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Assessment of Energy Efficient LED Ballasts Based on their Weight and Size

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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.

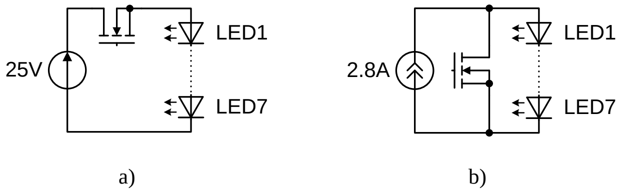
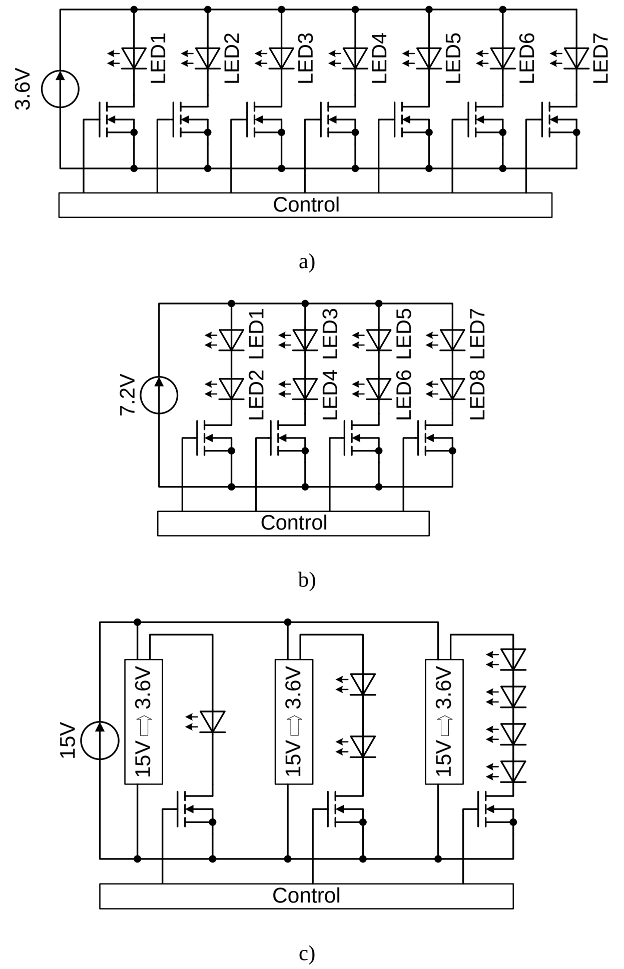


Fig. 1. Schemes of pulse regulators: a) voltage regulator; b) current regulator



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

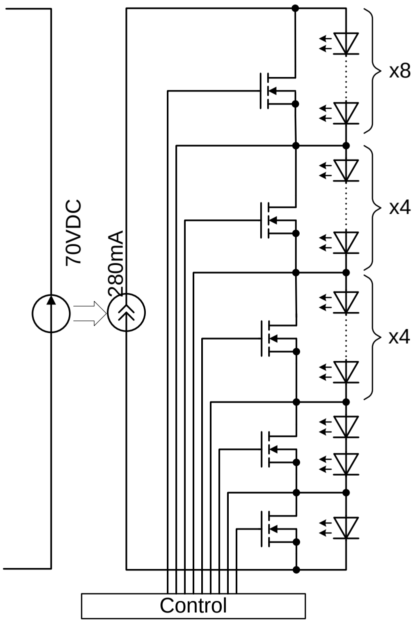
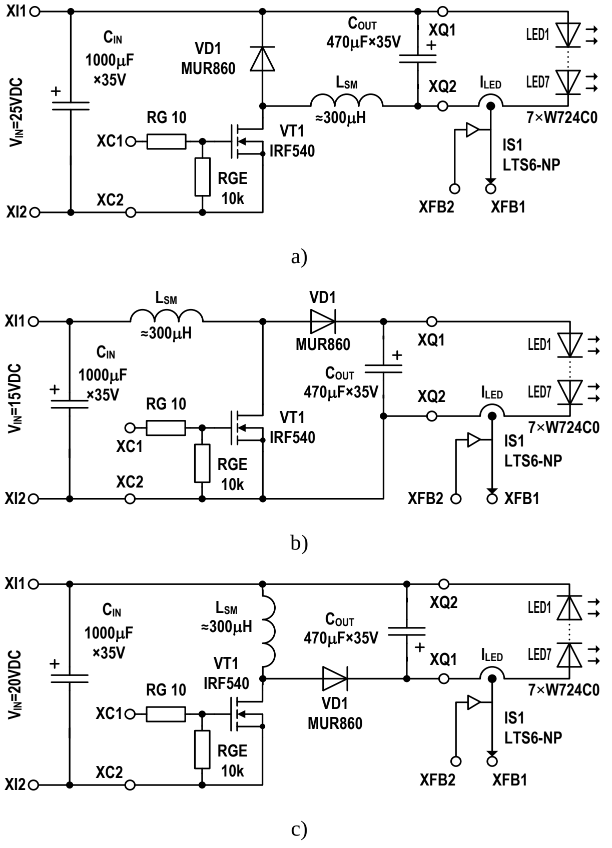


