International Journal of Future Generation Communication and Networking
Vol. 14, No. 1, (2021), pp. 4993 – 4999

Multiple PFC Circuit Topologies For 24 V BLDC Motor Drive

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Abstract

Simplicity and high reliability are common features of Brushless dc (BLDC) motors, so are commonly used.The conduction losses associated with Bridgelessconverters are less as compared to conventional diode bridge rectifiers so are preferred. In this paperspeed control analysis is carried out on three different bridgeless power factor correction converters and bridge converterforBLDC motor. The three bridgeless PFC converters consider here are Bridgeless Canonical Switching Cell converter, Bridgeless Buck-Boost converter and Bridgeless Luo converter. The absence of an input diode bridge and the presence of only semiconductor switches in the current flowing path during each switching cycle result in less conduction losses and an improved Efficiency of converter compared to the conventional PFC converter. BLDC motor speed and output DC voltage settling times are compared. The analysis is carried out in MATLAB software forwith design parameters.

Key words- PFC (Power Factor Correction), BL-CSC (BridgeLess Canonical Switching Cell),Luo converter,BLDC (BrushLess Direct Current), MATLAB (Matrix Laboratory).

I. INTRODUCTION

The DC loads used in all electrical systemsuse uncontrolled or controlled rectifiers and DC-DC converters [1] [2]to generate required voltage amplitude. Most of the circuits are either Buck or booster converters which decrease or increase the output voltage amplitude. These converters along with bridge rectifiers work together which convert AC to DC using power electronic devices. The usage of these conventional buck boost converters leads to power factor drop [4] in the input AC supply. The drop-in power factor is an after effect of heavy consumption of reactive power because of the conversion. In order to reduce this power factor, drop due to reactive power consumption, the conventional buck boost converters are replaced with PFC circuit which maintains the input AC supply at near to unity power factor even during heavy load conditions.

To drive BLDC motor the performances of four PFC circuits [5] circuits are considered with single phase AC supply. The Efficiency,DC voltage amplitude and speed of the BLDC motor are compared to get the best PFC converter for the drive application. The four PFC circuits considered are Cuk, Bridgeless buck-boost, BL-CSC and Bridgeless Luo converters. From the selected converters the only converter with diode bridge rectifier is 'Cuk' converter and all the three remaining converters are without bridge rectifier. The proposed converter circuits are given below in fig. 1. In the proposed circuits the input AC voltage considered is same for all the four circuits with 24 Vrms and 50Hz frequency. The controlled power electronic devices used in all the circuits are MOSFETs [4] (Metal Oxide Semiconductor Field Effect Transistor) which operate at high frequency in the range of 10kHz to 50kHz. The output of the circuits is connected to a six IGBT switch commutator which drives BLDC [3] machine. The rating of the BLDC machine used is also maintained same for all the circuits. The speed of the BLDC machine is controlled by the output voltage of the converters.

