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PFC of VSI Based Bridgeless Canonical Switching Cell Converter Fed BLDC Motor Drive

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ABSTRACT

This paper determines the Power Factor Correction (PFC) of Voltage Source Inverter (VSI) based Bridgeless Canonical Switching Cell (BL-CSC) converter fed Brushless DC (BLDC) motor drive. The BL-CSC converter will be operated in Discontinuous Inductor Current Mode (DICM) that will help to achieve unity power factor at ac mains by using voltage sensor. The speed control of BLDC motor is proposed by controlling the voltage at dc bus of VSI. For the reduction of switching losses, BLDC motor is electronically commutated such that voltage source inverter will be operating at fundamental frequency. The bridgeless topology of the Canonical Switching Cell (CSC) converter is designed for obtaining the low conduction losses due to partial elimination of DBR. Thus the proposed converter configuration efficiency is better than the conventional type. The performance of the proposed configuration improves power factor at ac mains by varying the wide range of speeds.

Keywords: Brushless DC (BLDC) motor drive, Bridgeless Canonical Switching Cell (BL-CSC) converter, Voltage Source Inverter (VSI), Power Factor Correction (PFC).

I. INTRODUCTION

Brushless dc (BLDC) motor drives are becoming popular in low and medium power applications because of its high efficiency, high torque, high reliability, high ruggedness, high energy density, low electromagnetic interference (EMI) problems, low maintenance requirement, and excellent performance over wide range of speed control [1], [2]. It has major applications in robotics, industrial tools, air conditioning, ventilation, medical equipment, heating, position actuators, transportation, motion control and also in household appliances like washing machines, fans, refrigerators, water pumps, etc [3-7]. The rotor of the BLDC motor is made of permanent magnet, thus it acts like synchronous motor and the stator of the BLDC motor is made of three phase windings. For elimination of the EMI, sparking noise and maintenance problems, Electronic commutation is done for rotor by sensing its position through Hall sensors [8].

A Power factor corrected (PFC) converter is usually used in this topology to improve the power quality at the ac mains. As if normal converters are used instead of PFC converters, it results in high supply across the dc link capacitor and also it leads to poor power factor that which cannot be encouraged by International power standards. Already regarding this so many surveys has been published, all of the results are same [9], [10].

Basically, the power factor converters are operated in two modes, they are Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM). These are the two modes which are widely used in theoretical and practical. Cost is the primary factor and it depends on which mode of operation to be used for PFC Converter. If the PFC converter operates in Continuous Conduction Mode (CCM), a single current multiplier is needed and it offers low stress on the converter for that three sensors which are to be

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utilized. Whereas, if the PFC converter is used in discontinuous conduction mode (DCM), a single voltage multiplier is needed at ac mains to measure the power factor across the ac main supply.

There are many converters aside of Canonical Switching Cell converter. They are cuk converter, buck converter, boost converter, buck-boost converter and sepic converter etc. In this, there are two configurations like conventional and bridgeless configurations. Preference of the bridgeless configuration is very high when compared to the conventional type of converters. Many surveys has been published, the results of which resembles the same [11-20]. Because in conventional type, the diode bridge rectifier is used and due to this conduction losses will be increased. But in bridgeless configuration, the diode bridge rectifier is partially eliminated and conduction losses will be reduced. The power factor also varies when the converter configuration changes.

Chapter 2 describes the proposed converter i.e., BL-CSC converter. Designing of converter is discussed in chapter-3, 4 and the results obtained through the simulation and hardware are discussed in the chapter 5.

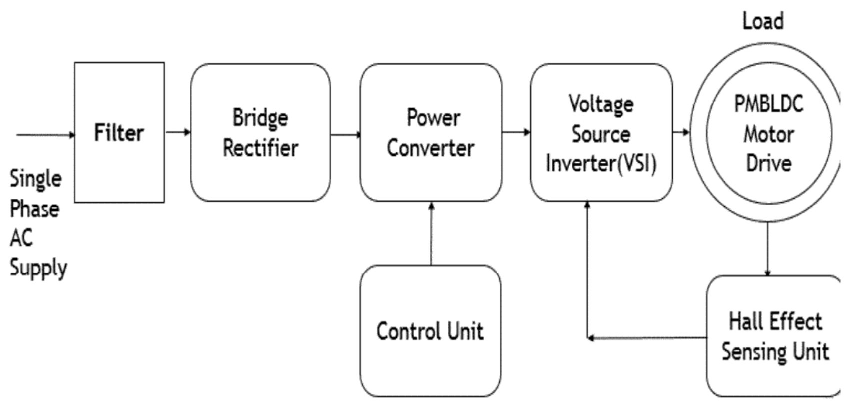

Figure 1: Block Diagram of PFC of VSI based BL-CSC Converter fed BLDC Motor

II. BL-CSC CONVERTER

This bridgeless converter is used instead of a conventional converter due to its low conduction losses. The switching losses are reduced by the variable dc link voltage so that it can control the dc link voltage. Therefore, by utilizingVSI at low frequencyas for the requirement of the electronic commutation of the BLDC motor, there will be reduction in switching losses.

