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Comparison And Performance Analysis of Multiple PFC Topologies for BLDC Motor Drive

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Abstract

Conventional DC-DC converters with diode bridge rectifiers utilized to operate DC load consume high reactive power from the source causing drop in power factor. The ripple of the output DC voltage will also be high which can damage the load or the equipment connected to the circuit. To ensure these problems to be mitigated PFC converters are used for reduced consumption of reactive power improving the power factor of the source. With these PFC converters there will also be reduction in output voltage ripple increasing the reliability of the load modules. In this paper different PFC based circuits are modeled and their performance is compared when they are operating a BLDC motor. The compared circuits are a) Cuk b) BL-Buck-Boost c) BL-CSC d) BL-Luo PFC based converters. All these converters are modeled to operate a 24V 400W 3000rpm rated BLDC motor and the results are compared to determine the best efficient converter among them. For the comparative analysis MATLAB Simulink software is considered for results generation and all the comparisons are taken with respect to time.

Keywords: PFC (Power Factor Correction), BL-CSC (Bridge-Less Canonical Switching Cell). BL-Luo (Bridge-Less Luo), BLDC (Brushless DC motor), MATLAB (Matrix Laboratory), Simulink.

I. INTRODUCTION

Most of the loads used in modern day to day life are DC loads which include all the electronic equipments like TV, mobile phones, laptops, computers, lighting, battery charging etc. For low power consumption devices in the range of 50W - 100W, voltage conversion is not a bigger issue. The power quality is also maintained well with better DC ripple and good power factor [1]. However, the power quality degrades when heavy loads with power consumption in range of 500W – 1000W are connected to the source. For these heavy loads with conventional AC – DC converters there will be huge ripple generated in the DC voltage output and high reactive power consumption from the source resulting in drop of power factor.

So, for heavy DC loads the conventional diode bridge rectifier (DBR) connected buck-boost converters need to be replaced with better PFC circuits [2] which improve the power factor of the source and also reduce the output voltage DC ripple [3]. However, there are two categories of PFC based converters [4] which are bifurcated as with bridge and Bridgeless. The bridge converters are included with DBR and the main DC-DC circuit only includes one high frequency operating switch [5]. The Bridgeless converters [6] do not have DBR but the DC-DC circuit has two high frequency operating switches.

In this paper we are considering four different types of PFC based circuits which are given as

a) Cuk PFC based circuit

b) BL-Buck-Boost PFC based circuit
c) BL-CSC PFC based circuit
d) BL-Luo PFC based circuit.

In all the above mentioned converters [11][12][13][14] only the Cuk PFC circuit has DBR which is considered to be lowest performing circuit. Hence only one DBR included PFC circuit is considered (which has less efficiency due to DBR) for comparison and remaining all the three are Bridgeless circuit [7] [8] topologies. The below figure 1 are the circuit topologies considered for the comparative analysis.

