

Cuk Converter Fed BLDC Motor with a Sensorless Control Method

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Abstract: Cuk converter fed brushless dc motor (BLDC) drive as a cost-effective solution for low-power applications is presented. The speed of the BLDC motor is controlled by varying the dc-bus voltage of a voltage source inverter (VSI) which uses a low frequency switching of VSI for low switching losses. A diode bridge rectifier followed by a Cuk converter working in a continuous conduction mode (CCM) is used for control of dc-link voltage with unity power factor at ac mains. Performance of the PFC Cuk converter is evaluated under continuous conduction mode of operation. The performance of the proposed system is simulated in a MATLAB/Simulink environment. The simulation of sensorless operation of permanent magnet brushless direct current (BLDC) motor in CCM is simulated and is based on detection of zero crossing from the terminal voltages differences. This method relies on a difference of line voltages measured at the terminals of the motor. This difference of line voltages provides an amplified version of an appropriate back EMF at its zero crossings. The commutation signals are obtained without the motor neutral voltage. The effectiveness of this method is demonstrated through simulation and hardware prototype of the drive is developed to validate its performance.

Keywords: Brushless dc (BLDC) motor, continuous conduction mode (CCM), Cuk converter, discontinuous conduction mode (DCM), sensorless operation, zero crossing.

1. Introduction

Brushless dc (BLDC) motors are recommended for many low and medium power drive applications because of their high efficiency, high flux density per unit volume, low maintenance requirement, low electromagnetic interference (EMI) problems, high ruggedness, and a wide range of speed control [1], [2]. Due to these advantages, they have applications in numerous areas such as household application [3], transportation (hybrid vehicle), aerospace, heating, ventilation and air conditioning [4], motion control and robotics, renewable energy applications etc. The BLDC motor is a three-phase synchronous motor consisting of a stator having a three-phase concentrated windings and a rotor having permanent magnets. It does not have mechanical brushes and commutator assembly; hence, wear and tear of the brushes and sparking issues as in case of conventional dc machines are eliminated in BLDC motor and thus it has low EMI problems.

The conventional scheme of a BLDC motor fed by a diode bridge rectifier (DBR) and a high value of dc-link capacitor draws a non-sinusoidal current, from ac mains which is rich in harmonics such that the THD of supply current is as high as 0.65, which results in PF as low as 0.8 [5]. These types of PQ indices cannot comply with the international PQ standards such as IEC 61000-3-2. Hence, single-phase power factor correction (PFC) converters are used to attain a unity PF at ac mains. These converters have gained attention due to single-stage requirement for dc-link voltage control with unity PF at ac mains. It also has low component count as compared to a multistage converter and therefore offers reduced losses.

Selection of operating mode of the front-end converter is a trade off between the allowed stresses on PFC switch and

cost of the overall system. Continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are the two different modes of operation. Depending on design parameters, either approach may force the converter to operate in the DCM or CCM. In this study, a BLDC motor drive fed by a PFC Cuk converter operates in CCM mode.

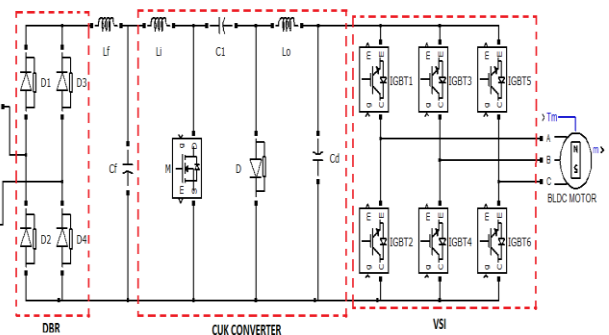


Figure 1: Cuk converter fed BLDC motor

2. Cuk Converter Operation

The operation of the Cuk converter in the CCM is described as follows. Fig. 2 and 3 shows the operation of the Cuk converter in two different intervals [1].

Interval 1: When switch is turned ON, inductor L_i stores energy while capacitor C_1 discharges and transfers its energy to dc-link capacitor C_d . Input inductor current i_{L_i} increases while the voltage across the intermediate capacitor V_{C_1} decreases.