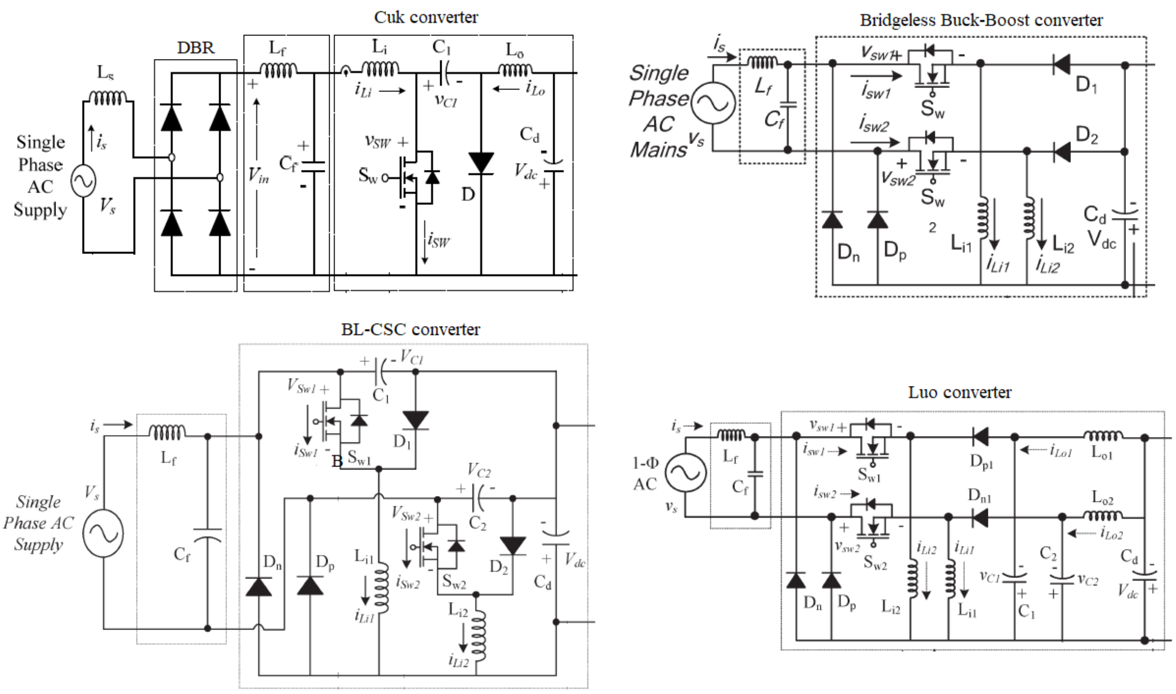

Fig. 1: Proposed PFC circuits for comparison

In the above figure it can be seen that number of MOSFET used in Cuk [6] is only one and in other topologies there are two. This makes the control of Cuk converter easier compared to other converters. However, the performances of all the converters are compared with consideration of DC output voltage ripple, stabilizing time of DC voltage and efficiency.

The voltage-oriented control for BLDC speed control is explained in section II and parametric calculations of proposed converters is discussed in section III, followed by section IV with results comparison using graphical representation. The final section V is conclusion with references and rating of the machine used.

II. CONTROL STRUCTURE OF PROPOSED CIRCUITS

The switching of MOSFET power electronic devices in the proposed converters [5] change the output voltage. The voltage-oriented control feedback system is used for the duty ratio (D) of MOSFETs of the converter. The reference speed generates the reference voltagethat will set the BLDC motor speed. A given table shows thevalue of reference generated voltage which develops the required voltage for the BLDC motor [1] to run at specific reference speed given by the user. The voltage and speed table which represents as reference voltage generator is given in table I.

TABLE I

Speed reference (RPM)	Voltage reference (V)
40	4
600	8
1100	12
1800	16
2400	20
2980	24

The generated reference voltage (Vdc*) from the Lookup table I, measured voltage (Vdc) from the output terminals of the converteris now compared and error is generated. The generated error (Ve) is given as feedback input to the PI (Proportional Integral) gain controller [7] which is a voltage controller producing the required duty ratio for the MOSFET devices. The common control structure for all the four proposed circuits is shown below in fig. 2.

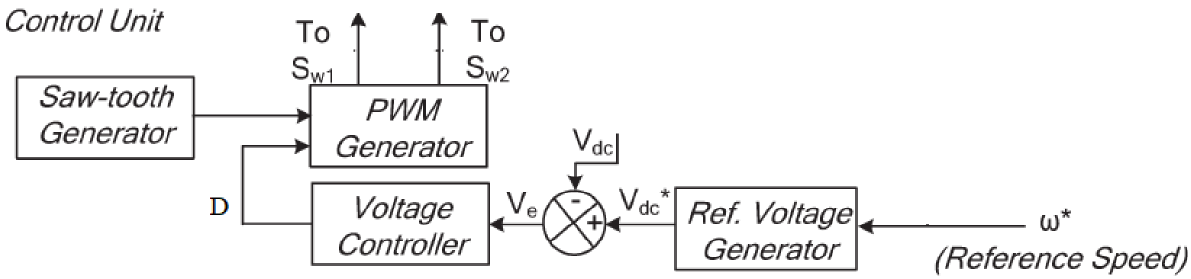

Fig. 2: Proposed voltage-oriented control for PFC converters

The duty ratio from the voltage controller is now compared to high frequency sawtooth waveform generating a high frequency pulse [4] for the MOSFETs in the circuit. However, the cuk converter has only one MOSFET device only a single pulse 'Sw1' can be fed to the converter. For the other converters the pulse is fed to both the switches alternatively depending on the input supply frequency. As it is mentioned in section I the AC supply voltage has frequency of 50Hz with positive voltage of 10msec and negative voltage of 10msec. Therefore, the switch Sw1 is operated for positive voltage time and switch Sw2 is operated for negative voltage time alternatively.

The values of Kp and Ki in the PI controller are set with tuning the control system with change in values using multiple iterations converging the output voltage to the required reference value. The final Kp and Ki values are taken as 0.3 and 0.001 respectively.

III. DESINGING OF CONVERTERS

The values for the passive elements in the converters are considered depending on switching frequency and input voltage amplitude. The switching frequency (fs) and voltage input (Vin) are maintained same for all the proposed PFC converter which are 20kHz and 220Vrms respectively.