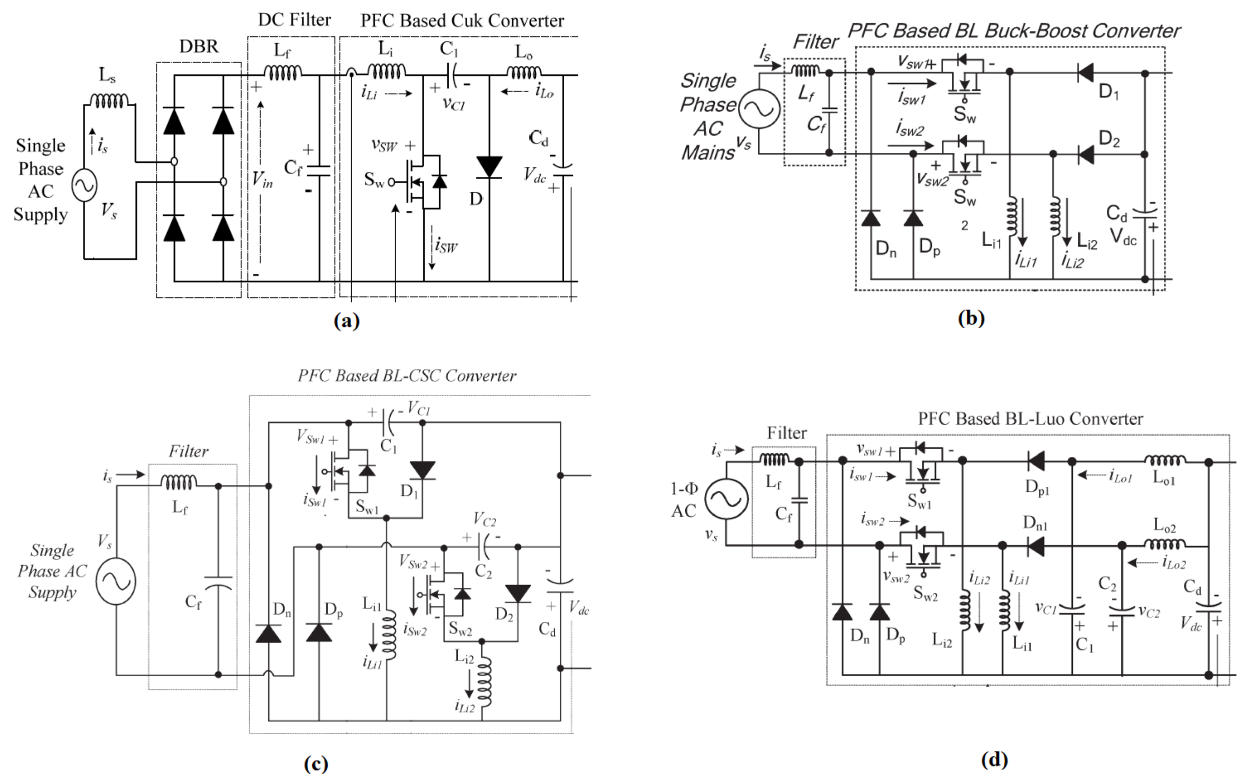

Fig. 1: (a) Cuk converter (b) BL Buck-Boost converter (c) BL-CSC converter (d) BL-Luo converter

As seen in figure 1 all the circuits are connected to single phase AC source [9] and are included with high frequency MOSFET switches [9] which operates at switching frequency of 20kHz. The output of all the circuits are connected to six-switch VSI connected BLDC motor operated by hall sensor commutation gate signals [18]. The speed of the BLDC motor varies with respect to the output DC voltage generation from these PFC based circuits. The below figure 2 is the common circuit of VSI connected BLDC motor.

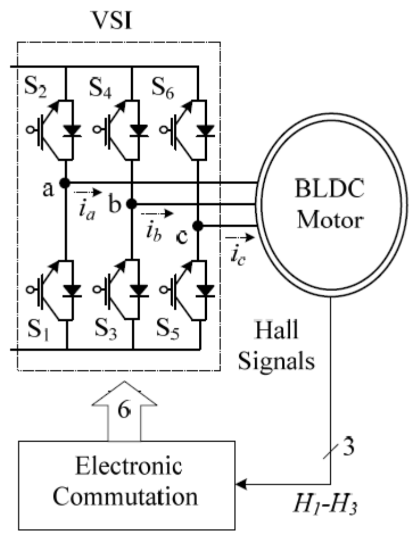

Figure 2: Six-switch VSI connected BLDC motor with electronic commutation

In this paper section I is included with introduction to proposed PFC based circuit topologies considered for the analysis followed by configuration of the PFC based circuits in section II. In section III the controller modeling is discussed which will be common for all the introduced circuits. Section IV is included with simulation results comparison of different parameters in the circuits for determining the most efficient converter. The final section V is conclusion to the paper included with comparison tables and final results followed by references used.

