An Interleaved Dual Double-Ended Forward Converter Based LED Driver for DC Lighting Grids

Mounika Dasohari
Department of Electrical Engineering
National Institute of Technology Warangal
Warangal, India
mounika.dasohari@gmail.com

Vishwanathan Neti
Department of Electrical Engineering
National Institute of Technology Warangal
Warangal, India
nvn@nitw.ac.in

Porpandiselvi S
Department of Electrical Engineering
National Institute of Technology Warangal
Warangal, India
selvi@nitw.ac.in

A V Ratna Manikyavani
Hyderabad,India
alamurvani@gmail.com

2020 21st National Power Systems Conference (NPSC) | 978-1-7281-8552-1/20/$31.00 ©2020 IEEE | DOI: 10.1109/NPSC49263.2020.9331892

***Abstract*— The article offers a dual double-ended forward converter based Light Emitting Diode (LED) driver for DC grid lighting applications. The converter has two complete double-ended forward converter modules operated in interleaved mode. This converter is operated at 100 kHz. The proposed configuration of interleaved dual DC-DC double ended forward converters provides many advantages compared to conventional double-ended forward converter such as very less current ripple, high efficiency and faster dynamics. Further using interleaving, device stress can be lowered and result in increased efficiency. This paper explores the use of dc micro-grid powered LED lighting. It can be used for residential, street lighting purposes. The detailed circuit operation, simulation results of the proposed circuit for 81.25 W are presented.**

Keywords*— *Interleaved Converter; Double-Ended Forward converter; DC Grid; LED lighting; Interleaving

I. Introduction

LEDs are gaining much popularity in recent times. It has various benefits such as high luminous intensity, long life time, compactness etc. They are slowly replacing conventional light sources. Considerable amount of the electrical energy [1] around the world is utilized for residential and other lighting schemes [2]. Hence there is a requirement for high efficient lamps. In comparison to other lighting sources, LED lighting has high efficacy. LEDs have higher lifetime. This reduces operating and maintenance costs. The various advantages of lighting through LEDs over other lighting schemes has been listed in [3]. Moreover, the LED lighting has less influence on environment in comparison to the influence of their counterpart bulbs i.e., fluorescent lamps [4]. As high brightness LED does not contain any gas or filament, they are less affected by shock and vibrations which indicate higher reliability. Hence LEDs are a better choice for illumination purposes [2], [6]-[8].

Several advantages provided by LEDs for lighting purpose create a need for efficient converter for driving LEDs. Different LED drivers include linear drivers, DC to DC and AC to DC converters [8], [9]. Mostly, Light Emitting Diodes are fed from the conventional AC-based lighting grids. They are connected to the supply mains i.e., 110 V or 230 V AC. Conventionally, the power electronic circuits are required in between the LEDs and the grid. They are known as LED drivers. Actual LEDs in combination with a LED driver is often referred as a LED lamp. DC power has recently returned as an effective alternative means of distributing electricity. It can be used in establishing a DC-based lighting network for LED bulbs. The basics of LED power supply, AC and DC comparison are available in [10]. The amount of illumination depends on the current through LED. Hence, to ensure proper operation, current through LEDs has to be controlled [10]. Drivers without electrolytic capacitors are preferred [11]. To obtain the required power output with less value of inductors and lesser size power transformers, the often used eminent method for high-power applications is converter power modules paralleling [12]. Parallelization provides the physical distribution of the magnetics. It distributes power losses and thermal voltages of semiconductors. This is due to the lower processing of power during each parallel power stage. The interleaving technique is considered as a variation of the parallelization technique. The switching elements in paralleling method over a switching period are phase shifted [13]. An equal phase shift is introduced between the parallel power levels. The total ripple currents through the inductors of the power stage are reduced due to the effect of ripple cancellation [14].