Fig. 3. Commutation of LEDs in groups (current sourced).



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

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.

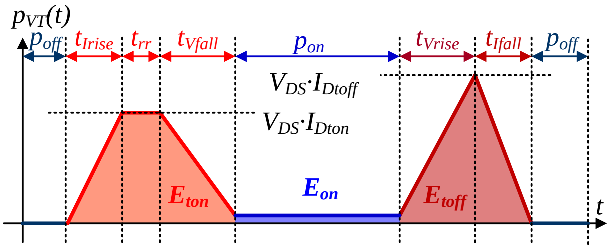


Fig. 5. Instantaneous power losses of a MOSFET transistor operating in a conjunction with a diode

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.

$$\Delta P = \frac{1}{T_{sw}} \int_{0}^{T_{sw}} p(t)dt = \frac{E_{ton} + E_{on} + E_{toff}}{T_{sw}} = \\ = \Delta P_{ton} + \Delta P_{on} + \Delta P_{toff} \quad . \tag{1}$$

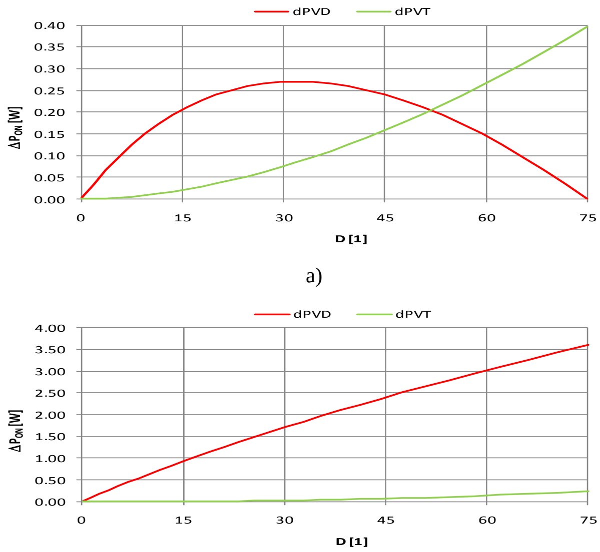
As it is seen from (1) the losses are divided into switching losses and conduction losses. The conduction losses in a MOSFET (that is used as a switch) are found as a product of the current through the switch that is equal the average current through the inductor I_L (in power 2), channel resistance 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):

$$\Delta P_{VTon} = I_L^2 \times R_{VTon} \times D \, . \tag{2}$$

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 ($1–D$):

$$\Delta P_{VDon} = I_L \times V_{VDon} \times (1 - D) \, . \tag{3}$$



a)

b)

