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PAUL SABATIER

Power Quality in DC Supplied Grids: Application to Lighting Networks

Dissertation Extended Abstract

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Author: **Ing. Leoš Kukačka**
Supervisors: doc. Ing. Milan Kolář, CSc., prof. Georges Zissis
Consultants: Ing. Jan Kraus, Ph.D., Dr. Ir. Pascal Dupuis

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Abstract

This dissertation thesis is concerned with temporal fluctuations of the luminous flux of LED lamps, a phenomenon referred to as *flicker*. Flicker is usually regarded as a disturbance due to its negative impact on human health. For lighting systems based on light emitting diodes (LED), its definition has recently been formalised in norm IEEE 1789:2015 and has been documented on devices supplied with AC voltage.

AC flicker results from interactions between network impedance, voltage and current harmonics, and the AC to DC converter. DC supplies are generally obtained by switching converters. Consequently, the same perturbing factors are present on DC networks. The thesis summarises the differences between the characteristic properties of flicker under AC and DC supplies.

It has been shown in the literature and also in this thesis that the key factor affecting flicker with LEDs is the design of the LED driver—a necessary part of the LED lighting systems. This thesis describes a methodology for the evaluation of the flicker sensitivity of DC supplied LED lamps and analyses how the sensitivity changes when the LED drivers are simplified and accustomed to DC supply.

The thesis presents a set of measurement experiments aimed to determine the typical flicker response of LED lamps both under AC and DC supply. Further experiments were performed to reveal the impact of accustomising the driver to the DC supply (removing the diode rectifier). It was found that some lamps show better flicker immunity while other lamps show worse flicker immunity. These experiments are accompanied by LED driver simulations aiming to reproduce and explain the measurement results.

The thesis further describes a measurement experiment aimed to show the typical severity of the voltage fluctuation in a low voltage DC network coupled to AC mains and its impact on the flicker. It is concluded that such a system is robust enough to filter out any perturbations coming from the AC supply, but an undesired interaction between the lamp and the supply may occur.

Key Words: DC grid, DC supply, flicker, LED driver, LED lamp, Power Quality

Abstrakt

Předkládaná dizertace se zabývá nežádoucím kolísáním světelného toku LED žárovek[1], běžně označovaným jako *flikr* (z angl. flicker). U systémů založených na principu svítivých diod (LED) byl tento jev podchycen v normě IEEE 1789:2015 a patřičně zdokumentován u žárovek napájených střídavým napětím.

Při střídavém napájecím napětí může flikr vznikat interakcí mezi vlastnostmi sítě (impedance, harmonické zkreslení napětí, proudu) a AC-DC měničem. Prvky v DC sítích jsou obvykle tvořeny DC-DC měniči, proto v nich mohou vzniknout obdobné podmínky. Tato práce popisuje typické rozdíly mezi flikrem v DC a AC sítích.

V dostupné odborné literatuře (a také v této práci) bylo již ukázáno, že klíčovým prvkem, který ovlivňuje flikr u LED žárovek je elektronický předřadník. Předřadník je nezbytnou součástí každého LED svítidla. V této práci je zdokumentováno měření citlivosti na flikr u LED žárovek napájených stejnosměrným napětím, a dále je zjišťováno, jakým způsobem bude tato citlivost ovlivněna, bude-li elektronický předřadník přizpůsoben stejnosměrnému napájení.

Dizertační práce popisuje několik experimentů, jejichž cílem je určit typickou odezvu (ve smyslu flikru) LED žárovek při střídavém a stejnosměrném napájení. Další experimenty mají za cíl určit, jakým způsobem bude ovlivněna citlivost LED žárovek na flikr, bude-li z elektronického předřadníku vyňat diodový usměrňovač. Z těchto experimentů vyplývá, že u některých žárovek ze zkoumaného vzorku se citlivost zlepší, u jiných žárovek se naopak zhorší. Proto jsou tyto experimenty doplněny simulacemi, které si kladou za cíl naměřené chování napodobit a následně vysvětlit.

Dále tato práce popisuje experiment, jenž má napodobit kolísání napětí v malé stejnosměrné síti s vazbou na střídavou síť a dopad tohoto kolísání na flikr. Výsledky ukazují, že taková soustava je poměrně odolná vůči rušení pocházejícímu ze střídavé sítě. Může však dojít k nežádoucí interakci mezi zdrojem a LED žárovkou.

Klíčová slova: DC napájení, DC síť, flikr, Kvalita elektrické energie, LED předřadník, LED žárovka

[1]Autor má za to, že – ač jde v technických souvislostech o jistý protimluv – lze v české terminologii užívat sousloví *LED žárovka* namísto dle jeho názoru poněkud neobratného *LED svítidlo* především proto, že je tento termín dosti intuitivní a zažitý rovněž u laické veřejnosti.

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List of Abbreviations

AC	Alternating Current
CFF	Critical Fusion Frequency
CFL	Compact Fluorescent Lamp
DB	Diode Bridge
DC	Direct Current
DER	Distributed Energy Resource
ELV	Extra Low Voltage
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ESR	Equivalent Series Resistance
ESS	Energy Storage System
FM	Flicker Meter
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IET	Institution of Engineering and Technology
LAPLACE	Laboratoire Plasma et Conversion de l'Energie
LED	Light Emitting Diode
LFM	Light Flicker Meter
LV	Low Voltage
OLED	Organic Light Emitting Diode
PELV	Protected Extra Low Voltage
PFC	Power Factor Correction
PQ	Power Quality
PV	Photovoltaics
PWM	Pulse Width Modulation
RM	Rectangular Modulation
SELV	Separated (or Safe) Extra Low Voltage
SM	Sinusoidal Modulation
SSL	Solid State Lighting
TR	Technical Report
TUL	Technical University of Liberec
UPS	Université Toulouse III Paul Sabatier
VQ	Voltage Quality

List of Symbols

Symbol	Unit	Description
C_{DC}	F	smoothing capacitor, its capacitance
CMR	dB	common mode rejection
CMRR	—	common mode rejection ratio
f_{ih}	Hz	interharmonic frequency
f_{m}	Hz	modulation frequency
FP	%	percent flicker
G	—	amplifier gain
G_{cm}	—	common mode amplifier gain
I_{L}	A	inductor current
L_{b}	H	converter inductor or its inductance
m_{DC}	%	rel. modulation mag. of the DC voltage
p_{inst}	—	instantaneous flicker
P	W	electric power (generally, or active)
P_{st}	—	flicker severity index evaluated from voltage
$P_{\mathrm{st}}^{\mathrm{LM}}$	—	flicker severity index evaluated from luminous flux
$P_{\mathrm{st1}}^{\mathrm{LM}}$	—	$P_{\mathrm{st}}^{\mathrm{LM}}$ evaluated in connection with the DB
$P_{\mathrm{st2}}^{\mathrm{LM}}$	—	$P_{\mathrm{st}}^{\mathrm{LM}}$ evaluated in connection without the DB
R_{b}	Ω	inductor series resistance
R_{sens}	Ω	sensing resistor, its resistance
$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$	%	rel. change of $P_{\mathrm{st}}^{\mathrm{LM}}$

1 Introduction

In the last decade, DC grids are an ever expanding field due to the advances of the related (mostly semiconductor based) technology, renewable power resources and LED lighting technology. DC grids are a promising concept in the field of electric power distribution for many reasons. Compared to AC grids they offer higher efficacy and reliability and they can reduce the complexity of the necessary technology.

AC grids have been used ever since the end of the 19^{th} century. The reason behind that was related to the technology available in that period. AC voltage is easily generated using alternators, it can be transformed to various voltage levels with very high efficiency and it can be easily used to power synchronous and asynchronous induction motors. Incandescent lamps can operate on AC with a small risk of causing flicker.

For AC power transmission and distribution there has been enough time for the concept of *power quality* (PQ) to become very well established, defined and limited by standards, ensuring that the impact on human health is minimised.

During the course of the 20^{th} century, the possibility to transmit and distribute power via DC was not given much attention. The use of DC was mostly restricted to special cases. Since then the character of both the loads and energy sources has dramatically changed. Some distributed energy resources (DERs) such as photovoltaics (PVs) and energy storage systems (ESSs) such as batteries are naturally DC devices. When these are connected to AC supply, the voltage needs to be converted to AC first; in the case of batteries, the conversion must be bi-directional.

In recent years, even natural AC loads (induction motors) are supplied through power semiconductor electronics (frequency converters, etc.) which can be supplied both by AC or DC. Most modern low–power appliances (household electronics power supplies, lighting applications) are supplied via switched supply where AC is rectified first. Particularly in lighting systems (according to [1], around 20 % of the total electricity consumption is on lighting), incandescent lamps were first replaced by fluorescent tubes and compact fluorescent lamps (CFLs), which in turn are to become obsolete due to the LED lighting technology. As is explained further on in the thesis, LED is a DC-friendly technology.

In an environment where these energy sources and appliances are used, the DC grids allow one to reduce the number of lossy AC-DC and DC-AC conversion stages in the grid either at the power sources, ESSs or at the load side. It is natural to expect that DC grids will be utilised even more frequently in new installations. Because it is a relatively young field, for the DC, the PQ concept is not established and the corresponding standards are either insufficient or missing.

As it has already been mentioned earlier, light emitting diodes represent a breakout technology promising to replace older and less energy efficient artificial light sources. LEDs have been available since the 60s of the 20th century. In the beginning they were not suited for high power applications and, moreover, only monochromatic LEDs existed for several decades. With intensive research in this area more colours at higher brightness are becoming available.

With the invention of the high power blue LED in 1994 [2] it also became possible to construct an LED emitting white light, either by a combination of blue, red and green LEDs, or by using a blue LED in combination with a suitable phosphor layer. Further research is being made on increasing the power and brightness, this key invention has opened door to using LEDs in general lighting applications. For inventing blue LEDs, a Nobel prize for physics was awarded in 2014.

According to [3], LED penetration increased from $0.3\,\%$ worldwide in 2010 to $26\,\%$ in 2016 and is still expected to grow. By 2014, the LED penetration in lighting applications reached $3\,\%$ in the US and it was estimated that a complete replacement of all light sources for LED might save up to $1\,400\,\mathrm{GW\,h}$ a year in the US only [4]. The same source states that the average efficacy of LED light sources ranged from $58\,\mathrm{lm\,W^{-1}}$ to $108\,\mathrm{lm\,W^{-1}}$ and the maximum efficacy reached up to $158\,\mathrm{lm\,W^{-1}}$.