This article describes an interleaved dual double-ended forward converter based LED driver. Double-ended forward converter is the widely used topology for various applications. It is considered to be the most reliable converter. The advantages include, but are not limited to, the lack of dead time requirements and sub-circuit requirements, ease of operation for a wide range of input voltages and load conditions. Double-ended forward converters have ability of multiple isolated outputs to be handled. An interleaved dual double-ended forward converter includes two double-ended forward converters. They are operated at 180° out of phase.

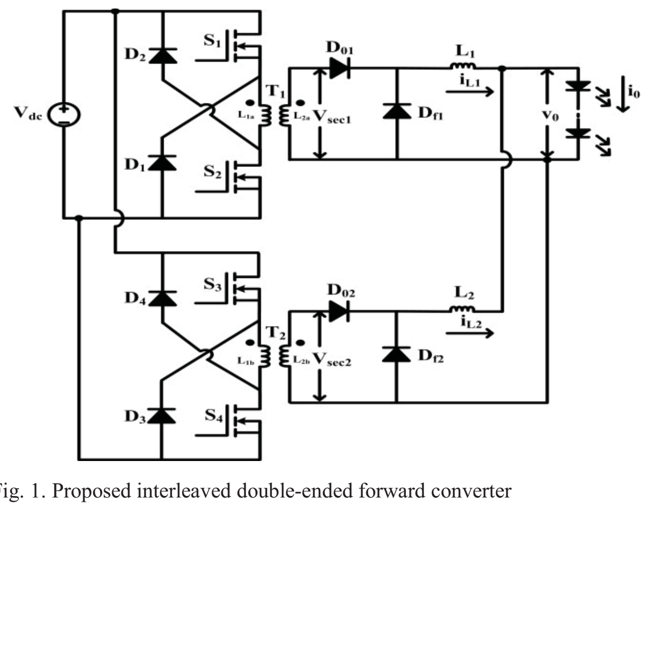

Fig. 1. Proposed interleaved double-ended forward converter

978-1-7281-8552-1/20/$31.00 ©2020 IEEE

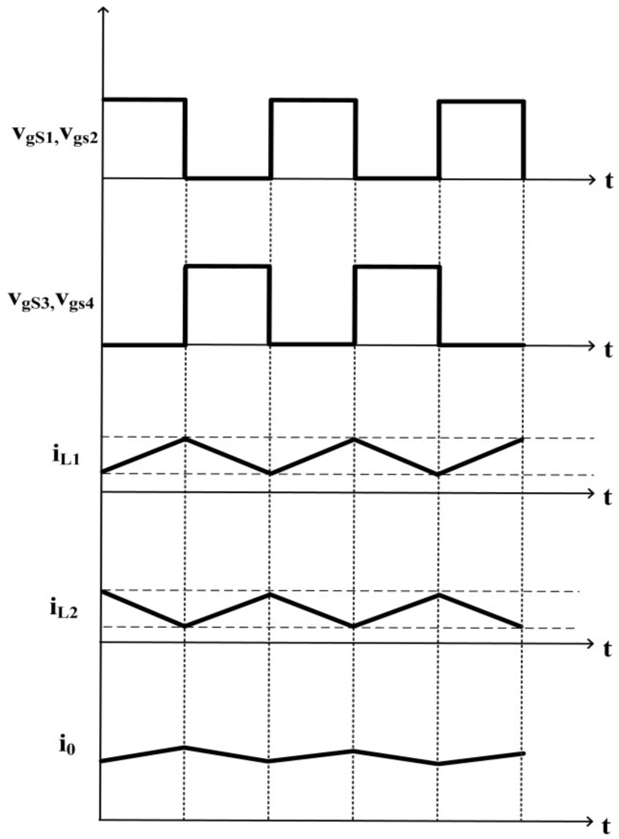

Fig. 1. a. Operating Waveforms

It provides the benefits of ripple current to be reduced. The current (i_0) through the load in the proposed interleaved converter is the sum of the currents through corresponding inductors ($i_{L1}+i_{L2}$). However, since both the converters are operated at 180° out of phase, ripple currents through the inductor cancel each other. Thereby, producing more continuous current in the output and approaches dc.