II. CONFIGURATION OF PFC BASED CIRCUITS

All four introduced PFC based converters have [11][12][13][14] multiple passive elements included in them. In order to generate required voltage at the output of the converters the passive elements are calculated as below.

a) Cuk converter [11]

$L_i = \frac{1}{\eta . f_s} . \left(\frac{V_{smin}^2}{P_{max}}\right) . \left(\frac{V_{DCmax}}{\sqrt{2}V_{smin}+V_{DC}}\right)$.........................(1)

Considering η = λ = 0.25, f_s = 20kHz, V_{smin}=15V, P_{max}=500W, V_{DCmax} = V_{DC} = 24V.

With the above parameters the input inductor Li is calculated as

L_i =47.7 uH.

$L_o = \left(\frac{V_{smin}^2}{P_{max}}\right) . \left(\frac{V_{DCmax}}{\lambda\sqrt{2}V_{smin} . f_s}\right) . \left(\frac{V_{DCmax}}{\sqrt{2}V_{smin}+V_{DC}}\right)$ ....(2)

L_o = 54.06 uH

$C_1 = \frac{P_{max}}{\kappa f_s\left(\sqrt{2}V_{smin}+V_{DC}\right)^2}$ ....(3)

Considering κ = 0.1.

C_1 = 4.315 mF

$$C_d = \frac{P_{min}}{2\omega\delta V_{DCmin}^2} \text{ ....(4)}$$

Here, P_{min} = 100W, ω = 2πf = 314, δ = 0.04, V_{DCmin}=5V.

C_d = 0.1592 F

b) BL Buck-Boost converter [12]

$$L_i = \frac{V_{DCmin}^2}{P_{min}} . \frac{(1-D_{min})^2}{2.f_s} \text{ ....(5)}$$

Here, D_{min} = 0.2

L_i = 4 uH

$$C_d = \frac{P_{omin}/V_{DCmin}}{2.\omega.\Delta.V_{DCmin}} \text{ ....(6)}$$

C_d = 0.1592 F

c) BL-CSC converter [13]

$$L_i = \frac{V_{smax}^2}{P_{max}} . \frac{D}{2.f_s} \text{ ....(7)}$$

Here, D = 0.7206

$L_{i1} = L_{i2}$ = 2.7 uH

$$C_1 = C_2 = \frac{V_{DCmax}.D}{\eta.(2.V_{smax}+V_{DC}) f_s.R_L} \text{ ....(8)}$$

Here, $R_L = \frac{V_{DC}^2}{P_i}$, η=0.1.

$C_1 = C_2$ =80.56 uF

$$C_d = \left(\frac{P_{min}}{V_{DCmin}}\right) \frac{1}{2.\omega.\Delta.V_{DCmin}} \text{ ....(9)}$$

C_d = 0.1592 F

d) Luo converter [14]

$L_{ic} = \frac{D_{min}.(1-D_{min}).V_{in}}{2.I_o.f_s}$ ……………………(10)

Here, I_o = 25A

$D_{min} = \frac{V_{DCmin}}{V_{in}+V_{DCmax}}$ ………………………(11)

$D_{max} = \frac{V_{DCmax}}{V_{in}+V_{DCmax}}$ ………………………(12)

$V_{in} = \frac{2.\sqrt{2}V_s}{\pi}$ ………………………………(13)

As per the above equations D_{min} = 0.1096, D_{max} = 0.5263, V_{in} = 21.6V.

With the above parameters L_{ic} is calculated as

L_{ic} = 2.107 uH

$C_1 = C_2 = \frac{D_{max}V_C}{2.f_s.R_L\left(\frac{\Delta V_C}{2}\right)}$ ……………………..(14)

Here, V_C = 48V, ΔV_C = 28.8V, R_L = 100.