Intensive research is still going on in the area of LED lighting. It is to be expected that the penetration of LED technology throughout the world would increase together with the efficacy, making it an even more attractive alternative to traditional light sources.

It is to be expected that LEDs would be used in modern supply (possibly smart) grids very soon. These, in turn, can be expected to operate with low voltage DC. Indeed such networks already exist at least in the scale of units of buildings ([5], the EDISON project [6, 7] or the ABCDE project [8]).

LEDs are a specific technology and as such they represent a specific type of electric load when connected to the supply grid. Their reaction to various voltage variations is also difficult to predict. Only very recently the emitted standards begin to reflect the specifics and requirements of LED lighting systems.

One of these specifics is flicker. The term *flicker* can refer to any disturbing temporal variations of artificial (or even natural) light. All artificial light sources can flicker, though the cause and severity may vary. Flicker represents a risk for human health and safety. The flicker phenomenon is sufficiently described and documented for traditional lighting technologies, such as incandescent lamps and fluorescent tubes. With traditional light sources, the cause of flicker is usually poor supply voltage quality (along with ageing). This is why flicker has become an inseparable part of power quality considerations and standards. LED lamps have been shown to produce significant amount of flicker if measures are not taken to minimise it [LK1][STD1][9, 10, 11].

Enough attention has been paid to the efficiency, feasibility and reliability of DC grids and microgrids in recent research and dedicated literature (in addition to previously cited works, also see for example [12, 13, 14]). As both the DC networks and LEDs are relatively recent technologies, research on power quality in DC networks is scarce though, and the discussions do not cover the topic of LEDs and flicker. (The author was surprised to see how little literature he could find on the topic of *power quality* in DC). This thesis aims to expand the work on this topic by analysing the flicker of LED lamps rated for extra low voltage. It aims to analyse how flicker properties of LED lamps would change if the lamps were adapted from an AC to DC supply.

2 Flicker

Flicker (both a noun and verb) is a term used for describing annoying rapid changes in the quality or quantity of artificial light. Because one of the main causes of flicker is poor voltage quality, it is very often considered as a specific part of VQ problems. In a more narrow sense, it is a VQ quantity used for evaluating the impact of poor VQ on a human exposed to artificial light.

The human retina has been shown to transfer frequencies as high as 165 Hz [15]. However, this does not mean that conscious flicker perception can be induced at such frequency. The term *critical fusion frequency* (CFF) refers to a frequency at which the human observer fails to perceive (sense, consciously observe and possibly report) flickering light and experiences steady perception. The CFF varies under different conditions (modulation depth, chromaticity, ambient light, etc.) but generally it is in the range from 50 Hz to 90 Hz [STD1].

CFF estimates do not take eye motion into account. A fast pulsing light (above CFF) may result in a series of repetitive visual patterns on the observer's retina during rapid eye movement (saccade) [16, 17]. This phenomenon is called *intrasaccadic flicker perception* and is the reason behind some common visual phenomena such as *rainbow effect* or *phantom array effect*. If the eye is steady and the light source is moving, the phenomenon is called *stroboscopic effect*. According to [16], the intrasaccadic perception can occur with light pulsing at up to 2 kHz. Thus, the flicker can be sorted in three categories [STD1][9, 15, 16, 18] according to the frequency:

Visible flicker below the CFF; visible flicker is sensed by the eye via direct observation, perceived by the brain, consciously recognised and can be reported;

Invisible flicker above the CFF, but below approx. 165 Hz to 200 Hz; invisible flicker is not consciously perceived by direct observation but is sensed by the eye retina and, thus, can also cause headaches and have other biological impact; interference with other flickering light sources may possibly result in visible flicker.

High frequency flicker up to 2 kHz can cause intrasaccadic flicker perception, stroboscopic effect or phantom array effect; interference with other flickering light sources may possibly result in visible flicker.

The causes of flicker are explained later in Sec. 3.2. Flicker at various frequencies can cause various problems in lighting applications. These can be sorted into two groups.

Health problems include tiredness, work inefficiency, headache, migraine (mostly in sub-clinical variants—not reported to a doctor) and epileptic seizures in the most extreme situations. A summary of the health impact of flicker is given in [19].

Safety issues include stroboscopic effect (moving parts of rotary equipment appear stationary) or phantom array effect (multiple perception of a single source). These effects pose a problem for workers in factories or late night drivers.

A very detailed summary of health risks and other flicker related issues is given in [STD1]. It is the author's impression that despite all the cited research and evidence, the flicker is not a recognised problem among the uninformed public.

2.1 IEC Flicker and Flicker Meter

The IEC standard 61000-4-15 [STD2] defines a way of estimating the annoyance of flicker produced by 60 W incandescent lamp produced for a distorted 230 V AC voltage from the voltage measurement without actually analysing the light output of the lamp.

In the standard, there are several indices defined; firstly the instantaneous flicker p_{inst}, the short–term flicker P_{st}, evaluated from 10-minute intervals and long–term flicker P_{lt}, evaluated from 2-hours intervals. Evaluation from an interval of arbitrary length (more than one minute) is allowed.

The IEC flicker meter is a device capable of calculating P_{lt} and P_{st} from the AC voltage measurements. Part of the IEC FM is a model of a 60 W two–filament incandescent lamp. This is why the IEC flicker corresponds to the actual photometric flicker only when such lamp is used. Other lighting technologies may behave in a completely different way. Furthermore, only visible flicker perception is taken into account. Invisible and high frequency flicker is disregarded with IEC FM.

2.2 Objective Flicker Meters

Since IEC FM evaluates P_{st} from public grid voltage measurements only, there have been efforts to evaluate the same quantity directly from light intensity measurements. Such devices are called *objective flicker meters* [20, 21, 22] or *light flicker meters* (LFM) [STD3]. A LFM implemented according to [20] was used in this work. The output quantity of LFM is $P_{\text{st}}^{\text{LM}}$.

The technical report IEC TR 61457-1:2015 [STD3] adopts the testing voltage signals from [STD2]. These signals are originally used for FM calibration purposes. The technical report suggests one to use these signals as immunity tests for lighting devices. As for P_{st}, the commonly recognised limit is 1, one can presume that the same limit will apply to $P_{\text{st}}^{\text{LM}}$, even though such information is missing in the TR.

3 Solid State Lighting Technology

Solid state lighting technology (SSL) is a term referring to lighting technologies based on semiconductors (LED and OLED) contrary to incandescent lamps and fluorescent tubes. While OLEDs find their usage in display technology, inorganic compound based LEDs are used in general lighting applications and therefore are more of concern for this thesis. An overview of solid state lighting technology, its features, advantages and drawbacks is available in [23, 24] and [25].

3.1 LED Lamps—Drivers

In order to ensure LEDs operate at a constant operating point, it is necessary that LEDs are supplied from a customised LED driver [LK2, LK1][STD1],[9, 11, 26]. The primary function of the driver is to ensure constant operating point for the LED matrix via a constant voltage or constant current control. If it is desired, the driver can also implement a dimming feature. A compact combination of LEDs (in the vast majority of cases there are more than one diode, connected in a series chain or series–parallel matrix) and a driver to form an LED lamp. In special applications, the driver can be separated from the LED head also [11]. Each lamp manufacturer uses their own driver design and thus there are many various driver topologies used [LK2, LK1][26].

The following text describes the parts of two stage LED drivers in more detail. Single stage drivers may be encountered where the PFC circuit is combined with a DC-DC converter.

Electromagnetic Interference Filter Under AC supply, the driver can produce a significant amount of harmonic current emission. Except for poor quality drivers where EMC is ignored, the high frequency part of the emission is removed by a simple EMI filter at the input of the driver. The filter can be implemented using a mutual inductance, a resistor, or a combination of both.

Diode Bridge In AC applications, the voltage needs to be rectified and converted to DC in the driver. This is why any driver declared for AC supply can be safely used with DC supply without the risk of harming the driver or the lamp. The rectification is done via a *diode bridge* (DB, also referred to as *diode rectifier* or *Graetz bridge*). The DB is a key subject of research in this thesis, so it is worthy to pay some attention to its properties.

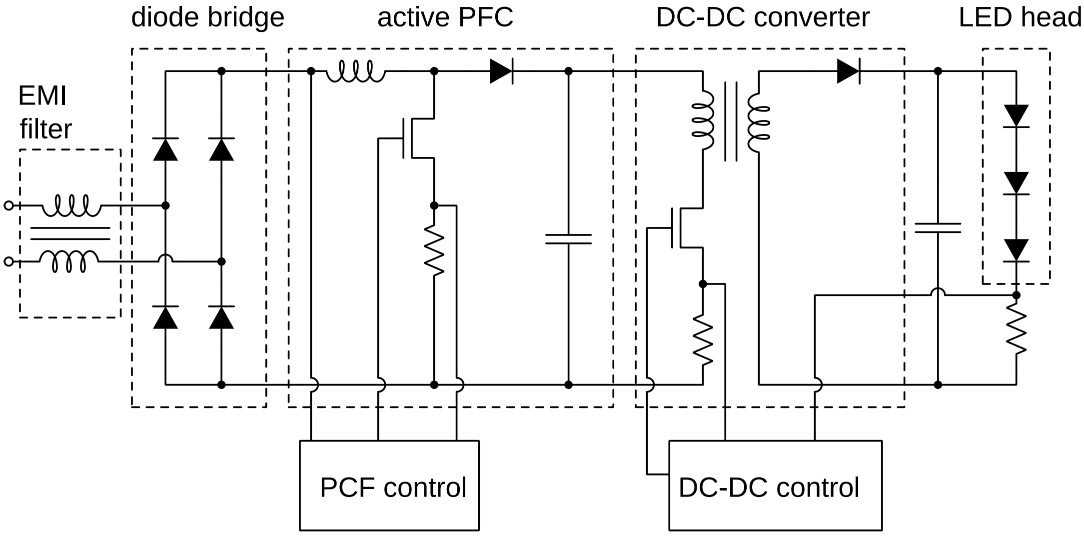


Figure 3.1: A schematic of a two stage LED driver for AC supply

The DB (shown in Fig. 3.1) is a two–port circuit consisting of four diodes in such a way that regardless on the voltage polarity at the input port, the voltage polarity at the output is always the same. When AC voltage is applied at the input, during each half–period, two of the diodes are in conduction mode and two are in blocking mode.