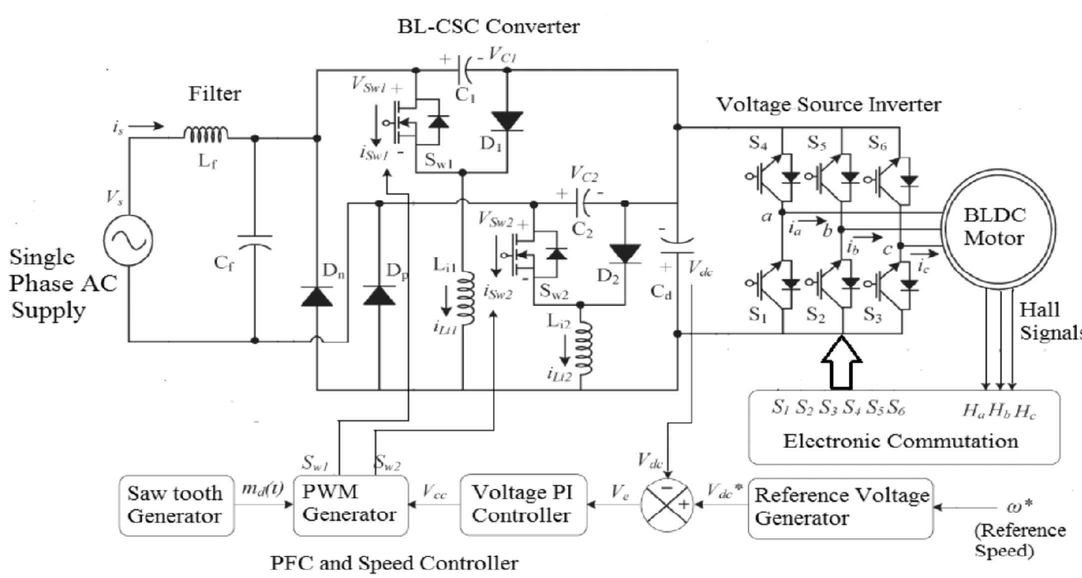

Figure 2: Proposed Bridgeless CSC Converter-fed BLDC Motor Drive

Due to partial elimination of the diode bridge rectifier in the circuit, bridgeless converter can reduce the conduction losses at the front end [21] – [24].

The canonical switching cell (CSC) converter is nothing but a combination of a diode, switch and a capacitor. With proper design parameters it can act as a very good PFC converter. For this, diode bridge rectifier and dc filter are used for better performance. Normally, the CSC converter is known for itsexcellent performance as power factor pre-regulator and good load regulation.

The bridgeless configuration results in harmonic elimination at the front end of the DBR and reduces the conduction losses.

Basically, the MOSFET is used for the BL-CSC converter for its high frequency switching and IGBT is used for the three phase VSI for its low frequency switching.

III. DESIGN OF PFC BL-CSC CONVERTER FOR THE BLDC MOTOR DRIVE

Bridgeless Canonical Switching Cell (BL-CSC) converter is operated in discontinuous conduction mode and the design values are calculated using the following formulas [25].

The Average input voltage at the ac mains is

$$V_{in} = \frac{2\sqrt{2}V_S}{\pi} \tag{1}$$

The Duty Ratio D is determined by the input voltage and the dc output voltage of the converter is

$$D(t) = \frac{V_{dc}}{V_{in}(t)+V_{dc}} = \frac{V_{dc}}{|V_m\, Sin(\omega t)|+V_{dc}} \tag{2}$$

The Instantaneous Power

$$P_i = \left(\frac{P_{\max}}{V_{dc\max}}\right)V_{dc} \tag{3}$$

Where,

$V_{dc\,max}$ = Maximum dc link voltage, Volts.

P_{max} = Rated power of the PFC converter, watts.

Critical input inductance

$$L_{ic} = \frac{V_{in}(t)\,D(t)}{2I_{in}(t)\,f_s} = \frac{R_{in}D(t)}{2\,f_s} = \left(\frac{V_s^2}{P_i}\right)\frac{D(t)}{2\,f_s} \tag{4}$$

Where,

R_{in} = Input resistance, ohms.

f_s = Switching frequency, Hz.

P_i = Instantaneous power, watts.

Minimum Critical value of input inductance

$$L_{ic\min} = \left(\frac{V_{s\min}^2}{P_{\max}}\right)\frac{D(t)}{2\,f_s} \tag{5}$$

Intermediate Capacitances

$$C_1 = C_2 = \frac{V_{dc} D(t)}{\Delta V_C(t)\, f_s R_L} \tag{6}$$

$$C_1 = C_2 = \frac{V_{dc\max}\, D(t)}{\eta\{\sqrt{2}\, V_{s\max}(t) + V_{dc}\}\, f_S R_L} \tag{7}$$

Where,

η = Ripple voltage across C_1 and C_2

The ripple voltage across the capacitors C_1 and C_2 (η) is taken as 10% of V_{dc}.

V_C = Intermediate capacitor's voltage, volts.

R_L = Load resistance, ohms.

$$R_L = \frac{V_{dc}^2}{P_i}$$

DC link Capacitance

$$C_d = \frac{I_{dc}}{2\omega \Delta V_{dc}} = \left(\frac{P_i}{V_{dc}}\right) \frac{1}{2\omega k V_{dc}} \tag{8}$$

$$C_d = \left(\frac{P_{\min}}{V_{dc\min}}\right) \frac{1}{2\omega\, \Delta V_{dc\,\min}} \tag{9}$$

Where,

k = Ripple in dc link voltage.

Filter Capacitance

$$C_f = \frac{I_m}{V_m\, w_L} \tan(\theta) \tag{10}$$

Filter inductance

$$L_f = \frac{1}{4\pi^2 f_c^2 C_f} - 0.05 \left(\frac{1}{W_L}\right)\left(\frac{V_S^2}{P_o}\right) \tag{11}$$

Where,

f_c = Cut-off frequency, which is selected such that

$f_L < f_c < f_S$.

