Control and Power Quality Improvement of BLDC Motor using BL-CSC Converter

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Abstract

This paper presents a power quality improvement of brushless dc (BLDC) motor using bridgeless canonical switching cell converter. Single voltage sensor is used to achieve unity power factor at ac mains where the proposed BL-CSC converter is operating in discontinuous inductor current mode. Single voltage sensor is used for dual objectives of voltage control as well as speed control. Moreover, the proposed bridgeless configuration is designed for reducing conduction losses due to partial elimination of DBR (diode bridge rectifier) at the front end. Power quality improvement isanalysedat ac mains as per PQ standard IEC 61000-3-2 for a wide range of speed control and supply voltages.

Keywords—*Power Factor, THD, Brushless DC Motor, IEC 61000-3-2.*

I. INTRODUCTION

In the last decade BRUSHLESS DC (BLDC) motor drives have gained importance due to power quality improvements[1] that have also resulted in exceptionalperformancecompared with other conventional drives. High efficiency, high reliablity, high ruggedness, low electromagnetic interference (EMI) problems, and good performance over a wide range of speed control[2],[3]are the advantages of this motor that have made popular in the industry. Medical equipment,position actuators, ventilation and air conditioning are the applications of the bldc motor[4]–[7]. Mainly BLDC motors are synchronous motors having three phase windings on the stator and permanent magnets on the rotor. Position of the rotor is sensed by the Hall-effect sensors. Electronic commutation[8]eliminates the problems such as noise,sparking and electromagnetic interference.A high value of dc link capacitor is connected in between diode bridge rectifier(DBR) and voltage source inverter(VSI)[9]. This combination results in high total harmonic distortion(THD) of supply current (as high as 65%)and low power factor(as low as 0.72) at the input ac mains IEC 6100-3-2[10].Such configurations of single stage power conversion with and without isolation have been reported in the literature[11], [12].Normally these converters have less number of components thus the losses which are very low. Cost of the system mainly depends upon the requirement of sensors

The converter operating in continuous conduction mode using current multiplier approach which offers low stress on the switch but it requires three sensors. In discontinuous conduction mode, voltage follower approach is used, where a single voltage sensor is used in the converter for improving power quality.

Many configurations have been reported in the literature for power factor correction converters based BLDC drive fed by three phase VSI. This topology is used for high power applications but the control circuit is very complex. Ozturk[13]and Wu andTzou[14] have proposed PFC based boost converter for feeding BLDC motor drive. Cheng [15] has used an active rectifier based BLDC motor drive. This configuration uses PWM based VSI for speed control and constant dc link voltage is maintained. This system offers high switching losses in six solid state switches used for voltage source inverter. Lee [16] has explored the possibilities of various reduced part configurations for PFC operation which also uses a PWM-based VSI and therefore has highswitching losses in it. Barkley [17]has proposed a buck converter operation as a front end converter for feeding a BLDC drive. This also offers high switching losses. The concept of variable dc link voltage for speed control which reduces the switching losses. Electronic commutation is required to operate VSI in low switching frequency.

Bridgeless CUK PFC converters[18] have gained importance due to low conduction losses at front end. Partial or complete elimination of diode bridge rectifier will reduce the conduction losses. A bridgeless boost and buck converters affected from limited voltage ratio. Hence wide range of voltage control is not possible. A novel bridgeless buck-boost converter[19] has been proposed to overcome the existing topology. It contains three switches thus the switching losses are very high. Atwo switch bridgeless buck–boost PFC converter [20] is proposed, which has low losses. Higher order PFC bridgeless Cuk, SEPIC and Zeta converters have been widely used but have a high number of components, However, no attention has been paid to the canonical switching cell converter, although it has excellent performance as a power factor pre regulator, a small component count (compared with the non-isolated cuk converter), and good light load regulation.