The price of the DB is negligible[1] and is not likely to be the reason for excluding the DB in DC applications. The DB represents a drawback mainly due to power losses. When a DB is employed in a circuit there are two diodes connected in series with the rest of the circuit at all times. The forward voltage of the DBs is usually above 1 V (0.5 V per diode). In LV and ELV applications, where the current consumption is higher, this voltage drop can cause non–negligible power losses. Schottky diodes are sometimes used to reduce the losses as they offer significantly smaller forward voltage, but they usually are more expensive than regular diodes by an order of magnitude. Therefore, excluding the DB in LV and ELV DC applications can be desirable and expected.

Power Factor Correction Circuit In high quality lamps or in drivers with power consumption above 25 W, where the limits for harmonic emission are more strict [STD4], low frequency EMI is removed using an active power factor correction (PFC) circuit. The PFC circuit is a DC-DC converter (boost) controlled in such a way that the current consumption is roughly sinusoidal in phase with the supply voltage. In common household LED lamps, however, the power consumption is smaller than 25 W and usually smaller than 10 W. Thus, the active PFC is usually missing [LK2]. With a DC supply, the PFC circuit becomes excessive.

[1]During the work on this thesis the prices of DBs were below € 0.5, minimum price being € 0.1

DC-DC Converter The DC-DC converter part is usually based on one of several typical topologies. According to a detailed overview [26], these can be

- **active**—containing a controller and probably a feedback loop; these topologies are able to eliminate voltage ripple up to certain level and have low losses (as low as units of % of lamp power consumption),
- **passive**—only passive parts are used (resistors, capacitors); these solutions are usually lossy (up to 35 % of the lamp power consumption) and unable to eliminate voltage ripple, thus flicker can be expected from these drivers.

Active solutions basically employ a variety of DC-DC converters. Other sorting is possible depending on the inclusion of a transformer:

- **isolated**—containing a transformer operated at high frequency provided that the connection assures galvanic isolation from the power source; this is useful if the driver serves to supply multiple lamps in which case the driver creates an enclosed SELV or PELV system ([7]). In isolated topologies, feedback for the controller is usually taken from a tertiary transformer winding,
- **non–isolated**—transformer–less topologies or with transformers, but without galvanic isolation.

More LED specific DC-DC converters exist employing various regulation techniques (for example, a high frequency peak current control via pulse density modulation (PDM) combined with low frequency dimming via pulse width modulation (PWM), [27]). It is beyond the scope of this thesis to make an exhausting list of the possible LED driver topologies.

Passive drivers may be implemented using either a resistor based voltage divider (a relatively lossy solution) or a capacitor based voltage divider. Such solution reduces losses, but because it contains a capacitor connected in series with the rest of the circuit, it is intended solely for AC supply.

LED Head The output voltage of the driver is dependant upon the arrangement of the LED head and can range from units up to tens of volts. The current is more important for driving the LEDs. For high power LEDs used in lighting applications, the nominal current is usually in the order of hundreds of mA. Power consumption is in units of watts. There is usually more than one LED in the LED head, especially in higher power lamps. They are arranged in a single or several series branches or to form a matrix.

Intensive research is going on on how to implement a good quality driver [28, 29, 30, 31, 32, 33, 34, 35]. Most often, the aim is to minimise cost and maximise the efficiency and lifetime, sometimes dimming is featured. Flicker immunity is only sometimes taken into account. DC supply is very scarcely assumed [7, 36].

3.2 LEDs and Flicker

Photobiological safety of LED produced light (where flicker is only one of the discussed aspects) is discussed in [10]. Until the recently released standard [STD1], there had been no normative definition of LED driver flicker properties.

Depending on the driver properties, flicker with LEDs can be induced by several causes:

Clean AC supply voltage can cause flicker with poor quality drivers. This kind of flicker is not detectable by IEC FM or any other voltage measurement based method; it needs to be detected by optical means. Flicker caused this way is constant and lasts for the entire lifetime of the device.

Distorted (AC or DC) supply voltage caused flicker can be detected from voltage measurements provided that the proper lamp model is known and used. Flicker caused this way lasts only for the duration of the disturbance.

Standard switched supply driver can cause high frequency flicker if a switched supply is used. This is rarely an issue as the frequencies are usually high enough (tens of kHz). Naturally, such flicker can only be detected using optical measurements. Flicker caused this way lasts for the entire lifetime of the device.

Dimmable PWM controlled driver can cause flicker in dependence on the PWM frequency and duty ratio. This kind of flicker usually lasts only when the dimming level smaller than 100 % is requested.

4 Thesis Objectives

This thesis is concerned with luminance flicker of LED lighting systems supplied with low or extra low DC voltage. The thesis looks at the problem of flicker in LED systems generally and aims to analyse the risk of flicker when DC supply is used instead of AC. It frames several experiments with flicker properties of LED lamps, whose results were published in [LK1, LK2, LK3, LK4]. In this thesis the work is expanded by more experiments and simulations.

One of the advantages of DC grids over AC ones is the reduction of the number of AC-DC and DC-AC conversions. AC-DC conversion causes VQ problems both on the AC and DC side (current harmonics, ripple). These problems need to be compensated for using more advanced circuitry (PFC, converters with feedback control). Replacing AC supply with DC seems to be a natural way to decrease the complexity of the network and the appliances connected to it.

In the DC network, most of the LED drivers may be operated without change. However, the diode rectifier will become excessive and, thus, it may be removed in order to increase the efficiency of the LED drivers. It can be expected that, as more and more devices become adapted to DC supply, their design will omit the lossy and excessive AC-DC conversion stage. While the power loss savings of such an adaptation are indisputable, especially in low voltage and extra low voltage scenarios, its impact on flicker immunity of the LED lamps has never been studied.

The primary aim of this thesis is to *analyse the effect of the diode bridge upon the flicker immunity of LED drivers.* The means to achieve this goal are:

1. determining the flicker level and perturbations immunity of several LED lamps by measurements of $P_{\mathrm{st}}^{\mathrm{LM}}$ and *FP*,

2. determining the change of flicker level and perturbations immunity of LED lamps when the diode bridge is bypassed (observing the relative change of $P_{\mathrm{st}}^{\mathrm{LM}}$),

3. explaining the observed behaviour using a suitable model of an LED driver; this means

    - creating a suitable model according to the known information about the analysed LED drivers,
    - successfully predicting the flicker level and its frequency dependency compared to the measurements,

4. analysing the conditions under which the removal of the diode bridge will not increase the flicker level of the LED lamps, i.e.

    - identifying the possible means of ripple amplification,
    - varying the identified circuit properties,
    - observing the impact of the variations on the flicker level ($P_{\mathrm{st}}^{\mathrm{LM}}$),
    - observing the impact of the variations upon the relative change of $P_{\mathrm{st}}^{\mathrm{LM}}$.

The thesis in general aims to contribute to an ongoing discussion over power quality in DC grids. To the author's knowledge it is for the first time that flicker and LED technology would enter this discussion. Furthermore the author hopes the knowledge accumulated in this thesis might be useful for upcoming standards about LED lighting technology and flicker.

5 Experimental Part

This chapter describes the core experiment performed in the scope of the thesis. A set of 12 V LED lamps was analysed. The lamps were supplied by distorted AC and distorted DC with 1 Hz resolution. The produced P_{st}^{LM} was acquired both in dependence on the frequency and modulation magnitude. The lamps were disassembled and the key elements of the drivers were noted. In the following part, of the experiment the measurements were repeated with the diode bridge electrically bypassed. The relative change of P_{st}^{LM} was evaluated.

Table 5.1: Declared properties of the analysed lamps

Label	Rated voltage	Power (W)	Socket	Flux (lm)	CCT (K)
LED1	12 VAC/50 Hz	1.4	GU5.3,MR16	45	4 300
LED2	12 VAC/DC	5	GU5.3	340	3 000
LED3	10–18 VAC/DC	5	GU5.3	260	3 700
LED4	12 VAC/DC	5	GU5.3,MR16	—	warm white
LED5	12 VAC/DC	4	GU5.3,MR16	200	3 000
LED6	12 VAC/DC	7	GU5.3,MR16	390	2 700

5.1 12 V LED Lamp Drivers—Reverse Engineering

Reverse engineering methods were applied on the lamps in order to link the lamp flicker properties and hardware implementation. This is important to understand what is going on in the drivers during regular operation or during experiments. The information is summarised in this section. Information from this section is also used for creating models used in Chapter 6.

The table 5.2 shows all key parts of the disassembled lamps. The diagrams are shown in Fig. 5.1.

Most notably, in the LED1, the driver is passive. Any kind of control mechanism is lacking; this allows for an interesting comparison of the LED1 properties with other lamps. Other tested lamps (LED2–6) contain active electronics to supply the LED matrix (see Fig. 5.1). A step–down (buck) converter is used in all cases. There are differences among the lamps in the LED matrix topology and in the part properties. For details see Tab. 5.2.

In the buck topology, the LED current is sensed by measuring the voltage drop

Table 5.2: LED lamps reverse engineering

Lamp label	R_{I} (Ω)	C_{B} (µF)	C_{B}/P (µF W^{-1})	μController	R_{Sens} (Ω)	LED matrix (ser x par)
LED1	3.4	10	6.67	N.A.	N.A.	3(2)x7
LED2	0	330	66	PT4205	0.43	3x5
LED3	0.15	430	86	PT4115	0.24	1x1
LED4	0	470	94	SD42527	0.1	1x1
LED5	0	250	66	—	—	3x1
LED6	0.5	330	47	—	—	1x1

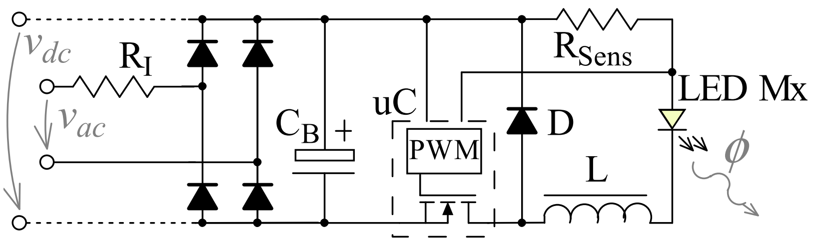


Figure 5.1: LED2–6 simplified connection diagram—a step–down DC-DC converter is employed to supply the LED matrix

over the sensing resistor R_{sens}. The sensed voltage is proportional to the inductor current:

$$V_{\mathrm{sens}} = R_{\mathrm{sens}} I_{\mathrm{L}} \,, \tag{5.1}$$

which is also equal to the LED current.