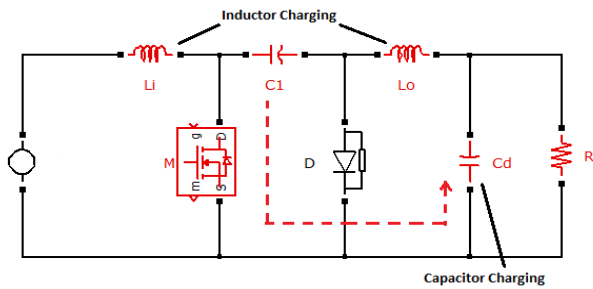


Figure 2: Cuk converter operation in interval 1

Interval 2: When switch is turned OFF, the energy stored in inductor L_o is transferred to dc-link capacitor C_d , and inductor L_i transfers its stored energy to the intermediate capacitor C_1 . The designed values of L_i , L_o , and C_1 are large enough such that a finite amount of energy is always stored in these components in a switching period.

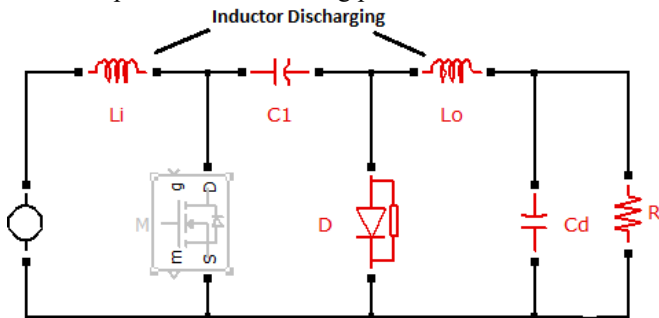


Figure 3: Cuk converter operation in interval 2

3. Sensorless Method

In BLDC motors, only two out of three phases are excited at any time leaving the third winding floating. The back emf in the floating winding can be measured to determine the switching sequence for commutation of power switching devices in the 3 phase inverter. The terminal voltage of the floating winding with respect to the neutral point of motor is needed to get the zero crossing time of the back emf. The sensorless control technique based on Zero Cross Point (ZCP) of the back emf has been widely used for low cost application. The zero crossings of the back EMF are estimated indirectly from the terminal voltages measured with respect to dc negative terminal. The method does not involve any integrations. Further, since line voltages are used, the requirement of neutral potential has been eliminated. This also eliminates the common mode noise. Device drops and their variations would also not play a part since line voltages are used.

Consider a BLDC motor having three stator phase windings connected in star. Permanent magnets are mounted on the rotor. The BLDC motor is driven by a three phase inverter in which the devices are triggered with respect to the rotor position. Consider the interval when phases A and C are conducting and phase B is open [5]. In this interval, phase A winding is connected to the positive terminal of the dc supply, phase C to the negative terminal of the dc supply and phase B is open. Therefore, $i_a = -i_c$ and $i_b = 0$. The back EMF in phases A and C are equal and opposite. Therefore, in that interval V_{abbc} may be simplified as

$$V_{abbc} = V_{ab} - V_{bc} = e_{an} - 2e_{bn} + e_{cn} = -2e_{bn}. \quad (1)$$

The difference of line voltages waveform is thus, an inverted representation of the back EMF waveform. The EMF values would be those in a resistance, inductance, [4] EMF (RLE) representation of the phase (not referred to ground). It may also be noted that the subtraction operation provides a gain of two to the EMF waveform thus amplifying it. It is again evident that during this interval the back EMF e_{bn} transits from one polarity to another crossing zero.

Therefore, the operation $V_{ab} - V_{bc}$ (V_a) enables detection of the zero crossing of the phase B EMF. Similarly, the difference of line voltages V_{bcc} enables the detection of zero crossing of phase C back EMF when phase B and C back EMFs are equal and opposite. The difference of line voltages V_{caa} waveform gives the zero crossing of phase A back EMF where phases C and B have equal and opposite back EMFs. Therefore, the zero crossing instants of the back EMF waveforms may be estimated indirectly from measurements of only the three terminal voltages of the motor.