Section II presents the description of the proposed circuit of the converter. In Section III, the principle of operation of proposed converter is explained. The mathematical analysis and design procedure of the circuit is carried out in Section IV. Finally, the simulation results are discussed in Section V and the conclusion of this paper are outlined in Section VI.

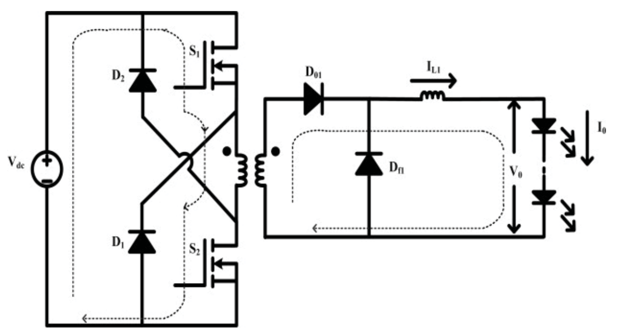

Fig. 2. When S_1, S_2 (or S_3 , S_4) are ON

II. Proposed Converter Configuration

The schematic diagram of interleaved dual double-ended forward converter that utilize two complete double-ended forward converter modules are shown in Fig. 1. An interleaved double-ended forward converter comprises two double-ended forward converters which are connected in parallel operating at 180^0 out of phase. In double-ended forward converter the DC Supply to either terminal of transformer primary side is connected through two MOSFET switches S_1 and S_2. During ON time (Forward conduction) of transformer simultaneous switching pulses applied to the S_1 and S_2. During OFF time (Reverse conduction) of transformer, diodes D_1 and D_2 connects the DC supply terminals with the opposite legs of the transformer.

During ON time, the step-down transformer primary gets magnetized through switches S_1 and S_2. During OFF time of switches the magnetizing current flows through diodes until the magnetized energy completely discharges. During this time, the dotted terminal of transformer is connected to $-V_{dc}$ through D_1 and another terminal is connected to $+V_{dc}$ through D_2 which causes the reversal of the primary voltage. The maximum voltage across each MOSFET during the turning off period is V_{dc}. The stored magnetizing energy is returned to the source and the path is D_2, $+V_{dc}$, $-V_{dc}$, D_1. Since the stored energy is fed back to the source, the necessity of energy dissipating resistive snubber or higher rating switches is eliminated. Hence, the magnetized energy is now clamped, the occurrence of ringing with discharge of this energy is eliminated, and thereby reducing system noise. Since snubber circuit is eliminated, electromagnetic interference is reduced. During turn OFF time, the reversal of the input supply voltage automatically resets the transformer.

The explanation also applies to the second double-ended forward converter with switching pulses 180^0 phase shift from the first one.

III. Principle of Operation

The circuits corresponding to different modes of working are represented in Fig. 2 and 3 during a switching cycle. In this section, the modes of working are explained in detail considering one double-ended forward converter. Brief description is provided when switches S_1, S_2 (or) S_3, S_4 are ON and a brief description when switches S_1, S_2 (or) S_3, S_4 are OFF is provided. The basic operation is as follows.