The driver datasheets [37, 38] explain that the v_{sens} voltage is kept within range from 170 mV to 230 mV. This means that the converter is operated by hysteretic control in continuous conduction mode. Regarding the relative complexity of synchronous switching implementation, it can be expected that the switching is asynchronous.

The sensing resistor is placed on the high side of the LED branch. This requires that the voltage is sensed by a differential amplifier. The situation is sketched in a simplified manner in Fig. 5.2. In an ideal case, the feedback voltage would be equal to

$$V_{\mathrm{fb}} = G(V_1 - V_2) = G V_{\mathrm{sens}} = G R_{\mathrm{sens}} I_{\mathrm{L}} \,, \tag{5.2}$$

with G being the amplifier gain, I_{L} the sensed inductor current, R_{sens} the sensing resistor value, V_1 and V_2 the voltages as shown in the Fig. 5.2. This way, the V_{fb} will always be proportional to the inductor current and voltage perturbations can only enter the feedback loop if they affect the I_{L} first.

However, differential amplifiers are known to amplify a common mode signal along with the differential signal. This property is usually quantified as *common mode rejection ratio* (*CMRR*) or *common mode rejection* (*CMR*). With *CMRR* assumed, the

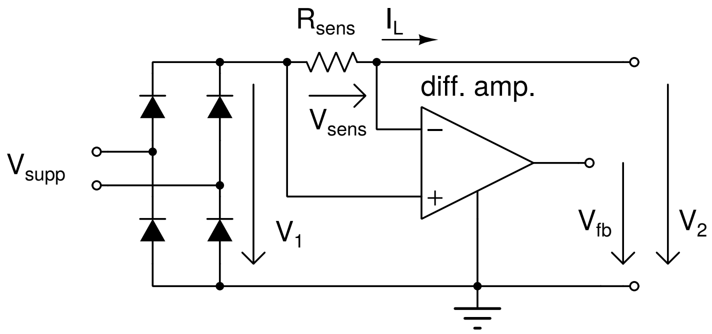


Figure 5.2: High side inductor current sensing

feedback voltage will be equal to

$$V_{fb} = G(V_1 - V_2) + G_{cm}\frac{1}{2}(V_1 + V_2), \tag{5.3}$$

where G_{cm} is the common mode gain. The *CMR* is then equal to ([39]):

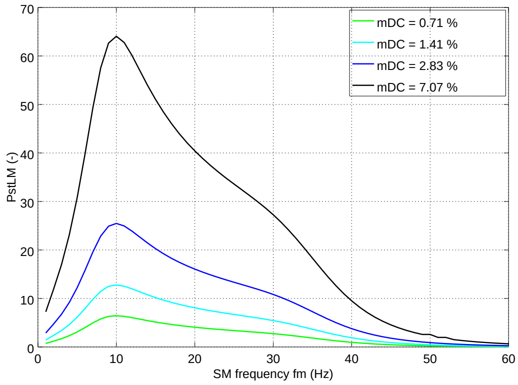
$$CMR = 20\log_{10} CMRR = 20\log_{10}\left(\frac{G}{G_{cm}}\right). \tag{5.4}$$

This way, the perturbations may enter the feedback loop directly and, thus, have a larger affect on flicker than in the ideal case. This hypothesis is tested in the simulations in Chapter 6. This problem may be removed completely if low side sensing is used. With low side current sensing, there is no need for a differential amplifier.

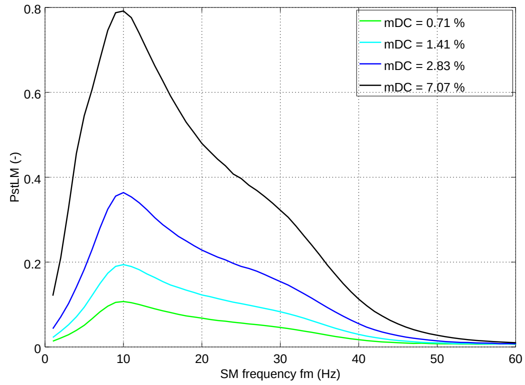
5.2 Measurements with Light Flicker Meter

In this part of the experiments the P_{st}^{LM} was evaluated from the produced light. The lamps under test were placed in an Ulbricht sphere (diam. 2.5 m) and supplied from the power amplifier APS 125, controlled by the controller PXI-8106 and the arbitrary wave generator NI PXI-5412. The lamps were supplied by both distorted AC and DC. The P_{st}^{LM} is measured by an LFM [20, 21]. The modulation frequency resolution was 1 Hz.

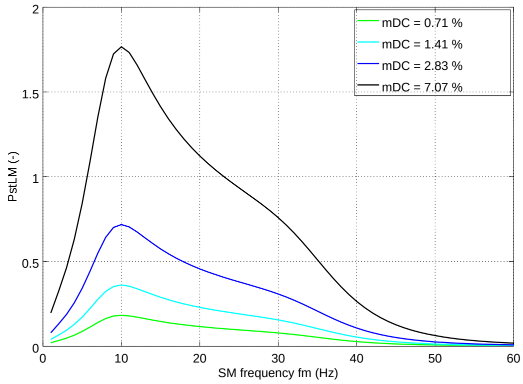
Figure 5.3 shows the P_{st}^{LM} measurements with a DC supply, where the intermodulation does not take effect. The figure compares measurements of all the lamps with sinusoidal and rectangular modulation (SM and RM, respectively). The curves for SM roughly follow the eye sensitivity curve used in LFM. The nature of the P_{st}^{LM} quantity does not allow one to distinguish between lamp properties and the effect of the eye response model.



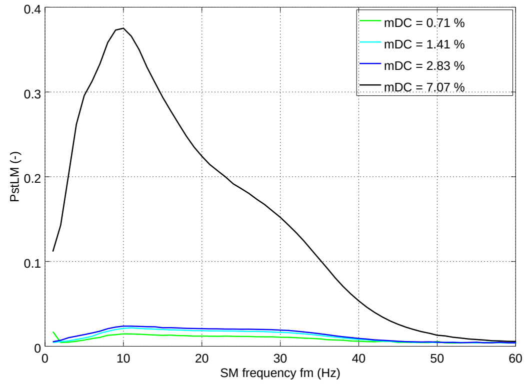
(a) LED 1—sinusoidal modulation



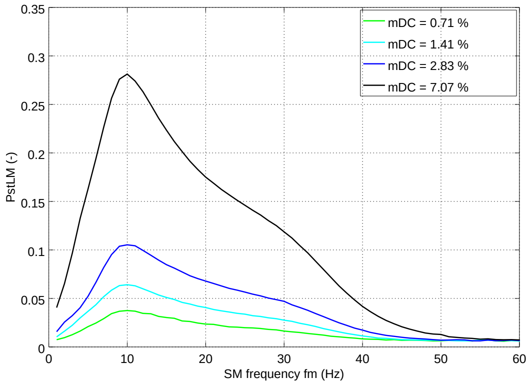
(b) LED 2—sinusoidal modulation



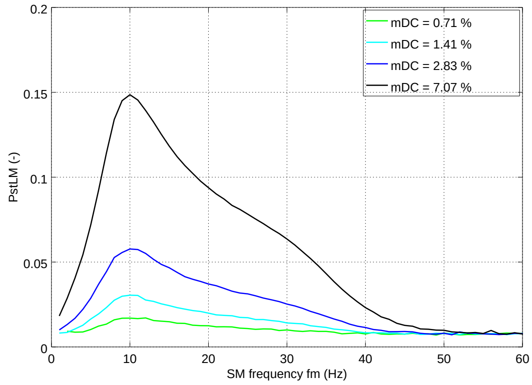
(c) LED 3—sinusoidal modulation



(d) LED 4—sinusoidal modulation



(e) LED 5—sinusoidal modulation



(f) LED 6—sinusoidal modulation

Figure 5.3: LED 1–6: comparison of sinusoidal and rectangular DC supply modulation; for DC the relevant frequencies are up to 60 Hz

5.3 The Impact of Diode Bridge on Flicker Properties of DC Supplied LED Lamps

In AC applications, the topology of LED drivers necessarily contains a diode bridge in order to rectify the voltage and convert it to DC. The diode bridge does not pose a problem under DC supply, on the contrary it protects the driver from the wrong voltage polarisation. Even though, so far it is not clear how the future DC–only lamp drivers can look like. The reduction of power losses and financial cost might result in excluding the DB in DC–only applications. This experiment was designed to analyse the impact of the DB presence on the flicker ($P_{\text{st}}^{\text{LM}}$) response.

Firstly, the lamps $P_{\text{st}}^{\text{LM}}$ response to DC supply with SM was measured. Afterwards the connection was changed to bypass the DB and the measurements were repeated. It is expected that the results will depend upon the driver topology. In one of the lamps (LED4), the DB could not have been bypassed; it is excluded from the analysis. The results are summarised in Tab. 5.3. The relative $P_{\text{st}}^{\text{LM}}$ change was evaluated as

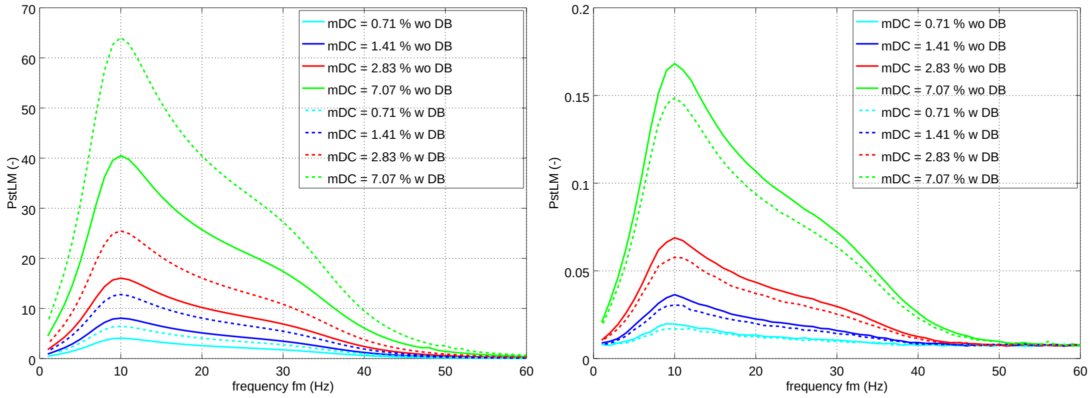
$$\Delta P_{\text{st}}^{\text{LM}} = \frac{P_{\text{st2}}^{\text{LM}} - P_{\text{st1}}^{\text{LM}}}{P_{\text{st1}}^{\text{LM}}} \cdot 100\,, \tag{5.5}$$

where $P_{\text{st1}}^{\text{LM}}$ denotes the $P_{\text{st}}^{\text{LM}}$ measured with the diode bridge and $f_{\text{m}} = 10\,\text{Hz}$ and $P_{\text{st2}}^{\text{LM}}$ denotes the $P_{\text{st}}^{\text{LM}}$ evaluated with the diode bridge bypassed. This way positive values of $\Delta P_{\text{st}}^{\text{LM}}$ indicate that the DB has a positive impact on flicker immunity (flicker is lower with the DB), negative $\Delta P_{\text{st}}^{\text{LM}}$ values indicate the opposite (flicker is higher with the DB).