$C_1 = C_2$ = 0.438 uF

$L_{o1} = L_{o2} = \frac{D_{max}.I_o}{16.f_s^2.C_{in}.\left(\frac{\Delta I_o}{2}\right)}$ ………………(15)

$L_{o1} = L_{o2} = 3.75$ mH

$C_d = \frac{I_o}{2.w_L.\Delta V_{DCmin}}$ ………………………..(16)

$C_d = 0.265$ F

The input filter passive elements Lreq and Cf are common for all the converters. They are calculated as

$C_f = \frac{P_p.\sqrt{2}/V_s}{w_L.\sqrt{2}V_s} tan\theta$ ……………………(17)

C_f = 48.227 uF

$L_{req} = L_f - L_s$ …………………………(18)

$= \frac{1}{4\pi^2 f_s^2 C_f} - 0.05.\left(\frac{1}{w_L}\right).\left(\frac{V_S^2}{P_o}\right)$

L_{req} = 42 uH

With the above parameters the PFC converters are modeled in MATLAB simulink using Sim power systems toolbox.

III. CONTROLLER MODELING

The controller scheme utilized for controlling the output DC voltage [15] of the converter is voltage oriented feedback control. The proposed control structure for all the converters is shown in figure 3.

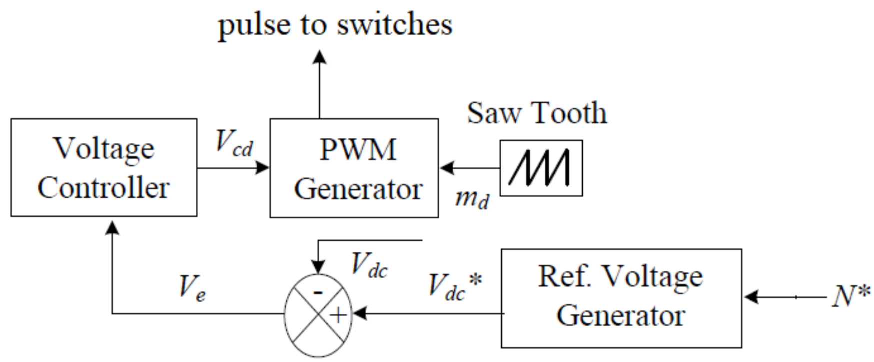

Figure 3: Voltage oriented feedback loop controller for PFC based converters

In the above controller the reference voltage generator [16] is used to generate reference voltage V_{dc}* from the reference speed N* input given by the user. This is achieved by a 1-D lookup table block set with some benchmark values of voltages and speeds of the machine [17]. The values in the lookup table are defined as in table 1.

Table 1: Reference voltage generator lookup table

Reference voltage Vdc* (V)	Speed generated N (rpm)
5V	200
10V	800
15V	1500
20V	2300
24V	3000

The reference voltage values are fed in table data row and the speed values are fed in breakpoints row. As per the reference speed N* the reference DC voltage Vdc* is generated as per the above benchmark values in table 1. The reference DC voltage Vdc* is compared to measured output DC voltage Vdc of the converter and the voltage error Ve is fed voltage controller which is PI controller [17]. PI controller is defined with specific proportional gain (Kp) and integral gain (Ki) values for generation of duty ratio Vcd for the power electronics switches of the converter.

The duty ratio Vcd is compared to high frequency saw-tooth waveform for generation of pulses for the switches. For single switch this pulse is directly fed but for two switches of the three bridgeless converters the pulse is fed to the switches as per the direction of the input voltage. During positive voltage the positive switch is operated and during negative voltage the negative switch is operated [12][13][14]. This is achieved by comparing the input voltage to zero and the signal generated by comparison is used for generation of pulses for the switches as shown in figure 4.