A. Cuk converter design [6]

The output voltage of the converter which depends on duty ratio of the MOSFET switch can be calculated as

$$Vdc = \frac{D}{(1-D)} Vin \text{ ………….(1)}$$

Vin is given as

Vin = √2 * 24Vrms

The input inductance Li is given as

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

With fs = 20kHz, Vsmin = 20V, Vdc = 24V (For 3000rpm), Pmax = 400 W the value of Li is calculated as

Li = 47.7μH

The output inductance Lo is given as

$$L_o = \left(\frac{V_{smin}{}^2}{P_{max}}\right)\left(\frac{V_{dcmax}}{\lambda .\sqrt{2}V_{smin} \cdot f_s}\right)\left(\frac{V_{dcmax}}{\sqrt{2}V_{smin} + V_{dcmax}}\right) \text{…….(3)}$$

Here $\boldsymbol{\lambda}$ is maximum ripple current in the circuit which is taken as 20%. Therefore, the output inductance value is calculated as

Lo = 54.06 μH

The value of intermediate capacitance is given as

$$C1 = \frac{Pmax}{k.fs\ (\sqrt{2}.Vsmax + Vdcmax)^2} \text{ ……(4)}$$

Here, ɗ is the change in voltage across the capacitor C1 which is considered to be 8%. The C1 is calculated as

$$C1 = \frac{400}{0.1 * 20000\,(\sqrt{2}.24 + 24)^2}$$

=4.315mF

The value of output capacitance Cd is given as

$$Cd = \frac{Pmin}{2.w.\Delta.Vdcmin^{\,2}} \text{……………….……(5)}$$

Here, Pmin = 200, Vdcmin = 5, w = 2*pi*50 = 314, Δ is maximum ripple in DC voltage allowed which is taken as 5%. Therefore, Cd is calculated as

$$Cd = \frac{200}{2 * 314 * 0.04 * 5^2}$$

= 0.1592 F

All the above calculated values are given to the cuk PFC circuit and is simulated with reference speed 3000rpm.

B. Bridgeless Buck-Boost converter [8]

With the same input voltage and switching frequency the parameters of Buck-Boost PFC converter are calculated as

$$L_{ixmin} = \frac{V_{dcmin}^{\;2}}{P_{min}} \frac{(1-D_{min})^2}{2.f_s} \text{….……(6)}$$

With D_{min} as 0.2 the inductances L_{i1} and L_{i2} are calculated as

$L_{i1} = L_{i2} = 4\mu H$

The output capacitance Cd is given as

$$Cd = \frac{Po/Vdc}{2.w.\Delta Vdc} \text{……………………….....(7)}$$

$C_d = 0.1592$ F

C. Bridge Less Canonical Switching Cell (BL-CSC) converter [9] [11]

The parameters of BL-CSC PFC converter are given as

$$L_{ix} = \frac{V_{smin}^{\;2}}{P_{max}} \frac{D}{2.f_s} \text{……………….…(8)}$$

With D at 0.72 Li1 and Li2 are calculated as

$L_{i1} = L_{i2} = 2.7\ \mu H$

The equation for intermediate capacitances C1 and C2 is given as

$$C_x = \frac{V_{dcmax}\,.D}{\eta\{\sqrt{2}V_{smax} + V_{dc}\}f_s.(\frac{V_{dc}^{\;2}}{P})} \text{………...(9)}$$

=70.56µF

Therefore $C_1 = C_2 = 70.56\mu F$

The output DC link capacitance is taken as

$$C_d = \frac{P_{min}}{V_{dcmin}} \frac{1}{2.w.\delta.V_{dcmin}} \text{…………....(10)}$$

= 0.1592F

D. Luo converter [14] [15]

The passive element parameters of Luo converter are given as

$$Lix = \frac{Dmin\ (1-Dmin)Vin}{2*\frac{Pmin}{Vdcmin}*fs} \text{………………(11)}$$

= 44µH

Therefore, Li1 and Li2 are taken as 40 µH

$$Cx = \frac{Dmax\ Vc}{2.fs.\frac{Vdc^{\,2}}{P}\frac{\Delta Vc}{2}} \text{…………………….……(12)}$$

= 0.44 µF

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In the above equation the permitted voltage ripple across the intermediate capacitors C_1 and C_2 (ΔVc) is considered to be 50%. Therefore, $C_1 = C_2 = 0.44$ µF

$$Lox = \frac{Dmax \frac{Pmin}{Vdcmin}}{16.fs^2.Cin\frac{\Delta io}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(13)$$

Therefore, $L_{o1} = L_{o2} = 1.78$mH

The output DC link capacitance is taken as

$$Cd = \frac{Io}{2 * w * \Delta Vdcmin}$$

$$= \frac{4}{2*314*0.03*50} = 2200 \text{ µF}$$

With all the above parameters the PFC converters are modelled using MATLAB Simulink environment. The circuit characteristics are compared with reference 2000rpm for all the PFC circuits. The outputs are shown in the next section IV.

