Research and Development of Electronic Ballasts for Smart Lighting Systems with Light Emitting Diodes

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree.

Irena Milaševski............................

Tarkades valgustussüsteemides kasutatavate LED-valgustite elektrooniliste ballastseadmete uurimine ja arendamine

IRENA MILAŠEVSKI

Contents

Acknowledgement

Abbreviations

AC	Alternative Current
ADC	analogue digital converter
CCM	Continuous Conduction Mode
CF	Current Fed
CFL	Compact fluorescent lamp
CPFM	Constant Pulse Frequency Modulation
CRI	colour rendering index
CZFM	Constant Pause Frequency Modulation
DC	Direct Current
DCM	Discontinuous Conduction Mode
DTC	data transfer controller
EMC	Electromagnetic compatibility
FL	fluorescent
FM	Frequency Modulation
GLS	Incandescent lamp
Hlg	halogen
HPS	high pressure sodium
IC	Integrated Circuit
Ind	Incandescent
IR	Infra-Red
LED	Light Emitting Diode
Lm-A	Lumen-Ampere
MCU	Microcontroller Unit
MH	metal-halide
MOSFET	metal–oxide–semiconductor field-effect transistor
MV	mercury-vapour
NL	Non-linear
PFC	Power Factor Corrector
PWM	Pulse Width Modulation
RLO	Relative Lighting Output
RMS	Root Mean Square
RO	Relative Output
SEPIC	single-ended primary-inductor converter
SLS	Smart Lighting System
SMPS	Switch Mode Power Supply
V-A	Volt-Ampere
VF	Voltage Fed
VVFM	Variable Pulse and Pause Frequency Modulation

Symbols

Symbol	Explanation
ΔD	step of duty cycle
ΔS	root-mean- square declination
Δt	step of timer
$a_0...a_3;\ b_0...b_2$	approximation polynomial coefficients
C	capacitor
C_{CF}	capacitor of current fed dimmer
C_{VF}	capacitor of voltage fed dimmer
D	switch duty cycle
D	duty cycle
D_{LEDmax}	maximum switch duty cycle of LED
D_{LEDmin}	minimum switch duty cycle of LED
$Dspan$	utilization of the duty cycle
f_{SW}	switching frequency
I_F	forward current
I_L	inductance current
I_{LED}	LED current
I_{LOAD}	load current
I_{OUT}	output current
I_s	reverse bias saturation current
K	Boltzman's constant
k	number of impulse in period
L	inductance
L_{CF}	inductance of current fed dimmer
L_{VF}	inductance of voltage fed dimmer
N	number of minimal time steps in period
n	number of elementary steps
n_d	diode ideality factor
P	number of elementary periods
P_{max}	maximal power
P_{out}	output power
R	resistance
R_p	parallel resistance
R_s	series resistance
S	root-mean-square
T	period
T_j	junction temperature
t_{PAUSE}	total length of pause time
t_{PULSE}	total length of pulse time
V_c	capacitor voltage
V_{c-}	capacitor voltage when the transistor is ON
V_{c+}	capacitor voltage when the transistor is OFF
V_F	forward voltage
V_{IN}	input voltage
V_{LED}	LED voltage
V_{LOAD}	load voltage

V_{LOADd}	discontinuous load voltage
$V_{LOADdmax}$	maximal discontinuous load voltage
V_o	voltage of working point
V_{OUT}	output voltage
Z	integer number of the steps
δ	relative time of zero voltage
Φ_{LED}	luminous flux

1 INTRODUCTION

1.1 Motivation

Reasons for Development of Lighting Technologies

Historically, the first real mass consumer of electrical energy is electrical lighting. There are 365 days or 8760 hours in a year, of which approximately 4000 hours are dark hours in Estonia [1] that require use of artificial lighting. Nowadays various electrical lamps are the most frequently used electrical devices. Across the world electrical lighting consumes about 19% of totally consumed electricity [2], [3]. That is why any improvement of lighting equipment may lead to serious reduction of energy consumption. Two directions of this improvement are possible: a) use of more energy efficient lighting technologies; b) use of intelligent lighting control solutions.

Besides that in many areas, such as medicine, security and military applications, the quality of lighting (provided level of lighting, its spectral content, time based pattern, as well as absence of "lighting pollution" – unnecessary light) is also extremely important. Therefore, when improving energy efficiency, it is important to keep other parameters at the satisfactory level.

History of Lighting

During the first half of the 19th century, gas lighting that had significant advantages over incandescent lighting with liquid fuel dominated. But with the development of production and growth of cities, such lighting was less satisfactory because the power of a single light torch was low and it was dangerous for a fire, harmful to health.

Electrical lighting developed in two directions: design of arc lamps and incandescent lamps. History of electric lighting starts with a reference to the experiments of V. Petrov in 1802. It was found that using an electric arc, "dark peace" can be lightened quite clear. At the same time, Davy in England showed the intensity of the conductor current.

In 1844 the French physicist Jean Bernard Foucault replaced the electrode charcoal electrodes of retort coal, increasing the burning lamp. Hand regulation was used, these lamps could be applied only for short time for intense light, for instance, for light microscope slide, the alarm in lighthouses.

Among the arc lights, the "electrical candle" of Yablochkov holds a special place. The invention deserves special evaluation, as it is the "electrical candle" that has caused the rapid growth of the electrical industry.

The earliest incandescent lamp was constructed in 1809 by an Englishman Delarue. This lamp was a heated platinum spiral in a glass tube. In 1828 Belgian Zhobar heated carbon rods in a rarefied space. The service life of the tube was negligible.

After 1840 numerous designs of incandescent glow with a body made of platinum, iridium, carbon or graphite were offered.

In 1860 English inventor Swann first used charred strips of thick paper or Bristol board heated in a vacuum for an incandescent lamp.

In 1870-1875 Lodygin decided to build a flying machine heavier than air, i.e., moving electricity ("elektrolet"). Lodygin began designing a bulb with a thin carbon rod enclosed in a glass bulb. In an effort to increase the burning, Lodygin proposed to install multiple carbon rods arranged so that when burned one automatically includes the following.

The first public demonstration of Lodygin's lamps was held in 1870, and in 1874 he received a Russian privilege (patent) for his lamp. Then he patented his invention in several countries of Western Europe. The first lamps were working about 30 - 40 minutes. When Lodygin started to use a vacuum flask, its life grew to several hundred hours. The new lamp with tungsten filament was presented at the Paris Exhibition by Lodygin in 1890.

Among inventors, Edison is the most prominent. However, electrical lamp is not Edison's invention. He developed the system of electrical lighting and the system of centralized power.

Edison's interest in the problem of electrical lighting dates back to 1879. There is enough compelling information that Edison knew the invention of his predecessors in the field of electrical light bulbs, including the work of Lodygin. He was also impressed by Yablochkov's success in the "electrical candle".

Edison immediately set two goals: to create a moderate light illumination, each should burn completely independently. His conclusion was that a filament of high resistance, which will include lamps in parallel (rather than sequentially, as before there were no electrical lights). On April 12, 1879 Edison received the first patent for a lamp with a platinum coil of high resistance, and then - to the lamps with carbon filaments in 1880.

Edison turned electricity into the product that is sold in all comers, and electrical installation became a centralized power.

Already in the 1880s a rapid development of electrical lighting started, the ever-expanding mass production of light bulbs, resulting in the advancement of the electric machine industry, electrical instruments, electrical equipment and improving methods of production and distribution of electrical energy [4].

Review of Electrical Lighting Technologies

As was mentioned above, electrical lighting plays a main role in human life. The two main categories of electrical light are incandescent lamps, which produce light by a filament heated white-hot by electrical current, and gas-discharge lamps, which produce light by an electrical arc through a gas. In the last years the energy efficiency of electrical lighting has increased dramatically. An energy effective lighting installation is energy efficient while at the same time provides necessary lighting requirements for a particular application. In addition, it has low maintenance and operating costs. The criteria for comparison of lighting technologies are presented in Table 1.1: luminaire efficacy, lamp life, control of light, Colour Rendering Index (CRI) [5], cost of installation and cost of operation. These parameters are explained below.

Table 1.1 Comparison of popular lighting technologies

| Lamp Type	Characteristics					
	Luminaire efficacy (lm/W)	Lamp life h	Dimming	CRI	Cost of installation	Cost of operation
GLS	5-15	1000	Excellent	100	low	very high
Tungsten halogen	12-35	2000-4000	Excellent	100	low	high
Mercury vapor	40-60	12000	Not possible	20 to 65	moderate	moderate
CFL	40-65	6000-12000	With special lamps	80	low	low
Fluorescent lamp	50-100	10000-16000	Good	82-95	low	low
Induction lamp	60-80	60000-100000	Not possible	100	high	low
Metal halide	50-100	6000-12000	Possible but not practical	80-90	high	low
High pressure sodium (standard)	80-100	12000-16000	Possible but not practical	20-30	high	low
LED	20-120	20000-100000	Excellent	85	high	low
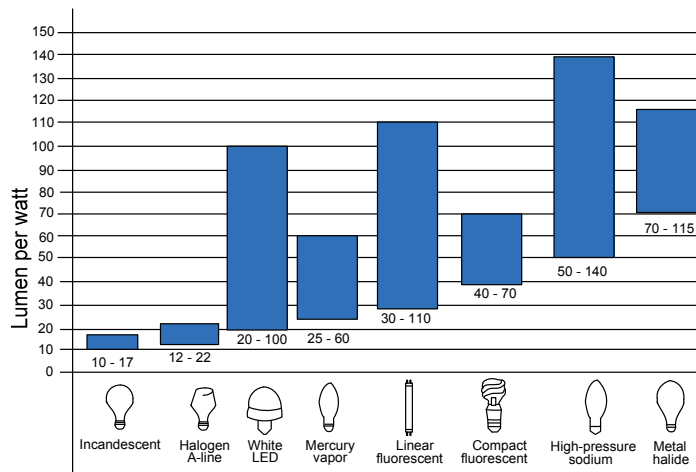
Figure 1.1 Comparison of luminous efficacy among different types of lighting sources

Luminous efficacy is defined as the ratio of light (luminous flux) emitted by a light source to the power consumed by the light source, including power consumed by any auxiliary control device associated with the light source (Lumens provided per Watt consumed).The higher the luminous efficacy, the more efficient the source is at producing light. Figure 1.1 presents the comparison of luminous efficacy of different types of lighting sources [6].

Lamp life is classified in two ways depending on the type of the lamp. The first is lamp's expiry time, also referred to as lamp mortality. This term refers mainly to light sources with filaments such as tungsten lamps. When the filament breaks, the life of the source has ended. The second classification is based on when the light output of the light source falls to 80 % of the maintained lumens (lumens given at 2,000 hours).

This is used for discharge forms of light source such as fluorescent, metal halide and sodium. Most of these light sources will continue to give light for longer periods of time, but will continue to decrease in light output until they expire. When a single lamp type is listed with varying life hours in the Lamp Comparison Table, it indicates that these types are available with differing life expectancies.

Dimming – is a possibility to adjust light level produced by the discussed lighting source. If available, this feature enables reduction of energy consumption if less light is required. Also, this feature helps to build smart lighting systems with different methods of occupancy detection, infra-red, ultrasonic or microwave.

The *colour rendering* properties of a light source indicate the ability of the light source to reproduce the colour relative to the same colour, or colours, illuminated by a reference source (daylight). Colour rendering properties of a light source are specified by the CRI and symbols as Ra. Good colour rendering equates to a high Ra value, the highest value is daylight with a colour rendering index of 100. Poor colour rendering equates to a low Ra, and the poorest colour rendering for a light source is low pressure sodium which has an Ra of 20.

Cost of installation includes several aspects such as the cost of lighting source itself, necessary accessories (such as plugs, reflectors, obligatory control devices etc.).

At the same time, the *Cost of operation* includes mostly cost of necessary maintenance works and consumables (if necessary).

It is also important to understand the dynamics of development of lighting technologies. For example, the high pressure sodium lighting technology has almost reached its saturation.

It means that the much cheaper and better sodium lamps are not expected in the nearest future. At the same time, LED lighting technology is rapidly advancing and therefore, further improvements of their parameters are very likely to be achieved.

Outlines of LED Lighting Technology

- *Main advantages and drawbacks*

Implementation of Light Emitting Diodes (LEDs) provides high efficacy [7], LEDs are ecologically friendly and their life time is significantly longer. On the other hand, LEDs are easily dimmable and dimming has no negative impact on them. It makes LEDs suitable for smart lighting technologies that provide light exactly where and when it is required.

The main disadvantage of LEDs is their still higher price (November 2012). Also, LEDs are heat sensitive, produce heat that requires certain cooling. Besides that, LEDs have to be supplied from a dedicated power source, the construction of which may be quite complex [8].

- *History*

In the second half of the 20th century, scientists found that diodes made of semiconductor materials may produce light when they conduct current [9]. Recognizing the great potential of LEDs in the future, many companies focused on the research of high efficiency LEDs.

In 1907 British experimenter H.J. Round found that the crystal of silicon carbide produces light when voltage is applied [10]. Nevertheless this breakthrough stayed practically unused for several decades. Next, Nick Holonyak, Jr. contributed to the practical invention of LEDs in 1962 [11]. The first commercially available LED was red (1962) [12]. His LED was made with gallium arsenide. Such devices were widely used as replacement for indicator lamps and in seven – segment displays [13]. This LED could be used only for backlight because its light output insufficient to illuminate a large area. Along with development of LED materials technology, in 1987 Hewlett Packard AlGaAs (aluminium gallium arsenide) diodes entered the market. These diodes had higher efficiency that enables replacement of incandescent and fluorescent lighting for LEDs for illumination [14], [15].

- *Features of LEDs for lighting*

A LED is a diode, i.e., a semiconductor device based on a sole PN-junction. The basic structure of a typical LED consists of a diode that is chip-established in a reflector cup and retained in place with a soft lead frames linked with a pair of electrical wires. PN-junction is a hole between two semiconductors with different types of conductivity. When the current flows across the junction of two different materials, light is produced from within the solid crystal chip. The shape or width of the emitted light beam is determined by a variety of factors: the shape of the reflector cup, the size of the LED chip, the shape of the epoxy lens and the distance between the LED chip and the epoxy lens. The composition of the semiconductor materials determines the wavelength and colour of light. In addition to visible wavelengths, LEDs are also available in infrared wavelengths, from 830 nm to 940 nm. The typical LED configuration is presented in Figure1.2 [16].
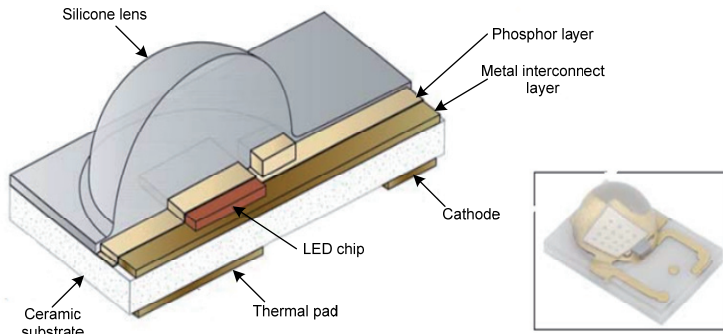
Figure1.2 Configuration of a LED
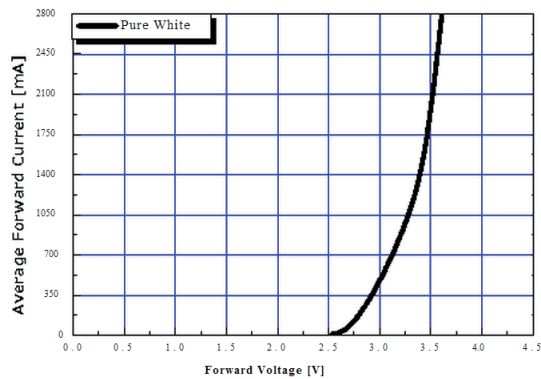
Figure 1.3 VA-curve of high power LEDs

Previously, lighting LEDs were made in very common 5 mm T1-3/4 and 3 mm T1 packages. Such LEDs were often recognized as «high brightness» LEDs. However, with higher power, it has become increasingly necessary to eliminate the heat, so the packages have become more complex and adapted for heat dissipation. Such kind of lighting LEDs are called «high power» LEDs. Packages for state-of-the-art high power LEDs bear little resemblance to early LEDs (example: Philips Lumileds) [8].

- *Model of LEDs*

Electrically, a LED is characterized by its forward current (I_F) and forward voltage (V_F). These parameters of the LED have the exponential relationship. Small changes of the forward voltage will cause much larger (in %) changes of current. The graph in Figure 1.3 shows how the forward of a particular LED [7] voltage drop depends on the LED current.

A simplified voltage-current relationship of LEDs can be presented by the expression:

$$I_F = I_S \cdot e^{eV_F/(n_d K T_j)} , \qquad (1.1)$$

where I_F – forward current, I_S – reverse bias saturation current, V_F – diode forward voltage, n_d – diode ideality factor (for ideal diodes it is equal to 1, for

real diodes the value of this factor is between 1,1 to 1,5), K – Boltzman's constant, T_j – temperature.

More accurate formulas include also parasitic series resistance of diodes, which take place due to the large resistance of contacts, or because of the resistance of the neutral area of the semiconductor structure. Any channels in pn-junction caused by destruction of its areas or defects on its surface lead to formation of parallel parasitic resistances. To take into account the parasitic resistances, Eq. (1.1) should be modified to Eq. (1.2):

$$I - \frac{(V_F - IR_s)}{R_p} = I_S \cdot e^{e(V_F - IR_s)/(n_d kT_j)}, \tag{1.2}$$

where R_s is the series resistance and R_p is the parallel resistance. If $R_p \to \infty$ and $R_s \to 0$, we obtain Eq. (1.1) [17].

Analytical estimation of the regulation curve requires an expression for the output voltage of the driver and the V-A curve of LEDs. The V-A curve of LEDs does not exist in the analytical view, but it has been measured experimentally (for 7-series connected LEDs). Based on the experimental data, the polynomial approximation of the curve was obtained. For this calculation, the 3rd order polynomial approximation was used:

$$I_{LED} = f(V_{LED}) = a_0 + a_1 \cdot (V_{LED} - V_0) + a_2 \cdot (V_{LED} - V_0)^2 + a_3 \cdot (V_{LED} - V_0)^3, \tag{1.3}$$

where V_0=20.2 V is the voltage value of the working point, and $a_0...a_3$ are the polynomial coefficients for the explored LEDs in the range of VLED from 17 to 23.5 V and I$_{LED}$ from 0 to 3000 mA. The polynomial coefficients calculated for the described working point are as follows: $a_0 = 557$, $a_1 = 442$, $a_2 = 89.6$ and $a_4 = 1.92$. With these coefficients, the accuracy is higher than 2%.

The same method was used to find Lm-A expression. The 2nd order polynomial was used:

$$\Phi_{LED} = f(I_{LED}) = b_0 + b_1 \cdot (I_{LED} - I_0) + b_1 \cdot (I_{LED} - I_0)^2 \tag{1.4}$$

For this approximation the current range is from 0 to 3000mA and the luminous flux Φ_{LED} is from 0 to 700lm. In this range optimal working point is $I_0 =$ 1487mA, but the coefficients are $b_0 = 442$, $b_1= 0.244$ and $b_2 = 0.0000241$, producing an accuracy of about 2%.

LEDs emit light when electrical current passes through [18]. A mechanism of luminescence of LEDs is the emission of photons by the recombination of electron-hole pairs. In this process the light power produced is proportional to the number of recombined electron-hole pairs, which define also the electrical current of the device. At the same time, when an electron meets a hole, it falls across the band gap from the higher to the lower energy level, releasing the band gap energy as a photon of light with the corresponding frequency, and, hence, the colour of radiation corresponds to the band gap energy, i.e., depends on the material.

The empirical data of the characteristic luminous flux – current curve (Figure 1.4) and luminous flux – the temperature curve (Figure 1.5) of an LED

enable us to draw two important conclusions: a) LEDs efficiency is much higher at lower current levels; b) increase in the temperature causes the decrease of the forward voltage (and power) needed to maintain a constant current. Moreover, the luminous output will also fall substantially. This means that even though less power is required to maintain a constant current level, the lower luminous output causes lower overall efficiency of the LED.

In conclusion, an LED is a current-driven device whose brightness is proportional to the conduction current [19]. The regulation must keep the current of an LED between its rated value and reasonable minimum to obtain luminous intensity of a definite range. LED power supply should have elements that limit the current through the LED according to its characteristics, which is provided by different regulators, so-called drivers or electronic ballasts.

- *Structure of an LED Luminaire*

LEDs are semiconductor devices that cannot be directly connected to an AC network. As it was shown before, LEDs are more inclined to use constant current driving instead of constant voltage [20]. In addition, the current in LEDs flows only in one direction (from the p-side (anode) to the n-side (cathode)).
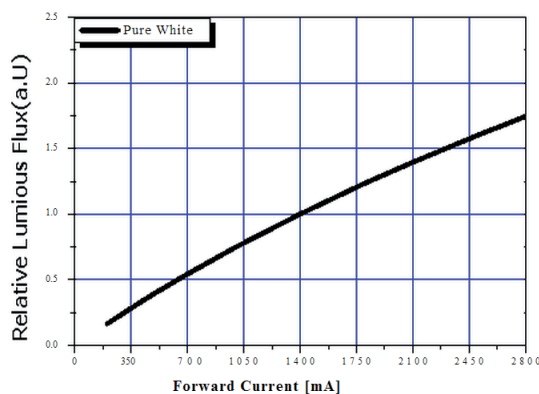
Figure 1.4 Luminous flux of an LED vs. forward current
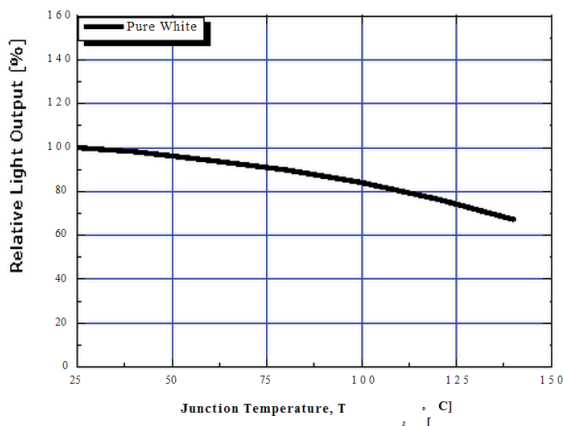
Figure 1.5 Relative light output vs. junction temperature of an LED
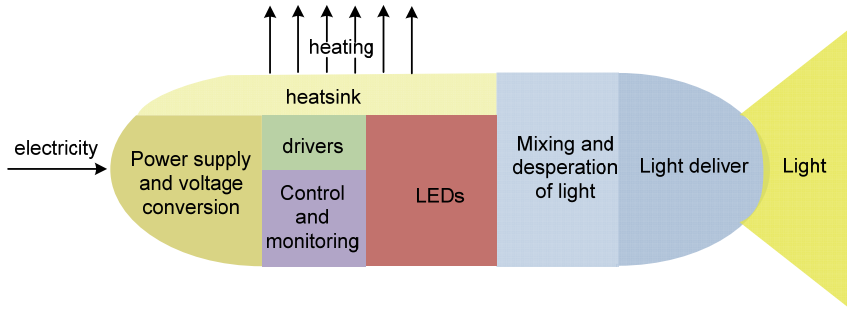
Figure 1.6 Typical content of an LED luminaire

Finally, it is beneficial to use LEDs in smart lighting systems where light level is adjustable. That is why lighting LEDs should be connected to a system, the main components of which are: LEDs, electronic circuit providing their current and voltage, a microprocessor control system equipped with a suitable communication interface, as well as power supply for all the elements mentioned. Besides that a LED luminaire (Figure 1.6) includes devices for cooling (radiators or fans), lenses and others optical devices for mixing and elimination of light [21].

1.2   Main hypotheses and objectives

The most significant part of an LED luminaire is a LED driver that provides the supply for LEDs and adjusts their current and illuminance. LED drivers are characterized by a set of criteria which express their correspondence to the selected task: a) efficiency; b) physical volume and weight; c) cost; d) controllability. The main aim of this research is to elaborate an energy efficient LED driver with improved parameters of controllability and efficiency that can be used in grids of intellectual sources of light.

The main hypotheses of the PhD research:

- Development of LED drivers utilizing the direct current regulation approach improves the parameters of controllability of the drivers keeping at the same time their efficiency at the level comparable with existing competitive topologies.
- Frequency modulated control signals equally improve the efficiency and the controllability of the drivers of known topologies.

The main objectives of the PhD research:

- to analyze the current state-of-the-art in the field of energy efficient dimmable LED drivers (electronic ballasts for LEDs) and to identify their main drawbacks and advantages;
- to propose develop and verify energy efficient dimmable LED drivers utilizing a direct current regulation technique;
- to verify operation of the existing dimmable LED drivers with frequency modulated signals for their transistor switching control;

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- to analyze the proposed approaches and compare them with existing ones, identify their drawbacks and define directions of their improvement.

1.3 Results and dissemination

Further sections present the most important results achieved in this doctoral research, including both the scientific and practical novelties. The scientific novelties expand theoretical background in the field of power electronic converters and their applications and can be used, for example, for improvement of the course of "power electronics". The practical novelties can be useful for companies who produce the electronic ballasts for LEDs, for instance, Philips, Osram. The prototypes elaborated during the PhD research can be used as direct templates for similar designs (besides their use for experimental verification purposes).

Scientific novelties:
- theory of utilization of frequency modulated control signals in dimmable amplitude modulated LED drivers;
- theory of utilization of direct current regulators as dimmable amplitude mode LED drivers.

Practical novelties:
- method and algorithm of control of voltage fed buck type dimmable LED drivers based on frequency modulation with constant pause and variable pulse durations;
- method and algorithm of control of voltage fed boost type dimmable LED drivers based on frequency modulation with constant pulse and variable pause durations;
- method and algorithm of control of voltage fed buck-boost type dimmable LED drivers based on frequency modulation with variable pulse and pause durations;
- methodology of calculation of parameters and choice of elements of dimmable LED drivers operating with frequency modulated control signals;
- methodology of design of dimmable LED drivers based on direct convention of current, calculation of their parameters and choice of their elements.
- new design of dimmable LED drivers based on direct current regulation;
- new design of dimmable LED drivers with frequency modulated control signals,

Dissemination of results and publications

The results of the PhD thesis were reported by their presentation at 10 international conferences. The author has published 9 international scientific works directly associated with the thesis. Six of the author's papers are presented in collections indexed by IEEE Explorer, ISI- Thomson Reuters and

others international databases. The most important papers directly connected to the research topic are listed in the Appendix.

Additionally, in terms of international collaboration, the PhD research helps to promote international cooperation between Tallinn University of Technology and other European universities and institutions

1.4   Summary

As shown in this section, the LED lighting technology provides good parameters of lighting devices such as higher luminous efficacy, longer lifetime, as well as excellent dimming possibility that make the technology attractive for use in the smart lighting applications. At the same time, the LED technology has not reached its technological saturation that promises lower process and better parameters of LEDs in the nearest future. It is concluded that success of the LED lighting technology depends considerably on the success of the electronic circuits intended for their supply and regulation of their current – LED drivers. It is hypothesized that the parameters of these drivers could be significantly improved with a direct current regulation approach and frequency modulated control signals for switching devices.

2 LIGHT REGULATION METHODS FOR SMART LIGHTING SYSTEMS

2.1 Definition, Content and Functions of a Smart Lighting System

A smart lighting system is a system that is capable of delivering light where and when and as much as is required [22]. The system adjusts an actual level of lighting depending on the ambient lighting, artificial lighting not included in the smart system, particular needs of its users, lighting schedules or scenarios, etc. [23]. The intelligent lighting system consists of sensors, lamps and control devices (Figure 2.1).

A smart lighting system can be systematized depending on the location of a control system to the distributed, centralized or combined [A1]. In the distributed control system, each lamp has its own control device capable of communicating with the neighboring ones providing necessary light regulation together. In contrast, the centralized control system is a system that allows controlling all lamps from one central location or centralized control device. In the report [A2] four groups of smart lighting systems are discussed: a) first, the system composed of an independent network of lamps, independent network of sensors are attached to a centralized control system – Fig. 1a in [A2]; b) second, a set of independent local groups of sensors lamps, as well as their control units, which are physically closely located – Fig. 1b in [A2]; c) third, based on the same principle, but each local group is connected to the centralized control system – Fig. 1c in [A2]; d) fourth, a system consisting of a network of lamps and sensors where control functions are distributed in all parts of the system – Fig. 1d in [A2]. The distributed system has been found to be safer in operation and to provide sufficient speed and quality of light regulation.

In addition, in smart lighting systems all or most their light source must be adjustable, i.e., capable of providing light of any value from a definite range. Therefore, the drivers installed in such systems supply adjustable current or adjustable voltage to the attached LEDs. There are two approaches of building drivers with such functionality. The first approach (composite drivers) assumes that there are dedicated direct current (DC/DC) converters for light regulation (dimmers) while other functional blocks of the driver (rectifier, filter etc.) ensure compatibility with the supply (usually AC grid) [24], [25] and [26].
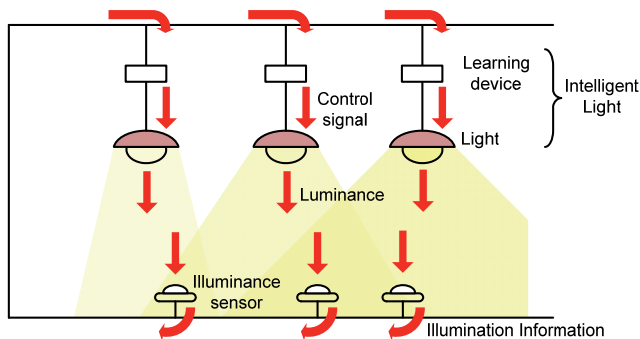
Figure 2.1 Configuration of a smart lighting system
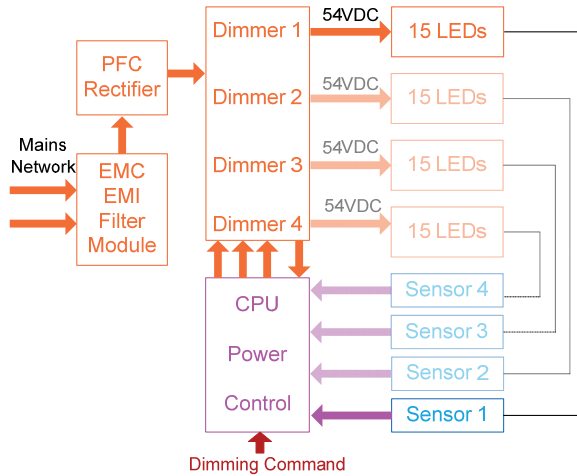
Figure 2.2 Example of an intelligent lighting system

This approach is technically reasonable if there are few LED matrices controlled separately, but supplied from the same source. In this case dimmers must also be separate while the other parts of the supply can be shared. An example of a multiple-lamp multiple-dimmer smart lighting unit is given in Figure 2.2. This unit contains its own set of sensors, several LED matrices and a control system, as well as a dimmer for each LED group. Separate dimmers (DC/DC converters) are also suitable and energy efficient if the supply is a direct voltage of value close to the LED's rated voltage, in the case of DC grids.

An alternative approach (monolithic drivers) [27] - [30] assumes that all blocks of the driver are combined in the same circuitry. Such drivers are more energy efficient, but suitable for single lamp (LED matrix) applications.

Most of the considered dimmers and monolithic drivers are based on Voltage Fed (VF) Switch Mode Power Supply (SMPS) with Pulse-Width Modulation (PWM) applied to their switches. Taking into account vertical V-A curve of LEDs (Figure 1.3), these devices must work with higher nonlinearity and lower accuracy that could be improved.

This thesis research analyzes dimmers of composite drivers for the following reasons: 1) they are suitable for all kinds of power supply; 2) these dimmers are more efficient in the case of DC supply; 3) as converters whose operation principles can be expanded to other types of the supply. DC/DC dimmers are here called "drivers", that is true in the case of DC supply.

2.2   Light Regulation Methods

LEDs allow spectral, spatial and temporal control of the light emitted that cannot be achieved with other light sources. However, the most requested task is regulation of light intensity of LEDs [A3]. Depending on the pattern of the luminous flux in the time domain, the light regulation methods can be divided into two groups: fluent regulation of the luminous flux and pulse mode regulation of the luminous flux. Also, a discrete version of the fluent mode is possible and can be identified as step regulation.

a)

b)

c)
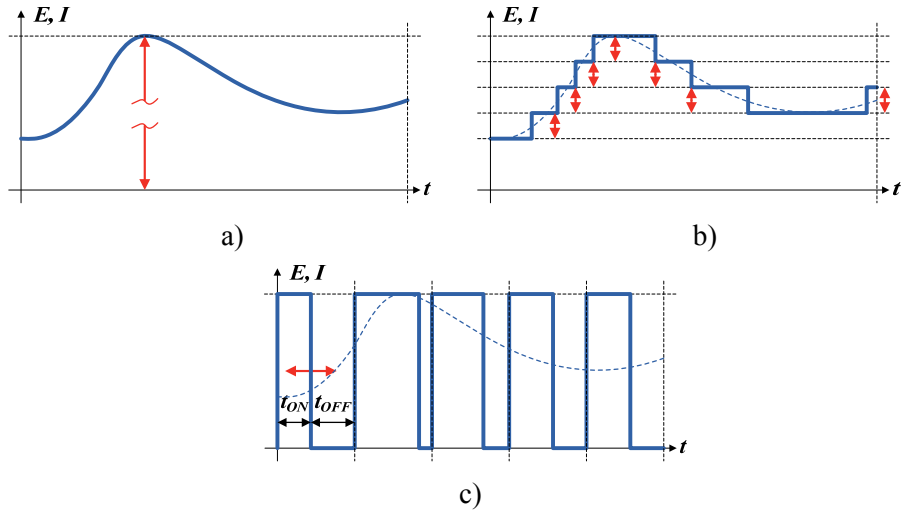
Figure 2.3 Light regulation methods: a) fluent mode (amplitude modulation); b) step mode (discrete amplitude modulation); c) pulse mode (pulse width modulation)

Fluent Regulation of LED Current and Luminous Flux

A luminous flux with this mode (Figure 2.3a) can take any value from maximum to zero. So, obviously, it is the most attractive method in terms of functionality because no restrictions are applicable. However, several drawbacks must be mentioned with regard to this method. The most important one – LED's brightness is not entirely proportional to LED's current. Moreover, not only a luminous flux but also the wavelength and therefore the colour of light are slightly different at different values of LED current. Also, a voltage or current regulator is required in this case.

Pulse Mode Regulation of LED Current and Luminous Flux

With this method, the value of a luminous flux at any time instant is either maximum or zero (Figure 2.3b). Then, if a change of the luminous flux occurs periodically, its average value depends on the ratio of flickers duration to the period of flickering. Obviously, this method provides pulse pattern of instantaneous luminous flux and adjusts only its average value. When the frequency of modulation is low, the pulsating character of light becomes visible to human eye. When the frequency is high, a stroboscopic effect may appear. Also, this method is less energy efficient and leads to higher operation temperature and shorter lifetime of LEDs [31], [32] and [33]. At the same time, the pulse mode dimming requires only one electronic switch that operates at much lower frequency than those of SMPS-s.

Step Regulation of a Luminous Flux

The third light regulation method is possible due to small typical power of LEDs. For this reason, LED luminaire usually includes a number of LEDs, which can be divided into groups and each group can be controlled separately.

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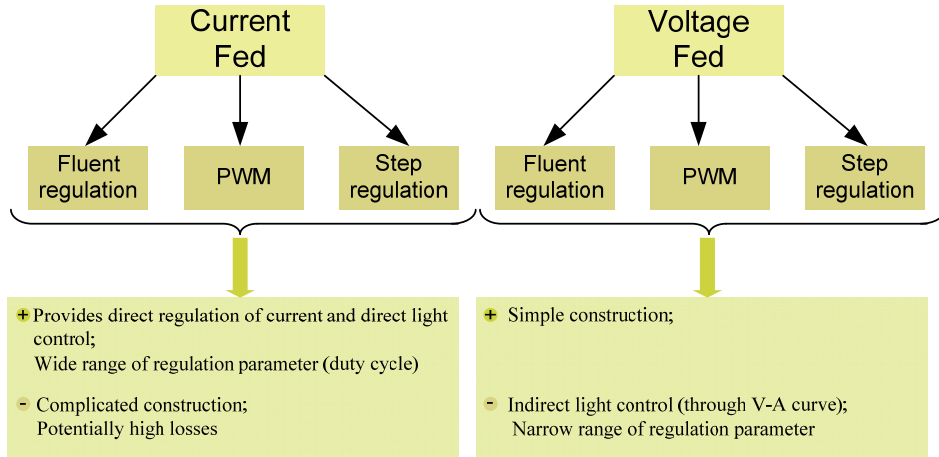
Figure 2.4 Comparison of types of sources

The total luminous flux is regulated through separate powering for each group by using switches activated by a control system. It is evident that the maximal number of regulation steps is equal to the number of LEDs groups while the step of regulation is equal to the power (or current or light) of a single group. With this method, a luminous flux changes stepwise in the range of fixed values between the maximum and zero. Dividing LEDs into groups enables us to adjust the brightness with a specific constant step (Figure 2.3c).

2.3   Dimmers for LEDs

As was mentioned above, LEDs are low voltage devices and their adjustable power supply (dimmer) should be specific. It can be built as a current source or voltage source. It is advantageous to supply LEDs from current sources, but nowadays most of available regulators operate as voltage sources (Figure 2.4). Another kind of the dimmer available uses a constant voltage source and current balancing element (variable resistor) to control the LED's forward current. Such kinds of dimmers are commonly known as analogue. However, voltage variations and power waste on the variable resistor make the analogue dimming method unsuitable for more demanding applications. From Figure 2.4 it is clear that a dimmer could be designed for each light regulation method either as a current fed or a voltage fed converter.

Dimmers for Pulse Mode Light Regulation

Most of LED drivers available on the market apply pulse mode modulation (PWM) for regulation of the power amount for the LED [34]. For such drivers one unregulated voltage (Figure 2.5a) or one current (Figure 2.5b) source is needed. In the case of a voltage regulator, a controllable switch (MOSFET) is connected in series with LEDs and applies the voltage during flickers. In the case of a current regulator, the switch is connected in parallel with LEDs and shorts them during the pauses between the flickers.

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Figure 2.5 Dimmers for pulse mode regulation: a) voltage fed; b) current fed

Figure 2.6 Dimmers for step mode light regulation; Voltage fed: a) equal groups; b) binary weighted groups; c) binary weighted with unitary supply; Current fed: d) equal groups; e) binary weighted groups

Figure 2.7 Dimmers for fluent mode regulation: a) voltage fed; b) current fed

Dimmers for Step Mode Light Regulation

The second method of luminous flux regulation is the step mode. Converters for this method are the arrays of electronic switches for commutation LEDs in groups. These commutation a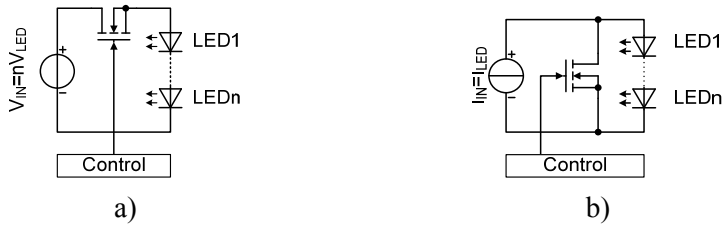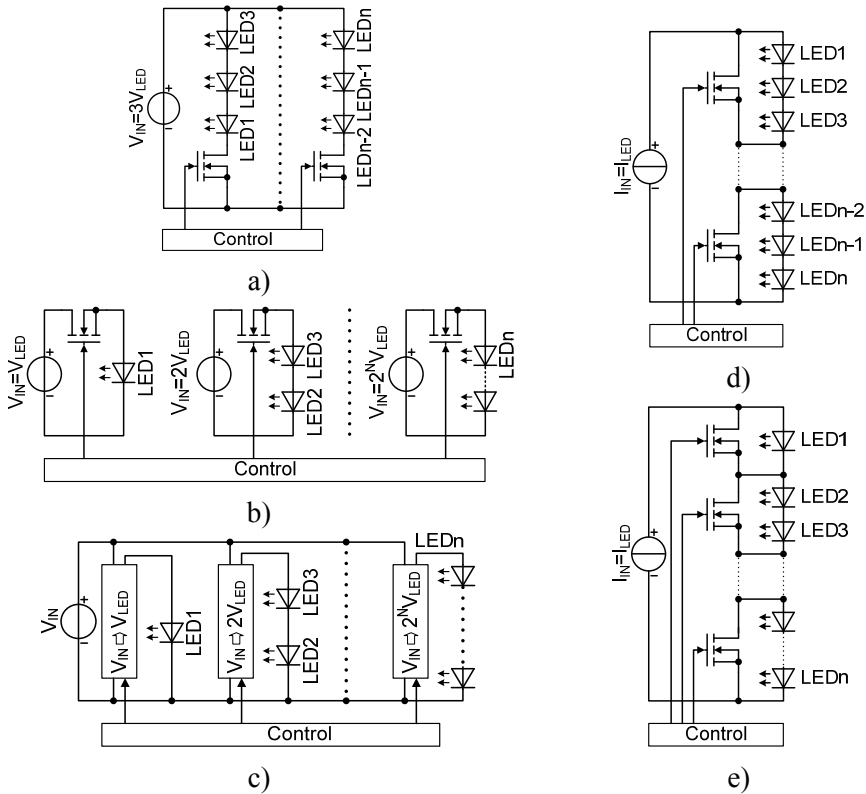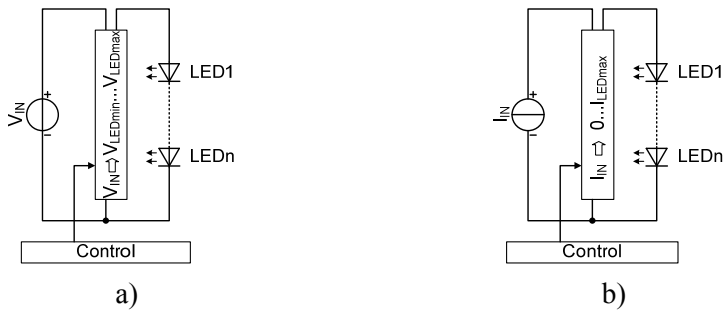rrays can also be voltage or current fed. Here an equal group approach and a binary weighted group approach can be emphasized. Voltage fed switch matrices are more practical [35]. However, this approach works well only if the number of LEDs in all groups is the same and if the dimmer is supplied from a voltage source of the LED's rated value. Then each group can be controlled by its own switch (Figure 2.6a). Each unequal group of LEDs (included binary weighted) needs its own voltage source and switch (Figure 2.6b) that is bulky and a less practical solution (usually needs a complicated transformer) or its own regulator (Figure 2.6c) that is more complicated and less energy efficient. In the case of a current fed switch matrix, only one current source for all LED groups is necessary. With a current supply like in the voltage supply case, each group has its own switch, but it short-circuits the LEDs. The difference between the equal (Figure 2.6-d) and the binary weighted (Figure 2.6e) group approach is only in the number of short-circuited LEDs.

Dimmers for Fluent Mode Light Regulation

- *Voltage Fed*

A fluent luminous flux LED dimmer supplied by voltage (Figure 2.7a) needs a voltage regulator which is an adjustable SMPS, providing necessary reduced voltage for dimming. LED's current reduction occurs indirectly – through its VA-curve. The output voltage used for dimming compared with the full voltage range is narrow [A5] – that is a significant drawback. In Chapter 3 it is shown that this drawback can be minimized if frequency modulation is used to control switchings of the converter. The dimming SMPS converter can be chosen depending on the relation of the supply voltage and LED's voltage. There are three cases: a) the supply voltage is always higher than the LED voltage; b) the supply voltage is always lower than the LED voltage; c) sometimes the supply voltage is higher than the LED voltage, and sometimes it is lower [36]. There are several well known topologies of switch mode regulators suitable for all mentioned occasions - buck, boost [37], buck-boost [38], SEPIC, Cuk [39] and others. These topologies are compared in [A3] and [A4]. This comparison reveals that a buck converter is preferable because it is more energy efficient.

- *Current Fed*

Fluent luminous flux LED dimmers supplied from a current source (Figure 2.7b) functionally look similar to voltage sourced regulators, i.e., in this case they include only one regulator – a current regulator. Studies of current fed converters [40] are mostly devoted to their applications with natural current sources like photovoltaic [41] and superconductive magnetic energy storages [42]. One of the hypotheses of this thesis assumes that the current fed LED

dimmers have certain benefits over the voltage fed ones. This hypothesis is developed and validated in Chapter 4.

Preliminary Assessment of Light Regulation Methods

In order to determine pros and cons of different dimmers, a preliminary investigation of some dimmers was made [A4]. In summary, the step mode light regulation is preferable over the other modes in the case of rather small number (10…20) of illuminance levels. Then the corresponding power and control hardware/software is simpler, provides lower losses keeping at the same time control parameters at comparable level. Pulse mode regulators are even more attractive, but they have also significant drawbacks (flickering, stroboscopic effects). It was also concluded that it is worth considering configurations of LED matrices with a larger number of elements of lower power (compared to a smaller number of elements of higher power). At the same time if the requested number of illuminance steps is higher – fluent mode dimmers have to be considered [A5] and [A6].

2.4   Laboratory Testbench

Both the preliminary assessment of the light regulation methods and estimation of the proposed hypotheses were made experimentally. In order to provide comprehensive analysis with necessary experimental data a flexible testbench was developed [A7]. The testbench consists of a configurable LED matrix, laboratory like power supply (which can operate as a voltage or current source) and a verified dimmer (Figure 2.8a).

