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High Efficiency Buck LED Driver Using SiC

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Abstract

In this paper, a Double Frequency Buck Driver (DFBD) using SiC diodes for LED lighting systems is presented.This topology enhances the efficiency of the Double Frequency Buck Converter (DFBC) by minimizing the switching losses in power diode. The design procedure, mathematical equations and efficiency calculations of the DFBD are discussed. A prototype of the Conventional Buck Converter (CBC) with Si and SiC diode, DFBC with SiC diode and Si diode is implemented for 10W LED in hardware. Experimental results are presented for the four different topologies to imply that the efficiency of the system increases with SiC diodes. In addition, the cost analysis and energy savings for a multi-storeyed official building are estimated for the DFBC with SiC topology and validated with the other topologies.

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Keywords: Double frequency Buck Driver (DFBD); Silicon Carbide Diodes (SiC);Energy; Efficiency.

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1. Introduction

The LEDs are becoming popular as light source nowadays, as they replace the conventional incandescent lamps, mercury based fluorescent lamps and halogen lamps[1, 2]. It has high luminous density, long life time, high power conversion efficiency and is compact in size. It has many applications such as display backlight, outdoor and indoor lighting and in automobiles [3, 4]. A single LED will have low output power. So to meet the desired lighting luminance, many LEDs may be connected in series and parallel. About 1038% of the total energy bill globally is used for lighting applications. One report published in 2004 by USAID and The Energy Research Institute (TERI) estimated that the cumulative lighting load was approximately 42% of the total energy consumed in India [5]. Therefore the electrical energy can be saved by increasing the efficiency of the lighting systems. To increase the efficiency, the focus should be on the electrical materials (LED) and driver circuits used. Low power [6], low cost [7], high efficiency LED drivers [8] are the need for the day. For supplying these LED strings, DC current is needed. Henceforth many converter topologies in AC/DC and DC/DC are developed. All the existing converter topologies can be classified as single stage , two stage and three stage topologies . Single stage [9] driver topologies are mostly used in domestic and commercial applications, whereas two stage [10] and three stage topologies [11] are used where cost in not a concern, rather they focus on reliability and efficiency. The three important factors that should be considered while manufacturing LED Lighting System are LED driver, LED package and mechanical/thermal component. The main driving technique used for LED drivers are PWM technique and amplitude mode driving technique. These drivers are mostly

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operated with switches and power diodes. The reverse recovery current during turn-off of the diode in a conventional buck driver causes significant power dissipation in switches and increased EMI generation. Therefore buck driver is realized with SiC diodes so as to address the power dissipation in the diodes. Among the semiconductor devices, the power diode is the first commercialized device with SiC Technology. SiC diodes have zero reverse recovery current and high breakdown voltage [12]. Replacing conventional diodes with SiC diodes will increase the system efficiency and power density as well. In this paper, a low power DFBD with SiC diodes is proposed [13] as a single stage LED driver. The converter consists of two cells namely high frequency cell (HFC) and Low Frequency Cell (LFC). Each cell has a MOSFET, Inductor and Silicon Carbide Schottky Barrier Diodes (SiC SBD). Both cells are operated at distinct frequencies in Continuous Conduction Mode (CCM). The circuit is simulated in MATLAB Simulink and a prototype is implemented to imply efficiency. This paper is organised as follows: The operation and design of DFBC are described in Section 2, control strategy for DFBD is presented in Section 3, Simulation and Experimental results are shown in Section 4 and 5, and a case study for a multi-storey official building is given in Section 6.

2. Circuit Operation and Design of DFBC

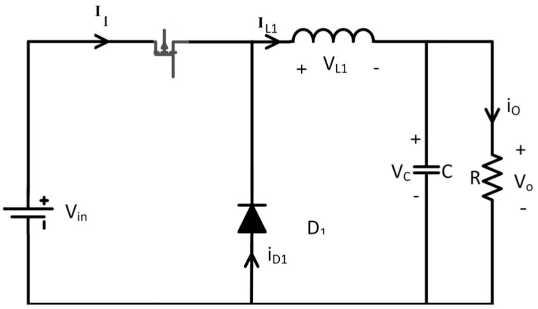


Fig. 1. Conventional Buck Converter Circuit Diagram

The topology of the Conventional Buck Converter (CBC) is shown in Fig.1. The input V_{in} and the output V_o of the converter in steady sate is related by the equation

$$V_o = DV_{in} \tag{1}$$

Where, D is the duty ratio.

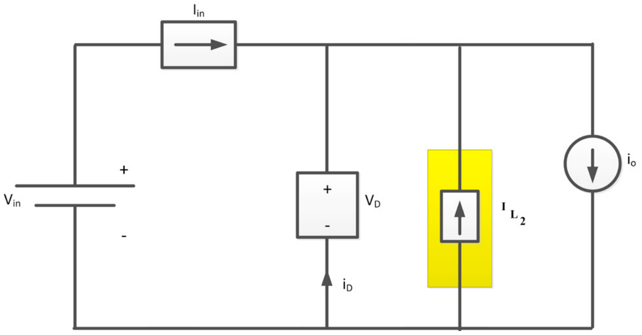


Fig. 2. Averaged Model of DFBC with the added CCS of DFBC.

