International Journal of Advanced Research in Computer and Communication Engineering
Vol. 3, Issue 3, March 2014

ISSN (Online) : 2278-1021
ISSN (Print) : 2319-5940

Comparative study of Single-Stage AC-DC Converters for LED Lighting with Power factor Correction

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Abstract: In recent years, LED light sources are widely used compared to the conventional light bulbs due to their compactness, lower heat dissipation, high levels of luminous efficiency, wide chromatic variety, high reliability, extreme robustness and long life term. But the main concern is to have high power quality LED power supplies in order to comply with the international standards. To ensure this and to maintain a high power factor at the line side, switch-mode DC-DC converters i.e High-frequency active PFC circuit generally known as 'Power Factor Correction' circuits, are designed. In this paper, a comparative analysis of the AC-DC Converter topologies with "Active" Power Factor Correction for LED applications is presented. Simulation studies have been carried out using MATLAB/SIMULINK. Performance parameters such as Supply Power factor, Distortion factor and supply current THD are analysed for the various active AC-DC converter topologies and the results are compared.

Keywords: LED, SEPIC Converter, THD, Power factor correction (PFC)

I. INTRODUCTION

LED lighting is gaining popularity in the recent years. As a result, it has become important to maintain high power quality for LED lighting. Since the advent of LED lighting; there has been more effort to ensure that it is as efficient as possible. The European standard IEC 61000-3-2 for class C equipments stipulates Power Factor and Total Harmonic Distortion (THD) requirements for all lighting products above 25 W. So, to comply with it, the input current waveform has to be shaped by a PFC circuit to improve power factor and to emulate a linear resistive behavior. This is commonly referred to as the Power Factor Correction – PFC [1]-[3].PFC circuits are categorized as passive and active; In "Passive" PFC, passive elements are used in addition to the diode bridge rectifier. But the output voltage is not controllable. In "Active" PFC, Active switches are used in conjunction with reactive elements so that the current waveform is proportional to the supply voltage waveform and a controllable output voltage is obtained.

II. ACTIVE POWER FACTOR TOPOLOGIES FOR LED LIGHTING

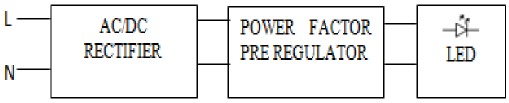

Fig.1 Basic LED Drive schematic

LED lights are driven by a Diode bridge rectifier followed by a DC to DC switching converter that provides a regulated constant output current. To improve power quality and to comply with the standards, a PFC stage which is known as power factor pre-regulators is required between Diode Bridge Rectifier and the LED module. The most commonly preferred single-stage "active" PFC topologies for LED Application are Boost converter, Flyback converter, Forward converter and SEPIC converter [3]. The analysis has been carried out for a switching frequency of 25 kHz and Input Voltage of 24V to drive a 48V LED system.

A. *Boost converter*

The boost converter is the most popular PFC topology because of its simple power circuitry and simple control scheme arising from its single-switch and ground-referenced switch design. However, the boost converter is limited by the fact that its input voltage must be smaller than its output voltage. [5]

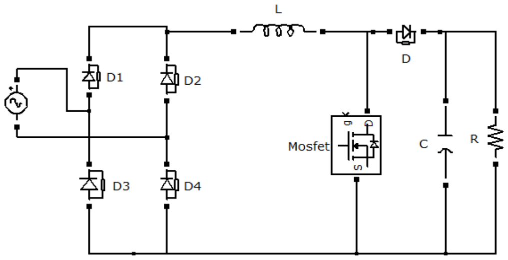

Fig 2. Boost converter

Design Considerations: [6]

- Selection of Duty ratio, D:

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{1}$$

where V_o is output voltage (V) and V_{in} is input voltage(V).

- Selection of Inductance , L:

$$L \geq \frac{(1-D)^2 DR}{2f_{sw}} \tag{2}$$

where f_{sw} is Switching frequency(kHz) and R is the Load Resistance(Ω) .