The number and configuration of LEDs were chosen taking into account the following considerations. Firstly, the step mode light regulation requires a sufficient number of LEDs. If the minimal step of light changes is about 5…10% (reasonable minimum for some street lighting applications), then the number of LEDs must be about 15…20. Secondly, available armature for the luminaire is not very large and cannot dissipate power more than 20 W. Thirdly, available LEDs are of 1W power. This makes a matrix of 15 1 W LEDs a reasonable choice. The placement of LEDs in the matrix must ensure symmetrical distribution of active LEDs when some of them are off (Figure 2.8b). Such number of LEDs (15) provides also numerous possible LED groups: 1×15 LED, 3×5 LED, 5×3 LED, 15×1 LED as well as binary weighted groups (1, 2, 4 and 8).
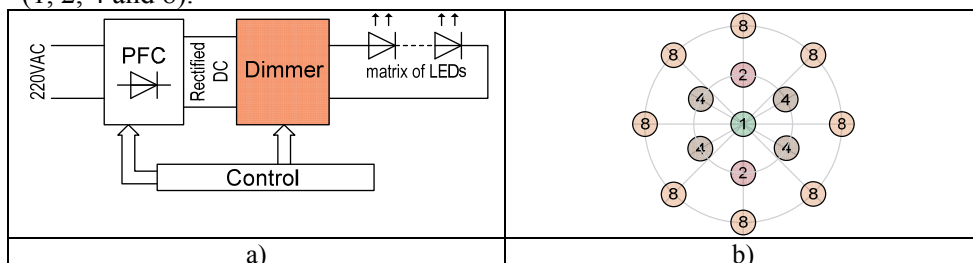
Figure 2.8 Configuration of the laboratory testbench: a) parts of the testbench b)physical placement of binary weighted groups of LEDs in the matrix

The main parameters of the primary supply are as follows: attached to common 220 V-50 Hz alternating current (AC) grid, 55 V output in the constant voltage mode and 280 mA in the constant current mode (that corresponds to 15 series connected 1W LED – in the rated point of operation). Assuming the worst case efficiency of the secondary regulator (90 %) and the primary power supply (90 %), the power of supply is 15 / (0.9*0.9) = 18.5 ≈ 20 W. Since LEDs should have galvanic isolation for safe use of AC power source, a flyback topology equipped with a power corrector was chosen («Power Integration's» LinkSwitch based solution) [A8].

It must be noted that an initial version of the testbench contained 19 LED [A3] matrix and 20 W-70 V-280 mA. Later this configuration was reconsidered in order to provide binary weighted groups. Also, for efficiency testing another configuration of the testbench was used. It contains 15 10 W LEDs and a laboratory power supply that also corresponds to the configuration given in Figure 2.8.

2.5   Summary

This chapter provides the definition of a smart lighting system. It is concluded that the function of such systems is light regulation. In the case of LEDs this can be achieved with fluent, pulse or step modes of light (and LED's current) regulation. The unit providing this function, the dimmer, can be a distinct part of the LED's driver (composite approach) or it can be integrated in its circuit (monolithic approach). Dimmers can utilize all these regulation modes and can be supplied from a voltage or current source. It was also found that high performance and energy efficient dimmers are based on the fluent mode light regulation. It has been proposed to improve the quality (linearity and accuracy) of light regulation of the voltage fed dimmers utilizing frequency modulation to control high frequency switchings of dimmer's transistors, as well as to use current fed dimmers. This chapter also describes a testbench built to provide a flexible experimenting base.

3 FLUENT MODE VOLTAGE FED DIMMERS WITH FREQUENCY MODULATION

As found previously, the dimmers providing fluent (continuous) light are basically SMPS used for particular need of the light regulation. They produce constant output voltage, current and, hence, constant illuminance without flickering or stroboscopic effects [43]. In such converters the amount of energy transferred through their reactive elements (inductors or capacitors), as well as their output power depend on the duty-cycle of switching of their transistors [44]. The majority of such LED dimmers use Pulse-Width Modulation (PWM) to adjust the duty cycle by changing pulse width [45] and [46]. Typical switching frequency of such dimmers is several hundred kHz that allows using of smaller reactive components.

Another approach is Frequency Modulation (FM) at which the required duty cycle is obtained with a variable period or frequency. At FM either pulse or pause may be constant or both of them may be variable. FM gives a number of benefits over PWM [A5], [A6] and [A9] that could prove to be very useful in lighting applications to be discussed below.

3.1 Accuracy of Modulation Methods

Each modulation method is characterized by an accuracy at which the corresponding dimmer is controlled with this method. In order to numerically evaluate this resolution the following parameters have been included: 1) practical step of duty cycle; 2) practical step of relative output of the dimmer. Below these parameters are explained (Figure 3.1) [A5].

Practical Step of Duty Cycle

The first parameter is the practical step of the duty cycle. It may be defined as a difference between its two neighboring values that are achievable in practice:

$$\Delta D = D_k - D_{k-1}, \tag{3.1}$$
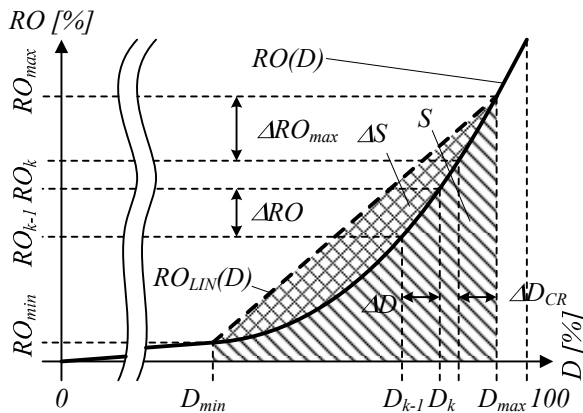
Figure 3.1 Typical regulation curve of an LED lamp

In the case of PWM this expression refers to the minimal time step which can be counted by the utilized control hardware Δt:

$$\Delta D = \Delta D_k = D_k - D_{k-1} = \frac{k \cdot \Delta t}{T} - \frac{(k-1) \cdot \Delta t}{T} = \frac{\Delta t}{T} = \frac{1}{N}, \qquad (3.2)$$

where N – the number of minimal time steps in period (which is constant for PWM). For example, if $\Delta t = 100ns$ and $T = 10\mu s$, then $N = 100$ and $\Delta D = 1\%$, or if $\Delta t = 100ns$ and $T = 5\mu s$, then $N = 50$ and $\Delta D = 2\%$.

Practical Step of Relative Output

The practical step of the output variable of the dimmer is expressed as a difference of two neighboring values of this variable (LED current or luminous flux) corresponding to neighboring duty cycle values given in (3.1):

$$\Delta RO_k = RO_k - RO_{k-1} = RO(D_k) - (D_{k-1}), \qquad (3.3)$$

where *RO(D)* is the regulation curve (Figure 3.1), which expresses the output variable as a function of the duty-cycle and that incorporates the regulation law of VF dimmers, as well as V-A and A-Lm curves of the LED matrix (the last one may be omitted to simplify calculations). It must be noted that *RO(D)* is a ratio of a physical variable vs. its maximal value measured in [%].

3.2   Accuracy of Frequency Modulation

Overview of Frequency Modulation Methods

General meaning of FM is achieving the required duty cycle values with a variable period or frequency (Figure 3.2).
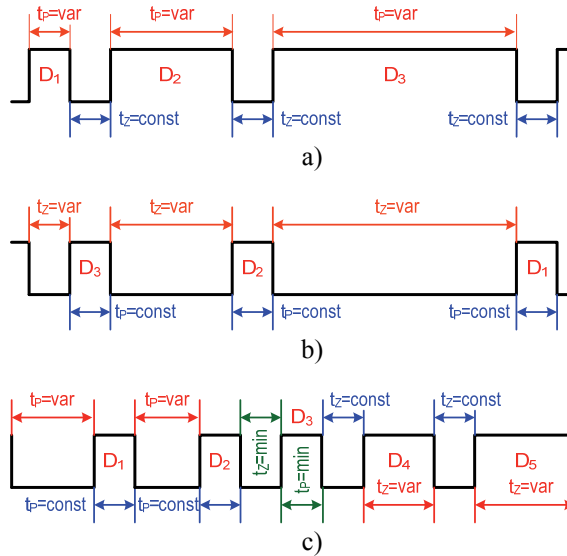
Figure 3.2 Pulse frequency modulation methods for LED dimmers: a) constant pause frequency modulation; c) constant pulse frequency modulation; d) variable pulse variable pause frequency modulation

In contrast to PWM this can be done in three ways: 1) with constant pause, but variable pulse widths (Figure 3.2-a); 2) with constant pulse, but variable pause (Figure 3.2-b) and 3) with variable pulse and pause (Figure 3.2-c). The accuracy of the duty cycle, LED's current and brightness obtained with these modes as well as their effect on the weight, size, losses and efficiency of the dimmer are quite different.

Constant Pause Frequency Modulation (CZFM)

This mode assumes that the pause between two neighboring impulses remains constant. It is generated as a series of minimal time steps with a total length $t_{PAUSE}=Z \cdot \Delta t$, where Z is an integer number of the steps. At the same time, the number of elementary time steps in period is n and it is a variable defined by the regulation loop. This period can be expressed as $T=n \cdot \Delta t$. Then the duty cycle can be defined as:

$$D(n) = \frac{t_{PULSE}}{T} = \frac{T - t_{PAUSE}}{T} = \frac{n - Z}{n} = 1 - \frac{Z}{n} . \qquad (3.4)$$

The step of the duty cycle is

$$\Delta D(n) = \left(1 - \frac{Z}{n+1}\right) - \left(1 - \frac{Z}{n}\right) = \frac{Z}{n^2 + n} . \qquad (3.5)$$

At such approach, the greater n is, the greater is the duty cycle. It achieves value 1 at infinity n:

$$D_{MAX} = \lim_{n \to \infty}\left(1 - \frac{Z}{n}\right) = 1 . \qquad (3.6)$$

The step of the duty cycle at such values is

$$\Delta D_{@DMAX} = \lim_{n \to \infty}\left(\frac{Z}{n} - \frac{Z}{n+1}\right) = 0 . \qquad (3.7)$$

Numerical values calculated with (3.4) and (3.5) for Z=1 are given in Table 3.1.

Equations (3.6) and (3.7), as well as Table 3.1 show that CZFM achieves very high accuracy of the duty-cycle at its values close to 100% (that is beneficial when the input voltage of buck dimmer is close to the rated voltage of LEDs). This accuracy is "virtual", i.e., it is much better than the control system can provide. Figure 3.3 demonstrates the difference between absolute and relative values of time periods at CZFM. In absolute values the pause is equal to 2µs (about 10% of the period), which corresponds to the relative value 1%.

Table 3.1 Duty Cycles Obtained with CZFM at Long Periods

n	D(n)	ΔD(n)
10	90%	0.91%
15	93%	0.42%
100	99%	0.01%
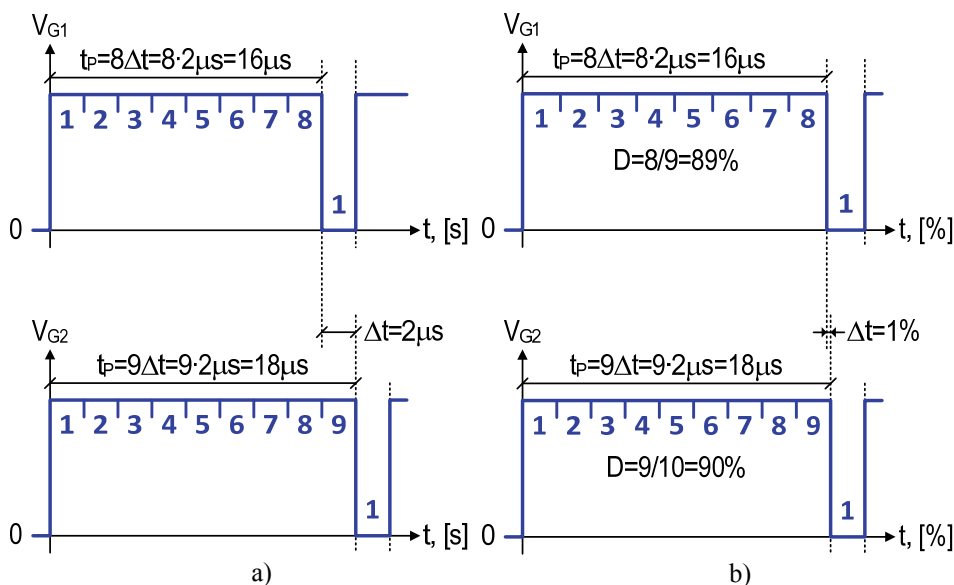
Figure 3.3 CZFM method for LEDs: a) absolute values; b) relative values

In the CZFM mode, lower values of the duty cycle are obtained at lower values of n. This means that there exists the minimal value of the duty cycle

$$D_{MIN} = 1 - \frac{Z}{n_{MIN}} = 1 - \frac{Z}{Z+1} = \frac{1}{Z+1}, \tag{3.8}$$

at which the step of the duty cycle is rather large

$$\Delta D_{@DMIN} = \left(1 - \frac{Z}{Z+2}\right) - \left(1 - \frac{Z}{Z+1}\right) = \frac{Z}{Z^2 + 3Z + 2}. \tag{3.9}$$

The values of the minimal duty cycle calculated with (3.4) and (3.5) are given in Table 3.2. As it is seen from the table this feature is a significant limitation of the described modulation method.

Table 3.1 and 3.2 prove that CZFM provides higher values of the duty cycle at lower frequency with the higher accuracy that corresponds to the requirements of DC/DC converters feeding LED elements. Lower values of the duty cycle are valid at higher frequency with lower accuracy, but this drawback is less important for the discussed application. The considerations stated above are directly shows that CZFM provides better relative accuracy (smaller steps) at higher values of the duty cycle. That suits well for combination of LEDs with a buck converter which operates at higher duty cycles.

Table 3.2 Duty Cycles Obtained with CZFM at Short Periods

Z	$D_{MIN}(n=Z+1)$	$\Delta D@D_{MIN}(n=Z+1)$
1	50%	17%
5	17%	12%
10	9%	8%

The obtained data, however, reflects only the accuracy of the modulation. To complete the estimation the steady state conversion formula of the buck converter (3.10), as well as approximation of LED's V-A curve (1.3) must be taken into consideration. Table 3.3 and Figure 3.4 take this into account and present the calculated values of *ΔRO* at different types of modulation.

$$V_{out} = D \cdot V_{in}.$$ (3.10)

From Table 3.3 and Figure 3.4 it follows that CZFM applied in a buck dimmer provides higher accuracy of the relative output (current) especially close to the rated point of LED operation. Finally, it leads to more accurate buck dimmer operation if its switch is controlled by the CZFM signal. This phenomenon is especially well seen in a regulation loop where the process variable is the relative LED output (Figure 3.5a…c) which undergoes a step response. In the case of PWM current steps are visible and significant (Figure 3.5d) while CZFM (Figure 3.5e) provides more accurate regulation.

Table 3.3 Calculated accuracy of a buck converter at CZFM (Z=1)

t_p	t_z	T	D, %	ΔD, %	I, %	ΔI, %
0	1	1			0	0
1	1	2	50	16	0	0
2	1	3	67	9	0	0
3	1	4	75	5	2.7	2.7
4	1	5	80	3	14.4	11.7
5	1	6	83	3	27.3	12.9
6	1	7	86	2	39.1	11.8
7	1	8	88	1	49.4	10.3
8	1	9	89	1	58.4	8.9
9	1	10	90	1	66.1	7.7
...	1	...	...	...	...	...
19	1	20	95	0,3	107.6	2.5
20	1	21	95.238	0.238	109.8	2.3
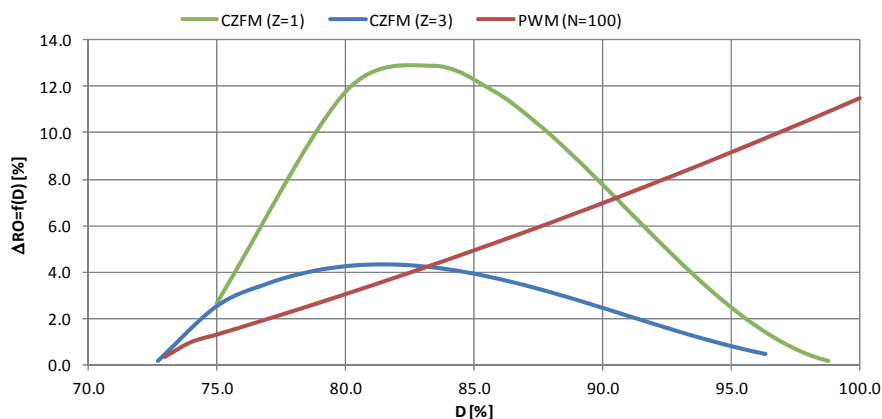
Figure 3.4 Total accuracy of the relative dimmer output at CZFM and PWM
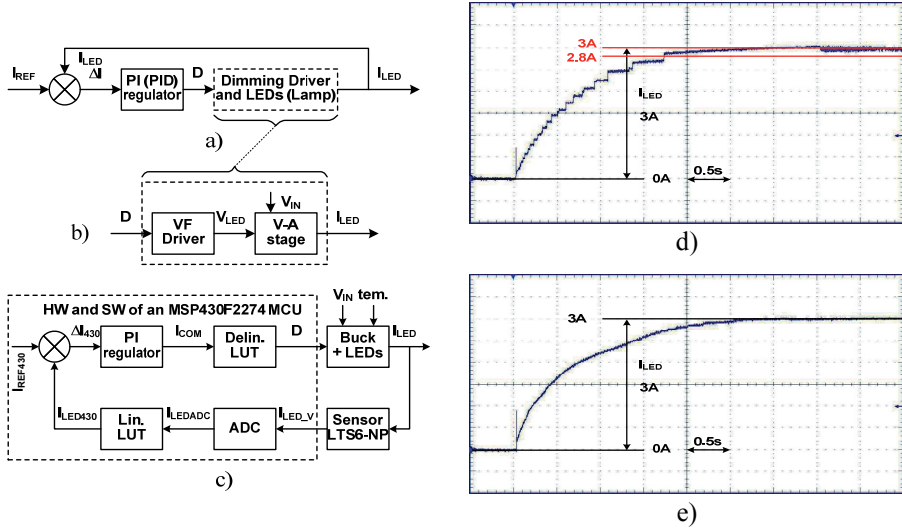
Figure 3.5 Step response of a buck LED dimmer operating with CZFM and PWM: a) control loop; b) LED lamp (LED matrix and dimmer); c) realization of control loop with MSP430 (Δt=125ns); d) step response with PWM (N=100); e) step response with CZFM (Z=1) .

Constant Pulse Frequency Modulation

At Constant Pulse Frequency Modulation (CPFM) pulse duration is a constant proportional to the elementary steps Δt and number of such periods P ($t_{PULSE}=P\cdot\Delta t$). At FM the period is variable. It can be expressed as $T=n\cdot\Delta t$, where n – is an integer number that is defined by the control system. Then the duty cycle can be expressed as the function of n:

$$D(n) = \frac{t_P}{T} = \frac{P}{n} .$$

(3.11)

At CPFM the step of the duty cycle is also the function of n. If it is defined as a difference of two closest values of the duty cycle, then

$$\Delta D(n) = \frac{P}{n} - \frac{P}{n+1} = \frac{P}{n^2 - n} .$$

(3.12)

The greater n is, the smaller is the duty cycle. Its minimal value is equal to 0 and it is achieved at infinity n:

$$D_{MIN} = \lim_{n \to \infty} \frac{P}{n} = 0 .$$

(3.13)

The step of the duty cycle at such values is also zero:

$$\Delta D_{@DMAX} = \lim_{n \to \infty} \left(\frac{P}{n} - \frac{P}{n+1} \right) = 0 .$$

(3.14)
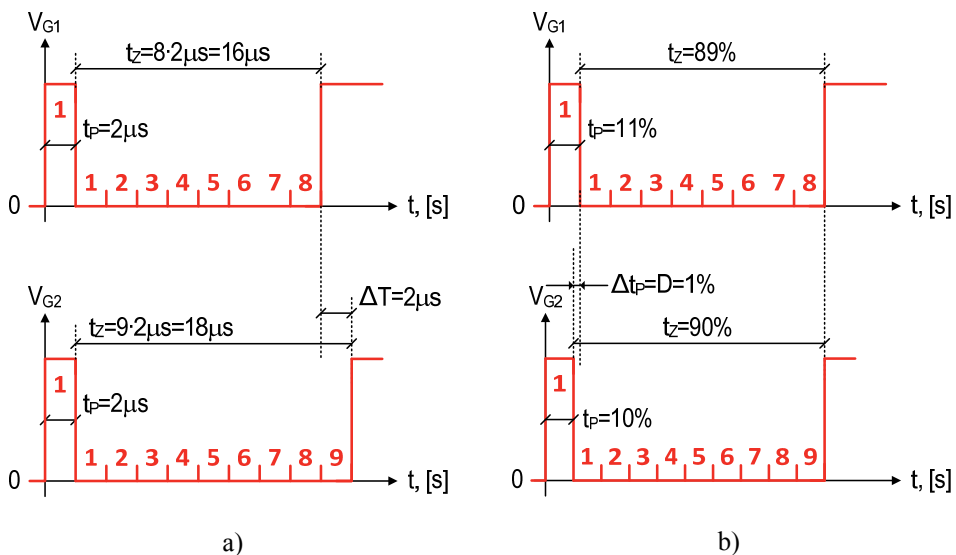
Figure 3.6 CPFM method for LEDs: a) absolute values; b) relative values

Figure 3.6 explains the changes of relative pause length. Figure 3.6a shows the absolute values of the pulse (which is constant) and the pause for two close occasions. In the first (upper) case, the pause is equal to 8 Δt=16μs, but in the second (lower one) it is 9 Δt=16μs). Thus, the periods are also different. In Figure 3.6b these two shapes are normalized in the same time frame. Then the first pause is 89% (pulse 11%), but the second one – 90% (10%). Thus, again, the accuracy of the duty cycle is higher than the accuracy of time counts (as compared to PWM).

Some numerical values calculated with (3.11) and (3.12) for P=1 are given in Table 3.4. As it is clear from this table, CPFM provides accuracy higher than the PWM accuracy at the duty cycle close to 0. In fact, no simple converter can provide high voltage at such duty cycle.

In the CPFM mode higher values of the duty cycle are obtained at lower values of n. The minimal number of the pulses is P+1. Then the maximal value of the duty cycle may be found as

$$D_{MAX} = \frac{P}{n_{MIN}} = \frac{P}{P+1} \qquad (3.15)$$

The step of the duty cycle then can be found as the difference of its maximal value and the next smaller value:

$$\Delta D_{@DMAX} = \frac{P}{P+1} - \frac{P}{P+2} = \frac{P}{P^2 + 3P + 2}. \qquad (3.16)$$

The values of the maximal duty cycle calculated with (3.15) and (3.16) are given in Table 3.5.

Table 3.4 Duty Cycles Obtained with CPFM at Long Periods

N	D(n)	ΔD(n)
10	10%	0.91%
20	5%	0.24%
100	1%	0.01%

Table 3.5 Duty Cycles Obtained with CPFM at Short Periods

P	$D_{MAX}(n=P+1)$	ΔD@DMAX(n=P+1)
1	50%	17%
5	83%	12%
10	91%	8%

Table 3.4 and 3.5 show that CPFM provides higher values of the duty cycle at high frequencies when the number of counted elementary steps Δt is low. The accuracy of the duty cycle at such conditions is extremely low. At the same time, this modulation method provides also high accuracy of the duty cycle, but only in the range of its low values if the number of counted elementary steps is high. This phenomenon contradicts the nature of DC/DC converters feeding LED elements that mostly require higher accuracy in the range of higher values of the duty cycle. Therefore, control of this hardware is rather complicated in the CPFM mode.

Variable Pulse and Pause Frequency Modulation (VVFM)

In the case of a buck/boost converter, its input voltage is 21 V that requires the values of the duty cycle 45…54 % for output voltage range of 17...25 V. The output voltage 21 V is obtained at D=50 %. Then the higher accuracy of the duty cycle for D>50 % is achieved with a rising pulse width, while D<50 % requires a rising pause width. The result is a more complicated variable pulse and variable pause FM (VVFM) that would produce the maximal switching frequency at 50 % but the minimal at the ends of the working range (at 45 and 54 %) [A6].

3.3   Assessment of Power Losses of Dimming SMPS at FM

The analysis of frequency modulation in LED dimmers is not complete without estimation of its effect on the losses and efficiency because these are very critical parameters of the dimming DC/DC converters. The loss calculation technology presented in [47], [48], [49] and [50] has been adapted to LED dimmers with not only PWM [51], but also with CZFM and CPFM [A6]. The corresponding loss and efficiency calculations and measurement were made for an LED matrix made of 15 series connected LEDs W724C0 (with rated power 10W, current I_{Omax}=2.8 A and voltage equal 54 V – see [7] for more details).

The power loss calculated utilizing the technology presented in [A6] and [A10] for buck and boost converters and taking into account real parameters of LEDs at different values of frequency and types of modulation are given in Table 3.6. Also, in order to find the actual effect of the modulation method and converter topology, a series of experiments were made. The corresponding graphs are presented in Figure 3.7.

Table 3.6 Numerical Calculation of Losses of DC/DC converters

P_{OUT} P_{max}=70W	Buck 10kHz	Buck 40kHz	Buck 80kHz	Buck CZFM 4µs	Boost 10kHz	Boost 40kHz	Boost 80kHz	Boost CPFM 4µs
0.1 P_{MAX}	92%	92%	87%	90%	89%	89%	86%	87.5%
0.5 P_{MAX}	97.5%	96.5%	95%	96%	91%	91%	90%	90%
0.9 P_{MAX}	98%	97%	96%	97%	90.5%	90.5%	89.5%	90%

a)   b)

*Figure 3.7 Dimming DC/DC choppers for light regulation with LEDs: a) buck;
b) boost*

Based on the results from Table 3.6 and 3.9, it is evident that the buck converter has better efficiency over practically the whole range of power and with all control methods. A boost converter is effective enough at low power. Also, it can be declared that FM has a positive effect on the efficiency in the case of a buck converter, while a boost converter shows almost no difference. It can be explained by the major influence of the conduction losses in the case of the boost converter and major influence of commutation losses in the case of a buck converter. The decrease of frequency (operation at higher duty cycle and power) leads to a significant reduction of total losses.

3.4   Summary

In this chapter focus was on the second hypothesis. The different types of frequency modulation were experimentally and numerically evaluated. It was observed that frequency modulation in general gives better accuracy close to a certain point of operation. Better accuracy of the duty cycle is achieved with CPFM at duty cycle values close to 0. However, CPFM is unsuitable for light regulation because there is no dimming converter that produces valuable light at *D=0*. However, CZFM in a buck converter ensures better accuracy and D in that case approaches 100 %. The losses and efficiency with FM are comparable with the PWM mode of regulation, moreover, buck converter with CZFM can present better efficiency at higher loads. Thus, in summary, the hypothesis of improvement of controllability of the fluent mode LED dimmers with frequency modulation holds.

4   CURRENT FED LED DIMMERS

Since DC-DC converters can be regarded as almost lossless, and their output voltage is proportional to input voltage as well as the input current – to the output current [52], they can be identified as DC transformers. In particular, this means that the schemes of well known voltage fed DC-DC converters are reversible in respect to their supply type. That is why simple topological rules enable the achievement of obviously novel schemes of current fed DC-DC converters. They are duals of some familiar voltage source converters.

On the other hand, most of the modern converters obtain energy from an ideal voltage source delivering it after the conversion to the loads which also can analyzed as ideal voltage sources. However, there exist applications where the current supply is advantageous. Examples of such applications are DC-DC convertors fed directly from the 3-phase grid through a rectifier and a large choke, current fed electrical motors and rectifiers with possible reversal power flow. Also, applications where the energy source is a "natural" current source, like photovoltaic and superconductive energy storages, can be accounted into this group. The current that flows from the input source cannot be uninterrupted in these cases. At the same time, the applications with constant output current also ask the supply from current fed converters. LED lighting sources can also be added to this group because brightness depends directly on their current. This chapter covers LEDs supplied from current fed converters.

4.1   Transformation of Converters

Transformation rules

The duality concept is well known in circuit theory [53] and was applied already in the late 1970s to construct current-sourced converters from the corresponding voltage-sourced converters [54].
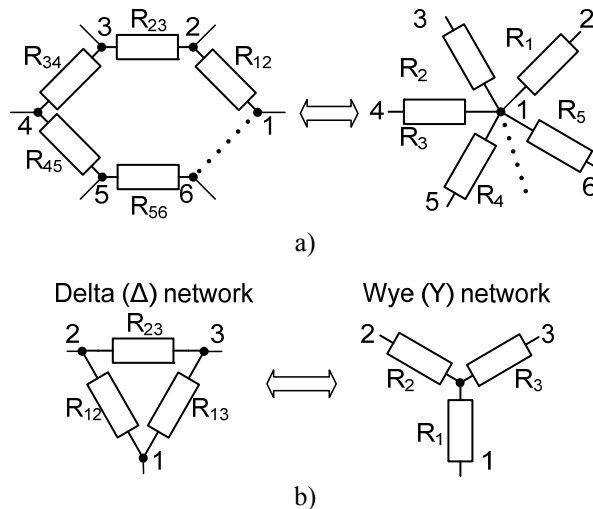

a)

b)

Figure 4.1 Transformation of circular connections into star connections: 1) general case; 2) Y and Δ connection

Table 4.1 Equations for impedance conversion

Δ to Y	Y to Δ
$$R_1 = \frac{R_{12} \cdot R_{13}}{R_1 + R_2 + R_3}$$	$$R_{12} = \frac{R_2 \cdot R_1 + R_2 \cdot R_3 + R_1 \cdot R_3}{R_3}$$
$$R_2 = \frac{R_{12} \cdot R_{23}}{R_1 + R_2 + R_3}$$	$$R_{23} = \frac{R_2 \cdot R_1 + R_2 \cdot R_3 + R_1 \cdot R_3}{R_1}$$
$$R_3 = \frac{R_{23} \cdot R_{13}}{R_1 + R_2 + R_3}$$	$$R_{13} = \frac{R_2 \cdot R_1 + R_2 \cdot R_3 + R_1 \cdot R_3}{R_2}$$

The transformation of voltage fed (VF) converters to the current fed (CF) converters is based on the following transformation methods for basic circuit elements: 1) voltage sources are replaced with current sources; 2) capacitors are replaced with inductors; 3) open circuit is turned into short circuit; 4) star, in particular Y, connection becomes a circular connection, in particular Δ and vice versa (Figure 4.1a).

The rule of transformation of Y connection to the Δ (Figure 4.1b) also known as pi (π) to tee (T) connection simplifies the analysis of an electrical network. The circuit transformation theory was published by Arthur Edwin Kennelly in 1899 [55].This rule is used to establish the equivalence for a network with three elements. Table 4.1 presents special equations for converting Δ to Y and vice versa:

These rules also can be applied on basic components of DC-DC converters, such as inductance, capacitor transistor and diode. The inductance and capacitor can be called as complex resistances. The transistor is nonlinear resistance which depends on time and the diode can be presented as nonlinear resistance.

Example of current fed circuit – current fed buck converter

- *Schematic*

The rules listed above enable us to transform different converters. The process of transformation of a conventional voltage supplied buck converter into the corresponding current supplied buck converter is presented Figure 4.2. There is a π (Δ) circuitry on the input and a T (Y) circuitry – on the output of this converter. If the transformation rules are applied to these distinct parts of the VF buck converter (Figure 4.2a), it is transformed into the CF buck converter (Figure 4.2c). The input delta transforms to the input star and the output star to the output delta (Figure 4.2b). Sources and base elements are replaced taking into account the above rules.

Operation parameters of a CF converter have considerable influence on the static accuracy and dynamic stability of the system where it is installed as an object of regulation [A11]. Static operation of CF converters (including CF buck) is defined by the currents balance in their capacitors, like operation of VF buck converters is defined by the voltage balance of their inductors. Depending on this balance, continuous and discontinuous conduction mode can be emphasized.
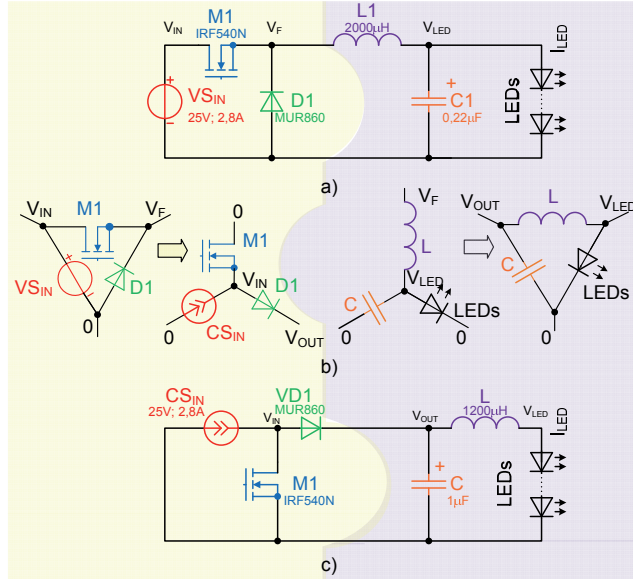
Figure 4.2 Transformation of a VF buck converter to a CF buck converter: right side (yellow) - input transformation; left side (purple) - output transformation

- *Static Operation in Continuous Capacitor's Voltage Mode*

In the continuous capacitor's voltage mode, this voltage never drops to zero level. This leads to a very simple equilibrium of a capacitor's charging and discharging currents.

When the input transistor M1 is on, the current source is short-circuited. When the capacitor is being discharged by the load current $-I_{LOAD}$, then the voltage across the capacitor C_{CF} decreases and can be expressed by the equation:

$$\Delta V_{C-} = \frac{1}{C_{CF}} \int_{D \cdot T}^{T} (-I_{LOAD}) dt = \frac{(-I_{LOAD}) \cdot D \cdot T}{C_{CF}}. \tag{4.1}$$

When the transistor is off, the current is conducted by diode D1 and the capacitor of the converter is charged by the difference of the supply I_{IN} and load $-I_{LOAD}$ currents. The corresponding voltage increase is expressed as follows:

$$\Delta V_{C+} = \frac{1}{C_{CF}} \int_{D \cdot T}^{T} (I_{IN} - I_{LOAD}) dt = \frac{(I_{IN} - I_{LOAD}) \cdot (1 - D) \cdot T}{C_{CF}}. \tag{4.2}$$

In (4.1) and (4.2) T is the switching period, but D is the duty cycle of its switch operation. In the case of static operation of the converter the voltage across the capacitor has to be the same at the borders of the switching period: $\Delta V_{C-} + \Delta V_{C+} = 0$. This gives the following current transformation equation:

$$I_{LOADc} = I_{IN} \cdot (1 - D). \tag{4.3}$$

- *Static Operation in Discontinuous Capacitor's Voltage Mode*

Equations (4.1)…(4.3) are valid if the voltage across the capacitor is always higher than zero (Figure 4.3a red curve). Otherwise (Figure 4.3b), the voltage fall time is shorter and Eq. (9) is expressed as:

$$I_{LOAD} \cdot \delta = (I_{IN} - I_{LOAD}) \cdot (1-D), \qquad (4.4)$$

where δ can be found based on the capacitor's voltage

$$V_{LOAD} = V_C = \frac{\Delta V_{C+}}{2} \cdot (t_+ + t_-) = \frac{(I_{IN} - I_{LOAD}) \cdot T}{C} \cdot (1 - D + \delta). \qquad (4.5)$$

Eqs. (4.4) and (4.5) together form the current transformation expression for a discontinuous voltage mode

$$I_{LOADd} = I_{IN} \cdot \frac{(1-D)^2}{V_{LOAD}/4V_{LOADd\,max} + (1-D)^2}. \qquad (4.6)$$

where

$$V_{LOADd\,max} = I_{IN} \cdot T/(8 \cdot C) \qquad (4.7)$$

is the maximal possible output voltage in the discontinuous mode reached at D=0.5. Equation (4.7) means that in this mode the output current is a function of both the duty cycle of the converter and its load. On the whole, (4.3) and (4.6) look quite similar to voltage transformation equations of the VF buck converter where *1–D* is used instead of *D*.

- *Example of operation*

The equation obtained and the operation modes were checked experimentally. During the experiments a reduced version of the LED matrix with 7 10 W LEDs was used. Further, in the case of the LED load, the output voltage is nearly constant (and very close to the nominal voltage of the LEDs, i.e., is quite high). For this reason, discontinuous voltage mode with CF drivers LED load is almost impossible (for this reason, the operation signals shown in Figure 4.3 are taken with a resistive load).

a)   b)
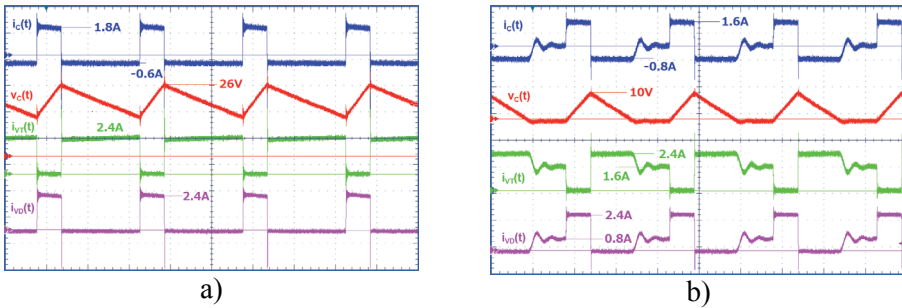
Figure 4.3 Static operation waveforms of a CF buck driver at I_{IN}=2.4A, T=25µs, C=1µF and gives $V_{LOADdmax}$=7.5V, as well as at D=75%: a) continuous capacitor's voltage at V_{LOAD}=20V and I_{LOAD}=0.6A; b) discontinuous capacitor's voltage at V_{LOAD}=4V and I_{LOAD}=0.8A.
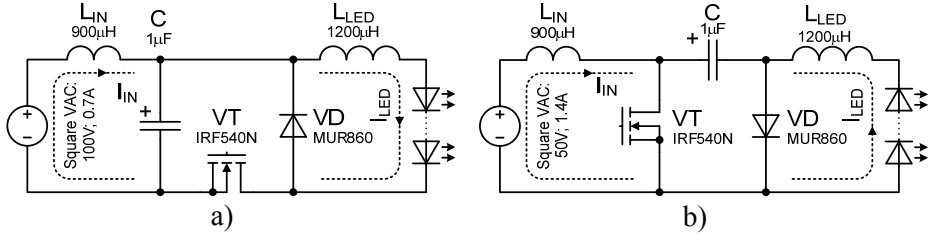
Figure 4.4 CF version of: a) boost; b) buck boost dimmer

Other current fed converters

In the same way it is possible to transform any traditional VF converter (or more sophisticated, like SEPIC, Zeta etc.) into the corresponding CF circuit. Since the target of this thesis is a well controllable LED dimmer, this approach was applied also to boost and buck-boost circuits, which have different transformation equations. The CF dimmers produced are given in Figure 4.4.

4.2 Controllability of Dimmers

The proposed hypothesis assumes that CF dimmers provide better controllability than the VF ones. In order to make a valuable comparison, several control parameters were chosen. They refer to the dimmer's regulation curve, which expresses its relative output *RO* (current or light) changes that occurred for particular duty cycle changes (Figure 3.1). These parameters are: a) nonlinearity of the regulation curve (NL); b) utilization of the duty cycle (D_{SPAN}) and c) maximal gain of the lamp (G_{LAMP}).

- *Nonlinearity of the regulation curve*

Nonlinearity has a strong effect on the stability and dynamic performance of the control system. It is an integral criterion that is equal to the root-mean-square declination ΔS of the regulation curve from a line connecting its border points to the root-mean-square value S of the curve itself:

$$NL = \frac{\Delta S}{S} ,\qquad(4.8)$$

where ΔS is defined as

$$S = \sqrt{\frac{1}{D_{\max} - D_{\min}} \int_{D_{\min}}^{D_{\max}} RO^2(D)dD} ,\qquad(4.9)$$

but S – as follows:

$$\Delta S = \sqrt{\frac{1}{D_{\max} - D_{\min}} \int_{D_{\min}}^{D_{\max}} \left[RO(D) - RO_{LIN}(D)\right]^2 dD}\qquad(4.10)$$

In Eqs. (4.8)…(4.10) D is the duty cycle of operation of the chosen converter. This control parameter depends on a physical parameter (pulse width or period)

that is variable with the particular modulation method. Its values at the ends of the regulation curve are obviously 0 and 100% while those corresponding to the minimal and maximal values of the relative output – D_{min} and D_{max}.

- *Utilization of the duty cycle*

The second parameter for comparison reflects which part of the duty cycle span is used practically to adjust the relative output. Then it can be defined as the parameter ratio:

$$\Delta D_{SPAN} = \frac{D_{max} - D_{min}}{100\% - 0} \cdot 100\% = D_{max} - D_{min} . \tag{4.11}$$

- *Maximal dynamic gain of the lamp*

Finally, the maximal gain of the lamp expresses the maximal rate of change of *RO* with changes of the duty cycle *D*. It can be exactly expressed as a duty cycle derivative of the regulation curve (4.12). It can be expressed also approximately as a ratio of RLO changes to the corresponding D changes:

$$G_{LAMP} = f(D) = \frac{dRLO}{dD} \approx \frac{\Delta RLO}{\Delta D} . \tag{4.12}$$

ΔRO and *ΔD* in (1) are explained in Figure 3.1. The maximal value of the gain that can be found as the worst ratio is

$$G_{LAMP\,max} = \frac{\Delta RO_{max}}{\Delta D_{CR}} \tag{4.13}$$

The maximal value expressed by (4.13) is especially important for the estimation of the stability of the lamp.

4.3 Assessment of Light Controllability Obtained with CF Dimmers

To confirm the hypothesis, CF and VF dimmers were analyzed based on several experiments with different VF and CF dimmers. Based on the formulas for comparison parameters presented in this chapter, a series of calculations and experiments were done and the corresponding graphs were built. The results are presented in Table 4.2 and Figure 4.5.

Table 4.2 Calculated and Measured Controllability Parameters of LEDs with CF and VF Drivers (for RO Working Range 10...100%)

	Calculated / Measured					
	VF			CF		
	Buck	**Boost**	**B-Boost**	**Buck**	**Boost**	**B-Boost**
$\lvert G_{LAMPmax}\rvert$, [%/%]	7 / 6	9 / 7	25 / 16	1 / 1	20 / 19	3 / 3
NL, [%]	11 / 11	17 / 11	14 / 5	7 / 13	107 / 115	22 / 16
D_{SPAN}, [%]	16 / 18	15 / 18	7 / 7	90 / 94	45 / 79	53 / 55
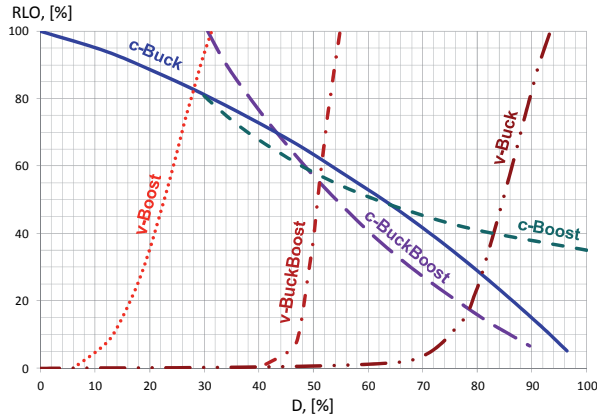
Figure 4.5 Graphical comparison of measured regulation curves of VF (solid and dashed graphs) and CF (dotted and dash-dotted) driven LED lamps

A set of deductions can be submitted based on the presented graphical and calculated results. The first one is identifying the ramp of the regulation curve. From Figure 4.5 it is clear that the light regulation curves of voltage dimmers are more "vertical", while the curves of CF dimmers are more "horizontal".

Such tendency of CF dimmers leads to lower maximal dynamic gain that, in turn, ensures higher stability. Moreover, a wider span of usable duty cycle values is available with CF dimmers. Another confirmation of this conclusion follows from Table 4.2.

The next conclusion based on Figure 4.5 and Table 4.2 is that the nonlinearity of the regulation curve is comparable for most of the dimmers except the boost dimmer. In addition, CF boost dimmers provide a rather narrow range of RO. The reason of this can be explained as follows. The values of LED's current I_{LOAD} are higher than the supply current I_{IN} and consequently low *RO* cannot be obtained due to the nature of the dimmer. At the same time, due to the almost constant LED voltage, the higher output current requires a higher input voltage, which is also difficult to achieve. For example, if $I_{IN}=0.2I_{LOAD}$, then $RO \approx 20\dots100\%$, but $V_{IN}=1\dots5V_{LOAD}$.

4.4   Power Losses of CF Buck Dimmers

To acquire a more comprehensive comparison of VF and CF dimmers, the energy efficiency of CF buck dimmers was also estimated. Figure 4.6 represents the experimentally obtained efficiency, Figure 4.7 – losses, but Table 4.3 shows temperatures of switches (thus indirectly showing also loss distribution) of such dimmers.