Fig. 6. On-state losses of diode and transistor in: a – buck; b – boost dimmer

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)	$\frac{V_{IN}}{1-D}$	$\frac{I_O}{1-D}$	$V_{VDon} \cdot \frac{I_O}{1-D} \cdot (1-D)$	$R_{VTon} \cdot (\frac{I_O}{1-D})^2 \cdot D$

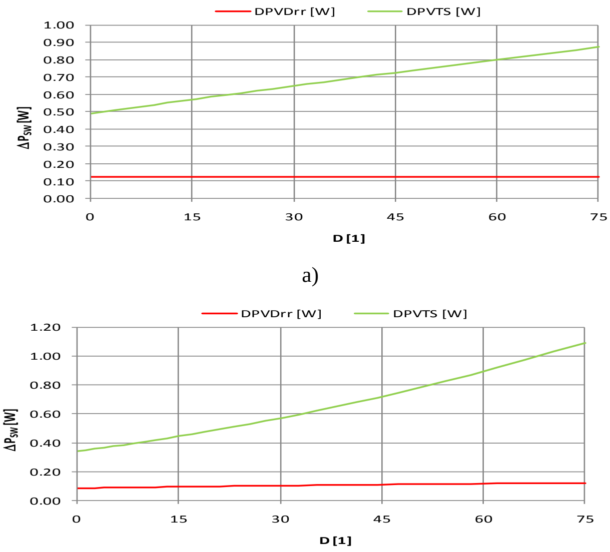
The expressions required for calculation of power losses in buck and boost dimmers (Table I) are based on the power equilibrium for input voltage V_{IN} and output current I_O. Nonlinearity of LED load is represented as no consumption at voltage less 17.5V and linear load 0…3A corresponding to voltage 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):

$$\Delta P_{VTsw} = (E_{VTton} + E_{VDtoff}) \times f_{sw}, \qquad (5)$$



a)

b)

Fig. 7. Switching losses of power diode and transistor in DC/DC LED dimmers: a – buck; b – boost

$$\Delta P_{VD} = (E_{VTrr} + E_{VDtoff}) \times f_{SW} \approx E_{VTrr} \times f_{SW}, \qquad (6)$$

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

$$E_{VTtoff} = V_{DS} \cdot I_{Dtoff} \cdot \frac{t_{Vrise} + t_{Ifall}}{2}, \qquad (8)$$

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

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 the 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.

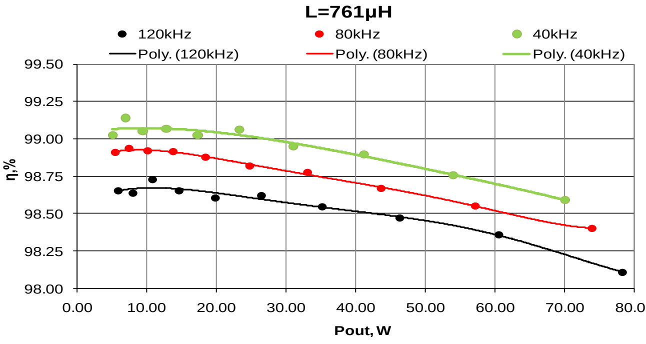
At the same time, smaller inductance leads to higher current pulsations in the coil and, hence, in the transistor and diode. Therefore, rms current of the transistor must be higher at lower inductance. The corresponding dependence may be presented in a simplified form as following:

$$I_{VTrms} = \sqrt{I_{La}^2 + \frac{K_1}{L_{SM}} + \frac{K_2}{L_{SM}^2}}\ , \tag{9}$$

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.



