RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Industrial Electronics and Electrical Engineering

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Doctoral Student of Programme "Computerised Control of Electrical Technologies"

DIRECT CURRENT CONTROL AND COMPENSATION OF NON-LINEARITY FOR THE IMPROVEMENT OF QUALITY PARAMETERS OF THE LED LAMP

Summary of Doctoral Thesis

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DOCTORAL THESIS
PROPOSED TO RIGA TECHNICAL UNIVERSITY
FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences (Dr.sc.ing.), the present Doctoral Thesis will be publicly presented on 13 May 2015 at the Faculty of Power and Electrical Engineering of Riga Technical University, Azenes Street 12/1, Room 212, at 1 p.m.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences (Dr. sc. ing.) is my own and does not contain any unacknowledged material from any source. I confirm that the Doctoral Thesis has not been submitted to any other university for the promotion to any other scientific degree.

Olegs Tetervenoks …………………………….

Date: ………………………

The Doctoral Thesis has been written in English. It consists of 5 chapters, including introduction, conclusions, bibliography with 139 reference sources and 17 appendices. The volume of the present Doctoral Thesis is 135 pages. It has been illustrated by 85 figures and 11 tables.

1. INTRODUCTION

TOPICALITY

Increasing energy consumption may have a strong impact on climate change due to greenhouse gases. At the same time, the shortage of primary energy sources is predicted in the near future, as well as the increase in the cost of electric energy due to implementation of new power plants on renewables [1]. This encourages researchers for new studies in the field of efficiency improvement for all kinds of electric devices. And the lighting systems are not an exception.

To date, LED lighting is gaining popularity and is becoming more and more common in lighting fixtures and lighting systems for different applications due to many advantages in comparison with other lighting technologies [3]. Also, in accordance with government directives and acts of many countries [4], [5], the production and sale of conventional incandescent bulbs used for general purpose lighting is banned (with some exceptions), but the halogen lamps will be phased out in the near future (in several years).

The main advantages of LEDs are high efficacy, high reliability and long life, convenient dimming possibilities for the smart lighting systems, as well as solid casing, which improves mechanical robustness. However, the proper supply as well as thermal and optical design is crucial to gain all the benefits of solid-state lighting (SSL). All these aspects are more or less considered in the framework of the present Doctoral Thesis as they are closely related, but the main attention is paid to the part of LED lamp, which ensures proper supply of LED and the control of luminous flux — LED driver.

The ballast is also the weakest node of the luminaire; thus, the ballast determines the reliability of whole luminaire to a great extent. It also determines the quality of the light, which depends on a dimming method to a great extent.

According to [6]–[10] LED is a powerful instrument for use in smart lighting systems to improve the efficiency and quality of lighting.

MAIN HYPOTHESES AND OBJECTIVES

Hypotheses

1. The accuracy of fluent light regulation can be improved by the compensation of nonlinearities of LED (volt-ampere, lumen-ampere curves) with nonlinearity of driver.
2. Direct LED current regulation can be implemented on the basis of non-inverting buck-boost converter.

Objectives

1. To find the appropriate converter topology and/or operation mode of the converter for the compensation of nonlinearity of the LED load.
2. To evaluate controllability parameters and efficiency of the proposed converters.
3. To synthesize a practical solution of direct current control converter.
4. To develop hardware part of the direct current control converter.
5. To develop control system for the direct current control converter.

MEANS AND METHODS OF RESEARCH

In order to simplify the process of theoretical calculations and graphically represent the obtained results, Mathcad and MS Excel programs have been used. Additionally PSIM and LTspice have been used for the simulation of electrical circuits.

The experimental verification of obtained results has been performed on the test bench in a laboratory. The configuration of the test bench depends on the test carried out, but the main elements are laboratory DC power supply with the constant current function, function generator capable of providing a control signal at different frequencies and duty cycles, precision power analyzer, one or several oscilloscopes, thermographic camera, luxmeter and configurable LED load (usually consisting of 7 high-power LEDs connected in series). Linear or polynomial interpolation has been used for graphical representation of the results of experiments.

IAR Embedded Workbench software has been used for the programming and debugging of MSP430 series microcontrollers. Printed circuit board designs have been developed using OrCAD software.

SCIENTIFIC NOVELTIES

1. Tapped-inductor buck converter has been used for the first time to compensate nonlinearities of LED, thus improving controllability parameters of the driver.
2. Discontinuous conduction mode of DC-DC converter has been used for the first time to compensate nonlinearities of LED, thus improving controllability parameters of the driver.
3. Non-inverting buck-boost converter with double closed loop control has been used for the first time to operate in a direct current regulation mode, thus increasing dimming resolution of the driver.
4. A new control algorithm has been developed for non-inverting buck-boost converter. It allows obtaining the direct current control.

PRACTICAL NOVELTIES

1. The technique for calculation of optimal turns ratio of tapped-inductor fitter-buck converter for the compensation of nonlinearity (improvement of controllability) of LED load has been proposed. A version of design for such a converter has been developed.
2. The energy efficient current measurement approach for the tapped-inductor converter has been implemented.
3. Parameters of switching frequency, duty cycle, and inductance for the compensation of nonlinearities of LED have been formulated using the converter in a discontinuous conduction mode.
4. Microcontroller based control system for non-inverting buck-boost has been implemented to obtain the properties of the converter with the direct current control.

PRACTICAL APPLICATION OF RESEARCH RESULTS

The presented prototypes of tapped-inductor fitter-buck based LED dimmer and non-inverting buck-boost converter with direct current control can be easily re-designed (equipped with an appropriate communication module) for market-ready solutions. Additional standard conversion blocks (rectifier with input filter, power factor corrector, DC/DC converter) are necessary for the ballast sourced from the AC power grid. The typical application could be high and middle power LED lamps, such as street and park lighting lamps. The considered converters can be used in a direct way with the low voltage DC grid (nanogrids for households of the future [11]).

DISSEMINATION OF RESEARCH RESULTS

There are 34 author's publications and 1 patent, in total. The following 11 publications, including 1 patent, are presented in the Doctoral Thesis:

1. **O. Tetervenoks**, «Reduction of Power Losses in Measurement Subsystem for Tapped — Inductor Based LED Driver, » in *Proceedings of the 15th European Conference on Power Electronics and Applications (EPE 2013)*, 2013, pp. 1–9.
2. I. Galkin and **O. Tetervenoks**, «Tapped — Inductor Converter for Dimmable Light — Emitting Diode Driver, » in *Proceedings of 4th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG 2013)*, 2013, pp. 1307–1311.
3. **O. Tetervenoks**, «Choice of Power and Control Coupling Elements for Dimmable LED Driver for Smart Lighting Networks,» in *Proceedings of the 39th Annual Conference of the IEEE Industrial Electronics Society (IECON 2013)*, 2013, pp. 5940–5944.
4. I. Galkin and **O. Tetervenoks**, «Validation of direct current control in LED lamp with non-inverting buck-boost converter,» in *39th Annual Conference of the IEEE Industrial Electronics Society (IECON 2013)*, 2013, pp. 6021–6026.
5. **O. Tetervenoks** and I. Milashevski, «Dimmable LED Drivers Operating in Discontinuous Conduction Mode,» *Electr. Control Commun. Eng.*, vol. 2, no. 1, pp. 27–33, 2013.
6. **O. Tetervenoks** and I. Galkin, «Assessment of Switch Mode Current Sources for Current Fed LED Drivers,» in *Technological Innovation for Collective Awareness System: 5th IFIP WG 5.5/SOCOLNET Doctoral Conference on Computing Electrical and Industrial Systems*, L. M. Camarinha — Matos, N. S. Barrento, and R. M. (Editor), Eds. Berlin: Springer Berlin Heidelberg, 2014, p. 621.
7. **O. Tetervenoks** and I. Galkin, «Assessment of Light Fluctuations of LED Lamp at Different Pulse Mode Regulation Methods,» *Elektron. ir Elektrotechnika*, vol. 20, no. 6, pp. 42–45, 2014.
8. I. Galkin and **O. Tetervenoks**, «Efficiency considerations for non-inverting buck-boost converter operating with direct current control,» in *2014 16th European Conference on Power Electronics and Applications*, 2014, pp. 1–8.

9. **O. Tetervenoks** and I. Galkin, «Considerations on Practical Implementation of Control System for Switch Mode Current Regulator,» in *Proceedings of 14th Biennial Baltic Electronics Conference (BEC2014)*, 2014, pp. 225–228.
10. **O. Tetervenoks** and I. Galkin, «Evaluation of Stability of Several LED Drivers in Smart Lighting Applications,» in *Proceedings of 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON2014)*, 2014, pp. 48–51.
11. I. Galkin, **O. Tetervenoks**. «Adjustable electronic current source with doubled current stabilization» Latvian patent. No. LV14796. 2014.04.20.