Therefore, f_c is taken as $f_S/10$.

The Switching sequence from Table 1 will be decided based upon the position of the rotor. Fig.8 represents the hall signals and commutation used in the simulation circuit.

Table I
Switching Sequences of the VSI

Θ (in degrees)	*Switching States*					
	S_1	S_2	S_3	S_4	S_5	S_6
0-60	1	0	0	0	0	1
60-120	0	1	1	0	0	0
120-180	0	0	1	0	0	1
180-240	0	0	0	1	1	0
240-300	1	0	0	1	0	0
300-360	0	1	0	0	1	0

IV. PROTOTYPE SPECIFICATIONS

- AC Input Voltage V_S = 20V, 50HZ
- Input Current I_S = 5A
- Output Voltage V_{dc} = 40V
- Switching Frequency f_s = 10KHZ
- Duty Ratio D = 58.57%
- Load Resistance R_L = 1.2Ω
- Capacitances C_f = 38.54μF, 30V

$C_1 = C_2$ = 1.1μF, 100V

C_d = 1000μF, 100V

- Inductances L_f = 164.44μH, 5A

L_{i1} = L_{i2} ==192.07μH, 5A

- Motor Ratings – 100W, 24V

V. RESULTS AND DISCUSSION

(A) Simulation Results

In open loop system, there is a change in output voltage when the duty ratio of change in the switches. For maintaining high power factor at ac mains throughout the process, a certain duty cycle is selected in open loop system which got high power factor. Using that duty ratio, a controller is designed to maintain that duty ratio constant. Therefore, closed loop system is designed for the power factor of 0.9 at ac mains.

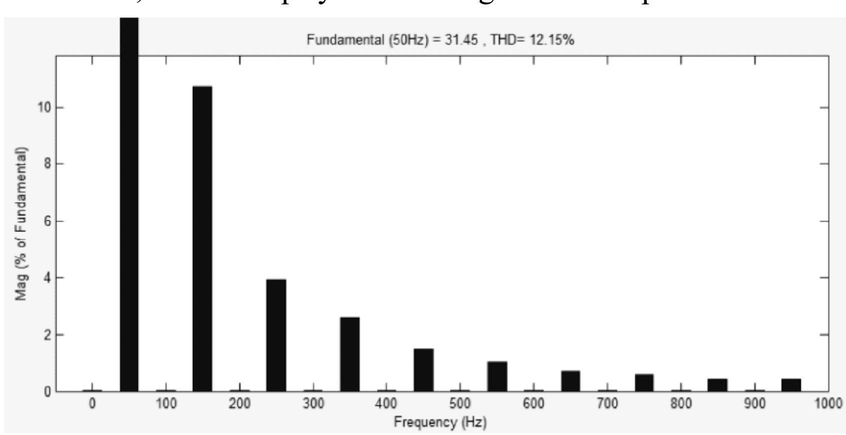

Figure 3: THD of Source Current

Thus from the simulation results, the Total Harmonic Distortion (THD) obtained as 12.5% as shown in the figure 3. The power factor across the ac mains is 0.9 and the switching sequence chosen is 0-60 degrees for commutation purpose of the BLDC motor.