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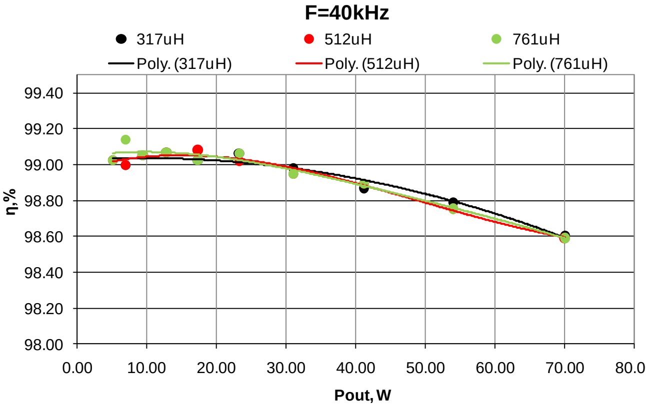
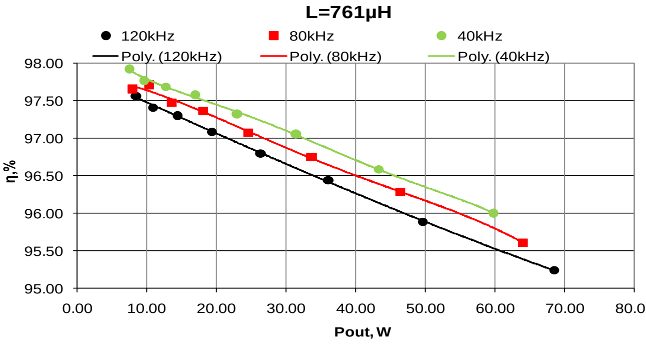


b)

Fig. 8. Results of PSpice simulation of buck converter: a) L_{SM}=761µH, f_{SW}=var; b) L_{SM}=var, f_{SW}=40kHz



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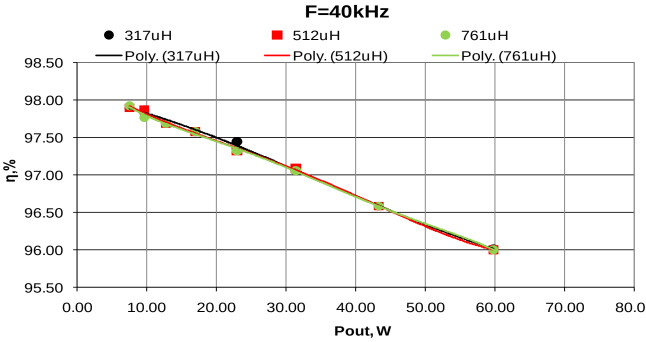

b)

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).

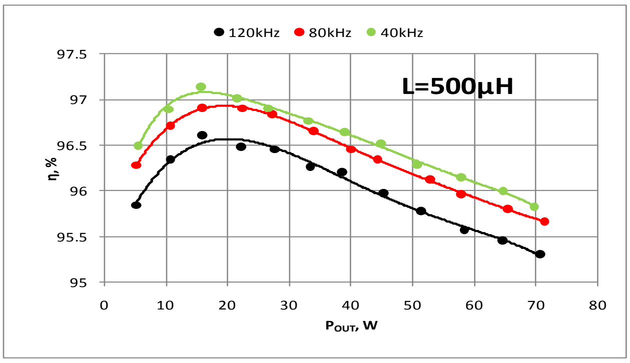

Fig. 10. Changes in efficiency of buck converter at different switching frequencies

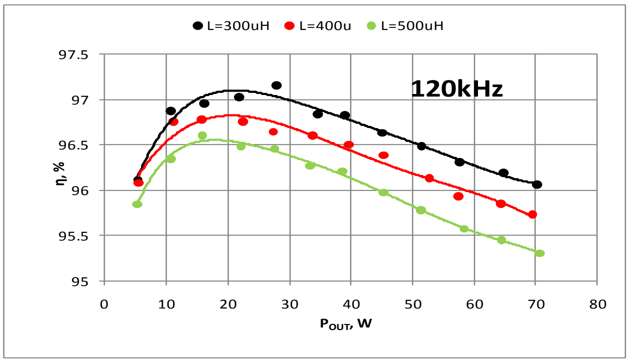

Fig. 11. Changes in efficiency of buck converter at different values of inductance coil

