Comparison of Brushless DC Motor Drive Performance fed by Two Different Front End DC – DC Power Converters

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Abstract— The importance of Brushless DC motors has been increasing across domestic and industrial applications for a multitude of advantages. This paper concerns the implementation of the brushless DC motor with two different front end DC–DC converter topologies, canonical switching cell (CSC) converter and Landsman converter. The performance of the motor in these topologies are compared. MATLAB/Simulink is used to design and simulate the converter circuits. The motor parameters under discussion are stator back emf, rotor speed and its ripple factor. A conscious effort has been made to present the parameter values in an easily comparable and a conclusion has been drawn on the best possible topology among these two to enable the motor to function efficiently and help us get desirable results when the motor is deployed in operation.

Key Terms: BLDC motor, DC–DC converters, CSC converter, Landsman converter.

I. Introduction

The exceptional performance, high reliability, ruggedness and wide range of speed control has made the BLDC motor gain its importance over the last decade [1-3]. Its application area is also wider, as it is well suited for all power ranges. Medical analysers, electric automotive and military applications are some of the key application areas of brushless dc motor in addition to house hold applications, motion control, industrial automation, ventilation and air conditioning applications [4,5]. The BLDC motors eliminates the sparking, noise, electro-magnetic interference (EMI) and maintenance problems associated with conventional DC motors, as these are synchronous motors with stator having three phase windings and a permanent magnets rotor with hall effect for position sensing. These enable easier commutation of the electronic commutator (VSI) feeding the motor. The drive is made simple, whereas supplying the VSI with appropriate DC link voltage is vital to achieve desired control over the drive. A dc link capacitor preceded by a diode bridge rectifier would serve the purpose. But, the problem is the high total harmonic distortion and injection of harmonics in the supply [10]. According to standard IEC 61000-3-2, these power quality indices are not acceptable. Literature reports many isolated and non-isolated power converters (single stage), which have minimal losses as the components are less in number[11,12]. Ozturk [13] and Wu [14] proposed a constant dc link fed VSI (using a boost topology) to feed the BLDC drive, whose speed is controlled by varying the VSI switching frequency. This results high switching loss due to the higher switching frequency of the PWM pulses. By having a variable DC link voltage the speed of the BLDC motor can be varied and at the mean time the switching losses can be reduced [19] as the VSI requires comparatively low switching frequency and need not change. A proposal of such concept with two current sensors in a SEPIC converter for feeding a BLDC motor is given in [18]. But the cost of the current sensors would increase the drive cost. Whereas, a single voltage sensor is required for operating the converter in voltage follower approach. Elimination of diode bridge rectifier (partial/complete) resulted in low conduction losses which made the bridgeless converters gain importance over the last decade [20]. Literature reveals many bridgeless converter configurations [20-30], starting from buck, boost and buck-boost converter (bridgeless configuration) each have their own limitations and losses. Hence, these are not preferable for wide range of voltage control (variable dc link voltage). The higher order converter configurations such as cuk [25-27], SEPIC[28,29] and Zeta[30] are widely used, still these have more number of switching components which leads to losses and emi. However less attention has been paid to canonical switching cell converter (CSC) and Landsman converter [17] even though they have good load regulation and lesser component count compared to non-isolated cuk converter [31-34]. Literature compares the conventional configurations with any of these converters to justify it is offering a better performance. It is essential to compare these trending converters to justify which offers an optimal performance among them. This paper presents performance comparison of these two converters (CSC and Landsman) driven BLDC drive.