CONTENTS OF DOCTORAL THESIS

2. LED LIGHTING TECHNOLOGIES

The manufacturing process of LED is very complicated resulting in slight differences in V-A curve even for LEDs made from the same wafer. The differences in V-A curve create restrictions in the choice of connection type for LEDs. Series connection is the most appropriate for LEDs to overcome this problem. Light output of all LEDs connected in series is almost proportional to the forward current flowing through them. Change of current amplitude in LEDs is the main dimming approach. There are also several other convenient dimming options, which are discussed in the next sections. Therefore, LEDs are also the most convenient for distributed lighting and smart lighting systems, where the dimming function is vital [12], [13].

There are different configurations for the ballasts of the dimmable LED lamps. Conventional configuration of the ballast powered from the grid consists of several typical stages: rectifier from the side of the power grid, filter, power factor corrector, DC/DC converter, and LED driver. Every stage has its own efficiency; therefore, the overall efficiency of the ballast decreases with increasing number of conversion stages (Fig. 2.1).

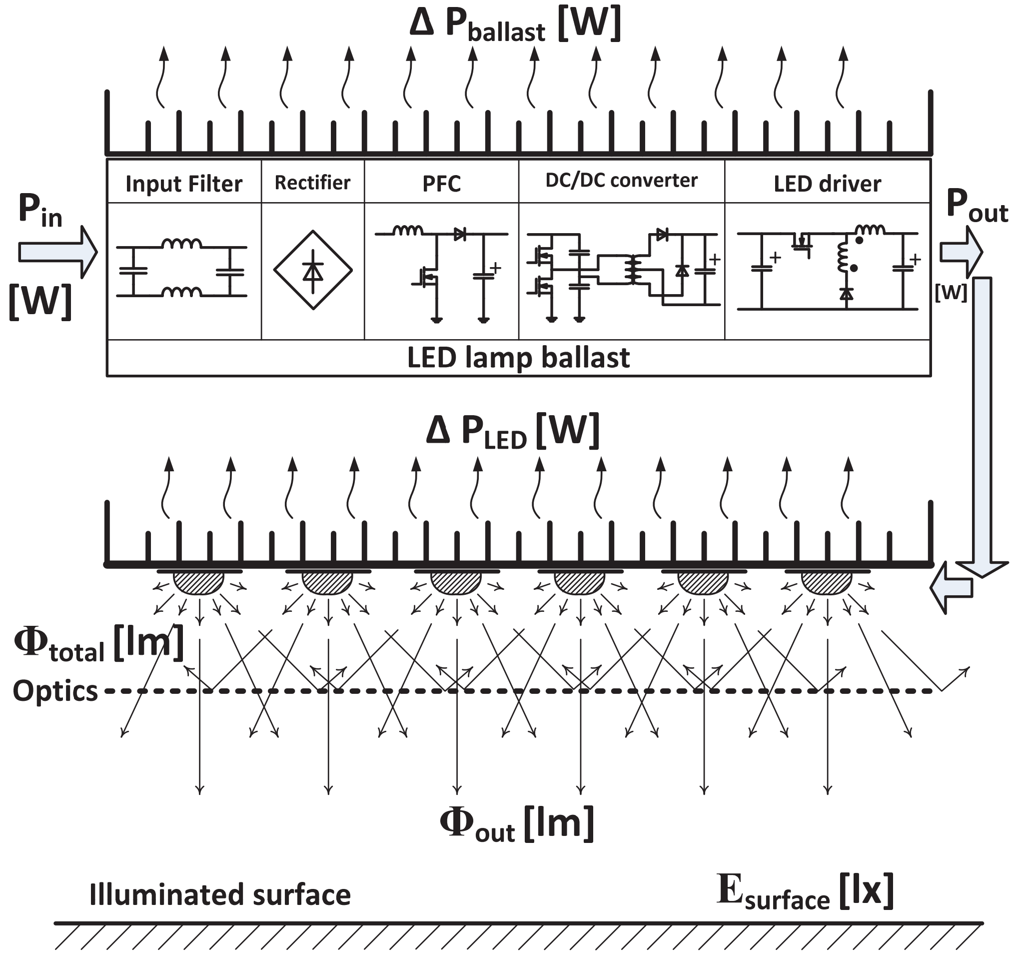


Fig. 2.1 Standard configuration of the LED lamp and the ballast for high power applications, including several conversion stages and power losses.

The standard approach to improve the efficiency is the combination of the functions of several typical stages in one [14]–[26], but the dimming function usually suffers in this case (TRIAC dimmer, or pulse mode dimming) [27]. Such complicated configuration (in case of multistage converter) or functionality (in case of a single stage converter) is dictated by the requirements for the existing power grid.

Single stage converters are usually used in small-to-middle power range applications (indoor lighting, office lighting, etc.). For high power applications (street and park lighting, floodlights) multistage configuration is still relevant. Typical LED lamp power ranges and applications are summarized in Fig. 2.2.

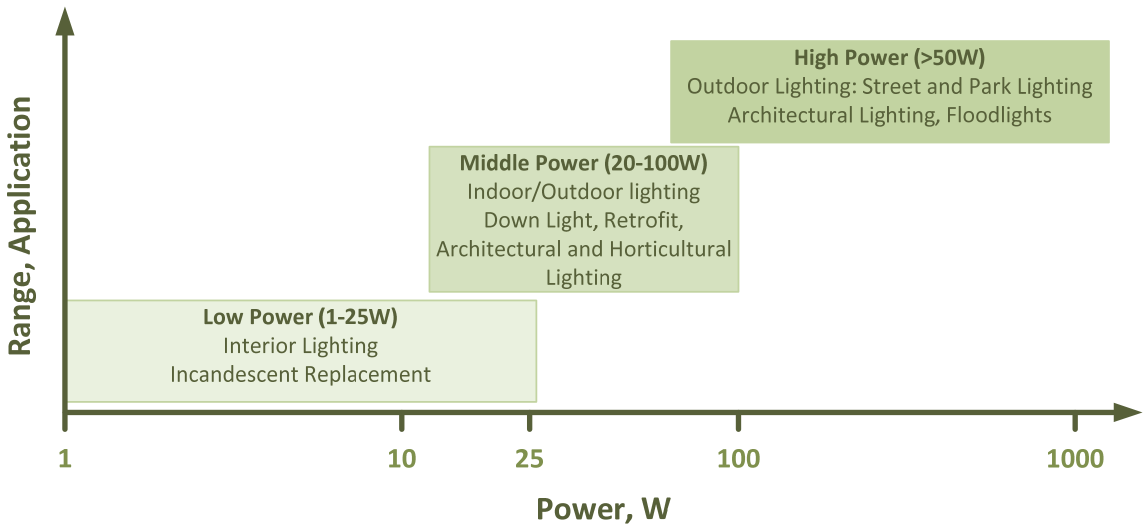


Fig. 2.2 Typical power ranges and applications of LED lamps [28].

There are also specific applications, where multistage converters are more convenient. They are multicolor LED lamps for architectural and stage lighting, horticultural lighting applications etc. Besides, the idea of smart grids is becoming more and more relevant. In accordance with this concept, some researchers and scientists propose the use of low voltage DC grid for domestic electrical systems [11] and smart LED lighting systems [13]. Thus, the studies in the field of conventional DC LED drivers with a dimming function are still relevant.

During development it is very important to achieve required functionality (dimming feature, current control, various protection features etc.) of the LED lamp, at the same time insuring high quality of the light produced by the lamp.

Dimming method has a great impact on the quality of produced light. Thus, it must be carefully evaluated during the development of the driver.

The considered light regulation techniques are summarized in Fig. 2.3. Their benefits and drawbacks are listed in Table 2.1. Pulse mode flux regulation is most appropriate for high performance devices where stable light color temperature is critical (backlit of LCD panels, displays) [30], [31]. This method might suffer from a stroboscopic effect (because the luminous flux of LED follows the forward current at a very high speed), which is unwanted phenomenon in general lighting. Stroboscopic effect is especially dangerous for industrial lighting, where spinning mechanisms under certain conditions may seem motionless. Therefore, step mode and amplitude (fluent) luminous flux regulation methods are most appropriate in general lighting applications; however, a fluent mode regulation technique allows utilizing LED in a more efficient way (approximately by 7 % in case of dimming at 50 %) [32].