- Selection of Capacitance, C:

$$C \geq \frac{DV_o}{RV_r f_{sw}} \tag{3}$$

ISSN (Online) : 2278-1021
ISSN (Print) : 2319-5940

The Simulation Parameters designed are L=220µH , C=1000µF and Duty cycle=50%.The Simulation results of Boost Converter are shown in Fig.3, Fig.4 and Fig.5 below.

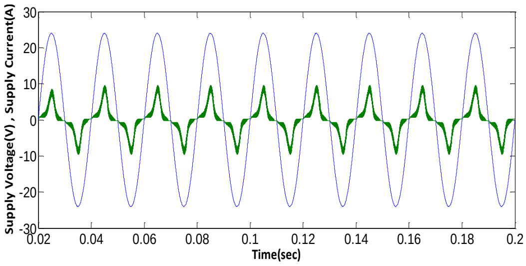

Fig.3 Supply Voltage and Supply current of Boost Converter

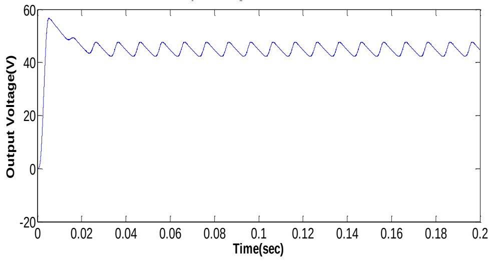

Fig.4 Output Voltage of Boost Converter

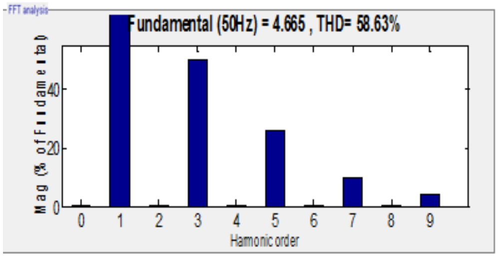

Fig.5 FFT Analysis of Supply current of Boost Converter

B. *Interleaved Boost converter*

An Interleaved Boost Converter (IBC) consists of a number of boost converters connected in parallel and the switches are operated at the same switching frequency with 180˚ phase shift.

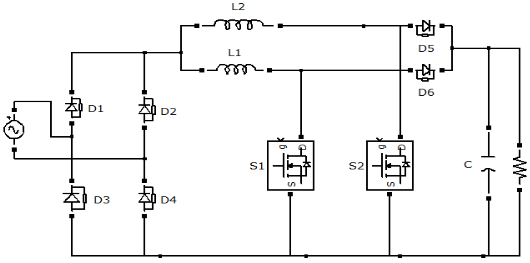

Fig.6 Interleaved Boost Converter

The Simulation results of interleaved boost Converter is shown in Fig.7, Fig.8 and Fig.9.