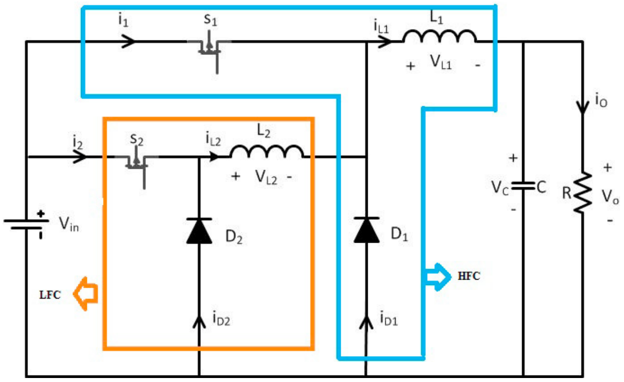


Fig. 3. Block Diagram of DFBC.

The DFBC is operated in CCM and can be considered as Controlled Current Source (CCS). Fig.2 shows the averaged model of DFBC with the CCS (I_{L_1}). This added current source enhances the transient and steady state operation when compared to a conventional buck converter. Fig. 3 shows the circuit diagram of DFBC. This converter has two cells namely HFC and LFC. The HFC consists of S_1, D_1, L_1 components and the LFC has S_2, D_2, L_2. Under steady state, the current through the main switch and the diode are given by (2) and (3).

$$I_{D_1} = D(I_{L_1} - I_{L_2}) = I_1 \tag{2}$$

$$I_{s_1} = (1 - D)(I_{L_1} - I_{L_2}) \tag{3}$$

Where, I_{S_1}=I_1 is the main switch current, I_{L_1} and I_{L_2} are the current through the inductors , I_{D_1} is the current through the main diode. From equation (2) and (3) it is visible that when both the currents are equal the current through the main switch and diode are zero. Therefore it is mandatory to operate both the switches at different frequencies. The switches S_1 and S_2 are operated at high frequency ,F_1 and low frequency , F_2 respectively. The high frequency is chosen to be the integral multiple of low frequency as given in (4).

$$F_1 = N * F_2 \tag{4}$$

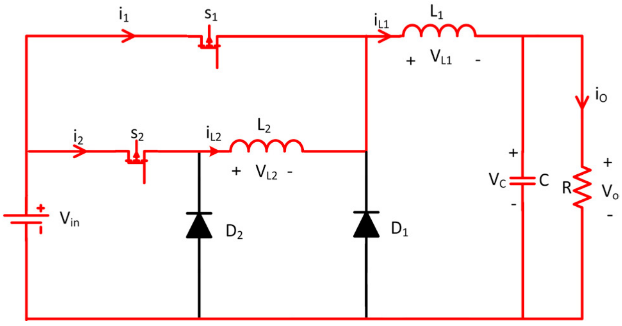


Fig. 4. Mode 1 (S_1-ON and S_2-ON).

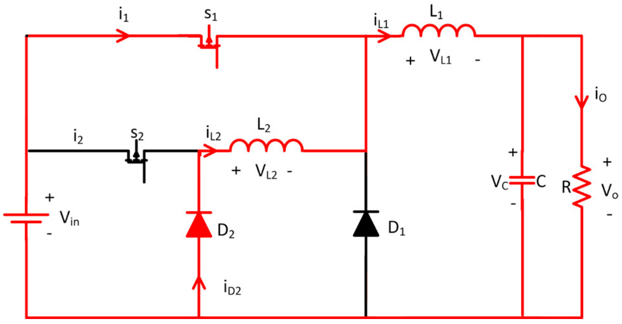


Fig. 5. Mode 2 (S_1ON and S_2-OFF).

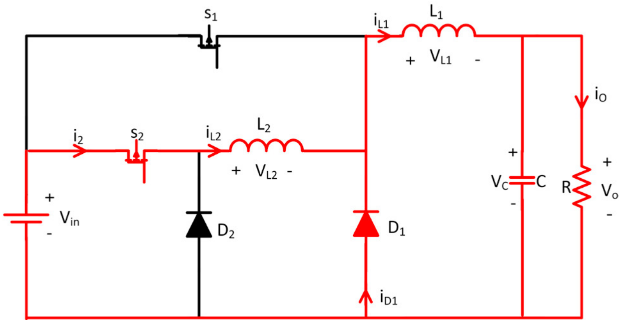


Fig. 6. Mode 3 (S_1 OFF and S_2-ON).