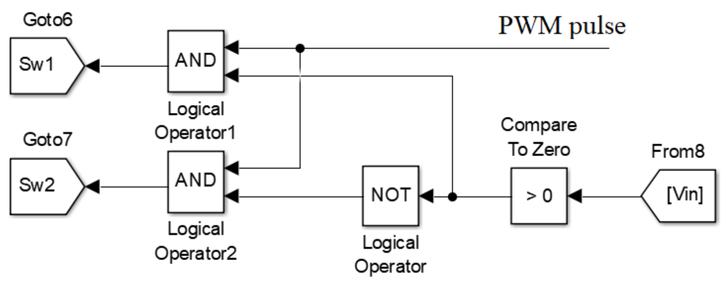

Fig. 4: Switching pulse generation for bridgeless converters

The BLDC motor is operated through six-switch VSI controlled by hall sensor signals feedback [18]. Back emf (electro motive force) signals are estimated using these hall sensors from the machine and the gate pulses for the electronic commutation are generated by these back emf signals.

IV. SIMULATION RESULTS COMPARISON

With all the above modules the simulations are modeled in MATLAB simulink software using Sim-power systems toolbox and the results are compared for analysis. Each model is run for 1sec of simulation time with same reference speed values. The rating of the BLDC motor are given in table 2.

Table 2: BLDC motor parameters

Name of the parameter	Value
Power and voltage	400W, 24V
Stator resistance Rs (Ohms)	0.085
Stator inductance Ls (H)	0.171×10^{-4}
Voltage constant Vc (Vp L-L/krpm)	6.7
Inertia J ($kg.mt^2$)	0.6×10^{-4}
Number of pole pairs	4
Flux linkage (Wb)	0.0079975

The same rating of BLDC motor is connected to all four PFC based converters and the measurement of different parameters of the circuit and the motor are compared as shown below.

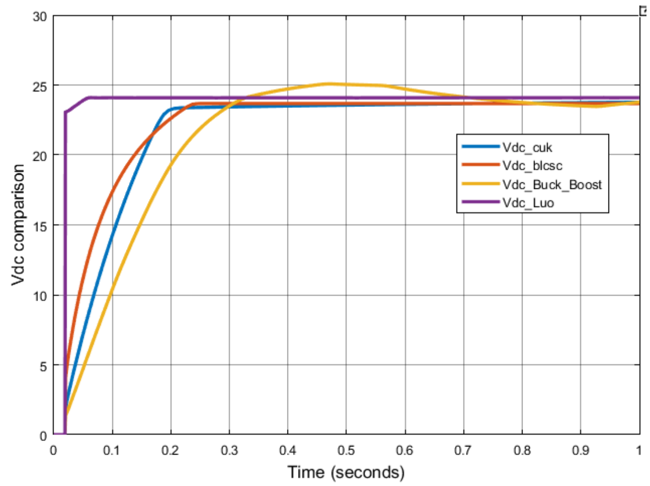

Fig. 5: DC link voltage comparison of all four PFC based converters

The above figure 5 is the DC link voltage comparison of all four PFC based converters with reference voltage value generation of 24V. All the converters voltage values are converged at 24V as per the reference speed of 3000rpm given by the user. The below graph in figure 6 are the power factors of the converters which are tend to maintain near to unity.

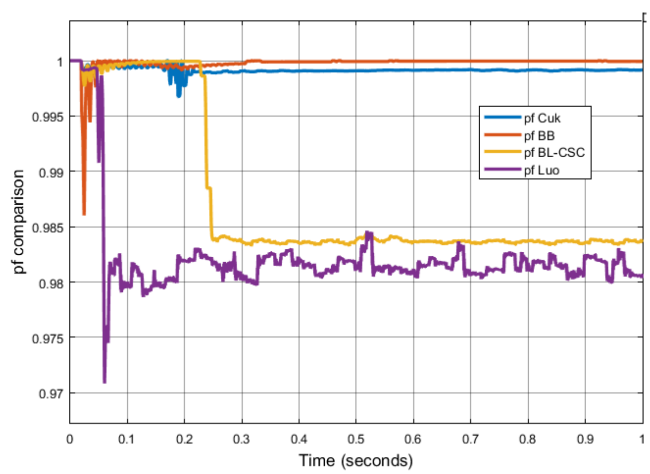

Fig. 6: Power factor comparison of all four PFC based converters

The efficiency comparison of the converters can be seen in figure 7 followed by BLDC motor speed comparison in figure 8.