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

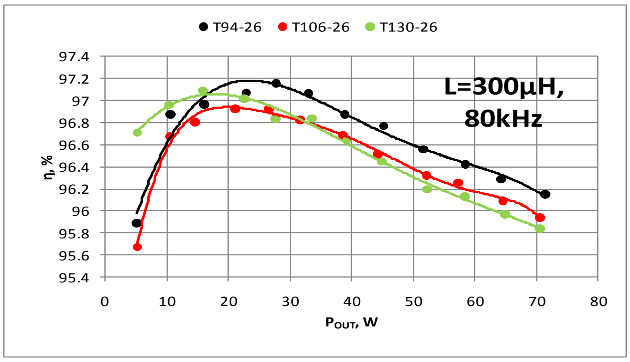

Fig. 12. Core size influence on buck converter efficiency

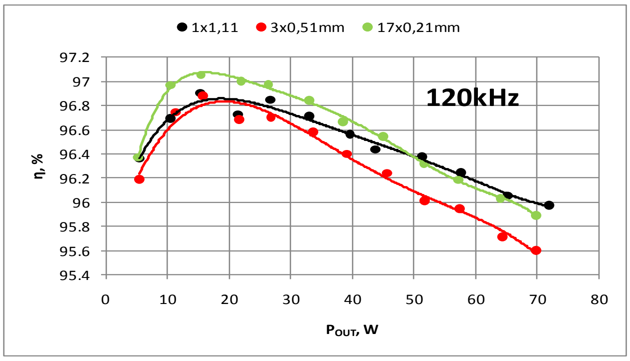

Fig. 13. Conductor skin effect influence on inductor losses

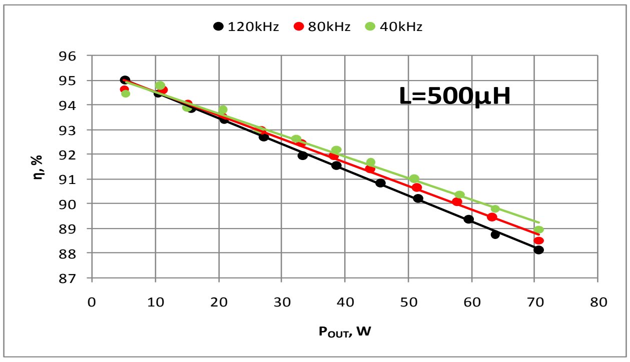

Fig. 14. Impact of switching frequency on boost converter efficiency

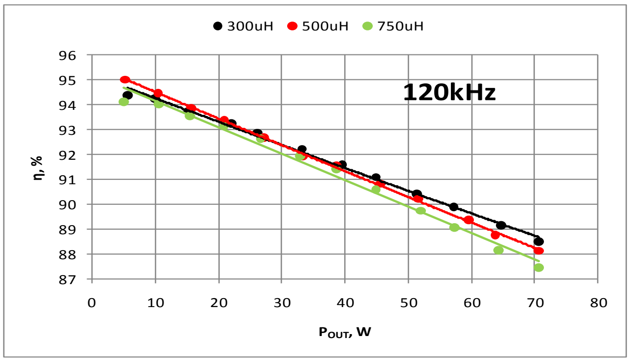

Fig. 15. Impact of inductance on boost converter efficiency

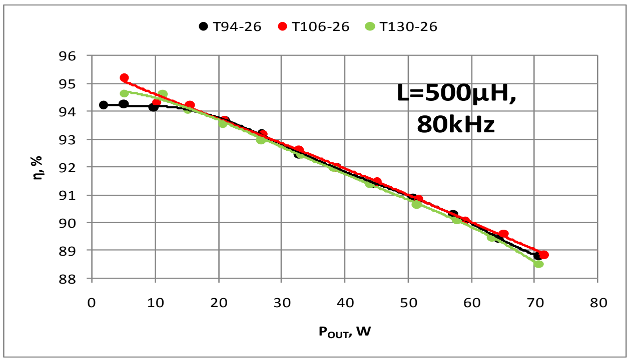

Fig. 16. Core size impact on the boost converter efficiency

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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