description about the history of automotive lighting starting with the raise of motorism at the beginning of the 20th century is followed by a part dealing with different types of lights used in any variation of vehicles nowadays. These types are described in various ways and different points of view, considering mainly their advantages and disadvantages. This description is supported by two figures of a given type of lights. One is the whole view of the light which can be seen on a vehicle and the other one is a cross-section where individual components can be seen and they are also highlighted by different colors to make the whole figure more understandable.

This is followed by a chapter about advantages and disadvantages of the LED lights in a use within automotive lighting in these days. Especially advantages and disadvantages of using LED lights in an automotive sector are taken into consideration and they are given a significance (an utmost) priority. What was discussed in this chapter of advantages and disadvantages is the result that it has its future in automotive branch. This leads to the nowadays use of these systems and components.

The next part is a brief introduction to the DC/DC converters used in automotive applications. Because these applications are of low voltage, also these DC/DC converters are low voltage ones as the lighting applications do not need any high voltage to run. These converters are more than necessary as any LED light application has some of these converters included to run smoothly, safely, and as they should.

In the following section Small Signal OptiMOS^{TM} 606 MOSFET is described. This type of MOSFET is used nowadays in automotive applications and it was recommended to me as a currently used technology component. Its basic parameters are picked-up in Table 2. This initial description of this MOSFET is followed by a DRL application example from a reference manual for this component. This is contiguous by basic circuit configuration and boundary conditions for DRLs applications. After the DRL application example there is a brief and basic introduction of the switching losses in DC/DC converters. These switching losses were part of the followed measurement and they are shown and discussed in the actual and real application that was measured.

Before the measurement itself I introduced MAX16833 LED driver. The most important key features are picked up as well as the important features and data needed for the measurement are mentioned.

The last part of the thesis is about the measurement itself. First of all it contains the initial description to the measurement. In the initial description I introduced all physical alterations such as changes of different settings, for example the connection of the probes to the oscilloscope, then component and measurement equipment adjustments such as soldered extra wires or removal of the damping components that had been done. The chapter includes also the list of all measurement equipment that was used with more information about each measuring component, e.g. how it works, what is measured by each measuring device or how it is set. This is followed by another subchapter about assumed values. These values are needed before the measurement itself mainly because the actually measured values and the values that should be measured should be verified. And if these two values correspond with each other, the measurement has been performed properly. These assumed values were written down into Table 4 and Table 5. Grounding is mentioned and in this thesis too. It should be done properly as it can cause a lot of problems afterwards or during the measurement. After the grounding was set correctly, the scales on the oscilloscope display were set to fit our displayed signals.

The next four sub-chapters are about the measurement itself. Individual results and pick-up outputs are discussed there. The screenshots from the measurement are placed in the text to show what it looked like during the measurement and also to show the output, especially in the second set of the measurement where no physical measurement was done. In the first set the behavior of the signal during different values of the input signal is shown in the important four cases of the measurement. These four values are the same for both measurements – with damping and without damping. The individual differences between these two circuits are discussed and shown in the figures for both sets of measurement. The differences between damping and non-damping circuit applications are written down in the following subchapter. This measurement shows us the differences of damping and non-damping applications at the same LED driver component. The results show noticeable differences and advantages of the damping application when the signal behavior is more suitable for automotive LED applications.

The output of the measurement and the observed and gained theoretical knowledge lead to a conclusion that the LED lighting used in automotive applications has its future and might have a great impact on the branch of automotive lighting.

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ENCLOSURES

No Damping			Under-voltage									Over-voltage	
Nominal configuration	Start	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	**14.00**	15.00	16.00	17.00	18.00
U_{BAT} [V]	**4.87**	**6.08**	**7.01**	**8.05**	**9.04**	**10.09**	**11.02**	**12.02**	**13.03**	**13.97**	**15.01**	**16.01**	**17.01**	**18.04**
I_{BAT} [A]	0.27	1.60	1.46	1.36	1.18	1.04	0.94	0.86	0.79	**0.74**	0.69	0.65	0.61	0.58
I_{LED} [mA]	26.10	261.00	307.56	339.93	339.79	339.91	340.13	340.19	340.25	**339.00**	339.88	340.13	339.99	340.19
U_{LEDS} [V]	21.14	23.46	23.67	23.72	23.72	23.66	23.64	23.63	23.62	**23.62**	23.62	23.61	23.58	23.61
P_{BAT} [W]	1.31	9.73	10.23	10.95	10.67	10.49	10.36	10.34	10.29	**10.34**	10.36	10.41	10.38	10.46
P_{LEDS} [W]	0.55	6.12	7.28	8.06	8.06	8.04	8.04	8.04	8.04	**8.01**	8.03	8.03	8.02	8.03
P[-]	0.76	3.60	2.95	2.88	2.61	2.45	2.32	2.30	2.26	**2.33**	2.33	2.38	2.36	2.43
Category			B						A				B	

Table 6 Non-damping measurement results – full

Damping			Under-voltage									Over-voltage	
Nominal configuration	Start	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	**14.00**	15.00	16.00	17.00	18.00
U_{BAT} [V]	**4.90**	**5.99**	**7.02**	**8.00**	**9.00**	**10.05**	**11.00**	**12.01**	**13.00**	**14.02**	**15.02**	**16.00**	**17.00**	**18.01**
I_{BAT} [A]	0.13	1.07	1.62	1.47	1.26	1.10	0.99	0.91	0.83	**0.77**	0.72	0.68	0.64	0.61
I_{LED} [mA]	15.40	156.92	304.68	340.13	340.24	340.52	340.76	340.68	340.58	**340.62**	340.52	340.66	340.46	340.67
U_{LEDS} [V]	20.77	22.72	23.58	23.68	23.64	23.64	23.61	23.61	23.60	**23.59**	23.59	23.58	23.58	23.58
P_{BAT} [W]	0.64	6.41	11.37	11.76	11.34	11.06	10.89	10.93	10.79	**10.80**	10.81	10.88	10.88	10.99
P_{LEDS} [W]	0.32	3.57	7.18	8.05	8.04	8.05	8.05	8.04	8.04	**8.04**	8.03	8.03	8.03	8.03
P[-]	0.32	2.84	4.19	3.71	3.30	3.01	2.84	2.89	2.75	**2.76**	2.78	2.85	2.85	2.95
Category			B						A				B	

Table 7 Damping measurement results – full