Fig 1 shows the existing diode bridge rectifier canonical switching cell converter fed BLDC motor drive. It contains the switch (S_{w1}), an intermediate capacitor (C_1) and diode(D) , inductor (L_i) and dc link capacitor (C_d).The proposed work develops a bridgeless topology of a canonical switching cell converter while reducing the conduction losses by partial elimination of diode bridge rectifier (DBR) at the front end

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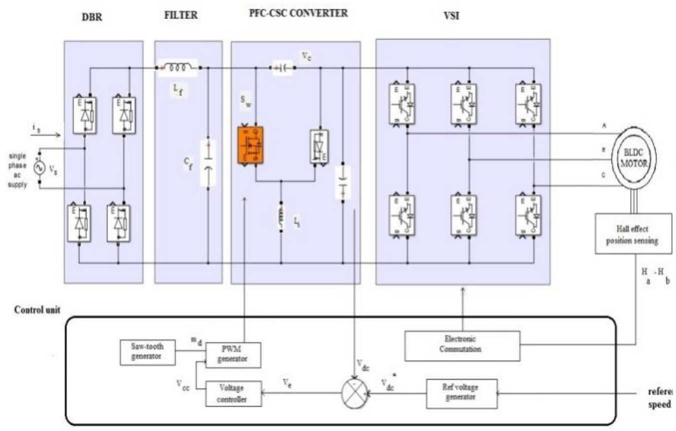

Fig.1. Conventional PFC-Based DBR- CSC Converter

This configuration fed BLDC motor drive is suitable for low-power application with low cost.

II. BL-CSC CONVERTER FED BLDC MOTOR DRIVE

The proposed BL-CSC-converter-based VSI fed BLDC motor drive is shown in fig.2

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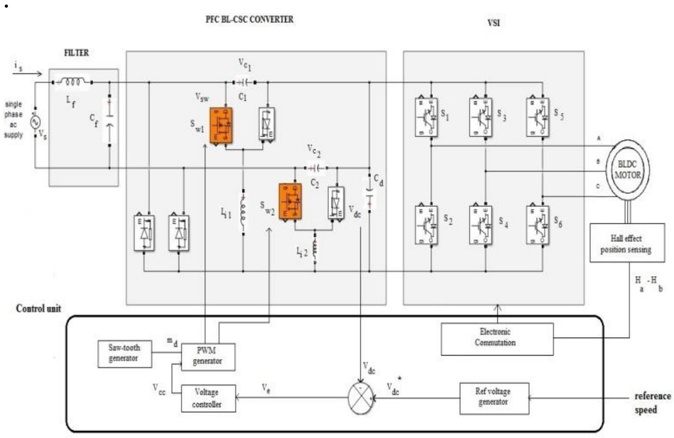

Fig.2. BL-CSC Converter-fed BLDC Motor Drive

Partial elimination of DBR in this BL-CSC converter will reduce the conduction losses. This converter is operated in DICM (discontinuous inductor current mode) and the current through the inductors L_{i1} and L_{i2} are continuous and the intermediate capacitor's voltages C_1 and C_2 are continuous. Speed control of the BLDC motor is done by varying the dc link voltage. Switching losses in the VSI fed BLDC drive is reduced by using electronic commutation. This bridgeless topology has least number of conducting devices and less number of components during each half-cycle of the supply voltage. The operation, design, and control of this BL-CSC converter fed BLDC motor drive is explained in the following sections.

III. OPERATING PRINCIPLE OF BL-CSC CONVERTER

A. *Operation in Positive and Negative Half-Cycles of Supply*

The positive and negative half-cycles of the supply voltages are operated by the switches (s_{w1}) and (s_{w2}) respectively. The input current flows through switch(s_{w1}) inductor L_{i1} and a fast recovery diode (D_2) for the positive cycle of the supply voltage as shown in Fig. 3(a)-(c).Similarly, for the negative cycle of the supply voltage, switch (s_{w2}), inductor (L_{i2}) and a diode D_2 as shown in Fig. 3(d)-(f).