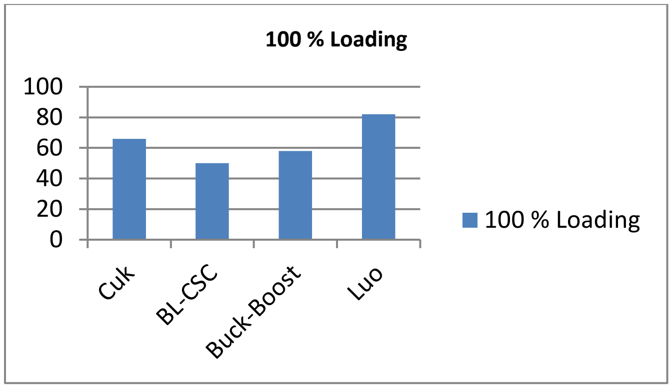

Fig. 7: Efficiency comparison of all four PFC based converters

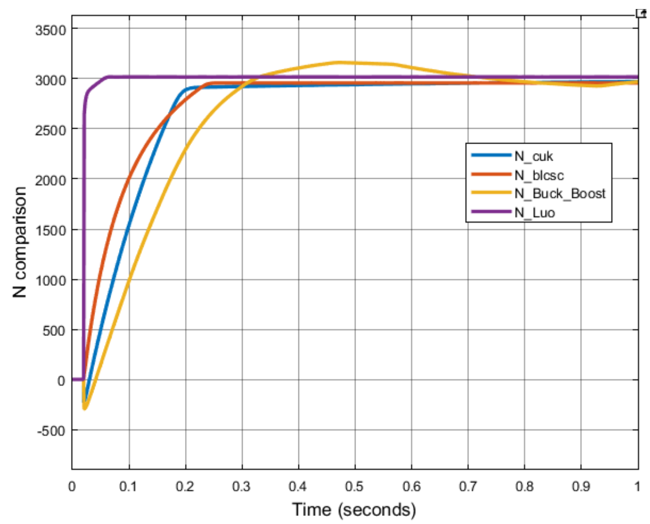

Fig. 8: BLDC motor speed N comparison of all four PFC based converters

The torque of the motor is maintained at 1.2N-mt for all the modules and is shown in figure 9.