Figure 5.4 shows the $P_{\text{st}}^{\text{LM}}$ response in the frequency domain both in connection with the DB and without. The figure only shows examples—LED1 (passive driver) and LED5 (active driver).

Table 5.3 shows the $P_{\text{st}}^{\text{LM}}$ results for both topologies as well as the $\Delta P_{\text{st}}^{\text{LM}}$ evaluated at four distinct modulation magnitude levels. In the table, the red colour (negative $\Delta P_{\text{st}}^{\text{LM}}$ values) indicates that the DB *worsens* the $P_{\text{st}}^{\text{LM}}$ response; the green colour (positive $\Delta P_{\text{st}}^{\text{LM}}$ values) indicates the opposite. In LED4, the DB bypass was not possible due to a protective cast around the driver; therefore, it was excluded from these comparisons.

Table 5.3 shows that, for some lamps, the DB helps to minimise the $P_{\text{st}}^{\text{LM}}$ while, for other lamps, it worsens the response. This experiment is accompanied by a simulation also, see the next chapter. The results from this section were published in [LK4].



(a) LED1: $P_{\mathrm{st}}^{\mathrm{LM}}$ caused by the SM in the DC supply—comparison in connection with the DB and without the DB.

(b) LED6: $P_{\mathrm{st}}^{\mathrm{LM}}$ caused by the SM in the DC supply—comparison in connection with the DB and without the DB.

Figure 5.4: Comparison: $P_{\mathrm{st}}^{\mathrm{LM}}$ with and without the DB; Subfigure a: DB worsens the flicker response, Subfigure b: DB attenuates the flicker response.

Table 5.3: The $P_{\mathrm{st}}^{\mathrm{LM}}$ and $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ measured for SM, $f_{\mathrm{m}} = 10\,\mathrm{Hz}$, varying m_{DC}; comparison of the lamps performance with ($P_{\mathrm{st1}}^{\mathrm{LM}}$) or without the DB ($P_{\mathrm{st2}}^{\mathrm{LM}}$)

	m_{DC} (%)	0.71	1.41	2.83	7.07
LED1	$P_{\mathrm{st1}}^{\mathrm{LM}}$	6.45	12.78	25.47	64.06
	$P_{\mathrm{st2}}^{\mathrm{LM}}$	4.07	8.06	16.05	40.49
	$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ (%)	−36.82	−36.94	−36.99	−36.79
LED2	$P_{\mathrm{st1}}^{\mathrm{LM}}$	0.11	0.19	0.36	0.79
	$P_{\mathrm{st2}}^{\mathrm{LM}}$	0.14	0.28	0.55	1.28
	$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ (%)	+34.89	+41.78	+49.84	+61.54
LED3	$P_{\mathrm{st1}}^{\mathrm{LM}}$	0.18	0.36	0.72	1.77
	$P_{\mathrm{st2}}^{\mathrm{LM}}$	0.17	0.34	0.67	1.69
	$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ (%)	−6.30	−6.60	−6.45	−4.53
LED5	$P_{\mathrm{st1}}^{\mathrm{LM}}$	0.04	0.06	0.11	0.28
	$P_{\mathrm{st2}}^{\mathrm{LM}}$	0.02	0.03	0.02	0.08
	$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ (%)	−52.04	−60.04	−77.83	−71.62
LED6	$P_{\mathrm{st1}}^{\mathrm{LM}}$	0.02	0.03	0.06	0.15
	$P_{\mathrm{st2}}^{\mathrm{LM}}$	0.02	0.04	0.07	0.17
	$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ (%)	+15.91	+19.55	+19.36	+13.21

5.4 Experiment Summary

This section described a thorough analysis of six ELV LED lamps. Several important observations can be noted.

Firstly, when comparing the flicker response between a clean AC supply and distorted DC one, the flicker level may be significantly higher for the distorted DC than for the clean AC one, even though the modulation depth is much smaller and the downslope is also less steep.

Secondly, the active drivers are based upon hysteretic control. Except for LED5 and LED6 where a detailed analysis was complicated, the lamps have the current sensing resistor placed on the high side. This means that a differential amplifier is necessary for acquiring the resistor voltage. These findings were published in [LK3].

Thirdly, for some of the lamps (LED1, LED3 and LED5) the diode bridge has a negative impact on the flicker sensitivity. Removing the DB helped to decrease the flicker level. For LED2 and LED6, the effect was the opposite. For these lamps, removing the DB increased the flicker level. These differences among the lamps may be caused by:

1. perturbations affecting the voltage reference inside the driver ICs at different levels,
2. various *CMRR* among the driver ICs,
3. various series resistance of the DB or a series resistor placed at the input,
4. various dimensioning of the circuit elements (inductor, smoothing capacitor) relative to the LED load.

The next chapter tests these hypotheses using a model.

Lastly, the m-$P_{\mathrm{st}}^{\mathrm{LM}}$ responses of the individual lamps were measured. It was experimentally verified that the $P_{\mathrm{st}}^{\mathrm{LM}}$ caused by an arbitrary DC modulation may be estimated from the $P_{\mathrm{st}}^{\mathrm{LM}}$ caused by the SM if the m-$P_{\mathrm{st}}^{\mathrm{LM}}$ response is linear. These findings were published in [LK4].

6 Simulations

This chapter is dedicated to simulations which are intended to explain the significance of the diode bridge in a DC supplied LED driver. The previous chapter presents measurement results from experiments where lamp flicker immunity was compared with and without the diode bridge. The results show that, for some lamps, the diode bridge has a positive impact on the flicker immunity and, for some lamps, the impact is negative. The purpose of the simulations described in this section is to try to model these results, explain the difference and, thus, to provide some particular conclusions and instructions for driver manufacturers.

For this purpose, a model of the LED drivers described in Sec. 5.1 was created in MATLAB Simulink [40]. The drivers all follow a very similar design, differing only in the smoothing capacitor sizes and the number of employed LEDs. The drivers may also differ in inductor and sensing resistor sizes which could not have been read from the disassembled circuits, but are prescribed in the datasheets.

The model comprises a driver and an LED chain. The model schematic is shown in Fig. 6.1. The model parameters are listed in Tab. 6.1. As has already been mentioned in Sec. 5.1, placing the sensing resistor on a high side of the LED branch requires using a differential amplifier. A common undesired property of differential amplifiers is the common mode voltage leakage. This property has been included in the model.

Table 6.1: LED lamp model—parameter values

parameter name	symbol	value	unit
supply DC voltage	V_{supp}	12	V
sensing resistor	R_{sens}	0.43	Ω
buck inductor size	L_{b}	47	µH
buck inductor ESR	R_{b}	0.128	Ω
smoothing capacitor size	C_{DC}	330	µF
smoothing capacitor ESR	R_{DC}	0.1	Ω
DB forward voltage	V_{DBfw}	0.5	V
DB on resistance	R_{DBon}	40	mΩ
DB snubber resistance	R_{DBoff}	100	kΩ
Schottky diode forward voltage	V_{Sfw}	0.2	V
switch transistor on resistance	R_{trans}	560	µΩ

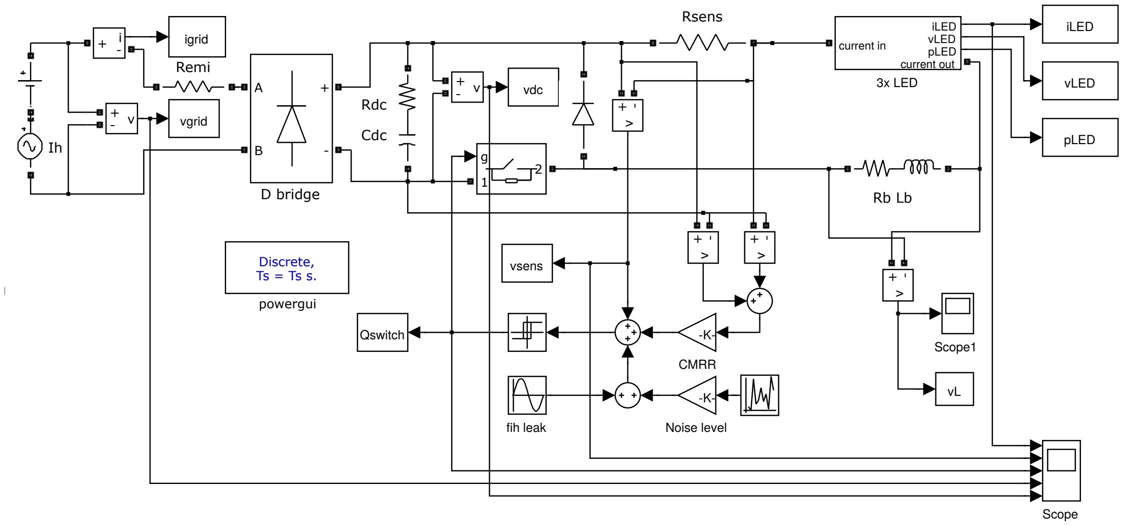
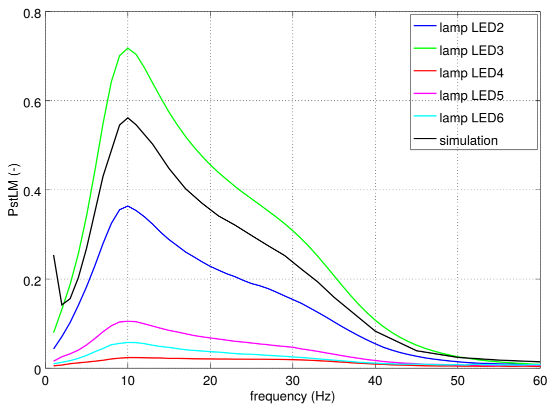