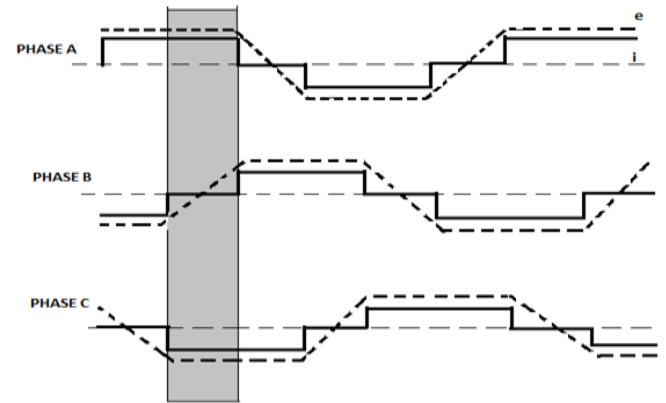


Figure 4: Functional sequence of operation

4. Design of Components

The Cuk converter [1] is designed to operate from a minimum dc voltage of 40 V (V_{dmin}) to a maximum dc-link voltage of 200 V (V_{dmax}). The PFC converter of maximum power rating of 350 W (P_{max}) and the switching frequency is taken as 20 kHz. For a minimum value of dc-link voltage as 40 V, the minimum power is calculated as 70 W.

The value of input inductor to operate in the CCM is decided by the amount of permitted ripple current, where the permitted amount of ripple current (η) is selected as 25% of the input current. The maximum inductor ripple current is obtained under the rated condition, i.e., $V_{dc} = 200$ V for a minimum supply voltage ($V_{smin} = 85$ V). Hence, the input side inductor is designed at the peak value of minimum supply voltage and got the value as 2.57mH.

$$L_{iccm} = \frac{1}{\eta f_s} \left(\frac{V_s^2}{P_{max}} \right) \frac{V_{dc}}{V_{in} + V_{dc}} \quad (2)$$

The value of output inductor to operate in the CCM is decided by the amount of permitted ripple current, where the

permitted amount of ripple current (λ) is selected as 25% of the input current. The maximum current occurs at maximum dc-link voltage (i.e., P_{max}) and the minimum supply voltage of 85 V (i.e., V_{smin}). Got the value as 4.29mH.

$$L_{occm} = \frac{V_s^2}{P_{max}} \frac{V_{dc}}{V_{in} + V_{dc}} \frac{V_{dc}}{V_{in} f_s \lambda} \quad (3)$$

The value of intermediate capacitance to operate in the CCM with a permitted ripple voltage, selected as 10% of the maximum voltage appearing across the intermediate capacitor. The value of intermediate capacitor is calculated at maximum ripple voltage in C_1 which occurs at maximum value of supply voltage (i.e., $V_{smax} = 270$ V) and maximum dc-link voltage and got the value as $0.6\mu F$.

$$C_{1ccm} = \frac{P_{max}}{k f_s (V_{in} + V_{dc})^2} \quad (4)$$

5. MATLAB Simulink Model and Simulation Results

The Simulink model of cuk converter fed BLDC motor using sensorless method is given in figure 5. Single phase input voltage is given. Switching frequency of 20 kHz is selected. First the input is rectified, then filtered and converted to DC using cuk converter. The DC link voltage is given as input to VSI and then to motor. For CCM operation, the values of L_i , C_1 and L_o are 2.5mH, $0.66\mu H$ and 4.3mH. The dc link voltage is made constant by closed loop. By varying the dc link voltage the speed of the motor can be varied.

Voltage follower technique requires a single voltage sensor for controlling the dc-link voltage with a unity PF. Reference voltage is compared with sensed dc-link voltage (V_{dc}) to generate a voltage error (V_e). This voltage error is given to the voltage PI controller to generate a controlled output (V_{cd}). Finally, the controller output is compared with the high frequency saw tooth waveform to generate the PWM signal to be given to PFC converter switch.