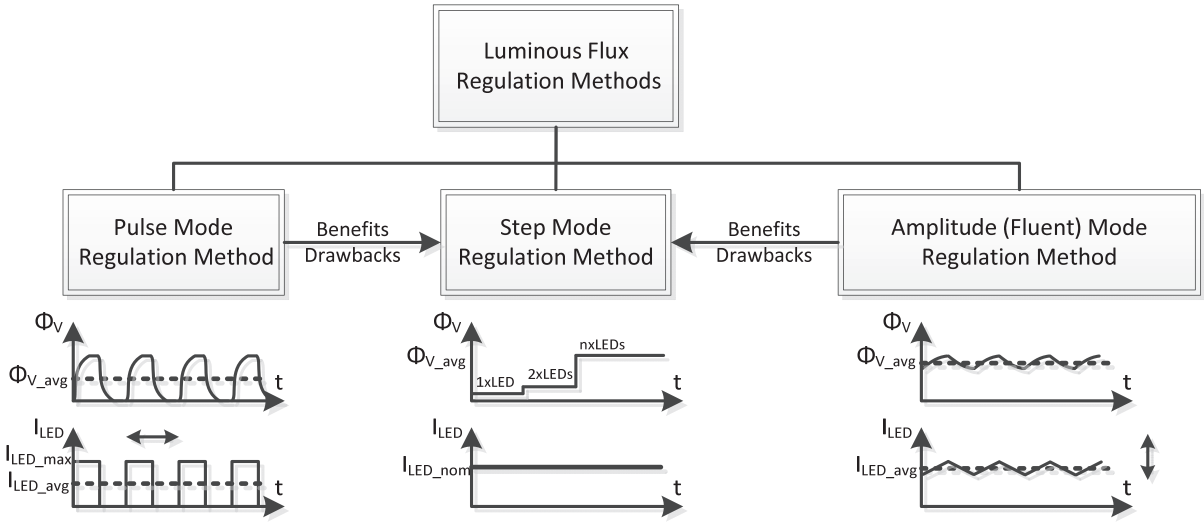


Fig. 2.3 Luminous flux regulation methods for LED lamps as well as typical waveforms of LED forward current and luminous flux.

In Fig. 2.4, the ampere-lumen (A-Lm) curve of the common high power LED is shown. In case of pulse mode or step mode luminous flux regulation the LED operates at a fixed point, usually maximum allowable or nominal (test) current. This maximum or nominal current is applied to LED periodically at a high frequency, but the luminous flux is proportional to the duty cycle D (ratio of the time when the current is applied to the time of the whole period). It can be imagined that a change in duty cycle moves the averaged operation point of LED in a straight line, which is connected between a crossing point of the axes and the previously mentioned fixed point (thick dashed line in Fig. 2.4).

In case of fluent luminous flux regulation, the operation point of LED moves along A-Lm curve, thus achieving higher efficacy, especially at a smaller input current (power) as it shown in Fig. 2.4. Therefore, amplitude mode regulation is the most suitable for general lighting applications.

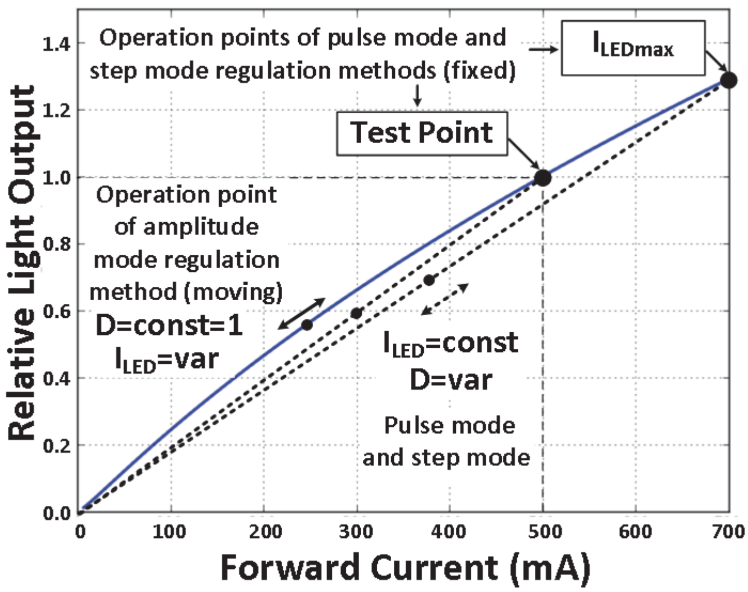


Fig. 2.4 Ampere-lumen curve of a common high power LED and operation points for different luminous flux regulation methods.

Table 2.1

Benefits and Drawbacks of Luminous Flux Regulation Methods

Pulse Mode	Step Mode	Amplitude (Fluent) Mode
+high accuracy and resolution	+ no stroboscopic effect	+ higher efficiency of LEDs
+ stable color temperature	+ stable color temperature	+ no stroboscopic effect
+ simple control system	+ simple control system	+ longer life span
− undesirable stroboscopic effect	− shorter life span	− relatively complex control system
− shorter life span	− low resolution (small number of regulation steps)	− unstable color temperature
− worse efficiency of LEDs	− worse efficiency of LEDs	− accuracy and resolution depends on complexity of control system

The following controllability parameters of LED dimmers [6] are used as criteria of evaluation:

1. Nonlinearity of regulation (*NL*):

$$NL = (\Delta S / S) \cdot 100\% \, , \tag{2.1}$$

where *ΔS* is root-mean declination of regulation curve *RO(D)* from the equivalent linear one $RO_L(D)$, as shown in Fig. 2.5

$$\Delta S = \sqrt{\frac{1}{D_{\max} - D\min} \int_{D_{\min}}^{D_{\max}} [RO(D) - RO_L(D)]^2 \, dD} \, , \tag{2.2}$$

but *S* is a root-mean value of the evaluated curve

$$S = \sqrt{\frac{1}{D_{\max} - D\min} \int_{D_{\min}}^{D_{\max}} RO(D)^2 \, dD} \tag{2.3}$$

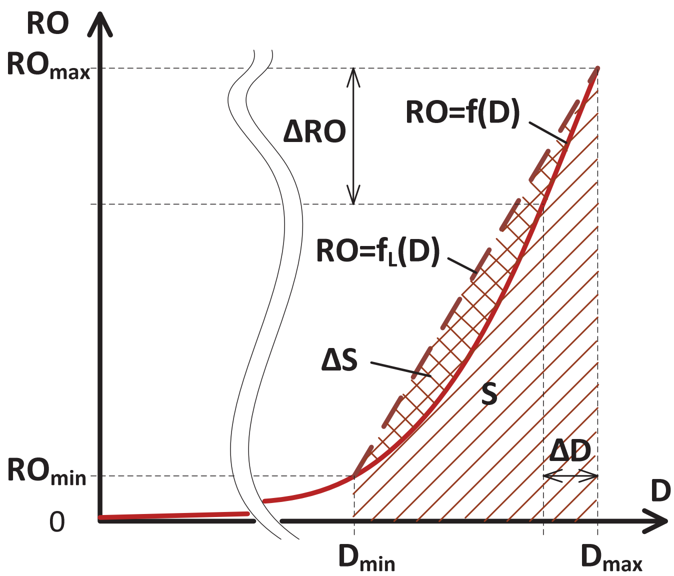


Fig. 2.5 Clarification to the calculation of the parameters of control performance.

2. Ratio of achievable span of relative output vs. span of usable values of duty cycle G_a:

$$G_a = \frac{RO_{\max} - RO_{\min}}{D_{\max} - D_{\min}} \cdot 100\% . \tag{2.4}$$

3. Dynamic range of gain RG_{LED}.

$$RG = \frac{G_{\max}}{G_{\min}} \tag{2.5}$$

where G_{max} and G_{min} are maximum and minimum values of the gain G, which is a derivative of RO with respect to D and is also function of D

$$G(D) = \frac{dRO}{dD} \approx \frac{\Delta RO_k}{\Delta D_k} , \tag{2.6}$$

where ΔRO_k and ΔD_k are the finite changes of RO and D in the k-th point of $RO(D)$ curve.

As the goal of these studies is LED lamp control system based on highly integrated MCU with reduced complexity and costs, the following sections concentrate on the search of converters (capable of providing amplitude mode dimming) with the properties, which allow achieving more or less linear relationship between the input and output signals of the plant (combination converter — LED load).

3. COMPENSATION OF NONLINEARITIES OF LED

One of the ways how to simplify the control system of the LED luminaire is to try to overcome the problems with nonlinear relationships in control chain (Fig. 3.1 (a)). LED is nonlinear part of this control chain; thus, one of the options is to try to compensate this nonlinearity by the nonlinearity of the other part, for example, by the relationship of the voltage regulator (converter) as shown in Fig. 3.1 (b) and (c).

To verify this hypothesis, it is necessary to find the converter with an appropriate relationship between the duty cycle and output voltage. Conventional step -up, step-down, and step-up/step-down topologies (the relationships are shown in Fig. 3.2 (a) as solid thick curves) are not suitable for this purpose (the required relationship is shown in Fig. 3.2 (c) as a dashed thick curve). Therefore, the family of tapped-inductor converters has been studied in order to find a suitable solution. It is worth mentioning that other authors have also considered tapped-inductor converters as LED drivers [33], [34]. Tapped-inductor based solutions are also available on the market [35], [36]. However, previously tapped-inductor solutions have been considered converters with a high input-to-output voltage step-down ratio or current step-up ratio. The capability of compensation of LED V-A curve has not been studied previously.