IV. RESULTS AND DISCUSSION

When the speed reference in the controllers of the PFC converters are taken at 3000rpm the reference voltage generated is 24V for the specific rating of BLDC machine which is operated using hall sensors and six switch voltage source converter [16]. The parameters of the machine are in given in Appendix I. To compare the PFC converters the output DC voltages of the converters, efficiency of the converters and speeds of the BLDC machine with each converter are recorded. The below are the graphical comparisons of all the modelled converters.

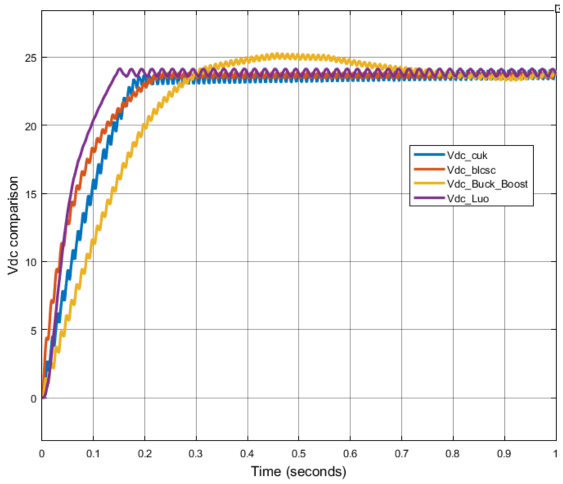

Fig. 3: Output DC voltage comparison of four PFC converters

In the above comparison it is observed that the DC voltage of all the converters settle at 24V. However, the Buck-Boost PFC converter settles to 24 V very slowly. The settling time is 0.8 sec for buck boost converter .The Buck-Boost converter also has initial peak value of 25V compared to other converters. The BL-CSC converter required time of 0.23 sec to settle the voltage at 24 V and Cuk converter required 0.24 sec to settle voltage at final value. The only converter with less settling time equal to 0.14 sec and no peak in voltage generation is BL-Luo PFC converter.

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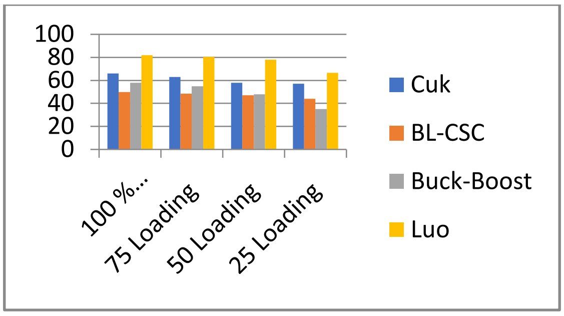

Fig. 4: Efficiency comparisons of all four PFC converters

The efficiency comparison graph shows that the Buck boost converter has efficiency of 58% with very high fluctuation and BL-CSC has the lowest efficiency of 50%. Luo converter has highest efficiency of 82% and Cuk converter have 65% efficiency.

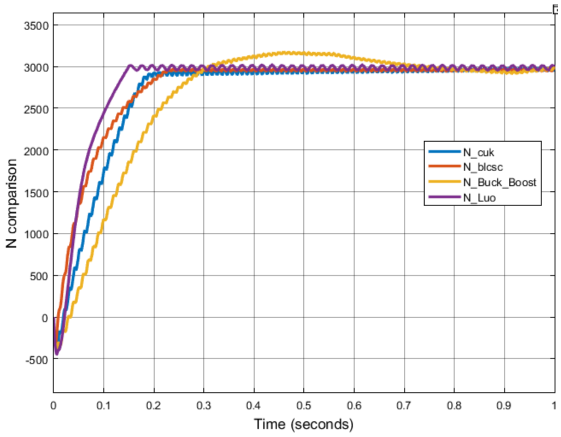

Fig. 5: BLDC motor speed comparison driven with four PFC converters

The variation in speed of BLDC motor is observed to be similar to variation in D.C link Voltage. Initially there is transient in speed for Buck-Boost converter. Settling time is high for Buck-Boost converter. Lowest for BL-Luo converter .Whereas for BL-CSC and Cuk converter it is same.

V. CONCLUSION

With the above results and comparison of different PFC converters it is denoted that Luo converter has better performance when analysed with comparison of all parameters. The Luo converter has lower settling time, fast response rate and majorly no peak value generation at the initial stage of the operation. The parametric value comparisons are given below in TABLE I.

TABLE I

Converter	SettlingTime(Sec)	Efficiency (%)	No. of Switches
Cuk	0.24	65	10
Buck-Boost	0.8	58	11
Bl-csc	0.22	50	11
Luo	0.14	82	12

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APPENDIX I

Parameters of BLDC motor

Name of the parameter	Value
T rated (rated torque)	1.27N·m
N rated (rated speed)	3000 r/min
Stator phase resistance Rph	0.73Ωohms
Kb(back EMF constant)	6.7 V/kr/min
J (moment of inertia)	0.6 x 10^{-4}N·m/A^2
Number of pole pair	4

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