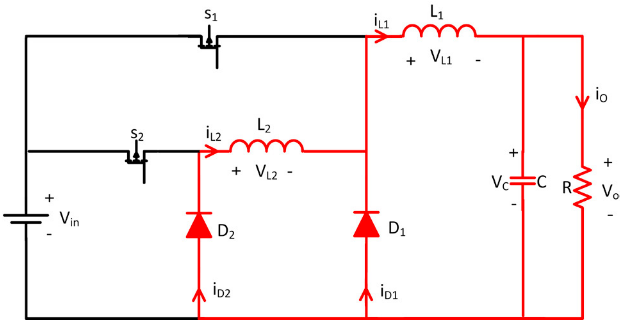


Fig. 7. Mode 4 (S_1-OFF and S_2-OFF).

The LFC cell enhances the efficiency and HFC cell improves the output performance. The power circuit is operated in four different modes. The equivalent circuit for each mode is given in Fig.4 to Fig.7. The averaged model for the controller design is derived from the differential equations of switching states as given from Fig.4 to Fig.7. This model is used to design the converter and the controller. The averaged model is given as follows

$$L_1\frac{di_{L1}}{dt} = v_{in} - d_1 i_o \tag{5}$$

$$L_2\frac{di_{L2}}{dt} = (d_1 - d_2)i_o \tag{6}$$

$$C\frac{dv_o}{dt} + \frac{v_o}{R} = (i_{L2} - i_{L1})d_1 - i_{L2}d_2 \tag{7}$$

The steady state equations are derived from (5)to(7) by equating the time derivatives to zero.

$$V_o = DV_{in} \tag{8}$$

$$D_1 = D_2 = D \tag{9}$$

$$D_1 i_{L1} = i_o \tag{10}$$

Where, V_{in} is the input voltage, R is the load, L is the inductor, C is the filter capacitor, V_o is the output voltage. D_1 and D_2 are the duty ratios of HFC and LFC respectively. The steady state equations derived is similar to conventional buck converter. Therefore the design equations for DFBC are similar to conventional buck converter and are given in Table 1. For calculating these values, the desired current ($\triangle I_L$) and voltage ripple ($\triangle V_o$) are taken as 0.204 A and 0.349 V .Whereas, N = 1 for HFC and 2 for LFC respectively.

Table 1. Specifications of DFBC LED Driver

Inductor	Capacitor
$L = \frac{D*(V_{in}-V_o)}{\triangle I_L * F_N}$	$C = \frac{\triangle I_L}{8*F_N*\triangle V_o}$

3. Design of Converter and PID Compensator

The Small Signal modelling (SSM) and the compensator design for the closed loop control for the DFBC is presented in this section.

3.1. Small Signal Modelling

Small Signal modelling (SSM) [14, 15] is required to design the closed loop control to achieve the desired performance. The first order small signal linearization is applied from (5)(7) to derive the state space model. The state space representation for the converter is given as

$$\triangle x = A\triangle x + B\triangle d + C\triangle v_{in} \tag{11}$$

Where,$\triangle$x= [$\triangle i_{L1}$,$\triangle i_{L2}$,$\triangle v_o$] and $\triangle$d =[$\triangle d_1$,$\triangle d_2$] respectively. The state matrices respectively A, B and C are given below

$$A = \begin{bmatrix} 0 & 0 & \frac{-1}{L_1} \\ 0 & 0 & 0 \\ \frac{1}{C} & 0 & \frac{-1}{RC} \end{bmatrix} \; ; \; C = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \; ; \; B = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix}$$

The transfer functions are derived by applying Laplace transform in (11).

$$X(s) = (sI - A)^{-1}Bd(s) + (sI - A)^{-1}CV_{in}(s) \tag{12}$$

From (12), I is a 3X3 identity matrix. Substituting the steady equations from (8) to (10) in (12) yields the following transfer functions in continuous domain.

$$G_{i_{L1}d_1}(s) = \frac{V_{in}}{R}\left[\frac{1 + sCR}{1 + s\frac{L_1}{R} + s^2L_1C}\right] \tag{13}$$

$$G_{i_{L2}d_2}(s) = \frac{V_{in}}{RL_1C}\left[\frac{1}{1 + s\frac{L_1}{R} + s^2L_1C}\right] \tag{14}$$

$$G_{v_od_1}(s) = \frac{V_{in}}{L_1C}\left[\frac{1}{1 + s\frac{L_1}{R} + s^2L_1C}\right] \tag{15}$$

$$G_{v_od_2}(s) = \frac{V_{in}}{RC}\left[\frac{s}{1 + s\frac{L_1}{R} + s^2L_1C}\right] \tag{16}$$

$$G_{v_ov_{in}}(s) = D\left[\frac{s}{1 + s\frac{L_1}{R} + s^2L_1C}\right] \tag{17}$$

$$G_{i_{L2}V_o}(s) = 0 \tag{18}$$

The inductor L_2 of LFC is not involved in any of the transfer functions from (13) - (17). The inclusion of LFC cell diverts the current from the main switch S_1 in HFC to LFC and thereby reduces the conduction losses in main switch.