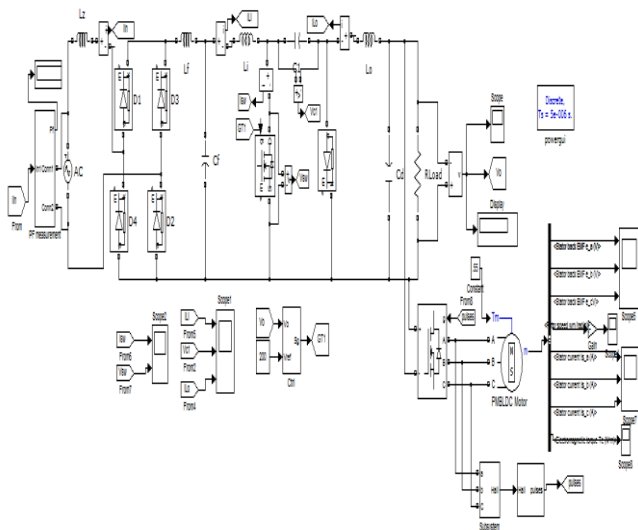


Figure 5: Simulink model of cuk converter fed BLDC motor

Simulation results of cuk converter fed BLDC motor using sensorless method is given below for CCM. The dc link voltage is taken as 200V. The speed is around 1400rpm.

Input voltage given is 220V. Here we got the power factor as 0.995 and its unity.