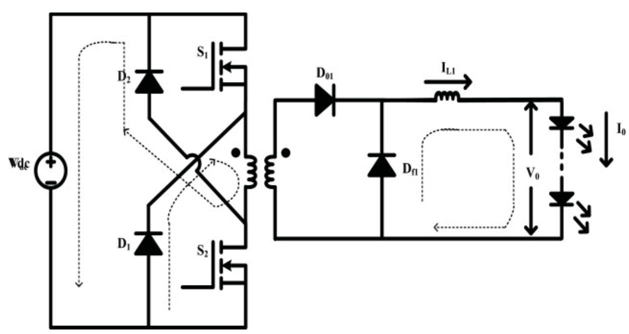

Fig. 3. When S_1, S_2 (or S_3 , S_4) are OFF

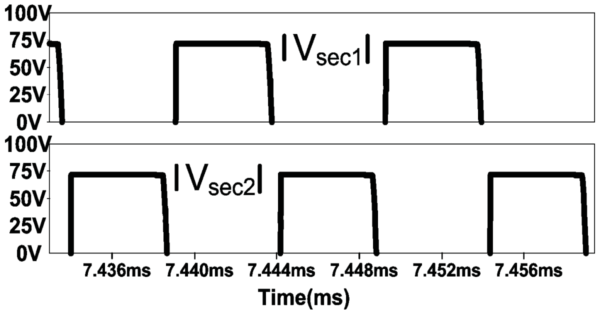

Fig. 4. a. Rectified secondary voltages at rated voltage of 400V

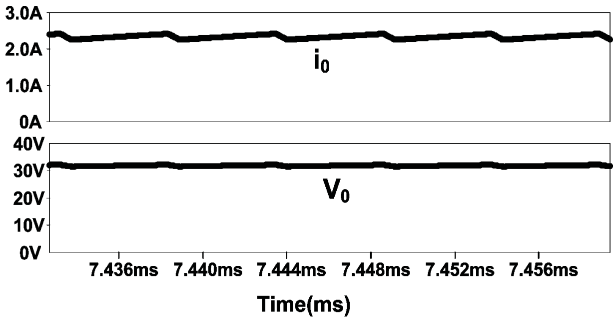

Fig. 4. c. Output voltage and LED lamp current at rated voltage of 400V

A. *When S_1, S_2 are ON*

Figure 2 shows the circuit when MOSFET switches S_1 and S_2, are turned on together. In this mode, an energy transfer occurs. Energy is transferred to the secondary load through the primary of transformer. The conduction of forward rectifying diode occurs on the secondary side. Hence, the energy is transferred to the output filter and load.

B. *When S_1, S_2 are OFF*

Figure 3 shows the circuit when MOSFETs S_1 and S_2 are turned off. In this mode the transformer magnetizing current returns to DC source through the Reverse-biased diodes D_1 and D_2. The conduction of reverse-biased diodes occurs until all the energy stored in the leakage inductance and the primary magnetizing energy is discharged to the input supply. Since diodes D_1 and D_2 are operating in reverse bias, no snubber circuit is required for commutation. In the secondary, the freewheeling diode conducts during the OFF period. This transfers the stored inductor energy to the load.

During the turn OFF time transformer discharges its energy, hence reset time is achieved. When the duty ratio is less than 50% i.e., the ON time is less than it's corresponding OFF time, the circuit works in stable condition. In other words, the nature of reset winding is provided by the primary winding itself. Reset of the transformer is always generally achieved by occurrence of the OFF time longer than the corresponding ON time.

Similar explanation can be considered for the second double-ended forward converter with the switching pulses given to each double-ended forward converter are 180^0 phase shifted to one another. During ON time the source current is linearly increasing current and during OFF time it is linearly decreasing current. Primary current of the transformer is combination of linearly increasing current of one converter and linearly decreasing current of another converter. This combination decreases the ripples in the primary current.

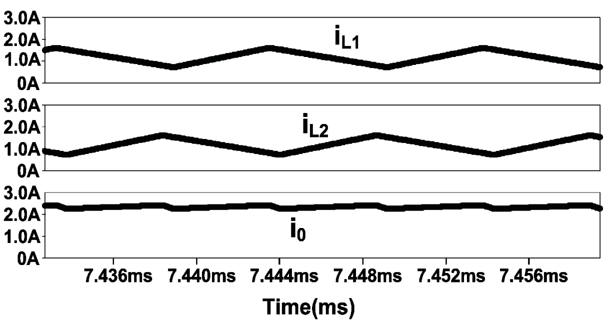

Fig. 4. b. Inductor Currents and LED lamp current at rated voltage of 400V

IV. Mathematical Analysis and Design Procedure of proposed LED Driver

The brief analysis of the proposed circuit is taken out by considering the following assumptions.

1. Steady state operation is considered.
2. Voltage across each LED to be constant.
3. Single double-ended converter is taken for analysis.

