PFC Based Bridgeless Buck Boost Converter Fed BLDCM Drive with Sensorless Speed Control

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Abstract - This paper deals with the Sensor-less speed control of a BLDC motor where the input power factor can be corrected using Bridgeless Buck-Boost converter. This one will be a valuable solution for low and medium power applications. Here, the Speed control is achieved by controlling the Controlled voltage of Voltage source Inverter with a Back-Emf zero crossing point detection technique. This offers the operation of VSI at fundamental frequency switching by using the Space Vector PWM which offers reduced switching losses. The projected converter is a bridgeless type which gives elimination of DBR (Diode Bridge Rectifier) thus reduces the conduction losses related with it. The projected Bridgeless converter operates in Continuous Current Mode to offer an essential PFC at the input AC mains. The proposed drive is evaluated over a wide range of speed control and varying supply voltages with improved Power Quality indices within the acceptable limits of international power quality standards such as IEC61000-3-2. Also, The Energy Regeneration is also possible above the rated speed of BLDC motor which is stored by battery. The Performance of the executed drive system is simulated in MATLAB/Simulink platform.

Key Words - Power Quality, Energy Regeneration, Bridgeless Buck-Boost Converter, Continuous current mode, PFC.

I. INTRODUCTION

Brushless Direct Current (BLDC) motors are one of the motor types rapidly gaining reputation. BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation.

As the name implies, BLDC motors do not use brushes for commutation; as a substitute, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Noiseless operation
- Long operating life
- High dynamic response
- High efficiency
- Better speed versus torque characteristics

In addition, the ratio of torque delivered the size of the motor is higher, creating it useful in applications where space and weight are significant factors. BLDC motors are a kind of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotates at the same frequency.

BLDC motors do not practice the “slip” that is normally seen in induction motors. Depending upon the control power supply capacity, the motor with the exact voltage rating of the stator can be preferred. Forty-eight volts, or less voltage rated motors are used in automotive, robotics, small arm movements and so on. Motors with 100 volts, or higher ratings, are used in appliances, automation and in industrial applications.

A power factor of one is the objective of any electric utility company since if the power factor is less than one, they have to supply more current to the user for a specified amount of power use. In so doing, they conquer more line losses. They also must have larger capacity equipment in place than would be otherwise necessary. As a result, an industrial ability will be charged a penalty if its power factor is much dissimilar from 1. Industrial amenities tend to have a "lagging power factor", where the current lags the voltage (like an inductor). So, Power quality problems have become considerable issues to be measured due to recommended limits of harmonics in supply current by several international power quality standards such as IEC 61000-3-2. For class-A type equipments, which consists of many household types of equipment; IEC 61000-3-2 restricts harmonics current of different order such that the Total Harmonics Distortion (THD) of supply current should be less than 19%. A BLDC motor when fed by a Diode Bridge Rectifier with high value of DC link capacitor draws peaky current which can lead to a THD of supply current of the order of 65% and power factor as low as 0.8. Choice of mode of operation of a Power Factor Corrected converter is an essential matter because it directly affects the cost and rating of the components used in proposed converter. Continuous Conduction Mode and Discontinuous Conduction Mode are the two modes of operation in which a PFC converter is intended to operate. In Continuous Current Mode, the current in the inductor or the voltage across intermediate capacitor remains continuous but it involves sensing of two voltages (DC link voltage and supply voltage) and input side current for PFC operation, which is not cost effective. This deals higher switching losses in VSI as the switching losses increases as a square function of switching frequency. As the speed of BLDC motor is directly proportional to the applied DC link voltage.

Back EMF: (E) ∝ N*lr*Bω ------- (**1**)

Hence the sensor-less speed control is achieved by trapezoidal back –emf zero crossing point detection method and switching losses are minimized by means of Variable DC-link voltage

II. SENSOR-LESS SPEED CONTROL-BACK EMF ZERO CROSSING POINT DETECTION METHOD

For typical operation of a BLDC motor, the phase current and back-EMF should be aligned to produce constant torque. The current commutation point can be estimated by the zero crossing point (ZCP) of back-EMFs and a 30° phase shift, using a six-step commutation scheme through a three-phase inverter for driving the BLDC motor. The conducting interval for each phase is 120 electrical degrees. Therefore, only two phases conduct current at any time, leaving the third phase floating.