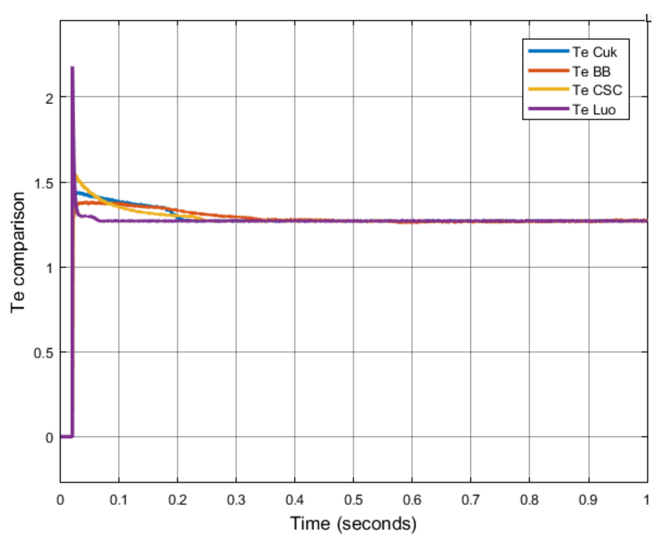

Fig. 9: Electromagnetic torque Te comparison of all four PFC based converters

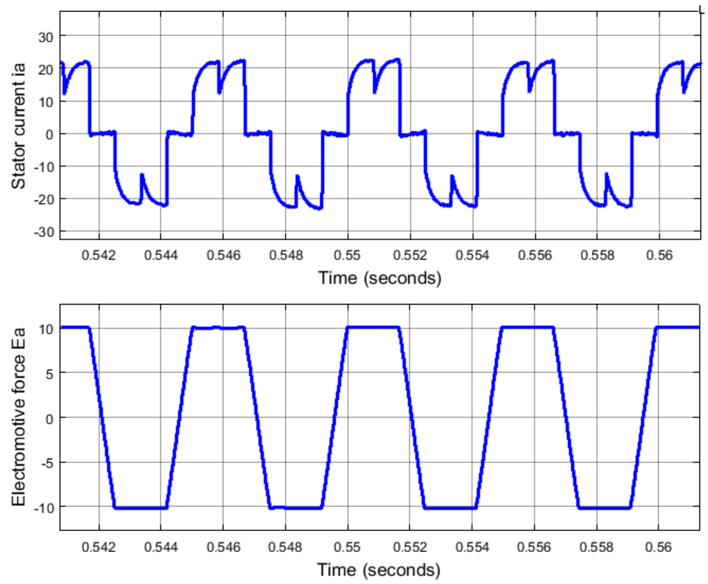

Fig. 10: Stator current and electromotive force of phase A of BLDC motor

The above graph is the stator current and electromotive force of phase A of the BLDC motor when it is operated at 3000rpm. The below is the settling time determination of the DC link voltage of the all the converters.