A good summary of the family of tapped-inductor converters is given in [33]. Like conventional step-up/step-down converters, tapped-inductor converters are classified in three main groups: buck, boost, and buck-boost. Parameter λ has been introduced in order to unify the study of all the converters [37]:

$$\lambda = N1/N2\,, \qquad (3.1)$$

where *N1* and *N2* are the numbers of turns of the windings of tapped-inductor. It has been found that a tapped-inductor buck converter is the most suitable one for the compensation of V-A curve (gain curves are given in Fig. 3.2). There are two tapped-inductor buck converter types: fitter-buck converter ($0 < \lambda < 1$) and reducer buck converter ($\lambda > 1$). The principal electrical circuits are given in Fig. 3.3.

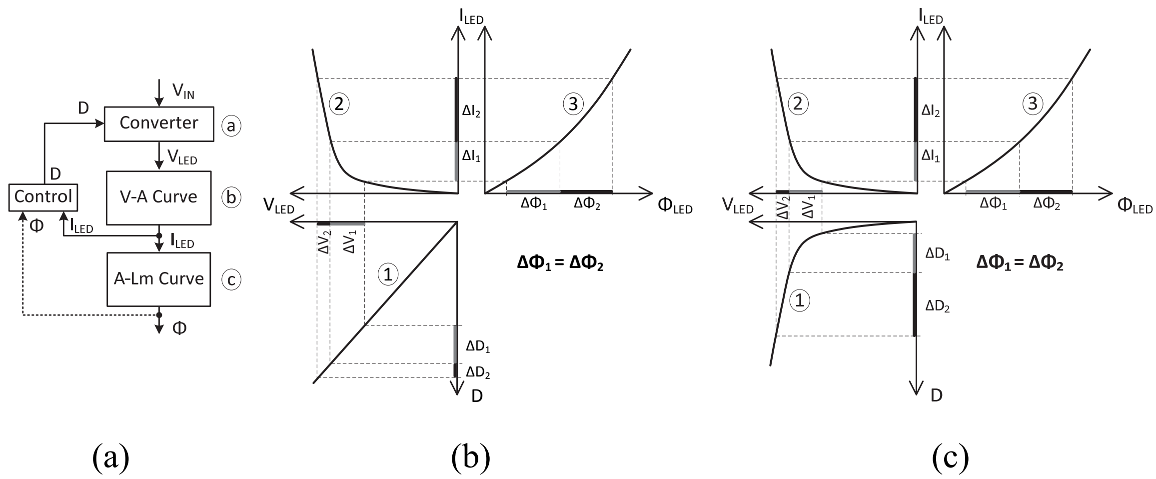


Fig. 3.1 Compensation of nonlinearity: a) simplified control chain structure; b) relationship between the duty cycle (control parameter) and luminous flux (parameter under control) in case of linear relationship of the converter; c) relationship between the duty cycle and luminous flux in case of nonlinear relationship of the converter.

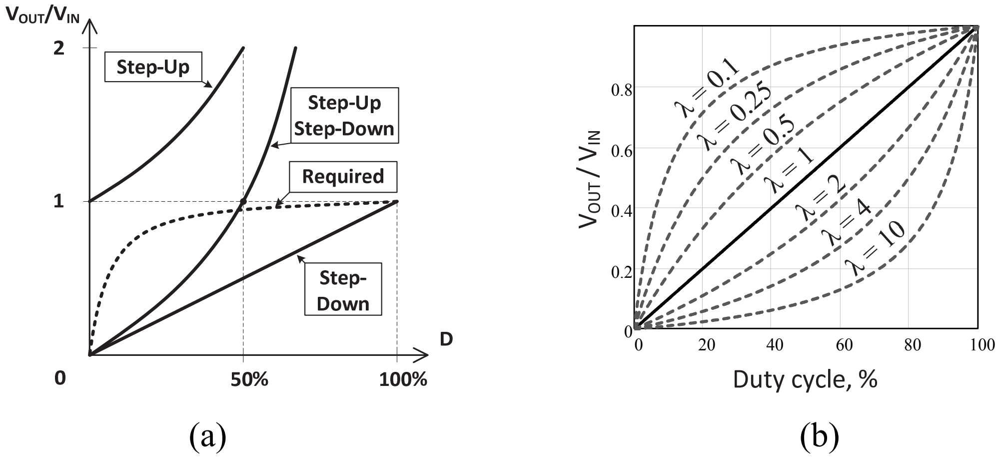


Fig. 3.2 The curve required for compensation of LED V-A curve: a) relationships between the gain of the converter and duty cycle for the conventional topologies; b) input-to-output gain curves of tapped-inductor buck converter at different duty cycles and parameter λ values.

The relationship between the gain V_{OUT}/V_{IN} and duty cycle D of tapped-inductor buck converter can be found from the expression [33]:

$$\frac{V_{OUT}}{V_{IN}} = \frac{D}{D + (1 - D) \cdot \lambda}, \tag{3.2}$$

where V_{IN} is the input voltage of the converter, V_{OUT} is the output voltage of the converter, D is the duty cycle.

First of all, the parameters of the load connected to the converter play a significant role in stable performance of the converter. The volt-ampere (V-A) curve of 7 Seoul Semiconductor W724C0 LEDs connected in series has been measured for the analysis of controllability parameters of the tapped inductor converters described above. 50 mA steps at the bottom part (below 600 mA) and 100 mA steps at the upper part (above 600 mA) of the V-A curve have been selected between measurements points (Fig. 3.4 (a)).

Linear interpolation between the measured points (Fig. 3.4 (a)) has been used for further numerical calculations of the controllability curves. Then the relationship between the duty cycle and LED load current can be found using expression:

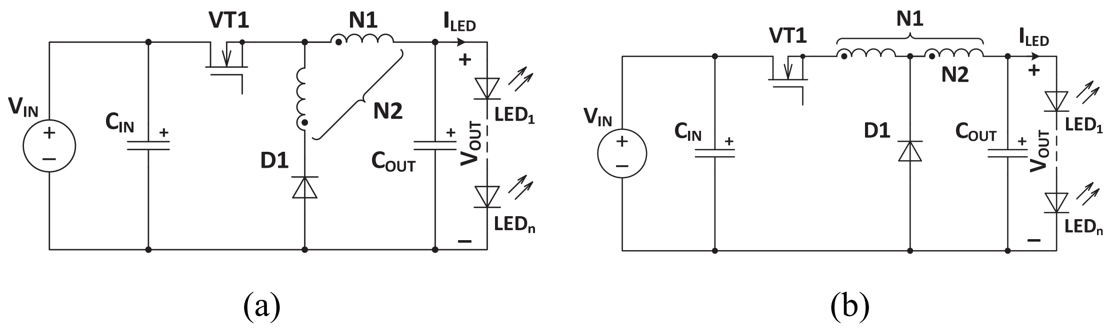
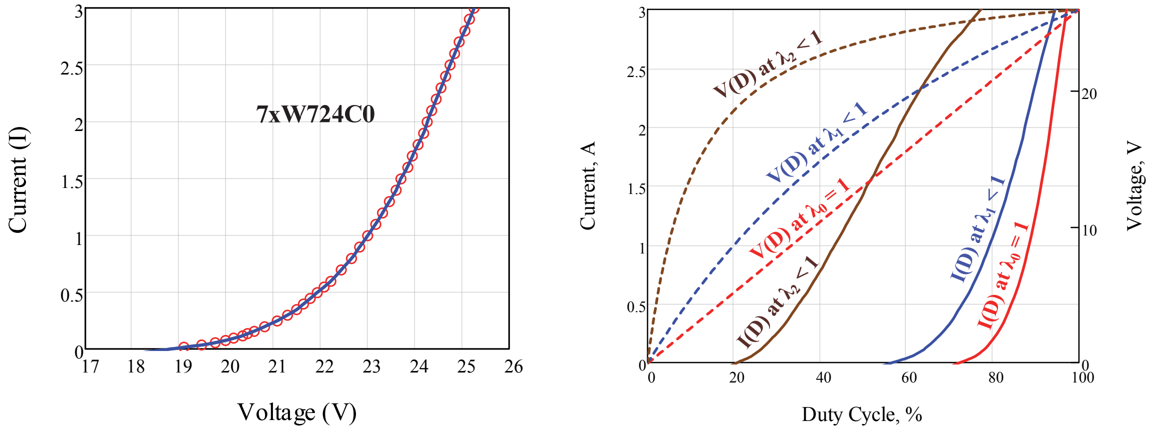


Fig. 3.3 The principal electrical circuits of tapped-inductor buck converter: a) fitter-buck converter (0 < λ < 1); b) reducer-buck converter (λ > 1).