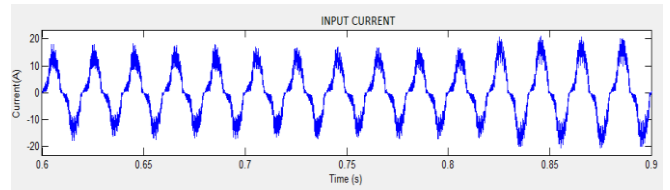


Figure 6: Input current waveform

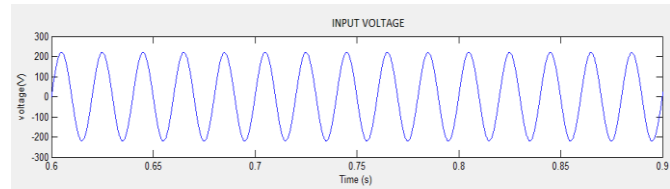


Figure 7: Input voltage waveform

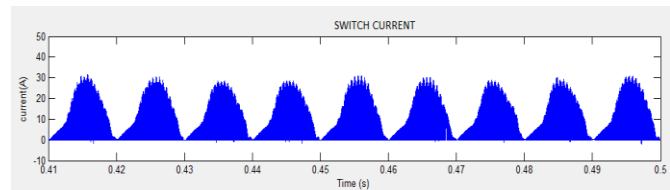


Figure 8: Switch current waveform

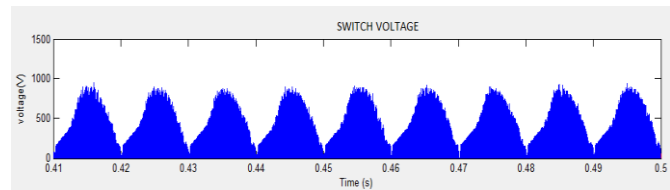


Figure 9: Switch voltage waveform

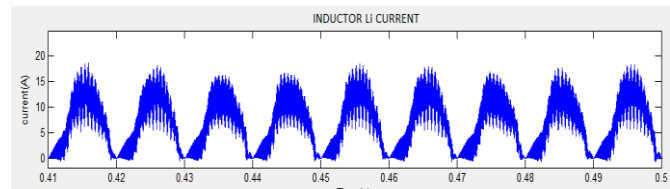


Figure 10: Current through inductor L_i

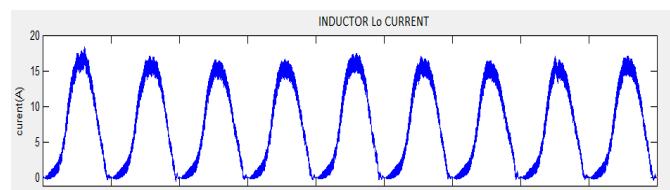


Figure 11: Current through inductor L_o

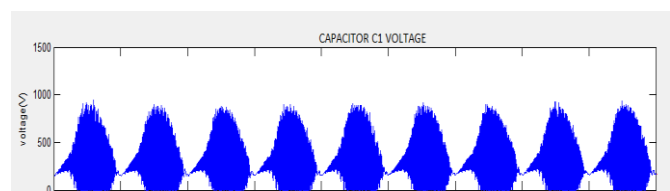


Figure 12: Voltage across capacitor C_1

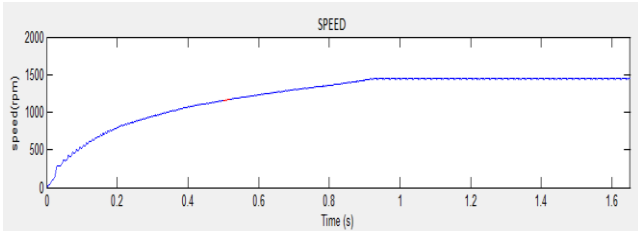


Figure 13: Speed waveform

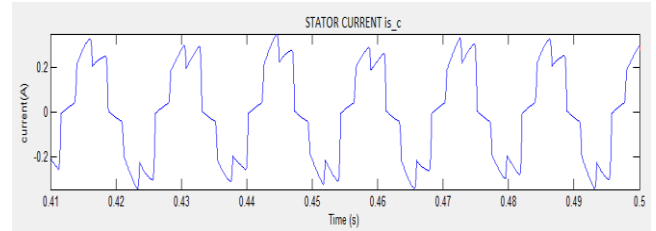


Figure 20: Stator current i_c waveform

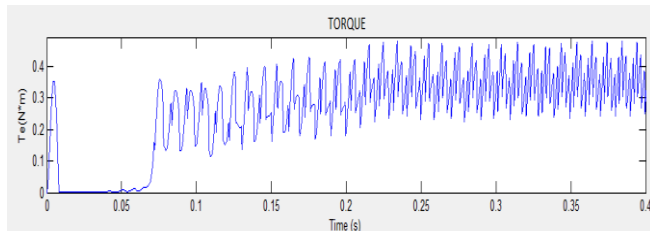


Figure 14: Torque waveform

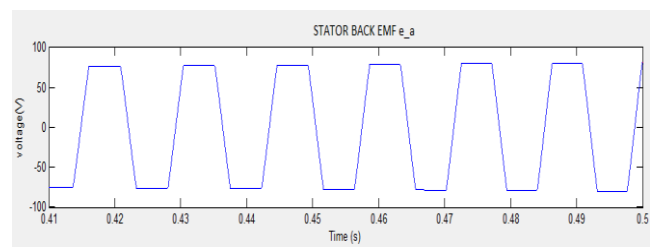


Figure 15: Back emf e_a waveform

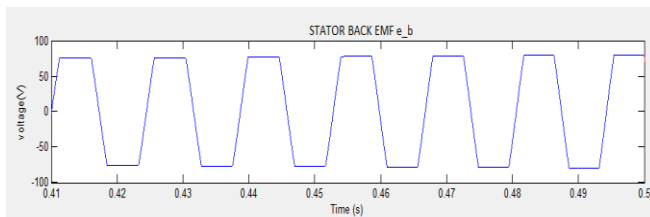


Figure 16: Back emf e_b waveform

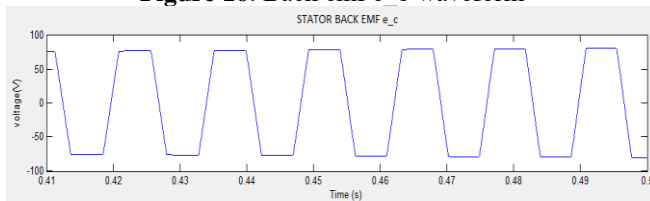


Figure 17: Back emf e_c waveform

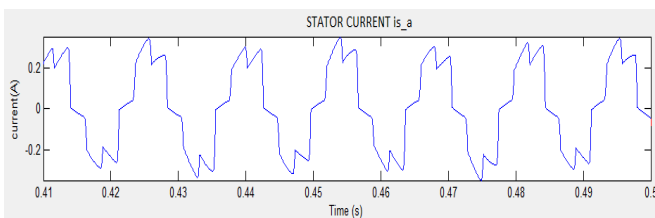


Figure 18: Stator current i_a waveform

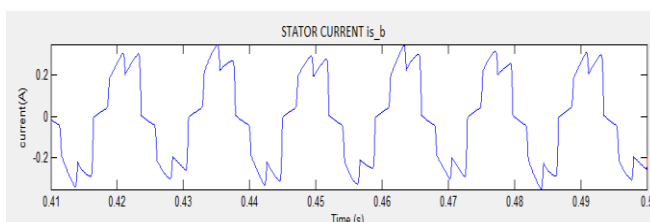


Figure 19: Stator current i_b waveform

6. Experimental Setup and Results

The prototype for cuk converter fed BLDC motor is designed for a voltage of 12V and a switching frequency of 50 KHz. The circuit of cuk converter is designed for an ac input voltage of 12v and power of 70w. The values got are $L_z=0.2\text{mH}$, $L_f=0.1\text{mH}$, $C_f=220\mu\text{F}$, $L_i=0.25\text{mH}$, $C_1=100\mu\text{F}$, $L_o=0.5\text{mH}$, $C_d=4700\mu\text{F}$. The experimental setup is done for CCM mode of operation. Here P60 is used as switch for prototype implementation.