3.2. Compensator Design

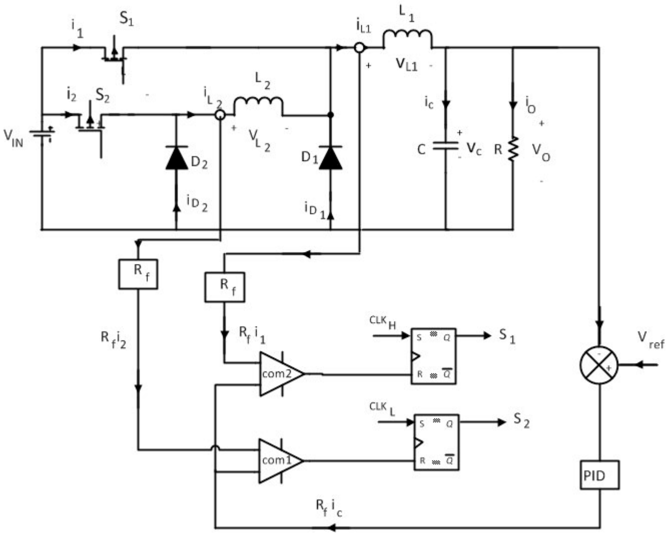


Fig. 8. Current Mode Control of DFBC

The closed loop control of DFBC converter using dual loop control strategy is given in Fig.8. The control of the DFBC is done to meet out the desired voltage and current output. The output voltage from the converter is fed to PIC16F877Abwhere it is compared with the reference signal. The error signal is processed by the PID controller. The sensed current waveforms of both the inductors are in turn compared with the outputs of PID controller. The resultant outputs are the PWM signals generated by the microcontroller for power switches S_1 and S_2.

The closed loop performance of the converter is veried by designing a suitable digital PID controller for the DFBC. The discrete control transfer function of the converter is derived using direct digital design approach. The control transfer function G vd (s) is discretized using Zero Order Hold (ZOH) and computational delay and given in (18).

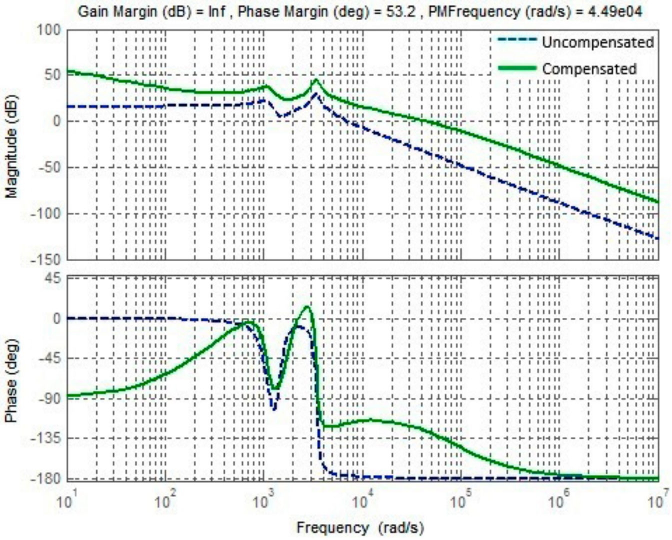


Fig. 9. Uncompensated and Compensated Bode Plots for DFBC

To derive the controller transfer function in Z domain, Single Input Single Output (SISO) tool of MATLAB is used. The control transfer functions as in (15) and (16) are given as inputs to SISO tool. The general discrete PID controller structure is given in (19).

$$G_{vd}(z) = z\Big[\frac{1 - e^{-sT_s}}{s} e^{-sT_s} G_{vd}(s)\Big] \tag{19}$$

$$G_c(z) = K_p + K_i \frac{T_s}{z - 1} + K_d\Big(\frac{z - 1}{z}\Big) \tag{20}$$

The bode plots for compensated and uncompensated control (Gvd(z)) transfer functions are given in Fig.9. From the plot, it is observed that voltage loop gain has a crossover frequency of 7.14 kHz with a phase margin of 53.2°. This ensures that the system is stable for any change in load or input voltage.

4. Simulation Results

4.1. Transient and Steady State Analysis

The DFBC is simulated in MATLAB/Simulink environment with the specifications given in Table 2.