Table 4.3 Case of Ambient Temperature Drop of CF Buck Driver at Different Values of Duty Cycle

	ΔT_{ca} at D=10%	ΔT_{ca} at D=40%	ΔT_{ca} at D=75%
Transistor	24^0C	19^0C	10^0C
Diode	31^0C	22^0C	15^0C

45
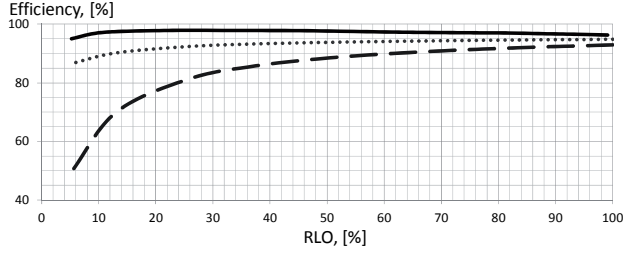
*Figure 4.6 Measured efficiency of VF and CF buck driven LED lamps (solid –
VF, dashed – CF, dotted – CF after inductor).*
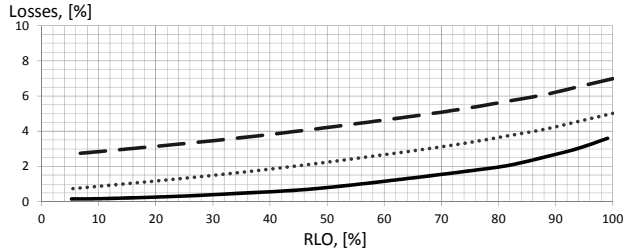
*Figure 4.7. Measured losses of VF and CF buck driven LED lamps (solid – VF,
dashed – CF, dotted – CF after inductor).*

As seen in Figure 4.6 and 4.8, the VF buck converter is more efficient at all values of RLO. The difference is especially significant at low loads, that can be explained by the differences in operation. The best range of D of VF driver is 75…95%, in which diode conduction losses are minor. In a CF driver all losses highly depend on D. At high load (low D), the MOSFET conducts input current for a shorter time, but the diode – for a longer and diode losses are significant. At small load (high D), the MOSFET conducts almost all the time and its losses are dominating. Moreover, in a CF driver one of the switches always conducts the full input current 2.8A. However, at high load the output power is also high and the efficiency is acceptable. Some static losses appear (Figure 4.7) also in the input inductor that is an optional element and its losses can be omitted (dotted line). Data in Table 4.3 prove the above statements.

4.5   Weight and Size of CF Dimmers

Both the VF and CF buck converters with the same load have the same set of components: MOSFET, diode, capacitor and inductor. The sizes of the inductor and capacitor, as well as heatsinks are the main factors that define the whole size of the converter. At the same time these elements finally define LED current ripples that have to be minimal.

In the case of a VF converter, LED's current ripples are defined by their voltage ripples that, in turn, are defined by the current ripples of the inductor and can be expressed with the following equation:

$$\Delta I_L = \frac{1}{L}\int_0^{t_1} V_L(t)dt = \frac{V_L \Delta t_1}{L} = \frac{V_{IN}D(1-D)T}{L}. \tag{4.14}$$

46

The maximal value of these ripples is achieved at D=0.5 and is equal to $\Delta I_{Lmax}=V_{IN}T/4L$. Then the voltage ripples can be found as

$$\Delta V_C = \frac{1}{C_{VF}} \int_0^{\Delta t_2} I_C(t)dt = \frac{1}{C_{VF}} \cdot \frac{1}{2} \cdot \frac{\Delta I_L}{2} \cdot \frac{T}{2} = \frac{\Delta I_L T}{8 \cdot C_{VF}} , \qquad (4.15)$$

where $I_C(t)$ is found as the difference of direct LEDs and the saw-tooth inductor's currents that is equal to the current ripples. (42) and maximum of (41) give the following product of the capacity C and inductance L:

$$L_{VF} \times C_{VF} \geq \frac{V_{IN}}{\Delta V} \cdot \frac{T^2}{32} . \qquad (4.16)$$

In the same way, the output current ripple of a CF converter gives:

$$L_{CF} \times C_{CF} \geq \frac{I_{IN}}{\Delta I} \cdot \frac{T^2}{32} \qquad (4.17)$$

LEDs current ripples have to be lower than 3% that, due to the features of the LED's V-A curve, requires 1% of voltage ripples. Therefore,

$$L_{VF} \times C_{VF} \geq (V_{IN}/0.01V_{IN}) \cdot (T^2/32) = 100 \cdot T^2/32 \text{ and} \qquad (4.18)$$

$$L_{CF} \times C_{CF} \geq (I_{IN}/0{,}03I_{IN}) \cdot (T^2/32) = 33 \cdot T^2/32 . \qquad (4.19)$$

Analysis of (4.18) and (4.19) leads to the following remarks: 1) the volume and weight of L and C elements of a CF buck converter can be up to three times smaller; 2) their linear dimensions are up to $\sqrt[3]{3} = 1.44$ times smaller than those of a VF buck converter.

4.6   Summary

In this chapter focus was on the second hypothesis. The static operation of LED luminaries with several VF and CF LED dimmers was investigated. The hypothesis that LED dimmers supplied by direct current improve the parameters of controllability of the dimmers at the same time keeping their efficiency at the level comparable with existing competitive VF topologies was proved. Moreover, the sizes of CF dimmers are potentially smaller. However, a CF buck dimmer is preferable due to its specific features. The control switch of a CF buck dimmer is connected to the same ground as its supply that makes its transistor driver simpler and cheaper. Practical utilization of a CF boost dimmer seems unrealistic because the input voltage of such dimmers should be high while its output current cannot be low, so that RO is limited.

5 CONCLUSIONS AND FUTURE WORK

5.1 Generalization

The thesis explores two different aspects of the electronic ballasts for luminaries with LEDs. The first aspect relates to the influence of frequency modulation on the efficiency and controllability of the drivers of known topologies. The second concerns the development of LED drivers utilizing direct current regulation approach to improve the parameters of controllability of the drivers keeping at the same time their efficiency at the level comparable with existing competitive topologies. Specifically, the contribution of the thesis is demonstrated by the following statements.

First, LED lamps are evaluated as eco-friendly lighting sources. LEDs are an energy efficient alternative as compared with traditional lighting sources. They provide longer lifetime and enable us to control a lighting flux that makes them attractive to use in smart lighting applications. It is concluded that the success of the LED lighting technology depends considerably on the success of the electronic circuits intended for their supply and regulation of their current – LED drivers.

Chapter 2 describes a smart lighting system. The principle of a smart lighting system is based on the function of lighting control and regulation. The current state-of-the-art in the field of energy efficient dimmable LED drivers (electronic ballasts for LEDs) was analyzed and their main drawbacks and advantages identified. It has been proposed to improve the quality (linearity and accuracy) of light regulation of the fluent mode voltage fed dimmers utilizing FM to control high frequency switchings of dimmer's transistors and to use CF dimmers. Also, a testbench built to provide a flexible experimenting base is described in this chapter.

Chapter 3 investigates various FM methods, analyzes their compatibility with different converter topologies and estimates the controllability and efficiency of LED dimmers. The proposed hypothesis is stated analytically and verified by experiments.

Chapter 4 discusses the second hypothesis. The static operation of LED luminaries with several VF and CF LED dimmers is investigated. CF LED dimmers are proposed as a solution that provides better light controllability. The synthesis rules and analysis of CF dimmer's operation are presented.

5.2 Conclusions

1) First, it was found and experimentally confirmed that high performance and energy efficient dimmers are based on the fluent mode light regulation. The pulse mode dimmers are undesirable due to their flickering and stroboscopic effects, but the step mode – due to the low number of provided light levels. However, if the required number of lighting levels is rather small (<20), the step mode light regulation may also be used.

2) It was found that in general, FM provides better accuracy close to a certain point of operation. However, this method of control of switchings has several options:

·   It is concluded that in the case of CZFM, accuracy is higher at higher values of the duty cycle (close to D=1). This corresponds well to the buck type LED dimmers that, due to the higher rate of change of V-A curve of LEDs, require higher accuracy at this point. It was checked that the losses and efficiency of the buck converter with FM are comparable with PWM and can even provide better efficiency at higher loads. Therefore, undoubtedly this method of dimmer's improvement is positive.

·   At the same time, CPFM achieves better accuracy of the duty cycle at its values close to 0. However, CPFM is unsuitable for light regulation, because there is no dimming converter that produces valuable light at D=0. Therefore, practical use of this modulation method is questionable.

3) The hypothesis that LED dimmers supplied by direct current have better controllability, at the same time keeping the efficiency at the level comparable with existing competitive VF topologies is confirmed. Moreover, the sizes of CF dimmers are potentially smaller. However, this kind of LED dimmer improvement also has options:

·   CF buck dimmers are advantageous due to their specific features. First, it is more practical, because it requires no high input voltage. Also, the driver of the switch of the CF buck dimmer is connected to the same ground as its supply, resulting in simpler and cheaper design. Therefore, this kind of LED dimmers can be recommended for practical use.

·   Practical utilization of CF boost dimmers seems unrealistic, because of the almost constant LED voltage, higher output current and power balance of the input voltage of such dimmers should be high. Also, output current of these dimmers cannot be low, so that the range of RO is limited.

5.3   Future Work

Attractive features of LEDs draw great interest from scientific communities and industry of lighting technologies. Based on the research and practical work done in this thesis, proposals for expansion and potential areas for further research are suggested.

1) CZFM and CPFM modulation was studied in Chapter 3, but VVFM was neglected because it is a mix of CZFM and CPFM. However, this modulation method is an interesting topic to study due to the opportunity to select the working point freely and to use VVFM with any type of the dimmer. However, the trade off between the higher accuracy and calculation capacity of a control system needs special focus in this case.

2) In the research of LED dimmers, a suggestion relevant to the efficiency of CF dimmers was made. The future objective is the practical realization of such dimmers. Therefore, it is necessary to develop an effective current source to a voltage source converter. The overall efficiency of such systems is also a subject of research.

Thus, finally, the fluent mode dimmers with frequency modulated switchings control as well as those designed as current converters are suitable for implementation in the smart lighting systems with LEDs, but as their parameters still can be improved further research is required.

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List of authors' publications directly connected to the topic of dissertation (copies shown in Appendix)

[A1]   **Milaševski, I.**; Armas, J. (2010). Smart Solution for Street Lighting. In: Abstract Book and Electronic Proceedings / The 51st Annual International Scientific Conference of Riga Technical University. Section of Power and Electrical Engineering: (Eds.) A. Bacauskas, L. Boronina, M. Budahs, V. Chuvychin. Riga: RTU Publishing House, 2010, 55.

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Abstract

Research and Development of Electronic Ballasts for Smart Lighting Systems with Light Emitting Diodes

In the recent years, the topic of smart systems including lighting has been widely discussed due to the need of reduction of energy consumption in the world. Implementation of LEDs in such systems improves the energy efficiency of lighting systems. LEDs offer many advantages over traditional lighting sources, such as: long lifetime, high efficiency, instant light-up, fully dimmable almost without colour variation, direct emission of coloured light without filters, complete spectrum of colours, dynamic colour control and tunable white point, total design freedom. Thus, LEDs are very suitable for more efficient systems, vibration-proof lighting, no mercury, no IR or UV radiation in visible light. However, LEDs are semiconductor devices that need to be powered from direct current or voltage source of rather low value, while the power supplies nowadays have mostly higher value voltages, often AC. Therefore, the special electronic circuit called ballast is needed.

The main aim of this PhD thesis is to analyze existing electronic ballasts for LEDs and propose ways to develop the energy-efficient dimming electronic ballast for LEDs. The definition of a smart lighting system is presented. Further, the smart lighting systems should have the light regulation function. According to this, different light regulation methods were studied and it was found that the fluent mode light regulation is the most accurate one.

It is proposed to improve the quality (accuracy) of light regulation of the different types of dimmers utilizing frequency modulation to control high frequency switchings of dimmer's transistors. Different types of frequency modulation were estimated analytically, experimentally and numerically. According to these estimations, the improvement of controllability and efficiency of DC-DC dimmers for LEDs were verified. It is concluded that the most promising combination for LED light regulation is constant pause frequency modulation used in a buck converter.

The idea of current fed LED dimmers was also verified. The synthesis rules, basics of operation and main relationship of such dimmers were described. It was found and verified that the current fed dimmer improves the parameters of controllability while the size of current fed dimmers is smaller than that of voltage fed LEDs dimmers. This conclusion, however, concerns mostly current fed buck dimmers.

The analyses, methods and results of this research can be useful for further studies of power electronics and for companies whose profile is development and production of electronic ballasts for LEDs.

Kokkuvõtte

Tarkades valgustussüsteemides kasutatavate LED-valgustite elektrooniliste ballastseadmete uurimine ja arendamine

Seoses vajadusega vähendada elektrienergia tarbimist on viimastel aastatel kogu maailmas arutluse all mitmesugused intellektuaalsed süsteemid, sealhulgas targad valgustussüsteemid. Valgusdioodide kasutamine sellistes süsteemides suurendab valgusallikate energiatõhusust ja funktsionaalsust. Valgusdioodidel on palju eeliseid, võrreldes traditsiooniliste valgusallikatega: pikk ekspluatatsiooniperiood, kõrge valgustootlikkus, hetkeline sisse- ja välja-lülitumine, täieliku hämardamise võimalus peaaegu ilma värvuse muutuseta ja tööiga vähendamata. Peale selle võivad valgusdioodid kiirata praktiliselt mistahes spektraalkoosseisuga valgust vajaduseta kasutada selleks valgus-filtreid, valgusdioodid võimaldavad teostada valgusspektri dünaamilist juhtimist ja valge punkti häälestamist. Samuti tuleb märkida valgusdioodide paindlikkust kasutamisel, nende vibratsioonikindlust, elavhõbeda puudumist, kõrvalise infrapuna- ja ultraviolettkiirguse puudumist (kui need on mittesoovitavad). Kuid pooljuhtseadmetena, mida toidetakse küllalt madala väljundsuurusega alalisvoolu- või alalispingeallikast (samal ajal on praegu peamiselt toiteallikateks kõrgema pingega vahelduvpingeallikad), nõuavad valgusdioodid spetsiaalsete elektrooniliste skeemide, nimetatakse ballastideks, kasutamist.

Käesoleva doktoritöö peamiseks eesmärgiks on valgusdioodide olemas-olevate ballastide analüüs, nende puuduste väljaselgitamine ja soovituste väljatöötamine olemasolevate puuduste kõrvaldamiseks. Seega on kõne all valgusdioodidele hämardamise energiatõhusa elektroonilise ballasti väljatöötamine.

Töö alguses esitatakse valgustuse intellektuaalse süsteemi määratlus. Näidatakse, et selline valgustussüsteem peab omama valguse reguleerimis-funktsiooni. Vastavalt sellele uuriti valgusvoo erinevaid juhtimismeetodeid. Selgitati välja, et valgusparameetrite pidevreguleerimine on kõige eelistatum reguleerimistäpsuse vaatekohalt.

Töös on ettepanek parandada valgusparameetrite reguleerimise juhitavust (täpsus, mittelineaarsus ja praktiline diapasoon), kasutades sagedus-modulatsiooni erinevate valgusregulaatorite transistoride kõrgsageduslike ümberlülituste juhtimiseks. Analüütiliselt, eksperimentaalselt ja numbrilise modelleerimise teel uuriti sagedusmoduleerimise erinevaid viise. Saadud andmete põhjal võib lugeda tõestatuks juhitavuse ja efektiivsuse parandamine väljapakutud meetodiga valgusdioodide valgusregulaatorites, mis on ehitatud pingemuunduri põhimõttel. Samuti tehti järeldus, et kõige perspektiivsem on energiatõhususe ja reguleerimistäpsuse seisukohalt ühildada konstantse pausiga sagedusmodulatsioon ja madaldav pingemuundur.

Töö järgmises osas kontrollitakse ideed ehitada valgusdioodi dimmer (valgusregulaator) kui vooluregulaator toitega alalisvooluallikast. Töös tuuakse selliste valgusregulaatorite sünteesi juhised, nende töö põhiprintsiibid ja selliste valgusregulaatorite põhilised võrrandid. Teostatud töö põhjal määratleti ja

tõestati, et voolumuundurina projekteeritud valgusregulaator parandab juhitavuse näitajaid. Samal ajal võivad sellise valgusregulaatori mõõtmed olla väiksemad pingemuundurina ehitatud valgusregulaatori omadest. See järeldus käib peamiselt madaldava voolumuunduri kohta.

Selle uuringu meetodid ja tulemused võivad olla kasulikud edasistes uuringutes jõuelektroonikas, aga samuti kompaniides, kelle profiiliks on valgusdioodidega valgustusaparatuuri, sealhulgas valgusdioodide elektroonsed ballastid, väljatöötamine ja tootmine.

Elulookirjeldus

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Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Kesklinna Vene Gümnaasium	2003	keskharidus
Tallinna Tehnikaülikool, Elektriajamite ja jõuelektroonika instituut	2006	bakalaureusekraad
Tallinna Tehnikaülikool, Elektriajamite ja jõuelektroonika instituut	2008	magistrikraad

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Vene	emakeel
Inglise	kesktase
Eesti	kõrgtase
Saksa	algtase
Soome	algtase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
2011	Riga Technical University, Latvia

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
suvi, 2004	AS Prisma	kassiir
11.09.2006- jätkub	KH Energia – Konsult	elektriprojekteerija

7. Teadustegevus
8. Kaitstud lõputööd

Irena Milaševski, magistrikraad, 2008, (juh) Raivo Teemets, Pärnu ümbersõidu Ehitajate tee lõigu tänavavalgustuse projekteerimine, Tallinna Tehnikaülikool, Energeetikateaduskond, Elektriajamite ja jõuelektroonika instituut, Elektriajamite ja elektrivarustuse õppetool.

9. Teadustöö põhisuunad

- Loodusteadused ja tehnika
- Energeetikaalased uuringud

10. Teised uurimisprojektid

- SF0140016s11 "Aktiivsete elektrijaotusvõrkude muundurite topologiad ja juhtimismeetodid"

Curriculum vitae

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3. Education

Educational institution	Graduation year	Education (field of tudy/degree)
Tallinn Central Russian High School	2003	Secondary education
Tallinn University of Technology, Department of electrical drives and power electronics	2006	Bachelor degree
Tallinn University of Technology, Department of electrical drives and power electronics	2008	Master of science degree

4. Language competence/skills (fluent; average, basic skills)

Language	Level
Russian	native
English	average
Estonian	fluent
German	begginer
Finnish	begginer

5. Special Courses

Period	Educational or other organisation
2011	Riga Technical University, Latvia

6. Professional Employment

Period	Organisation	Position
Summer, 2004	The AS Prisma company	cashier position
11.09.2011 - continous	KH Energia-Konsult	Elecrical designer

7. Scientific work

8. Defended theses

Irena Milashevski, Master's Degree, 2008, (sup) Raivo Teemets, Street Lighting Design of Pärnu Bypass on Ehitajate tee Corridor, Tallinn University of Technology, Faculty of Power Engineering, Department of Electrical Drives and Power Electronics, Chair of Electrical Drives and Electrical Supply

9. Main areas of scientific work/Current research topics

- Natural Sciences and Engineering
- Energetic Research

10. Other research projects

- SF20140016s11 "New Converter Topologies and Control Methods for Electronic Power Distribution Networks"

Appendix

[A1] **Milaševski, I**.; Armas, J. (2010). Smart Solution for Street Lighting. In: Abstract Book and Electronic Proceedings / The 51st Annual International Scientific Conference of Riga Technical University. Section of Power and Electrical Engineering: (Eds.) A. Bacauskas, L. Boronina, M. Budahs, V. Chuvychin. Riga: RTU Publishing House, 2010, 55.

Smart Solutions for Street Lighting

Irena Milashevski (*Ph.D. student, Tallinn University of Technology*), Jelena Armas (*Ph.D., Tallinn University of Technology*)

Abstract – **The development of smart street lighting system is outgrowing nowadays. Choosing sustainable lighting solutions is an excellent way to save on energy and operational costs while providing long-lasting, dependable, high-quality light that demonstrates environmental responsibility. These are major design considerations for modern street lighting systems. This paper is devoted to study which smart solutions for street lighting are used today for fulfill design criteria. Selecting technologies and using them effectively is a true challenge. Experimental calculation is obtained and analyzed to identify the energy savings by replacing HPS street lamps with LED street lamps.**

Keywords – **Diodes, LEDs, lighting control, environmental factors**

I. INTRODUCTION

Street lighting is an integral part of the municipal environment, serving communities and local businesses, promoting economic development, and enhancing safety, security, and the aesthetic appeal of surrounding property. However, many municipalities are not aware of all the available choices in technology and design. While municipalities may have certain goals in mind, they might not know how to begin the process or what questions to ask when researching opportunities.

There are several reasons for installing street lighting, such as:
- to increase perception of safety and security;
- to reduce vehicular accidents;
- to improve pedestrian visibility;
- to help create a particular architectural "look" or style;
- to illuminate building facades and enhance surrounding architectural details;
- to respond to public demand.

Today, most street lighting is selected based solely on providing a recommended amount of light to a street, or as is the case with many business district improvement projects, selected based on the general style of the pole and fixture to meet architectural requirements.

Many streets are lighted inefficiently and ineffectively with outdated equipment. The result is wasted energy, glare, light pollution, and light trespass. Several states now have or are considering legislation that specifies certain types of luminaires for new outdoor installations. Requiring specific equipment, however, limits options and may not provide the best solution to outdoor lighting problems. Better information about energy-efficient and effective road lighting as well as better luminaire designs are needed.

Effective energy-efficient street lighting uses a balance of proper energy-efficient technologies and design layout to meet performance, aesthetic and energy criteria required by pedestrians, motorists, community residents, municipalities and utilities.

Economy, the environment, and an increasing desire among people to live a greener lifestyle are driving the streetlight market.

Some innovative cities have implemented or are planning to implement energy-saving programs involving streetlights. Streetlights can account for up to 40 % of a city's electricity use, and with rising energy costs, streetlights can consume a huge portion of a city's annual electricity budget.

The easiest solution would be to turn off the lights. Doing so, some would argue, – if that reduces the electricity costs associated with a lighting segment to zero, yielding the following benefits:
- no light pollution for that segment – no cost;
- easy implementation – no problem;
- CO_2 emissions absent.

On the surface this sounds perfect. In fact, many cities have either implemented this solution or are planning to do so. Yet it is far from ideal. According to a recent study by the Cochrane Library reported in the Telegraph.co.uk, street lighting has reduced the number of fatal crashes by 77 % and other collisions by between 32 and 55 %. Fiona Beyer, one of the study's authors, noted, "Road crashes are not just the unfortunate culmination of chance, but are events that can be analyzed, so the risk factors are identified and then addressed." According to Beyer, "Darkness is a risk factor – street lighting is, therefore, a valuable tool" [1].

As a result, cities are once again examining their methods of managing streetlight electricity. Our proposal is to embed smart control networks into streetlights. The end result is far better than turning off the lights:
- decreased energy use – as much as 70 % lower energy use;
- improved safety – lights stay on. The whiter quality of our proposed streetlights can also increase visual acuity as well as improve the quality of images captured on existing security cameras;
- lower maintenance costs – advanced monitoring notifies cities of impending light failure and actual failures;
- better living conditions – lighting can be tuned to residential or commercial preferences [2].

The main aim of this article is to analyse different solutions for street lighting, which are used in the World and to use them in pilot project in Tallinn, which has been started in May 2010. In the future we should confirm is it worth to use LEDs in our city or not based on the experimental results.

II. SMART GRID

A smart grid is an energy network that includes power generation, transmission and distribution, a low-power neighborhood network, and a grid – plus energy consuming devices. A smart grid is capable of two way interactions from the smallest device to the most complicated expert system [3].

Project development and investment, light emitting diode (LED) streetlight and smart grid technology are being combined and systems rolled out in a growing number of cities. Touted as being good for 20 years, LED streetlights are said to be much more energy efficient than the High Intensity Discharge (HID) and High Pressure Sodium (HPS) streetlights currently in use in cities, other municipalities and streets.

III. SMART SOLUTIONS FOR STREET LIGHTING

Theoretical methods are usually performed for ideal conditions to determine the illuminance and luminance but other design limitations should be considered in the real world. High performance lighting engineering design has been today's major concern and a topic of interest due to energy saving and green house considerations. That is why it is very important to find out optimal and smart solutions for street lighting. There are some opportunities to improve street lighting like:

- improved lighting optics – flat glass lens to reduce glare, energy but not light levels;
- electronic ballasts – for High Pressure Sodium (HPS) street lighting;
- lighting control – to reduce light levels as traffic patterns change;
- new more efficient technologies – other light sources-induction, LED, etc;
- reduced lighting levels – scotopic vision issues.

A. Lighting Optics

Unshielded streetlamps, or semi-cutoff luminaires, fail to make streets safer because their high-wattage bulbs light throughout the entire surrounding area. Full cutoff optics are a less bright and ultimately safer alternative. Full cutoff optics use flat glass lenses and external shielding to direct light to the roadway this is the effect of overhead. This problem can be solved by improvements in optics system design, lamp placement, reflector design, lens design – dropped, sagged or flat and lighting maintenance.

B. Electronic Ballasts

High-frequency electronic ballasts for fluorescent lighting systems, also called solid-state ballasts, are promoted as providing significant energy saving over magnetic ballasts.

Tests indicate that there is a potential 20 % efficiency improvement over the standard magnetic ballasts.

C. Lighting Control

Street lighting networks differ from others electrical energy consumers, because almost all lamps need to be controlled.

Streetlight Intelligence is a developer of street lighting control systems. Its street light energy management technologies can reduce energy costs by 30-50 % [4].

The whole monitoring and controlling system in Tallinn is based on GSM data. GSM (Global System for Mobile Communications: originally from *Groupe Spécial Mobile*) is the most popular standard for mobile telephone systems in the world. By this data the central computer controls the work of street lighting in the real time according to the program of turning on and off. All 601 switching boxes turn on and off during 6 minutes due to the program given.

The lighting of pedestrian roads in Tallinn is connected with the security signalization. It means that if the breaking or opening of a box of control happens, the signal of alarm immediately goes to the control panel in KH Energia-Konsult. This signal reaches the people responsible for organization of work and maintenance of the street lighting system.

Thus, all the switching boxes are connected into one system of controlling and monitoring – RVS (Est. Rahva Valgustuse Süsteem, in Engl. Public Lighting System) (Fig. 1) [5].

RVS enables a large number of panels to be involved, switch- offs to be made, many parameters of the system to be kept and stored from the controlling centre.

The functional system is quickly being enlarged. The system consists of:

- hard soft (for controller, monitoring, administration);
- server and data;
- module system of management;
- data exchange with a server is with the help of the Internet and ISDN and GSM.

It is possible to use wireless Bluetooth PDA – tester in order to control and to test outdoor [5].

Other countries, for example, England, China, USA use a similar lighting control system. Each country is trying to find the right solution for economy and the environment.

Another solution for saving energy and city budget was found in small towns across Germany where it was decided to turn off all public lighting at night. The people on the town councils pointer out that if streets are anyway unpopulated at night, why should they pay for the electricity to run the street lights. Yet in light of this (no pun intended), citizens within these towns feel concerned about their safety, whether stumbling through the dark streets to walk the dog or return from a late night out. This particular instance has raised a call for human ingenuity to raise and solve this concern.

In the small town of Döblitz, a German inventor Heinrich Frühauf has responded to that call. By installing a modified mobile telephone in the electrical box controlling the street lamps, citizens can enjoy walking their dogs once again at night. Inspired by falling over things during the evening hours, Frühauf created his mobile telephone invention to allow all citizens of Döblitz to call the particular number so that the lights come on; a timer shuts the lights off again in 15 minutes.
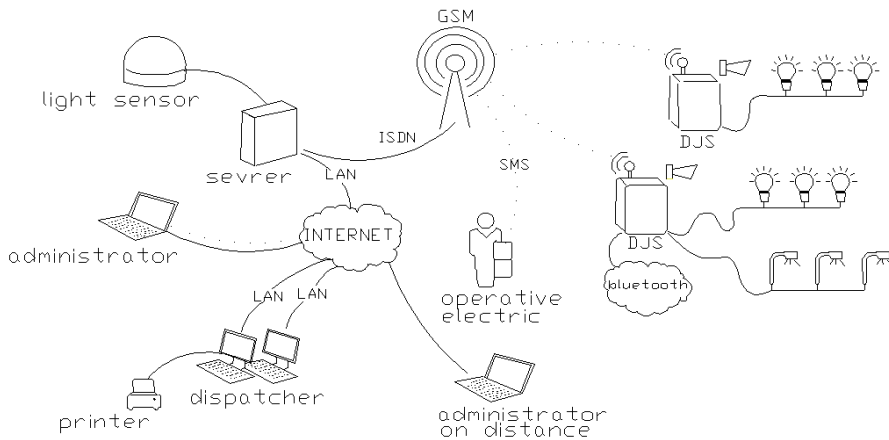
Fig. 1. The components of the RVS system and communication between the RVS and switching panels.

Similarly, a resident in Dörentrup Dieter Grote came up with his own dial-in system. Whilst his system is slightly more complicated than the aforementioned system, it requires the recipient to register with the service and the recipients must enter a 6-digit number to identify the area which they want lit: Users must know the number of the area where they want light – either by looking the numbers up in an on-line database, or finding the numbers posted on the nearby streetlamp, probably a difficult task given that the streetlamps are not yet lit. Although this system may not effectively work in larger populated cities, Starry Night Lights has the following benefit: Motion Sensor lighting. Leaving your lights on from dusk to dawn will not ensure anyone's safety. It will, however, ensure that far too much money is spent on electricity. Motion sensors are an excellent way to have the lights on when needed, and off when there is no need. Lights are much more likely to attract attention if they suddenly come on at 2:00 am [6].
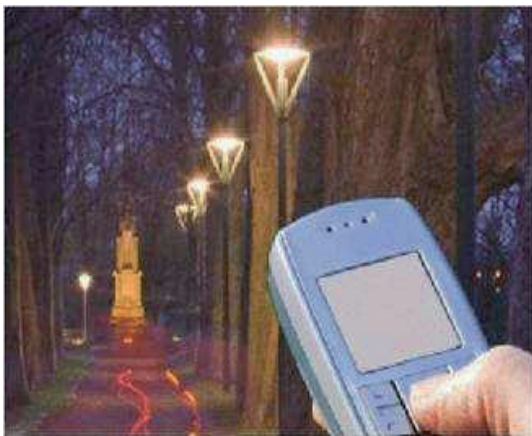

Fig. 2. On Call Street Lights.

Lemgo, a German town situated between Hannover and Dortmund, has been testing a new mobile application in a field trial: By sending a 50-cent premium-SMS a street of houses can be illuminated for 15 minutes. Many communities in Germany turn off their street lighting system from 11 pm to save energy and funds. It's a bad solution for pedestrians at night, but a town like Lemgo saves about 50,000 Euro a year. A Lemgo citizen came up with a brilliant solution which serves both needs: saving funds and lighting the streets for pedestrians late at night: A mobile application. Just send an SMS to the streetlight – respectively to a GSM-modem in the junction box – and the way home is illuminated. The new service is called Dial4Light and the inventor Dieter Grote cooperates with the Lemgo public services to bring the service into the market. The requests for the patent pending technology accumulate. The inventor is thinking of many other areas of application: Emergency services can illuminate the scene. Taxi drivers can switch on the lights for their passengers. Joggers can turn on the floodlight at the sports field in the evening. Whether one premium-SMS is enough for turning on the floodlight stays open. Also it gives possibility to buy car-parking tickets by mobile phone in Lemgo.

D. New More Efficient Technologies

Many cities are upgrading their streetlight technologies to LED lights. LED technology has advanced rapidly, with improved chip designs and materials facilitating the development of brighter and longer-lasting light sources that can be used in a wide spectrum of applications. A growing awareness of the need to reduce energy costs has also made LED lighting increasingly popular.

It is a great, green way to lower energy costs – especially when switching from mercury-vapor or high-pressure sodium lamps. Adding an intelligent network to control those lights is even smarter, allowing for reduction of energy costs by 60 % or more. The extra benefits of this network – streamlined operations, lower maintenance costs, improved safety, less

light pollution, and enhanced urban environments – may end up being even greater than the energy savings [7].

Lighting accounts for nearly 10 % of global CO_2 emissions, more than cars worldwide. We can make a considerable dent in carbon emissions if we make lighting much more energy efficient.

Light-emitting diode lamps, combined with smart controls, can cut CO_2 emissions from 50 to 70 %. LED outdoor lighting also reduces costs, enhances public safety, minimizes light pollution and makes public spaces friendlier at night.

The main barriers to acceptance are skepticism, outdated government policies and cost. We are addressing these barriers head on with a three-part program called LightSavers. The LightSavers program [8], initiated and funded through Toronto AtmosphericFund (TAF), works to stimulate outdoor lighting market transformation for both LED and intelligent lighting system controls. These technologies can reduce power consumption and therefore reduce emissions related to lighting streets, parks, pathways and surface and underground parking areas, among other applications. First, we are conducting a global trial of LED lamps in large world cities to evaluate how newly commercial products actually perform. Next, we will work with these cities to scale up their pilot projects and further enlist our broader membership as early adopters. Finally, we will work with governments to encourage more friendly LED and smart control policies [8].

Smart LED's should not be seen as just a replacement technology for compact fluorescent lamps (CFLs) and incandescent lamps but as a serious disruptive technology. Regular bulbs can only be turned on or off, whereas LEDs can be tuned like a radio. LEDs have novel capabilities that make them extremely useful when going beyond the replacement paradigm. In contrast to conventional light sources, a number of new dimensions are opened up by the unique controllability of LEDs. These include control over the emission spectrum, color temperature, polarization, temporal modulation, hue and spatial emission pattern. These controllable LED sources called smart lighting sources will result in tremendous benefits to society and humankind, including:

• biology and imaging: leapfrog advances in quantitative biology, particularly the rapid identification and counting of biological cells through adaptive and fully tunable reflectance and fluorescence imaging.

• display systems: liquid-crystal-displays and projectors with unprecedented efficiency and brilliancy (huge color gamut) through polarization-controlled lighting sources.

• transportation: enhanced visibility (less glare) and safety through polarization controlled headlights, temporal-controlled communicating headlights / brake lights / traffic lights, and interactive roadways.

• communications: fundamentally new modes of broadcasting, communications, and sensing through temporal control of solid-state-light sources.

• human factors: reduced dependency on sleep-inducing pharmaceuticals, higher productivity, prevention of certain cancers, and higher quality of life.

• agriculture: efficient plant growth in non-native regions (including space) and non-native seasons. Revolutionize indoor agriculture and Urban indoor Vertical Farming or sky farming [9].

The economic benefits for municipalities to invest in LEDs are clear as they save energy, reduce environmental impact and improve the quality of light.

IV. THE LED CITY

The LED City program is an international initiative to promote and deploy energy-efficient LED lighting. The LED City program [10] offers participation in a growing community of cities from around the world that are switching to LED lighting for significant energy and maintenance cost savings. Many program participants see LED lighting as a strategic step toward achieving their goals to reduce carbon dioxide emissions. The first LED City is Tiahjin in China.

A. LED City Advantages

Ten to twenty percent of the world's electricity is used for lighting. Ninety percent of the power used by a light bulb produces heat, not light. LEDs are more than four times more efficient than incandescent bulbs. They are more efficient than compact fluorescents (CFLs), the next most efficient light source available today. CFLs contain 5 milligrams of mercury, making them hazardous waste when they break or burn out.

Glass bulbs with filaments and glass tubes break easily and often. Solid-state technology offers far more durability and much longer life times. LED fixtures can last for 10-25 years, which can significantly reduce maintenance costs and impact on the environment.

LEDs offer the most efficient and environmentally friendly lighting source which contains no mercury or lead.

B. Calculations of Energy Savings by Replacing HPS Street Lamps with LED Street Lamps in Tähesaju street

Energy saving calculation were held on one stretch of a street named Tähesaju in the city of Tallinn (Fig. 3).

The calculation program included different powered HPS lamps used in that stretch of the street and the replacement LED lamps of the Cree Company with their parameters (Table I) [11].
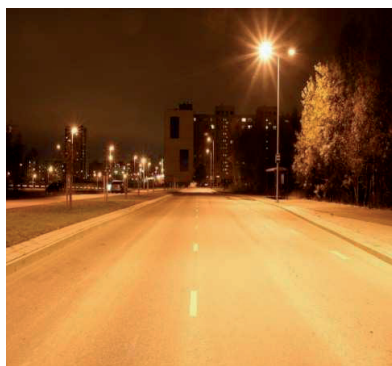

Fig. 3. Tähesaju street.

1. HPS lamps, W	70	100	150	250
2. # of Lamps	62	2	2	46
3. HPS power consumption, W	97	130	185	295
4. Mercury content in HPS bulb, mg	15	15	15	15
5. Replacement LED fixture type, W	20	30	60	90
6. Replacement LED fixture unit cost before tax	350	420	650	980
7. Installation cost per unit	50	50	50	50
9. % wattage reduction	-58	-57	-41	-43
10. LED bulb useful life, hours	106000	106000	89000	80000
11. LED bulb useful life, years	25.9	25.9	21.7	19.5

Common Inputs			Annual Increase	
12. Number of hours in operation per year	4100		NA	
13. Price of Electricity, $/kWh	0.080		3.0 %	
14. Cost to recycle one HPS bulb, $	2		NA	
15. Maximum life assumed for LED (Life limit years)	25			
16. Maximum life assumed for HPS (Life limit years)	5			

17. HPS Material Costs per unit (all $ before tax), W	70	100	150	250
18. Bulb cost, $	10.78	10.77	10.75	12.14
19. Bulb life, hours	24000	24000	24000	24000
20. Bulb replacement shedule, years	5	5	5	5
21. Ballast cost, $	90.92	93.88	95.38	108.2
22. Ballast life, years	20	20	20	20
23. Fixture cost, $	78	140.72	189.44	214.1
24. Fixture life, years	50	50	50	50
25. Photocell cost, $	8.42	8.42	8.42	8.2
26. Photocell life, years	15	15	15	15

The results show that replacement of HPS lamps for LEDs will save the cost from switching by $358.375. Lifetime cost for LEDs will be $708.402, cumulative savings will amount to $538.452. Thus, the cost savings will be $169.950. All calculations and results were made on calculation program which is presented by company LEDCity. Chart on the Fig. 4 shows clearly that originally the cost of replacement bulbs will begin to pay back with the first year and after the fifth year income start to grow.

Even a simple calculation of economic benefits (Table II) based on amount of consumed energy and its annual cost, it is clear that it is profitable to substitute HPS for LED lamps. The economic benefits for municipalities to invest in LEDs are clearly as they save energy, reduce environmental impact and improve the quality of light.

TABLE II
CALCULATIONS OF SAVINGS BY REPLACING HPS STREET LAMPS WITH LED LAMPS

HPS, W	70	100	150	250
LED, W	20	30	60	90
Amount	62	2	2	46
price for 1 kW/h, eek	0.474	0.474	0.474	0.474
Hours in year	4077	4077	4077	4077
HPS cost for energy, eek	8387.04	386.50	579.75	22223.75
LED cost for energy, eek	2396.30	115.95	231.90	8000.55
Difference between costs for energy, eek	5990.75	270.55	347.85	14223.20

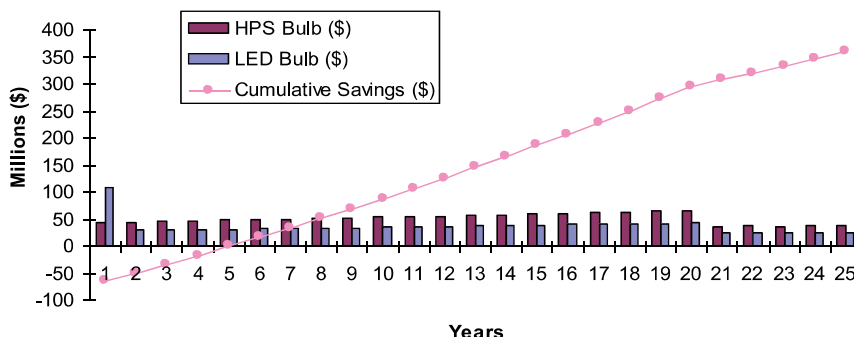## Break-Even Analysis of LED Streetlighting Replacemnet

Fig. 4. Payback chart.

V. CONCLUSION

More than half of world's population lives in cities. The number is increasing year after year and so is the demand for power. It is obvious that the demand for electricity in the world will grow. Worldwide the price of electricity has increased drastically over the last years. It will be very hard to use electricity in a right, effective, and safe way. One opportunity to address the demand side of this issue is to save electricity by finding and implementing intelligent, smart lighting technology to municipal street lighting.

Today's trend is look for intelligent, smart solutions for street lighting. The main features of a street lighting system are being considered to find an optimized solution. This paper has presented the part of smart solutions for street lighting. The effectiveness in one proposed solution for street lighting was examined, and the results was verified via energy saving calculation. Based on these results, clearly winning LEDs. But in favor of energy conservation should not forget about their drawbacks, such as lower high luminous efficacy, lower flux with time of their use. All these points will be controlled by measurements by special equipments.

In May Tallinn municipalities started the pilot project. The purpose of this project is determine a suitable replacement for LED fixture on a Pelguranna street. The future development will be connected with analyzing and identifying the best solution for street lighting in Tallinn.

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[10] [Online]. Available: http://www.ledcity.com/.
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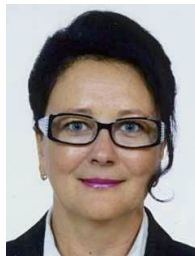
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The author's contributions are: processing the measured data, preparing the diagrams, drawing conclusions.

Comparative Study of Smart Lighting Grids with LEDs Operated with Concentrated, Localized or Distributed Control

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Abstract—Smart lighting grids, consisted of smart luminaries with capability to communicate with each other, have great potential to reduce power consumption in the sphere of artificial illumination. This paper provides comparative study of concentrated, localized or distributed control approaches of smart lighting grids and summarizes mentioned approaches by comparing safety, functionality and expandability factors. Afterwards the illumination diagrams are drawn with mathematically and experimentally acquired data for each of the proposed control methods, energy consumption by each of approaches is calculated and discussed.

Index Terms -- centralized control, distributed control, intellectual lighting, lighting grids

I. INTRODUCTION

Lighting systems not only consume significant part of electrical energy produced worldwide [1], but also have significant impact on the quality of human life, as well as influence on various production processes (starting from agriculture and ending with the high-tech). That is why any improvement of lighting equipment leads to reduction of its energy consumption and to its new functionality. Two directions of this improvement are possible: 1) use of more efficient lighting technologies; 2) use of intelligent control lighting solutions. Implementation of Light Emitting Diodes (LEDs) gives the opportunity to implement both methods.

LED technology can be characterized, first of all, by rather small power and voltage of light sources (LEDs – see [2] for example). At the same time LEDs are easy dimmable and the dimming does not have any negative impact on them. Altogether this makes possible the development of very flexible lighting systems with a big number of small lighting sources that are activated when and where their light is required. Besides such LEDs systems also includes a set of sensors that detects the object to be enlightened and its position, as well as a control system that provides a smart link between sensors and LEDs.

This research compares different configuration of the control system and sensor's network in the context of providing of the necessary lighting level, as well as in the context of better energy efficiency.

II. STATE OF THE ART IN THE FIELD OF SMART LIGHTING

Smart lighting is a lighting technology designed for energy efficiency and higher functionality. It includes high efficiency fixtures that can be controlled, illuminance sensors, microprocessors and electric meter connected to network [3]. Lighting control systems that are currently available on market vary from simple wall switches to complex microprocessor-based dimming systems that are often networked with other building automation systems. Smart lighting systems can offer features such as light harvesting, optimized lighting levels, dynamic lighting output based on sensors, and dynamic or on-demand color shifting. Smart light fixtures can communicate impending failures that help to reduce maintenance costs. This makes it possible for each individual lighting fixture to operate autonomously [4]. Based on the illuminance information that flows through the network, individual control devices apply to optimal algorithm and exert control autonomously, facilitating the optimum lighting pattern. Some existing lighting control systems have been compared in Table I (see also [5]).

III. REVIEW OF CONTROL APPROACHES

There are many approaches that may be applied to development of control for intellectual lighting grids. The corresponding control systems, however, can be divided into three significant groups: 1) with centralized control functions; 2) with localized and 3) distributed. These systems can be estimated from the point of view of amount and complicity of their control, data acquisition and diagnostic functions (functionality), safety, as well as possibility to expand them (expandability). These criteria are more or less equally significant for the estimation of the system.