(a) (b)

Fig. 3.4 The analysis of the loaded converter: a) V-A curve of the LED load used in experiments and for numerical calculations; b) examples of analytical relationships between the duty cycle and output voltage/current of loaded converter.

$$I_{LED}(D) = I_{LED1} + \frac{\dfrac{V_{IN} \cdot D}{D + (1-D) \cdot \lambda} - V_{LED1}}{V_{LED2} - V_{LED1}} \cdot (I_{LED2} - I_{LED1}), \tag{3.3}$$

where I_{LED} is the forward current of LED load at the corresponding forward voltage V_{LED} arbitrary selected between two known (measured) points $I_{LED1}(V_{LED1})$ and $I_{LED2}(V_{LED2})$. The calculation examples (calculated curves) are given in Fig. 3.4 (b).

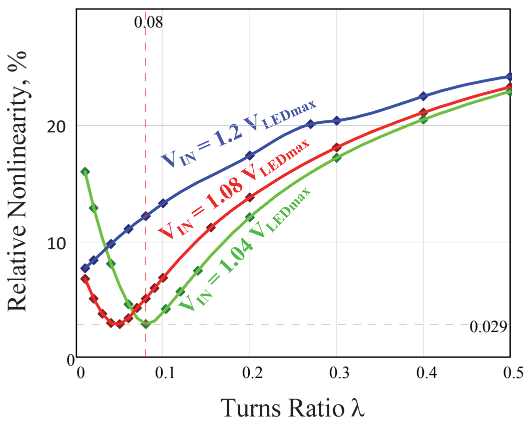
The analysis of these curves provides insight about the controllability parameters discussed above (2.1)–(2.6). The calculation results are summarized in Fig. 3.5, where a few plots with controllability curves at three different input voltages have been constructed.

The optimal value of parameter λ can be found from the obtained curves (Fig. 3.5). It is clearly seen that the better values are achieved approximately at $\lambda = 0.1$, when the input voltage of the converter is slightly higher (by 5…10 %) than the maximum output voltage.

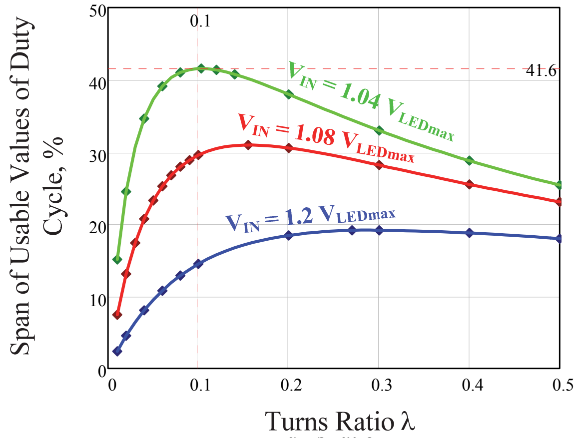
The analysis for the other tapped-inductor converters (boost and buck-boost topology) has been done in a similar way (full analysis is given in the Doctoral Thesis). However, it has been found that these topologies are less suitable for the compensation of LED V-A curve: their controllability parameters are not better in comparison with traditional non-tapped converters.

For the converter control systems based on inductor current feedback are usually more stable compared to systems with output current feedback [38]. The typical tappet-inductor current waveforms (in both windings) of fitter-buck converter operating in CCM are shown in Fig. 3.7. For correct inductor current measurements the sensor should be placed in series with winding L1. However, the measurements of the current flowing in winding L2` can also be used for calculation of the current in L1. The analysis of the waveforms (Fig. 3.7 (b)) of the converter (small ripple approximation) gives the following expressions:

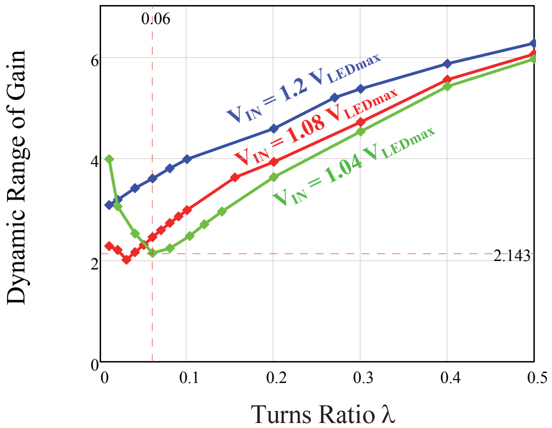
$$I_{OUT} = I_{off} \cdot \left(D/_{\lambda} + 1 - D \right), \text{ or } I_{OUT} = I_{off} \cdot (9 \cdot D + 1) \text{ if } \lambda = 0.1 \tag{3.4}$$



(a)

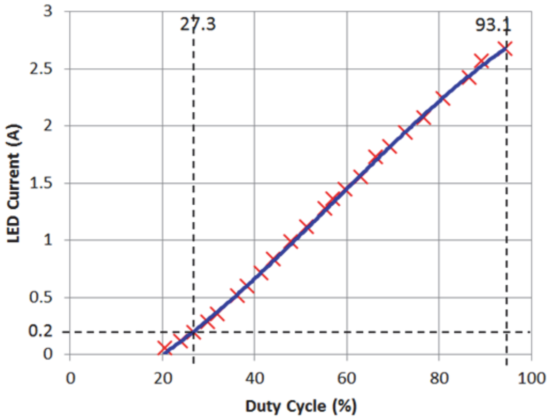


(b)

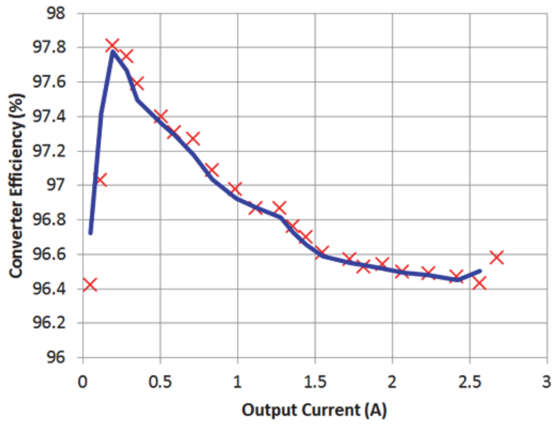


(c)

Fig. 3.5 Controllability parameters of the tapped-inductor buck converter connected to the LED load at different input voltages and tapped-inductor turns ratio λ values: a) nonlinearity; b) usable duty cycle span; c) dynamic range of gain.



(a)



(b)

Fig. 3.6 Results of the experiments with the prototype of fitter-buck (λ = 0.1) tapped-inductor converter: a) measured controllability curve; b) efficiency in the whole regulation range.

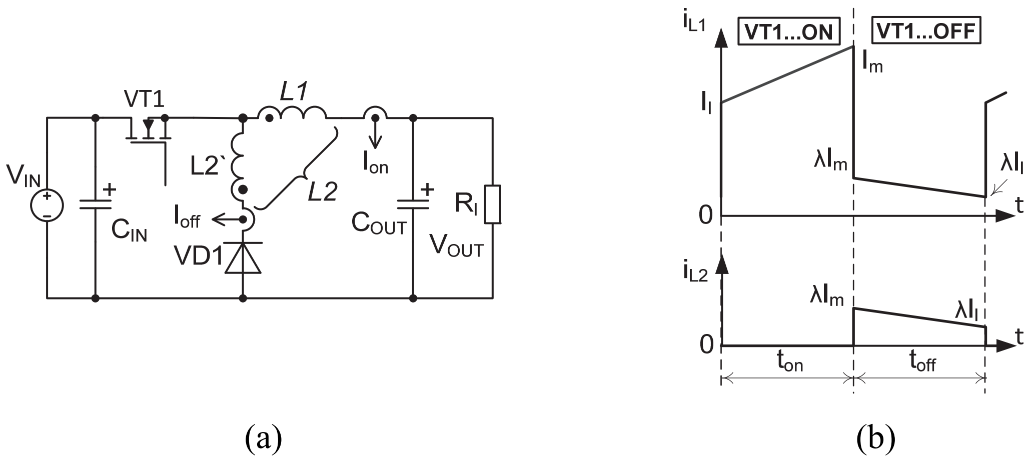


Fig. 3.7 Energy efficient inductor current measurement approach: a) possible placing of current sensor; b) typical current waveforms of tapped-inductor.

It is seen from (3.4) that the measurements of output current can be performed in an indirect way placing the current sensor in series with the winding L2`, if the turns ratio λ and duty cycle of transistor VT1 are known. If the turns ratio is equal to 0.1 (the optimal value from the point of view of controllability determined above), then the amplitude values of the current flowing in winding L2` will be 10 times less than in winding L1. However, the main drawback should be taken into account: the approach can be implemented in digital control system and it additionally consumes computational resources of the processor.

The additional experiments have been made to confirm analytical expression (3.4) of the relationship between the inductor current and output current. In this expression I_{on} is an average current value in winding L1 during on-state of the transistor VT1, I_{off} is an average current value in windings L1 and L2` during off-state of the transistor VT1 (Fig. 3.7 (b)):

$$I_{on} = \left(\frac{I_l + I_m}{2}\right) \text{ and } I_{off} = \left(\frac{\lambda \cdot I_l + \lambda \cdot I_m}{2}\right) = \lambda \cdot I_{on}. \quad (3.5)$$

The following parameters have been measured during the experiments: output current I_{OUT}, the oscillograms of the winding L1 and winding L2` of the tapped-inductor. The values of I_{on} and I_{off} have been obtained from these oscillograms, and the results are summarized in Fig. 3.8.