Table 2. Specifications of DFBC LED Driver

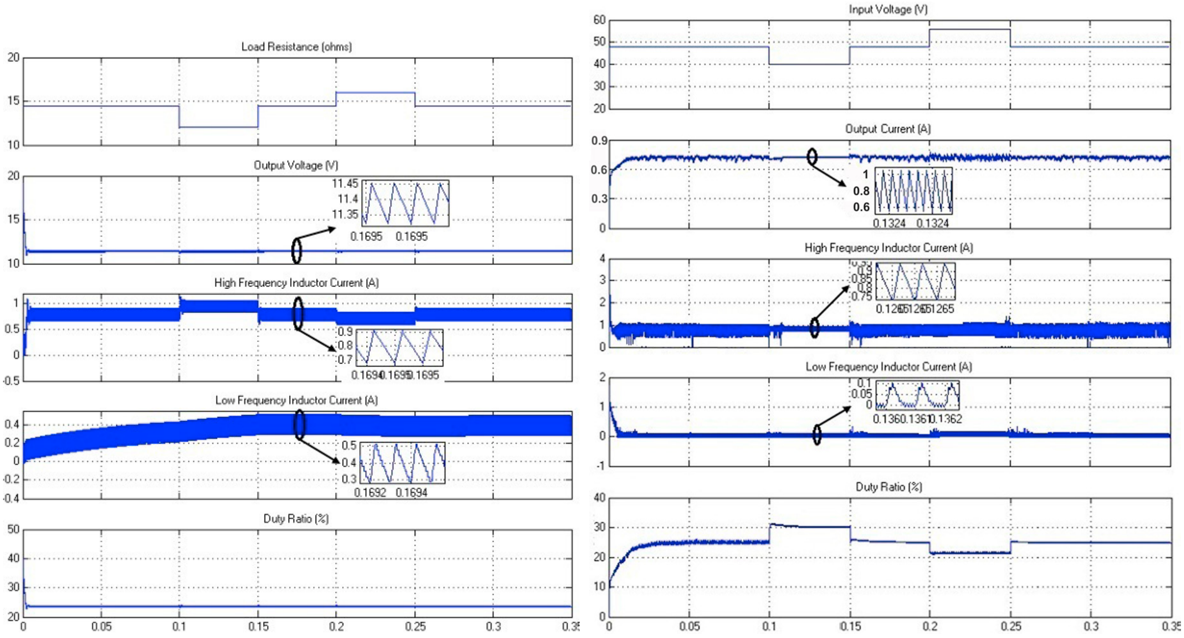
Parameters	Value	Parameters	Value
Input Voltage (V_{in})	48 V	Inductor ($L_1 and L_2$)	L_1=390 μH L_2=3900 μH
Output Voltage (V_o)	12 V	C (μF)	220
Input Current (I_{in})	0.208 A	Inductor current Ripple (△I)	0.204 A
Duty Ratio (D)	0.25 A	Output Power (P_o)	10 W
Load (R)	14.4 Ω	Frequency ($F_1 and F_2$)	F_1=100 kHz F_2=10 kHz

The transient performance of DFBC is analysed for variations in load and input voltage as shown in the Fig. 10 respectively. The transient performance is observed for a change of load (step down) from 14Ω to 12Ω during 0.1 ms to 0.15 ms and from 14Ω to 16Ω (step up) during 0.2 to 0.25 ms respectively as shown in Fig.10. Similarly it can be seen from Fig.11, that there is a change in the input voltage from 48V to 40V (step down) during 0.1 to 0.15ms and from 48V to 58V (step up) during 0.2 to 0.25 ms. It is evident from Fig. 10 and 11, the output voltage is regulated with the designed control circuit for any kind of disturbances in the system.

4.2. Efficiency Calculation

The efficiency of DFBC [16] is computed by calculating the conduction and switching losses of the power semiconductor devices. Based on the specification given in Table 2 suitable Si and SiC diodes are selected. The key parameters used for calculating the losses are given in Table 3. The static characteristics are used to calculate the conduction losses. The static characteristics from datasheets of the devices clearly indicate that the MOSFET is strongly dependent on temperature. Hence heat sink is to be properly designed to improve its performance. Moreover the Si diodes have negative temperature coefficient and SiC diodes have positive temperature coefficient. This clearly indicates that the conduction losses of Si diodes will be lesser than SiC diodes.

The dynamic characteristics are used to calculate the switching losses of the device. The MOSFET/Si Diode and MOSFET/SiC diode do not have any difference in the turn-off process as it has similar turn-off waveforms. But the



(a) (b)

Fig. 10. Dynamic load change and input voltage change.

turn-on process is different for both the topologies.This is because of the large reverse recovery current of Si diode and ultimately zero reverse recovery current for SiC diodes. Hence the turn-off losses will be similar for both diodes and turn-on losses will be quite dissimilar because of large reverse recovery current. The total semiconductor losses are calculated for the two topologies and are given in Fig.11 for a particular input and output condition.