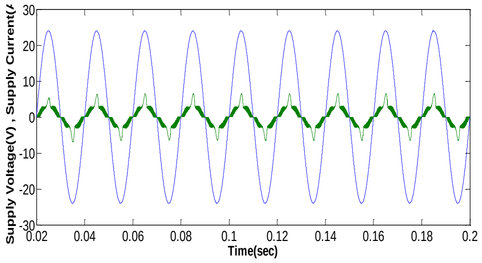

Fig.7 Supply Voltage and Supply current of IBC

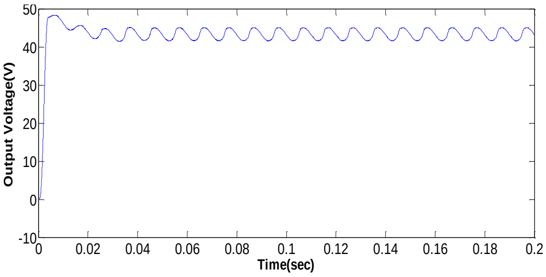

Fig.8 Output Voltage of IBC

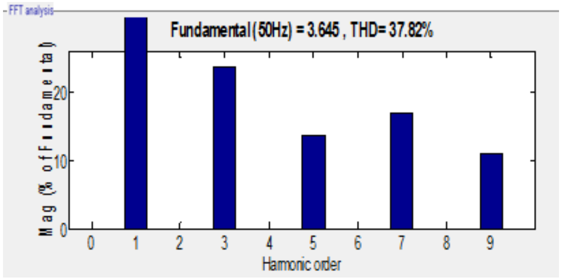

Fig.9 FFT Analysis of Supply current of IBC

C. *Bridgeless Boost converter*

Conventional boost PFC converters have a bridge rectifier for AC-DC conversion. Bridgeless Boost Converter omits rectifier-bridge by replacing a pair of bridge rectifier diodes with two switches and an ac side boost inductor in any given conduction path.[7].

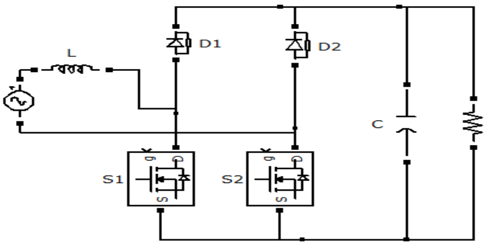

Fig.10 Bridgeless Boost Converter

The Simulation results of Bridgeless boost Converter is shown in Fig.11, Fig.12 and Fig.13.

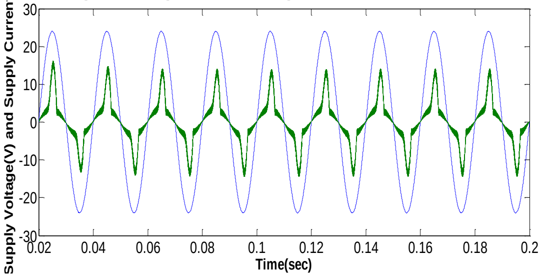

Fig.11 Supply Voltage and Supply current of Bridgeless Boost Converter

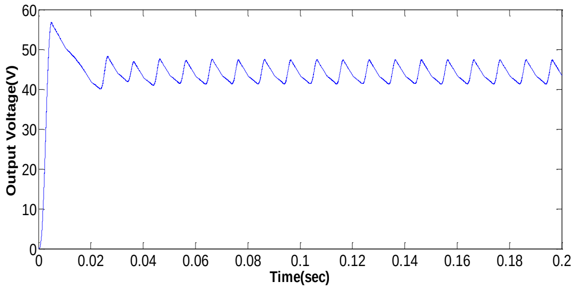

Fig.12 Output Voltage of Bridgeless Boost Converter

ISSN (Online) : 2278-1021
ISSN (Print) : 2319-5940

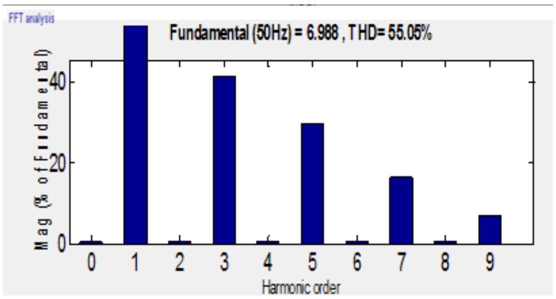

Fig.13 FFT Analysis of Supply current of Bridgeless Boost Converter

D. *Flyback converter*

The Flyback converter is an isolated buck-boost power converter with the inductor split to form a transformer, so that the voltage ratios are multiplied with an additional advantage of isolation. [8]. This topology allows electrical isolation between the LEDs and the ac line and thus is a popular PFC topology as it provides a safety requirement in most LED lamps.