The position sensors can be entirely eliminated, thus reducing added cost and size of motor assembly, in those application in which only variable speed control is necessary and system dynamic is not predominantly demanding. In fact, some control methods, such as back-EMF and current sensing, provide, in most cases, enough information to estimate with the sufficient Precession rotor position and therefore to drive the motor with synchronous phase currents. The BLDC motor provides a striking application for sensor-less operation because the nature of its excitation inherently offers a low-cost way to extract rotor position information from the motor-terminal voltages. In the excitation of a three-phase BLDC motor, except for the phase-commutation periods, only two of the three phase windings are conducting at a time and the no conducting phases carries the back-EMF. There are many categories of sensor-less control strategies that are given bellow. The zero-crossing approach is one of the simplest methods of back-EMF sensing techniques, and is based on detecting the instant at which the back-EMF in the unexcited phase cross zero. This zero crossing triggers a timer, which may be as simple as an RC time constant, so that the next sequential inverter commutation occurs at the end of this timing interval.

In order to produce maximum torque, the inverter should be commutated every 60° by detecting zero crossing of back-EMF on the floating coil of the motor, so that current is in phase with the back-EMF.

The following techniques are generally used to estimate rotor position in applications that rely on Sensor-less Control of a BLDC motor:

- BEMF zero-crossing detection method
- Flux level detection method
- Various kinds of system state observers
- Signal injection methods

From a control perspective, two logical mechanisms must be employed:-

• ***Commutation control*****:** where the phases are energized according to rotor position with the Quasi-square current waveforms.

• ***Speed/torque control*****:** where the amplitude of the quasi-square current waveform applied to the phases is controlled to attain the desired speed/torque performance. Here, Back-EMF zero crossing point detection technique is used.

III. BRIDGELESS BUCK-BOOST CONVERTER

This section denotes a BL (bridgeless) buck-boost converter feeding BLDC motor drive with variable DC link voltage of VSI for improved power quality at AC mains with reduced components.

In the projected design of bridgeless buck-boost converter has the minimum number of components and least number of conduction devices during each half cycle of supply voltage which governs the choice of BL buck-boost converter for this application. The operation of the PFC bridgeless buck-boost converter is classified into two parts which incorporate the operation during the positive and negative half cycles of supply voltage and during the complete switching cycle.

A buck-boost converter circuit is a combination of the buck converter topology and a boost converter topology in cascade. The output to input conversion ratio is also a product of ratios in buck converter and the boost converter. The output voltage is controlled by controlling the switch-duty cycle.

The ratio of output voltage to input voltage is given by**:**

$$V_o/V_{in} = D/(1-D) = I_{in}/I_o \qquad \text{----- (2)}$$

Where, V_o and V_{in} are the output and input voltages, respectively. The term Io and Iin are the outputs and input currents, respectively. The term D is the duty ratio and defined as the ratio of the on time of the switch to the total switching period.

The buck-boost is a non-isolated inverting power stage topology, sometimes called a step-up/down power stage. Power supply designers select the buck-boost power stage because the required output is inverted from the input voltage, and the output voltage can be either higher or lower than the input voltage. The input current for a buck-boost power stage is discontinuous, or pulsating, because the power switch (Q1) current that pulses from zero to IL every switching cycle. The output current for a buck-boost power stage is also discontinuous or pulsating because the output diode only conducts during a portion of the switching cycle.

IV. VOLTAGE SOURCE INVERTER

The word ‘Inverter’ in the context of power-electronics denotes a class of power conditioning circuits that operates from a dc voltage source or a dc current source and converts it into ac voltage or current. The “inverter‟ does reverse of what ac-to-dc “converter‟ does (refer to ac to dc converters).