With the centralized approach (Fig. 1-a), data acquisition and control functions are concentrated in one unit that acquires information from sensors, makes decision and drives sources of light. Since all control functions are located in one unit, its fault leads to a global malfunction of the entire lighting grid too. This system is also not friendly for further expansion. At the same time, with this approach more productive control unit allows realization of more sophisticated control functions as well as better communication with higher level control equipment. In this case matrix of sensors can be arbitrary configured and may not correspond to the matrix of light sources.

| Feature	Pyxos	CAN	AS-I	DALI	RS-485
Includes Protocol	+	-	+	+	-
Self-organizing Network	+	-	-	-	-
Deterministic Operation	+	-	+	+	-
High-speed Signaling	+ (312,5 kbps)	+ (up to 1 Mbps)	+ (167 kbps)	- (1,2 kbps)	+
Direct Digital I/O without a Microcontroller	+	-	+	-	-
Maximum Network Size	32	~100 in short-distance buses	31 or 64 (with reduced I/Os)	64 nodes or 250 mA system current	Variable
Free Topology Wiring	+	-	+	+	-
High Common Mode Noise Immunity	+	-	+	-	Variable
Polarity-insensitive	+	-	-	+	-
Power and Data on Same Wires (Link Power)	+ (up to 100mA per node)	-	+ (~30 mA per node)	+ (Limited to 2 mA per node)	-
18-bit CRC	+	+	-	-	N/A
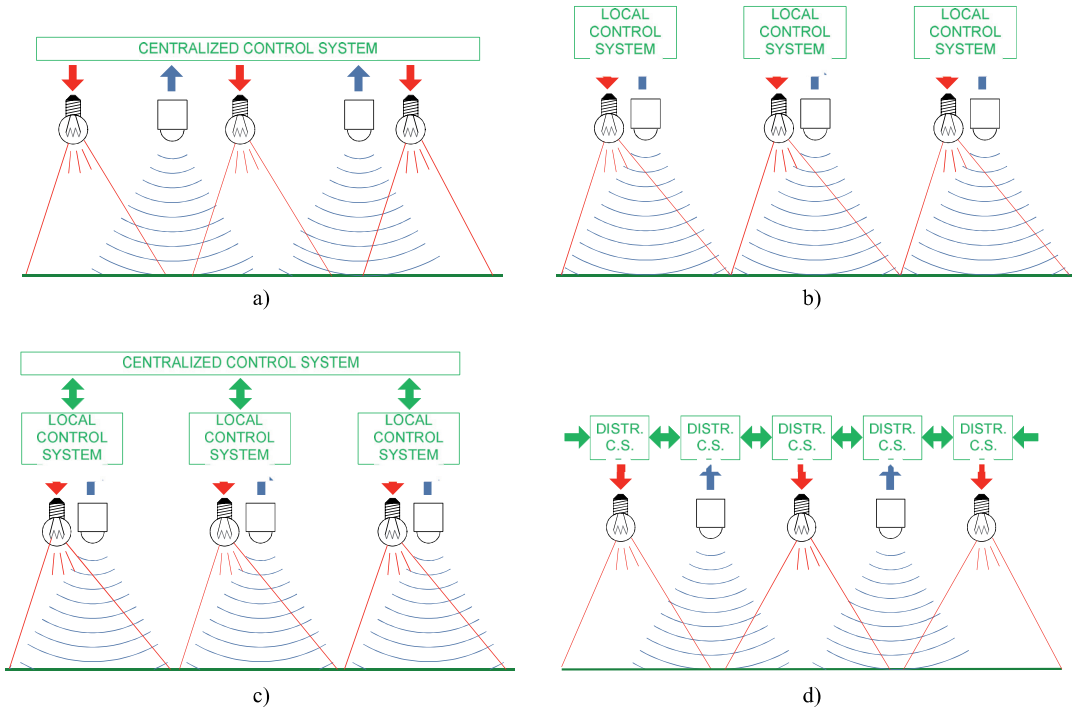
Fig. 1. Potential Configurations of Smart Lighting Grid: a) Centralized; b) Localized; c) Localized with Central Supervision; d) Distributed

The next approach assumes that data gathering and control functions for a local part of the object are concentrated in the part and communicates only with dedicated sensors and sources of light (Fig. 1-b). For this reason, each light source is associated with its own set of sensors that globally leads to correspondence of sensor matrix and matrix of light sources. In this case control units are simpler and control functions are also limited, but at the same time faults are critical only for the corresponding part of the object. It is quite obvious, that with this approach lighting grid can be easily expanded. Control functionality of such system can be improved through applying of a supervisory unit (Fig. 1-c) of higher level (of course, at the cost of lower expandability). This configuration can be regarded as a safer version of the centralized control system.

The approach proposed in this paper assumes that the control functions for a local part of the object are distributed between the given part and closer or further neighbor parts of the object (Fig. 1-d). Then the system is equally expandable and safe. The functionality in this case depends on the data throughput of the communication between the distributed control parts, as well as their own productivity, and may be high. In this case sensor matrix and matrix of light sources may not correspond.

The above described approaches to localization of control functions of a smart lighting grid are roughly summarized in Table II. In this table correspondence of the parameter and approach is given as a numerical mark (the higher the better). Marks for safety, functionality and expandability are equally weighted. The total mark is calculated after all. As it can be seen, the distributed localization of control functions looks prospective

because it provides good safety and expandability with only slightly reduced functionality.

TABLE II. COMPARISON OF CONTROL AND DATA ACQUISITION SYSTEMS FOR SMART LIGHTING GRIDS (ESTIMATED WITH A MARK FROM 0 TO 3)

	Safe-ty	Func-tionality	Expan-dability	Total Mark
Centralized	1	3	1	5
Localized	3	1	3	7
Localized with supervision	2	3	1	6
Distributed	3	2	3	8

IV. PHYSICAL MODEL OF SMART LIGHTING GRID

In order to practically verify and compare the above described and proposed approaches of control functions localization, a physical model of smart lighting grid has been developed. The model consists of 9 lighting nodes placed in-line with a constant step of 1 m and at 1 m height in a dark room with dark surfaces (for fewer impact of the ambient lighting and reflections). An object (mobile robot with an IR diode) is moving across the internal 5 LEDs with a constant speed 0.5m/s. The desired illuminance within this track is 30lx. The node (Fig. 2-b) consists of a 3W LED lamp, its driver (buck DC/DC converter), IR occupancy detector, control and communication board eZ430-RF2500, as well as primary power supply. The control and communication module in turn contains an MSP430F2274 MCU, and a CC2500 RF wireless communication module. The lamp at full power provides illuminance of about 60lx in the dark room from a distance 1m.
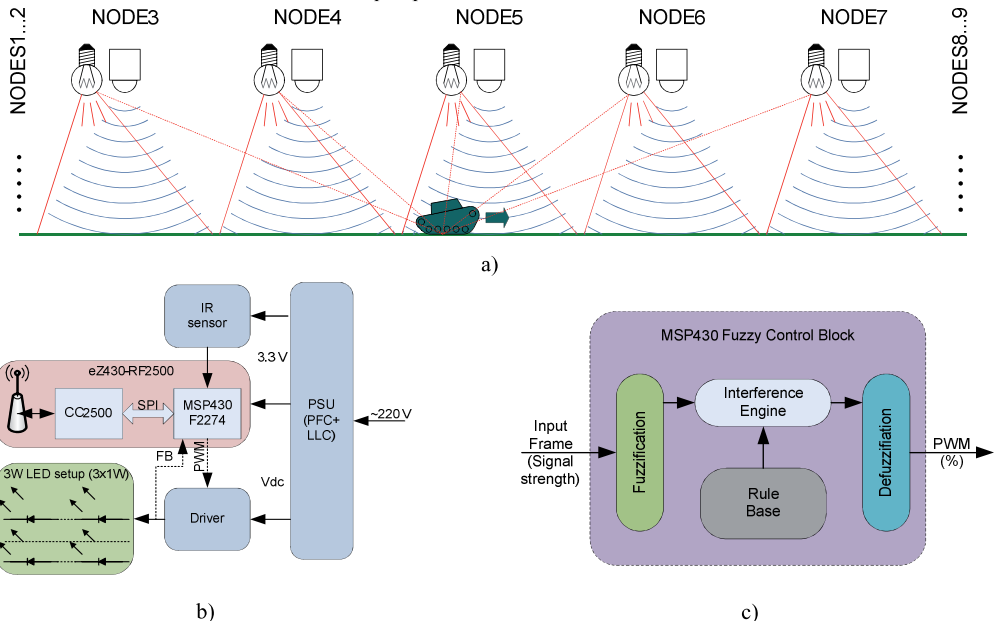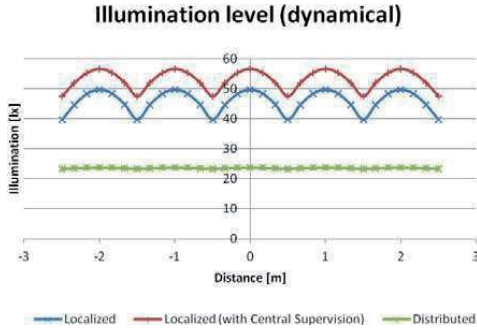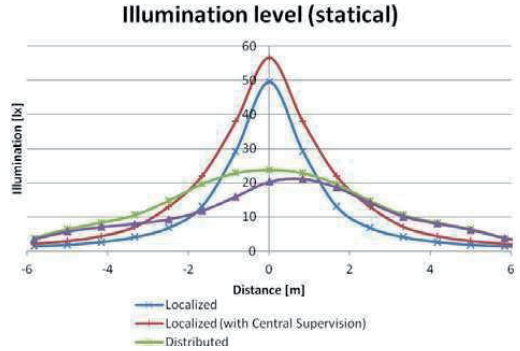

Fig. 2. Configuration of Physical Model of Smart Lighting Grid: a) Generalized Configuration; b) Diagram of the node; c) Software Configured for Distributed Control

TABLE III. LUMINARIE'S LUMINOUS OUTPUT AT CERTAIN DISTANCE FOR DIFFERENT CONTROL APPROACHES

Method / Distance [m]	Localized	Localized (with Central Supervision)	Distributed	Distributed (with Direction detection)
-2	0%	10%	15%	5%
-1	0%	10%	20%	10%
0	100%	100%	20%	20%
1	0%	10%	20%	20%
2	0%	10%	15%	15%

a)   b)

Fig. 3. Path illumination by distance in two views: a) dynamical, showing path illumination level in certain coordinates of moving object and b) static, showing path illumination at certain distance from moving object

The node can be programmed as separated light source and occupancy sensor with their own communication channels that is useful in case of centralized and distributed control function. At the same time in case of localized control functions the node can be programmed as set of sensor, light source and their control.

In case of distributed control functions the node is configured as simple fuzzy controller that indirectly, based on the occupancy sensor activation in the neighbor nodes, estimates the distance to the object and drives the corresponding LEDs.

V. ANALYTICAL AND EXPERIMENTAL ESTIMATION OF CONTROL APPROACHES

A. Calculation of parameters

Different control approaches were evaluated taking into account its functionality, by choosing appropriate illumination level for each lamp. The luminous output of each LED luminary was taken accordingly to the fallowing table (see Table III), for which data was previously calculated.

These parameters were taken in calculations of theoretical illumination level for different control approaches. Corresponding data is shown in diagram below (see Fig. 3).

B. Description of the experiments

The experiments were conducted with small scale of hallway model, where 5 LED luminaries were located with 1 m distance on 1 m height. The LED module was controlled by means of eZ430-RF2500 development tool, which allows controlling the LED driver and communicating with other nodes by means of available radio transceiver on board.

C. Review of experimental results

Experimental results revealed advantages and disadvantages of various control approaches. Firstly, consumed energy is maximal under localized with central supervision control approach (see Table I, Table IV), due one lamp with 100% luminous flux and four others with 10% output, as a result it causes illumination level above normal.

Another disadvantage of first two control approaches is that quality of the illuminated path is not applicable (see Fig. 3 and Fig. 4), because mentioned control approaches deal with local illumination and do not control uniform illumination level. From this perspective, distributed light control approach is more advantageous, due to evenly illuminated surface; on the other hand, energy consumption of the lamps is slightly less than with localized approach.

TABLE IV. COMPARISON OF ENERGY CONSUMPTION BY DIFFERENT
CONTROL APPROACHES, DURING THE TIME WHEN MOVING OBJECT
PASSES ONE CONTROLLABLE ZONE [J]

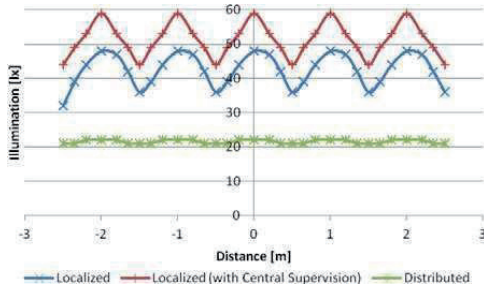| Localized	Localized (with Central Supervision)	Distributed	Distributed (with Direction detection)
6.9	9.7	8.3	6.9

Fig. 4. Experimental data of illumination level for different control
approaches.

The obtained results confirm the proposal given in
Table II that the distributed configuration of control
system provides as good lighting parameters (necessary
level and flattened pattern) as centralized and is also
energy efficient. The pattern or lighting may be even
more flat, but efficiency − higher at more accurate
position detection. This, first of all, requires separate
sensor network with bigger number of sensors or/and
their higher accuracy. These parameters may be even
more improved if not only location but also speed and
direction are detected (this, however, is a subject of
specific research).

VI. CHOICE OF EQUIPMENT AND FUTURE PLANS

From the above mentioned calculations and
experiments is seen that smart lighting networks with
distributed control may be as functional as with
centralized control providing, at the same time, higher
safety. However, elaboration and development of the
smart lighting grids requires additional investigations in
the following fields:

• Power configuration of the smart lighting grids. This
topic first of all includes the choice of optimal
relationship between the number, power and
placement of light sources in the grid providing
reasonably equalized illuminance. Then the
configuration of power supply (AC or DC, voltage or
current source, value of the source) has to be chosen.
Primary power supply for the grid (if necessary) has
to be chosen, designed and optimized at the final
stage (in particular, parameters on the electricity grid
side are very important [6]);

• Elaboration and development of lighting grid's nodes.
This part includes choice of number, power and
configuration of node's LEDs, choice of light
regulation mode, design of their driver and control
unit. This part of work may also include choice and
implementation of sensors in the node (if the sensors
are included);

• Elaboration and development of sensor grid's nodes
includes choice of number, type and configuration of
sensors, design of their communication unit;

• Choice of wired or wireless communication between
grid elements (light source, sensor and combined
nodes). Choice or development of data exchange
protocol;

• Elaboration and optimization of control algorithms for
separate grid nodes (light source, sensor and
combined) and their combinations.

VII. SUMMARY AND CONCLUSIONS

In the beginning of this report existing control
solutions for smart lighting grids have been briefly
reviewed and possible configurations of control systems
have been analyzed. An improved configuration with
distributed control function has also been presented. In
the following sections these configurations have been
analyzed and compared from the point of view of lighting
parameters (level of illuminance and its pattern), as well
as energy efficiency. It is proved (through calculations
and experiments) that the proposed principle of
distributed control approach is more prospective.

Therefore, it is reasonable to continue experimenting
with this kind of smart lighting grids. In the paper
possible directions of elaboration and development of the
distributed control system for the smart lighting grids has
also been outlined. Future works will be mainly focused
on power configuration, lighting/sensor/combined node
development, communications and protocols, as well as
elaboration of advanced control methods in the context of
the proposed principle of distributed control.

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Design of Laboratory Equipment for Investigation of Regulators for LED Luminary

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Abstract – **The main purpose of this work is to chose and design flexible laboratory testbench for investigation of various light regulators with LED elements. The achievement of this aim assumes detailed analysis of configurations of LED luminaries and their elements. In the paper various LED dimmers are studied and suitable configuration of the testbench is proposed. Particular schematic solutions of luminary composing modules are presented.**

I. REVIEW OF ADVANTAGES AND DRAWBACKS OF LED TECHNOLOGY

Nowadays problem of efficient energy consumption is very topical. Artificial lighting is one of the most energy consuming areas in the world [1]. Therefore, increasing energy efficiency of lighting systems is very important and could give significant energy savings. The reduction of energy consumption can be achieved by two strategies: use of next generation lighting technologies or use of intelligent lighting control solutions.

Implementation of LED luminaries gives the opportunity to implement both methods. As a rather new technology, LEDs provide higher efficacy [2], better quality of light and are ecologically friendly. The life time of LEDs is significantly longer if compared to traditional lighting sources. They also do not emit IR-radiation and it is possible to use them in IR critical environments. Furthermore, the dimming of LEDs does not have negative impact on them.

The main disadvantage of LEDs is that they are currently more expensive than conventional lighting technologies. Other disadvantage of LEDs is their high heat sensitivity and need for a cooling system. LEDs are also low voltage elements and for this reason they require a special power sources (electronic ballasts), which makes lighting system more expensive.

Main characteristics of various types of lighting technologies are presented in the Table I: Incandescent (Ind), Halogen (Hlg), Fluorescent (FL), Mercury-vapor (MV), Metal halide lamp (MH), High pressure sodium lamp (HPS), Light Emitted Diode (LED). The table shows that some types of lamps have a limited range of regulation (fluorescent lamp), others are negatively affected by regulation (it influences their color and decrease their life time). The main parameter is energy efficacy. LEDs have the biggest value of efficacy today which is still increasing [3].

TABLE I
COMPARISON OF DIFFERENT TYPES OF LIGHT SOURCES

Lamp	Efficacy [Lm/W]	Life time [t. hours]	CRI	Dimming [%]	Influence of dimming	Start up time
Ind	8-17	1	100	100	+: life time increases	0 s
Hlg	12-18	2-2,5	100	100	-: life time shorten	0 s
FL	50-70	10-12,5	80	10	Neutral	1-5s
MV	25-40	14-20	80	50	-: life time shorten, color change	5-7 min
MH	70-100	3,5-20	65-90	50	-: life time shorten, color change	2-5 min
HPS	100-120	8-12	30	80	+: life time increases	5-10 min
LED	120-140	50-100	70-90	100	+: efficiency increases, life time increases	0 s

II. LIGHT REGULATION TECHNIQUES OF LEDs

LEDs are semiconductor devices that cannot be directly connected to AC network. For this reason different types of DC converters are used to supply LED matrix. There are three main methods of regulation of light intensity of LEDs: regulation of LED's current, pulse width modulation of LED's current, step regulation commutating LED groups.

A. Smooth Regulation of LED Current and Luminous Flux

Smooth regulation of luminous flux by current regulation is a method when the value of luminous flux can be of any value between maximum and zero. This method has two significant disadvantages. Firstly, the LED brightness is not completely proportional to current. Secondly, not only luminous flux but also the wave length and therefore color of light are different at different values of LED current.

B. Pulse Mode Regulation of LED current and Luminous Flux

With pulse regulation method the value of luminous flux can be either the maximum value or zero. The average brightness of LEDs depends on the ratio of on-time to the switching period of LED. In this case the LED brightness can

be adjusted by the most common method – pulse width modulation (PWM). However, this method provides pulse pattern of instantaneous luminous flux. When the frequency of modulation is low, the pulsating character of light becomes visible to human eye. When the frequency is high a stroboscopic effect may appear [4] and [5].

C. Step Regulation of Luminous Flux Commutating LEDs groups

With this method luminous flux changes stepwise over a range of fixed values between maximum and zero. Dividing LEDs in groups gives an opportunity to regulate brightness with a certain constant step.

III. PREMILINARY COMPARISON OF LIGHT REGULATION METHODS

As it has been mentioned above, LEDs are low voltage devices. They need a special low voltage energy source that can be designed as current source or voltage source. The comparison of regulation methods for both energy sources is presented in Table II.

TABLE II

COMPARISON OF DIFFERENT METHODS OF REGULATION

Method	Type of power source	Advantages	Disadvantages
Smooth regulation	Current	• One source	• Current source should be regulated
	Voltage	• One source	• Voltage source should be regulated • narrow practical voltage range
Pulse regulation	Current	• One unregulated source	• Current source, switch is needed
	Voltage	• One unregulated source	• Switch is needed
Group regulation	Current	• One source	• Current source, should be "n" number of switches
	Voltage	• Voltage sources for each group of LEDs	• should be "n" number of switches

For smooth regulation of luminous flux by current one source is needed, but this source should be regulated. If it is a current source, it will have a complicated construction. If the voltage source is used, the span of practical voltage values is rather narrow.

The advantage of pulse regulator is that it needs one unregulated power source. The only disadvantage from the construction point of view is that a switch for connection of power source and LEDs matrix is needed. Most often this is a MOSFET or bipolar transistor.

Regulation of LED groups powered from current source assumes series connection of groups and short circuiting of unnecessary LEDs groups by the corresponding switch. When the switch is off, the group of LEDs lit, thereby adjusting overall brightness. LEDs group regulation with

voltage source assumes using as many voltage sources as there are groups of LEDs. In this case the size of device becomes bigger because of a big amount of power sources and switches.

Pulse regulation seems to be the most simple and useful method but it is necessary to take into account its disadvantages which are related to pulsating character of luminous flux (flickering, stroboscope effect). Smooth regulation and group regulation methods should be investigated more carefully. Preliminary comparison shows that both these methods have advantages and drawbacks.

IV. DEVELOPMENT OF LABORATORY PROTOTYPE OF LED LUMINARY

Development of testbench consists of several tasks. First, power of LED matrix and its configuration should be chosen. Second, the overall structure of luminary should be selected. Third, parts of the selected structure have to be chosen.

A. Selection of Power and Configuration of LED Matrix

The number and configuration of LEDs have been chosen taking into account the following considerations. Firstly, the group method of light regulation requires sufficient number of LEDs. If the minimal step of light changes is about 5% (reasonable minimum for some street lighting applications) then the number of LEDs must be about 20. Secondly, available armature for the luminary is not very big and cannot dissipate power more than 20W. Thirdly, available LEDs are of 1W power. Taking into account possible hexagonal placement of LEDs the final configuration is 19 1W LEDs. The total power of such matrix is about 20W.

The placement of LEDs in the matrix must ensure symmetrical distribution of active LEDs when some of them are off. Fig. 1 shows two possible configurations of the matrix. The first one (Fig. 1-a) presents a full three level hexagonal placement of 19 LEDs intended for binary weighted groups (1, 2, 4, 8 and 4). Another configuration (Fig. 1-b) is aligned for equal groups of 2, 3, 6 or 9 (the fig. shows 6 groups of three LEDs).
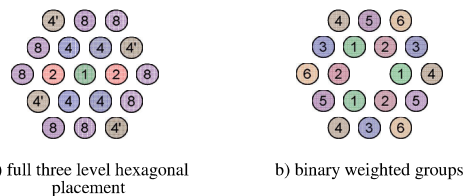

a) full three level hexagonal placement   b) binary weighted groups

Fig. 1. Physical placement of LEDs in matrix.

B. Selection of Overall Structure of LED Luminary

First step in designing the laboratory prototype is selection of its overall configuration: monolithic or composite (composed of different blocks). The comparison of model types is presented in Table III.

TABLE III

COMPARISON OF MODEL TYPES

Type of model	advantages	disadvantages
Monolithic	• Gathered scheme • ready to use • high efficiency	• Poor possibility to research regulators
Composite	• Possibility to change regulators for different experiments	• Lower efficiency • more complex construction • big size

TABLE IV

COMPARISON OF TYPES OF SOURCES

Type of source	advantages	disadvantages
Current source	• Provides direct regulation of current and direct light control • wide range of regulation parameter (duty cycle)	• Complicated construction • potentially high losses
Voltage source	• Simple construction	• Indirect light control (through VA curve) • narrow range of regulation parameter

TABLE V

COMPARISON OF TOPOLOGIES OF SWITCH MODE REGULATORS

Topology	advantages	disadvantages
Buck	• High efficiency • small losses • Simple schematic	• Switch is not connected to the ground (hard to control)
Boost	• Switch is connected to the ground (easy to control) • easy to measure output voltage and current of LEDs • Simple schematic	• The efficiency is lower (due to diode conduction losses)
Buck-boost	• Simple schematic • possibility to increase and reduce the input voltage	• Switch is not connected to the ground (hard to control such switch). • Negative polarity of the output voltage • Narrow regulation range
Cuk	• Possibility to increase and reduce the input voltage capacitive • decoupling inductors are on the input and output (minimal current ripple)	• Switch is not connected to the ground (hard to control) • Negative polarity of the output voltage • More complicated schematic • Narrow regulation range
SEPIC	• Possibility to increase and reduce the input voltage • Output voltage is the same polarity as the input voltage • input and output of the converter are decupled through the capacitor	• More complicated schematic • Narrow regulation range

The composite model has been chosen, because further research will be held on LEDs and their characteristics at the different methods of regulation. It consists of primary power supply, secondary regulator and the LED matrix. Such structure gives opportunity to investigate different regulators with different configuration of the LED matrix.

As it has been mentioned above LED are low voltage devices and they need a special power supply that can be built as a current source or voltage source. Investigation of these regulators is question of further research however some regulator has to be chosen initially (Table IV).

It is advantageous to supply LEDs from current sources, but nowadays most of available regulators operate as voltage sources. In order to convert a voltage regulator to a current regulator, it is necessary to modify the scheme. A voltage regulator has been chosen at the initial stage of testing of the laboratory prototype, but in further research work regulators of other types will be investigated.

There are several well known topologies of switch mode regulators such as buck, boost, buck-boost [6], SEPIC, Cuk [7] and flyback. The comparison of this topologies is presented in the table V.

Due to simple construction, lower losses and good compatibility with other regulation methods (nominal voltage is needed also for PWM light regulation) it has been decided to build the regulator (for smooth regulation of luminous flux) based on the buck topology.

C. Design of Primary Power Source

It is necessary to determine main parameters of the primary supply before designing it. Input voltage of this supply is AC grid voltage 220V. Since the buck converter has been chosen as the secondary regulator, the output voltage of AC (primary) power source should be 70V (19 series connected 1W LED – in the rated point of operation). Assuming the worst case efficiency of secondary regulator (90%) and primary power supply (90%) the power of supply is 20/(0.9*0.9)=25W. LEDs in the matrix are connected in series, therefore the current of the primary AC source is equal to the rated LED current 280mA (for 1W device). Modern equipment should consume a sinusoidal current. Primary power source with diode bridge and output capacitor does not satisfy this requirement. Therefore a PFC has to be included into the schematic. Power line and LED part should have galvanic isolation for safe use of AC power source. For this reason a flyback topology equipped with a power corrector has been chosen.

D. Overview of Luminous Flux Regulators

Pulse Mode Luminous Flux Regulators

Pulse regulators can be divided into two groups: voltage regulators (Fig.2-a) and current regulators (Fig.2-b). In voltage regulator a controllable switch (MOSFET) is connected in series with LEDs. This configuration is a simplified voltage buck converter with PWM regulation

utilizing the switch. In current regulator the switch is connected in parallel with LEDs and shorts them.
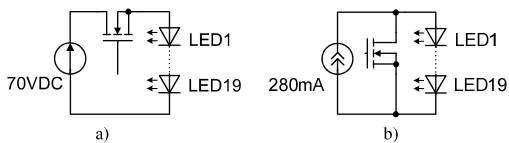

Fig. 2. Schemes of pulse regulators: a) voltage regulator; b) current regulator.

LED Groups Luminous Flux Regulators

Regulators for commutation devices also can be divided to voltage and current regulators. In Fig. 3a and 3b commutation of LED groups is shown. In Fig. 3-a the groups are equal while in Fig. 3-b they are different. In the first case (pic.3a) all groups get power from one regulator 70V to 3*3,6V=11V.
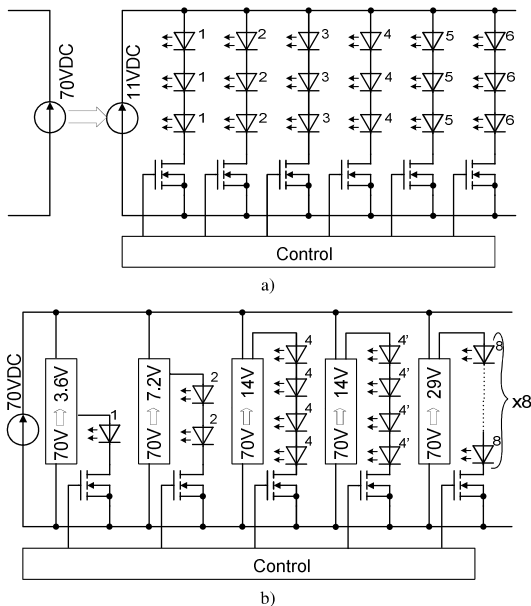
Fig. 3.Commutation of LEDs in groups (voltage sourced):a) groups with the same number of LEDs, b) groups with different number of LEDs.

Regulation of the overall luminous flux is done through separate powering of each group by switches which are driven by the control system. In the case when there are different numbers of LEDs in groups each group gets power from its own voltage source, with voltage level equal to the rated voltage of one LED voltage multiplied by the number of LEDs in the group (1*3.6V, 2*3.6V, 4*3.6V and 8*3.6V).
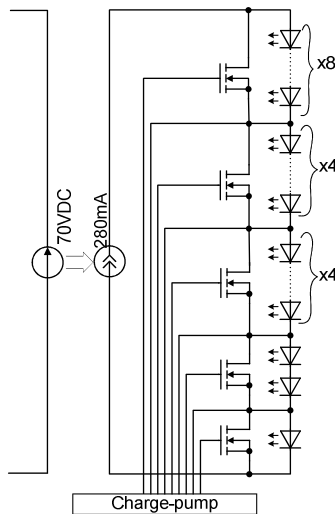

Fig. 4.Commutation of LEDs in groups (current sourced).

The commutation regulator with a current source on its input is given in Fig.4. The current source is the same for all groups, but each group has its own short-circuiting switch.

E. Design of simplified voltage sourced smooth luminous flux regulator

The design of a simplified regulator is based on already chosen parameters: designed AC input source and buck topology. Base schematic of the buck converter is shown in Fig. 5. It consists of two semiconductor elements. One of them is controllable MOSFET while the second one is non-controllable diode. Classic topology of the buck converter also has one inductance and one capacitor. Such regulator is not perfect for laboratory prototype, because the source of the transistor is not of the same as ground potential as input and output voltages. Input source, current sensor and transistor's driver should be tied to one ground. For this reason the basic buck converter schematic has been rebuilt. Controllable switch is now placed so that its control signal is referred to the same ground as the supply of regulator. The sensor is still placed in the output branch, however, since it is a Hall sensor its output part is isolated and can be placed in a suitable place.
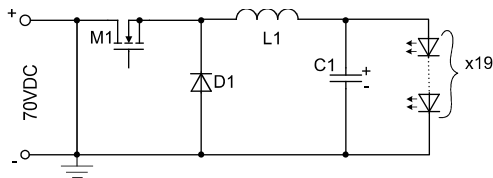
a) Basic topology of buck converter
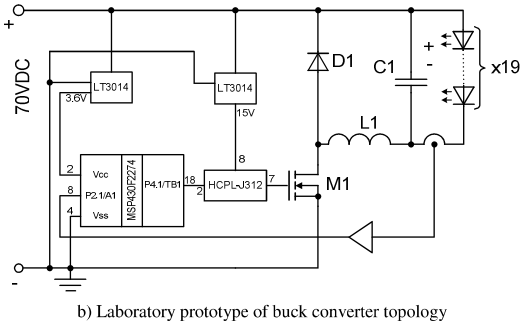
b) Laboratory prototype of buck converter topology

Fig. 5. Schemes of buck converter for controlling luminous flux.

Subsequently the parameters of elements have been calculated and the elements have been chosen. Rated voltage of 19 1W LEDs is 70V (input voltage), but the current is 280mA. Accordingly, the choice of the MOSFET and the diode is based on these values.

The power MOSFET is chosen based on maximum stress voltage and RMS MOSFET current. The peak voltage for MOSFET is equal to the maximum input voltage in buck converter 70V. Applying a 40% safety margin, the following value of voltage is obtained (1):

$$V_{FET} = 1.4 \cdot 70V = 98V \tag{1}$$

The RMS current through the MOSFET depends on the maximum duty cycle. Applying a doubled safety margin to current through the MOSFET (that in the worst case is equal to 280mA) leads to RMS value of 500-600mA. For the laboratory model a nearest suitable device is a ZXMN10A08E6 rated at 100V and 1,9A.

The power diode D1 is chosen based on its maximal stress voltage and maximal RMS current. The peak voltage rating of the diode is the same as the MOSFET $V_{diode}=V_{FET}=100V$. The average and RMS current through the diode are found based on the output voltage equation (Vo =Vd*D), literalized LED equation and reverse duty cycle ratio for diode current pattern (1-D). In the worst case it is 245mA. A Schottky diode STPS1H100U (V=100V, I$_f$=1A) has been chosen.

Passive components – current smoothing inductor L_{SM} and output capacitor C_{OUT} have been chosen taking into account voltage and current ripples. The inductor LSM can be computed at the rectified value of the nominal input voltage as (2):

$$L_{SM} > (V_{in\,max} - V_{out}) \cdot \frac{V_{out}}{V_{in\,max}} \cdot \frac{1}{f_{sw}} \cdot \frac{1}{\Delta I} =$$
$$= \frac{(70-56) \cdot 56 \cdot 1 \cdot 1}{70 \cdot 12.5 \cdot 0.1 \cdot 0.28} = \frac{784}{24.5} \approx 32\mu H \tag{2}$$

The peak current of the inductor is 280mA plus ripple (3):

$$I_{L_{SM}} = 0.28 \cdot 1.15 = 0.32mA \cdot \tag{3}$$

The output capacitor C_{OUT} is required for suppression of voltage ripples which occurs in buck converter. It has been chosen to keep the changes of the output current ILED below 5% of its maximum (0,014A), within all switching period. The required capacitance can be computed as (4):

$$C_{OUT} > \frac{I_{C\,max} \cdot \Delta t_{max}}{\Delta V_{min}} = \frac{I_{LED} \cdot T}{0.014} =$$
$$= \frac{0.28 \cdot 12.5}{0.014} \approx 250\mu F \tag{4}$$

The capacitor C_{OUT} should be located close to the inductor LSM and MOSFET switch M1, to keep stray inductance of the commutation loop as low as possible, but switching frequency - high.

D. Control core of the proposed luminous flux regulator

Buck converter which was described above must have some control device performing measurements, processing data and generating PWM signal for the MOSFET. A microcontroller can perform these functions. For laboratory prototype an MSP430 microcontroller has been chosen. The particular control core is based on MSP430F2274 (Fig. 6). This microcontroller consumes extremely low power. The device features a powerful 16-bit RISC CPU, 16-bit registers, two built-in timers, a universal serial communication interface, 10-bit A/D converter with integrated reference and data transfer controller (DTC).

Analogue measurements are provided by internal analogue to digital converter (ADC10). Current signal (taken from a sensor) is connected analogue input A0 (P2.0). Control pulses may be generated by the internal timer of MSP430 (Timer B). The generated control signal is passed through a driver HCPL-3120. DA1 is a high voltage, micro-power low dropout linear regulator, that provides 15V to the MOSFET switch and DA3 is used to supply MCU with 3V.

V. ASSESSMENT OF WORK AND FURTHER TASKS FOR FUTURE

The use of high power LEDs in lighting applications is becoming increasingly popular due to rapid improvements in lighting efficiency, longer life and higher reliability. Dimming functions are more easily implemented in LEDs, and they are more robust and offer wider design flexibility compared to other light sources.
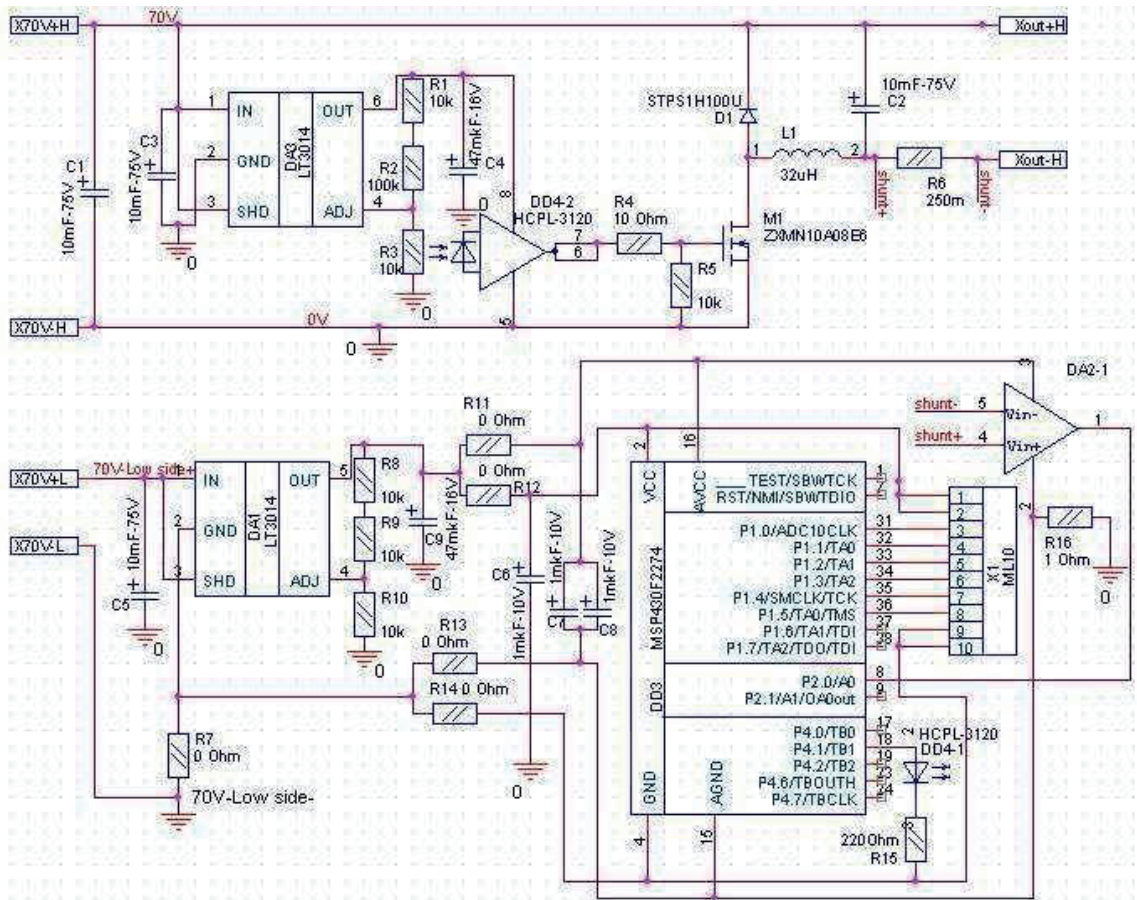
Fig..6 . Laboratory prototype of buck converter.

Various LED drivers have been compared by their topologies, dimming approach, etc. The comparison results show that the most suitable configuration of laboratory prototype is a composite system with LED matrix, primary power supply and secondary regulator. It is planned to investigate various types of this regulator, but at the initial stage a buck dimmer has been proposed. It shows higher efficiency if the input voltage is close to the rated voltage across the LED load (70V). Based on presented analysis the laboratory prototype has been elaborated and documentation for its production has been prepared. The future work will be focused on assembling of the luminary, its testing and experimental analysis of various light regulators.

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Comparative Study of LED Ballasts for Different Light Regulation Techniques

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Abstract — **Electronic ballast constitutes a significant part of a luminary equipped with light emitting diodes. Its topology affects strongly the energy efficiency, controllability, as well as weight, size and cost of the luminary. Therefore, this part of the luminary has to be designed especially carefully. Previous research has covered these parameters of dimmable ballasts of several topologies and different modulation techniques intended for the fluent mode light regulation. The findings show that buck topology is preferable for many reasons. This part of research extends the estimation procedure proposed earlier to the step mode and pulse mode light regulators. The controllability and power losses of regulators were taken as criteria for our comparison. First, the controllability and losses were analytically estimated and then the obtained result was experimentally verified. In the concluding part, the preferable light regulation technique is presented.**

Keywords — **light emitting diode, electronic ballast, light regulation technique.**

I. INTRODUCTION

Lighting systems consume a significant part of electrical energy produced worldwide [1]. That is why any improvement of lighting equipment leads to serious reduction of its energy consumption. Two directions of this improvement are possible: 1) use of more energy efficient lighting technologies; 2) use of intelligent lighting control solutions.

Implementation of LEDs gives the opportunity to implement both methods. On one hand, they provide higher efficacy [2], are ecologically friendly and their life time is significantly longer, besides, LEDs are easy dimmable and the dimming does not have any negative impact on them. On the other hand the main disadvantage of LEDs is their higher price. Also, LEDs are heat sensitive, produce heat and require cooling. In addition, LEDs have to be supplied from a dedicated power source, the construction of which may be quite complex.

Energy efficiency, controllability of light, as well as weight, size and cost of the ballast depend, first of all, on the light regulation technique that is applied with the ballast. Previous studies that have compared several dimmable ballasts for the fluent mode light regulation report that a buck converter is advantageous from many aspects ([3] to [9]). At the same time it may be concluded that the described simple fluent mode ballasts are not always efficient enough and do not provide perfect light regulation in the wide range and at a high accuracy. For this reason the next sections provide an analysis of other light regulation techniques.

II. LIGHT REGULATION TECHNIQUES

Three light regulation techniques with a specific time-lighting pattern can be distinguished: fluent, step and pulse. To implement each of these techniques dedicated hardware is required that may be more or less energy efficient. The techniques and hardware are briefly reviewed below.

A. Fluent Mode Light Regulation

With the fluent mode light regulation technique, any value of luminous flux from zero to the maximum is achievable at any time instant and in the fluent mode it changes proportionally to a control command without significant steps (Fig. 1-a). This method has two significant disadvantages. Firstly, LED brightness is not completely proportional to the current. Secondly, both the luminous flux and the wave length and therefore the color of light differ at different values of LED current.
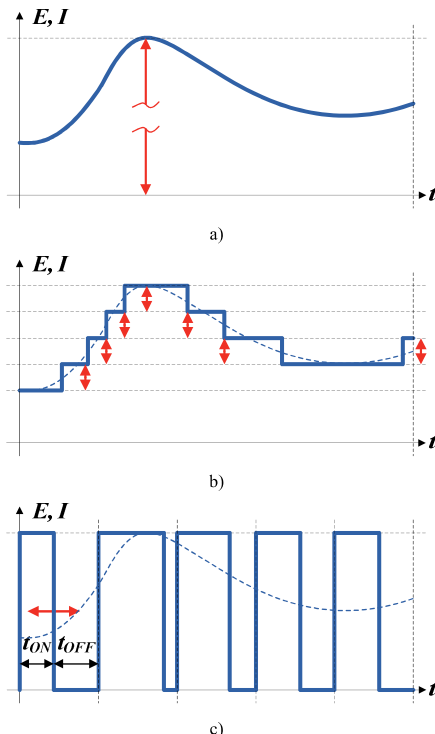

Fig. 1. Luminous flux regulation: a) fluent mode regulation; b) step mode regulation; c) pulse mode regulation.
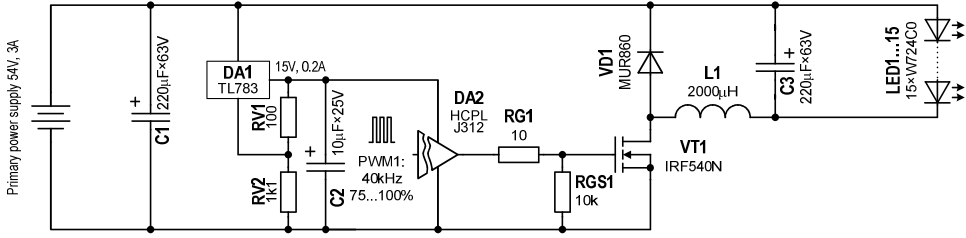
Fig. 2. Schematic of a testbench for the fluent mode regulation (the PWM signal is obtained from an MCU MSP430G2274 through a HCPL-J312 driver).
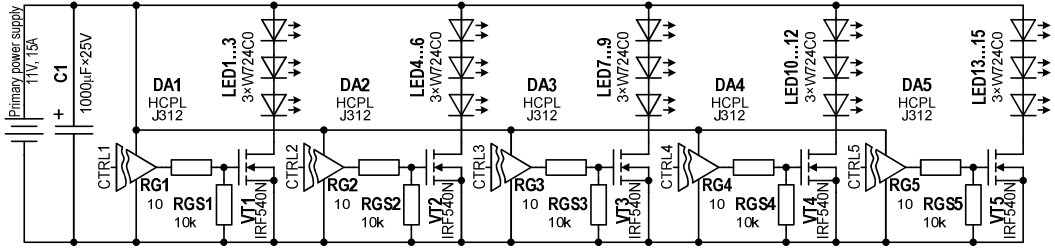

Fig. 3. Schematic of a testbench for the step mode regulation with equal LED branches (the control signal is CTRLx obtained from an MCU MSP430G2274 through a HCPL-J312 drivers).
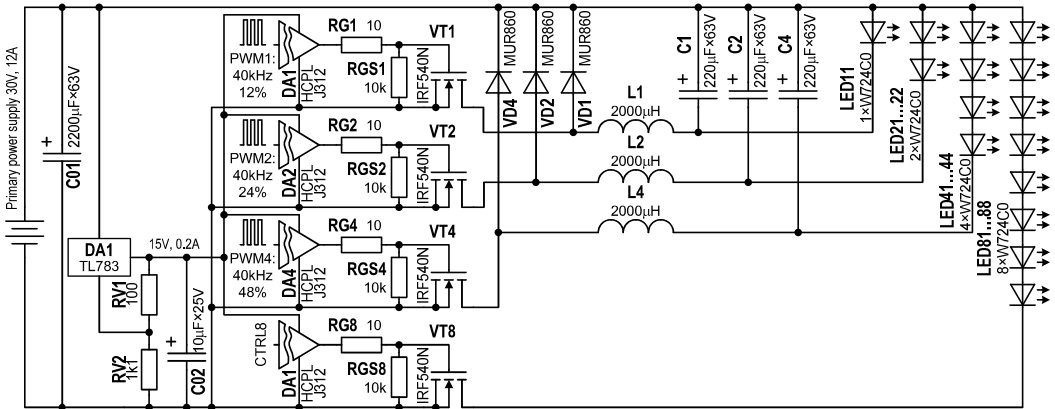

Fig. 4. Schematic of a testbench for the step mode regulation with binary weighted LED branches (the control signals PWM1…4 and CTRL8 and are obtained from an MCU MSP430G2274 through HCPL-J312 drivers).
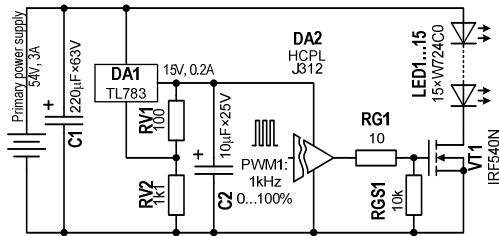

Fig. 5. Schematic of a testbench for the pulse mode regulation (where PWM1 is obtained from MCU MSP430G2274).

B. Step Mode Light Regulation

In the step mode a luminous flux undergoes stepwise changes over a range of fixed values between maximum and zero (Fig. 1-b). Step mode regulation can be achieved through dividing LEDs in several groups that can be equal or different (most practical – binary weighted).

C. Pulse Mode Light Regulation

Many LED drivers use pulse width modulation (PWM) to regulate the amount of power to the LED. At this method, the value of a luminous flux can be either of the maximum value or zero (Fig. 1-c). The average brightness of LEDs depends on the ratio of on-time to the switching period of the LED – duty cycle. At the same time, this method provides a pulse pattern of an instantaneous luminous flux. When the frequency of modulation is low, the pulsating character of light becomes visible to a human eye. When the frequency is high, a stroboscopic effect may appear [6].

D. Comparison of Equipment

The above discussed methods require the dedicated hardware. In the case of the fluent mode light regulation an adjustable power source is necessary. If this source is built as a voltage source, like in [8] and [9], its input and maximal output voltage have to be equal to the rated voltage of one LED multiplied by the number of LEDs.