II. BL-CSC converter fed BLDC motor drive

A bridgeless canonical switching cell converter based brushless dc motor drive is given in figure 1. The bridgeless configuration eliminates the diode bridge, resulting in reduction of conduction losses. The converter is designed such that the current through the input side inductors L1 and L2 are discontinuous and the intermittent capacitors (C1 and C2) voltage is continuous for a switching cycle. This enables the converter to operate in discontinuous conduction mode.
III. Operation of the BL-CSC converter

The two cycle (+ve and -ve) operation of bridgeless canonical switching cell converter is shown in figure 2 to 7. The figures 2 to 4 depicts the operation of the converter in positive half cycle. As shown in figure, path of the current is through, S_w1, L_i1 and D_p. Similarly, during the negative half cycle the current takes the path of switch S_w2, inductor L_i2 and diode D_n as shown in figures 5 to 7.

IV. CSC converter design

A 314W BLDC motor (Full specifications are given in Table 1) is preferred for the experimental studies. To feed the BLDC motor drive, a 500 W front end canonical switching cell converter is designed such that it provides a minimum dc link voltage of 70 V and a maximum of 200 V. This voltage variation facilitates speed variation of the drive. The converter input voltage $V_i$ is given by,

$$V_i(t) = V_m \sin(2\pi f_L t) = \frac{220\sqrt{2}}{\sqrt{3}} \sin(314t) \text{V}$$  \hspace{1cm} (1)

$V_m$ – peak input voltage (i.e. $\sqrt{2}V_s$),

$f_L$ – line frequency (i.e. 50 Hz)

The equation (2) gives the instantaneous voltage across any switch (S_w0) and inductor combination (L_in) and the equation (3) gives the expression for output dc voltage of the converter [9].

$$V_{in}(t) = \left[ V_m \sin(\omega t) \right] = \frac{220\sqrt{2}}{\sqrt{3}} \sin(314t) \text{V}$$  \hspace{1cm} (2)

$$V_{dc} = \frac{V_{in}}{(1-D)} V_{in}$$  \hspace{1cm} (3)

D is the duty ratio, the instantaneous duty ratio D (t) depends on the instantaneous input voltage $V_{in}(t)$ and the dc output voltage, $V_{dc}$ as given in (4).

$$D(t) = \frac{V_{dc}}{(V_{in}(t)-V_{oc})} = \frac{V_{in}}{(V_{in}(t)-V_{oc})} \text{V}$$  \hspace{1cm} (4)

The instantaneous power ($P_i$) is taken as linear function of the dc output of the converter) as it varies with it and the speed of the drive also varies with the converter output voltage, therefore $P_i$ is given as,

$$P_i = \left( \frac{P_{max}}{V_{dc_{max}}} \right) V_{dc}$$  \hspace{1cm} (5)

$V_{dc_{max}}$ – maximum DC link voltage

$P_{max}$ – rated power for the converter

Equation (5) is used to calculate the minimum output power (as 175 W) of the converter for a minimum dc link voltage of 70 V.

Input Inductor design ($L_{ic}$)

The critical value of the input inductor $L_{ic}$ is expressed as, [12]

$$L_{ic} = \frac{V_{in}(t)}{2\pi f_L f_s} = \frac{P_{L} f_s}{2\pi f_L} = \left( \frac{f_s}{f_L} \right) P_{L}$$  \hspace{1cm} (6)

$R_{in}$ represents the input resistance,

$f_s$ is the switching frequency

$P_{L}$ is the instantaneous power.

The inductor value and the switching frequency are inversely proportional, lower the inductor value higher is the switching frequency and the losses associated with the converter switches. Also, in DCIM operation the current stress on the converter switches will increase for low value of inductance. To have reduced stress on the switches and to achieve desired performance, the switching frequency of 20 kHz is selected. The $L_{ic_{min}}$ is calculated at $V_{in_{min}}$ (85 V) to
enable it to operate in universal voltage of 85 V to 270 V [17].

\[ L_{ic\_min} = \frac{(V_{dc\_min})^2}{2R_{L}} = \frac{(200V)^2}{2 \times 20\Omega} \approx 260 \mu F \]  

(7)

\[ L_{ic\_min} \rightarrow \text{minimum critical input inductor} \]

\[ V_{s\_min} \rightarrow \text{minimum supply voltage} \]

Duty ratio is determined at maximum converter output voltage \( (V_{dc} = 200 \text{ V}) \) and at peak value of the minimum input voltage \( (V_{s\_min\_peak} = 85\sqrt{2} \text{ V}) \). The value of \( L_{ic\_min} \) must be greater than \( L_{i1} \) and \( L_{i2} \), therefore it is selected as \( L_{i1} = L_{i2} = \frac{1}{4} \). \( L_{i\_min} = 70\mu H \) (approx.) to enable discontinuous conduction mode.