1) *Mode I: (Inductor Charging)*

When switch1 (s_{w1}) is triggered, the input inductor charges through the diode(D) . Now the current (L_i) increases and the capacitor discharges through the switch to charge the dc-link capacitor (C_d). As thedc-link voltage increases, the voltage across the intermediate capacitor(V_{c1})decreases. The mode is shown in Fig. 3(a)

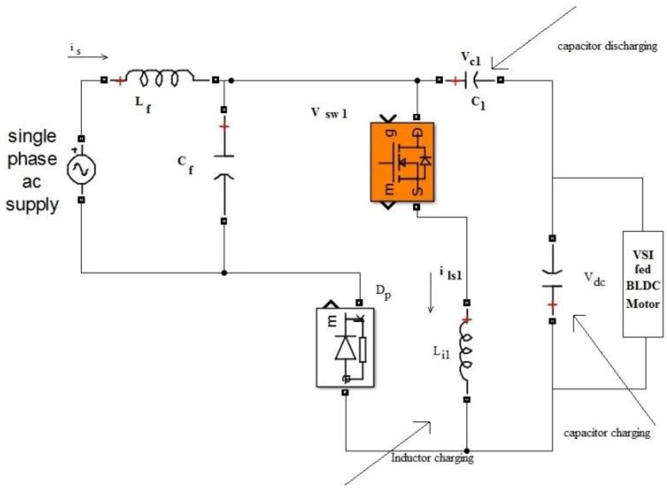

Fig 3(a)Mode I

2) *Mode II: (Inductor Discharging)*

When the switch S_{w1} is triggered off, the energy in the inductor is discharged through dc link capacitor and diode.Now the current i_{Li1}decreases and the voltage across the capacitors(C_1) and (C_d) increases, thereby charging theintermediate capacitor C_1.The mode is shown in Fig. 3(b)

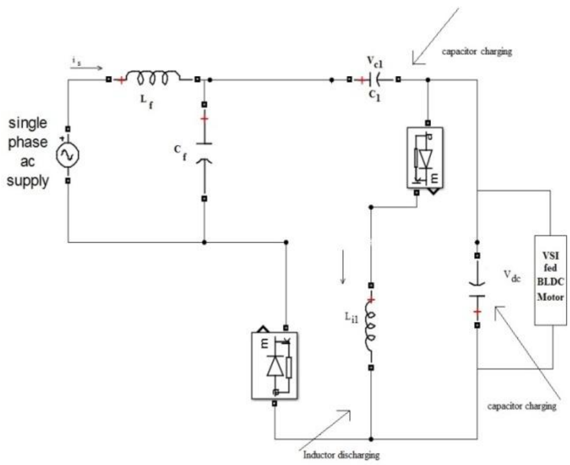

Fig 3(b)Mode II

3) Mode III: (DCM Mode of Operation)

In this mode of operation, the inductor current is completely discharged to zero, whereas, the intermediate capacitor C_1 Retains its energy, and the dc link capacitor C_d supplies energy to the load. The mode is shown in Fig. 3(c)

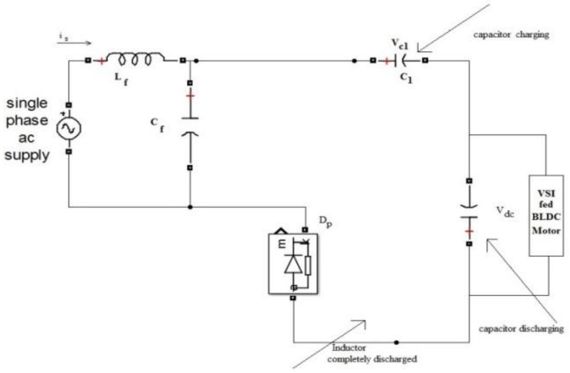

Fig 3(c) Mode III

For the negative half-cycle of the supply voltage, the inductor (L_{i2}), intermediate capacitor (C_2) and diodes (D_n) and (D_2) conduct and the same modes of operation repeats their respective modes of operations are shown in Fig.3 (d)-(f)