TABLE I
COMPARISON OF EQUIPMENT

Method	LF Switches	Voltage converter	
		fixed	adjustable
Fluent	-	-	1
Step (x3 Fig. 3)	K/3	-	-
Step (bin. Fig. 4)	1	$\log_2(K+1)-1$	-
Pulse	1	1	-

Fig. 2 represents a typical buck regulator developed for 15 LEDs W724C0 (Seoul Semiconductors) connected in series. In order to provide single supply for entire power circuit an LDO regulator for driver supply is included in the schematic. It must be also noted that the span of practical voltage values used for light regulation is narrower than the full voltage range [5].

The converters for the step mode regulation are in fact arrays of electronic switches for commutation of LED groups. The overall luminous flux is regulated through separate powering of each group by the switches driven by the control system. It is obvious that the maximal number of regulation steps is equal to the number of LEDs while the step of regulation is equal to the power (or light) of a single LED. If all groups are equal, this method assumes one switch per each group and one voltage source per all LEDs (Fig. 3). If the groups are different (for instance, binary weighted), the method requires as many voltage sources and switches as there are groups of LEDs (Fig. 4). In this case the size of the device is enlarged because of the large number of power sources or fixed regulators.

In the case of the pulse mode regulation the regulator is extremely simple – it practically contains only one switch, as well as its driver and power supply, intended for entire LED matrix (Fig. 5).

The above described features of hardware for different light regulation methods are compared in Table I (where K – is a number of LED in the matrix).

From this table it is obvious that the fluent regulation method requires only one source and one voltage converter, but this converter has to be adjustable.

LEDs group regulation in the generalized case requires as many switches as there are LED groups. However, for binary weighted groups this number is minimal, but the sources are easily achievable from additional converters optimized for particular duty cycle of from additional transformer windings.

The advantage of a pulse mode regulator is that it needs only one unregulated voltage source and one switch that make this method very attractive.

From the above mentioned it follows that the simplest hardware corresponds to the pulse mode regulation. However, for other light regulation methods it may also be simple. This together gives no preference to a method in terms of hardware resources.

III. CALCULATION OF LOSSES FOR DIFFERENT LIGHT REGULATION METHODS

Since all the above described light regulation methods require dedicated hardware the loss calculation is also different for different occasions.

A. Power Losses at the Fluent Mode Light Regulation

In the case of the fluent mode light regulation with the buck converter given in Fig. 2 the losses can be divided into transistor losses, diode losses and inductor losses [7]:

$$\Delta P_{FMLR} = \Delta P_{VTon} + \Delta P_{VDon} + ...$$
$$+ \Delta P_{VTsw} + \Delta P_{VDsw} + \Delta P_{FE} + \Delta P_{CU} . \qquad (1)$$

A methodology for the calculation of transistor and diode losses for simple choppers is described in [11]. For a buck converter it can roughly be simplified to the following set of equations. For the on-state losses:

$$\Delta P_{VTon} = I_O^2 \times R_{VTon} \times D \quad \text{and} \qquad (2)$$

$$\Delta P_{VDon} = I_O \times V_{VDon} \times (1-D) , \qquad (3)$$

where I_O is expressed as a function of the input voltage (V_{IN}=54V) and the duty cycle of a chopper's operation:

$$I_O = \frac{V_{IN} \cdot D - V_{LED\min}}{V_{LED\max} - V_{LED\min}} \cdot I_{O\max} . \qquad (4)$$

In (4) $V_{LED\max}$ is the maximal voltage over 15 in series connected LEDs W724C0 (Fig. 2) at their maximal current $I_{O\max}$=2.8A equal to 54V (see [2] for details), but $V_{LED\min}$=36V – the corresponding minimal voltage.

Switching losses are found as:

$$\Delta P_{VTsw} = (E_{VTton} + E_{VTtoff}) \times f_{sw} \quad \text{and} \qquad (5)$$

$$\Delta P_{VTsw} = (E_{VDton} + E_{VDrr}) \times f_{sw} \approx E_{VDrr} \times f_{sw} , \qquad (6)$$

where

$$E_{VTton} = V_{IN} \cdot I_O \cdot \frac{t_{Irise} + t_{Vfall}}{2} + Q_{rr} \cdot V_{IN} , \qquad (7)$$

$$E_{VTtoff} = V_{IN} \cdot I_O \cdot \frac{t_{Vrise} + t_{Ifall}}{2} \quad \text{and} \qquad (8)$$

$$E_{VDrr} = \frac{V_{IN} \cdot Q_{rr}}{2} , \qquad (9)$$

but

$$t_{Vrise} \approx V_{IN} \times R_G \times \frac{C_{GD}}{V_{GSload}} , \qquad (10)$$

$$t_{Vfall} \approx V_{IN} \times R_G \times \frac{C_{GD}}{V_{DR} - V_{GSload}} . \qquad (11)$$

In (5)…(11) t_{Irise}= t_{Ifall} =35ns, Q_{rr} =195nC, V_{GSload}=4.5V, as well as C_{GD}=1nF are found from datasheets of the transistor and diode, f_{sw}=100kHz, V_{IN}=54V, V_{DR}=15V and R_G=10Ohm – are design parameters, but LEDs current I_O is found from (4). Core losses of the inductor can be found from a simplified empirical formula:

$$\Delta P_{FE} \approx K_h \cdot f^\alpha \cdot B_{\max}^\beta \cdot W_{FE} . \qquad (12)$$

In (12) K_h, α, β and $B_{\max}$ are empirical coefficients found based on the datasheet of the core material, but the core volume W_{FE} – from the datasheet of the core. Some more sophisticated equations can be found in [12] and [13].

Inductor's wire losses are found from a common formula of power losses in a round cross section wire:

$$\Delta P_{FE} = \frac{\rho}{\pi \cdot r_{CU}^2} \cdot l \cdot I_O^2 . \qquad (13)$$

In (13) ρ is resistance per length/square, r_{CU} − diameter of the wire, l − its length, but I_O is found from (4).

B. Power Losses at the Step Mode Light Regulation

In the step mode light regulation, power losses are mainly defined by the on-state losses of the electronic switches that commutate LED branches. In the case of transistors they are defined by (2) written for $D=1$ that gives:

$$\Delta P_{VTon\,max} = I_{O\,max}^2 \times R_{VTon} , \qquad (14)$$

where I_{Omax} − is the maximal LED current (2.8A for W724C0), but R_{VTon} − on-state resistance of a MOSFET (44mOhm in the case of IRF540). If the number of branches is N, then the maximal losses at such regulation method are expressed by the formula:

$$\Delta P_{SMLR} = \Delta P_{VTon\,max} \times N = I_{O\,max}^2 \times R_{VTon} \times N . \qquad (15)$$

For $N=5$ (Fig. 3) − 1.7W, but for $N=4$ (Fig. 4) − 1.4W, but for one switch − 0.34W. The maximal losses are proportional to the number of branches. Moreover, in the case of binary-weighted branches the losses do not correlate with the level of produced illuminance.

In the case of voltage obtained from the regulators, their losses must also be taken into account. The methodology of the calculation of these losses is described by (2)…(13). It can be noticed that these regulators can be optimized for a particular duty cycle and output power. For these reasons, the corresponding losses are estimated (at 98% of efficiency) as

$$\Delta P_{buck} = (1-0.98) \times P_{branch} =$$
$$0.02 \cdot (N_{LED} \cdot V_{LED\,max} \cdot I_{O\,max} + I_{O\,max}^2 \cdot R_{VTon}) , \qquad (16)$$

where N_{LED} − is the number of LEDs in the branch (1, 2, 4, and 8, respectively) or together (15).

C. Power Losses at the Pulse Mode Light Regulation

In the pulse mode light regulation (Fig. 5), the losses are also concentrated in the switch. They, however, contain both on-state and switching part

$$\Delta P_{PMLR} = \Delta P_{VTon} + \Delta P_{VTsw} , \qquad (17)$$

where ΔP_{VTon} is expressed by (2) with $I_O=I_{Omax}=2.8$A, but ΔP_{VTsw} − by (5)…(11). However, the switching frequency in this case (f_{swPMLR}) is defined by a flickering phenomenon and is much lower (1kHz was taken for calculations).

D. Comparison of Calculated Losses

The above formulas for different light regulation methods have been applied to the LED matrix made of 15 10W LEDs W724C0 (Fig. 2, Fig. 3, Fig. 4 and Fig. 5). The results of these calculations are listed in Table II.

This table shows that the losses in the fluent mode light regulation are not minimal. They are lower if the number of branches in the step mode regulation is small. The difference can be explained by rather high commutation and inductor losses in the regulator in the fluent mode light regulation.

In the pulse mode regulation, the losses are even smaller because they are mostly defined by the on-state losses in the transistor. However, this regulation method is not desirable due to the flickering and possible stroboscopic effects.

TABLE II
MAXIMAL POWER LOSSES WITH
DIFFERENT LIGHT REGULATION METHODS [W]

Method	ΔP_{static}	ΔP_{sw}	ΔP_{msic}	$\Sigma\Delta P$
Fluent	0.35	2.05	1.9	4.3
Step (x3, Fig. 3)	1.72	0	0	1.72
Step (binary, Fig. 4)	0.34	0	3	3.34
Pulse	0.34	0.02	0	0.36

E. Analysis and Features of Experiments

To verify the calculated data experimentally a previously described LED light source with 15 10W LEDs (W724C0) was practically built. The source has been tested with different regulation methods measuring illuminance E_v at a 1m distant point just under its center. Total power losses as a function of illuminance for different regulation methods are shown in Fig. 6. For the step regulation with binary weighted groups the losses are proportional to the number of branches which is not proportional to the illuminance (for this reason the column chart was chosen, Fig. 6-a).
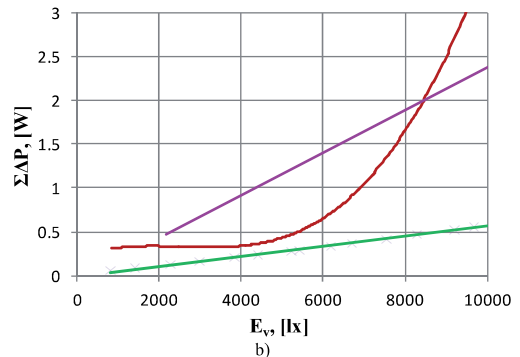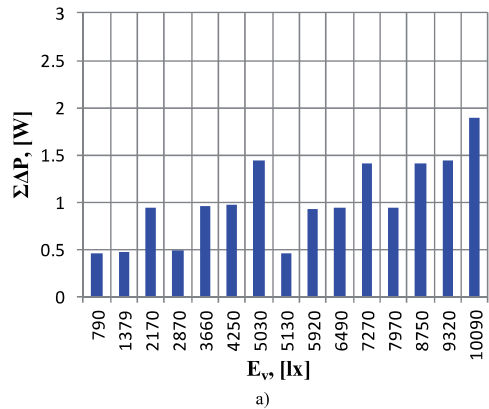

a)

b)

Fig. 6. Power losses vs. illuminance level measured for: a) binary weighted step regulation method; b) fluent (red), step (violet) and PWM (green) techniques.
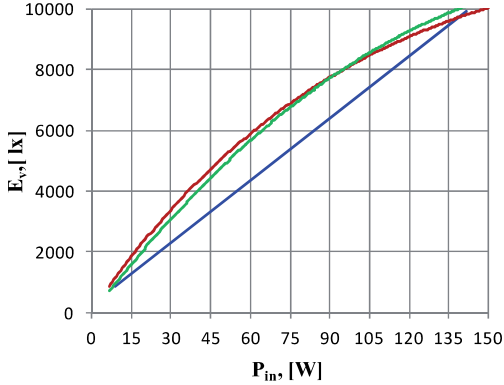
Fig. 7. Illuminance vs. input power for the fluent (red), the binary weighted step (blue) and the PWM (green) regulation techniques.

The highest losses were measured with the fluent mode light regulation method at higher output power levels, while the smallest ones – with the pulse mode technique (as it was expected). In general, experimental measurements show that the results are very similar to those of theoretical calculations.

In the pulse mode light regulation, direct measurement of the losses was complicated due to their small value (Fig. 6-b). For this reason the losses were calculated using the experimentally measured voltage drop over the on-state transistor for the corresponding current and duty cycle. Also, switching losses were calculated based on the practically measured voltages and currents at the moment of commutation at 1 kHz switching frequency and added to the final result. The second smallest losses appeared at binary weighted step regulation.

Fig. 7 shows illuminance as a function of input power (including power losses). This curve for the binary step regulation is almost linear, because all LEDs operate at almost the same power and, therefore, with the same efficacy (note that the maximal power is not the most efficient power point for LED operation). It should also be taken into account that power losses for the binary step regulation depend on the number of connected branches, not the total input power (Fig. 6-a) that makes this curve slightly nonlinear. Fig. 7 shows that the fluent and the pulse mode light regulation are more efficient at middle power ranges. This can be explained by higher efficacy of LEDs at lower power operation points.

IV. CONTROLLABILITY AT DIFFERENT LIGHT REGULATION METHODS

A. Controllability in the Fluent Mode

Controllability (the resolution of regulation and its nonlinearity) are well stated in [5]. With the buck regulator, the measured nonlinearity is about 12% and is mostly defined by the nonlinearity of V-A and A-E [Lx] curves of LEDs.

The resolution of the regulation depends on the resolution of PWM that, in turn, depends on the performance of the control system. With the MCU based system, it can be expressed based on the system clock frequency f_{CLK} as

$$\Delta E_{FMLR} = \Delta PWM \cdot K_{II} = 100\% \cdot \frac{f_{CLK}}{f_{PWM}} \cdot K_{II} , \qquad (18)$$

where f_{PWM} is the switching frequency of the regulator, but K_{II} is the ratio of practically usable range of PWM values to their full range that is approximately 6 for common LEDs. At f_{PWM} =100kHz and f_{CLK} =10MHz, the resolution of PWM is 1% but the resolution of regulation is 6% (that is equal to 17 steps of illuminance).

B. Controllability in the Step Mode

In the step mode, if the commutated branches are equivalent, the resolution is reverse proportional to the number of branches B_{eq}:

$$\Delta E_{SMLR1} = \frac{100\%}{B_{eq}} . \qquad (19)$$

If the branches are binary weighted (and their number is B_B), then the expression for resolution is as follows:

$$\Delta E_{SMLR1} = \frac{100\%}{2^{B_b} - 1} . \qquad (20)$$

In the step mode, LEDs are run at full power. Their nonlinearities, therefore, have no influence on the lighting parameters. For this reason total power is proportional to the regulation command, but the regulation is linear.

C. Controllability in the Pulse Mode

In the pulse mode, the resolution of regulation is also defined by the PWM resolution of the control system. However, in this case all the PWM values are possible. Therefore

$$\Delta E_{PMLR} = \Delta PWM = 100\% \cdot \frac{f_{CLK}}{f_{PWM}} , \qquad (21)$$

Since the modulation frequency is much lower with this method, the resolution is high.

In the pulse mode light regulation (like in the step mode), LEDs are either fully on or off. That is why nonlinearities of LEDs are not included in the control loop and overall nonlinearity is 0.

D. Comparison of Controllability

With real data, the expressions (19)…(21) above produce the results given in Table III. Thus, it can be concluded that in terms of control performance, the fluent mode and the step mode regulation are quite close. The pulse mode technique is better, but it produces undesirable effects.

TABLE III
CONTROLLABILITY (NONLINEARITY AND RESOLUTION) WITH DIFFERENT LIGHT REGULATION METHODS

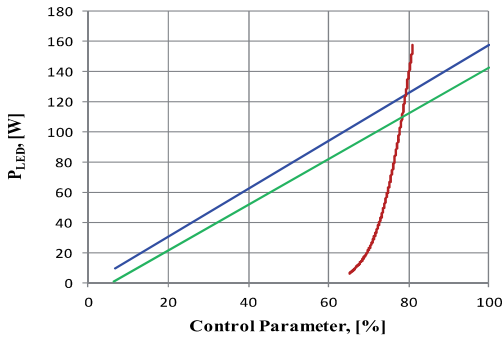| Method	NL	ΔLx
Fluent	12%	6% (17 steps)
Step (x3 LEDs)	0%	20% (5 steps)
Step (binary + reg)	0%	7% (15 steps)
Pulse	0%	0.01% (10^4 steps)

Fig. 8. Measured output power vs. control parameter for the fluent (red), the step (blue) and the PWM (green) mode of light regulation.
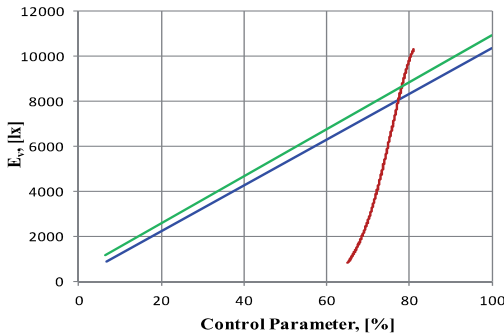

Fig. 9. Illuminance vs. control parameter for the fluent (red), the step (blue) and the PWM (green) light regulation methods.

E. Analysis and Features of Experiments

A series of experiments were made to analyze the controllability of the LED luminary at fluent, step and pulse modes of light regulation. The results are summarized in Fig. 8 and Fig. 9. Fig. 8 shows that in the fluent regulation mode, the range of the control parameter (that is the duty cycle for the fluent and pulse modes and % of the maximal number of LEDs for the step mode of regulation) is quite narrow in comparison with the step and pulse modes. Also, nonlinearity in the fluent mode is higher, which is related to the LED V-A curve. Hence, from this point of view, it is reasonable to implement LED luminaries utilizing the pulse and step modes.

Fig. 9 shows illuminance as a function of the control parameter. Its shape looks similar to that of power. However, even a brief comparison of the curves in Fig. 8 and 10 reveals their difference that can be explained by the nonlinearity of the A-E[Lx] curve of LEDs.

V. Conclusions

The generalized conclusion that can be drawn from the above presented calculations and experiments states that the step mode light regulation is preferable over the other modes in the case of rather small number (10…20) of illuminance levels. Then the corresponding power and control hardware/software is simpler (Table I), provides lower losses (Table II) keeping at the same time control parameters at comparable level (Table III). Pulse mode regulators are even more attractive, but they have also significant drawbacks (flickering, stroboscopic effects).

Practical implementation of the step mode regulators for binary weighted LED groups is preferable due to the lower number of the groups and switches. However, this approach in practice requires additional hardware like dedicated DC/DC converters or a specific transformer.

In addition, in the case of step mode regulation, it is worth considering configurations of LED matrices with a larger number of elements of lower power (compared to a smaller number of elements of higher power).

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The author's contributions are: background analysis, preliminary simulation, processing the measured data, numerical calculations of efficiency, preparing the diagrams, drawing conclusions.

Comparative Study of Steady-State Performance of LED Drivers at Different Modulation Techniques

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Abstract – **The paper deals with current and light regulators for luminaries with Light Emitting Diodes. Several topologies of the regulators with typical control formula (buck, boost and buck-boost) and several control methods (pulse-width and frequency modulation) are analyzed from the point of view of their control performance. Special attention is paid to the non-linearity of the proposed solutions and their accuracy in practically available control platforms. The control solutions are analyzed analytically and through simulations as well as confirmed experimentally. The conclusions about the most prospective solution are made.**

I. INTRODUCTION

Lighting is one of the most energy consuming industrial and household technologies. According to [1] about 19% of the electrical energy produced over the world is spent to lighting. Therefore it is quite reasonable to improve efficiency of lighting systems that can be done in two basic ways: utilization of the lighting technologies that produce more light per power unit and making lighting systems intelligent – provide lighting exactly when and where it is required.

Utilization of Light Emitting Diodes (LEDs) provides an excellent opportunity to use both of them. On the one hand modern LEDs have efficiency of several tens lumens per watt [2] that is comparable with high pressure sodium lamps (about 140lm/W) [3]. On the other hand it is possible to effectively adjust light produced by a LED lamp with no negative impact on the lamp itself.

Amount of light produced by a LED lamp is proportional to the current of its LED elements. This brings forward two light control methods: 1) fluent regulation mode when LED current remains constant for the same value of the control command; 2) pulse regulation mode when the current is either maximal or zero but its average value is constant for the same value of the control command. The third light regulation method is possible with LEDs because their power is rather small. For this reason LED lamp usually includes a number of LEDs and it is possible to divide them into groups and control each group separately utilizing some kind of Pulse Code Modulation (PCM). This method, however, ensures lesser dimming levels and lower accuracy of lighting and is not preferable for this reason. The second mentioned method is also undesirable because the light produced by the LED follows its current at a very high rate ([4] and [5]) which leads to flickering and stroboscopic effects. Therefore the fluent regulation mode is preferable.

The fluent regulation of LED current is possible with a current regulator. However, design and implementation of such regulators is not an easy task due to the more complicated schematics. For this reason various DC choppers are usually discussed as the power supplies for LED luminaries [6]: buck, boost, buck-boost and Cuk [7]. Each of these converters may be controlled in different ways – Pulse Width Modulation (PWM), Frequency Modulation (FM) etc.

The particular schematic and control method have strong impact on the efficiency and accuracy of the light regulation as well as on the weight and size of the regulator. Previously authors have studied the impact of the control method of a buck converter on its losses [8]. This research tries to find the best solution form the point of view of the control performance.

II. GENERAL ASSUMPTIONS AND CRITERIA FOR COMPARISON

A set of criteria that relates to the regulation curve (Fig. 1) of an LED lamp has been chosen in order to form a clear base for comparison of drivers and modulation methods. The meaning and importance of these criteria are explained below.
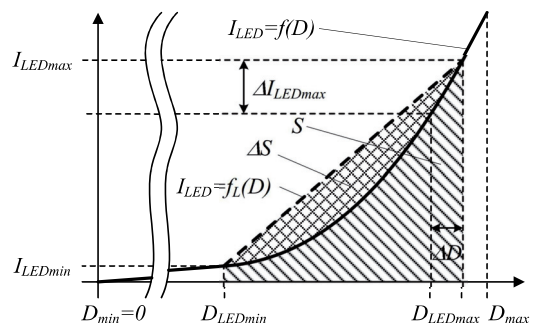

Fig. 1. General definitions for comparison of control performance.

The first one is nonlinearity of the regulation curve. The nonlinearity has a strong effect on the stability and dynamic performance of the control system. It is an integral criterion that is equal to the root-mean-square declination ΔS of the regulation curve from a line connecting its border points to the root-mean-square value S of the curve itself:

$$NL = \frac{\Delta S}{S}. \qquad (1)$$

In (1) ΔS is defined as

$$S = \sqrt{\frac{1}{D_{LED\max} - D_{LED\min}} \int_{D_{LED\min}}^{D_{LED\max}} f^2(D)dD} , \qquad (2)$$

but $S -$ as follows

$$\Delta S = \sqrt{\frac{1}{D_{LED\max} - D_{LED\min}} \int_{D_{LED\min}}^{D_{LED\max}} \left[f(D) - f_L(D) \right]^2 dD} . \qquad (3)$$

In (1)…(3) D is duty cycle of operation of the chosen converter. This control parameter depends on a physical parameter (pulse width or period) that is variable with the particular modulation method. Its values at the ends of the regulation curve are obvious $D_{min}=0$ and $D_{max}=1$ while those, corresponding to the minimal and maximal values of LED current $-$ D_{LEDmin} and D_{LEDmax}.

The second parameter for comparison reflects practical utilization of the duty cycle. It can be defined as the span of active values of this parameter:

$$D_{SPAN} = \frac{D_{LED\max} - D_{LED\min}}{D_{\max} - D_{\min}} = D_{LED\max} - D_{LED\min} . \qquad (4)$$

Another parameter is the practical inaccuracy of the duty cycle. It may be defined as a ratio of technically achievable inaccuracy ΔD of the duty cycle to its practical span:

$$\Delta D_P = \frac{\Delta D}{D_{LED\max} - D_{LED\min}} = K_{II} \cdot \Delta D , \qquad (5)$$

where $K_{II}=1/(D_{LEDmax}-D_{LEDmin})$ is inaccuracy increase ratio. This coefficient expresses the impact of the converter and LEDs V-A curve on the tolerance of regulation. Technical inaccuracy ΔD is defined differently for different modulation techniques and has to be analyzed for each of them.

The last (but not the least one) parameter is the relative inaccuracy of LED current:

$$\Delta I_{LED}\% = \frac{\Delta I_{LED\max}}{I_{LED\max} - I_{LED\min}} \cdot 100\% , \qquad (6)$$

where ΔI_{LEDmax} is changes of LED current corresponding to the changes of control parameter ΔD in the worst point of the regulation curve.

III. NONLINEARITY AND PRACTICAL OF DUTY CYCLE

The nonlinearity of regulation curve of a LED lamp and practical utilization of duty cycle depend only on regulation curve of the chosen converter and Volt-Ampere curve of utilized LEDs. At the same time, modulation technique has

no direct impact on them. In this section these parameters are estimated for different converters and with different values of the input voltage. This estimation has been made analytically and also based on experimental data.

A. Approximation of V-A Curve

Analytical estimation of the regulation curve requires expressions for output voltage of the dimming converter and Volt-Ampere curve of LED series. The last one does not exist in analytical form but has been measured experimentally (for 7 series connected LEDs type W724C0 produced by Seoul Semiconductor). Based on the experimental data a polynomial approximation of the curve has been obtained. In this work approximation with a 3rd order polynomial has been utilized:

$$I_{LED} = f(V_{LED}) = a_0 + a_1 \cdot (V_{LED} - V_0) + ... \qquad (7)$$
$$... + a_2 \cdot (V_{LED} - V_0)^2 + a_3 \cdot (V_{LED} - V_0)^3 .$$

where V_0 is the voltage of the working point, but coefficients $a_0...a_3$ depend on the choice of the working point. Usually only a workspace is approximated, but not the whole characteristic. In this work V_{LED} domain is [17…23,5V] and the corresponding I_{LED} is from the range [0, 3A]. For this range suitable working point is V_0=20.2V that gives coefficients a_0=557, a_1=442, a_2=89.6 and a_3=1.92. These values of coefficients provide accuracy of about 2% that is sufficient at the preliminary stage. More accurate and valuable results are obtained experimentally.

B. Impact of regulators

Steady state formula of buck converter can be found from learning and scientific literature. Taking into account that the output voltage is applied to LEDs it can be written as:

$$V_{LED} = f(V_{IN}, D) = D \cdot V_{IN} . \qquad (8)$$

Applying (8) to (7) produces:

$$I_{LED} = f(V_{LED}) = a_0 + a_1 \cdot (D \cdot V_{IN} - V_0) + ... \qquad (9)$$
$$... + a_2 \cdot (D \cdot V_{IN} - V_0)^2 + a_3 \cdot (D \cdot V_{IN} - V_0)^3 .$$

In a similar way applying of steady state formula of the boost converter

$$V_{LED} = f(V_{IN}, D) = \frac{V_{IN}}{1-D} \qquad (10)$$

produce

$$I_{LED} = f(V_{LED}) = a_0 + a_1 \cdot (\frac{V_{IN}}{1-D} - V_0) + ... \qquad (11)$$
$$... + a_2 \cdot (\frac{V_{IN}}{1-D} - V_0)^2 + a_3 \cdot (\frac{V_{IN}}{1-D} - V_0)^3 ,$$

but those of the buck-boost

$$V_{LED} = f(V_{IN}, D) = \frac{D \cdot V_{IN}}{1 - D} \qquad (12)$$

produces the following

$$I_{LED} = f(V_{LED}) = a_0 + a_1 \cdot (\frac{D \cdot V_{IN}}{1 - D} - V_0) + ... \qquad (13)$$

$$... + a_2 \cdot (\frac{D \cdot V_{IN}}{1 - D} - V_0)^2 + a_3 \cdot (\frac{D \cdot V_{IN}}{1 - D} - V_0)^3 .$$

Equations (9), (11) and (13) have been utilized to calculate nonlinearity of regulation curve (Table I), practical utilization of duty cycle (Table I, see also Fig. 2) and increase of inaccuracy with particular converter.

a)

b)

c)
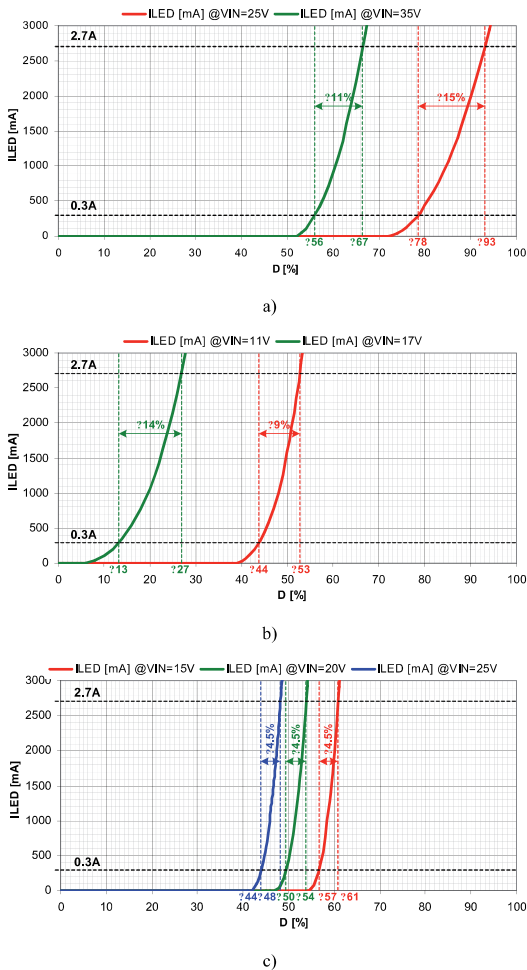
Fig. 2. Regulation curve of a LED lamp containing 7 series connected LEDs W724C0 made by Seoul Semiconductor and fed by a DC/DC converter: a) buck; b) boost; c) buck-boost.

TABLE I
CALCULATED NONLINEARITY AND ACCURACY OF LED LUMINARIES
(FOR THE WORKING RANGE OF CURRENT 0.3…2.7A)

	Buck		Boost		Buck-Boost		
	25V	35V	11V	17V	15V	20V	25V
NL	16%	16%	20%	22%	20%	18%	18%
D_{SPANa}	15%	11%	9%	14%	5%	5%	5%
K_{II}	6.7	9.1	11.1	7.1	20	20	20

IV. ACCURACY OF MODULATION TECHNIQUE

There are two basic modulation modes: pulse width modulation (PWM - Fig. 3-a) and frequency modulation (FM). Besides that two kinds of frequency modulation can be introduced: constant pulse frequency modulation (CPFM - Fig. 3-b) and constant pause frequency modulation (CZFM - Fig. 3-c). Accuracy of the duty cycle and LED's current obtained with these modes are quite different. Their analysis is presented below.
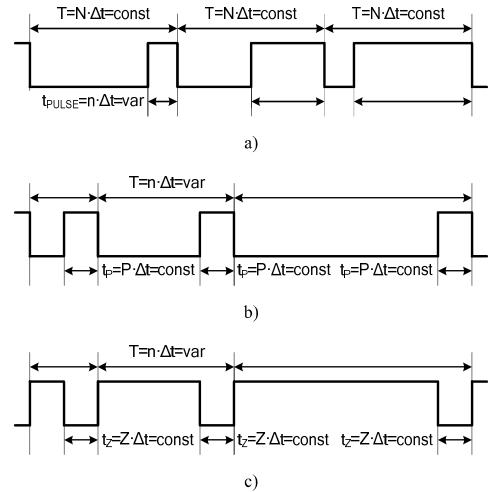

Fig. 3. Modes of pulse modulation: a) pulse width modulation; b) constant pulse frequency modulation; c) constant pause frequency modulation.

A. Pulse Width Modulation

At PWM modulation period T is a constant which is proportional to minimal countable time step (elementary step) Δt and number of such steps N that together produces $T = N \cdot \Delta t$. At the same time pulse width is variable $t_P = P \cdot \Delta t$, where n – is an integer number that is defined by the control system depending on the control conditions. Then the duty cycle is a function of n:

$$D(n) = \frac{t_P}{T} = \frac{n}{N} . \qquad (14)$$

Inaccuracy of duty cycle can be defined as a difference of its two closest values:

$$\Delta D = \frac{n+1}{N} - \frac{n}{N} = \frac{1}{N}. \tag{15}$$

From (15) is obvious that the inaccuracy at PWM is inversely proportional to the number of elementary time steps in the modulation period. For instance at N=100 the inaccuracy is 1%. In practice N is limited by the performance of control system and cannot be chosen infinitely high.

B. Constant Pulse Frequency Modulation

At CPFM pulse duration is a constant proportional to the elementary step Δt and number of such periods P ($t_P=P\cdot\Delta t$). At FM period is variable. It can be expressed as $T=n\cdot\Delta t$, where n − is an integer number that defined by the control. Then the duty cycle can be expressed a function of n:

$$D(n) = \frac{t_P}{T} = \frac{P}{n}. \tag{16}$$

At CPFM the inaccuracy of duty cycle is also function of n. If it is defined as a difference of two closest values of the duty cycle then:

$$\Delta D(n) = \frac{P}{n} - \frac{P}{n+1} = \frac{P}{n^2 - n}. \tag{17}$$

The bigger is n, the smaller is duty cycle. Its minimal value is equal to 0 and it is achieved at infinity n:

$$D_{MIN} = \lim_{n\to\infty} \frac{P}{n} = 0 \tag{18}$$

The same regards also inaccuracy of the duty cycle at such values:

$$\Delta D_{@DMIN} = \lim_{n\to\infty} \left(\frac{P}{n} - \frac{P}{n+1} \right) = 0. \tag{19}$$

Some numerical values calculated with (16) and (17) for *P=1* are given in Table II. The last row in this table shows that FM provides much higher than PWM inaccuracy of the duty cycle at comparable length of period.

TABLE II
DUTY CYCLES OBTAINED WITH CPFM AT LONG PERIODS

n	$D(n)$	$\Delta D(n)$
10	10%	0.91%
20	5%	0.24%
100	1%	0.01%

In CPFM mode higher values of the duty cycle are obtained at lower values of n. The minimal value of this index is *P+1*. Then the maximal value of the duty cycle may be fond as:

$$D_{MAX} = \frac{P}{n_{MIN}} = \frac{P}{P+1}. \tag{20}$$

The inaccuracy of the duty cycle then can be found as the difference of its maximal value and the next smaller value:

$$\Delta D_{@DMAX} = \frac{P}{P+1} - \frac{P}{P+2} = \frac{P}{P^2 + 3P + 2}. \tag{21}$$

The values of the maximal duty cycle calculated with (20) and (21) are given in Table III.

TABLE III
DUTY CYCLES OBTAINED WITH CPFM AT SHORT PERIODS

P	$D_{MAX}(n=P+1)$	$\Delta D@_{DMAX}(n=P+1)$
1	50%	17%
5	83%	12%
10	91%	8%

Table II and Table III show that CPFM provides higher values of the duty cycle at high frequencies when number of counted elementary steps Δt is low. The accuracy of duty cycle at such conditions is extremely low. At the same time this modulation method provides also high accuracy of the duty cycle, but only in the range of its low values if number of counted elementary steps is high. This phenomenon contradicts with nature of DC/DC converters feeding LED elements that mostly require higher accuracy in the range of higher values of duty cycle. Therefore control of this hardware is rater complicated in CPFM mode.

C. Constant Pause Frequency Modulation

This mode assumes that pause between two neighbor impulses remains constant. It is generated as a short series of the elementary time steps with total length $t_{PAUSE}=Z\cdot\Delta t$, where Z is number of the steps. At the same time the number of elementary time steps in period n is a variable whose value is defined by regulation loop and this period still can be expressed as $T=n\cdot\Delta t$. Then the duty cycle can be defined as:

$$D(n) = \frac{t_{PULSE}}{T} = \frac{T - t_{PAUSE}}{T} = \frac{n - Z}{n} = 1 - \frac{Z}{n}. \tag{22}$$

The inaccuracy of duty cycle then is:

$$\Delta D(n) = \left(1 - \frac{Z}{n+1} \right) - \left(1 - \frac{Z}{n} \right) = \frac{Z}{n^2 + n}. \tag{23}$$

At such approach the bigger is n, the bigger is duty cycle. It achieves value 1 at infinity n:

$$D_{MIN} = \lim_{n\to\infty} \left(1 - \frac{Z}{n} \right) = 1 \tag{24}$$

Inaccuracy of the duty cycle at such values is:

$$\Delta D_{@DMIN} = \lim_{n \to \infty} \left(\frac{N}{n} - \frac{N}{n+1} \right) = 0 . \qquad (25)$$

Numerical values calculated with (22) and (23) for $Z=1$ are given in Table IV.

TABLE IV
DUTY CYCLES OBTAINED WITH CZFM AT LONG PERIODS

n	D(n)	ΔD(n)
10	90%	0.91%
15	93%	0.42%
100	99%	0.01%

In CPFM mode lower values of the duty cycle are obtained at lower values of *n*. Then the minimal duty cycle is:

$$D_{MAX} = 1 - \frac{Z}{n_{MIN}} = 1 - \frac{Z}{Z+1} = \frac{1}{Z+1} . \qquad (26)$$

The inaccuracy of the duty cycle then can be found as:

$$\Delta D_{@DMAX} = \left(1 - \frac{Z}{Z+2} \right) - \left(1 - \frac{Z}{Z+1} \right) = \frac{Z}{Z^2 + 3Z + 2} . \qquad (27)$$

The values of the minimal duty cycle calculated with (26) and (27) are given in Table V.

TABLE V
DUTY CYCLES OBTAINED WITH CZFM AT SHORT PERIODS

Z	D_MIN(n=Z+1)	ΔD@_DMIN(n=Z+1)
1	50%	17%
5	17%	12%
10	9%	8%

Table IV and Table V prove that CZFM provides higher values of the duty cycle at lower frequency with the higher accuracy that corresponds to the requirements of DC/DC converters feeding LED elements. Lower values of the duty cycle are valid at higher frequency with lower accuracy, but this drawback is less important for the discussed application.

V. ANALYSIS OF EXPERIMENTAL VERIFICATION

A series of experiments has been conducted in order to check the above listed analytical assumptions. First of the all static regulation curve of the LED luminaries have been measured (Fig. 4) and the corresponding parameters found (Table VI). Comparison of these results with purely analytically calculated (Fig. 2 and Table I) proves the expected tendencies.

At the same time there is a certain difference that could be explained with impact of the parasitic parameters of elements of real converters. This especially regards boost converter

with high transfer gain (with 11V input). The higher output voltage is necessary the bigger is the difference between calculated and measured duty cycle. That is why the measured span in the case of boost and buck-boost converters is higher than calculated. Increase of the span, in turn, has impact on the corresponding V-A curves making the total relative non-linearity lower.

TABLE VI
MEASURED NONLINEARITY AND ACCURACY OF LED LUMINARIES
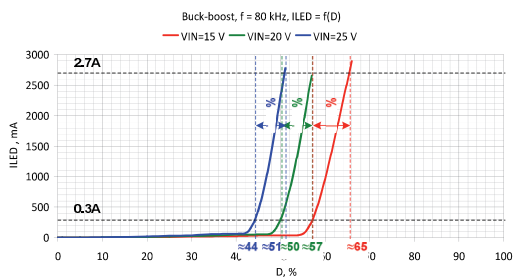(FOR THE WORKING RANGE OF CURRENT 0.3…2.7A)

	Buck		Boost		Buck-Boost		
	25V	35V	11V	17V	15V	20V	25V
NL	12%	12%	9%	14%	7%	8%	11%
D_SPANa	17%	11%	16%	19%	8%	7%	7%
K_II	5.9	9.1	6.3	5.3	12.5	14.3	14.3
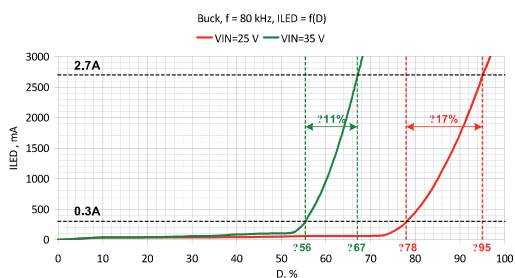
a)
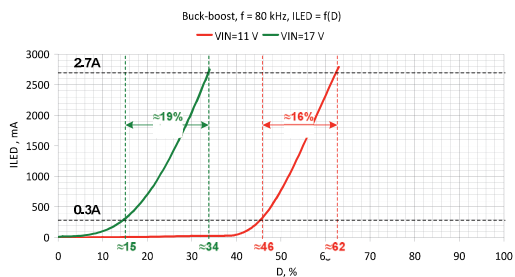
b)

c)

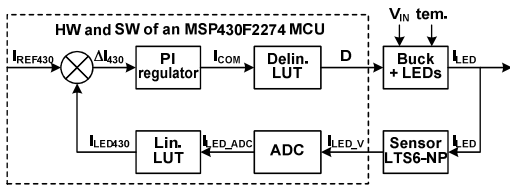Fig. 4. Measured regulation curve of the above described LED lamp fed by a DC/DC converter: a) buck; b) boost; c) buck-boost.
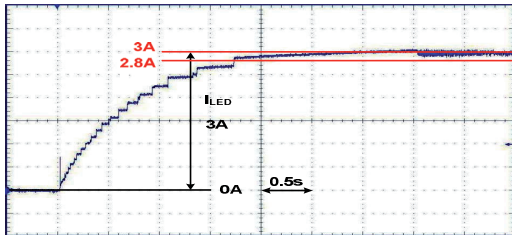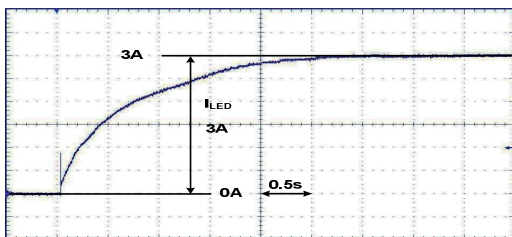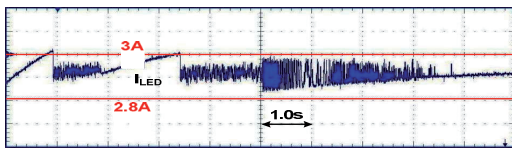
Fig. 5. Functional diagram of the test-bench for control parameters testing composed of a buck converter, sensor and control system with PI regulator.

a)

b)

c)

Fig. 6. Influence of modulation technique on the performance of control system: a) startup step response at PWM (Δt=125ns; N=100); b) startup step response at CZFM (Δt=125ns; Z=1); c) steady-state operation at PWM.

At the next stage the impact of modulation technique has been investigated. As it has been previously shown CZFM technique provides more accurate regulation than PWM. This is especially well seen in the startup of LED lamp operating in a closed loop (Fig. 5). CZFM (Fig. 6-a) obviously produce less current steps than PWM (Fig. 6-b). Significant inaccuracy also leads to unavoidable static error. This, in turn, initiates low frequency oscillations between closest available current levels (red lines in Fig. 6) during steady-state operation (Fig. 6-c) if the reference current level is different.

VI. CONCLUSIONS

In the given paper the impact of dimming converter and its pulse modulation technique on its control performance have

been investigated. The results of analytical estimation correspond (taking into account differences between real lamp and its mathematical model) to those experimentally obtained. This correspondence validates the proposed assumptions and the conclusions drawn from them.

The type of dimming converter has a significant effect on the overall control performance. The nonlinearity of regulation curve in the case of boost converter is more significant due to the higher nonlinearity of the converter itself. It must also be noted that the nonlinearity of the V-A curve of LEDs has the most significant contribution in the total nonlinearity of the system.

All the discussed converters show narrow span of active (practically useful) values of the duty cycle. In the case of buck (especially with the input voltage equal to maximal operating voltage of LEDs) and boost (especially with the input voltage equal to minimal operating voltage of LEDs) the practical span is acceptable, but in the case of buck-boost converter – it is too narrow.

The choice of modulation technique is also important. In general FM shows better accuracy than PWM. However, since in the case of FM accuracy is not a constant, specific FM type must correspond to the converter and to the working point. In the case of CZFM the accuracy is higher at higher values of the duty cycle. This makes CZFM suitable for a LED lamp fed from buck converter at high current working point. At the same time a LED lamp with boost converter and low current working point requires CPFM.

It must also be noted that wide frequency band in case of FM may have negative effect on other parameters of the lamp – weight and size of reactive components, loses, EMC etc. These topics, however, require a special research on them.

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[A6] Galkin, I.; Tetervenok, O.; **Milashevski, I.** (2011). Comparative estimation of efficiency of LED dimmers at different modulation techniques. In: Proceedings of the 2011-14th European Conference on Power Electronics and Applications (EPE 2011): August 30 2011-September 1 2011. IEEE Publishing , 2011, 1 - 9.

The author's contributions are: background analysis, preliminary simulation, preparing and editing text, numerical calculations of efficiency, controllability, preparing the diagrams.

Comparative Estimation of Efficiency of LED Dimmers at Different Modulation Techniques

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Keywords

Lighting, electronic ballast, DC power supply, efficiency.

Abstract

There are two basic ways to improve the energy efficiency of lighting equipment - utilization of more effective technologies of light generation and implementation of intelligent control of lighting (providing the light where and when it is needed). LED lighting technology provides both these opportunities: LED luminaries have high efficacy and it is possible to dim them. At the same time LED lamps always require some electronic ballast. Operation of these ballasts depends on their topology and control features. This paper estimates the efficiency of several LED ballasts at different conditions. The efficiency is analyzed numerically, simulated and experimentally tested.

Introduction

Nowadays demand for electrical energy is constantly growing while prospects of new electrical energy sources are quite questionable that together makes to solve the problem of energy efficiency: increase the self-efficiency of electrical equipment and avoid its unnecessary operation – making it "smart". Utilization of Light Emitting Diodes (LEDs) successfully combines these two ways in lighting systems. On the one hand modern LEDs have efficacy of several tens lumens per watt (for instance, W724C0 from "Seoul Semiconductor" ensures 700lm at 10W or 70lm/W [1]) that is comparable with high pressure sodium lamps (up to 140lm/W [2]). On the other hand it is possible to effectively adjust the light produced by LED lamps with no negative impact on them.