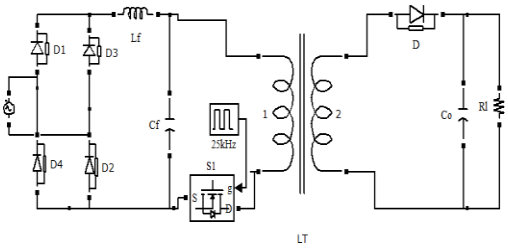

Fig.14 Flyback Converter

Design Considerations:

- Selection of Duty Cycle , D :

$$\frac{V_o}{V_{in}} = \frac{D}{1-D} \qquad (4)$$

where 'n' is the turns ratio.

- Selection of Output Capacitor , C_o:

$$C_o \geq \frac{I_o}{\Delta V_o f_{sw}} \qquad (5)$$

where f_{sw} is switching frequency(kHz) , I_o is output current , ΔV_o is change in output voltage.

- Magnetising Inductance , L_m:

$$L_m \geq \frac{D^2 V_{inmin}}{2 I_{in} f_{sw}} \qquad (6)$$

- Primary to secondary turns ratio ,n :

$$n = \frac{V_r}{V_o + V_f} \qquad (7)$$

where V_f is forward voltage (V) and V_r is Reflected voltage (V).

The Simulation Parameters chosen are Duty cycle=70%, C_o =1000μF and L_m = 1mH.The Simulation results of Flyback Converter is shown in Fig.15, Fig.16 and Fig.17.

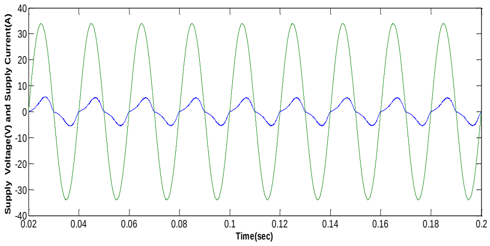

Fig.15 Supply Voltage and Supply Current of Flyback Converter

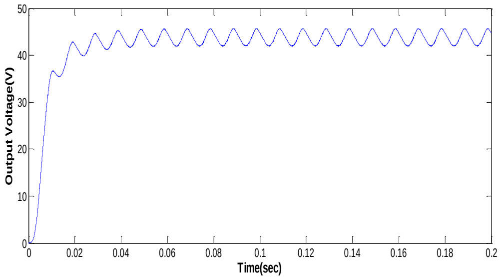

Fig.16 Output Voltage of Flyback Converter

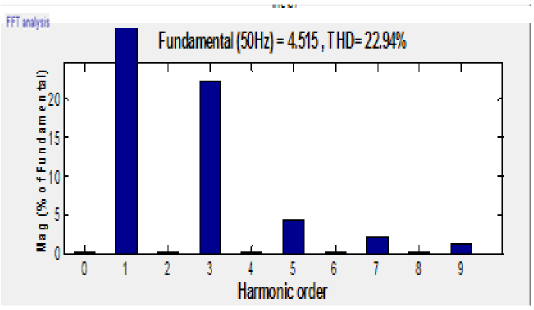

Fig.17 FFT Analysis of Supply current of Flyback Converter

E. *Forward converter*

The forward converter is a DC/DC converter that uses a transformer to increase or decrease the output voltage depending on the transformer ratio and provide galvanic isolation for the load.

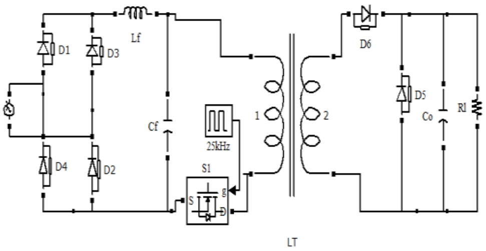

Fig.18 Forward converter

Design Considerations:

- Selection of Duty Cycle , D:

$$\frac{V_o}{V_{in}} = D\frac{Ns}{N_p} \qquad (8)$$

where Ns, N_p is Secondary and Primary turns of transformer respectively.