**Intermittent Capacitor design** \( (C_i) \)

The value of \( C_i \) (intermittent capacitor) is calculated at \( \eta_{max} \), which occurs at \( V_{dc\_max} \) and \( V_{s\_max} \).

\[ C_i = \frac{V_{dc\_max}D(\omega_f)}{V_{dc\_max}\Delta V_{dc\_rms}R_L} = \frac{V_{dc\_max}D(\omega_f)}{\eta(V_s\_max\_rms)+V_{dc\_max}R_L} \]

\[ C_i = \frac{0.1[(270\sqrt{2}+200)2000000X200]}{2000000X200} \approx 0.985 \mu F \]

\[ V_c \rightarrow \text{voltage across the intermittent capacitor} \]

\[ \eta \rightarrow \text{ripple voltage} \]

\[ R_L \rightarrow \text{load resistance, } R_L = V_{dc}/P_i \]

\[ C_i = C_1 = C_2 \]

The permitted \( \eta \) across the capacitor is 10 % of the capacitor voltage and hence the \( C_i \) is selected as 0.47 (nearest possible value).

**DC Link Capacitor \( (C_d) \) design**

The value of DC link capacitor is calculated as given in (10) [11], \( k \) is the permitted ripple in the dc link voltage.

\[ U_{dc} = \frac{k_{dc}}{20\mu F} = \frac{(V_{dc})^2}{20\mu F} \]  

(10)

\[ C_d = \frac{U_{dc}V_{dc}}{20\mu F} = \frac{1}{20\mu F} \]  

(11)

\[ C_d = \frac{175}{76} \approx 4372 \mu F \]

The DC link capacitor with a nearest possible value of 4700\( \mu F \) is selected for this application.

**Filter parameters \( (L_f \text{ and } C_f) \) design**

The higher order harmonics in the supply side is avoided by a low pass filter, the required capacitance and inductance values are calculated with (12) and (13) [36]. The \( L_f \) is designed consider the source impedance.

\[ C_{min} = \frac{I_{in}}{\omega_k V_{dc}} = \frac{P_{dc}/V_{dc}}{\omega_k (V_{dc})} \]  

(12)

\[ C_{min} = \frac{(220V/220V)}{20\mu F} \approx 0.6277 \mu F \]

\[ L_f = \frac{L_{eq}+L_p}{2} = \frac{1}{4} \]  

(13)

\[ L_{eq} = \frac{1}{47^2 \times (220V)(220V)2000X20} \approx 0.05 \]  

\[ L_{eq} = 15.493 \Phi H \]

\[ f_c \rightarrow \text{cutoff frequency. } \]

\[ f_s \rightarrow \text{switching frequency} \]

the (possible) values of \( L_f \) and \( C_f \) are selected as 15 mH and 820 nF from the derived values.

**Control of BL-CSC converter fed BLDC motor drive**

The control of the drives is done in two stages, one at the front-end converter to control the dc link voltage (voltage follower approach) and the other for the electronic commutation (PWM control of VSI) for driving the motor.

**Design of controller for Converter**

The figure 8 shows the controller for the converter which has four major blocks, reference voltage generator, error voltage generator, PI controller and PWM generator.

![Figure 8 Control of BL-CSC converter.](image-url)
Sw1 and Sw2 represent the gate signals to converter switches Sw1 and Sw2 respectively.