Table 3. Parameters of the Semiconductor Devices

Parameter	Symbol	Devices		
		CoolMOS	Si Diode	SiC Diode
Manufacturer		Vishay	GME	Vishay
Part No		IRF530	MUR405G	UF5400
Type		Cool MOS	Superfast	SiC Schotkhy
Breakdown Voltage ,V	V_{BD}	100	50	50
Rated Current, A	I_D	9.2	4	3
Junction Temperature,°C	T_{jmax}	175	175	150
Thermal Resistance,°CW	R°_{jA}	62	28	8.5
Package		TO-220-3	DO-201AD	DO-201AD

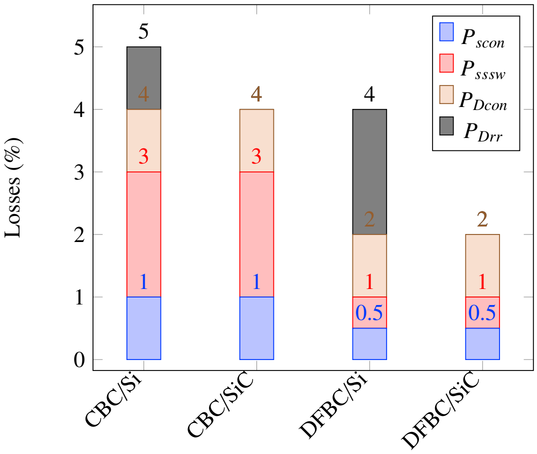


Fig. 11. Fig.12. Distributed Power Loss ($V_{in} = 20V$, V_{out}=5V and D=0.25)

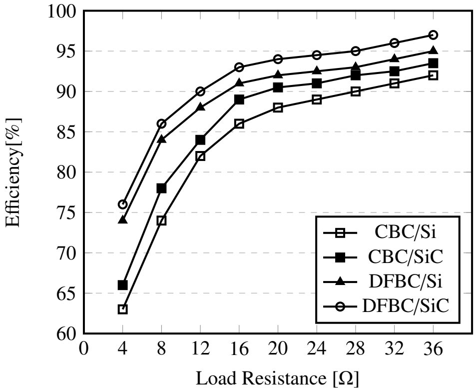


Fig. 12. Load change Vs Efficiency

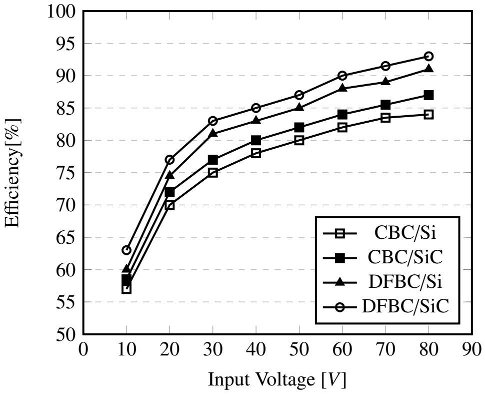


Fig. 13. Input Voltage Vs Efficiency

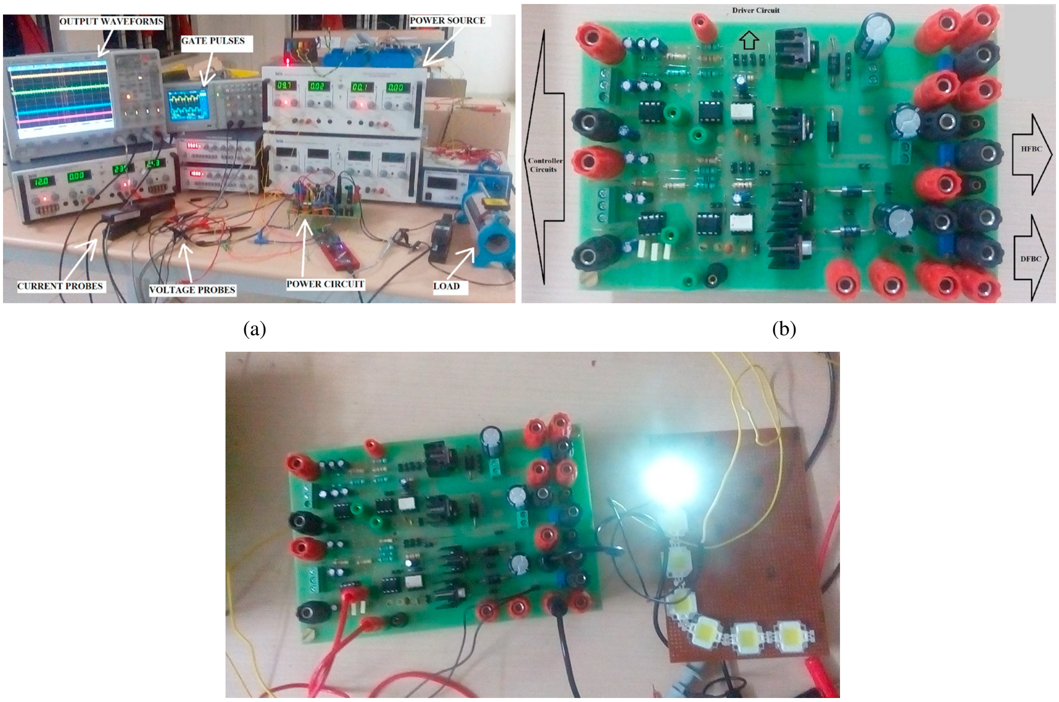
Efficiency is calculated for all the topologies namely CBC,CBC with SiC diode, DFBC with Si diode and DFBC with SiC diode for change in duty ratio and input voltage. The efficiency for the four different topologies are plotted as shown in Fig. 12 and 13 for variation in load change and input voltage change. It is evident from the plots that DFBC with SiC has higher efficiency than other topologies.