Two curves are given in this figure for comparison: experimentally obtained relationship between the average current in the primary winding (inductance L1) during the on-state of transistor VT1 to the output current and the same dependency calculated from measurements of current in the secondary winding (inductance L2`) during off-state using (3.4). There is only a slight discrepancy between the measured and calculated curves that can be explained by measurement inaccuracy caused by the precision of measurement equipment. It is worth mentioning that the values of output current obtained during the transient process will be incorrect. However, the output current always tends to the calculated value and reaches this value after the transient. The use of this current measurement approach in the closed loop control can slow down the transient processes (depends on the output capacitor), but the overshoots will be reduced.

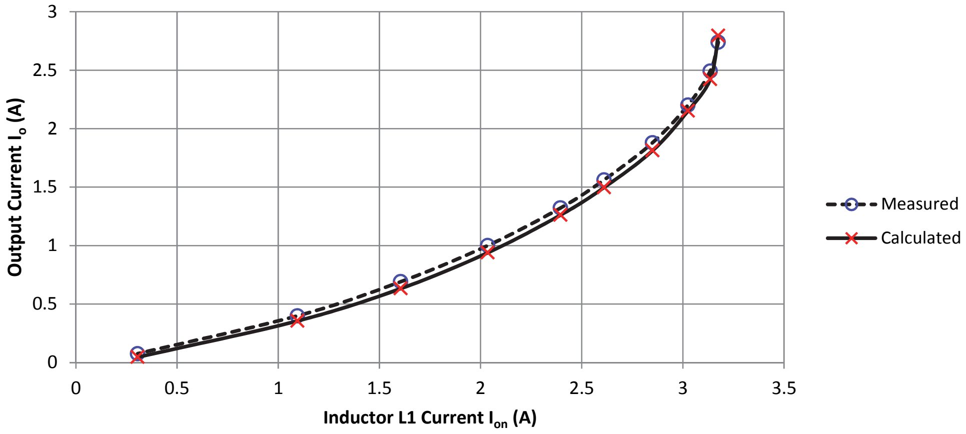


Fig. 3.8 Relationship between the output current and average current I_{on} in the primary winding of tapped-inductor: comparison of measured and calculated values of output current of the converter.

Another way to compensate nonlinearity of LED V-A curve — use of discontinuous conduction mode (DCM) of the conventional buck converter — was considered in [6] and [39].

The converter operates in a discontinuous mode when low current is drawn by the load. For DCM operation of the buck converter the following criteria should be fulfilled:

$$\frac{V_{out}}{V_{IN}} = \begin{cases} D \quad if \quad \dfrac{2L \cdot f_{sw}}{R} < (1-D) \\ \dfrac{2}{1+\sqrt{1+\left(\dfrac{8L \cdot f_{sw}}{R}\right) \Big/ D^2}} \quad otherwise \end{cases}, \tag{3.6}$$

where L is inductance of the main choke, f_{sw} is switching frequency, R is the resistance of resistive load [40]. Several relationships calculated using (3.6) are given in Fig. 3.9 (a). The same resistance and switching frequency have been used in these calculations. It is seen from Fig. 3.9 (a) that the buck converter with the lower inductance value L of the main choke allows achieving the relationship required for the compensation of nonlinearity of LEDs, as shown in Fig. 3.1 (c).

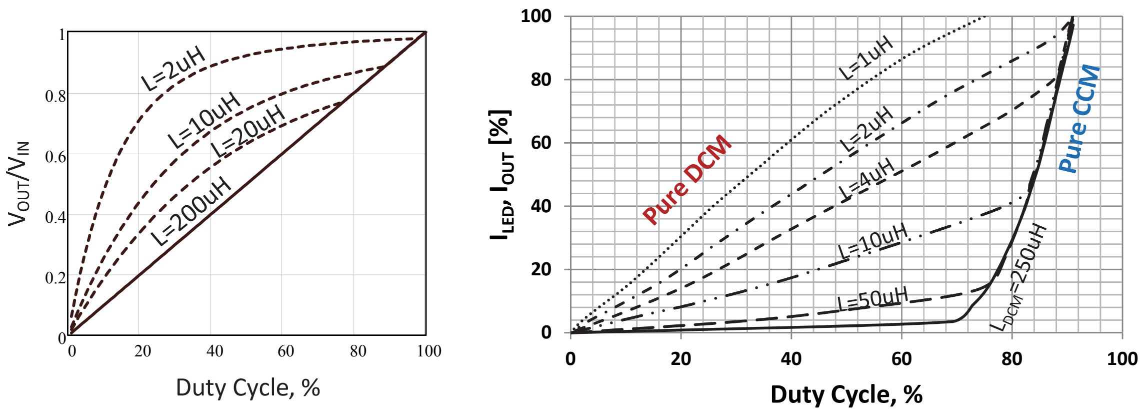


Fig. 3.9 Discontinuous conduction mode operation of the buck converter: a) with resistive load (analytical calculations); b) with LED load (obtained from experiments).

The analytical results for both approaches have been confirmed by the experiments with the built prototypes of the tapped-inductor fitter-buck converter (using the circuit shown in Fig. 3.9 (b)) and conventional buck converter. The results of the tests of this prototype are summarized in Fig. 3.6 and compared with the analytical ones (Table 3.1).

Table 3.1

The Comparison of Analytical and Experimental Data

	Topology	NL, %	G_a, %	RG
Analytical	Buck	29	16	5.9
	Fitter-buck ($\lambda = 0.1$)	4	42	2.5
	Buck (DCM)	13	62	3.0
Experimental	Buck	20	18	3.6
	Fitter-buck ($\lambda = 0.1$)	2	67	1.9
	Buck (DCM)	2	69	1.4

4. DIRECT CURRENT CONTROL

In previous studies it has been hypothesized that current fed (CF) converters are more suitable for driving LEDs, as the LED current is regulated in a direct way [6], [41], [42]. Also, the circuits for three basic topologies of the current fed converters have been derived [6], [42]. The most widely spread VF converters and their CF versions are summarized in Fig. 4.1.

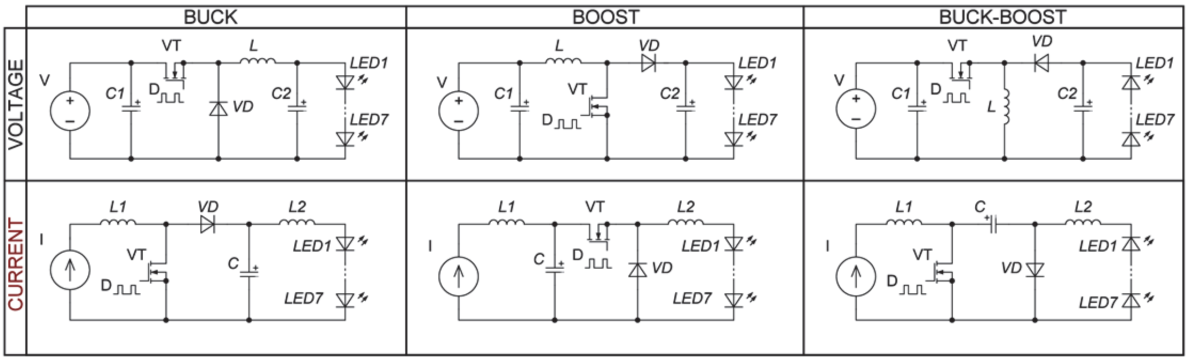


Fig. 4.1 The most widely spread VF converters and their CF versions.

The main drawback of current fed converter has also been stated: the constant current source (CS) at the input is necessary. One of the solutions to this problem was proposed in [43]. In the present research, non-inverting buck-boost converter has been considered the constant current (CS) source and current regulator (CR) as shown in Fig. 4.2.

There are rather many ICs, which are based on this topology and are available on the market, for example [44]. A number of studies have been performed recently to improve different parameters of such circuits. For example, [45] is devoted to optimization of accuracy and energy efficiency of current sensing technique of such ICs, but [46] — optimizes operation of this converter in general purpose applications. However, all these solutions consider the converter to be VF circuit.