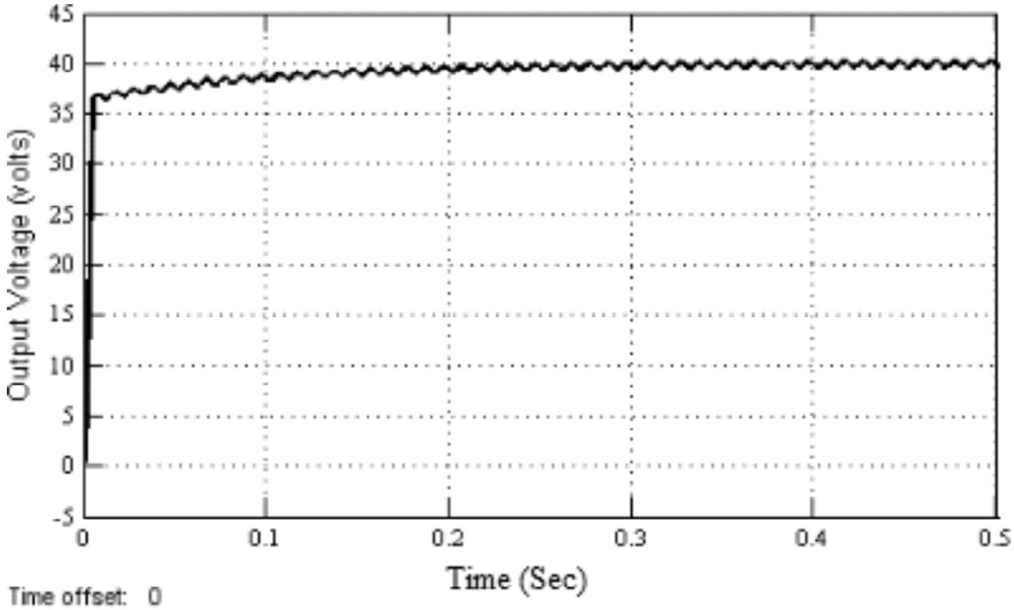

Figure 4: Output voltage of the Converter

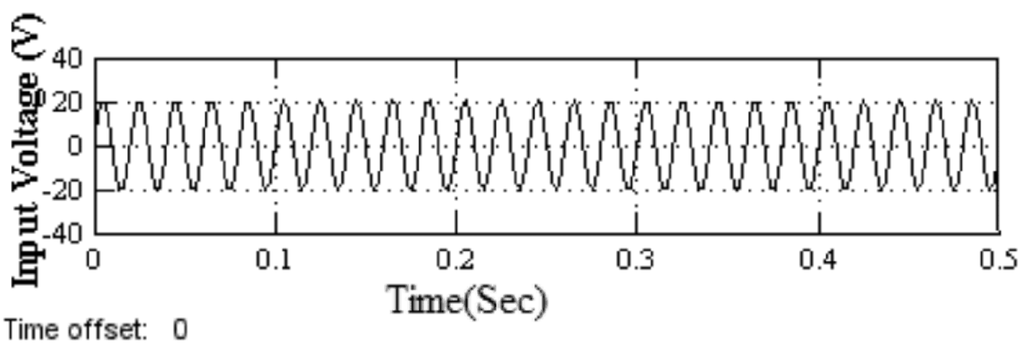

Figure 5: Input Voltage of Converter

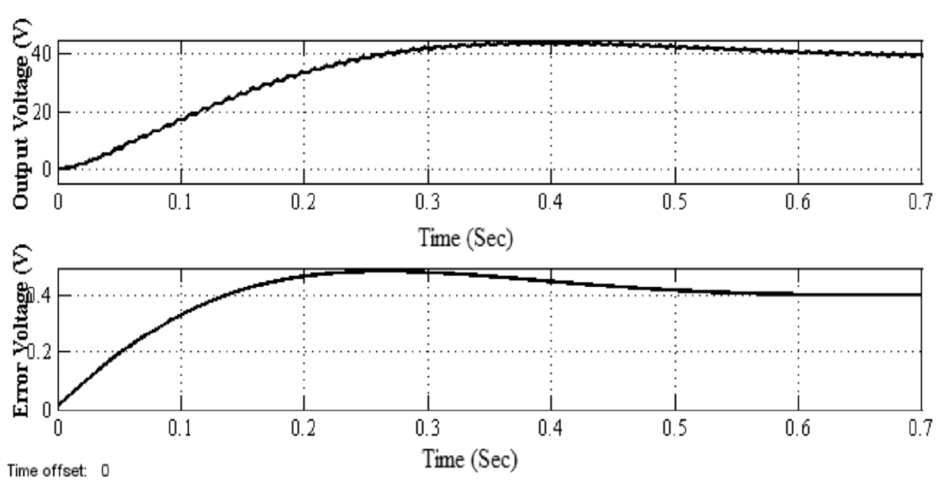

Figure 6: Closed loop output of the Converter

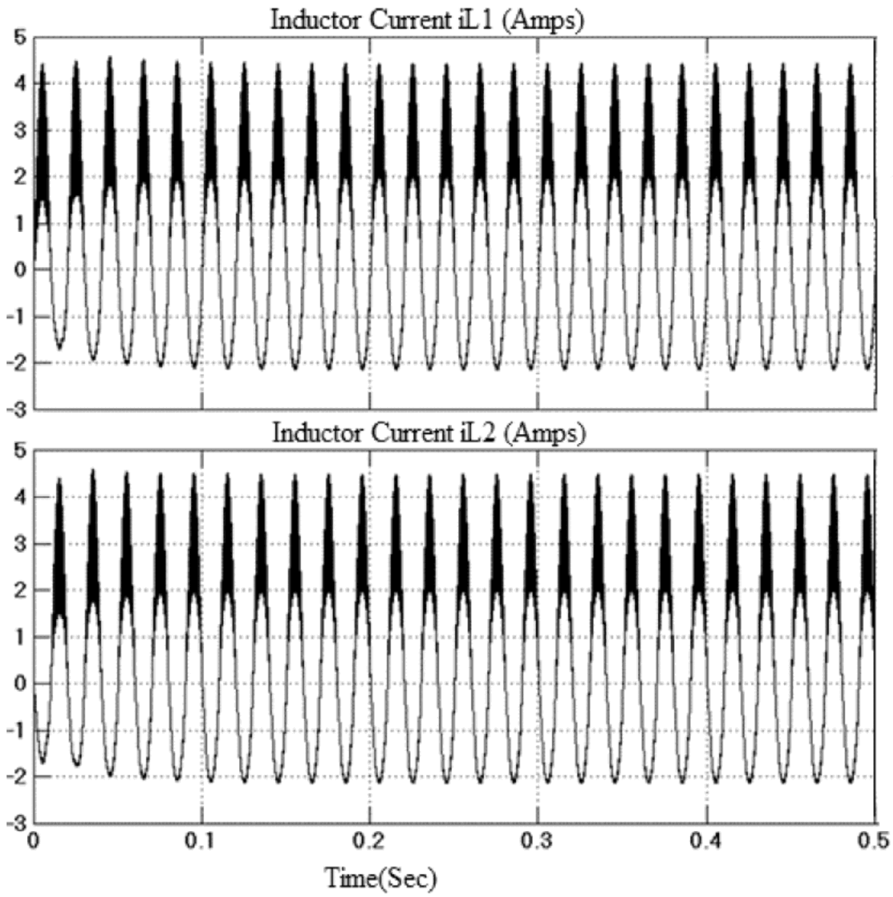

Figure 7: Inductor Currents in Converter

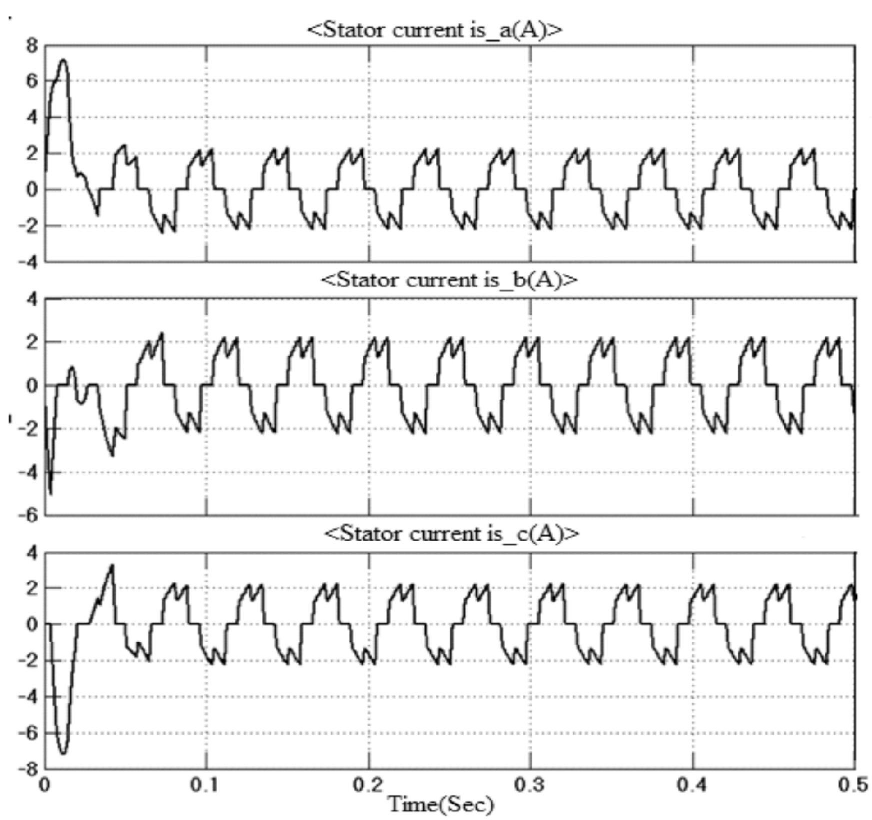

Figure 8: Hall signals and Back EMF of the BLDC Motor

Fig. 4 represents the open loop output voltage of the proposed converter. For the input voltage of 20 V as shown in fig 5, the output voltage obtained is 40V as per the designed calculations.

Fig. 6 represents the closed loop output of the proposed converter. In this, PI controller is used for closed loop and thus the output obtained is 40V constant with settling time is 0.5sec. Thus the power factor across the ac mains is increased to 0.95.

Fig. 7 represents the two inductor currents of the BL-CSC converter i.e. 4A.