5. Experimental Results

The hardware prototype is developed for Conventional Buck Converter and Double Frequency Buck Converter. Both the converters are realized using Si and SiC diodes. The converters are designed and developed for 10W. The simulation parameters and the experimental prototype parameters are the same. The part No's of the components used in hardware prototype are listed in Table 4. The specifications of the LED light used herein are described as follows. The LED's are made with 10W, with a Forward Voltage (V_F) of DC 9-12V and Forward current (I_F) of 1050mA. Other details of the specified LED includes Output Lumens of 600-700 Lm,Color and Temperature as White(6000-6500K),Beam Angle - 140 degrees and with a life span greater than 50,000 hours. The experimental setup and prototype of the converters is shown in Fig. 14 (a), (b) and (c) respectively.

Table 4. Part Nos of Components used In Prototype

Devices	CBC	CBC with SiC diode	DFBC with Si diode	DFBC with SiC diode
MOSFET	IRF530			
Diode	IRF530		UF5400	
Inductors	MSS1278T-394		L_1=1140-222K-RC	
			L_2=1130-212K-RC	
Capacitor	SKR221M2AK25M			
Driver	TLP250			
LED	SMD LED (10W, 12V)			



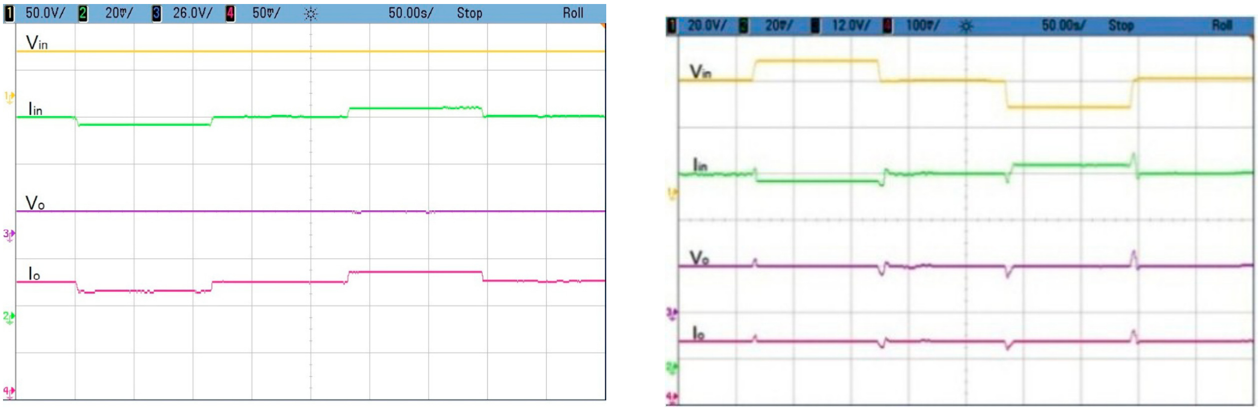
(a)

(b)

(c)

Fig. 14. (a) Experimental setup (b) Prototype Board for CBC and DFBC (c)Topology as LED Driver

All the converter topologies are subjected to load change and input voltage change to study the dynamic performance. However, the dynamic performance of DFBC with SiC is shown in Fig. 15 (a) and (b) respectively. The converter load is changed from 14Ω to 12 Ω and 12 Ω to 14 Ω as shown in Fig. 15 (a). It is also subjected to an input voltage change of 48V to 58V and from 48V to 38V for input voltage change and is shown in Fig. 15 (b). In both the cases, it is observed that the output voltage V_o is regulated irrespective of the disturbances due to the closed loop control. The experimentation is also done with LED for change in input voltage and load. The luminous intensity is measured for all the fout topologies in open loop using digital Lux Meter MS6610 and is given in Table 5. The input and output currents and voltages are measured to calculate the efficiency.



(a) (b)

Fig. 15. Dynamic :oad and Input Voltage Change of DFBC

Table 5. Actual Output Measured from Prototype

Parameters	For V_{in} = 47.5V ,I_{in} = 0.22A, d = 0.25 Load Change				For V_{in} = 47.10V, I_{in} = 0.22A, d = 0.25 Input voltage change			
	CBC	CBC with SiC diode	DFBC with Si diode	DFBC with SiC diode	CBC	CBC with Si diode	DFBC with Si diode	DFBC with SiC diode
Output Power (W)	8.2	8.96	9.2	9.45	8.15	8.35	8.62	8.9
Output Lumens (Lm)	510	553	570	581	505	515	530	548

The hardware efficiency plots for the converters are given in Fig. 16 and 17. It can be seen from the plots that the efficiency has been increased for DFBC with SiC diodes when compared to other topologies.