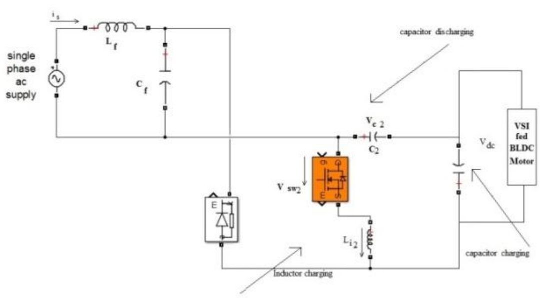

Fig 3(d) Mode IV

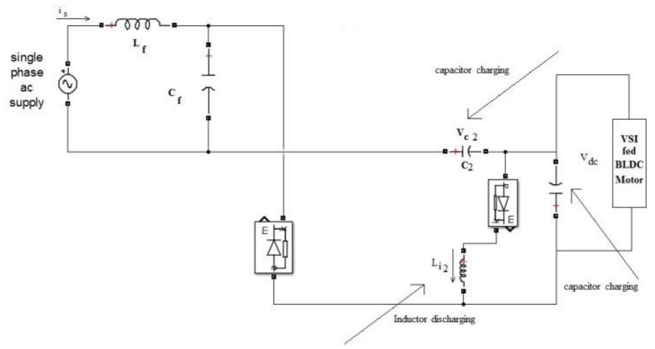

Fig 3(e) Mode V

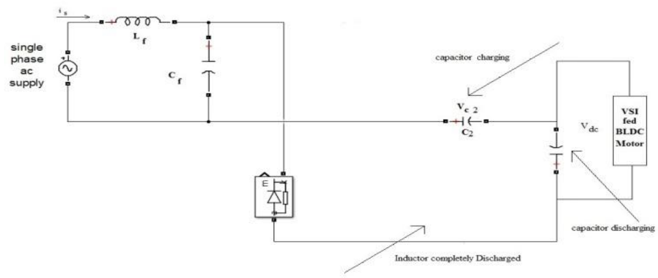

Fig 3(f) Mode VI

Fig.3. Different modes of operation of the proposed BL-CSC converter (a) Mode I (b) Mode II (c) Mode III (d) Mode IV (e) Mode V (f) Mode VI

IV. CONTROL OF THE BL-CSC CONVERTER FED BLDC MOTOR DRIVE

The main control strategies involved in the PFC based BL-CSC converter fed BLDC motor drive is control offront-end PFC converter.

A. Control of Front-end PFC-Converter:

1) Voltage Follower Approach:

The control of BLDC motor in DICM can be done using voltage follower approach which requires a single voltage sensor to control the dc link voltage, which in turns, controls the speed of the BLDC motor and attain an inherent PFC at ac mains.

The block diagram for the control of dc link voltage is shown in Fig. 4. It consists of a 'reference voltage generator', 'voltage error generator', 'voltage controller'and a PWM generator.

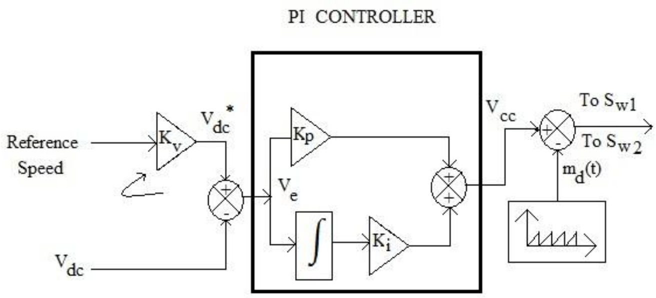

Fig.4 Control of the BL-CSC Converter Feeding BLDC Motor Drive.