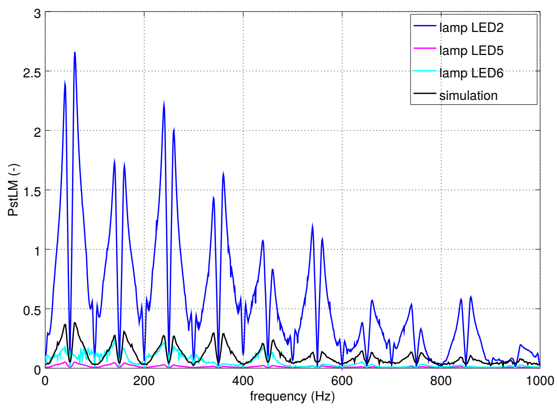
Figure 6.1: LED lamp model—driver, hysteretic control

6.1 Model Verification

The model was verified comparing $P_{\mathrm{st}}^{\mathrm{LM}}$ from the simulation and measurements of lamps LED2–6 in frequency domain. The comparison is shown in Fig. 6.2. The simulated $P_{\mathrm{st}}^{\mathrm{LM}}$ corresponds with the measured values. Importantly, the curve shape in 6.2a is identical to the measurements. The largest notable difference is at the modulation frequency $f_{\mathrm{m}} = 1\,\mathrm{Hz}$, where the simulated $P_{\mathrm{st}}^{\mathrm{LM}}$ unexpectedly rises. With AC supply, the simulation results correspond roughly to the real behaviour. It is concluded that the model is suitable for simulating the $P_{\mathrm{st}}^{\mathrm{LM}}$ response of lamps LED2–6.



(a) DC supply—frequencies up to 60 Hz



(b) AC supply—frequencies up to 1 kHz

Figure 6.2: Active driver—model verification, frequency domain

6.2 Flicker Simulations

After verifying and examining the model in a frequency domain, the simulation was run with sinusoidal modulation of the DC supply. The sinusoidal modulation simulates the ripple of the DC grid supplying the lamp. The simulation time was chosen to be one second in order to provide $1\,\mathrm{Hz}$ resolution for the choice of modulation frequency and for the frequency domain analysis. For the frequency domain simulations, the frequencies were chosen from the range $1\,\mathrm{Hz}$ to $60\,\mathrm{Hz}$ and the modulation magnitude was $m_{\mathrm{DC}} = 2.83\,\%$. Flicker quantities were evaluated from the LED current; most importantly, the $P_{\mathrm{st}}^{\mathrm{LM}}$, which is shown in the figures and tables of this section. A second model with identical parameters, but without the DB was used; its results were used to acquire and evaluate $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$.

The minimum time for the $P_{\mathrm{st}}^{\mathrm{LM}}$ evaluation is $10\,\mathrm{s}$ plus approx. $5\,\mathrm{s}$ for the step response of the inner LFM filters. The simulation would be extremely demanding to generate such a long signal. Therefore, the signal was downsampled to $5\,\mathrm{kHz}$ and repeated in order to generate $15\,\mathrm{s}$ long signal.

Section 5.4 discussed several hypotheses about the cause of $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$. Let us remind that these were:

1. perturbations affecting the voltage reference inside the driver ICs,
2. various *CMRR* among the driver ICs,
3. various series resistance of the DB or a series resistor placed at the input,
4. various dimensioning of circuit elements (inductor, smoothing capacitor) relative to the LED load.

At this point we will try to address each of these and test them by introducing a proper variation in the simulated model.

Reference voltage sensitivity In the default setup, the flicker is caused by the supply voltage ripple, which results in the DC link voltage ripple being transferred to the LED head. In an ideal case, the ripple is eliminated as the LED current is kept within the predefined boundaries. These boundaries are defined by a reference voltage within the driver IC. If the supply voltage is perturbed, it is possible that the reference voltage is also subject to certain level of perturbation. In order to simulate this leakage, a copy of the ripple signal was injected into the current sensing signal (see the model diagram in Fig. 6.1). The simulations were repeated with the perturbation leakage magnitude being 0.1 and $0.2\,\%$ of m_{DC}.

Common mode The next possible way of ripple amplification is the *CMRR* of the differential amplifier sensing the inductor current. This is why the simulations were run with a common mode signal added to the sensed voltage at several values of the *CMRR*.

Series resistance Series resistance may represent a parasitic property of the DB, or, as we can see in one of the analysed lamps (Tab. 5.2), there may be a series resistor included in the design intended as a simple EMI filter (this is why this parameter is denoted as R_{EMI}). During the measurements, such a resistor was necessarily bypassed along with the DB and, thus, might affect the measurement results. In order to be able to differentiate the effect of series resistance from other parameters, simulations were run with several values of extra series resistance connected at the supply port.

Circuit elements variations The datasheets for driver ICs [37, 38, 41] only give us recommendations about the size of circuit elements like smoothing capacitor, inductor and its series resistance or the current sensing resistor. The particular choice depends on the designer and will probably depend on the load (the size of the LED matrix) and supply voltage level. Engineers will also look for a way to minimise the cost and volume of the driver. This is why the values of key elements affecting the driver behaviour were varied. R_{b} represents the inductor series resistance and is not an element on its own. Various inductors may have different series resistance, this is why this property was included in this analysis.

6.3 Results

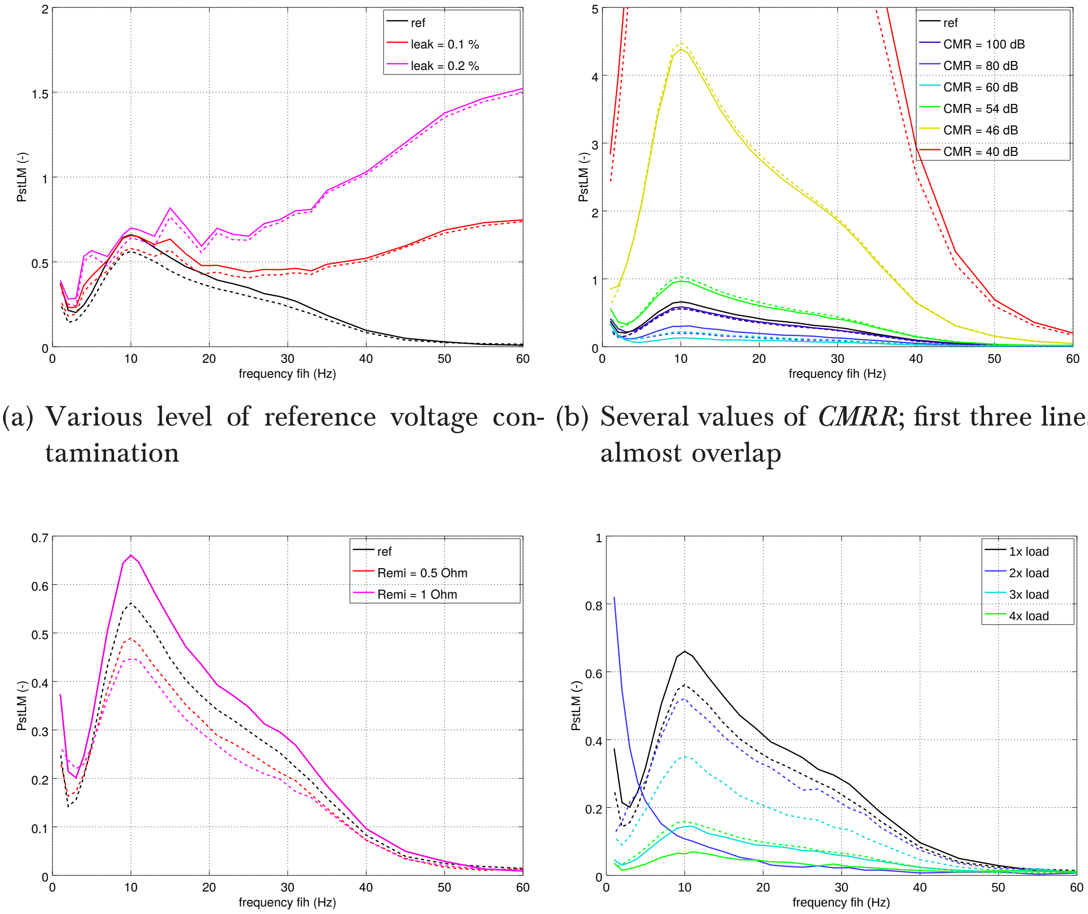
Table 6.2 shows the numerical results of the simulation with varying modulation depth m_{DC}. The $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ is calculated and compared to measurements. Let us recall that $P_{\mathrm{st1}}^{\mathrm{LM}}$ is the flicker level achieved by the original driver and $P_{\mathrm{st2}}^{\mathrm{LM}}$ is the flicker level after bypassing the DB. The quantity $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ is defined in such a way (see Eq. (5.5)) that positive values indicate the DB helps minimise the flicker response and negative values indicate that DB worsens the flicker response.

Figure 6.3a shows the simulation results with varied reference voltage sensitivity to supply the voltage perturbation. This sensitivity is noted as *leak* and is given in % of m_{DC}.

From the figure, it can be seen that the perturbation injection causes flicker at higher frequencies. This means that a perturbation at f_{ih} causes flicker at frequencies

Table 6.2: Simulated $P_{\mathrm{st}}^{\mathrm{LM}}$ with the DB ($P_{\mathrm{st1}}^{\mathrm{LM}}$) and without ($P_{\mathrm{st2}}^{\mathrm{LM}}$); $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ for LED2,3,5,6 and simulation; various m_{DC}, constant $f_{\mathrm{ih}} = 10\,\mathrm{Hz}$

m_{DC} (%)		0.71	1.41	2.83	7.07
$P_{\mathrm{st1}}^{\mathrm{LM}}$	sim.	0.21	0.31	0.55	1.40
$P_{\mathrm{st2}}^{\mathrm{LM}}$	sim.	0.37	0.36	0.65	1.60
$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$	sim.	+77.45	+17.36	+17.93	+14.69
	LED2	+34.89	+41.78	+49.84	+61.54
	LED3	−6.30	−6.60	−6.45	−4.53
	LED5	−52.04	−60.04	−77.83	−71.62
	LED6	+15.91	+19.55	+19.36	+13.21



(a) Various level of reference voltage contamination

(b) Several values of *CMRR*; first three lines almost overlap

(c) Several values of R_{EMI}

(d) Adding extra LED branches as additional load

Figure 6.3: Simulated $P_{\mathrm{st}}^{\mathrm{LM}}$ with various changes to the model; dotted line with DB, solid line without DB

below f_{ih}. This phenomenon was never observed in the measurements and, thus, it can be concluded that it does not occur in real situations.