Even though input to an inverter circuit is a dc source, it is not unusual to have this dc derived from an ac source such as utility ac supply. Thus, for example, the major source of input power may be utility ac voltage supply that is converted to dc by an ac to dc converter and then ‘inverted’ back to ac using an inverter. Here, the final ac output may be of a dissimilar frequency and magnitude than the input ac of the utility supply. According to the type of ac output waveform, these topologies can be measured as voltage source inverters (VSIs), where the independently controlled ac output is a voltage waveform. These structures are the most widely used because they obviously act as voltage sources as required by many industrial applications, such as adjustable speed drives (ASDs), which are the most popular application of inverters. Similarly, these topologies can be found as current source inverters (CSIs), where the independently controlled ac output is a current waveform. These structures are still widely used in medium-voltage industrial applications, where High-quality voltage waveforms are required. Static power converters, specifically inverters, are constructed from power switches and the ac output waveforms are therefore made up of discrete values. This leads to the generation of waveforms that marks fast transitions rather than smooth ones. Here we have utilized Voltage Source Inverter. The simplest dc voltage source for a VSI may be a battery bank, which may consist of numerous cells in series parallel combination. Solar photovoltaic cells can be an added dc voltage source. An ac voltage supply, after rectification into dc will also qualify as a dc voltage source. A voltage source is called stiff, if the source voltage magnitude does not depend on load connected to it. All voltage source inverters limited by the magnitude of input (dc bus) voltage. In ordinary household inverters the battery voltage may be just 12 volts and the inverter circuit may be able of supplying ac voltage of around 10 volts (rms) only. In such cases the inverter output voltage is stepped up using a transformer to assemble the load requirement of, say, 230 volts.

The parameters of BL buck-boost converter are designed such that it operates in ‘Discontinuous Inductor Current Mode’ to achieve an innate power factor correction at AC mains. The speed control of BLDC motor is achieved by DC link voltage control of VSI using a BL buck-boost converter. This reduces the switching losses in VSI due to low frequency operation of VSI for electronic commutation of BLDC motor. The performance of proposed drive is evaluated for wide range of speed control with enhanced power quality at AC mains. Furthermore, effect of supply voltage variation at universal AC mains is also calculated to display the performance of the drive in practical supply conditions. Voltage and current stresses on the PFC converter switch are also evaluated for decisive the switch rating and heat sink design.

The projected design of BL buck-boost converter has the minimum number of components and least number of conduction devices during each half cycle of supply voltage which governs the choice of BL buck-boost converter for this application.

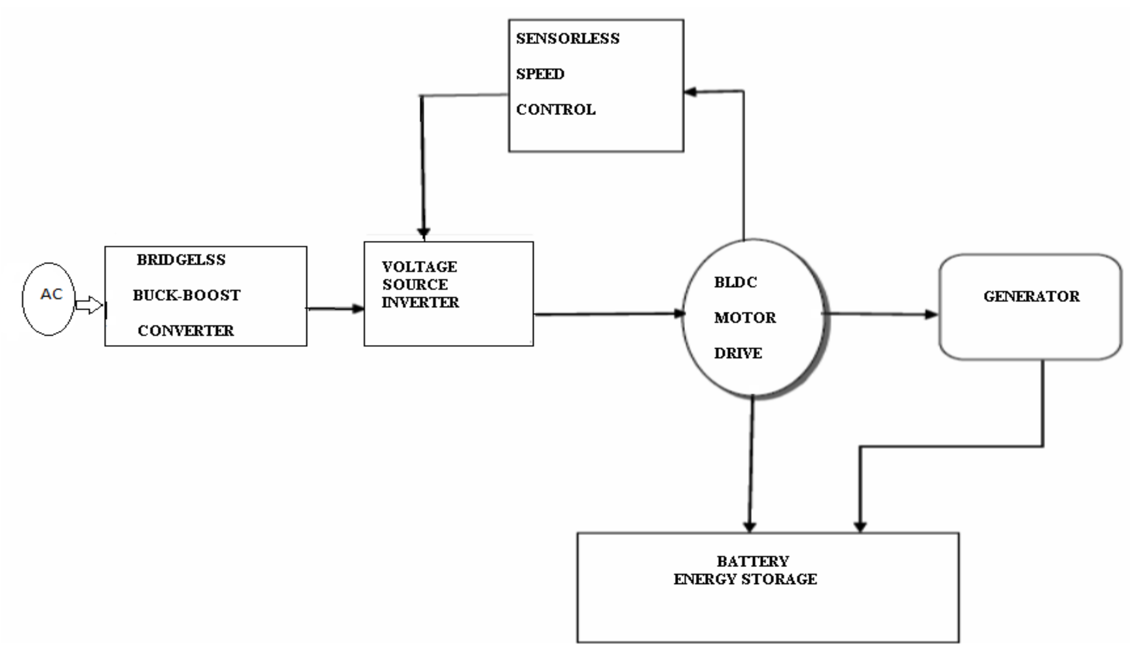

Fig: 1 Block Diagram of proposed system.