A reference voltage generator generates a reference voltage (V_{dc}^*) by multiplying the reference speed (ω∗) with the motor's voltage constant (K_V) as

$$V_{dc}^* = K_V\ \omega^* \quad -(1)$$

The voltage error generator generates an error voltage V_e (k) by comparing the reference dc link voltage (V_{dc}^*) with the sensed dc link voltage (V_{dc}), and is given by equation (2)

$$V_e\ (k) = V_{dc}^*(k) - V_{dc}(k) \quad -(2)$$

Where k represents the kth sampling instance.

A controlled output voltage is generated by giving the error voltage to a voltage proportional integral (PI) controller, and is given by equation (3)

$$V_{CC}(k) = V_{CC}(k-1) + K_P\{V_e\ (k) - V_e\ (k-1)\} + K_i\ V_e\ (k) - (3)$$

Where K_p and K_i are the proportional and integral gains of the PI controller, respectively.

The output of PI controller (V_{CC}) and high-frequency saw tooth signal (m_d) are compared and the PWM signals are generated, which is given by equation (4)

$$\text{For } V_S > 0; \begin{Bmatrix} if\ m_d < V_{CC}\ then\ S_{w1} = \text{ON} \\ if\ m_d \geq V_{CC}\ then\ S_{w1} = \text{OFF} \end{Bmatrix}$$

$$\text{For } V_S < 0; \begin{Bmatrix} if\ m_d < V_{CC}\ then\ S_{w2} = \text{ON} \\ if\ m_d \geq V_{CC}\ then\ S_{w2} = \text{OFF} \end{Bmatrix} \quad -(4)$$

Where the gate signals to the PFC switches are S_{w1} and S_{w2}

V. RESULTS AND DISCUSSION

The proposed drive is modeled in MATLAB/Simulink environment and the performance is validated. Test results are discussed below which shows a satisfactory performance of the BLDC drive

A. *Steady-State Performance*

The drive is operated at rated conditions with 110V supply voltage as shown in figure 5.1(a) and 5.2(a)and dc link voltages (310V and 70V) as shown in figure 5.1(c) and 5.2(c). The test results are shown in Fig. 5.1 and 5.2 which demonstrates a wide range of speed control of BLDC motor.

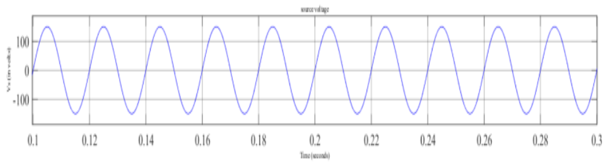

Fig 5.1(a) Source Voltage

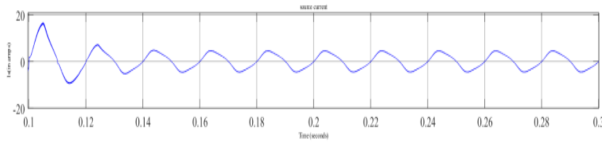

Fig 5.1 (b) Source Current

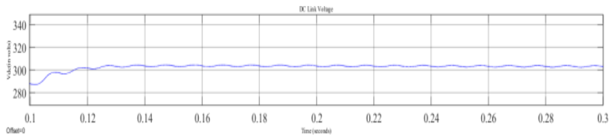

Fig 5.1 (c) dc link voltage

Fig.5.1. Performance of the Proposed Drive at Rated Condition with Supply Voltage as 110 V and Dc Link Voltage as 310 V