The *CMRR* is usually between 70 and 120 dB [39]. For poor quality amplifiers embedded in ICs, it may be lower. The simulations were run for four levels of the *CMRR*. The results are summarised in Tab. 6.3 and a graphical comparison of these results is in Fig. 6.3b. The results show that *CMRR* has large impact on the produced flicker. Interestingly, for a certain value of *CMRR* (60 dB) the flicker level decreases; this is because the perturbing signal enters the system at two different points, each time with an opposite phase. This causes a cancellation at a certain level. The numerical results in Tab. 6.3 show that the *CMRR* of the differential amplifier affects not only absolute flicker level, but also the $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$.

Figure 6.3c shows the results for various values of R_{EMI}. Numerical results for $f_{\mathrm{ih}} = 10\,\mathrm{Hz}$ are in Tab. 6.3. It can be observed that the series resistance decreases the flicker response. Thus, with higher values of R_{EMI}, the $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ rises also.

Table 6.3: Simulated $P_{\text{st}}^{\text{LM}}$ results with various changes to the simulation, $m_{\text{DC}} = 2.83\,\%$, $f_{\text{ih}} = 10\,\text{Hz}$

(a) Reference voltage contamination

leak (%)	$P_{\text{st1}}^{\text{LM}}$	$P_{\text{st2}}^{\text{LM}}$	$\Delta P_{\text{st}}^{\text{LM}}$
0	0.56	0.66	+17.93
0.1	0.58	0.66	+13.44
0.2	0.64	0.70	+8.99

(b) Series resistance at the input

R_{EMI} (Ω)	$P_{\text{st1}}^{\text{LM}}$	$P_{\text{st2}}^{\text{LM}}$	$\Delta P_{\text{st}}^{\text{LM}}$
0	0.56	0.66	+17.93
0.5	0.49	0.66	+34.97
1	0.45	0.66	+47.94

(c) Sensing amplifier *CMR*

CMR (dB)	$P_{\text{st1}}^{\text{LM}}$	$P_{\text{st2}}^{\text{LM}}$	$\Delta P_{\text{st}}^{\text{LM}}$
∞	0.56	0.66	+17.93
140	0.56	0.66	+17.75
100	0.57	0.65	+14.30
80	0.52	0.57	+9.42
60	0.22	0.13	−40.56
53.98	1.03	0.97	−5.77
46.02	4.48	4.39	−2.03
40	17.35	20.06	+15.63

(d) Extra parallel branches of LEDs

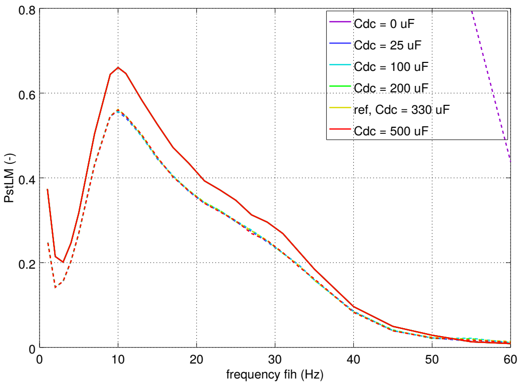
branches	$P_{\text{st1}}^{\text{LM}}$	$P_{\text{st2}}^{\text{LM}}$	$\Delta P_{\text{st}}^{\text{LM}}$
0	0.56	0.66	+17.93
1	0.52	0.11	−79.39
2	0.35	0.14	−58.91
3	0.16	0.06	−60.01

Figure 6.3d shows the flicker response when extra LED branches were added to provide more load. In order to feed sufficient level of current, the R_{sens} was changed accordingly also (half the original value for two parallel LED branches, etc.). The numerical results are shown in Tab. 6.3d.

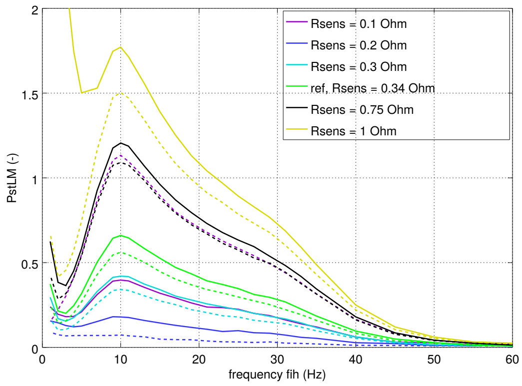
Figure 6.4 and Tab. 6.4 show the results for circuit element variations. It is apparent (Subfig. 6.4a, Tab. 6.4a) that the size of the smoothing capacitor relative to the rest of the circuit has absolutely no impact on the flicker level. Removing the capacitor completely will result in a voltage drop of the DC link and the lamp will not operate.

Changing the value of R_{sens} will result in changing the LED current. This increases the power consumption and the luminous flux output also. Subfigure 6.4b and Tab. 6.4b show how flicker sensitivity is changed. For larger values, the circuit is more loaded and, thus, without proper change of the inductor, more prone to flicker.

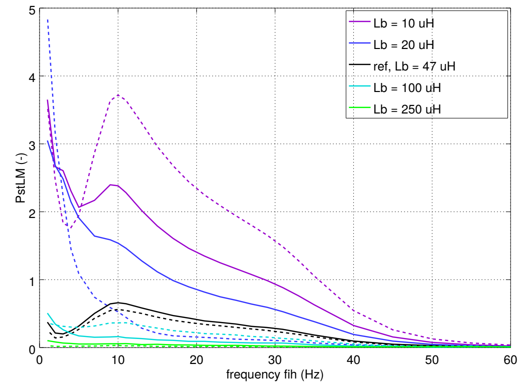
Generally, larger L_{b} values will decrease the flicker. However, it is difficult to observe a clear trend in the effect on $\Delta P_{\text{st}}^{\text{LM}}$.



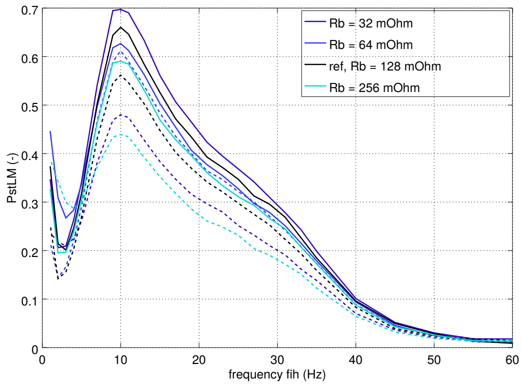
(a) C_{dc} variations



(b) R_{sens} variations



(c) L_{b} variations



(d) R_{b} variations

Figure 6.4: Simulation results with varied circuit elements, dotted line with DB, solid line without DB; $m_{\mathrm{DC}} = 2.83\,\%$

Table 6.4: Simulated $P_{\mathrm{st}}^{\mathrm{LM}}$ and $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ results with various changes to the circuit elements, $m_{\mathrm{DC}} = 2.83\,\%$, $f_{\mathrm{ih}} = 10\,\mathrm{Hz}$

(a) Smoothing capacitor, C_{DC}

C_{DC} (µF)	$P_{\mathrm{st1}}^{\mathrm{LM}}$	$P_{\mathrm{st2}}^{\mathrm{LM}}$	$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$
2	0.55	0.66	+19.38
25	0.56	0.66	+18.70
100	0.56	0.66	+18.67
200	0.56	0.66	+17.64
330	0.56	0.66	+17.93
500	0.56	0.66	+17.84

(b) Sensing resistor, R_{sens}

R_{sens} (Ω)	$P_{\mathrm{st1}}^{\mathrm{LM}}$	$P_{\mathrm{st2}}^{\mathrm{LM}}$	$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$
0.1	1.13	0.40	−64.94
0.2	0.07	0.18	+144.06
0.3	0.34	0.42	+23.08
0.34	0.56	0.66	+17.93
0.75	1.09	1.21	+10.54
1	1.50	1.77	+17.81

(c) Inductor, L_{b}

L_{b} (µH)	$P_{\mathrm{st1}}^{\mathrm{LM}}$	$P_{\mathrm{st2}}^{\mathrm{LM}}$	$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$
10	3.72	2.38	−35.93
20	0.53	1.54	+192.43
47	0.56	0.66	+17.93
100	0.36	0.16	−55.44
500	0.05	0.08	+67.21

(d) Inductor resistance, R_{b}

R_{b} (mΩ)	$P_{\mathrm{st1}}^{\mathrm{LM}}$	$P_{\mathrm{st2}}^{\mathrm{LM}}$	$\Delta P_{\mathrm{st}}^{\mathrm{LM}}$
32	0.48	0.70	+45.20
64	0.61	0.63	+2.44
128	0.56	0.66	+17.93
256	0.44	0.59	+34.41

6.4 Simulations Summary

This chapter was concerned with simulating the $P_{\mathrm{st}}^{\mathrm{LM}}$ and $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ of $12\,\mathrm{V}$ LED lamps analysed in Chapter 5. In the same section, several hypotheses were proposed, aiming to explain the results. In this section, a model was created and verified. The purpose of the simulations was to determine the conditions under which removing the DB from the circuit will not raise the flicker response of the circuit. This means that the $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ must be non-positive. The shown figures depict the flicker levels for the modulation frequencies $f_{\mathrm{m}} = 1$ to $60\,\mathrm{Hz}$; in the tables, only values for $f_{\mathrm{m}} = 10\,\mathrm{Hz}$ are shown and used to determine the $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$. Throughout this section, the modulation magnitude was kept constant at $m_{\mathrm{DC}} = 2.83\,\%$. It is to be noted that the flicker level is always below $P_{\mathrm{st}}^{\mathrm{LM}} = 1$, except for special cases (e.g., too small a *CMRR*).

Hypothesis 1: Voltage Reference From the simulation results several conclusions may be drawn. Firstly, hypothesis no. 1 (perturbations affecting the voltage reference inside the driver IC) may be rejected, as the simulation results do not correspond to any performed measurements. This means that, in the studied lamps, the voltage reference is not compromised by voltage perturbations.