**Controller for VSI to fed BLDC Motor**

The electronic commutation of the BLDC motor is achieved by sensing the rotor position using the hall effect position sensor. Three hall effect sensors (Ha, Hb, Hc) are placed on the rotor in a span of 60°. Based on the rotor position, the switching of the VSI is done as in table 2. The figure 9 shows conduction of two switched S1 and S4. The switching is done in such way, at point of time only switches are ON, energizing any two phases of the motor. This enables proper rotation and rotation in the correct direction.

### Table 2 Switching states based on hall effect position signals.

<table>
<thead>
<tr>
<th>θ(°)</th>
<th>Hall Signals</th>
<th>Switching States</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0 – 60</td>
<td>0</td>
<td>0</td>
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<tr>
<td>60 – 120</td>
<td>0</td>
<td>0</td>
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<tr>
<td>120 – 180</td>
<td>0</td>
<td>0</td>
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<tr>
<td>180 – 240</td>
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<td>0</td>
</tr>
<tr>
<td>240 – 300</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>300 – 360</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>NA</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

### V. Simulation of BL CSC fed BLDC drive

**Simulink model**

The Simulink model of the CSC converter fed brushless DC motor drive is given in Figure 10. The functional parameters the back emf, stator current and speed of the of the motor along with the DC link voltage of the converter are observed and presented in the figures 11 to 14 respectively.

![Figure 9 Conduction states of switches S1 and S4](image)

![Table 2 Switching states based on hall effect position signals.](table)

![Figure 10 Simulink model of BL-CSC fed BLDC drive](image)

![Figure 11 Stator back emf of CSC fed BLDC motor](image)

![Figure 12 Stator current of CSC fed BLDC motor](image)

![Figure 13 Speed Characteristics of CSC fed BLDC drive](image)

![Figure 14 DC link voltage of CSC converter](image)

**Steady state response**

The model is simulated with rated load torque with a dc link voltage of 200 V and 100 V, the corresponding speed and dc link voltage is given in Figure 15 and 16. Figure 17 gives speed characteristics of the model with 50 % of the rated load torque and a dc link voltage of 200 V. The time domain analysis in terms of integral square error, integral absolute error, integral time square error and integral time absolute error are obtained for the dc link.
voltage of the converter and speed of the motor in addition to ripple factor and are tabulated in Table 3 and Table 4.

Table 3 Summary of errors and ripple factor of \( V_{dc} \) of CSC

<table>
<thead>
<tr>
<th>S. No</th>
<th>DC link Voltage (V)</th>
<th>Load</th>
<th>IAE</th>
<th>ITAE</th>
<th>Ripple factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>Full load</td>
<td>1.75</td>
<td>0.141</td>
<td>0.0268</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>½ load</td>
<td>20.9</td>
<td>12.6</td>
<td>0.0817</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>Full load</td>
<td>0.60</td>
<td>0.680</td>
<td>0.0212</td>
</tr>
</tbody>
</table>

Table 4 Summary of errors and ripple factor of BLDC motor’s speed

<table>
<thead>
<tr>
<th>S. No</th>
<th>DC link Voltage (V)</th>
<th>Load</th>
<th>IAE</th>
<th>ITAE</th>
<th>Ripple factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>Full load</td>
<td>20.75</td>
<td>1.598</td>
<td>0.1853</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>½ load</td>
<td>10.75</td>
<td>0.923</td>
<td>0.1792</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>Full load</td>
<td>45.32</td>
<td>6.564</td>
<td>0.6065</td>
</tr>
</tbody>
</table>

Figure 15 DC link voltage at 200 V and Speed of BLDC motor at rated load torque

**Dynamic response**

The dynamic response of the system by varying dc link voltage and load torque are shown in figures 18 and Figure 19 respectively. The dc link voltage is initially set to \( V_{dc} (=200\,\mathrm{V}) \), around 0.5 second it is decreased to 50 % of \( V_{dc} (=100\,\mathrm{V}) \) and again around 0.8 second the voltage is raised to its \( V_{dc} (=200\,\mathrm{V}) \), the corresponding back emf, stator current and speed are given in Figure 18. Likewise initially the load torque is set to 50 % of the rated torque (0.75 Nm) and around 0.52 second it is increased to 100 % of the rated load torque (1.5 Nm), the corresponding back emf, stator current and speed are given in Figure 19. It is observed that the system settles quickly after the change in both the cases.