Amount of light produced by an LED is proportional to its current. This brings forward two light control methods: fluent regulation of LEDs current and pulse width modulation (PWM) of LEDs current (and light produced by LEDs). Since the light produced by LED follows its current at a very high rate ([3] and [4]) the second method may lead to flickering and stroboscopic effects. Another light

regulation method is possible because rated power of LEDs is usually small. For this reason LED luminary includes a number of LEDs and it is possible to divide them into groups and control each group separately. This method, however, ensures less dimming levels and lower accuracy of regulation. Therefore, taking into account possible drawbacks and benefits, the first regulation method – fluent regulation of LED current is preferable.

LED itself is a low voltage element. This mostly requires DC/DC stage for dimming even if the LED luminary is fed from AC line. This argument is especially significant if the luminary has few LED groups that must be dimmed separately. Various DC choppers can be used as the regulators: buck, boost, buck-boost [5] and Cuk [6]. Each of these converters may be driven in different ways. The chosen topology and control method has significant effect on the efficiency of the dimmer. Previously [7] this parameter has been roughly estimated for a buck type DC/DC dimmer. This paper expands the research also to the boost and buck/boost types of dimmers.

Configuration of the testbench

In order to provide experimental comparison of dimming converters a testbench has been formed. It consists of a laboratory power supply, dimmer and LED load. The load contains 7 series connected 10W LEDs (attached through XQ1 and XQ2) that gives the maximal power of 70W.

Three dimming circuits with one active switch have been analyzed: buck, boost and buck-boost. Their basic schematics are well known from the literature. However, their practical implementation has certain features (Fig. 1). First of the all controllable switches are located so that their control signals are referred to the same grounding as their supply voltage (attached through its contacts XI1 (+) and XI2 (−)). This makes driver circuits for these switches very simple – their output voltage is obtained from a complementary transistor leg powered (through a converter) from the same power supply as the dimming circuit itself. The control pulses are passed through a resistor to the gate of the transistor (connectors XC1 and XC2).

It is also easy to install a transistor current sensor at such configuration because its power supply also has to be referred to the same ground. The converters also include an output current sensor that provides feedback to the control system (through XFB1 and XFB2).

The value of input voltage of converters has to be chosen so that LEDs voltage is within its working range 17…25V. At the same time the range of the duty cycle has to be as wide as possible (for better control performance of the dimmer). Taking into account the above mentioned, the buck converter has to operate with input voltage equal to the maximal operating value voltage of LEDs (25V). The boost converter operates optimally with the minimal LED voltage (17V). The input voltage of the buck/boost converter at such conditions has to be chosen from the middle of the operating LEDs voltage range. Reasonable value is 22.5V at which the half of the maximal power (35W) is achieved.
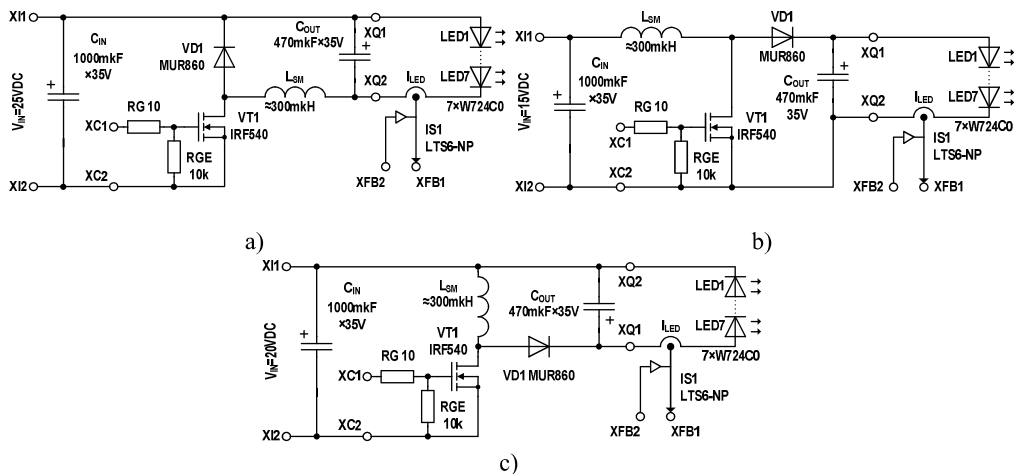

Fig. 1. DC/DC converters for light regulation with LEDs: a) buck; b) boost; c) buck-boost

Voltage modulation methods

The above mentioned converters are pulse mode circuits, where transistor has to be controlled by a pulse mode signal. Then its duty cycle defines the amount of energy transferred from the input of the converter to its output. There are several approaches of generation of such signal depending on a control command.

The most widely used is PWM (Fig. 2-a), which provides the required duty cycle with constant period of the pulse signal. In case of PWM the value of the carrier frequency has a significant impact on the losses in the converter. That is way this method has been tested with several frequency values (40, 80 and 120kHz).There are plenty of control hardware and software solutions for PWM generation.

Another approach is frequency modulation (FM) at which the required duty cycle is obtained with variable period or frequency. At FM either pulse or pause may be constant or both of them may be variables.

In the case of buck converter applicable values of the duty cycle are within the range of 68…100% (for the input voltage equal to the minimal LED voltage 17V). Higher accuracy of the duty cycle [8] for such range can be achieved with fixed value of the pause and variable value of the pulse width. This modulation method is described in [8] as a Constant Pause Frequency Modulation (CZFM – Fig. 2-b).

In the case of boost converter the range of the duty cycle is 0…32%. Higher accuracy of the duty cycle for this range is possible with fixed value of the pulse and variable value of the pause. This modulation method is described in [8] as a Constant Pulse Frequency Modulation (CPFM – Fig. 2-c).

In the case of buck/boost converter its input voltage is 21V that for output voltage range 17…25V requires the values of duty cycle 45…54%. The output voltage 21V is obtained at D=50%. Then the higher accuracy of the duty cycle for D>50% is achieved with rising pulse width, while D<50% requires rising pause width. This brings forward more complicated Variable Pulse and pause FM (VPZFM – Fig. 2-d) that produces the maximal switching frequency at 50% but the minimal at the ends of the working range (at 45 and 54%).
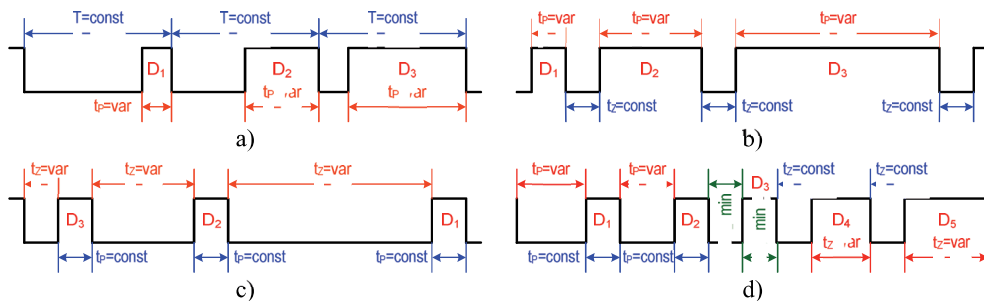

Fig. 2. Pulse modulation methods for LED dimmers: a) pulse-width modulation; b) constant pause frequency modulation; c) constant pulse frequency modulation; d) variable pulse variable pause frequency modulation

Numerical calculation of losses

There are three major sources of losses for those DC/DC converters: MOSFET VT1, diode VD1 and inductor L_{SM}. Losses in semiconductor devices can be divided into switching (ΔP_{sw}), conduction (ΔP_{cond}) and blocking (ΔP_{bl}) components. The switching losses are proportional to operation frequency. The conduction losses are defined mostly by the operation current of elements and their internal parameters. Blocking (leakage) losses normally are neglected. Inductor losses also can be divided into core (ΔP_{Lcore}) and conduction loses (P_{Lcond}).

The expressions required for calculation of power losses in buck and boost dimmers (Table I) are based on the power equilibrium for input voltage V_{IN} and output current I_O. It is also assumed that the inductance of the coil is infinite – i.e. the switch and diode conducts pulse mode current.

LED load is composed of seven W724C0 diodes (manufactured by "Seoul semiconductor") connected in series. Volt-ampere curve of this load has been measured experimentally (Fig. 3). Nonlinearity of

this curve is represented as no consumption at voltage less than 17V and linear load 0…3A at voltage of 17…25V (differential resistance is 8V/3A=2.67Ω):

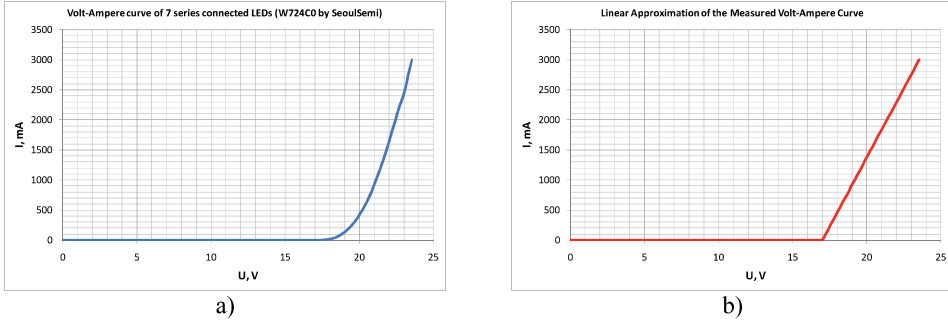$$I_O = \frac{V_O - 17V}{25V - 17V} \cdot 3A . \tag{1}$$

Fig. 3. Volt-ampere curve of 7 series connected LEDs W724C0 (Seoul Semiconductor): a) measured curve; b) linear approximation of the measured curve

From Table I and (1) follows that in the buck converter the on-state losses of the transistor dominate at high duty cycles, while in the boost converter – the diode losses are more significant. Besides that it is obvious that the on-state losses of the boost converter are higher in absolute value (mostly due to diode losses). Indeed, if power of converters is the same, the boost converter has much higher input (coil) current that leads to higher losses in semiconductor switches.

Table I. Calculation losses of buck and boost dimmers

Conv.	$V_O(1)$	$I_L(2)$	$P_{VD}(3)$	$P_{VT}(4)$
Buck (A)	$V_{IN} \cdot D$	I_O	$V_{VDon} \cdot I_O \cdot (1-D)$	$R_{VTon} \cdot I_O^2 \cdot D$
Boost (B)	$\dfrac{V_{IN}}{1-D}$	$\dfrac{I_O}{1-D}$	$V_{VDon} \cdot \dfrac{I_O}{1-D} \cdot (1-D)$	$R_{VTon} \cdot (\dfrac{I_O}{1-D})^2 \cdot D$

The configuration of the dimmer has impact on its switching losses too. The technology of calculation of these losses is given in [9]. In slightly simplified version (for the worst case analysis) it is represented by the following formulas:

$$\Delta P_{VT} = (E_{VTton} + E_{VTtoff}) \cdot f_{SW} , \tag{2}$$

$$\Delta P_{VD} = (E_{VDrr} + E_{VDtoff}) \cdot f_{SW} \approx E_{VDrr} \cdot f_{SW} , \tag{3}$$

$$E_{VTton} = V_{DS} \cdot I_{Dton} \cdot \frac{t_{Irise} + t_{Vfall}}{2} + Q_{rr} \cdot V_{DS} , \tag{4}$$

$$E_{VTtoff} = V_{DS} \cdot I_{Dtoff} \cdot \frac{t_{Vrise} + t_{Ifall}}{2} , \tag{5}$$

$$E_{VDrr} = \frac{V_{DS} \cdot Q_{rr}}{4} . \tag{6}$$

where voltage rise and fall times are found as:

$$t_{Vrise} \approx V_{DS} \cdot R_G \frac{C_{GD}}{V_{GSload}} , \tag{7}$$

$$t_{Vfall} \approx V_{DS} \cdot R_G \frac{C_{GD}}{V_{DR} - V_{GSload}} . \tag{8}$$

Other parameters are either known as the initial conditions (V_{DS} – is operation voltage of the switch is equal to V_{IN} for buck, V_O – for boost and $V_{IN} + V_O$ – for buck/boost converter; I_{Dton} and I_{Dtoff} –

commutated current at turn-on and turn-off transients respectively are assumed to be equal to I_O, f_{SW} – switching frequency, R_G – value of gate resistor) or found from the datasheets (Q_{rr} – reverse recovery charge of the utilized diode, t_{Irise} and t_{Ifall} – drain current rise and fall time, C_{GD} – gate to drain capacitance, V_{GSload} – gate voltage at the drain equal to load).

Equations (2)…(8) provide a basis for switching loss calculation. However, distribution of the losses across the operation range depends on the dimmer.

In the case of buck converter $V_{DS}=V_{IN}$ is a constant, $I_D=I_O$ depends on the duty cycle as expressed in (1), but the switching losses of the transistor rise linearly with current.

In the case of boost converter when $V_{DS}=V_O$ the losses are also a function of the duty cycle (Table I – B1). At the same time $I_D=I_{IN}$ that can be expressed by (B2), where I_O is still expressed by (1). Therefore, in this converter transistor commutates the current that, due to power equilibrium, undergoes doubled $1/(1-D)$ effect. This leads to more strong impact of D on the switching losses.

Losses of the inductor have been calculated with "Inductor Design Software 2010" provided by Micrometals Inc [10]. The result of the calculation is added to those made with (1)…(8) thus forming the final result.

Taking in account the above-described reasons and the parameters of the chosen components the efficiency of the converters has been calculated and listed in Table II. Two basic tendencies can be observed in this table: 1) boost converter is less efficient (mostly due to the higher conduction losses of its diode); 2) FM provides more constant efficiency over the complete range of the output power. It has been found that more detailed estimation of the losses through simulation and experiments is required.

Table II. Numerical calculation of losses of DC/DC converters

P_{OUT} $P_{max}=70W$	Buck 10kHz	Buck 40kHz	Buck 80kHz	Buck CZFM 4µs	Boost 10kHz	Boost 40kHz	Boost 80kHz	Boost CZFM 4µs
0.1 P_{MAX}	92%	92%	87%	90%	89%	89%	86%	87.5%
0.5 P_{MAX}	97.5%	96.5%	95%	96%	91%	91%	90%	90%
0.9 P_{MAX}	98%	97%	96%	97%	90.5%	90.5%	89.5%	90%

Preliminary Simulation of Converters

Initial evaluation of the DC/DC buck and boost dimmers has been made by means of PSpice simulation. For the most of the elements a compromise between the complicity of its model and tolerance has been reached: power diode and MOSFET are simulated as proper PSpice models with particular values of parameters corresponding to datasheets of elements. At the same time models of the coil and LED load utilize macro-circuits that were built also based on datasheet parameters of these elements. Input voltage source, control source and driver have been simulated as ideal elements. The simulation results of the buck and boost converters are presented in this subsection. The switching frequency in the simulation has been set to 40 kHz, 80kHz and 120kHz.

The initial simulation shows basically the same tendencies as the previously presented numerical analysis: 1) buck converter is more efficient (due to lower on-state losses of the diode); 2) FM provides better results than PWM especially for buck converter where switching losses are dominant. However, further experimental investigation is necessary in order to prove these conclusions.

Table III. PSpice simulation of DC/DC converters with different modulation techniques

P_{OUT} ($P_{max}=70W$)	Buck $V_{IN}=25V$ PWM100kHz	Buck $V_{IN}=25V$ CZFM 2µs	Boost $V_{IN}=17V$ PWM100kHz	Boost $V_{IN}=17V$ CPFM 4µs	Buck-Boost $V_{IN}=22V$ PWM100kHz	Buck-Boost $V_{IN}=22V$ VPZFM f_{MAX} 100kHz
0.1 P_{MAX}	98%	98%	95%	96%	94%	94%
0.5 P_{MAX}	98%	98%	93%	94%	89%	89%
0.9 P_{MAX}	97%	98%	92%	92%	85%	85%

Experimental comparison of losses for different modulation methods

A series of experiments have been conducted in order to find the actual effect of the modulation method and converters topology. The corresponding plots are presented in Fig. 4.
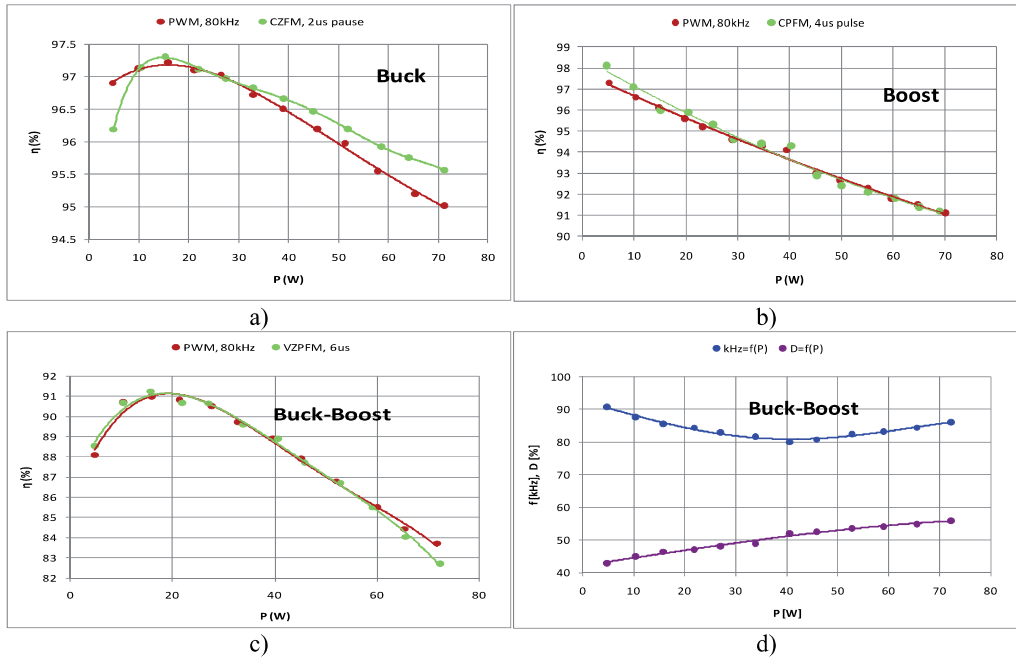

a)   b)

c)   d)

Fig. 4. Dimming DC/DC choppers for light regulation with LEDs: a) buck; b) boost; c) buck-boost; d) frequency and duty cycle vs. output power

As obvious form these plots the buck converter has better efficiency over almost all power range and with all control methods. It must also be noted that FM has positive effect in the case of the buck converter, while the boost converter shows almost no difference. This can be explained by the dominance of the conduction losses in the case of the boost converter and commutation losses – in the case of the buck converter. Then the decreasing of the frequency (at higher duty cycle and output power) leads to significant reduction of the total losses. The dominance of the conduction losses in the boost converter may be also a reason for its lower efficiency. The arguments valid for the boost converter are quite valid also for buck/boost due to the similar configuration of its input. For this reason conduction losses in this converter are also significant. At the same time, as it is obvious from Fig. 4-d, frequency and duty cycle variations for this converter and frequency modulation strategy are not very high. For this reason loss distribution in the case of pulse width and frequency modulation is similar, but impact of the frequency modulation – weak.

Impact of features of converters on their efficiency

Another series of experiments has been conducted with different values of the switching frequency, inductance, as well as with different configurations of the coil. The purpose of these experiments is determination of impact of the mentioned features on the efficiency of converters.

Buck converter

Efficiency of the buck converter has been evaluated with three switching frequencies - 40, 80 and 120kHz (Fig. 5Fig. 4-a). It is obvious that the overall efficiency of the converter decreases with frequency growth. The reason is the increasing increased switching losses in semiconductor switches, inductor core losses and skin effect.
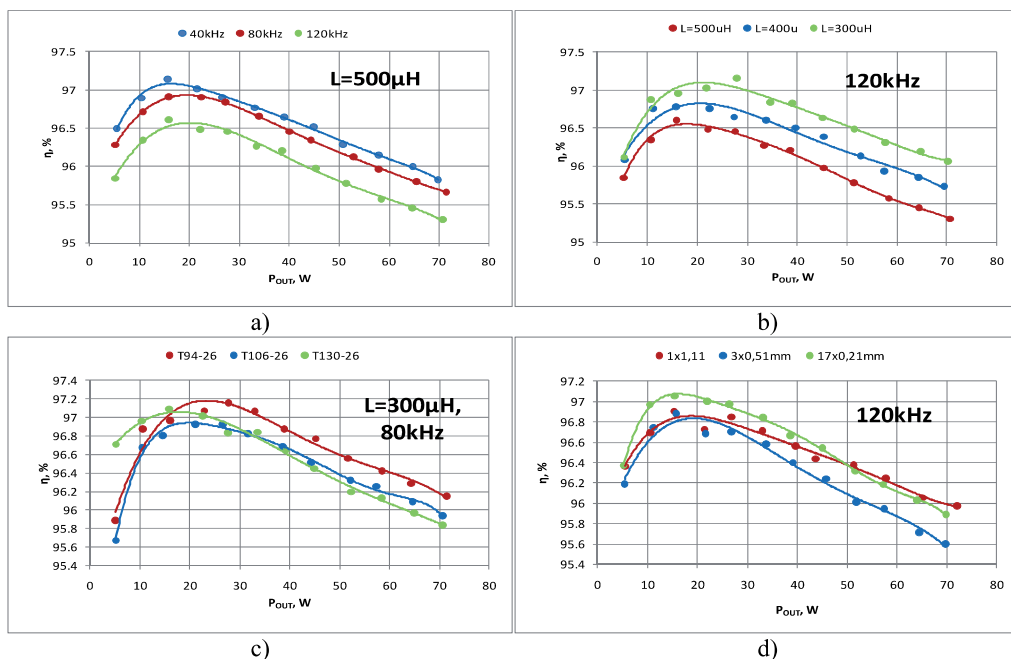
Fig. 5. Efficiency of buck converter: a) at different switching frequencies, b) at different values of inductance; c) with different core size of inductor; d) with different skin effect

Table IV. Exact parameters of inductance coil

Toroidal iron powder core T94-26		
Number of turns	Precise inductance at 25kHz, µH	Active resistance, mΩ
70	314	75
80	410	87
89	507	98
98	606	110

One more series of experiments has been conducted with different value of the inductance coil (Fig. 5-b). The tendency found in Fig. 5-b is the same for different frequencies – the efficiency curve becomes lower at bigger inductance. Besides that the efficiency increases at smaller output powers. Smaller inductances provide better performance at higher output powers because of their shorter wire length and, therefore, smaller active resistance (Table IV).

Table V. Exact inductor parameters for core size test

Inductance coil 300µH		
Core size	Exact inductance at 25kHz, µH	Active resistance, mΩ
T94-26	314	75
T106-26	311	75
T130-26	317	80

Table VI. Exact parameters of inductance coli for skin effect test

Toroidal iron powder core T94-26			
Precise inductance at 25kHz, µH	Wire diameter, mm	Active resistance, mΩ	Number of wires
307	0,21	80	17
317	0,51	80	3
320	1,11	60	1

Inductors with three different cores (T94-26, T106-26 and T130-26) have been investigated in order to evaluate the influence of core size of the inductor on the efficiency of converter (Fig. 5-a). From Fig. 5-a is seen that bigger inductor core size is better at lower output power. At the same time at higher output power smaller core is preferable because of smaller active resistance of its wire (Table V).

Skin effect has been evaluated on the next stage (Fig. 5-b). This effect appears at higher frequencies and reduces effectively used conductor cross sectional area. To reduce conductors skin effect several parallel wires of the smaller diameter can be used (Table VI).

Boost converter

The analysis of experiments with boost converter shows almost linear decrease of efficiency with increase of the output power. This effect is slightly stronger at higher frequency (Fig. 6-a) and with bigger inductance (Fig. 6-b). The last phenomenon can be explained by growth of the inductors active resistance (Table VII).

The impact of inductors core size and the skin effect has been investigated also in the boost converter. However, Fig. 6 shows that this impact is quite weak. As previously, this can be explained with the dominance of on-state losses of the diode not only over switching losses, but also over losses of the inductor (both the copper losses and iron losses are relatively low).

Table VII. Exact parameters of inductance coil

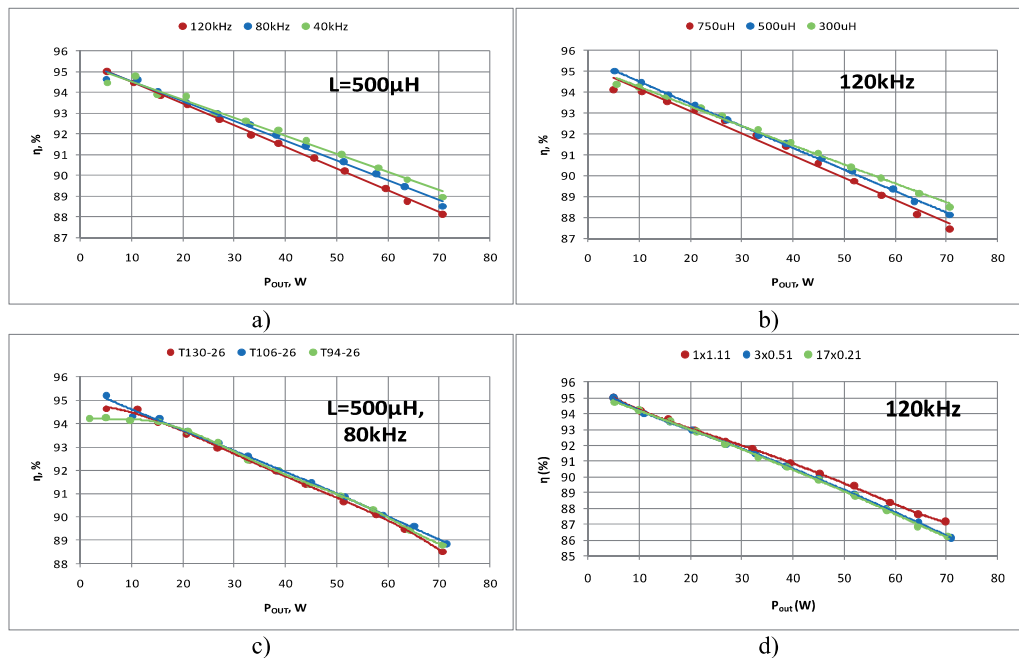| Toroidal iron powder core T106-26		
Number of turns	Precise inductance at 25kHz, µH	Active resistance, mΩ
64	317	88
80	510	105
98	761	151

Fig. 6. Efficiency of boost converter: a) at different switching frequencies; b) at different values of inductance; c) with different core size of inductor; d) with different skin effect

Conclusions

The above presented analysis, simulation results and results of experimental testing allow drawing several conclusions. First of the all it has been found that the buck converter in LED control applications shows much better efficiency that the boost of buck/boost converters. This effect can be explained by the dominance of diodes on-state loses at particular duty cycles suitable for control of boost (0…32%) and buck/boost (45…54%) converters. At such duty cycles the diode of boost and buck/boost converters is conducting a significant part of the period and conducts high current that leads to high power losses. For this reason the impact of modulation mode, switching frequency and parameters of inductor on the losses of these converters is negligible as it is seen form Fig. 6.

Secondly, the effect of frequency modulation (that is significant in the case of buck converter and is called Constant Pause Frequency Modulation CZFM) is rather positive. It reduces switching and inductor losses of the converter at higher duty cycles that take place at lower switching frequency.

Thirdly, the impact of core size is quite significant in the case of buck converter. It depends on the iron losses that may be significant at higher frequency and full load, as well as on the copper losses that depend on the wire length and core size. A reasonable tradeoff between cores size, iron losses (higher for smaller cores), copper losses (higher for bigger cores) and price has to be found. In this work cores were slightly oversized and, for this reason, wire length and copper losses were more significant.

The same can be said about winding type. Utilization of smaller parallel wires reduces skin effect, but may lead to wire length increase. However, this feature has mostly positive effect on the losses.

It must also be noted that although buck/boost converter showed rather weak results it is quite reasonable to investigate it (and identically controlled circuits) with different working ranges of the duty cycle. Right choice may diminish conduction losses and increase impact of modulation mode and other parameters.

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A CONCEPT OF LABORATORY TESTBENCH FOR INVESTIGATION OF LED DIMMERS

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Abstract – Основной целью данной работы является разработка испытательного стенда, пригодного для испытаний электронных балластов осветительных светодиодов. В статье оцениваются возможные конфигурации такого стенда, а также варианты его отдельных блоков. В статье также сравнивается энерго- эффективность и управляемость понижающе/повышающего и понижающего преобразователей напряжения, работающих в качестве светодиодных балластов.

Keywords – Освещение, электронный балласт светодиодов, энергоэффективность.

REVIEW OF ADVANTAGES AND DRAWBACKS OF LED TECHNOLOGY

Artificial lighting is one of the most energy consuming areas in the world [1]. Therefore, increasing energy efficiency of lighting systems is very important and could give significant energy savings. The reduction of energy consumption can be achieved by two strategies: use of more energy efficient lighting technologies and use of intelligent lighting control solutions.

Implementation of LED luminaries gives the opportunity to implement both methods. As a rather new technology, LEDs provide higher efficacy [2] which also today is still increasing [3], better quality of light and are ecologically friendly. The life time of LEDs is significantly longer if compared to traditional lighting sources. They also do not emit IR-radiation and it is possible to use them in IR critical environments. Furthermore, the dimming of LEDs does not have negative impact on them.

The main disadvantage of LEDs is that they are currently more expensive than conventional lighting technologies. Other disadvantage of LEDs is their high heat sensitivity and need for a cooling system. LEDs are also low voltage elements and for this reason they require a special power sources (electronic ballasts), which makes lighting system more expensive. The main parameter is energy efficacy. LEDs have the biggest value of efficacy.

LIGHT REGULATION TECHNIQUES OF LEDS

LEDs are low voltage semiconductor devices that can be connected to AC network only through a converter that operates as voltage source or current source. At the same time there are three main methods of regulation of light intensity of LEDs: fluent regulation of LED's current and flux, pulse mode regulation of LED's current and flux, stepwise regulation, commutating LED groups. The comparison of the above mentioned regulation methods and both energy sources is presented in Table 1.

A. Fluent Mode Regulation

Fluent regulation of luminous flux by current regulation is a method when the value of luminous flux can be of any value between maximum and zero. This method has two significant disadvantages. Firstly, the LED brightness is not completely proportional to current. Secondly, not only luminous flux but also the wave length and therefore color of light are different at different values of LED current.

B. Pulse Mode Regulation

With pulse regulation method the value of luminous flux can be either the maximum value or zero. The average brightness of LEDs depends on the ratio of on-time to the switching period of LED. In this case the LED brightness can be adjusted by the most common method – pulse width modulation

(PWM). However, this method provides pulse pattern of instantaneous luminous flux. When the frequency of modulation is low, the pulsating character of light becomes visible to human eye. When the frequency is high a stroboscopic effect may appear [4] and [5].

C. Step Mode Regulation

With this method luminous flux changes stepwise over a range of fixed values between maximum and zero. Dividing LEDs in groups gives an opportunity to regulate brightness with a certain constant step.

Table 1

Method	Source	Advantages	Disadvantages
Fluent regulation	Current	• One source	• Current source should be regulated
	Voltage	• One source	• Voltage source should be regulated • Narrow usable voltage range
Pulse regulation	Current	• One unregulated source	• Current source, switch is needed
	Voltage	• One unregulated source	• Switch is needed
Step regulation	Current	• One source	• Current source, should be "n" number of switches
	Voltage	• Voltage sources for each group of LEDs	• should be "n" number of switches

As it is seen from Table 1, pulse mode regulation seems to be the most simple and useful method but it is necessary to take into account its disadvantages which are related to pulsating character of luminous flux (flickering, stroboscope effect). Fluent regulation and group regulation methods should be investigated more carefully. Preliminary comparison shows that both these methods have advantages and drawbacks.

DEVELOPMENT PROCEDURE OF THE TESTBENCH

This work is focused on elaboration of an easy reconfigurable testbench for investigation of light regulation methods for LEDs. Development of such testbench consists of several tasks. First, power of LED matrix and its configuration should be chosen. Second, the overall structure of testbench should be selected. Third, parts of the selected structure have to be chosen.

A. Selection of LED Matrix

The number and configuration of LEDs have been chosen taking into account the following considerations. Firstly, the group method of light regulation requires sufficient number of LEDs. If the minimal step of light changes is about 5% (reasonable minimum for some street lighting applications) then the number of LEDs must be about 20. Secondly, available armature for the testbench is not very big and cannot dissipate power more than 20W. Thirdly, available LEDs are of 1W power. Taking into account possible hexagonal placement of LEDs the final configuration is 19 1W LEDs. The total power of such matrix is about 20W.

The placement of LEDs in the matrix must ensure symmetrical distribution of active LEDs when some of them are off. Fig. 1 shows two possible configurations of the matrix. The first one (Fig. 1-a) presents a full three level hexagonal placement of 19 LEDs intended for binary weighted groups (1, 2, 4, 8 and 4). Another configuration (Fig. 1-b) is aligned for equal groups of 2, 3, 6 or 9 (the figure shows 6 groups of three LEDs).
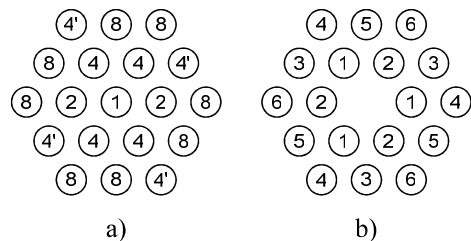

a)   b)

Fig. 1. Physical placement of LEDs in matrix: a) binary weighted groups; b) equalized groups.

B. Selection of Structure of the Testbench

First step of the laboratory prototype design procedure is selection of its overall configuration: monolithic or composite (composed of different blocks). The comparison of model types, their pros and cons are presented in Table 2.

Table 2

Type of model	Advantages	Disadvantages
Monolithic	• Gathered scheme • Ready to use • High efficiency	• Poor possibility to research regulators
Composite	• Easy reconfigurable • Convenient for research	• Lower efficiency • More complex construction • Big size

The composite model shown in Fig. 2 has been chosen, because further research will be held on LEDs and their characteristics at the different methods of regulation. It consists of primary power supply, secondary regulator and the LED matrix. Such structure gives opportunity to investigate different regulators with different configuration of the LED matrix. One more expansion of the described ballast is a communication module that provides an opportunity of external control that is necessary for development of smart lighting system.
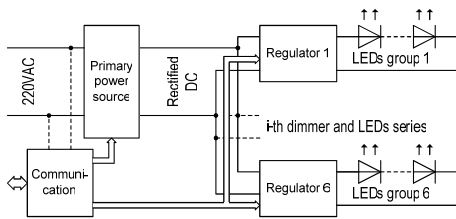
Fig. 2. Composite model of the LED ballast testbench.

C. Choice of Primary Power Source

It is necessary to determine main parameters of the primary supply before designing it. Input voltage of this supply is AC grid voltage 220V. Since the buck converter has been chosen as the secondary regulator, the output voltage of AC (primary) power source should be 70V (19 series connected 1W LED – in the rated point of operation). Assuming the worst case efficiency of secondary regulator (90%) and primary power supply (90%) the power of supply is 20/(0.9*0.9)=25W. LEDs in the matrix are connected in series, therefore the current of the primary AC source is equal to the rated LED current 280mA (for 1W device). Modern equipment should consume a sinusoidal current. Primary power source with diode bridge and output capacitor does not satisfy this requirement. Therefore a PFC has to be included into the schematic. Power line and LED part should have galvanic isolation for safe use of AC power source. For this reason a flyback topology equipped with a power corrector has been chosen.

D. Overview of Luminous Flux Regulators

Pulse Mode Luminous Flux Regulators

Pulse regulators provide square shaped current pulses to LEDs. They can be divided into two groups: indirect voltage regulators and direct current regulators. In voltage regulator a controllable switch (MOSFET) is connected in series with LEDs. This configuration is a simplified voltage buck converter with PWM regulation utilizing the switch. In current regulator the switch is connected in parallel with LEDs and shorts them.

LED Groups Luminous Flux Regulators

With this method regulation of the overall luminous flux is done through separate powering of each group. Regulators for commutation devices can be divided into voltage and current regulators. Besides that equal group approach and weighted group approach can be emphasized. In case there are different numbers of LEDs in groups each group gets power from its own voltage source. Otherwise several voltage sources have to be utilized. In the case of current mode power supply the current source is the same for all groups, but each group has its own short-circuiting switch.

Fluent mode regulators for initial debugging

The last part of the chosen testbench topology is the secondary regulator of LEDs current. It may be built as a current source that has direct influence on the light produced by LEDs or as a voltage source that applies voltage to LEDs that, in turn, initiates LED current. Both approaches have their own pros and cons. However, at the initial stage, for simplicity and safety reasons voltage source topology has been chosen for initial debugging.

There are several well known topologies of switch mode voltage regulators such as buck, boost, buck-boost [6], SEPIC, Cuk [7] and flyback. With the chosen topology (primary power supply produces the maximal voltage of LED series) of the testbench only circuits with step-down capability are suitable. The set of such converters includes buck converters and buck-boost converters (like Cuk, SEPIC and flyback) in the buck mode of operation.

In order to find the most suitable solution buck and buck/boost converters have been developed (Fig. 3) and tested together with LED load.

EXPERIMENTAL COMPARISON OF FLUENT MODE REGULATORS

The mentioned buck and buck-boost converters (in the buck mode) for fluent mode regulators have been developed, assembled and tested. These circuits have been studied from the point of view of their efficiency and controllability (with a digital control system) in two modulation modes: PWM and constant pause frequency modulation (CZFM) [8].

A. Comparison of efficiency

The experimentally obtained efficiency, duty-cycle and switching frequency is presented in Fig. 4 and Fig. 5.
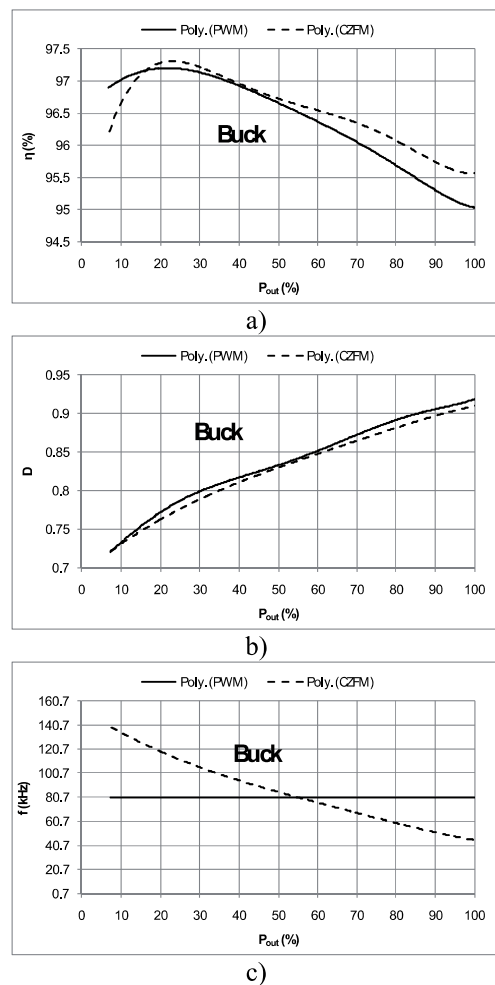

a)

b)

c)

Fig. 3. Topologies of fluent mode regulators for initial debugging: a) buck; b) buck/boost.

Fig. 4. Efficiency (a), switching frequency (b) and duty-cycle (c) of buck LED dimmer.
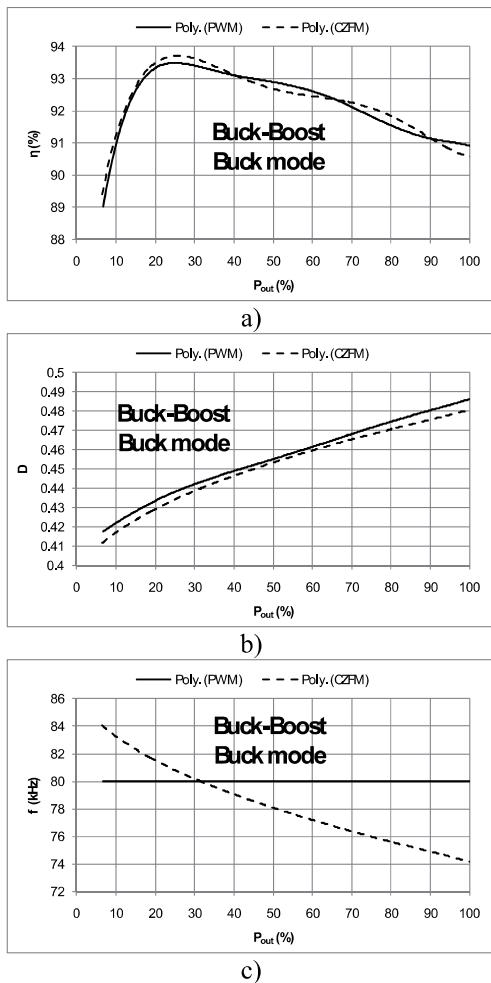
a)

b)

c)

Fig. 5. Efficiency (a), duty-cycle (b) and switching frequency (c) of buck-boost LED dimmer.

The presented data shows that: 1) the buck dimmer is more effective; 2) in the case of CZFM efficiency is less dependant on the output power. The lower efficiency can be explained by distribution of the on-state losses. In the case of buck converter due to the specific range of duty-cycle (75…100%) the transistor of converter is on during most of the switching period, while the diode is off. For this reason on-state losses of the diode are low due to low duty cycle, but those of transistor are low due to low on-state resistance. The total amount of on-state losses is then rather small and switching losses are dominant. This dominance is also

the reason for more "flat" loss distribution in the case of CZFM. Then, at higher duty-cycle frequency and switching losses are lower, but efficiency – higher.

In the case of buck-boost converter in the buck operation mode range of duty-cycle is 45…50%. Therefore, balance of the on-state losses is shifted to diode, but on state losses themselves are higher. In this case, due to the dominance of the on-state losses relative impact of the switching losses is negligible, but efficiency curves for PWM and CZFM are similar. The above mentioned assumption is also illustrated with duty-cycle and frequency graphs shown in Fig. 4-b,c and Fig. 5-b, c.

B. Comparison of controllability

The controllability is estimated with a set of parameters: 1) nonlinearity of control chain; 2) practical utilization of the duty-cycle and 3) its practical inaccuracy. The first parameter is important for estimation of stability of LED current regulator. It is defined as a root-mean-square declination of the actual regulation curve (Fig. 6) from the line connecting its end-points.
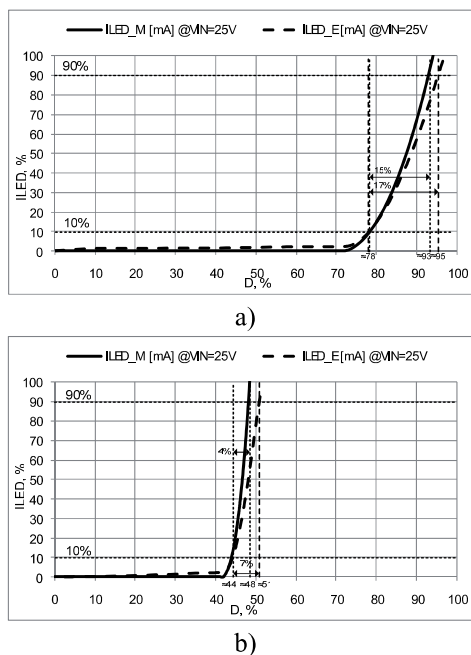

a)

b)

Fig. 6. Regulation curve of buck (a) and buck-boost converters (b).

The practical utilization of the duty cycle is defined as a ratio of those values of the duty-cycle that actually affect LED current to the whole range 100%. This parameter is shown graphically in Fig. 6. Another parameter is the practical inaccuracy of the duty cycle that is defined as a ratio of technically achievable inaccuracy of the duty cycle to its practical span. The last two parameters show real performance of the control system of the dimmer.

From Fig. 6 a certain difference between calculated and experimental curve can be seen. It can be explained by non-ideality of real converters that is especially significant in the case of the buck-boost converter.

The above mentioned calculated and measured controllability parameters are presented in Table 3. As can be seen from this table, nonlinearity has no dependence on the type of dimming converter (although it is a little bit higher for buck-boost converter). Practical utilization of the duty cycle is better for buck converter supplied with input voltage equal to maximal operating voltage of the LEDs. Practical inaccuracy is reversely proportional to the practical span. For buck converter it is lower than for buck-boost converter.

Table 3

	Buck Calculated (measured)	**Buck-Boost** Calculated (measured)
NL	16% (12%)	18% (11%)
D_{SPAN}	15% (17%)	5% (7%)
ΔD_P	6.7 (5.9)	20 (14.3)

SUMMARY AND CONCLUSIONS

In the paper a concept of laboratory testbench for LED dimmer research purposes has been presented. After brief analysis it has been concluded that the most suitable configuration of the testbench is a composite system (with LED matrix, primary power supply and a dimmer) that provides higher flexibility for further research. Stages of development of the testbench have been briefly discussed.

Various fluent mode voltage type LED drivers have been compared. Two of them (buck and buck-boost dimmers) have been experimentally investigated. It has been concluded that PWM/CZFM controlled buck dimmer provides better efficiency and is more controllable.

Finally it has been concluded that the developed testbench provides a good basis for future works focused on the experimental research of various LED light regulators.

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Design of Primary Power Supply for Composite LED Luminary

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Abstract-The main purpose of this work is to design a primary power supply for composite LED luminary. The achievement of this aim includes choice of topology of the power supply, its components and step-by-step design of the chosen converter. In the paper the final configuration of primary power supply, which is needed to convert AC voltage of the grid into DC voltage on the output providing at the same time an output current limitation function, is presented. Particular schematic solution of luminary primary power supply is presented.