Hypothesis 2: *CMR* Secondly, hypothesis no. 2 (*CMR* of the current sensing subsystem) may be accepted. It was shown that the *CMR* directly affects the absolute level of $P_{\mathrm{st}}^{\mathrm{LM}}$ both with the DB and without. The simulations revealed that with an increasing *CMR*, the $P_{\mathrm{st}}^{\mathrm{LM}}$ drops until it reaches a minimum at $CMR = 60\,\mathrm{dB}$, only to start rising for higher values of a *CMR*. A similar pattern can be observed with $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$.

Hypothesis 3: Input Port Series Resistance Hypothesis no. 3 (series resistance at the supply port) may be accepted too. The simulations show that the series resistance decreases the $P_{\mathrm{st}}^{\mathrm{LM}}$ of the lamp, which in turn leads to higher values of $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$. In this sense the effect of the DB is positive. The same flicker attenuation effect may be achieved by placing a series resistor at the supply port even when the DB is not used; this is a lossy approach though and, thus, the bonus of increasing the power efficiency is lost.

Hypothesis 4: Circuit Elements Dimensioning The answer to hypothesis no. 4 (other circuit elements dimensioning) must be given in several parts. Firstly, the smoothing capacitor size was shown to have no impact on the flicker when a DC supply is used. With an AC supply, the smoothing capacitor is an important factor affecting the flicker response.

When more LED branches are connected in parallel, flicker is decreased, as is shown in Tab. 6.3d. Additionally, the $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ drops significantly to negative values. Adding more LED branches to the circuit means more load for the converter.

The sensing resistor itself is used to set the desired LED current; thus, too small or too large values may lead to instability if the load is not changed appropriately. From the results, one can see that small increase in its value causes larger flicker, while decreasing the sensing resistor (increasing the LED current) decreases the flicker response. This might be the same effect as when more parallel LED branches were added to the circuit.

The inductor effect on flicker is very simple—larger inductor values help decrease flicker significantly. Its effect upon $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ is ambiguous though. The same can be said about its series resistance. In these cases, the simulation results are inconclusive.

7 Conclusion

LEDs are a relatively young technology compared to other technologies. This is why most of the standards were not updated yet to cover all specificities linked with LEDs. It has already been recognised that, with LEDs, the responsibility for flicker has moved towards the lamp manufacturer and their driver design. This further means that the lamps' reaction to perturbations may vary significantly from lamp to lamp. The ways to measure flicker need to reflect this fact, which is already happening [STD1, STD3].

This thesis is concerned with analysing flicker properties of LED lamps under DC supply. The core experiment was designed to determine the role of a diode bridge in flicker immunity of ELV LED lamps equipped with a hysteretically controlled buck converter. The measurement results are ambiguous; some of the tested lamps show better flicker response with the DB bypassed while other lamps show the opposite (see Chpt. 5). This is why simulations were necessary to provide a more detailed explanation.

7.1 Results Summary

The following paragraph describes the results obtained from the core work; other experiments and simulations are discussed afterwards.

Simulation Results In Chapter 5 several hypotheses were proposed to explain a lamps' behaviour. As for the flicker response, generally, the simulations show that:

- removing the DB results in applying a higher voltage to the DC-DC converter input port, which may affect its operating point and switching frequency;
- the reference voltage in the lamps' driver IC is not compromised by supply voltage perturbations;
- flicker immunity is not affected by the size of the smoothing capacitor placed at the DC-DC converter input ports, regardless of the DB presence; this is in accordance with the measurements and conclusions presented in [LK3];
- the *CMR* of the current sensing subsystem plays a role; it is possible to decrease the flicker response by introducing a certain level of *CMR*;

- a larger L_{b}, R_{b} and a larger load (more parallel LEDs and / or smaller current sensing resistor) help decrease the flicker response.

The main aim of the simulations was to reveal under which conditions the $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ metric becomes negative (i.e., removing the diode bridge will not increase the flicker response). It was concluded that:

- in most simulations, the $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ was positive;
- DB series resistance may play a role in decreasing the flicker level and thus relatively increasing the flicker response when the DB is removed (increase the $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$);
- for certain levels of introduced *CMR* in the current sensing subsystem of the driver (in particular the value $CMR = 60\,\mathrm{dB}$), apart from flicker response decrease, a negative $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$ was achieved also, which means that a given level of *CMR* positively affects the driver flicker properties and the DB may be removed for further decreasing the flicker response also;
- using more LED branches in the LED head (more load for the DC-DC converter) results in better flicker response, but also helps decrease the $\Delta P_{\mathrm{st}}^{\mathrm{LM}}$.

Recommendations for DB–less Driver Design Considering the above described findings, it may be recommended that if the DB is to be removed from the driver design, the following conditions should be met:

- the driver should be loaded properly;
- in the case when high side current sensing is used, the *CMR* of the current sensing subsystem should be known and, in the particular case of buck converter with hysteretic control, it should be ideally around $CMR = 60\,\mathrm{dB}$.

Regardless of the DB removal, it is advisable that the inductor is sufficiently large in order to decrease the flicker response of the driver.

In the lamps analysed experimentally, all the simulated effects may have combined and counteracted each other. Because not all details about the driver circuitries were available, there are some uncertainties about the particular values of some circuit elements. For this reason, a direct comparison of the simulation results with real measurements is impossible.

7.2 Flicker in DC Grids—Assessment

Due to the fundamental nature of DC voltage, it might be expected that the risk of flicker is much lower with DC than with AC. The reality is not so trivial. AC voltage itself is only one of the possible causes of flicker and it is not difficult to compensate. The other possible causes of flicker (see Sec. 3.2—distorted supply voltage and driver switching frequency) still pose a risk in the DC environment.

Table 7.1: Causes of flicker with LED lamps—comparison of AC and DC supply

flicker cause	char. property	AC	DC
clean AC supply	invisible	yes	no
supply perturbations	visible, invisible	yes	lower risk
switching noise	very high frequency	yes, irrelevant	yes, irrelevant
PWM dimming	only with PWM	yes, avoidable	yes, avoidable

It is true that in the AC scenario, flicker may be caused by interharmonic components at up to units of kHz due to their intermodulation with the fundamental frequency. This phenomenon was identified in literature already [42, 43]. With DC supply, the intermodulation does not take place and, thus, the set of flicker–relevant frequencies is smaller. Visible flicker may be caused by frequencies below 60 Hz only, invisible flicker below 200 Hz, etc. Driver immunity is then given purely by the transfer function of the driver expressed by the gain factor.

Table 7.1 summarises the individual possible causes of flicker of LED lamps (as listed in Sec. 3.2) and their risk under AC and DC supply. It can be seen that adopting DC to supply the LED lamps will mitigate some of the typical causes of flicker.

7.3 Discussion

Standard IEC 61000-3-3 [STD4] lays the requirements upon electrical appliances concerning P_{st} emissions in AC grids. A question is appropriate, whether a similar standard should be issued concerning DC grids. If LED lighting is expected to be a major lighting technology in DC grids, the P_{st} metric—even if the standard flickermeter were adapted to DC—would become obsolete. Thus, issuing such a standard seems unnecessary.

P_{st} and P_{st}^{LM} Metrics In the context of LED technology, it is obvious that the metric P_{st} is losing its importance as a flicker index since it may not be related to actual level of flicker any more. It still may be used as one of the VQ indices for evaluating the severity of low frequency phenomena, although other indices may be more appropriate for that purpose.

The P_{st}^{LM} metric is a more proper way of evaluating flicker severity with LED technology. The transition from voltage evaluation to luminous flux evaluation means that flicker is not purely a voltage quality phenomenon any more. Such an approach still does not respect all aspects of LED flicker though. The P_{st}^{LM} metric only evaluates visible flicker; this is the heritage of P_{st} and its incandescent lamp model where invisible and high frequency flicker was irrelevant. Because invisible and high frequency flicker may pose a risk to human health and safety and is relevant with LEDs, these phenomena should be also covered by P_{st}^{LM} (or a similar metric).

Immunity Requirements The theoretical research revealed that there is a lack of standardised immunity requirements for LED lamps with respect to flicker. For future work on immunity requirements for LEDs in DC grids there is a key observation that zero flicker level with clean AC voltage does not imply good flicker immunity with perturbed DC supply, as is shown in Sec. 5.4. This means that *AC may not be assumed as a worst-case scenario when laying requirements on flicker immunity in DC environment.* Extra considerations need to be taken.

7.4 Recommendations About Future Research

During the work on this thesis the following points were found worthy of attention for future directions of research in the discussed field:

- Interaction between equipment in DC grids need to be analysed deeper. This phenomenon need to be examined and its cause identified and described properly.
- Simulations testing the *CMRR*'s effect on flicker response should be tested experimentally in order to validate the results.
- $P_{\mathrm{st}}^{\mathrm{LM}}$ should be adapted to account for invisible flicker and high frequency flicker also. Alternatively, a similar index should be defined which would account for these phenomena and which would be used in parallel with the contemporary $P_{\mathrm{st}}^{\mathrm{LM}}$ metric.
- Heterochromatic flicker is a phenomenon never deeply studied with LEDs and, as such, it represents an appealing field of research.

7.5 Closing Statements

There is still surely a long way to go before DC grids will enter people's everyday life. Many practical aspects need to be settled and appropriate standards issued. Together with other positive aspects they can offer, they also represent a way to mitigate flicker, which is shown in this thesis.

LED lamps entered the lighting applications field even before appropriate standards could have been issued to reflect their specific behaviour. This means that some products available on the market may be a source of flicker at a hazardous level. Fortunately, this aspect has been recognised and appropriate standards are being issued to address this topic.

But even so, it is the author's personal experience that the wide public is not familiar with the flicker phenomenon and does not recognise it as a problem. Some people may report headaches or dizziness when using LEDs for lighting, unaware that these symptoms may be caused by invisible flicker. The end user has absolutely no means of telling whether the product he intends to buy will flicker or not. For the lamp manufacturers, there is no obligation to quantify the flicker response of given product and to state it on the package label.

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The author has seven publications indexed in the *Web of Science* database where one of them has been cited once. Ten publications are indexed in the *Scopus* database with eleven citations in total. Autocitations are not counted. One paper ([LK15]) was published in a journal with impact factor 1.35, another paper ([LK17]) was conditionally accepted for publication in a journal with impact factor 0.97.

The author participates in the research project TAČR TA185S01001 "Modular system for complex monitoring and management of DC and AC/DC hybrid smart grids", Technology Agency of the Czech Republic. A co-authored patent application was submitted to the Industrial Property Office of the Czech Republic.

The author supervised three successfully defended bachelor projects and two successfully defended bachelor theses. One master thesis is being supervised in the year 2017/2018.