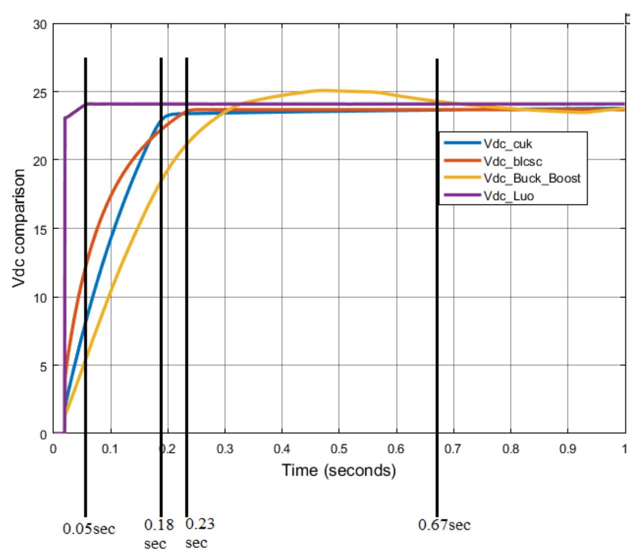

Fig. 11: Settling time of DC link voltage of all four PFC based converters

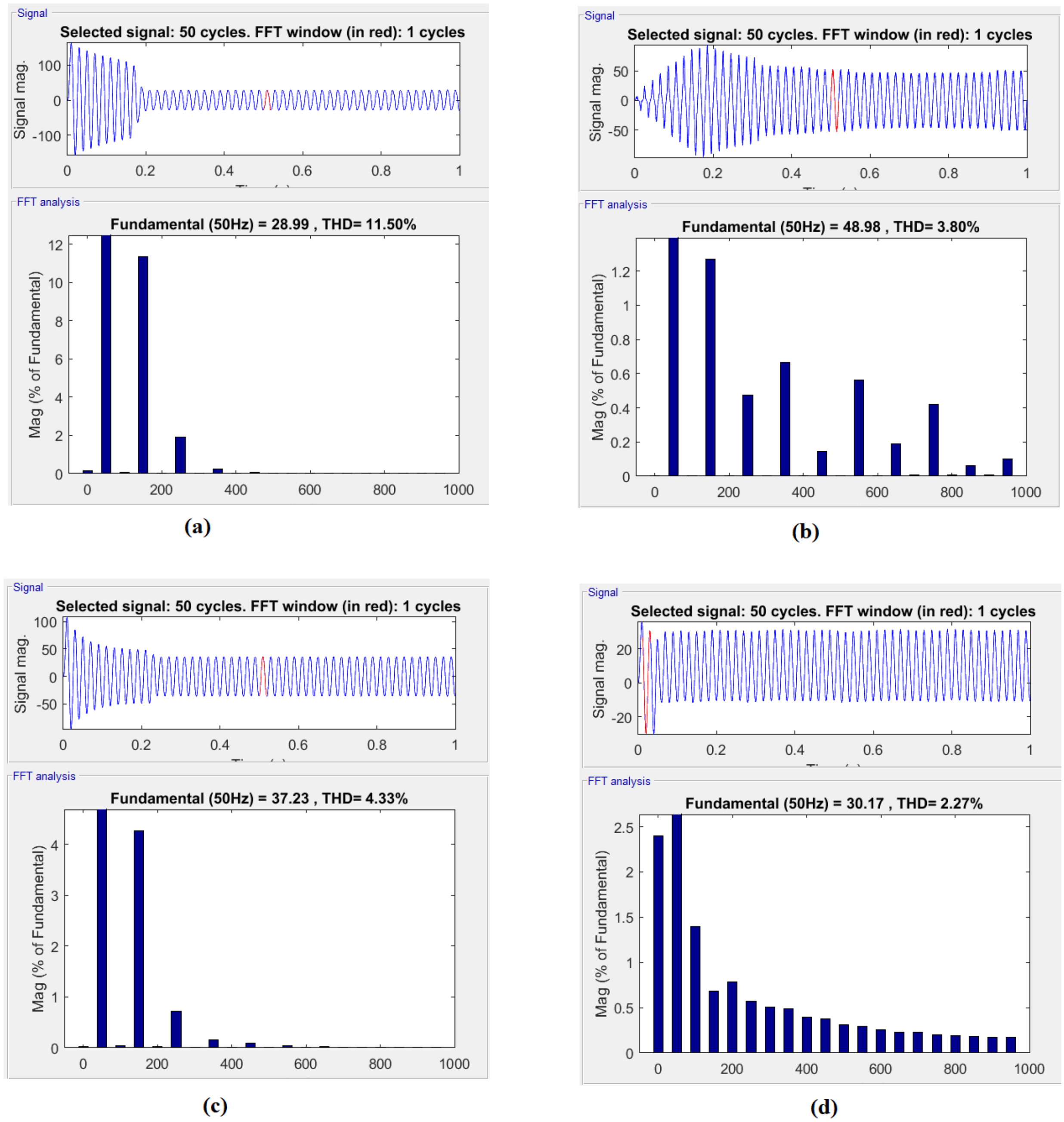

Fig. 12: THD of the source current of all the four converters a) Cuk b) BL-BB c) BL-CSC d) BL-Luo

The above are the THDs of the source current of all the four converters determined using FFT analysis tool available in MATLAB powergui toolbox. The analysis is done using by signal exported to workspace of the software.

V. CONCLUSION

As per the given results in section IV with the comparison of parameters like DC link voltage, Speed of BLDC motor, efficiency of the converters, settling time of the DC link voltage it is determined that the BL-Luo PFC based converter is more efficient and reliable selective converter as compared to the other three converters. Comparative analysis tables of the four converters considering different parameters are given below.

Table 3: Parameters comparison of the converters

Name of the converter	Efficiency (%)	Settling time (sec)	Power factor	THD (%)
Cuk converter	65	0.18	0.99	11.46
BL Buck-Boost	60	0.67	0.99	3.8
BL-CSC	50	0.23	0.98	4.33
BL-Luo	86	0.05	0.98	2.27

With the above parametric comparison the BL Luo converter has the highest efficiency of 86% for the given BLDC motor load with less DC link voltage settling time of 0.05sec. However, the power factor is maintained near to unity for all the converters the THD of source current for BL-Luo converter is also maintained very less in the range of 2.27%. Therefore, the BL Luo converter is considered to be the best PFC based converter for 24V 400W load application compared to conventional PFC converters.

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