I. INTRODUCTION

Design of the converters for efficient lighting is one of the most rapidly developing fields of the modern electronic [1]. Artificial lighting consumes significant part of all electrical energy consumed worldwide. Therefore, increasing energy efficiency of lighting systems is very important and could give significant energy savings. The reduction of energy consumption can be achieved by two strategies: use of next generation lighting technologies or use of intelligent lighting control solutions.

Implementation of LED luminaries gives the opportunity to implement both methods. Although they are many relatively new players in industrial and residential lighting, LEDs provide higher efficacy [2], better quality of light and are ecologically friendly. The life time of LEDs is significantly longer if compared to traditional lighting sources. They also do not emit IR-radiation and it is possible to use them in IR critical environments. Furthermore, the dimming of LEDs does not have negative impact on them.

The main disadvantage of LEDs is that they are currently more expensive than conventional lighting technologies. Other disadvantage of LEDs is their high heat sensitivity and need for a cooling system. LEDs are also low voltage elements and for this reason they require a special power sources (electronic ballasts), which makes lighting system more expensive.

LED is a diode structure is essence, so the current and voltage of the LED has the exponential relationship. Small changes of the forward voltage will cause a much larger changes of current. For this reason, LED are more inclined to use with constant current flow driving instead of constant voltage driving [3].

There three basic kinds of luminous flux regulation and the corresponding electronic equipment: a) pulse mode; b) step mode and c) fluent mode luminous flux regulation presented in Fig. 1.

A) Pulse mode regulation takes place when the luminous flux may be either zero or maximal. The average value then is defined by the duty cycle of the luminous flux pulses.

B) These converters are in fact arrays of electronic switches for commutation of LED groups. Regulation of the overall luminous flux is done through separate powering of each group by switches driven by the control system. It is obvious that the maximal number of regulation steps is equal to the number of LEDs while the step of regulation is equal to power (or light) of a single LED. At such regulation approach switch arrays can be supplied from either voltage or current sources. The configuration of switch arrays is different for these two occasions.

C) Continuous regulation provides all values of the luminous flux from zero to the maximum.

In the previous papers of authors the composite LED luminary has been chosen [4], [5], because further research will be held on LEDs and their characteristics at the different methods of regulation. It consists of primary power supply, secondary regulator and the LED matrix. Such structure gives opportunity to investigate different regulators with different configuration of the LED matrix.

As it has been mentioned above LED are low voltage devices and they need a special power supply that can be built as a current source or voltage source. Investigation of these regulators is question of further research.
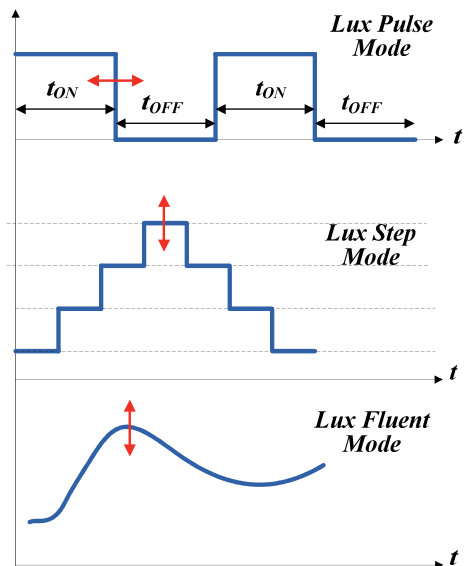

Fig. 1. The basic kinds of luminous flux regulation.

It is advantageous to supply LEDs from current sources, but nowadays most of available regulators operate as voltage sources. In order to convert a voltage regulator to a current regulator, it is necessary to modify the scheme. This paper presents the basic steps of design of primary power supply for composite LED luminary.

II. Primary Power Supply

The design of AC/DC power supply involves many aspects of electrical engineering: analog and digital circuits, MOS power device characteristics, magnetic, thermal considerations, control loop stability, etc. The design of a switch mode power supply is iterative process with many variables that have to be adjusted to optimize the design.

This paper presents design considerations of a power supply for LED luminary systems. It includes designing the transformer and output filter, selecting the components, and implementing constant- current control. The step-by-step procedure completes a power supply design.

The chosen power supply is based on flyback topology, because nowadays there are many integrated solutions for this topology are presented on the market. The flyback topology has also been chosen because it has a low parts count, wide input voltage range, inherent feedback voltage sensing, single or multiple output voltage capability, output voltages that can be higher or lower than the input voltage, and ability to provide both positive and negative voltages. The particular design is based on a TOP-Switch IC made by Power Integrations [6]. The basic circuit configuration flyback power supply is shown in Fig. 2.

Typical waveforms of a flyback converter operation are presented in Fig. 3. Discontinuous Conduction Mode (DCM) operation is preferred for primary-side regulation since it allows better output regulation and includes one zero-current commutation.

In DCM there are three distinct stages in each operation cycle. *Stage I* – During the MOSFET ON time (t_{ON}), input voltage (VAC) is applied across the primary-side winding. Then MOSFET current increases linearly from zero to the peak value (I_{PK}). During this time, the energy is drawn from the input and stored in the transformer. *Stage II* – When the MOSFET is turn off, the energy stored in the transformer forces the rectifier diode (D7) on the secondary side to be turned on. During this stage (t_{DIS}), the output voltage (VDC), together with diode forward-voltage drop (V_F) are supplied from the secondary winding and the diode current (I_F) decreases linearly from the peak value to zero. At the end of t_{DIS}, all the energy stored in the transformer has been delivered to the output.

Stage III –When the diode current reaches zero, the transformer windings begins to oscillate due to the energy stored in parasitic inductances and capacitances the primary winding and of MOSFET.

It is necessary to determine main parameters of the primary supply before designing it. With the basic circuit configuration shown in Fig.2, the logic behind this design approach can be summarized as following:

A) Determine system requirements and decide on feedback accordingly.

B) Design the smallest transformer for the chosen TOP-Switch.

C) Select all the other components in Figure 2 to compete the design.

Modern equipment should consume a sinusoidal current. Primary power source with diode bridge and output capacitor does not satisfy this requirement. Therefore a PFC has to be included into the schematic. Power line and LED part should have galvanic isolation for safe use of AC power source. This is the next reason why a flyback topology equipped with a power corrector has been chosen.
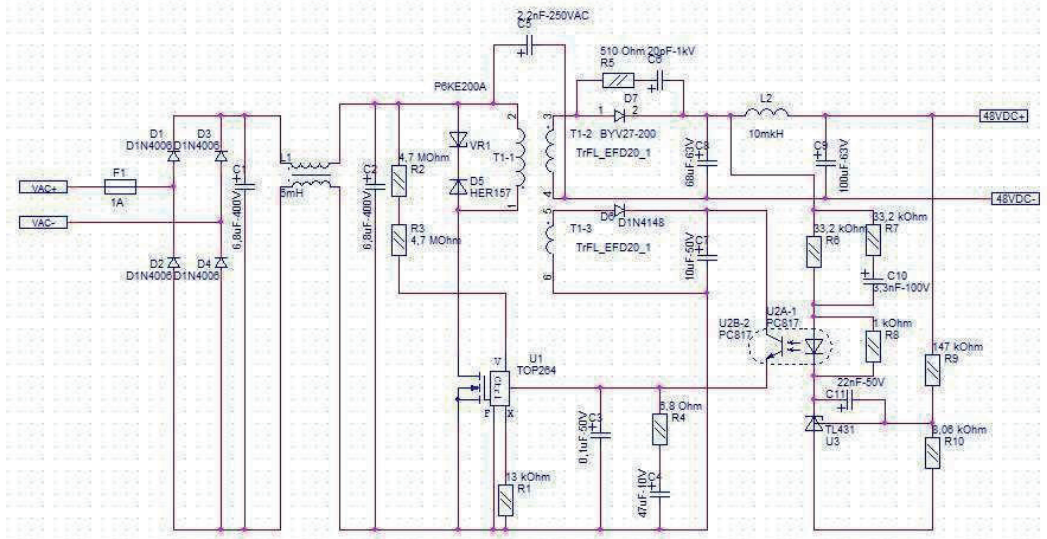

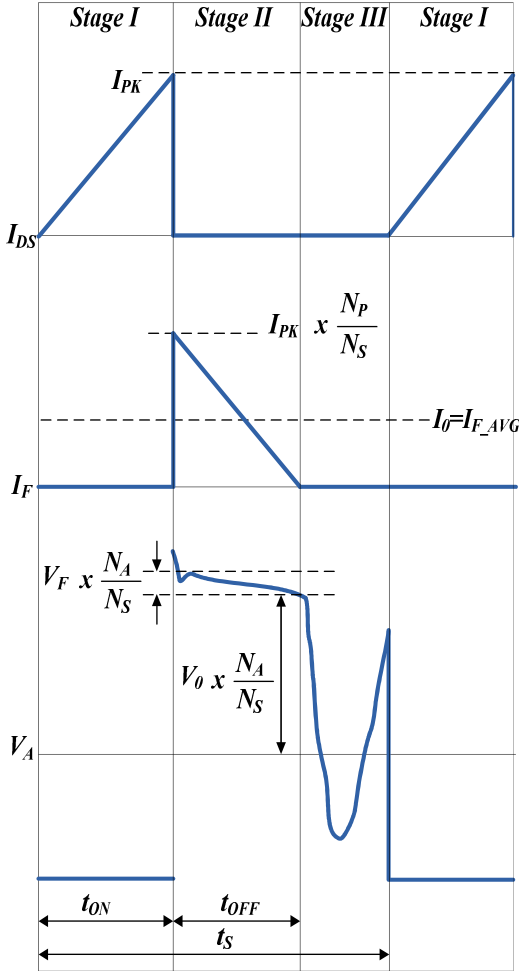Fig. 2. The basic configuration of flyback power supply.

Fig. 3. Key waveforms of flyback converter.

A. Determine System Requirements and Decide on a Feedback Circuit

Input voltage of this supply is AC grid voltage 220V. Efficiency η is the ratio of output and input power. Since efficiency can vary significantly with output voltage due to secondary diode loss, it is best to use a number that is representative of similar power supply [7]. Assuming the worst case efficiency of secondary regulator (90%) and primary power supply (85%) the power of supply is 20/(0.9*0.85)=26W.

For a power supply with an output power P_0 and an efficiency η, $P_0x(1- η)/ η$ watts of power is lost somewhere in the system: part in the secondary circuit and the balance in the primary circuits. It is important to know the loss distribution between primary and secondary because only the secondary losses represent power must be processed by the transformer and considered in the transformer design. For accurate feedback an opto-coupler and precise reference source (TL431) have been chosen.

B. Design the Smallest Transformer for the Chosen TOP-Switch

When developing flyback power supply based on TOP-Switch, transformer design is one of the stumbling phases of design. A transformer in flyback topology stores energy in the core. The core must be gapped. Current effectively flows in either the primary or secondary winding but never in both windings at the same time [8].

Proper transformer optimal construction techniques are necessary for reducing common mode emissions. The first step in the design is choosing of the minimum transformer size consistent with the output power requirements. In the proposed design an EF20 transformer has been chosen at first iteration. In addition to the selection of core size, a total number of parameters must be specified in the construction of the transformer: primary inductance L_p, core gap length L_g, number of turns for primary N_p, secondary N_s and bias N_B, wire outside diameter for primary OD and secondary OD_S, bare conductor diameter for primary DIA and secondary DIA_S.

The primary number of turns N_P is related to the secondary number of turns N_S by the ratio between V_{OR} and V_O+V_D, (1):

$$N_P=N_S\times\frac{V_{OR}}{V_O+V_D} ,\qquad(1)$$

where V_{OR} is the allowed reflected output voltage V_O is the output voltage and V_D is the output rectifier forward voltage drop.

Similarly, the number of bias winding turns N_B can be derived from (2):

$$N_B=N_S\times\frac{V_B+V_{DB}}{V_O+V_D} ,\qquad(2)$$

where V_B is the bias voltage and V_{DB} is the bias rectifier forward voltage drop.

From the core size, it is possible to determine the outside diameter of the primary wire OD in mm that is required to accommodate the primary turns in one or two full layers allowing for margins as appropriate.

The next step is to find out if the conductor size is sufficient for maximum I_{RMS}. Another critical parameter that must be checked is the maximum flux density in the core B_M (3):

$$B_M=\frac{100\times I_P\times L_P}{N_P\times A_e} ,\qquad(3)$$

where A_e is the effective cross sectional area of the core. This parameter can be found from the data sheet for the core.

One other parameter always required by transformer manufacturer is the gapped core effective inductance, A_{LG}, which can be determined only after N_P is fixed (4):

$$A_{LG}=1000\times\frac{L_P}{N_P^2} .\qquad(4)$$

The calculation parameters required for transformer design is presented in Table I.

TABLE I
CALCULATION PARAMETERS REQUIRED FOR TRANSFORMER DESIGN

Var	Value	Units
Core size	E20/10/6	
L_p	2349	
N_P	128	turns
N_B	13	turns
N_S	46	turns
B_M	2091	Gauss
A_e	32,10	mm^2
A_{LG}	145	nH/T^2
CMA	266	Cmils/A

TABLE II
RESULTS OF SELECTION COMPONENTS FOR PRIMARY POWER SUPPLY

Var	Value	Units
Output voltage	48	VDC
Output current	0,35	A
Output capacitor (C8)	68	μF
I_{RIPPLE}	0,40	A
I_{SRMS}	0,53	A
I_O	0,35	A
Bias capacitor (C7)	10	uF
Post filter inductance	100	mkH
Post filter capacitor	100	uF

C. Selecting all the Other Components to Complete the Design

Output rectifier: The diodes should be with a reverse voltage rating V_R equal to or greater than $1,25 \times PIV_s$, at no more than 80% of the diode V_R rating (PIV_s is peak inverse voltage across the secondary rectifier diode).

Output capacitor: Equivalent Series Resistance (ESR) is the most important parameter for output filter capacitor selection. Capacitor ESR directly determines the output ripple voltage of the power supply and the ripple current rating of the capacitor while actual capacitance value only affects control loop bandwidth.

Actual ripple current of the output capacitor can be calculated as follows (5):

$$I_{RIPPLE} = \sqrt{I_{SRMS}^2 - I_O^2} \qquad (5)$$

where I_{SRMS} is the secondary winding RMS current and I_O is the DC output current.

Bias rectifier and capacitor: Bias rectifier selection is similar to output rectifier selection with the exception that since the bias winding carries very little current, the considerations for current capability and very fast recovery no longer apply.

Because of the low voltage and the minimal power required at the bias output, 10 uF.

Since the buck converter has been chosen as the secondary regulator, the output voltage of AC (primary)

power source should be 48V (15 series connected 1W LED – in the rated point of operation). LEDs in the matrix are connected in series, therefore the current of the primary AC source is equal to the rated LED current 350mA (for 1W device).

Table II presents the results of selection components for design power supply.

Following all steps procedure completes the design of a primary power source for composite LED luminary. Finally a 1N4006 diodes have been chosen as input rectifiers, 1N4148 diode has been chosen as the bias rectifier, HER157 – as blocking diode, core type was chosen as E20/10/6, as output diode was selected BYV26B, feedback opto-coupler is HCPL-817-060E.

III. ASSESSMENT OF WORK AND CONCLUSIONS

Designing power supply for high power LED is difficult task. In the paper the design of flyback primary power supply has been presented and described in detail. Steps of designing have been briefly discussed. LEDs usually take their drive from a constant dc-current source to maintain constant luminescence. Most dc/dc converters, however, deliver a constant voltage by comparing a feedback voltage to an internal reference via an internal error amplifier. The constant voltage feature provides output over-voltage protection in the case when an LEDs fail open-circuit. Constant current region in such power supplies provides an over-current protection function. Then further increase in the demand for load current causes the output voltage to drop. However, use of such supplies as current sources is quite questionable and requires some extra research.

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The author's contributions are: background analysis, preliminary simulation, preparing and editing the text, numerical calculations, preparing the diagrams, drawing conclusions.

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Weight and Size Estimation of Energy Efficient LED Ballasts

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Introduction

At the given time, the demand for electrical energy is growing while prospects of new electrical energy sources are quite questionable. This requires for an increase in energy efficiency that, in turn, can be achieved through increasing of self-efficiency of electrical technologies. Another way is making electrical equipment "smart" that means reasonable limitation of its operation. In particular, in the field of electrical lighting these two ways can be combined if Light Emitting Diodes (LEDs) are used [1]. On the one hand modern LEDs have efficacy of several tens lumens per watt that is comparable with high pressure sodium lamps. On the other hand it is possible to effectively adjust the light produced by LEDs with no negative impact on them. This paper estimates the efficiency of various LED ballasts in the context of optimization of their weight and size.

Amount of light produced by an LED is proportional to its current. This brings forward two light control methods [2]: 1) fluent regulation of LEDs current - when its value varies depending on the light request; 2) pulse mode regulation of LEDs current - when it is either zero or maximum but its average value varies depending on the light request. Since the light produced by LED follows its current at a very high rate [3] the second method may lead to flickering and stroboscopic effects. One more light regulation method [2] is possible because rated power of LEDs is usually small. For this reason LED luminary usually includes a number of LEDs. Then it is possible to divide them into groups and control each group separately. This method, however, ensures lesser dimming levels and lower accuracy of regulation. Therefore, the first regulation method – fluent regulation of LED current is preferable.

LED itself is a low voltage element. This mostly requires a DC/DC stage for dimming even if the LED luminary is fed from AC line. This argument is especially significant if the luminary has few LED groups that must be dimmed separately, for instance, in the case of street lighting. Various DC choppers can be used as the

regulators: buck, boost, buck-boost etc [4]. All these converters are pulse mode circuits that may be driven in different ways – pulse width modulation, frequency modulation etc. The chosen topology and control method has significant impact on the efficiency of the dimmer [5]. They also have influence on its size and weight.

The given paper investigates buck and boost dimmers operating in pulse width modulation mode form the point of view of weight/size and efficiency. The converters are estimated analytically and through simulation as well as tested experimentally. Then the conclusions about the optimal choice are formulated at the end.

General considerations

Weight and size of any electronic converter depend on those of its elements. However, from this point of view some elements are dominating over the others and their contribution has to be taken into account first. The most significant components of one-switch DC/DC dimmers are inductance coil, power diode and power transistor together with their heatsink (whose size depends on the power losses) and driver. Previous experience shows that they take up to 50% of the total volume and up to 40% of the total weight. That is why this paper is focused on the estimation of these elements.

In this research buck and boost topologies of the dimmers has been investigated due to their potentially better control performance.

Schematics of experimental setup for buck converter is shown in Fig. 1-a, but for boost – in Fig. 1-b. All elements of the testbench (VT1 – IRF540 MOSFET, VD1 – ultrafast diode MUR860, and the load containing seven series connected LEDs W724C0 made by Seoul Semiconductor) were the same during all experiments to ensure that difference of measured values between tests depends only on inductor parameter changes. Values of inductance coil L_{SM} were changed during experiments. Several values of the switching frequency have been applied as well. The output power has been used as an

argument for output curves.

Control signal have been obtained from a function generator G1 and fed to VT1 transistor through HCPL-J312 driver. To carry out measurements four Extech EX430 multimeters were used with 0.3% basic accuracy.
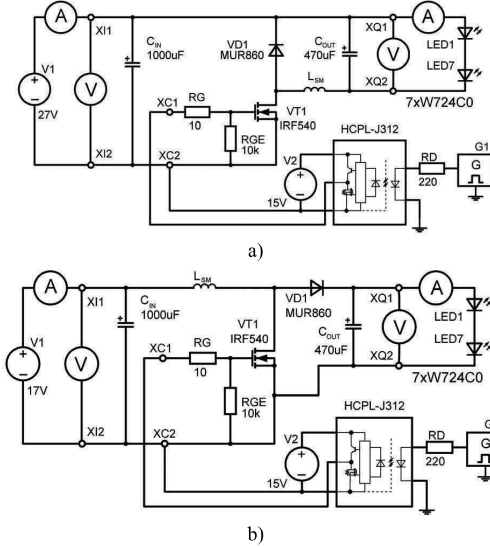

a)

b)

Fig. 1. Testbench for evaluation of dimmers for light regulation with LEDs: a – buck configuration; b – boost configuration

Estimated influence of parameters

Expected influence of the dimmer type. If the choice of input voltage for dimmer is not limited then the dimmer can also be quite arbitrarily chosen. In this case the impact of topology of the dimmer on its weight/size may be the main criterion for its choice. At the same time it must be noted that the influence of the topology is not direct.

The utilized diodes W724C have operating voltage of 2.5…3.6V that corresponds to operating current 0…2.8A. Therefore seven such diodes require from 17.5 to 25V for full range of current regulation. Such voltage can be obtained from a buck, boost or buck/boost converter. The last one does not provide good performance from the point of view of control and is not discussed here. The buck dimmer operates better (from the same point of view) at 25V input and requires 70…100% of duty cycle in this case. Similarly the boost dimmer must have 17.5V on its input and 0…30% of the duty cycle. Therefore, the first dimmer works with higher on-state losses in the switch while the second one – in the diode.

The expressions required for calculation of power losses in buck and boost dimmers (Table 1) are based on the power equilibrium for input voltage V_{IN} and output current I_O. It is also assumed that the inductance of the coil is infinite – i.e. the switch and diode conducts pulse mode current. Nonlinearity of LED load is represented as no consumption at voltage less 17.5V and linear load 0…3A corresponding to voltage of 17.5…25 V

$$I_O = \frac{V_O - 17.5V}{25V - 17.5V} \cdot 3A \,. \qquad (1)$$

Table 1. Calculation losses of buck and boost dimmers

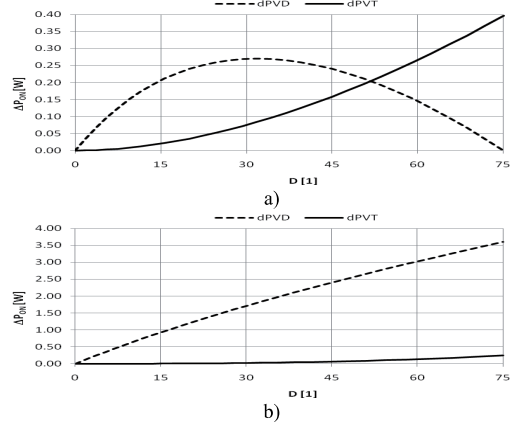| Conv.	V_O(1)	I_L(2)	P_{VD}(3)	P_{VT}(4)
Buck (A)	$V_{IN} \cdot D$	I_O	$V_{VDon} \cdot I_O \cdot (1-D)$	$R_{VTon} \cdot I_O^2 \cdot D$
Boost (B)	$\dfrac{V_{IN}}{1-D}$	$\dfrac{I_O}{1-D}$	$V_{VDon} \cdot \dfrac{I_O}{1-D} \cdot (1-D)$	$R_{VTon} \cdot (\dfrac{I_O}{1-D})^2 \cdot D$

a)

b)

Fig. 2. On-state losses of power diode and transistor in DC/DC LED dimmers: a – buck; b – boost
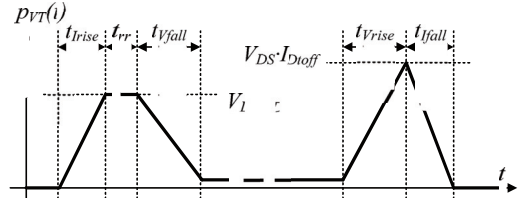

Fig. 3. Instantaneous power losses of a MOSFET transistor operating in a conjunction with a diode

Utilizing (1) and equations from Table 1 it becomes possible to calculate the power losses and present them graphically (Fig. 2). This picture demonstrates that, as it has been previously noted, in the buck converter on-state losses of the transistor dominates at high duty cycles, while in the buck – diode losses are more significant. Besides that it is obvious that the on-state losses of the boost converter are higher in absolute value (mostly due to diode losses). Indeed, if power of converters is the same then the boost converter has much higher input (coil) current that leads to higher losses in semiconductor switches.

The configuration of the dimmer has impact on its switching losses too. The technology of calculation of these losses is given in [6]. In slightly simplified version (for the worst case analysis) it is represented by the following formulas (see Fig. 3 for details):

$$\Delta P_{VT} = (E_{VTton} + E_{VTtoff}) \cdot f_{SW} \,, \qquad (2)$$

$$\Delta P_{VD} = (E_{VDrr} + E_{VDtoff}) \cdot f_{SW} \approx E_{VDrr} \cdot f_{SW} \,, \qquad (3)$$

$$E_{VTton} = V_{DS} \cdot I_{Dton} \cdot \frac{t_{Irise} + t_{Vfall}}{2} + Q_{rr} \cdot V_{DS} \,, \qquad (4)$$

$$E_{VToff} = V_{DS} \cdot I_{Dtoff} \cdot \frac{t_{Vrise} + t_{Ifall}}{2} , \qquad (5)$$

$$E_{VDrr} = \frac{V_{DS} \cdot Q_{rr}}{4} , \qquad (6)$$

where voltage rise and fall times are found as:

$$t_{Vrise} \approx V_{DS} \cdot R_G \frac{C_{GD}}{V_{GSload}} , \qquad (7)$$

$$t_{Vfall} \approx V_{DS} \cdot R_G \frac{C_{GD}}{V_{DR} - V_{GSload}} . \qquad (8)$$

Other parameters are either known as the initial conditions (V_{DS} – is operation voltage of the switch, I_{Dton} and I_{Dtoff} – commutated current at turn-on and turn-off transients respectively, f_{SW} – switching frequency, R_G – value of gate resistor) or found from the datasheets (Q_{rr} – reverse recovery charge of the utilized diode, t_{Irise} and t_{Ifall} – drain current rise and fall time, C_{GD} – gate to drain capacitance, V_{GSload} – gate voltage at the drain equal to load).

(2)–(8) provide a basis for switching loss calculation. However, distribution of the losses across the operation range depends on the dimmer. In the case of buck converter $V_{DS}=V_{IN}$ is a constant, but $I_D=I_O$ depends on the duty cycle as expressed in (1). Then the switching losses of the transistor rise linearly with current (Fig. 4-a).

In the boost converter $V_{DS}=V_O$, hence the losses are also a function of the duty cycle (Table 1-B1). At the same time $I_D=I_{IN}$ that can be expressed by (B2), where I_O is still expressed by (1). Therefore, in this converter transistor commutates the current that, due to power equilibrium, undergoes doubled $1/(1-D)$ effect. This leads to more strong effect of D on the switching losses (Fig. 4).
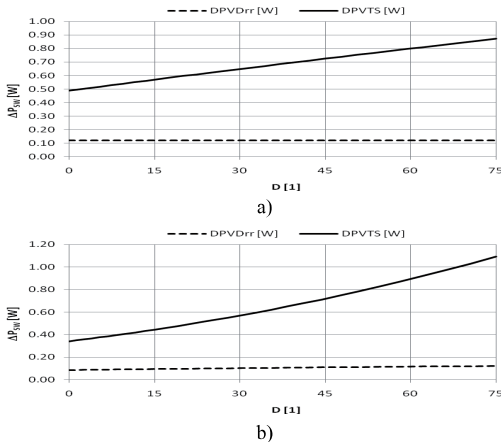

a)

b)

Fig. 4. Switching losses of power diode and transistor in DC/DC LED dimmers: a – buck; b – boost

Expected influence of modulation frequency. Switching losses in the diode are defined mostly by its recovery process. In the bust converter they depend on the

duty cycle D, but are still small compared with those of transistor and, especially with its on-state losses.

The impact of the switching frequency f_{SW} on the commutation losses is linear and is expressed by (2) and (3). On the other hand from Table 1-A3...B4 it is seen that this frequency has no effect on the conduction losses. If the thermal parameters of the transistor and diode are known then it is possible to determine the maximal power losses and maximal frequency of operation. For instance for no heatsink situation transistor losses are ΔP_{VTmax}=(175-25)/62=2.4W but diode losses ΔP_{VDmax}=(175-25)/75=2W. Then the maximal switching losses are 2.4–0.4=2W for the transistor, but for the diode 2–0.27=1.73W. From where and from (2)...(3) maximal frequency of the diode is 1.72W/1219nJ=1.41MHz, but this of the transistor – 2W/8370nJ=0.24Mhz. There switching energy have been found previously utilizing (4)...(6).

On the other hand increasing the frequency decreases the value of reactive components linearly while their physical volume has square-root dependence.

Expected influence of inductance. The inductance of a coil has direct impact on its volume expressed with proportionality coefficient A_L that ties the inductance of the coil and number of its turns in power 2. Therefore if the coil utilizes the available wire window well it is possible to say that the volume of the coil proportional to the square-root of its inductance.

At the same time, smaller inductance leads to higher current pulsations in the coil and, hence, in the transistor and diode. Therefore, rms current of the transistor must be higher at lower inductance. The corresponding dependence may be presented in a simplified form as following

$$I_{VTrms} = \sqrt{I_{La}^2 + \frac{K_1}{L_{SM}} + \frac{K_2}{L_{SM}^2}} . \qquad (9)$$

However (9) shows that this dependence is quite weak and can mostly be ignored.

Development of model and simulation

Initial evaluation of the DC/DC buck and boost dimmer has been made through PSpice simulation. For the most of the elements a compromise between the complicity of the model and tolerance has been achieved: power diode and MOSFET are simulated as inherent PSpice models while models of the coil and LED load utilize macro-circuits based on a datasheet parameters of the elements. At the same time input voltage source, control source and driver are simulated as ideal elements.

The simulation results of the buck and boost converters are presented in this subsection. The switching frequencies through the simulation have been set to 40 kHz, 80kHz and 120kHz, but values in inductance of the coil – to 317uH, 417uH, 512uH, 610uH and the 761uH.

The comparison of efficiency is presented in Fig. 5 and Fig. 6. Efficiency at fixed value of L_{SM} and different values of frequency for buck converter is given in Fig. 5-a, but for boost – in Fig. 6-a. Efficiency at fixed value of f_{SW} different values of inductance for buck converter is given in Fig. 5-b, but for boost – in Fig. 6-b.

As can be seen from the graphs, the higher switching frequency reduces the efficiency. The highest efficiency can be observed with frequency 40 kHz.
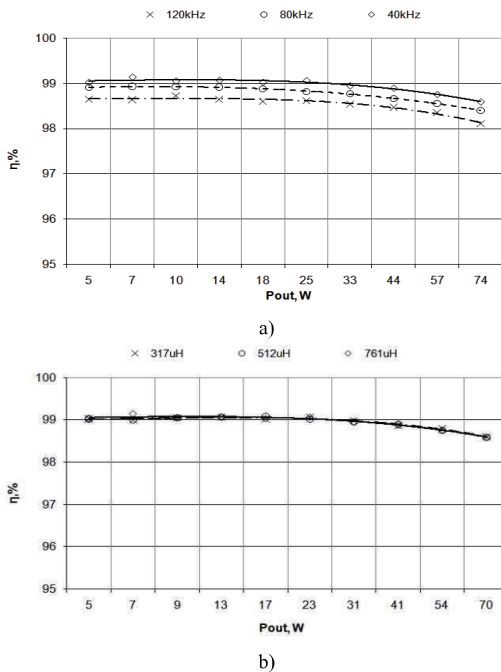

a)

b)

Fig. 5. Results of PSpice simulation of buck converter: a) $L_{SM}=761\mu H$, $f_{SW}=var$; b) $L_{SM}=var$, $f_{SW}=40$ kHz
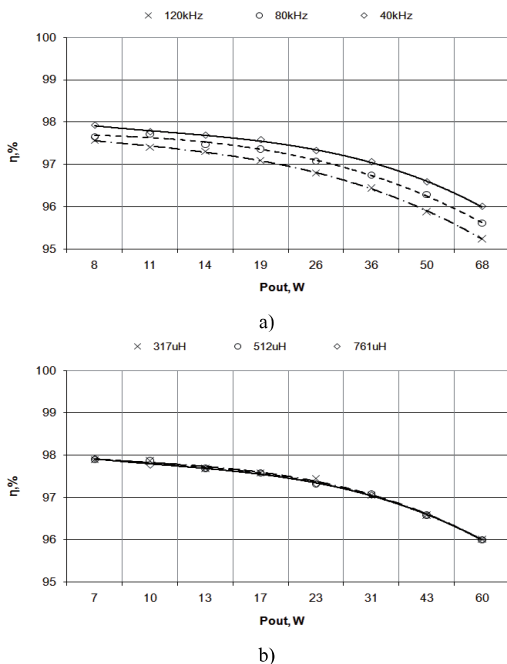

a)

b)

Fig. 6. Results of PSpice simulation of boost converter: a) $L_{SM}=761\mu H$, $f_{SW}=var$; b) $L_{SM}=var$, $f_{SW}=40kHz$

According to the presented figures the influence of the inductor is quite weak. This, however, may be a result of inaccuracy of its model. A more detailed model of the inductor could reveal decreased efficiency.

Simulation results show that buck converter switching topology is a good platform for a high efficiency LED drive system, because it provides higher efficiency than the boost converter.

Experimental evaluation of the dimmers

Buck converter. Efficiency of the buck converter has been evaluated with three switching frequencies - 40, 80 and 120kHz (Fig. 7). It can be seen that the overall efficiency of the converter decreases with frequency growth. The reason is increasing switching losses in semiconductor switches, inductor core losses and conductor skin effect.

One more series of experiments has been conducted with different value of the inductance coil (Fig. 8).
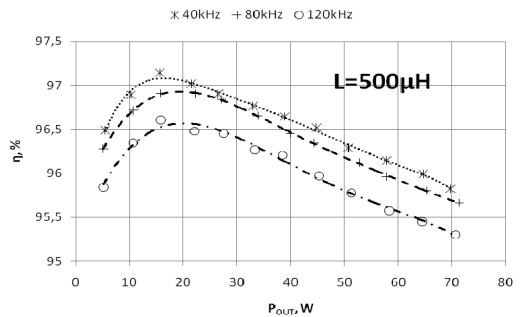

Fig. 7. Changes in efficiency of buck converter at different switching frequencies (experimental data)
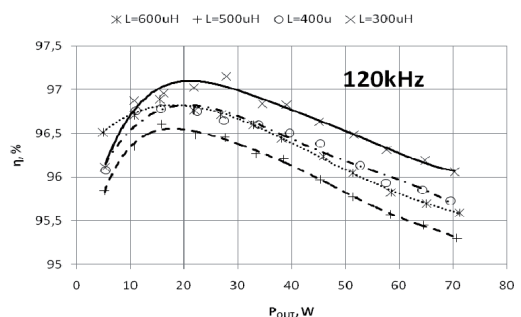

Fig. 8. Changes in efficiency of buck converter at different values of inductance coil (experimental data)

The tendency found in Fig. 8 is the same for different frequencies – efficiency curve becomes more linear at bigger inductance. Efficiency increases at smaller output powers with bigger inductance. Smaller inductances provide better performance at higher output powers because of its smaller active.

Three different cores (T94-26, T106-26 and T130-26) were used to evaluate influence the core size of a coil on its performance (Fig. 9).

Table 2. Exact parameters of inductance coil

Toroidal iron powder core T94-26		
Number of turns	Precise inductance at 25kHz, µH	Active resistance, mΩ
70	314	75
80	410	87
89	507	98
98	606	110

Table 3. Exact inductor parameters for core size test

Inductance coil 300µH		
Core size	Exact inductance at 25kHz, µH	Active resistance, mΩ
T94-26	314	75
T106-26	311	75
T130-26	317	80

Table 4. Exact parameters of inductance coli for skin effect test

Toroidal iron powder core T94-26			
Precise inductance at 25kHz, µH	Wire diameter, mm	Active resistance, mΩ	Number of wires
307	0,21	80	17
317	0,51	80	3
320	1,11	60	1

From Fig. 9 is seen that bigger inductor core size is better at lower output powers. At the same time at higher output power smaller core is preferable because of smaller active resistance of wires (Table 3).

Skin effect has been evaluated on the next stage (Fig. 10). This effect appears at higher frequencies and reduce effectively used conductor cross sectional area. To reduce conductor skin effect several parallel wires of the smaller diameter can be used (Table 4).
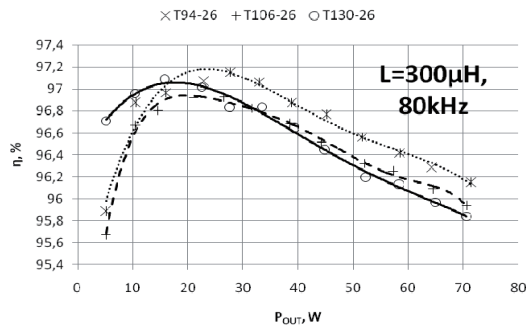

Fig. 9. Core size influence on buck converter efficiency (experimental data)

Boost converter. The analysis of experiments for boost converter shows that at higher frequency losses increases, especially at higher output power (Fig. 11). At the same time increase of inductance (Fig. 12) causes increase of losses at higher output powers. This can be explained by growth of the inductor active resistance (Table 5). Fig. 13 shows that there no significant impact of the core size.
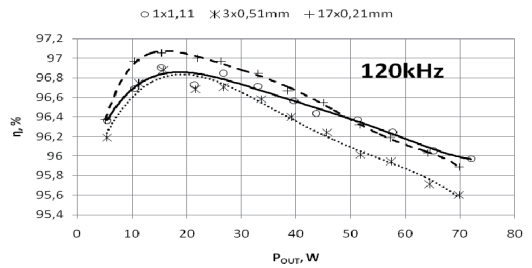

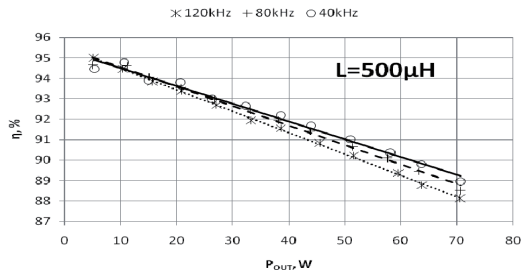**Fig. 10.** Conductor skin effect influence on inductor losses (experimental data)

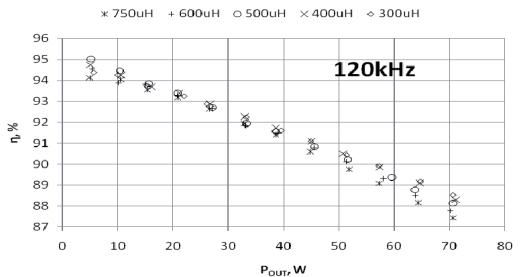**Fig. 11.** Impact of switching frequency on boost converter efficiency (measured)

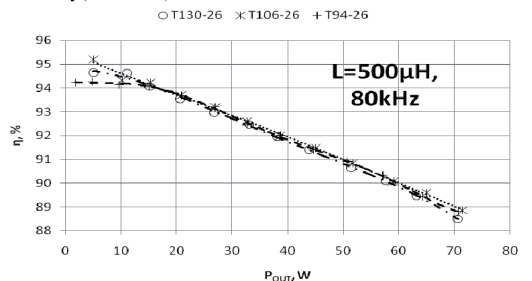**Fig. 12.** Impact of inductance on boost converter efficiency(measured)

Fig. 13. Core size impact on the boost converter efficiency (experimental data)

Table 5. Exact parameters of inductance coil

Toroidal iron powder core T106-26		
Number of turns	Precise inductance at 25kHz, µH	Active resistance, mΩ
64	317	88
72	417	94

Toroidal iron powder core T106-26		
Number of turns	Precise inductance at 25kHz, μH	Active resistance, mΩ
80	510	105
88	612	131
98	761	151

Conclusions

The most important conclusion is that the efficiency of the discussed converters and their weight /size is much related. Losses of the semiconductor elements define the size of their heatsinks. The inductor itself has a strong contribution in the overall size of the converter.

The presented data proves that buck dimmers may be more compact because of their better overall efficiency, especially at higher output power. This can be explained by longer operation time of the transistor and shorter – of the diode. This leads to smaller conduction losses in the diode and higher but acceptable in the transistor.

Using lower frequency of operation reduces losses of semiconductor elements but requires bigger inductor and vice versa. Some compromise can be found if switches with reasonable heatsink operate at the highest heat transfer level.

Inductor has a contradictory effect on the size of converter. Bigger inductor allows reduction of frequency and losses but it is bulky itself. It must also be noted that converter efficiency at higher output power can be improved by using smaller cores that reduces resistance of the winding.

It must be specially emphasized that the impact of wire resistance of the inductor is significant. Therefore,

effective (including skin and proximity effects) cross-sectional area of the wires must be kept high enough but their length – short enough. For smaller inductances this can be achieved by using smaller inductor cores.

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I. Galkin, O. Teteryonok, I. Milashevski. Weight and Size Estimation of Energy Efficient LED Ballasts // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 4(120). – P. 55–60.

Constantly growing demand for electrical energy compels for energy efficient electrical equipment. In lighting this assumes utilization of energy effective and intellectual lighting technologies. LED lighting technology combines both of these two ways. LED elements always require some electronic ballast that may consist of a primary power supply and a number of secondary dimmers for light regulation. These circuits can be implemented as DC/DC converters. In the paper buck and boost dimmers have been investigated from the point of view of their losses, weight and size. In has been found that buck converter can be the smaller and operate with the smaller losses. Higher switching frequency is preferable while the power switches of the dimmer have to be used with reasonable heatsinks. Larger values of inductance may reduce the total dimensions in spite of additional size due to the bigger coils. Ill. 13, bibl. 6, tabl. 5 (in English; abstracts in English and Lithuanian).

I. Galkin, O. Teteryonok, I. Milashevski. Efektyvių LED balastų svorio ir dydžio optimizavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 4(120). – P. 55–60.

Nuolat didėjanti elektros energijos paklausa verčia naudoti energiškai efektyvią elektros įrangą. Taikomos efektyvios ir intelektualios apšvietimo technologijos. LED apšvietimo technologija jungia abi šias sritis. LED elementams visada reikia tam tikro elektroninio balasto, kurį gali sudaryti pradinis energijos šaltinis ir keletas antrinių reguliatorių šviesai reguliuoti. Šie grandynai gali būti sukurti kaip DC/DC keitikliai. Buvo ištirti žeminantieji ir aukštinantieji reguliatoriai vertinant jų nuostolius, svorį ir dydį. Buvo nustatyta, kad žeminantysis keitiklis gali būti mažesnis ir sukelia mažiau nuostolių. Didėjant induktyvumui bendri matmenys gali mažėti, nors ričių matmenys padidėja. Il. 13, bibl. 6, lent. 5 (anglų kalba; santraukos anglų ir lietuvių k.).

[A10] **Milaševski, I.**; Tetervenok, O.; Galkin, I. (2011). Assesment of Energy Efficient LED Ballasts Based on their Weight and Size. Scientific Journal of Riga Technical University. Power and Electrical Engineering, 29, 105 - 112.

Assessment of Energy Efficient LED Ballasts

Based on their Weight and Size

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Oleg Tetervenok, *Riga Technical University,* Ilya Galkin, *Riga Technical University*

Abstract – **LED elements always require some electronic ballast that may consist of a primary power supply and a number of secondary dimmers for light regulation. These circuits can be implemented as DC/DC converters. In the paper buck and boost dimmers are investigated from the point of view of their weight and size, that are close related to their losses. The analysis is provided for various modulation techniques and configurations of the converters. The above mention converters are investigated analytically, through simulation and experimentally.**

Keywords – **Electronic ballast, energy efficiency, lighting control, pulse width modulation, frequency modulation.**

I. INTRODUCTION

Nowadays, electric energy consumption in the world has been increasing steadily while possibilities of new electrical energy sources are quite doubtful. There are two most impactful, technology-grounded strategies for reducing electricity consumption associated with lighting are: using more self-efficiency lighting technologies and making lighting systems "smart". It means to use lighting control solutions, that give opportunity to produce light when and where it is needed [1], [2]. In particular, in the field of electrical lighting these two ways can be combined if Light Emitting Diodes (LEDs) are used. On the one hand modern LED technology has been improving the lumen/watt output for last years. Now modern LEDs have efficacy of several tens lumens per watt that is comparable with high pressure sodium lamps. On the other hand it is possible to effectively adjust the light produced by LEDs with no negative impact on them. This paper estimates the efficiency of various LED ballasts in the context of optimization of their weight and size.

Amount of light produced by an LED is proportional to its current [3]. This brings forward two light control methods [4]: 1) fluent regulation of LEDs current - when its value varies depending on the light request; 2) pulse mode regulation of LEDs current - when it is either zero or maximum but its average value varies depending on the light request. Since the light produced by LED follows its current at a very high rate [5]] the second method may lead to flickering and stroboscopic effects. One more light regulation method [4] is possible because rated power of LEDs is usually small. For this reason LED luminary usually includes a number of LEDs. Then it is possible to divide them into groups and control each group separately. This method, however, ensures lesser dimming levels and lower accuracy of regulation. Therefore,

the first regulation method – fluent regulation of LED current is preferable.

LED itself is a low voltage element. This mostly demands a DC/DC stage for dimming even if the LED luminary is fed from AC line. This argument is especially essential if the luminary has few LED groups that must be dimmed separately, for instance, in the case of street lighting. Various DC choppers can be used as the regulators: buck, boost, buck-boost etc [6]. All these converters are pulse mode circuits that may be driven in different ways [7] – pulse width modulation, frequency modulation etc. The chosen topology and control method has significant impact on the efficiency of the dimmer [8] and [9]. They also have influence on its size and weight.

DC/DC converter topologies have been subjects of different power electronics research aimed at low power losses, high efficiency (for instance, [10]). However, study of converters efficiency in dependence of their weight and size had not been done by others researchers. The given paper investigates buck and boost dimmers operating in pulse width modulation mode from the point of view of weight/size and efficiency. The converters are estimated analytically and through simulation as well as tested experimentally. Then the conclusions about the optimal choice are formulated at the end.

II. APPROACHES TO LUMINOUS FLUX REGULATION

There three basic kinds of luminous flux regulation and the corresponding electronic equipment: a) pulse mode; b) step mode and c) fluent mode luminous flux regulation.