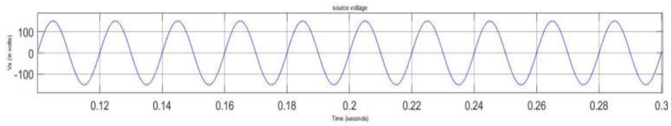

Fig 5.2(a) Source Voltage

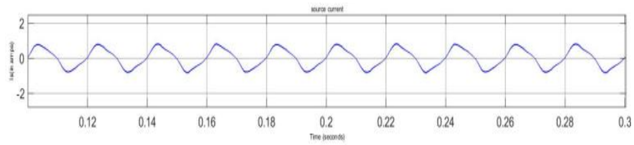

Fig 5.2 (b) Source Current

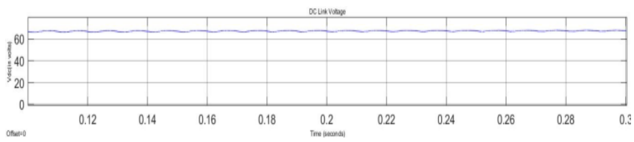

Fig 5.2 (c) DC Link Voltage

Fig.5.2. Performance of the Proposed Drive at Rated Condition with Supply Voltage as 220 V and dc Link Voltage as 70 V

Almost a near unity power factor is achieved at bothdc link voltages which are indicated by the supply current as shown in figure 5.1(b) and 5.2(b) in phase with the supply voltage.

B. *Dynamic Performance*

At different supply voltages and dc link voltages, the dynamic performance of the drive is validated and the results are shown in Fig: (5.3 to 5.5).Starting of dc link voltage from (0 to 70V) as shown in figure5.3(c) with supply voltage of 110v in fig 5.3(a) indicates a limited supply current in fig 5.3(b).and finally motor runs at the speed of 590rpm as shown in figure 5.3(d).

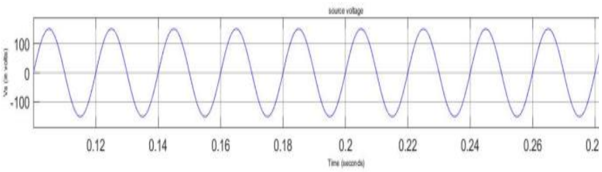

Fig: 5.3(A) Source Voltage

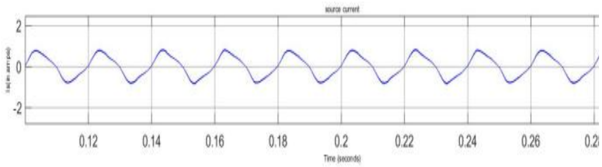

Fig: 5.3(B) Source Current

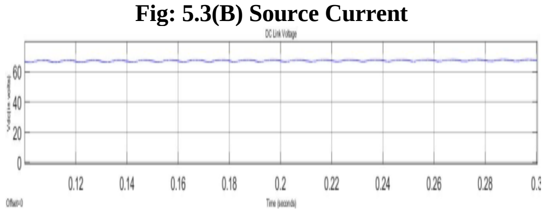

Fig: 5.3(C) Dc Link Voltage

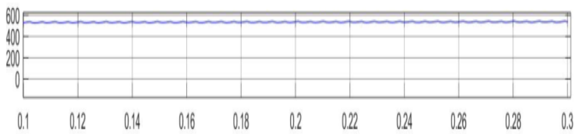

Fig: 5.3(d) Rotor Speed

Fig.5.3. Simulated Dynamic Performance of the Proposed Drive at Rated Load on the BLDC Motor Starting at V_{dc} =70 V

A step change in dc link voltage from 100V to 170Vis shown in figure 5.4(c).Simultaneously rotor speed changes from 890rpm to 1630 rpm is shown in figure 5.4(d) and a limited overshoot in supply current is shown in figure 5.4(b) which in turn proves the smooth control of the BLDC motor.