- Selection of Output Capacitor :

$$C_o \geq \frac{I_o}{20\Delta V_o f_{sw}} \qquad (9)$$

where I_o is Output Current and ΔV_o is Change in Capacitor voltage .

The Simulation parameters designed are Duty Cycle=70% and C_o=1000μF.The Simulation results of Forward Converter is shown in Fig.19, Fig.20 and Fig.21.

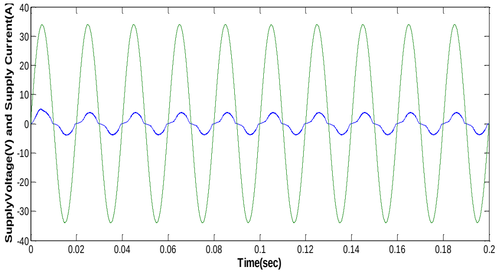

Fig.19 Supply Voltage and Supply Current of Forward Converter

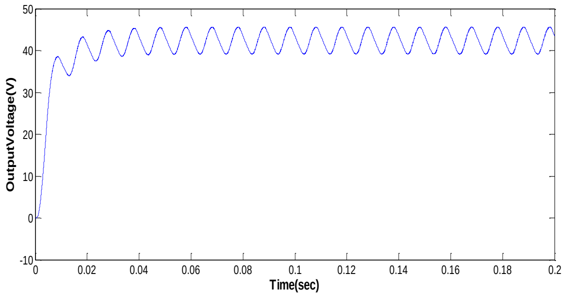

Fig.20 Output Voltage of Forward Converter

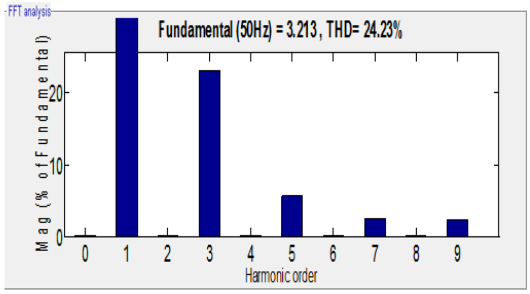

Fig.21 FFT Analysis of Supply current of Forward converter

F. SEPIC Converter

The single-ended primary-inductance converter (SEPIC) is a DC/DC-converter topology that provides a positive regulated output voltage from an input voltage that varies from above to below the output voltage. So SEPIC PFC converter does not require an additional dc/dc stage for LED applications i.e it can be used as a single-stage power conversion instead of two stages.[9][10]

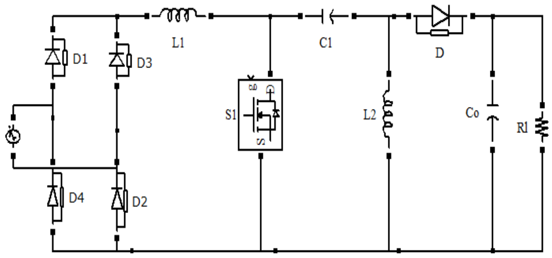

Fig.22 SEPIC converter

Design Considerations: [12]

- Selection of Duty cycle, D:

$$\frac{V_o}{V_{in}} = \frac{D}{1-D} \tag{10}$$

where V_o is Output voltage (V) and V_{in} is Input Voltage (V).

- Selection of Inductor:

$$L \geq \frac{DV_{in}}{\Delta I_L f_{sw}} \tag{11}$$

$$\Delta I_L = 18\% \frac{V_o I_o}{V_{in} \eta} \tag{12}$$

where f_{sw} is Switching Frequency (kHz), ΔI_L is Inductor current ripple, ΔV_o is change in output voltage and η is Efficiency.

- Selection of Output Capacitor:

$$C_o \geq \frac{P_o}{2\Delta V_o V_o * 2\pi f_s} \tag{13}$$

where f_s is supply frequency (Hz), P_o is output power (W).

- Selection of SEPIC Capacitor:

$$C \geq \frac{DI_o}{\Delta V_c f_{sw}} \tag{14}$$

where ΔV_c is Capacitor Voltage Ripple and I_o is the load current.