A. Converters for Pulse Mode Luminous Flux Regulation

Pulse mode regulation takes place when the luminous flux may be either zero or maximal. The average value then is defined by the duty cycle of the luminous flux pulses.
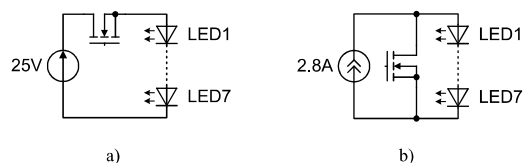
Fig. 1. Schemes of pulse regulators: a) voltage regulator; b) current regulator
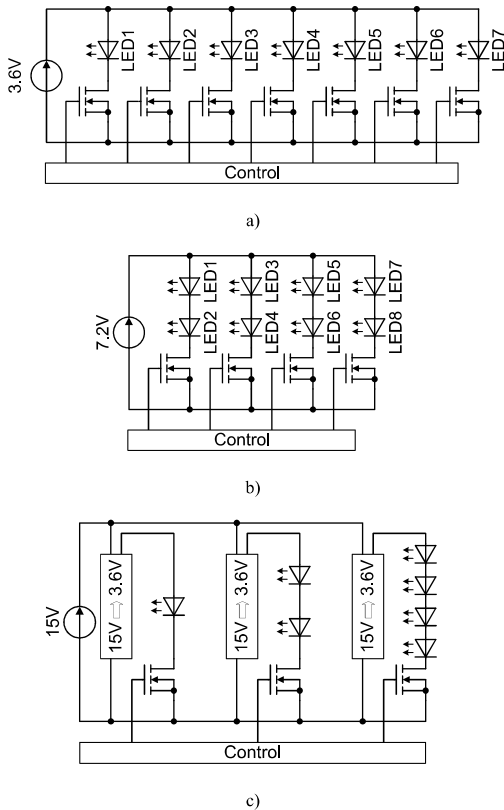
a)

b)

c)

Fig. 2. Commutation of LEDs in groups (voltage sourced): a) separately controlled; b) groups with the same number of LEDs (2); c) groups with different number of LEDs
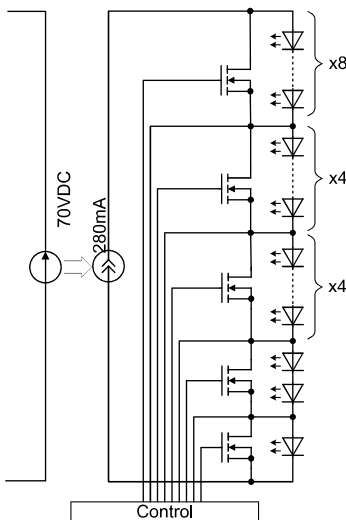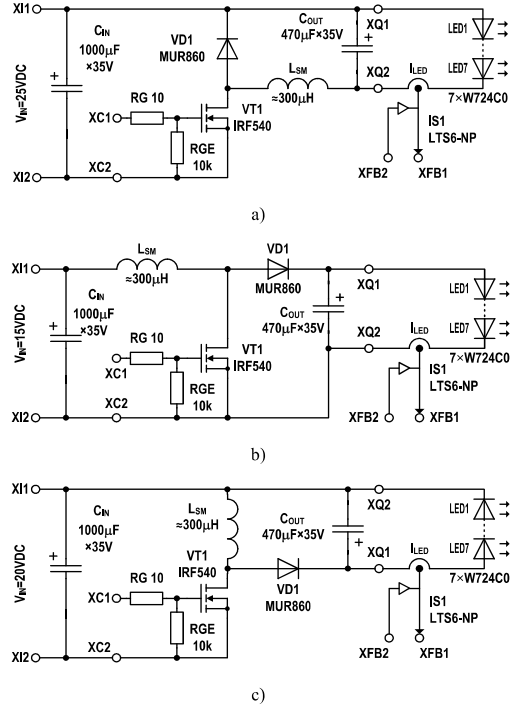

a)

b)

c)

Fig. 4. Testbench for evaluation of dimmers for light regulation with LEDs: a – buck configuration; b – boost configuration; c- buck-boost configuration

These regulators can be divided into two groups: voltage fed regulators (Fig. 1-a) and current fed regulators (Fig. 1-b). In the voltage fed regulator a controllable switch (MOSFET) is connected in series with LEDs. This configuration can be regarded as a simplified voltage buck converter with PWM regulation utilizing the switch. In current regulator the switch is connected in parallel with LEDs and shorts them.

In this research the load of all tested converters contains seven series connected 10W LEDs W724C0 (made by Seoul Semiconductor [3]). This load reaches its maximal power 70W at 25V and 2.8A. This defines the values of voltage and current sources with this regulation technique.

B. Converters for Step Mode Luminous Flux Regulation

These converters are in fact arrays of electronic switches for commutation of LED groups. Regulation of the overall luminous flux is done through separate powering of each group by switches driven by the control system. It is obvious that the maximal number of regulation steps is equal to the number of LEDs (7) while the step of regulation is equal to power (or light) of sole LED. At such regulation approach switch arrays can be supplied from either voltage or current sources. The configuration of switch arrays is different for these two occasions.

In the case of voltage source the most obvious configuration is a set of switches that connect input voltage to each LED separately (Fig. 2-a). However, it is possible to obtain bigger groups of LEDs. For example, Fig. 2-b represents a similar

Fig. 3. Commutation of LEDs in groups (current sourced).

LED matrix grouped by 2. In Fig. 2-a and Fig. 2-b groups are equal while in Fig. 2-c they are different. In the first case all groups get power from the same regulator. In the case when there are different numbers of LEDs in groups each group gets power from its own voltage source, with voltage level equal to the rated voltage of one LED voltage multiplied by the number of LEDs in the group.

C. Converters for Fluent (Continuous) Mode Luminous Flux Regulation

Continuous regulation provides all values of the luminous flux from zero to the maximum. Like for previous methods there may be two kinds of fluent mode regulators: current and voltage. However, design of the energy efficient current regulators is more complicated and not discussed here, while the voltage regulators are discussed in details (Fig. 4).

In this research buck and boost topologies of the dimmers has been investigated due to their better control performance [7]. Buck-boost topology has shown unsatisfactory results for control performance [7] and for energy efficiency of LED ballasts [9]. For this reason it also has not been taken into account.

D. Configuration of Testbench

Schematics of experimental setup for buck converter is shown in Fig. 4-a, for boost – in Fig. 4-b, but for buck-boost – in Fig. 4-c. All elements of the testbench (VT1 – IRF540 MOSFET, VD1 – ultrafast diode MUR860) were the same during all experiments to ensure that difference of measured values between tests depends only on inductor parameter changes. Values of inductance coil L_{SM} were changed during experiments. Several values of the switching frequency have been applied as well. The output power has been used as an argument for output curves.

Transistors are located so that their control signals are referred to the same ground as the input voltage of the converter (attached through clamps XI1 (+) and XI2 (-)). Control pulses are passed through a resistor to the gate of the transistor (clamps XC1 and XC2). A transistor current sensor is installed in these schematics so, that its power supply also referred to the same ground as the input voltage. The investigated converters also include an output current sensor that provides feedback to the control system (through XB1 and XB2). To carry out measurements four Extech EX430 multimeters were used with 0.3% basic accuracy.

III. ESTIMATED INFLUENCE OF PARAMETERS

Weight and size of any electronic converter depend on those of its elements. However, from this point of view some elements are dominating over the others and their contribution has to be taken into account first. The most significant components of one-switch DC/DC dimmers are inductance coil, power diode and power transistor together with their heatsink (whose size depends on the power losses) and driver. Previous experience shows that they take up to 50% of the total volume and up to 40% of the total weight. That is why this paper is focused on the estimation of these elements.
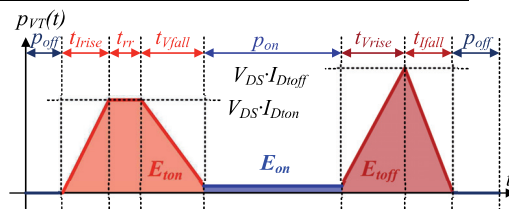

Fig. 5. Instantaneous power losses of a MOSFET transistor operating in a conjunction with a diode

A. Expected influence of the dimmer type

If the choice of input voltage for dimmer is not limited then the dimmer can also be quite arbitrarily chosen. In this case the impact of topology of the dimmer on its weight/size may be the main criterion for its choice. At the same time it must be noted that the influence of the topology is not direct.

The utilized diodes W724C have operating voltage of 2.5…3.6V [3] that corresponds to operating current 0…2.8A. Therefore seven such diodes require from 17.5 to 25V for full range of current regulation. Such voltage can be obtained from a buck, boost or buck/boost converter. The last one does not provide good performance from the point of view of control and is not discussed here. The buck dimmer operates better (from the same point of view) at 25V input and requires 70…100% of duty cycle in this case. Similarly the boost dimmer must have 17.5V on its input and 0…30% of the duty cycle. Therefore, the first dimmer works with higher on-state losses in the switch while the second one – in the diode.

Losses of a semiconductor switch are regarded as a significant parameter that affects size of its heatsink. They are found as a definite integral of instantaneous power (Fig. 5) in the semiconductor switch within its switching period divided by the period.

$$\Delta P = \frac{1}{T_{sw}} \int_0^{T_{sw}} p(t)dt = \frac{E_{ton} + E_{on} + E_{toff}}{T_{sw}} =$$

$$= \Delta P_{ton} + \Delta P_{on} + \Delta P_{toff} \quad . \qquad (1)$$

As it is seen from (1) the losses are divided into switching losses and conduction losses. The conduction losses in a MOSFET (that is used as a switch) are found as a product of the current through the switch that is equal the average current through the inductor I_L (in power 2), channel resistance R_{VTon} and duty cycle D of converter's operation (it is assumed that the inductance of the coil is infinite – i.e. the switch and diode conducts pulse mode current):

$$\Delta P_{VTon} = I_L^2 \times R_{VTon} \times D . \qquad (2)$$

This expression corresponds to blue rectangle in Fig. 5.

The conduction losses in a diode are found in a similar way as a product of the same current, voltage drop across the diode and factor $(1–D)$:

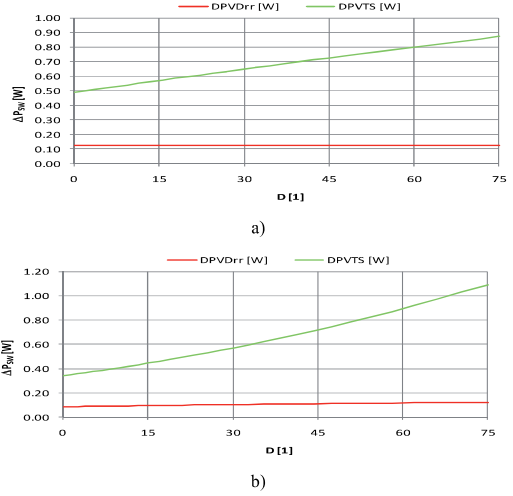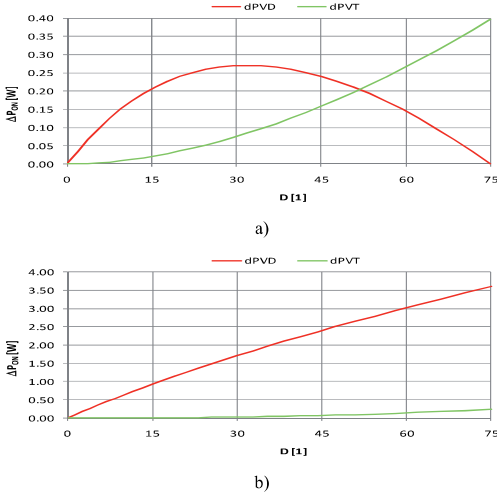$$\Delta P_{VDon} = I_L \times V_{VDon} \times (1-D) . \qquad (3)$$

a)

b)

Fig. 6. On-state losses of diode and transistor in: a – buck; b – boost dimmer

a)

b)

Fig. 7. Switching losses of power diode and transistor in DC/DC LED dimmers: a – buck; b – boost

TABLE I
CALCULATION LOSSES OF BUCK AND BOOST DIMMERS

Conv.	V_O(1)	I_L(2)	ΔP_{VDon}(3)	ΔP_{VTon}(4)
Buck (A)	$V_{IN} \cdot D$	I_O	$V_{VDon} \cdot I_O \cdot (1-D)$	$R_{VTon} \cdot I_O^2 \cdot D$
Boost (B)	$\dfrac{V_{IN}}{1-D}$	$\dfrac{I_O}{1-D}$	$V_{VDon} \cdot \dfrac{I_O}{1-D} \cdot (1-D)$	$R_{VTon} \cdot (\dfrac{I_O}{1-D})^2 \cdot D$

The expressions required for calculation of power losses in buck and boost dimmers (Table I) are based on the power equilibrium for input voltage V_{IN} and output current I_O. Nonlinearity of LED load is represented as no consumption at voltage less 17.5V and linear load 0…3A corresponding to voltage of 17.5…25V.

$$I_O = f(V_O) = \frac{V_O - 17.5V}{25V - 17.5V} \cdot 2.8A . \qquad (4)$$

Utilizing (4) and equations from Table I it becomes possible to calculate the conduction power losses and present them graphically (Fig. 6). This picture demonstrates that, as it has been previously noted, in the buck converter on-state losses of the transistor dominates at high duty cycles, while in the boost – diode losses are more significant. Besides that it is obvious that the on-state losses of the boost converter are higher in absolute value (mostly due to diode losses). Indeed, if power of converters is the same then the boost converter has much higher input (coil) current that leads to higher losses in semiconductor switches.

The configuration of the dimmer has impact on its switching losses too. The technology of calculation of these losses is given in [11] and [12]. In slightly simplified version (for the worst case analysis) it is represented by the following formulas (see Fig. 5 for details):

$$\Delta P_{VTsw} = (E_{VTton} + E_{VDtoff}) \times f_{sw}, \qquad (5)$$

$$\Delta P_{VD} = (E_{VTrr} + E_{VDtoff}) \times f_{SW} \approx E_{VTrr} \times f_{SW} , \qquad (6)$$

$$E_{VTton} = V_{DS} \cdot I_{Dton} \cdot \frac{t_{Irise} + t_{Vfall}}{2} + Q_{rr} \cdot V_{DS} , \qquad (7)$$

$$E_{VToff} = V_{DS} \cdot I_{Dtoff} \cdot \frac{t_{Vrise} + t_{Ifall}}{2} , \qquad (8)$$

$$E_{VDrr} = \frac{V_{DS} \cdot Q_{rr}}{2} , \qquad (9)$$

where voltage rise and fall times are found as:

$$t_{Vrise} \approx V_{DS} \times R_G \times \frac{C_{GD}}{V_{GSload}} , \qquad (10)$$

$$t_{Vfall} \approx V_{DS} \times R_G \times \frac{C_{GD}}{V_{DR} - V_{GSload}} , \qquad (11)$$

Other parameters are either known as the initial conditions (V_{DS} – is operation voltage of the switch, I_{Dton} and I_{Dtoff} – commutated current at turn-on and turn-off transients respectively, f_{SW} – switching frequency, R_G – value of gate resistor) or found from the datasheets (Q_{rr} – reverse recovery charge of the utilized diode, t_{Irise} and t_{Ifall} – drain current rise and fall time, C_{GD} – gate to drain capacitance, V_{GSload} – gate voltage at the drain equal to load).

Equations (5)…(11) provide a basis for switching loss calculation. However, distribution of the losses across the operation range depends on the dimmer. In the case of buck converter $V_{DS}=V_{IN}$ is a constant, but $I_L=I_O$ (for average values) depends on the duty cycle as expressed in (1). Then the switching losses of the transistor rise linearly with current (Fig. 7-a).

In the boost converter $V_{DS}=V_O$, hence the losses are also a function of the duty cycle (Table I – B1). At the same time $I_D=I_{IN}$ that can be expressed by (Table I – B2), where I_O is still

expressed by (1). Therefore, in this converter transistor commutates the current that, due to power equilibrium, undergoes doubled 1/(1-D) effect. This leads to more strong effect of *D* on the switching losses (Fig. 7).

B. Expected influence of modulation frequency

Switching losses in the diode are defined mostly by its recovery process. In the bust converter they depend on the duty cycle *D*, but are still small compared with those of transistor and, especially with its on-state losses. The impact of the switching frequency f_{SW} on the commutation losses expressed by (2) and (3) is linear. On the other hand Table I – A3…B4 shows that this frequency has no effect on the conduction losses. If the thermal parameters of the transistor/diode are known then it is possible to determine the maximal power losses and maximal frequency. For instance without a heatsink transistor losses are ΔP_{VTmax}=(175-25)/62=2.4W but diode losses ΔP_{VDmax}=(175-25)/75=2W. Then the maximal switching losses of the transistor are 2.4–0.4=2W, but of the diode 2–0.27=1.73W. From where and from (2)…(3) maximal frequency of the diode is 1.72W/1219nJ=1.41MHz, but of the transistor – 2W/8370nJ=0.24Mhz. Here switching energy have been found previously utilizing (4)…(6). On the other hand increasing frequency decreases the value of reactive components linearly while their physical volume has square-root dependence.

C. Expected influence of inductance

The inductance of a coil has direct impact on its volume expressed with proportionality coefficient A_L that ties the inductance of the coil and number of its turns in power 2. Therefore if the coil utilizes the entire available wire window its volume is proportional to the square-root of its inductance.

At the same time, smaller inductance leads to higher current pulsations in the coil and, hence, in the transistor and diode. Therefore, rms current of the transistor must be higher at lower inductance. The corresponding dependence may be presented in a simplified form as following:

$$I_{VTrms} = \sqrt{I_{La}^2 + \frac{K_1}{L_{SM}} + \frac{K_2}{L_{SM}^2}} \quad , \tag{9}$$

However (9) shows that this dependence is quite weak and can mostly be ignored.

IV. DEVELOPMENT OF MODEL AND SIMULATION

Initial evaluation (the corresponding results are presented Fig. 8 and Fig. 9) of the DC/DC buck and boost dimmer has been made through PSpice simulation. For the most of the elements a compromise between the complicity of the model and tolerance has been achieved: power diode and MOSFET are simulated as PSpice models while models of the coil and LEDs utilize macro-circuits based on the datasheet parameters of the elements. At the same time input voltage source, control source and driver are simulated as ideal elements.
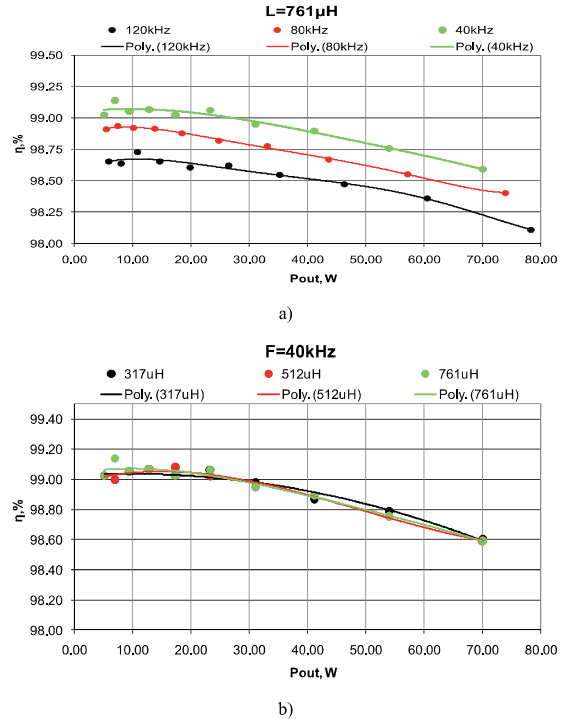

Fig. 8. Results of PSpice simulation of buck converter: a) L_{SM}=761μH, f_{SW}=var; b) L_{SM}=var, f_{SW}=40kHz
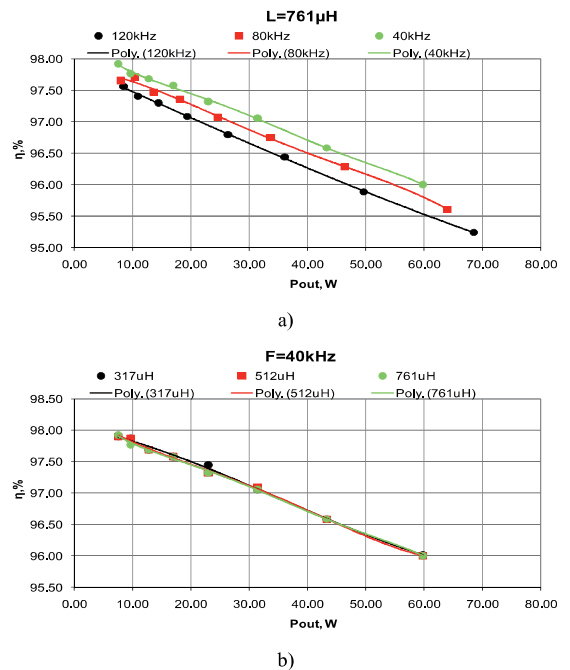

Fig. 9. Results of PSpice simulation of boost converter: a) LSM=761μH, f_{SW}=var; b) L_{SM}=var, f_{SW}=40kHz

The simulation results of the buck and boost converters are presented in this subsection. The switching frequencies through the simulation have been set to 40 kHz, 80kHz and 120kHz, but values in inductance of the coil – to 317uH, 417uH, 512uH, 610uH and the 761uH.

Efficiency at fixed value of L_{SM} and different values of frequency for buck converter is given in Fig. 8-a, but for boost – in Fig. 9-a. Efficiency at fixed value of f_{SW} and different values of inductance for buck converter is given in Fig. 8-b, but for boost – in Fig. 9-b.

As can be seen from the graphs, the higher switching frequency reduces the efficiency. The highest efficiency can be observed with frequency 40 kHz. To reduce the size of the passive devices, the switching frequency must be increased but – at the cost of lower efficiency.

Simulation results show that buck converter switching topology is a good platform for a high efficiency LED drive system, because it provides higher efficiency than the boost converter.

V. EXPERIMENTAL EVALUATION OF THE DIMMERS

A. Buck converter

Efficiency of the buck converter has been evaluated with three switching frequencies - 40, 80 and 120kHz (Fig. 10). As can be seen from the Fig. 10, the overall efficiency of the converter decreases with frequency growth. The reason is increasing switching losses in semiconductor switches, inductor core losses and conductor skin effect. Increasing the switching frequency has a beneficial effect on the output filter size and in turn, on the converter size.

One more series of experiments has been conducted with different value of the inductance coil (Fig. 11).

The tendency found in Fig. 11 is the same for different frequencies – efficiency curve becomes more linear at bigger inductance. Efficiency increases at smaller output powers with bigger inductance. Smaller inductances provide better performance at higher output powers because of its smaller active resistance (Table II).

Three different inductor cores (T94-26, T106-26 and T130-26) were used to evaluate influence the core size of a coil on its performance (Fig. 12).

From Fig. 12 is seen that bigger inductor core size is better at lower output powers. At the same time at higher output power smaller core is preferable because of smaller active resistance of wires (Table III).

Optimization of the switching frequency considers the skin effect of the inductor. Skin effect has been evaluated on the next stage (Fig. 13). This effect appears at higher frequencies and reduce effectively used conductor cross sectional area. To reduce conductor skin effect several parallel wires of the smaller diameter can be used (Table IV).
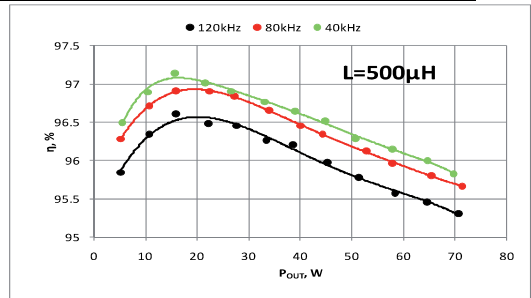

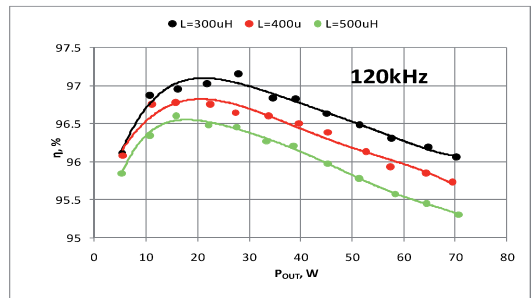Fig. 10. Changes in efficiency of buck converter at different switching frequencies

Fig. 11. Changes in efficiency of buck converter at different values of inductance coil

TABLE II
EXACT PARAMETERS OF INDUCTANCE COIL

Toroidal iron powder core T94-26		
Number of turns	Precise inductance at 25kHz, µH	Active resistance, mΩ
70	314	75
80	410	87
89	507	98
98	606	110

TABLE III
EXACT INDUCTOR PARAMETERS FOR CORE SIZE TEST

Inductance coil 300µH		
Core size	Exact inductance at 25kHz, µH	Active resistance, mΩ
T94-26	314	75
T106-26	311	75
T130-26	317	80

TABLE IV
EXACT PARAMETERS OF INDUCTANCE COIL FOR SKIN EFFECT TEST

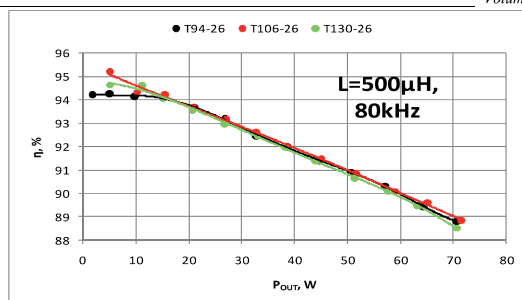| Toroidal iron powder core T94-26			
Precise inductance at 25kHz, µH	Wire diameter, mm	Active resistance, mΩ	Number of wires
307	0,21	80	17
317	0,51	80	3
320	1,11	60	1

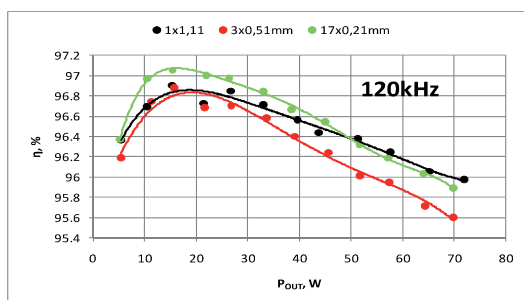Fig. 12. Core size influence on buck converter efficiency
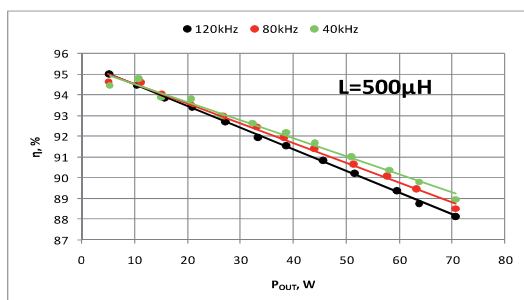

Fig. 13. Conductor skin effect influence on inductor losses

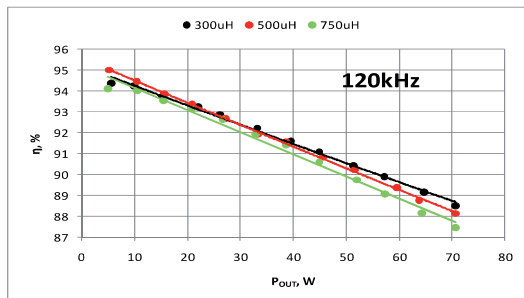Fig. 14. Impact of switching frequency on boost converter efficiency

Fig. 15. Impact of inductance on boost converter efficiency

Fig. 16. Core size impact on the boost converter efficiency

TABLE V

EXACT PARAMETERS OF INDUCTANCE COIL

Toroidal iron powder core T106-26		
Number of turns	Precise inductance at 25kHz, µH	Active resistance, mΩ
64	317	88
72	417	94
80	510	105
88	612	131
98	761	151

B. Boost converter

The analysis of experiments for boost converter shows that at higher frequency losses increases, especially at higher output power (Fig. 14). At the same time increase of inductance (Fig. 15) causes increase of losses at higher output powers. This can be explained by growth of the inductor active resistance (Table V). Fig. 16 shows that there no significant impact of the core size.

VI. CONCLUSION

The most important conclusion is that the efficiency of the discussed converters and their weight /size are very related. Losses of the semiconductor elements define the size of their heatsink. At the same time the size of the coil also has strong impact on these losses.

The presented data proves that buck dimmers may be more compact because of their better overall efficiency, especially at higher output power. This can be explained by longer operation time of the transistor and shorter – of the diode. This leads to smaller conduction losses in the diode and higher but acceptable in the transistor.

Using lower switching frequency reduce losses of switches but requires bigger coil and vice versa. Some compromise can be found if switches with reasonable heatsink operate at the highest heat transfer level.

Inductance has contradictory effect on the converter size. Bigger inductance may reduce frequency and losses but is bulky itself. It must also be noted that converter efficiency at higher output power can be improved by using of smaller cores that reduce resistance of the coil.

It must be especially noted that the impact of wire resistance of the inductor coil is significant. Therefore, effective (including skin and proximity effects) cross-sectional area of the wires must be kept high enough but their length – short enough. For smaller inductances this can be reached by using of smaller inductor cores.

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Ilya Galkin is IEEE member since 2006 in societies of Power Electronics, Industrial Electronics, Automatic control and Education.

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Assessment of Buck Converter Powered by Current or Voltage Sources for LEDs Luminary

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ABSTRACT: This paper presents comparative investigation of both voltage and current fed buck converters. This comparison takes into account the controllability, efficiency and size of the converters. The first section of the paper briefly describes a standard voltage fed buck converter. Transformation of voltage fed buck converter into the current fed converter is presented next. Then the operation of current fed buck converter is discussed. On the next stage experimental estimation of current fed buck converter is described. Finally conclusions about current fed buck converter with LEDs are drawn.

1 Introduction

Artificial lighting consumes a considerable amount of electricity generated in the world. Taking into account the increase of energy consumption in other segments and limited facilities of energy generation, development of more efficient lighting systems is becoming more important. Current market of lighting devices is recently supplemented by novel light sources that enable revolutionary improvements of lighting and electrical parameters of lighting systems while ensuring also high reliability and durability.

One of these sources is the Lighting Emitting Diode (LED) [1]. The use of high power LEDs in lighting applications is becoming increasingly popular due to rapid and constant improvements of LED's efficacy, lifetime, reliability and overall cost. Dimming functions are also more easily implemented with LEDs. Dimming of LEDs does not have negative impact on them. Besides that they are more robust and offer wider design flexibility compared to other light sources. Furthermore, LED lighting devices have advantages in their slim sizes and low pollution due to the elimination of heavy metals.

Typical consumer applications, like those of home appliance, have to be plugged into an AC power source. At the same time LED has to be powered by DC source, the voltage level of which depends on the number of LEDs. Therefore, AC should be converted into DC for LED correct supply and LEDs always require some electronic ballast. The conversion efficiency and cost of the converter are two main concerns for application of white light LED illumination [2]. The LED ballast often

gives an opportunity of dimming. Then it can be configured as monolithic circuit providing rectifier and dimmer functions or as a composite unit consisting of several stages. From the light regulation point of view the ballasts can be divided into three groups: ballasts with pulse mode luminous flux regulation, with fluent mode regulation and that of step-mode.

It is advantageous to supply LEDs from current sources, because LEDs luminous flux depends on their current [3]. However, nowadays most of available power suppliers operate as voltage sources. There are a few researches of current fed converters [4], mostly devoted to applications with natural current sources like photovoltaic [5] and superconductive magnetic energy storages [6]. This paper discusses which one - voltage fed or current fed buck converter - is more usable in LED applications, taking into account controllability and their sizes.

2 Voltage Supplied Buck Converter

The buck converter is one of the high efficiency (about 95%) topologies often used in Switch Mode Power Supplies (SMPS). This topology is also known as step-down converter because of its main feature - the output voltage is always lower or equal than the input voltage. Fig. 1-a shows a simplified diagram of the common buck converter supplied from a voltage source and attached to LED load.

The purpose of this part of work is to find out the dependency of the luminous flux on the duty cycle D. This relation is not explicit. It consists of several stages: stage of the regulation curve of the converter (V_{LED} vs D), then Volt-Ampere (V-A) curve of LEDs and the Lumen-Ampere (Lm-A) curve of LEDs. The output voltage V_{LED} of the voltage fed buck converter is determined as the following well-known expression:

$$V_{LED} = V_{IN} \times D. \tag{1}$$

The analytical expression of V-A curve (of 7 in series connected LEDs W724C made by Seoul Semiconductors) of LEDs exists only as the graphic in the datasheet or can be found experimentally.

Based to these data it is possible to find approximated V-A expression (the 3rd order polynomial):

$$I_{LED} = f(V_{LED}) = a_0 + a_1 \cdot (V_{LED} - V_0) + ...$$
$$... + a_2 \cdot (V_{LED} - V_0)^2 + a_3 \cdot (V_{LED} - V_0)^3 \quad , \quad (2)$$

where $V_0 = 20.2V$ is the voltage value of the working point, and a0...a3 are the polynomial coefficients for the explored LEDs in the range of VLED from 17 to 23,5V and ILED from 0 to 3000mA. The polynomial coefficients calculated for the described working point are equal: a0 = 557, a1 = 442, a2 = 89,6 and a4 = 1,92.With this coefficients the accuracy is higher than 2%.

On the basis of the same principle the Lm-A expression was constructed as the 2nd order approximation polynomial:

$$\Phi_{LED} = f(I_{LED}) = b_0 + b_1 \cdot (I_{LED} - I_0) + ...$$
$$... + b_1 \cdot (I_{LED} - I_0)^2 . \quad (3)$$

For this approximation the current range is from 0 to 3000mA and the luminous flux Φ_{LED} is from 0 to 700lm. In this range optimal working point is $I_0 = 1487mA$, but the coefficients are b0 = 442, b1= 0,244 and the b2 = 0,0000241 producing accuracy about 2%.

3 Transformation of Voltage Fed Converters into Current Fed Converters

The transformation of voltage fed (VF) converter to the current fed (CF) converter is based on the following transformation methods for basic circuit elements: 1) voltage sources are replaced with current sources; 2) capacitors are replaced with inductors; 3) open circuit is turned into short circuit; 4) star connection becomes a circular connection (and vice versa). This process is presented in Fig. 1-b, Fig. 1-c, while Fig. 1-d presents the results of these transformations - CF buck converter.

Static operation of CF buck converter is defined by the currents balance of its capacitor, like operation of VF converter is defined by the voltage balance of its inductor. When the transistor M1 is on the current source is short-circuited. Then the capacitor is being charged by the load current $-I_{LED}$ (discharged). Then voltage across capacitor C_{CF} decreases and can be expressed by the equation:

$$\Delta V_{C-} = \frac{1}{C_{CF}} \int_{D \cdot T}^{T} (-I_{LED}) dt = \frac{(-I_{LED}) \cdot D \cdot T}{C_{CF}} . \quad (4)$$

When the transistor is off the current is conducted by diode D1 and the capacitor of the converter is charged by the difference of the supply and load currents $I_{IN} - I_{LED}$. The corresponding voltage increasing by:

$$\Delta V_{C+} = \frac{1}{C_{CF}} \int_{D \cdot T}^{T} (I_{IN} - I_{LED}) dt =$$
$$= \frac{(I_{IN} - I_{LED}) \cdot (1 - D) \cdot T}{C_{CF}} . \quad (5)$$

In (4) and (5) T is switching period, but D – the duty cycle of its switch operation. In the case of static operation of the converter the voltage across capacitor has to be the same at the borders of the switching period: $\Delta V_{C-} + \Delta V_{C+} = 0$. This gives the following current transformation equation:

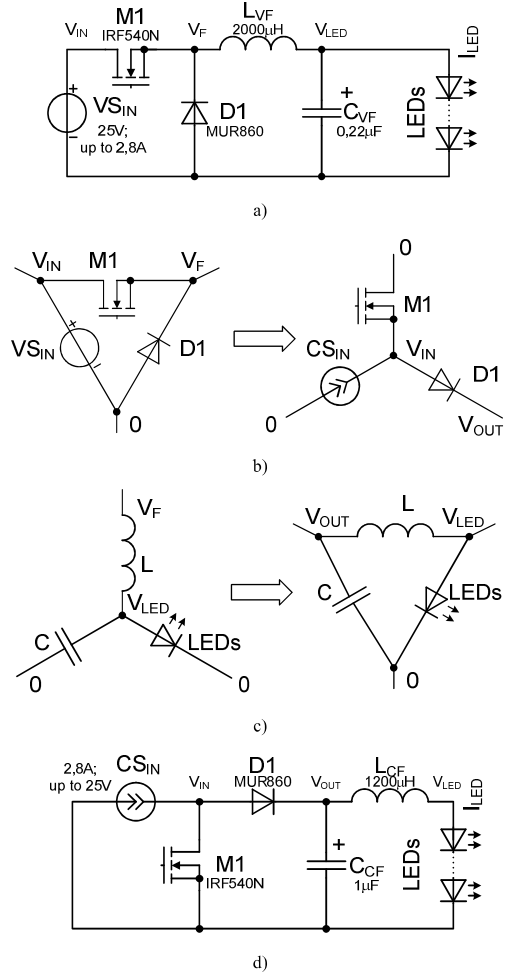$$I_{LEDcbuck} = I_{IN} \cdot (1 - D) . \quad (6)$$

Fig. 1. Transformation of VF buck converter to CF buck converter: a) VF buck converter; b) input transformation; c) output transformation; d) CF buck converter.

TABLE I. CALCULATED AND MEASUREMENT CONTROL PARAMETERS OF LEDS WITH CF AND VF DIMMING LED DRIVERS

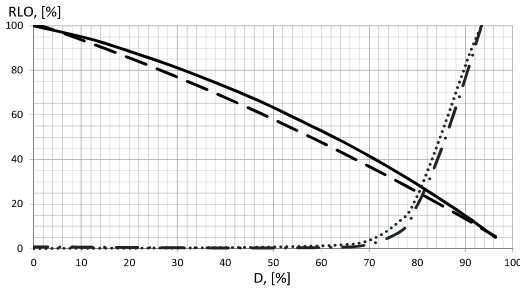|	NL, %		D_{SPANa} %		G_{LAMP}, %	
	EXP	MATH	EXP	MATH	EXP	MATH
VBuck	11	11	18	16	6	7
CBuck	13	7	94	90	1	1

Fig. 2. Calculated/measured regulation curves of LED lamp with buck driver (solid – CF/measured, dashed – CF/calculated, dotted – VF/measured, dash-dotted – VF/calculated).

4 Comparison of Controllability

In order to compare controllability of VF and CF buck converter the parameters to compare are to be determined. These parameters are: 1) maximal gain of the lamp; 2) nonlinearity of light regulation and 3) span of values of duty cycle practically usable for light regulation. The explanation of these parameters is presented below.

The first parameter is the rate of changes of Relative Light output (RLO) with changes of D expressed by (7):

$$G_{LAMP} = f(D) = \frac{dRLO}{dD} \approx \frac{\Delta RLO}{\Delta D}, \qquad (7)$$

where ΔRLO and ΔD are finite changes of RLO and D The maximal value of the gain is important:

$$G_{LAMP\max} = \Delta RLO_{\max} / \Delta D_{CR}. \qquad (8)$$

The nonlinearity is relative RMS declination of regulation curve from the corresponding linear curve (9). This parameter has very strong effect on the stability of the system and is equal to the root-mean declination ΔS of the regulation curve $RLO(D)$ from a line connecting its borders $RLO_L(D)$ to root-mean value S of $RLO(D)$:

$$NL = (\Delta S / S) \cdot 100\%. \qquad (9)$$

where S is defined as

$$S = \sqrt{\frac{1}{D_{\max} - D_{\min}} \int_{D_{\min}}^{D_{\max}} RLO^2(D) dD}, \qquad (10)$$

but ΔS – as

$$\Delta S = \sqrt{\frac{1}{D_{\max} - D_{\min}} \int_{D_{\min}}^{D_{\max}} \left[RLO(D) - RLO_L(D)\right]^2 dD}. \qquad (11)$$

In (7)…(11) RLO_{min} and RLO_{max} are minimum and maximum values of RLO achieved at D_{min} and D_{max}. The difference of these values produces duty cycle span:

$$D_{SPAN} = D_{\max} - D_{\min}. \qquad (12)$$

The above mentioned equations (1), (2) and (3) give an opportunity to calculate the regulation curve of VF buck converter, but (3) and (6) – those of CF buck converter. The corresponding curves, as well as those taken experimentally are presented in Fig. 2. Based on these data the parameters of controllability defined by (8), (9) and (12) have been calculated (Table I).

Note that the calculated and measured lighting parameters are different. Due to the limited laboratory facilities it was possible to measure the illuminance at a distant point (1m) from the LEDs only. At the same time the datasheet of LEDs provides information about Lm-A curve. That is why normalization has been applied and RLO calculated (bases values are 5180lx and 700lm). Fig. 2 and Table I demonstrate that CF has wider span of usable duty cycle values. It provides also a comparable nonlinearity and lower value of the gain that together can make regulation loop with CF buck converter more stable.

5 Comparison of Efficiency

Due to the limited size of the paper the losses and efficiency were only approximately estimated. Fig. 3 represents the experimentally obtained efficiency, Fig. 4 – losses, but Table II – shows temperatures of switches (thus indirectly showing also loss distribution).

As it is seen in Fig.3 and Fig. 4 the VF buck converter is more efficient at all values of RLO. The difference is especially significant at low load that can be explained by the differences in operation. The best range of D of VF driver is 75…95% and diode losses are minor. In CF driver all losses highly depend on D. At the high load (low D) the MOSFET conducts input current shorter time, but the diode – longer and diode losses are significant. At the small load (high D) the MOSFET conducts almost all the time and its losses are dominating. Moreover in CF driver the one of the switches always conduct the full input current 2.8A. However, at the high load the output power is also high and the efficiency is acceptable.
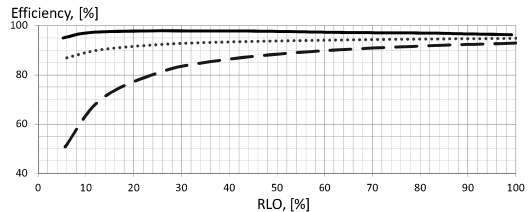

Fig. 3. Measured efficiency of VF and CF buck driven LED lamps (solid – VF, dashed – CF, dotted – CF after inductor).
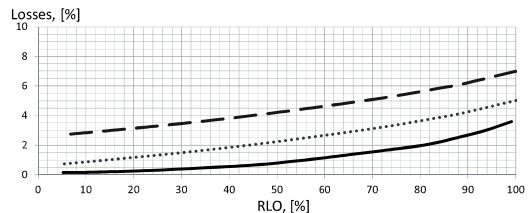

Fig. 4. Measured losses of VF and CF buck driven LED lamps (solid – VF, dashed – CF, dotted – CF after inductor).

	ΔT_{ca} at D=10%	ΔT_{ca} at D=40%	ΔT_{ca} at D=75%
M1	24^0C	19^0C	10^0C
D1	31^0C	22^0C	15^0C

Some static losses appear (Fig. 4) also in the input inductor that is optional element and its losses can be omitted (dotted line). Data in Table II approve the above statements.

6 Comparison of Size

Both VF and CF buck converters with the same load have the same set of components: MOSFET, diode, capacitor and inductor. The sizes of the inductor and capacitor are the main factors that define the whole size of the converter. At the same time these elements finally define LED current ripples that have to be minimal.

In the case of VF converter LED's current ripples are defined by their voltage ripples that, in turn, are defined by the current ripples of inductor and can be expressed as:

$$\Delta I_L = \frac{1}{L}\int_0^{t_1} V_L(t)dt = \frac{V_L \Delta t_1}{L} = \frac{V_{IN}D(1-D)T}{L}. \quad (13)$$

The maximal value of these ripples is achieved at D=0.5 and is $\Delta I_{Lmax}=V_{IN}T/4L$. Then the voltage ripples are:

$$\Delta V_C = \frac{1}{C_{VF}}\int_0^{\Delta t_2} I_C(t)dt = \frac{1}{C_{VF}}\cdot\frac{1}{2}\cdot\frac{\Delta I_L}{2}\cdot\frac{T}{2} = \frac{\Delta I_L T}{8\cdot C_{VF}}, (14)$$

where $I_C(t)$ is found as a difference of direct LEDs and the saw-tooth inductor's currents that is equal to the current ripples. (14) and maximum of (13) give the following product of the capacity C and inductance L:

$$L_{VF}\times C_{VF} \geq \frac{V_{IN}}{\Delta V}\cdot\frac{T^2}{32}. \quad (15)$$

Similarly, the output current ripple of CF converter gives:

$$L_{CF}\times C_{CF} \geq \frac{I_{IN}}{\Delta I}\cdot\frac{T^2}{32}. \quad (16)$$

LEDs current ripples have to be lower than 3% that, due to the V-A curve, requires 1% of voltage ripples:

$$L_{VF}\times C_{VF} \geq (V_{IN}/0.01V_{IN})\cdot(T^2/32) = 100\cdot T^2/32, \quad (17)$$

$$L_{CF}\times C_{CF} \geq (I_{IN}/0,03I_{IN})\cdot(T^2/32) = 33\cdot T^2/32. \quad (18)$$

Analysis of (17) and (18) leads to the following remarks: 1) the volume and weight of L and C elements of CF buck converter can be up to 3 times smaller; 2) their linear dimensions are up to $\sqrt[3]{3}\approx1,44$ times smaller than those of VF buck converter.

7 Conclusions

In this paper the comparative investigation of VF and CF buck converters has been presented. The results of this investigation shows the CF buck converter has the lower gain and wider span of practically usable duty cycle values that gives to it preferences from the controllability point of view.

The second conclusion regards the efficiency that in the case of VF buck is higher but is comparable in both occasions. The detailed distribution of the losses, localization of their most significant part, as well as means of their reduction requires one dedicated research.

At the same time the volume and weight of CF buck converter can be significantly lower. This, however, also requires some special investigation.

Finally, it can be concluded that CF buck converters can serve as a good alternative to other LED drivers.

Acknowledgment

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