The input and output currents and voltages are measured to calculate the efficiency. The hardware efficiency plots for the converters are given in Fig. 16 and 17. It can be seen from the plots that the efficiency has been increased for DFBC with SiC diodes when compared to other topologies. From Table 5, it is clear that the output power of DFBC with SiC diode is higher than other topologies. Consider the case for Input voltage change in Table 5. To deliver same output power as like CBC with Si diode the input power can be reduced by a factor of 1.1 for DFBC with SiC diode.

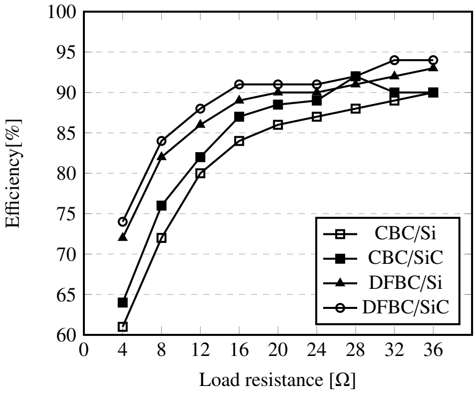


Fig. 16. Load change Vs Efficiency

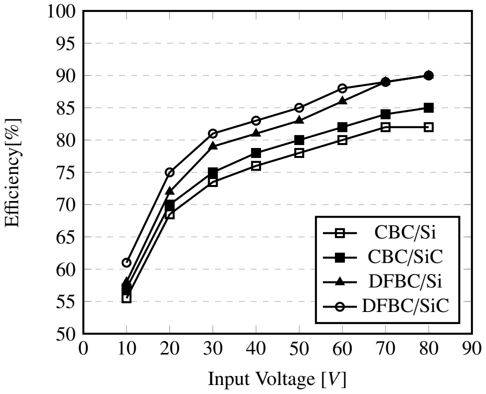


Fig. 17. Input Voltage Vs Efficiency

6. Case Study for a VIT University Office Building

Energy and efficiency in buildings [17] are of major concern nowadays. If the topologies are developed and implemented as retrofit in an official VIT University building, then the energy saved is estimated in this section. The lighting loads for the official building are fed by a separate feeder I, which consumes 8124 units/month. The number of 18W fluorescent tube lights with T12 fixtures connected to feeder I is 508. Assuming each light consumes power for 8 hours/day, the total power consumed/month by lighting load is nearly 30% i.e. 73.15kWhr. The tariff for energy consumed id Rs.5.50/unit. The estimated energy consumed and energy saved for an official multistorey building with 508 lamps is tabulated in Table 6. From Table 8, it is clear that the topology with DFBC/SiC diode saves energy of 1370 Kw-hr and cost/30 days of Rs.7536. The installation cost and payback period are also estimated and shown in Fig 18. The LED and the driver have longer life time. If it serves for nearly 14 years, the amount saved after the payback period is Rs. 1,63,224.

Table 6. Estimated Cost and Energy Savings

Components	Fluorescent tube and T12 fixture	CBC with Si	CBC with SiC	DFBC with Si	DFBC with SiC
Total Installation Cost (Rs)	2,23,520	4,52,628	4,51,668	6,01,472	5,99,948
Power consumed / bill (Kw-hr)	2194	1097	998	906	824
Bill amount (Rs)	12070	6035	5486	4987	4534
Payback Period (years)	1.5	6.3	6.8	10	11

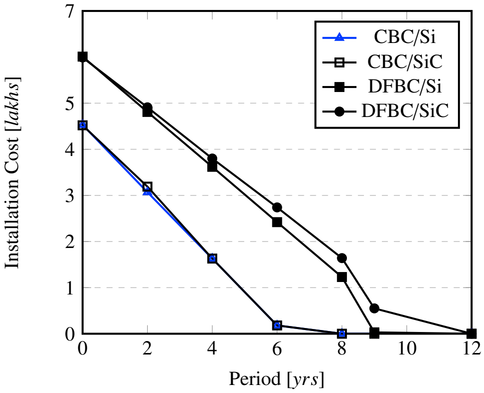


Fig. 18. Installation Cost Vs Payback period of converters

7. Conclusion

A DFBC based LED driver with Si and SiC diodes is implemented and presented in this paper. The efficiency is calculated for all the four combinations in software and in hardware. The dynamic performance of the converter is analyzed for load change and input voltage change. To validate the simulation results, hardware prototype of 10W is developed and tested. Results showed that in terms of efficiency and output lumens, the converter using the SiC diodes performed better than the converter using the Si diodes. Likewise energy saving and cost savings are achieved using converter with SiC diodes.

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