The Simulation Parameters designed are Duty Cycle=59%, L_1=2.8mH, L_2=1.4mH, C=6.7µF and C_o=3200µF.The Simulation results of SEPIC Converter is shown in Fig.23, Fig.24 and Fig.25.

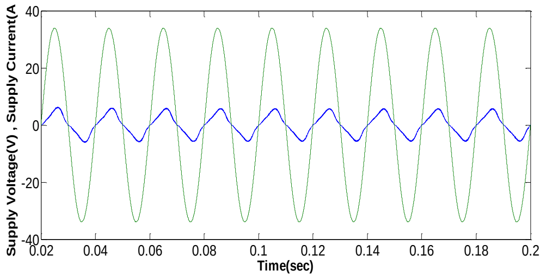

Fig.23 Supply Voltage and Supply Current of SEPIC converter

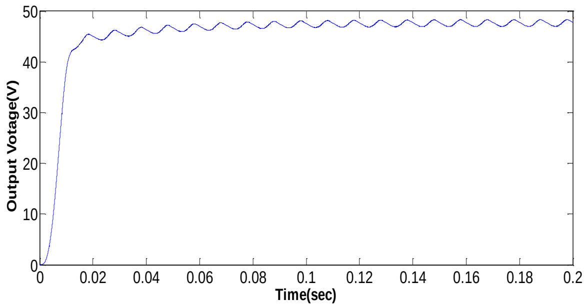

Fig.24 Output Voltage of SEPIC converter

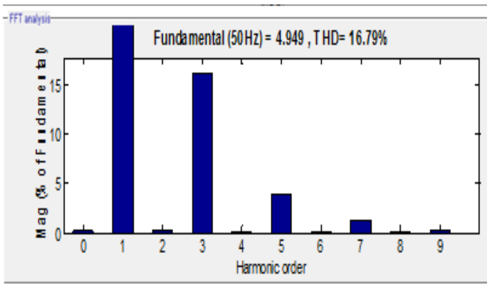

Fig.25 FFT Analysis of Supply current of SEPIC converter

G. Bridgeless SEPIC converter

In a conventional SEPIC converter, input diode bridge circuit carries out the AC-DC Conversion. During each half cycle, two diodes conduct and due to this conduction loss increases. To minimize this loss, bridgeless topology is adopted. [11].

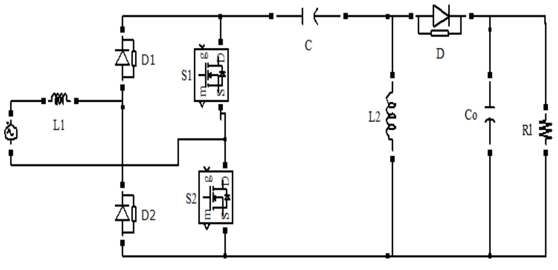

Fig.26 Bridgeless SEPIC converter

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ISSN (Print) : 2319-5940

The Simulation results of Bridgeless SEPIC Converter is shown in Fig.27, Fig.28 and Fig.29.