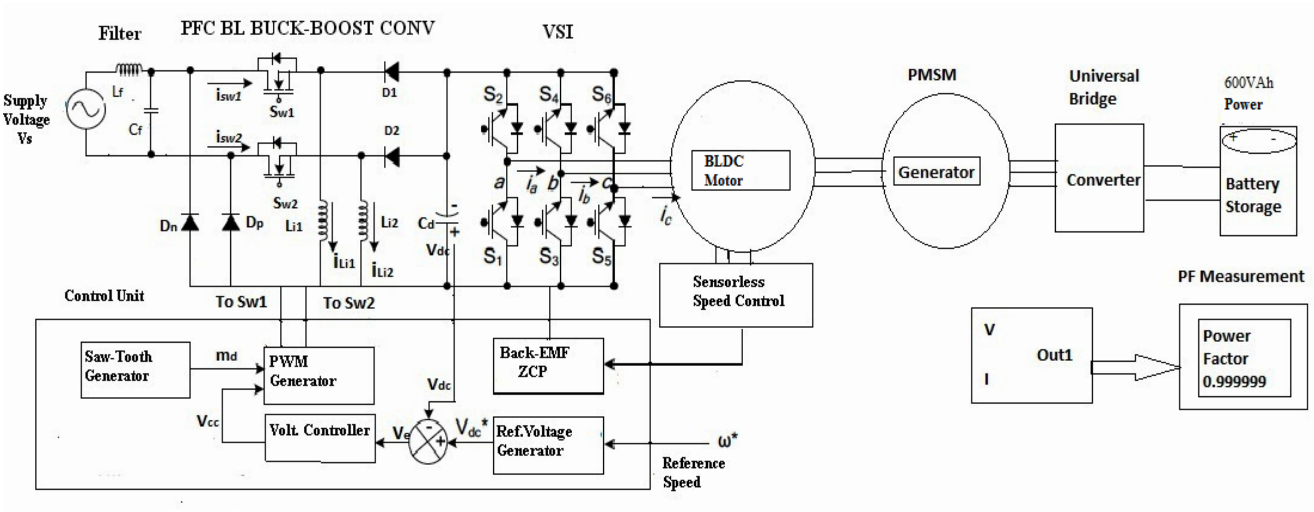

Fig: 2 Circuit Diagram of Proposed System

V.OPERATING PRINCIPLE OF PFC BL BUCK-BOOST CONVERTER

The operation of the PFC bridgeless buck-boost converter is classified into two parts which include the operation during the positive and negative half cycles of supply voltage and during the complete switching cycle. Operation during Positive and Negative half Cycle of Supply Voltage

In the proposed scheme of BL buck boost converter switches S_{w1} and S_{w2} operate for positive and negative half cycle of supply voltage respectively. During positive half cycle of supply voltage switch S_{w1}, inductor L_{i1} and diodes D_1 and D_p are operated to transfer energy to DC link capacitor C_d as shown in Figs. 3(a-c). Similarly for negative half cycle of supply voltage switch S_{w2}, inductor L_{i2} and diode D_2 and D_n conduct as shown in Figs. 4(a-c).In CCM operation of BL buck boost converter the current in inductor L_i becomes continuous for certain duration in a switching period.

Operation during Complete Switching Cycle

Three modes of operation during a complete switching cycle are discussed for the positive half cycle of supply voltage as shown below.

Mode I: In this mode, switch S_{w1} conducts to charge the inductor L_{i1}, hence an inductor current i_{Li1} increases in this mode as shown in Fig.3 (a). Diode D_p completes the input side circuitry whereas s, the DC link capacitor C_d is discharged by the VSI fed BLDC motor as shown in Fig. 3(c).

Mode II: As shown in Fig. 3(b), in this mode of operation, switch S_{w1} is turned off and the stored energy in inductor L_{i1} is transferred to DC link capacitor C_d till the inductor is completely discharged. The current in inductor L_{i1} reduces and reaches zero as shown in Fig. 3(c).

Mode III: In this mode, inductor L_{i1} enters discontinuous conduction i.e. no energy is left in inductor hence current i_{Li1} becomes zero for the rest of switching period. As shown in Fig. 3(c), none of the switch or diode is conducting in this mode and DC link capacitor C_d supplies energy to the load hence voltage V_{dc} across DC link capacitor C_d starts decreasing. The operation is repeated when switch S_{w1} is turned on again after a complete switching cycle. Similarly for negative half cycle of supply voltage switch S_{w2}, inductor L_{i2} and diodes D_n and D_2 operate for voltage control and PFC operation.