The LED driver can be regarded as a parallel connection of two double-ended forward converters operated in interleaved manner with DC grid voltages.

The output voltage is given by:

$$V_0 = V_{dc}*(N_2/N_1)*D \qquad (1)$$

Where N_1 is the number of primary turns of transformer,
N_2 is the number of secondary turns of transformer,
V_0 is the voltage across LED,
V_{dc} is the input voltage,
D is the duty ratio of the switches

Equation (1) can be rewritten as:

$$V_0 = V_{sec}*D \qquad (2)$$

Where V_{sec} is the voltage applied across the secondary of transformer.

TABLE I. Design Parameters of proposed LED driver

S. No.	Parameters	
	Parameter Description	*Value*
1	Input DC voltage, v_{dc}	400 V
2	Number of LEDs used	50
3	Number of parallel strings	5
4	Number of LEDs in each string	10
5	Switching frequency, f_s	100 kHz
6	Duty ratio of switches in bridge configuration	0.44
7	Inductance L_{1a} of each transformer	160 µH
8	Transformer turns ratio	5.53
9	Inductance L_{2a} of each transformer	5.23 µH
10	L_1, L_2	200 µH
11	LED operating current, i_0	2.5 A
12	Output Voltage, V_0	32.5 V

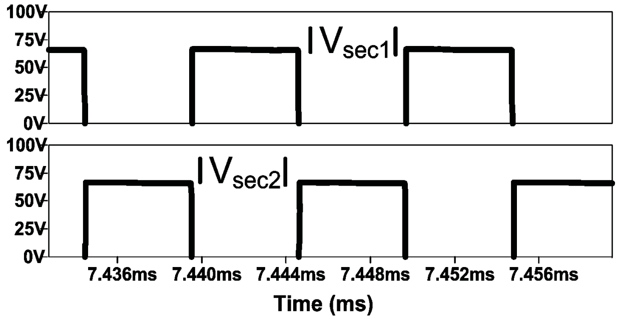

Fig. 5. a. Rectified secondary voltages at -10% of rated voltage (i.e., 360V)

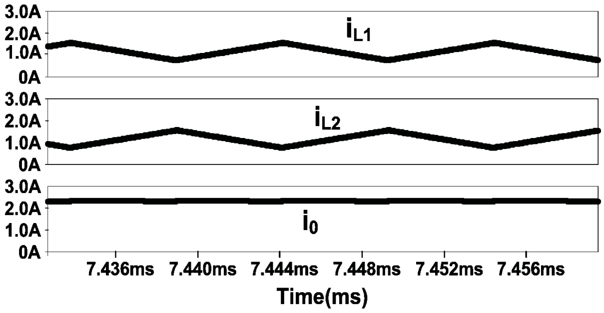

Fig. 5. b. Inductor Currents and LED lamp current at -10% of rated voltage (i.e., 360V)

For a rated current of 2.5A through LED lamp, the required output voltage is 32.5V.

Equation (1) and (2) indicate that the lamp current and the output voltage can be regulated by controlling simultaneously the duty ratio of individual double-ended forward converters with a phase shift of 180^0.

Hence, for a duty ratio of 50% and input voltage of 360V, the turns ratio ($n=N_1/N_2$) is calculated to be 5.53.

The relation between turns ratio and inductances (L_{1a}, L_{2a}) for transformer T_1 is given by:

$$L_{1a}/L_{2a} = (N_1/N_2)^2 \qquad (3)$$

The design procedure can be done by considering the equivalent circuit of the required load. In the proposed circuit, the number of LEDs connected in parallel are five. Each of the string consists of 10 LEDs in series. The rating of each LED is 3.25V, 500mA and 1.625W. So, the LED lamp is conducted at 32.5V, 2.5A and 81.25W.

The high switching frequency of the converter is chosen to be operated at 100 kHz.

The current through LED is given by:

$$i_0 = i_{L1} + i_{L2} \qquad (4)$$

The current through LED is obtained after the ripple cancellation of currents i_{L1} and i_{L2} obtained by operating two double-ended forward converters in interleaving mode of operation (i.e., 180^0 out of phase).