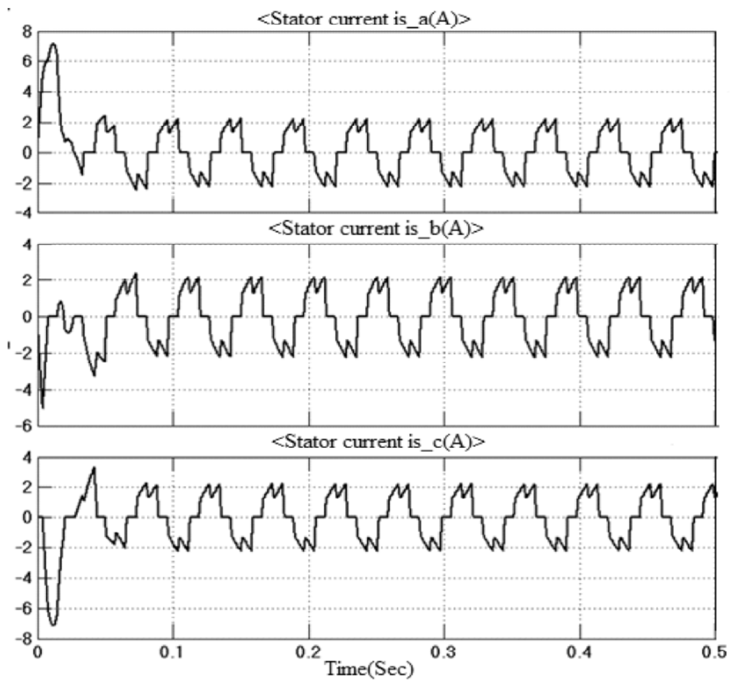

Figure 9: Stator Currents of three phases in BLDC Motor

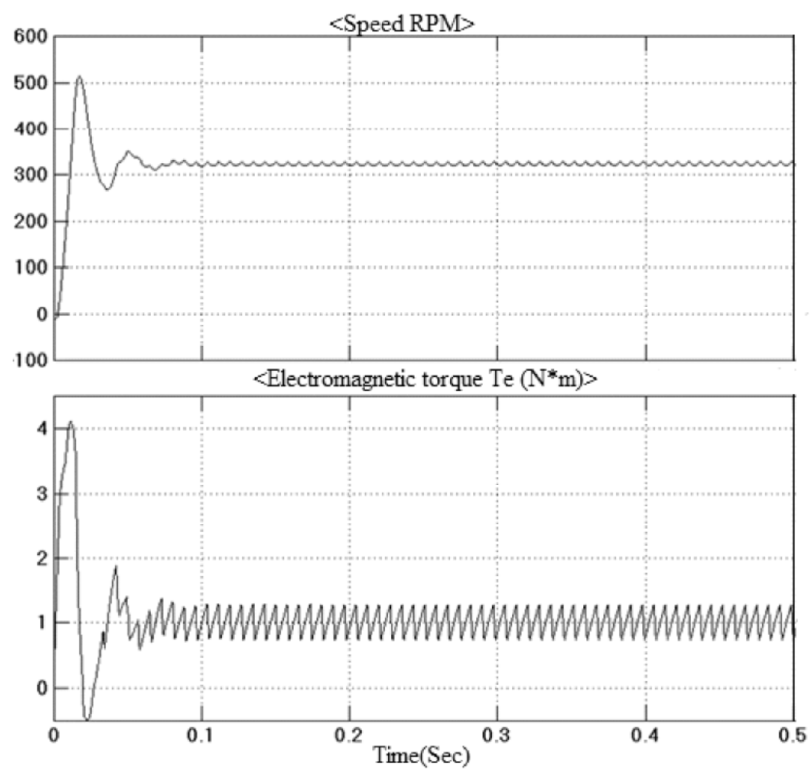

Figure 10: Speed and Electromagnetic Torque of BLDC Motor

From Fig 8, Fig 9 and Fig 10, the BLDC motor results are as follows: Back EMF- 18V, Stator Current – 2Amps, Speed – 350 rpm, and torque- 1.2 N-m.

In Fig 10, there is a sudden peak due to inrush current in the motor. But in running condition, the speed and torque is constant because of high starting torque in dc motor.

(B) Hardware Results

Design of prototype converter has been built and implemented for the designed values.Ratings of the related parameters are selected according to the designed specifications.

Driver circuit is also developed for the switches to generate pulses. Relevant experimental results are shown in the Fig-11 to Fig-16. Gate pulse given to the switches for duty cycle of 58.57% and switching frequency of 10 kHz as shown in the Fig-13. For 20V AC input, the output voltage is 39.9V as shown in Fig. 15.