Similarly for negative half cycle of supply voltage switch Sw_2, inductor L_{i2} and diodes D_n and D_2 operate for voltage control and PFC operation.

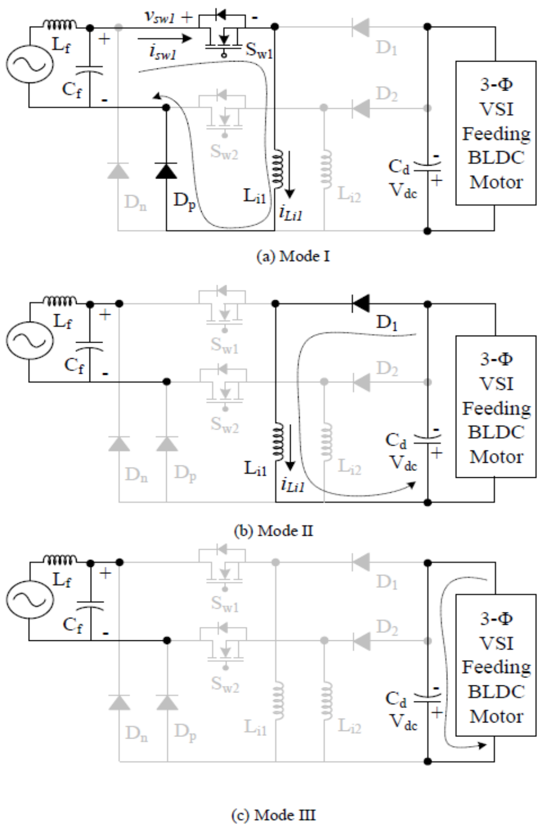

Fig: 3 Positive Half Cycle of Bridgeless Converter

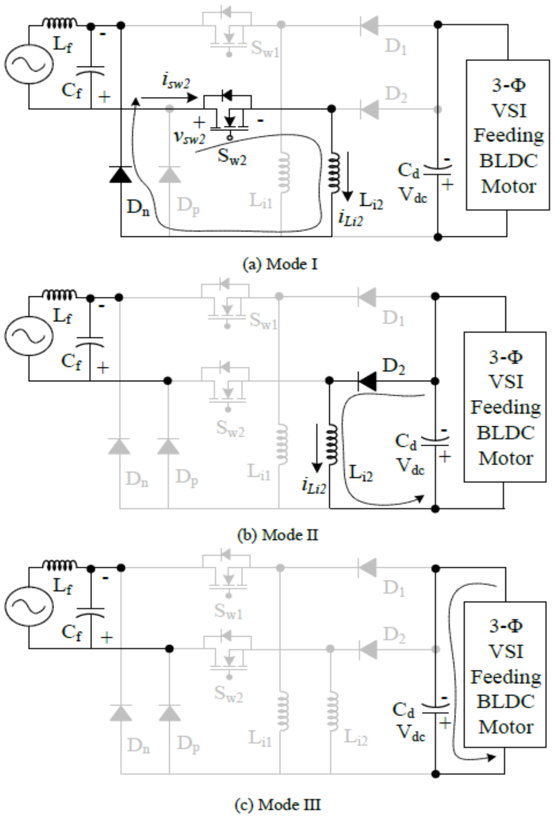

Fig: 4 Negative Half Cycle of Bridgeless Converter

VI. CONTROL OF PFC BL BUCK BOOST CONVERTER FED BLDC MOTOR DRIVE

The control of the PFC bridgeless buck-boost converter fed BLDC motor drive is classified into two parts as follows.

A. Control of Front-End PFC Converter: Voltage Follower Approach

The control of the front-end PFC converter generates the PWM pulses for the PFC converter switches (Sw1 and Sw2) for DC link voltage control with PFC operation at AC mains. A single voltage control loop (voltage follower approach) is utilized for the PFC BL buck-boost converter operating in DICM. A reference DC link voltage (V_{dc}*) is generated as,

$$V_{dc}=V*k_w* \quad \text{------- (X)}$$

Where k_v and ω* are the motor's voltage constant and the reference speed respectively. The voltage error signal (Ve) is generated by comparing the reference DC link voltage (Vdc*) with the sensed DC link voltage (Vdc) as,

$$V_e\,(k) = V_{dc}*(k) - V_{dc}\,(k) \quad \text{------ (Y)}$$

Where k represents the 'k'th sampling instant.