V. Simulation Results

In order to verify the proposed LED driver, it has been simulated in ORCAD PSpice software. The circuit parameters used for the simulation of the discussed converter are listed in Table 1. The input voltage V_{dc} for the proposed converter is chosen as 400V.

Fig. 4a shows simulation waveforms of rectified secondary voltages of individual double-ended forward converters T_1 and T_2 respectively. Fig. 4b represents the inductor currents (i_{L1}, i_{L2}) and LED lamp current (i_0) waveforms showing ripple cancellation for 44% duty ratio under nominal voltage condition. Fig. 4c indicates the output voltage (V_0) and LED lamp current (i_0) at nominal voltage of 400V.

For a rated current of 2.5A, the output voltage required is 32.5V. The required value of output voltage is obtained at a duty ratio of 44% at nominal value of voltage of $V_{dc} = 400V$. The output inductors L_1 and L_2 are selected in such a way that ripples in voltage and current at specified limits.

Through DC grid voltages, the specified converter can be operated. Considering the driver is operated at rated voltage of 400V. For a varied input voltage of ±10% i.e., a reduction or increase of 40V in input voltage.

At a variation of -10% in input voltage, i.e., 360V, the rated current through LED is obtained by varying the duty ratio of respective double-ended forward converters to 50%. Fig. 5*a* represents waveforms of simulation for rectified secondary voltages of individual double-ended forward converters T_1 and T_2 respectively at -10% of rated voltage. Fig. 5*b* represents the inductor currents (i_{L1}, i_{L2}) and LED lamp current (i_0) waveforms at -10% of rated voltage showing ripple cancellation for adjusted duty ratio of 50% duty ratio.

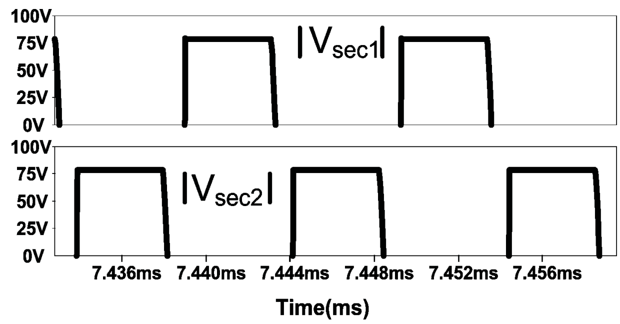

Fig. 6. a. Rectified secondary voltages at +10% of rated voltage (i.e., 440V)

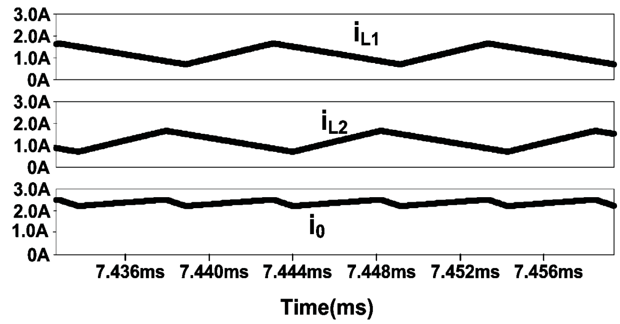

Fig. 6. b. Inductor Currents and LED lamp current at +10% of rated voltage (i.e., 440V)

For a varied voltage in input of +10%, i.e., 440V. The rated current through LED is obtained by adjusting the duty ratio of respective double-ended forward converters. At a duty ratio of 40%, the rated current can be obtained. Fig. 6a shows waveforms of simulation of rectified secondary voltages of individual double-ended forward converters T_1 and T_2 respectively at +10% of rated voltage. Fig. 6b represents the inductor currents (i_{L1}, i_{L2}) and LED lamp current (i_0) waveforms at +10% of rated voltage at adjusted duty ratio.