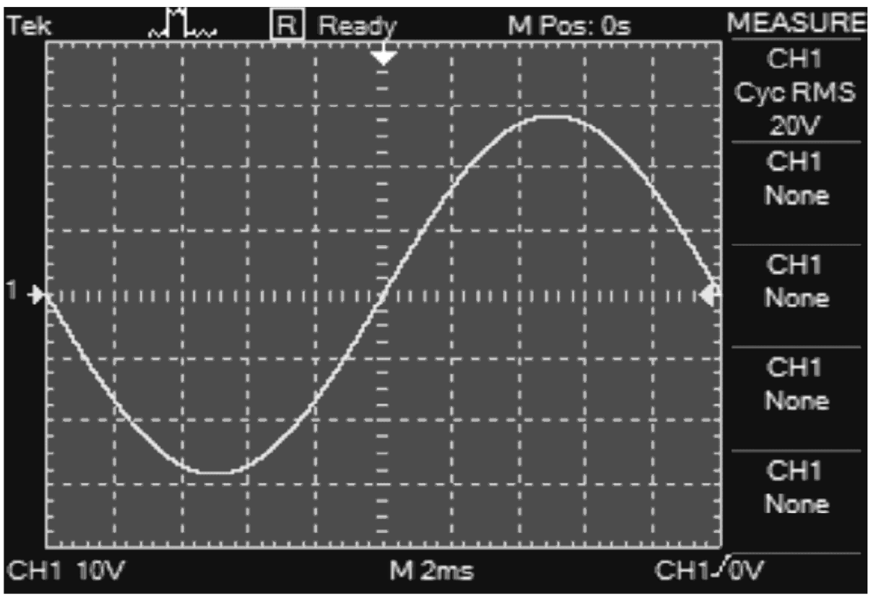

Figure 11: Input Voltage of the Converter

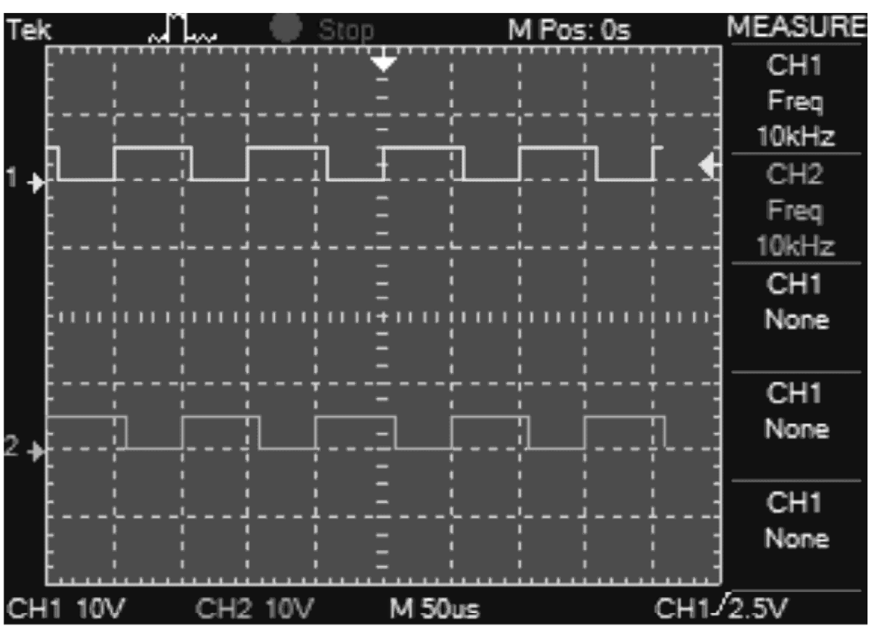

Figure 12: Switching Pulses of the Converter

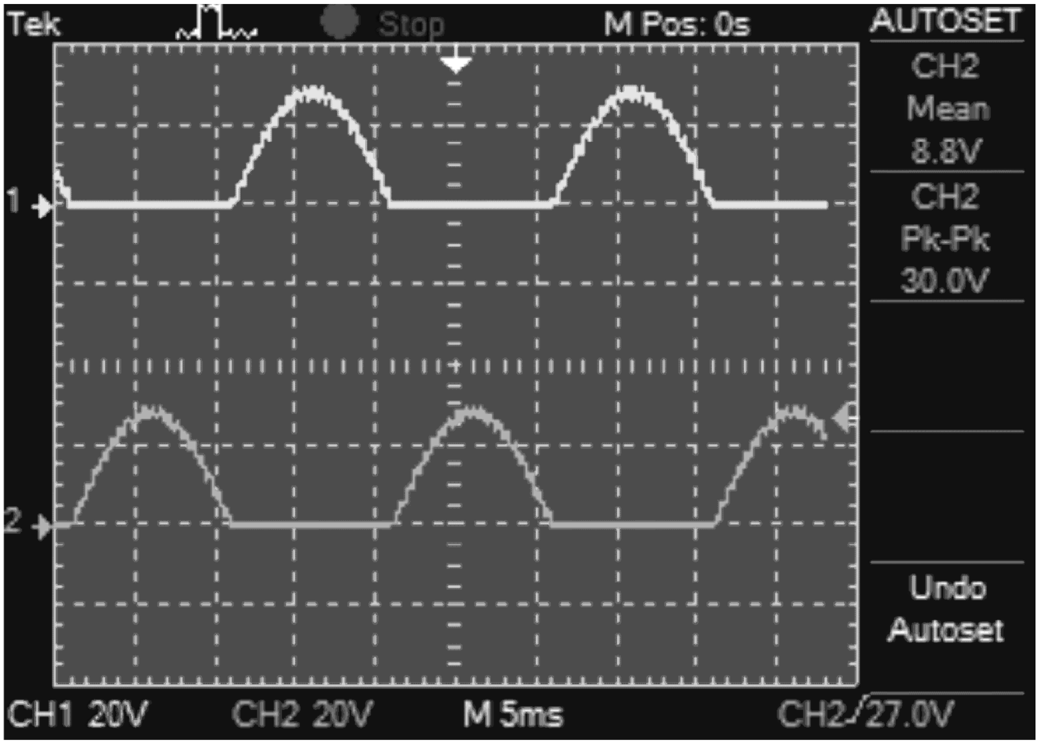

Figure 13: Voltage across both the Switches of the Converter

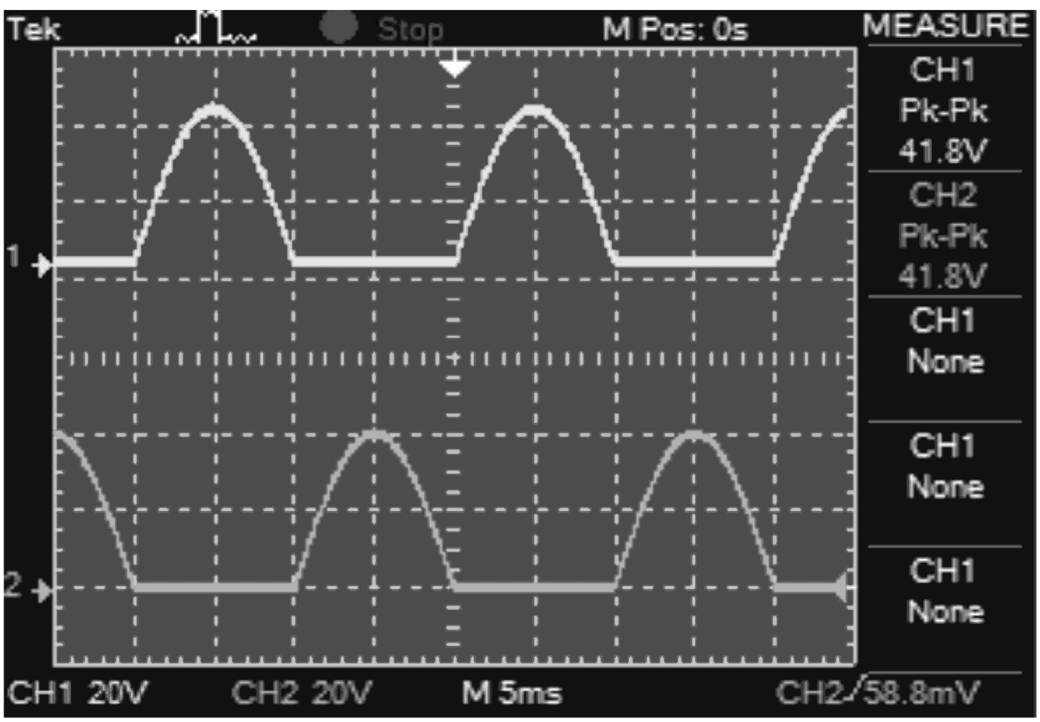

Figure 14: Intermediate capacitance voltages of the Converter

For the input of 20V AC, the voltage across both the switches obtained is 30V as shown in Fig 13. In this, the phase shift between the two switches is 180 degrees. So, both the switches are conducting in different cycles. Likewise, the intermediate capacitor charging and discharging is done in the same way as shown in the Fig 14.