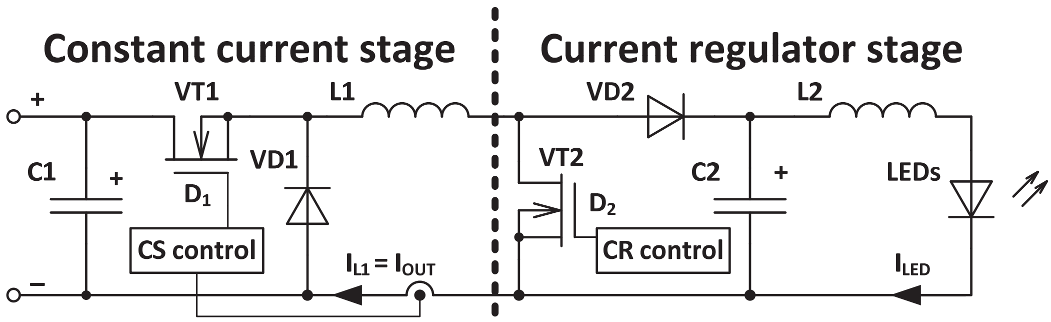


Fig. 4.2 Principal circuit of non-inverting buck-boost converter, considered to be the combination of constant current (CS) source and current regulator (CR).

As mentioned previously, the approach presented here is different and considers the topology to be a constant current source and current regulator. This may have impact on the values of capacitors and inductors and, therefore, on their weight and size, as well as on the efficiency of the converter. However, the main hypothesis of the research states that by means of this approach it is possible to obtain the regulation curve of the lamp that has high linearity and low averaged gain that, in turn, also provides better accuracy of the regulation and stability of the regulator with a feedback.

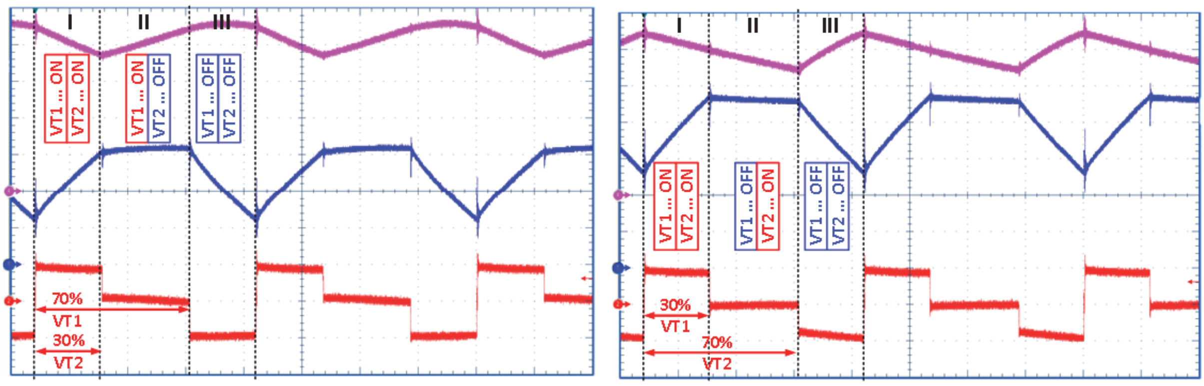
According to [43], transistor VT1 must operate in such a way that average current of inductor L1 is constant (with a variable duty cycle), while the transistor VT2 operates with a constant duty cycle, which determines the value of output current. Transistors can operate either independently or synchronously. In the simplest configuration it is possible to organize a regulation system using only one current feedback in CS stage (Fig. 4.2).

Several configurations of control system for non-inverting buck-boost converter with independent and synchronous operation of transistors VT1 and VT2 and one current feedback are considered in the following subsections.

To ensure energy balance of the coil, the transistors VT1 and VT2 of the non-inverting buck-boost converter should be controlled with complementary signals (as shown in Fig. 4.3) using the control law

$$D_1 + D_2 \approx 100\% . \tag{4.1}$$

The above-mentioned converter with the control algorithm defined by (4.1) has been tested experimentally. The obtained regulation curves are given in Fig. 4.4. In general, the expected regulation of the output current is achieved if condition (4.1) is fulfilled. Also, the current of the CS stage is rather stable within a wide range (40…100 %), as evident from Fig. 4.4.



(a) (b)

Fig. 4.3 Inductor L1 current (blue), voltage (red) and CR capacitor voltage (magenta): a) at duty cycle D_1 = 30 % of transistor VT1; b) duty cycle D_1 = 70 % of transistor VT1 (time scale is 5 μs/div, voltage scale for inductor (red) is 50 V/div, voltage scale for capacitor is 10 V/div, but current scale is 0.2 A/div).

The charge stage has to be balanced with the discharge stage, which is possible if (4.1) is valid; therefore, the converter is very sensitive to the charge/discharge unbalance; if $D_1 + D_2 > 1$ the output current and power rise rapidly and the converter is under the risk of damage; if $D_1 + D_2 < 1$ then the converter does not produce the required source and output currents. The balance rule described above makes development of control solutions for the converter more complex; however, there is a range of values of the duty cycles (pink area in Fig. 4.4) providing a possibility of a linear regulation curve; the duty cycle itself (whether D_1 or D_2) is the main regulation parameter, while the balance $D_1 + D_2$ plays an additional tuning role.

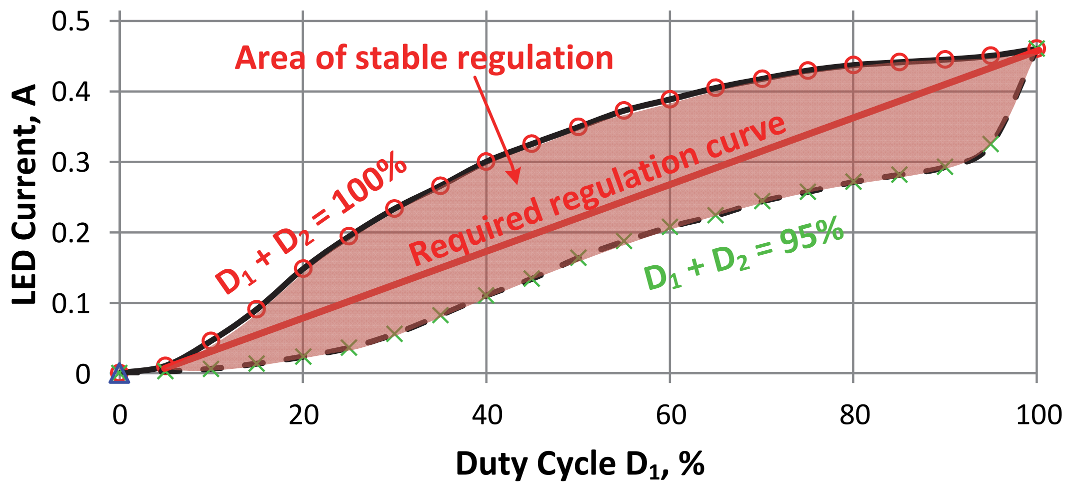


Fig. 4.4 Possible regulation area of tested non-inverting buck-boost converter controlled as combination of current source and current regulator.

For the control system based on this algorithm, the duty cycle of one transistor determines the required output current I_{SET_LED}, which is set by a user, for instance D_2:

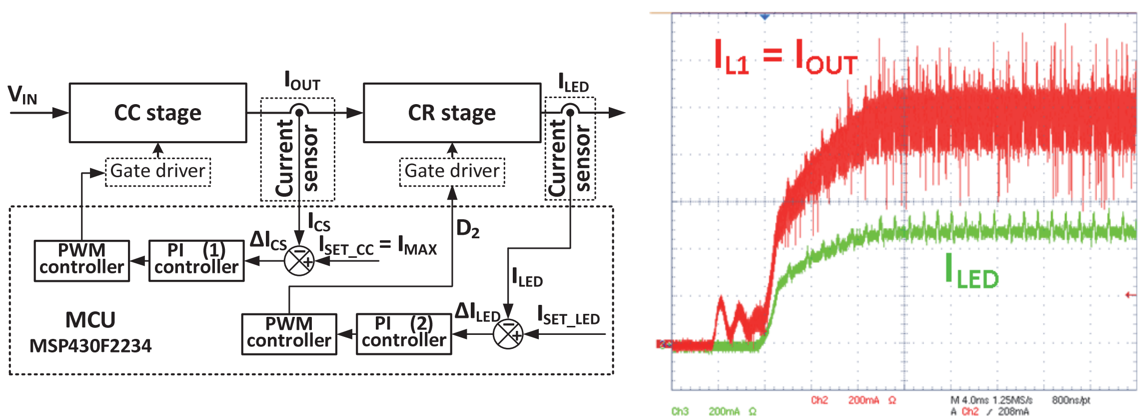
$$D_2 = 1 - I_{SET\_LED} / I_{SET\_CC}\ , \tag{4.2}$$

where I_{SET_CC} is a current value set point of CS stage (determines maximum current). In accordance with (4.1.) and (4.2), the duty cycle of second transistor D_1 can be found using:

$$D_1 \approx I_{SET\_LED} / I_{SET\_CC}\ . \tag{4.3}$$

Therefore, the duty cycles of the transistors VT1 and VT2 can be calculated for the appropriate LED current I_{LED} using (4.2) and (4.3), and fast acting closed loop regulation can be implemented for only one stage (here closed loop control implemented in CS stage, as it is the most critical one for proper converter operation) as shown in Fig. 4.5 (a).