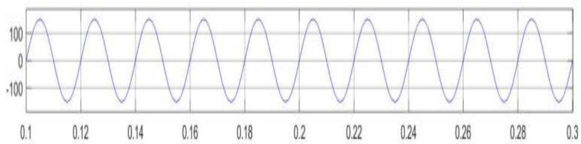

Fig: 5.4(A) Source Voltage

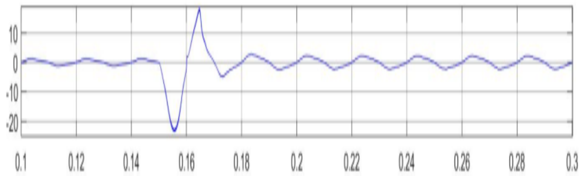

Fig: 5.4(B) Source Current

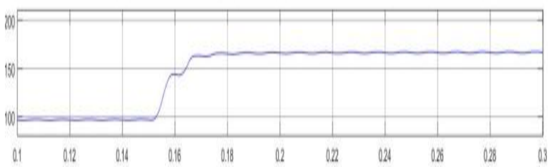

Fig: 5.4(C) Dc Link Voltage

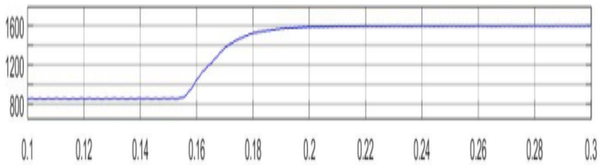

Fig: 5.4(D) Rotor Speed

Fig.5.4. Simulated Dynamic Performance of the Proposed Drive at Rated Load on the BLDC Motor Speed Control during Change in dc Link Voltage from 100 to 170 V

A step change in supply voltage from 110V to 70v is shown in figure 5.5(a), where the dc link voltage and speed of the motor reduces and comes back to its original position as shown in figure 5.5(c) and 5.5(d). Hence constant dc link voltage proves a satisfactory closed-loop performance of the drive

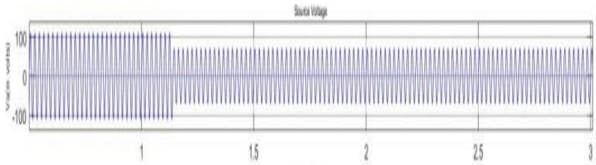

Fig: 5.5(A) Source Voltage

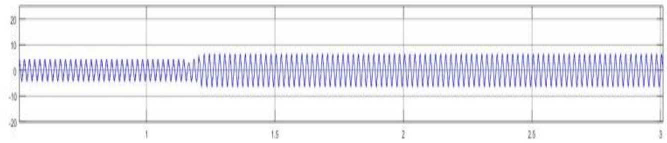

Fig: 5.5(B) Source Current

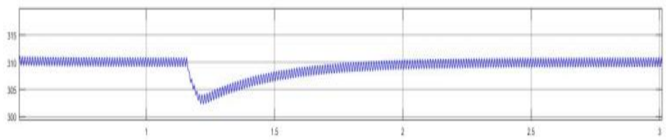

Fig: 5.5(C) Dc Link Voltage

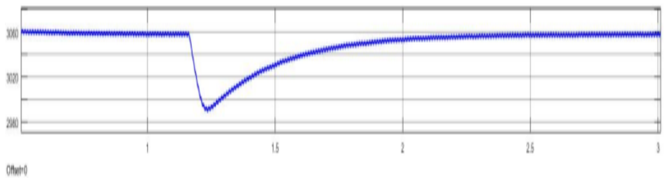

Fig: 5.5(D) Rotor Speed

Fig.5.5. Simulated Dynamic Performance of the Proposed Drive at Rated Load on the BLDC Motor During Sudden Change in Supply Voltage From 110 To 70 V

C. PFC and Improved Power Quality at AC Mains

The harmonic spectrum which is a power quality index is measured and is shown in Fig: 5.6 (a) – (c) at different values of the dc link voltages and supply voltages.The THD is measured for the supply current at ac mains. Figure 5.6(a) shows THD of 3.29 % , where starting the dc link voltage at 70 V with supply voltage of 110V. Figure 5.6(b) shows THD of 6.01 % , where starting the dc link voltage at

300 V with supply voltage 110V.Figure 5.6(c) shows THD of 2.93 % , where starting the dc link voltage at 300 V with supply voltage of 70V. In all cases almost unity power factor and the low THD at ac mains indicates an improved power quality operation which are within the limits of IEC 61000-3-2.