The number of components required for interleaving operation is more compared to without interleaving operation to achieve same ripple. But the overall cost of the converter increases considerably high when operated without interleaving. This is due to the high value of transformer required and the large filter inductance required to achieve the same ripple without interleaving which in turn increases the overall cost of the converter.

VI. Conclusion

This paper deals with design and simulation of interleaved double-ended forward converter for LED lighting applications for DC grid voltages. An efficient driver circuit configuration for LED lighting is proposed in this paper. The driver circuit can be used for street lighting and residential purposes with proper design. The simulation results of the converter for 81.25W show that there is considerable reduction in current ripple and output current approaches constant dc with interleaved operation (i.e., 180^0 phase shift) for nominal voltage of 400 volts, ±10% voltage variations. It provides low ripple content. It eliminates the need of bulk electrolytic capacitors. The proposed converter can be operated from DC grid voltages.

References

[1] Rodrigues, W. A., Morais, L. M. F., Donoso-Garcia, P.F., et al.:'Comparative analysis of power LEDs dimming methods', XI Brazilian Power Electronics Conference, Praiamar, 2011,pp.378-383.

[2] Ye, Z., Greenfeld, F., Liang, Z.: 'Offline SEPIC converter to drive the high brightness white LED for lighting applications', Proc. 34th Annual Conference of IEEE Industrial Electronics, Orlando, 2008, pp. 1994-2000.

[3] Schratz, M.; Gupta, C.; Struhs, T.; Gray, K. A New Way to See the Light: Improving Light Quality with Cost-Effective LED Technology. IEEE Ind. Appl. Mag. 2016, 22, 55–62.

[4] Principi, P.; Fioretti, R. A comparative life cycle assessment of luminaires for general lighting for the office—Compact fluorescent (CFL) vs Light Emitting Diode (LED)—A case study. J. Clean. Prod. 2014, 83, 96–107.

[5] J. de Groot and J. van Vliet: 'The High-Pressure Sodium Lamp', Philips Technical Library, 1986.

[6] Manuel Arias, Aitor Vázquez, Javier Sebastián: 'An Overview of the AC-DC and DC-DC Converters for LED Lighting Applications', AUTOMATIKA, 2012, 53, (2) pp.156–172.

[7] Liu Yu, Jinming Yang: 'The topologies of white LED lamps' power drivers', 3rd International Conference on Power Electronics Systems and Applications (PESA) 2009.

[8] Iturriaga-Medina, S., Martinez-Rodriguez, P. R., Juarez-Balderas, et al.:'A buck converter controller design in an electronic drive for LED lighting applications',Proc. IEEE International Autumn Meeting on Power, Electronics and Computing, Ixtapa, 2015, pp. 1-5.

[9] Agrawal, A., Jana, K. C., Shrivastava, A.: 'A review of different DC/DC converters for power quality improvement in LED lighting load', Proc. International Conference on Energy Economics and Environment, Noida, 2015, pp. 1-6

[10] Steffen Thielemans, Dario Di Zenobio, et.al, 'DC Grids for Smart LED-Based Lighting':The EDISON Solution,e nergies, 2017

[11] Broeck, H. V., Sauerlander, G., Wendt, M.: 'Power driver topologies and control schemes for LEDs', Proc. 22nd Annual IEEE Applied Power Electronics Conference and Exposition, Anaheim, 2007, pp. 1319-1325.

[12] W. A. Tabisz, M. M. Jovanovi´c, and F. C. Lee, 'Present and future ofdistributed power systems,' in Proc. IEEE Appl. Power Electron. Conf.,1992, pp. 11–18.

[13] B. A. Miwa, D. M. Otten, and M. F. Schlecht, 'High efficiency power factor correction using interleaving techniques,' in Proc. IEEE Appl.Power Electron. Conf., 1992, pp. 557–568.

[14] Michael T. Zhang, Milan M.Jovanovi, Fred C. Y. Lee, 'Analysis and Evaluation of Interleaving Techniques in Forward Converters' in IEEE Transactions on Power Electronics, Vol. 13,1998, pp. 690-698