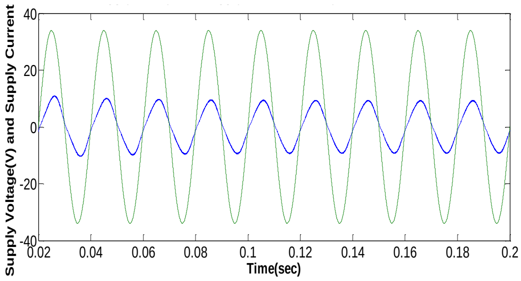

Fig.27 Supply voltage and Supply current of Bridgeless SEPIC converter

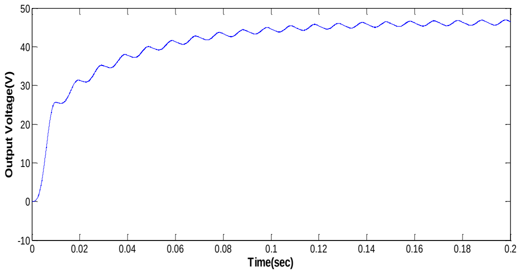

Fig.28 Output Voltage of Bridgeless SEPIC converter

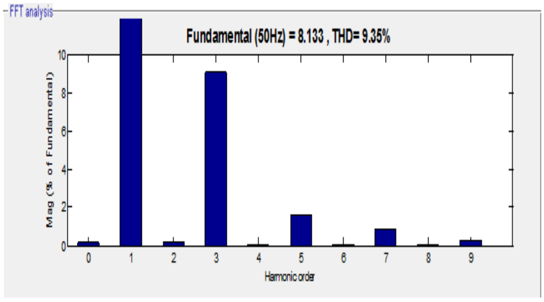

Fig.29 FFT Analysis of Supply current of Bridgeless SEPIC converter

III. PERFORMANCE PARAMETERS OF PFC TOPOLOGIES

a) Power factor :

Power factor can be expressed as the product of the distortion factor and the displacement factor.

$$PF = \frac{V_{rms}\ I_{rms\ 1} \cos\emptyset}{V_{rms}\ I_{rms}} = K_d K_\theta \qquad (15)$$

b) Distortion factor (K_d):

The distortion factor K_d is the ratio of the fundamental RMS current, I_{rms1} to the total RMS current, I_{rms}.

$$K_d = \frac{1}{\sqrt{1+THD^2}} \qquad (16)$$

c) Total Harmonic Distortion:

Total harmonic distortion (THD) is an important figure of merit used to quantify the level of harmonics in voltage or current waveforms.

d) Displacement factor(K_θ):

The displacement factor K_θ is the cosine of the displacement angle (φ) between the fundamental input current and the input voltage.

$$K_\theta = \cos\varphi \qquad (17)$$

IV. COMPARISON OF DIFFERENT ACTIVE PFC TOPOLOGIES

The following conclusions can be drawn from the Table I below:

1. The THD which signifies the amount of distortion present in the signal is found to be least for the SEPIC topology.
2. For LED applications, the PFC stage with the SEPIC topology is more popular as it can be used as a single-stage power conversion instead of two stages because its output voltage can be lower or higher than the input voltage.
3. Bridgeless SEPIC topology further reduces THD. This leads to an improved value of power factor in comparison to the other Active PFC topologies.

TABLE I. COMPARISON OF PERFORMANCE PARAMETERS OF ACTIVE POWER FACTOR TOPOLOGIES FOR LED

S.No	**Active PFC Topology**	**Performance Parameters**			
		THD (%)	**K_d**	**K_θ**	**Power Factor**
1	Boost Converter	58.62	0.8627	0.9984	0.8613
	Bridgeless Boost Converter	55.03	0.876	0.9995	0.8756
	Interleaved Boost Converter	37.82	0.9353	0.995	0.9306
2	Flyback Converter	22.94	0.9746	0.9933	0.9680
3	Forward Converter	24.21	0.9719	0.9981	0.9701
4	SEPIC Converter	16.79	0.9862	0.9855	0.9719
	Bridgeless SEPIC Converter	9.35	0.9956	0.9855	0.9738

V. CONCLUSION

LED represents a very interesting alternative to the traditional lighting devices due to their outstanding characteristics. Nevertheless, they need high quality power supply which mandates power factor corrected AC-DC Converter topologies. In this paper, a comparative study of various active power factor Correction topologies for LED Applications has been carried out using MATLAB/SIMULINK. Their performance parameters are compared. From the results, it is found that the Bridgeless SEPIC Converter topology has lesser THD and power factor closer to unity. The power factor can be improved even more by adopting closed loop current control strategies such as Average current control, Peak current control, Hysteresis control and Non-Linear carrier current control.

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