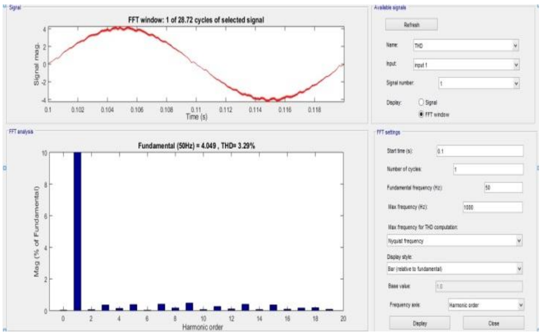

Fig.5.6 (a)V_{dc} = 300 V, V_S = 110 V

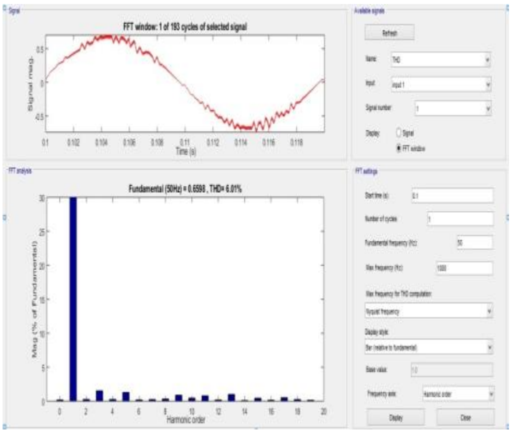

Fig.5.6 (b) V_{dc} =70 V, V_S =110 V

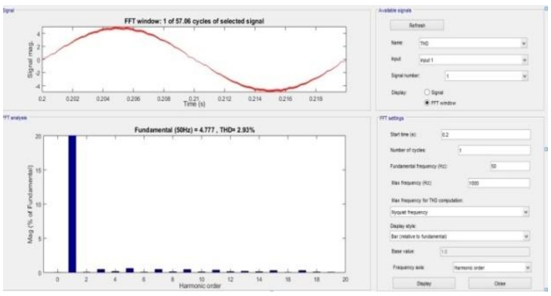

Fig.5.6(c)V_{dc} =300 V,V_S =70 V.

Fig.5.6. Simulated Power Quality Indices of the Proposed Drive at Rated Load on the BLDC Motor for (a) V_{dc} = 300 V, V_S = 110 V; (b) V_{dc} =70 V, V_S =110 V; and (c) V_{dc} =300 V,V_S =70 V.

VI. CONCLUSION

A PFC Based BL-CSC converter fed BLDC motor with improved power quality at ac mains has been proposed. By controlling the DC link voltage, the speed of the BLDC motor can be controlled. The drive has the below advantages:

- The bridgeless configuration at the front-end provides reduced conduction losses at the PFC converter.
- A single voltage sensor has been used for a wide range of speed control, supply voltage and PFC at ac mains.
- Electronic commutation at fundamental switching frequency reduces the switching losses at VSI.
- The power quality indices are within the limits of IEC 61000-3-2 thereby providing a satisfactory performance of the drive. It is best suited for low-power applications.

APPENDIX

BLDC MOTOR RATING

No of poles	4
Prated (Rated Power)	424.11 W (0.5 HP)
(Rated DC Link Voltage)	310 V
T rated (Rated Torque)	1.35 N- m
N rated (Rated Speed)	3000 rpm
Kb (Back EMF Constant)	78 V/k rpm
Kt (Torque Constant)	0.74 Nm/A
Rph (Phase Resistance)	14.56 Ω
Lph (Phase Inductance)	25.71 mH
J (Moment of Inertia)	1.3 × 10−4 Nm/s^2

Table 1 Specifications of BLDC Motor

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