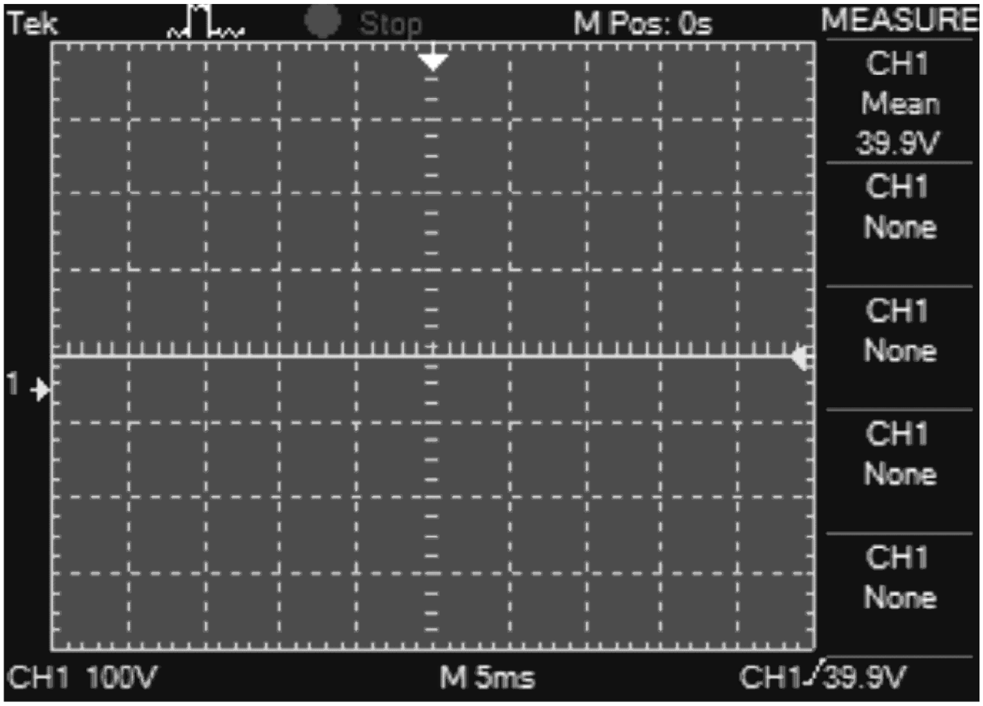

Figure 15: Output Voltage of the Converter

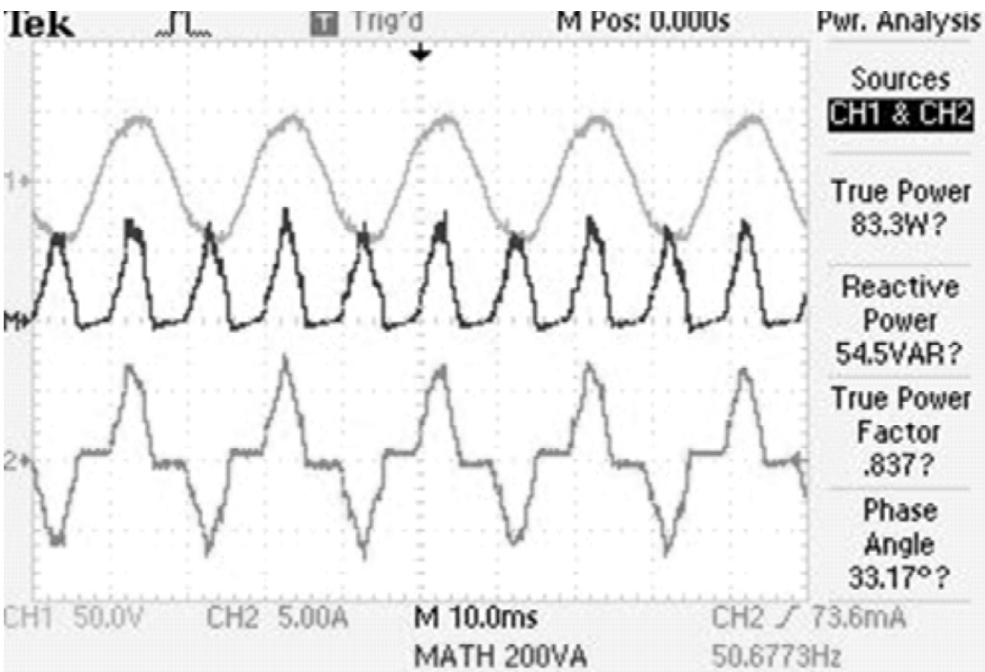

Figure 16: Power factor at the Source Current

In the above figure,the power factor is approximately 0.84, because of the distortions in the supply current.

VI. CONCLUSION

A PFC of VSI based BL-CSC converter fed BLDC motor has been proposed to improve the power quality across mains. Bridgeless configuration is used for reduction of the conduction losses in the converter. The BLDC motor speed is controlled by controlling the voltage of the dc link of the VSI. The power factor is calculated across the front end of the ac supply mains. Thus the proposed system shows improvement in power quality and high power factor across ac mains.

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