Figure 16 DC link voltage at 100 V and Speed of BLDC motor at rated load torque

Figure 17 DC link voltage at 200 V and Speed of BLDC motor at 50 % rated load torque

Figure 18 DC link variation of CSC converter fed BLDC motor
VI. Landsman converter fed BLDC motor drive

Similar to CSC converter, Landsman converter also has variable dc link voltage. In landsman converter the input side inductor ($L_{i1}$, $L_{i2}$) current is discontinuous, while the voltage across the capacitor ($C_1$, $C_2$) and the current in the output side inductor ($L_{o1}$, $L_{o2}$) are continuous for any switching cycle.

VII. Operation during complete switching period

The BL-Landsman converter is designed to operate in DICM such that current in inductor's $L_{i1}$ and $L_{i2}$ becomes discontinuous for a switching period by switching the corresponding switch for positive and negative half cycles of supply voltage. Figures 21 to 23 show different modes of operation during a positive half cycle of supply voltage.

Mode P1: The switch $S_{w1}$ is turned ON and the energy out of the supply along with the energy stored in the intermittent capacitor $C_1$ is transported to input inductor $L_{i1}$. The output inductor $L_{o1}$ starts settling and voltage of intermediary capacitor $v_{C1}$ starts reducing while an input inductor current $i_{L_{i1}}$ and dc voltage $V_{dc}$ start increasing. Calculated value of intermittent capacitance is adequate to retain suitable energy such that a continuous voltage is available throughout the operation.

For negative half cycle, the sequence of operation is similar to positive half cycle's mode 1, 2 and 3 where the inductors $L_{i2}$, $L_{o2}$ and capacitor $C_2$ operates instead of $L_{i1}$, $L_{o1}$ and $C_1$ respectively.

VIII. BL-Landsman converter design

As the Landsman converter is modified CSC converter and the modification is addition of an output inductor, converter given in CSC converter can be adopted for the converter's input inductor, intermittent capacitor and filter L-C values. Design of output inductor is given below.

Design of output Inductors

The value of the output inductors $L_{o1}$ and $L_{o2}$ for functioning in continuous conduction mode are determined considering the ripple current in the inductors [17] as given in (18).

\[
L_{o1} = L_{o2} = \left(\frac{V_{dc}}{\Delta i_{L_{o}}}\right) = \frac{1}{\Delta i_{L_{o}}} \left(\frac{V_{dc}}{V_{dc} + V_s}\right)
\]

The allowed peak ripple current in the inductor occurs at rated $V_{dc}$ for minimum $V_s$. Hence, the output inductor value is determined at maximum value of DC output with minimal input voltage.

\[
L_{o1} = L_{o2} = \left(\frac{V_{dc}}{\Delta i_{L_{o}}}\right) = \frac{1}{\Delta i_{L_{o}}} \left(\frac{V_{dc}}{V_{dc} + V_s}\right)
\]
The control of the BL-CSC converter can be adopted for Landsman converter fed BLDC motor, since it is modified from it.

IX. Simulation of Landsman converter fed BLDC drive

The Simulink model of the Landsman converter fed brushless DC motor drive is given in Figure 24, the functional parameters such as back emf, stator current speed of the motor and DC link voltage of the converter are observed and presented in the figures 25 to 28.