The main part in development of the prototype is the generation of the switching signal, here PIC 16F877A is used. Here an embedded C language and MP lab IDE is used to generate the signal. For burning the program to PIC the kit used is PIC kit2. The simulations of the signal generated is readily available once programmed. The gate signal generated by PIC is taken from the port ccpl pin. These pulse are given to optocoupler TLP250 through a resistor. The output of optocoupler from pin 6 or 7 is given to switch P60 through a resistor. The line voltages are given to the ICs having two opamps each. Three ICs are used here. The differential output is then given to pins RB0, RB1 and RB2 of PIC 16F877A. The gate signal generated by PIC is taken from the RC0-RC5. The pulses generated are given to upper and lower phase points in the circuit through a 220Ω resistor to optocoupler TLP250. The output of optocoupler from pin 6 or 7 is given to each phases. From each upper and lower phases point the pulses are given to VSI and then to motor. Here the speed of the motor can be varied by varying the dc link voltage. Closed loop is provided here.

Figure 21 shows the experimental setup done for cuk converter fed BLDC motor which uses the sensorless method for giving pulses to the VSI.

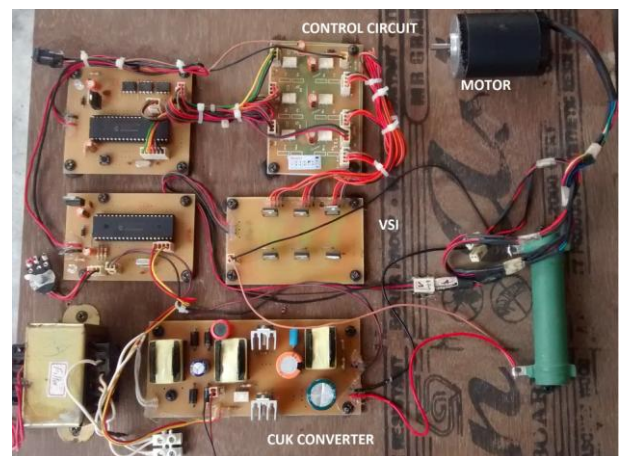


Figure 21: Experimental setup

Figure 22 and 23 shows the ac input 12V and corresponding dc link output of 20V of cuk converter. Figure 24 show the pulse given to cuk converter switch and the frequency selected is 50kHz.