All the experiments have been conducted at similar conditions: input voltage V_{IN} = 35 V; LED load of 8 Seoul Semiconductor W724C0 LEDs connected in series.



(a) (b)

Fig. 4.5 Microcontroller based synchronous operation of transistors VT1 and VT2 of non-inverting buck-boost converter: a) block diagram of the control system; b) results of the tests — start-up process and further operation at half load.

The tests in accordance with the control law (4.1) and the efficiency tests at different transistor control approaches and in a wide regulation range have been conducted (the results are summarized in Fig. 4.6).

According to the obtained results (Fig. 4.6), all considered approaches are suitable for implementation of direct current control. However, the hysteretic controller is most suitable for the asynchronous operation under the described conditions. At the same time, only the proposed synchronous operation allows eliminating ASIC to implement completely MCU based control system, thus reducing initial costs. It also gives better efficiency results (Fig. 4.6) due to lower switching frequency of CS stage (the same with CR stage).

One of built prototypes is demonstrated in Fig. 4.7.

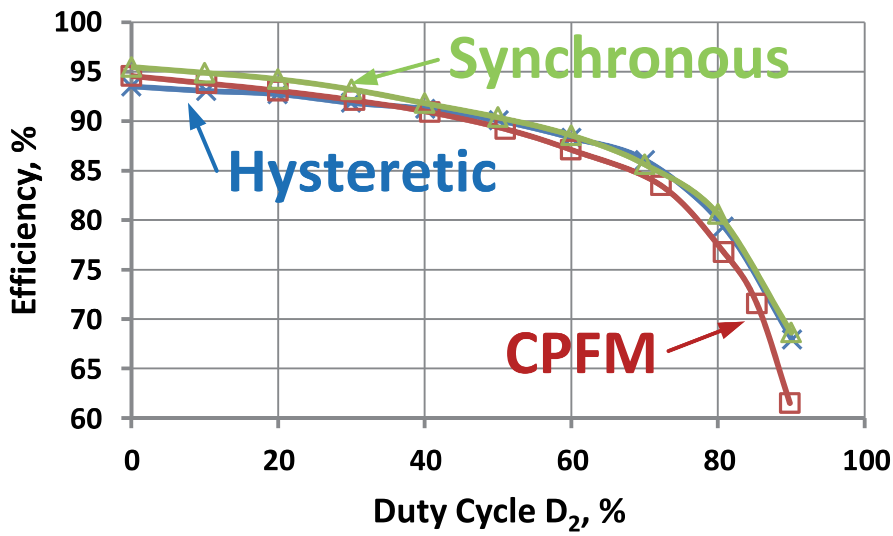


Fig. 4.6 Efficiency of non-inverting buck-boost considered to be combination of CS and CR stages using synchronous control approach and two asynchronous approaches (with hysteretic and constant pause frequency modulation controllers of CS).

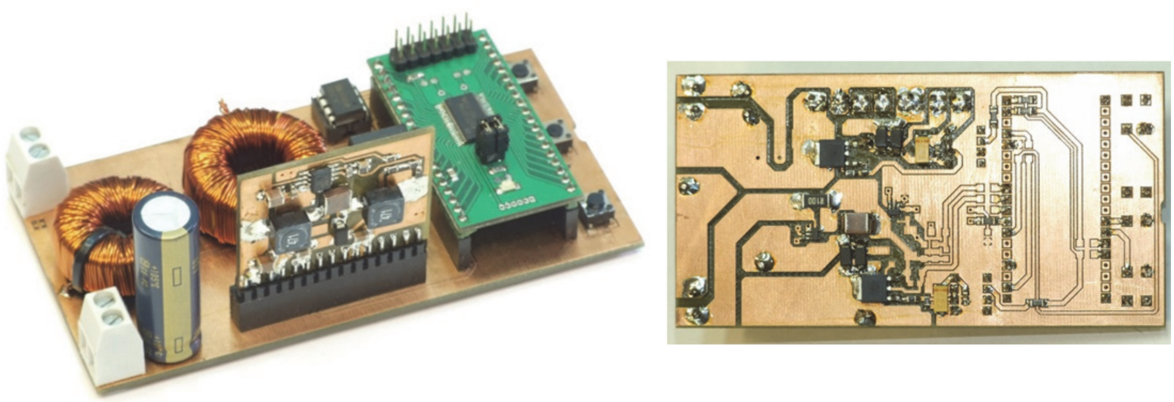


Fig. 4.7 One of the built prototypes: a) top view — the control board with a microcontroller is seen, auxiliary power supply board for control circuit and transistor driver circuits, as well as main inductor L1 and filtering inductor L2; b) bottom view — surface mount transistors VT1, VT2 and diodes VD1 and VD2, as well as CR stage capacitor.

5. CONCLUSIONS

Two main hypotheses have been formulated at the beginning of the present Doctoral Thesis:

1. The accuracy of fluent light regulation can be improved by the compensation of nonlinearities of LED (volt-ampere, lumen-ampere curves) with nonlinearity of driver;
2. Direct LED current regulation can be implemented on the basis of non-inverting buck-boost converter.

1. For the confirmation/refutation of the first hypothesis the different converter topologies with nonlinear input-to-output transfer functions have been studied, as well as operation of DC-DC converter in a discontinuous conduction mode.

During these studies it has been found that the fitter-buck converter, which is the member of the family of tapped-inductor converters, is capable of providing the required nonlinear input-to-output transfer function. This transfer function can be tuned by the ratio of winding turns of tapped-inductor $\lambda = N1/N2$. The optimal value of parameter λ and the operation conditions of the converter have been found in analytical way by evaluation of controllability parameters: nonlinearity, gain, usable duty cycle range, dynamic range, etc. The controllability parameters for tapped-inductor fitter-buck converter are optimal, when the input voltage is slightly higher (5 to 10 %) than output voltage (maximum LED load voltage at full load operation), and the ratio of winding turns of tapped-inductor approximately is equal to $\lambda \approx 0.1$.

The analytical results have been confirmed by the experiments with the built prototype of the tapped-inductor fitter-buck converter: the accuracy of fluent light regulation improves as the dimming resolution increases at least 4 times in comparison with the conventional converter topologies. In addition, the efficiency of this converter is higher or stays at the same level with conventional converter topologies. The efficiency of the tapped-inductor fitter-buck converter can be improved in practical solutions, where output current or inductor current measurements are required for the implementation of closed loop control. The energy efficient inductor current measurement approach can be implemented by placing current sensor in the secondary branch of tapped-inductor, where average current is noticeably smaller than in the primary branch.

Also, it has been found that DC-DC converter operating in a discontinuous conduction mode is capable of compensating nonlinearities of LED. Using DCM, it is also possible to increase dimming resolution in comparison with conventional converter topologies. The results have been confirmed both in analytical and practical way, like in the case with the tapped-inductor fitter-buck converter. However, the efficiency of the DC-DC converter operating in DCM suffers from the higher peak-to-average currents and higher losses in inductor cores. The efficiency and operation stability can be improved by careful selection of material for the inductor core.

In this way, the first hypothesis has been fully confirmed during these studies. This approach not only improves the accuracy of fluent light regulation, but also gives an opportunity to increase the efficiency.

2. For the confirmation of the second hypothesis non-inverting buck-boost converter has been considered. In accordance with [6], the constant current source is necessary at the input of the current fed (CF) converter for the proper operation. It has

been found that the simplest as well as the most efficient way to make the constant current source is to form constant current in the inductor. Therefore, non-inverting buck-boost converter can be considered the simplest combination of constant current source (CS) and current regulator (CR), which in this case is the current fed buck converter.

Different control approaches and hardware configuration for the non-inverting buck-boost converter have been studied in the scope of the present research. Also, the main control algorithm has been developed ($D1 + D2 \approx 100$ %).

It has been found that the non-inverting buck-boost converter operating under the proposed control approach (adhering to the main rule) allows achieving direct current control, thus increasing dimming resolution in comparison with the conventional converter topologies. Efficiency of this converter is slightly worse than of conventional converters. However, this efficiency difference can be minimized by the proper selection of the hardware configuration of the non-inverting buck-boost converter depending on the dimming profile of the lighting system.

Thus, also the second hypothesis has been confirmed in the present Doctoral Thesis.

Further research is related to the development of smart lighting systems. In the framework of the research, the energy efficient LED drivers with convenient dimming function have been considered. However, these drivers are capable of operating directly only in low voltage DC applications (portable devices, automotive lighting, nanogrids for households of the future). At the same time, AC power grids are still the most common energy transmission systems, also in households. Thus, development of the ballast, which incorporates single stage primary converter from the AC grid side with one of the proposed converters, is still topical.

Also, the heart of the smart lighting systems is the main controller, and the lamps must interact with this controller. The choice and integration of appropriate communication modules and sensors in the ballast is the task for the near future.

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