![Simulink model of BL-Landsman fed BLDC drive](image)

Figure 24 Simulink model of BL-Landsman fed BLDC drive

![Stator back emf of Landsman converter fed BLDC motor](image)

Figure 25 Stator back emf of Landsman converter fed BLDC motor

![Stator current of Landsman converter fed BLDC motor](image)

Figure 26 Stator current of Landsman converter fed BLDC motor

Steady state response

The model is simulated with rated load torque with a dc link voltage of 200 V and 100 V, the corresponding speed and dc link voltage is given in Figure 29 and 30 respectively. Figure 31 gives speed characteristics of the model with 50% of the rated load torque and a dc link voltage of 200 V. The time domain analysis in terms of integral square error, integral absolute error, integral time square error and integral time absolute error are obtained for the dc link voltage of the converter and speed of the motor in addition to ripple factor and are tabulated in Table 5 and Table 6 respectively.

![DC link voltage at 200 V and Speed of BLDC motor at rated load torque](image)

Figure 29 DC link voltage at 200 V and Speed of BLDC motor at rated load torque

![Speed Characteristics of Landsman converter fed BLDC drive](image)

Figure 27 Speed Characteristics of Landsman converter fed BLDC drive

![DC link voltage of CSC converter](image)

Figure 28 DC link voltage of CSC converter

![Steady state response](image)
Dynamic response

The dynamic response of the system by varying dc link voltage and load torque are shown in figures 32 and Figure 33 respectively.

The dc link voltage is initially set to \( V_{dc} (= 200 \text{ V}) \), around 0.4 second it is decreased to 50 % of \( V_{dc} (=100 \text{ V}) \) and again around 0.8 second the voltage is raised to its \( V_{dc} (= 200\text{V}) \). The corresponding back emf, stator current and speed are given in Figure 32. Likewise initially the load torque is set to 50 % of the rated torque (0.75 Nm) and around 0.4 second it is increased to 100 % of the rated load torque (1.5 Nm), the corresponding back emf, stator current and speed are given in Figure 33. It is observed that the system settles quickly after the change in both the cases.
Table 8 Comparison of errors and ripple factor of BLDC motor's speed

<table>
<thead>
<tr>
<th>S. No</th>
<th>Converter</th>
<th>DC link Voltage (V)</th>
<th>Load</th>
<th>IAE</th>
<th>ITAE</th>
<th>Ripple factor</th>
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<tr>
<td>1</td>
<td>CSC</td>
<td>200</td>
<td>Full load</td>
<td>39.8</td>
<td>2.648</td>
<td>0.2159</td>
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<tr>
<td>2</td>
<td>Landsman</td>
<td>200</td>
<td>Full load</td>
<td>20.75</td>
<td>1.598</td>
<td>0.1853</td>
</tr>
<tr>
<td>3</td>
<td>CSC</td>
<td>200</td>
<td>½ load</td>
<td>36.1</td>
<td>8.003</td>
<td>0.7805</td>
</tr>
<tr>
<td>4</td>
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<td>10.75</td>
<td>0.923</td>
<td>0.1792</td>
</tr>
<tr>
<td>5</td>
<td>CSC</td>
<td>100</td>
<td>Full load</td>
<td>21.2</td>
<td>1.421</td>
<td>0.1943</td>
</tr>
<tr>
<td>6</td>
<td>Landsman</td>
<td>100</td>
<td>Full load</td>
<td>45.32</td>
<td>6.564</td>
<td>0.6065</td>
</tr>
</tbody>
</table>

X. Conclusion

The analysis of canonical switching cell converter and landsman converter reveals that both the converters render appreciable performance in steady state and dynamic condition. The performance betterment is measure in terms of integral time absolute error and ripple factor of the dc link voltage and motor speed at converter output and drive accordingly. The analysis and comparison showcase that landsman converter fed BLDC drive have reduced error and ripple factor at converter output and in motor speed. This leads to conclude, Landsman converter fed BLDC drive offers better performance for different load conditions and speeds.

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Author Bibliography

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