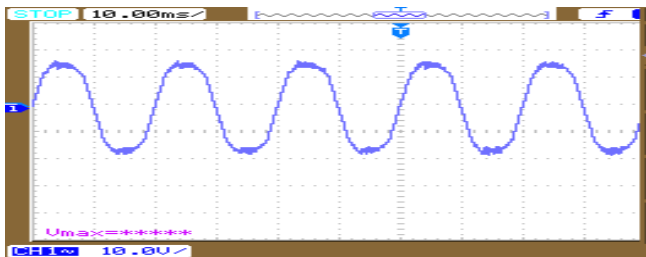


Figure 22: Input voltage waveform

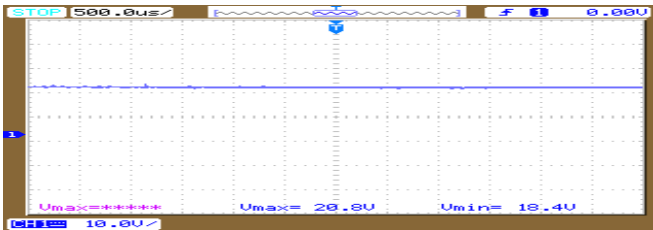


Figure 23: Dc link output voltage waveform

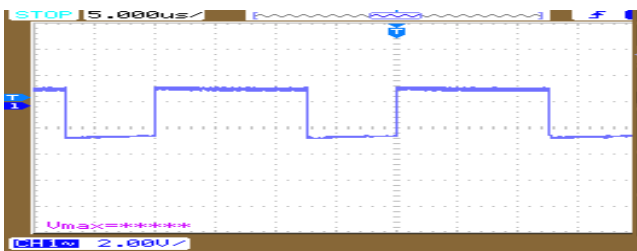


Figure 24: Pulse given to cuk converter

Figure 25 show the back emf generated (only one waveform is shown here). Figure 26 show the one of the six pulses given to VSI by using sensorless method.

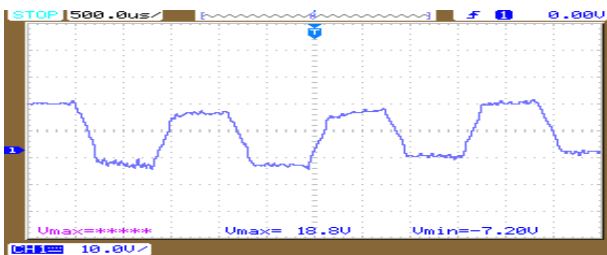


Figure 25: Waveform of back emf

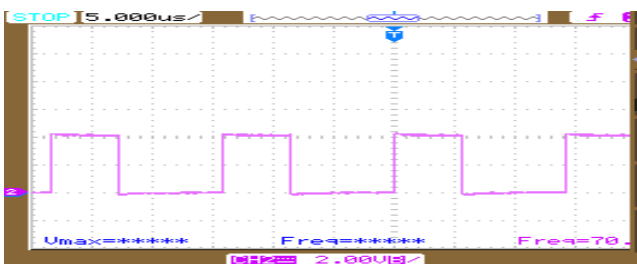


Figure 26: Pulse given to VSI

7. Conclusion

A Cuk converter for VSI-fed BLDC motor drive has been designed for achieving a unity PF at ac mains for the development of the low-cost PFC motor for numerous low-power equipments such as fans, blowers, water pumps, etc. The speed of the BLDC motor drive has been controlled by varying the dc-link voltage of VSI, which allows the VSI to operate in the fundamental frequency switching mode for reduced switching losses. Cuk converter operating in the CCM have been explored for the development of the BLDC motor drive with PF near to unity (0.995) at ac mains.

The pulses for VSI is generated by sensing the rotor position. Here the pulses are generated using sensorless method. Sensors have a number of drawbacks. They increase the cost of the motor and need special mechanical arrangements to be mounted. Further, Hall sensors are temperature sensitive, and hence limit the operation of the motor. They could reduce system reliability because of the extra components and wiring. Furthermore, sensorless control is the only reliable way to operate the motor for applications in harsh environments. If low cost is the primary concern and motor speed is not an issue, then sensorless control will be the better choice.

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