This error voltage signal (Ve) is given to the voltage PI controller to generate a controlled output voltage (Vcc) as,

$$V_{cc}\,(k) = V_{cc}\,(k\text{-}1) + k_p\,\{V_e\,(k) - V_e\,(k\text{-}1) + k_i V_e\,(k) \quad \text{---- (Z)}$$

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

Finally, the output of voltage controller is compared with a high frequency saw-tooth signal (m_d) to generate the PWM pulses as,

For $V_s > 0$; [If $m_d < V_{cc}$ then Sw_1 = 'ON';]

[If $m_d >= V_{cc}$ then Sw_1 = 'OFF']

For $V_s < 0$; [If $m_d < V_{cc}$ then Sw_2 = 'ON']

[If $m_d >= V_{cc}$ then Sw_2 = 'OFF']

Where Sw_1, Sw_2 represents the switching signals for the switches of PFC converter.

VII. PFC BL BUCK-BOOST CONVERTER-CALCULATIONS

A PFC BL buck-boost converter is designed to operate in CCM such that the current in inductors L_{i1} and L_{i2} becomes discontinuous in a switching period. For a supply voltage with rms value of 210V, the average voltage appearing at the input side is given as,

$$V_o = (2*1.414*V_s)/3.14 \quad \text{---- (3)}$$

$$= (2*1.414*210)/3.14$$

$$V_o = 189 \text{ Volts}$$

The relation governing the voltage conversion ratio of a BL Buck-boost converter is given as,

$$d = V_{dc} / (V_{dc} + V_{in}); \quad \text{------ (4)}$$

The proposed converter is designed for DC link voltage control from 50V (V_{dcmin}) to 200V (V_{dcmax}) with a nominal value (V_{dcdes}) of 100V, hence the minimum and maximum duty ratio (dmin and dmax) corresponding to V_{dcmin} and V_{dcmax} are calculated as 0.2016 and 0.5025 respectively.

ii. DC Link Capacitor (C_d)

The design of DC link capacitor is governed by the amount of second order harmonic (lowest) current flowing in the capacitor and is derived as follows. For the PFC operation, the supply current (is) is in phase with the supply voltage (vs). Hence the input power Pin is given as,

$$P_{in} = 2*V_s*\sin\omega t*I_s*\sin\omega t$$

$$= V_s*I_s*(1-\cos 2\omega t) \quad \text{------ (5)}$$

Where the later term corresponds to the second order harmonic, which is reflected in the DC link capacitor as,

$$I_c\,(t) = \{-V_s I_s \cos 2\omega t)/V_{dc}\} \quad \text{----- (6)}$$

For a maximum value of voltage ripple at DC link capacitor, Sin (ωt) is taken as 1. Hence eqn. (7) is re-written as,

$$C_d = I_d / (2\omega.V_{dc}) \quad \text{------ (7)}$$

Now the value of DC link capacitor is calculated for the designed value Vdcdes with permitted ripple in the DC link voltage (ΔVdc) taken as 3% as,

$$C_d = (I_d / 2\omega . \Delta V_{dc})$$

$$= 350/ (100*8*314) \quad = 1393.1 \text{ uF} \qquad \text{------ (8)}$$

Hence the nearest possible value of DC link capacitor Cd is selected as 1000µF.

ii. Input Filter (L_f and C_f)

A second order low pass LC filter is used at the input side to absorb the higher order harmonics such that it is not reflected in supply current. The maximum value of filter capacitance is given as

$$C_{max} = (I_{peak}/ \omega_L V_{peak})* \tan (1)$$

$$= 172\text{uF} \qquad \text{----- (9)}$$

Where I_{peak}, V_{peak}, ω_L and θ represent the peak value of supply current, peak value of supply voltage, line frequency in rad/sec and displacement angle between the supply voltage and supply current respectively. Hence a value of C_f is taken as 100uF.

Now the value of inductor Lf is calculated as,

$$L_f = L_{req} + L_s \Rightarrow \frac{1}{4\pi^2 f_c^2 C_f} = L_{req} + 0.04\left(\frac{1}{\omega_L}\right)\left(\frac{V_s^2}{P_o}\right)$$

$$L_{req} = \frac{1}{4\pi^2 x 2000^2 x 330x10^{-9}} - 0.04 \frac{1}{314}\left(\frac{220^2}{350}\right) = 1.57\text{mH} \qquad \text{-- (10)}$$

VIII. MATLAB/SIMULINK PROPOSED MODEL

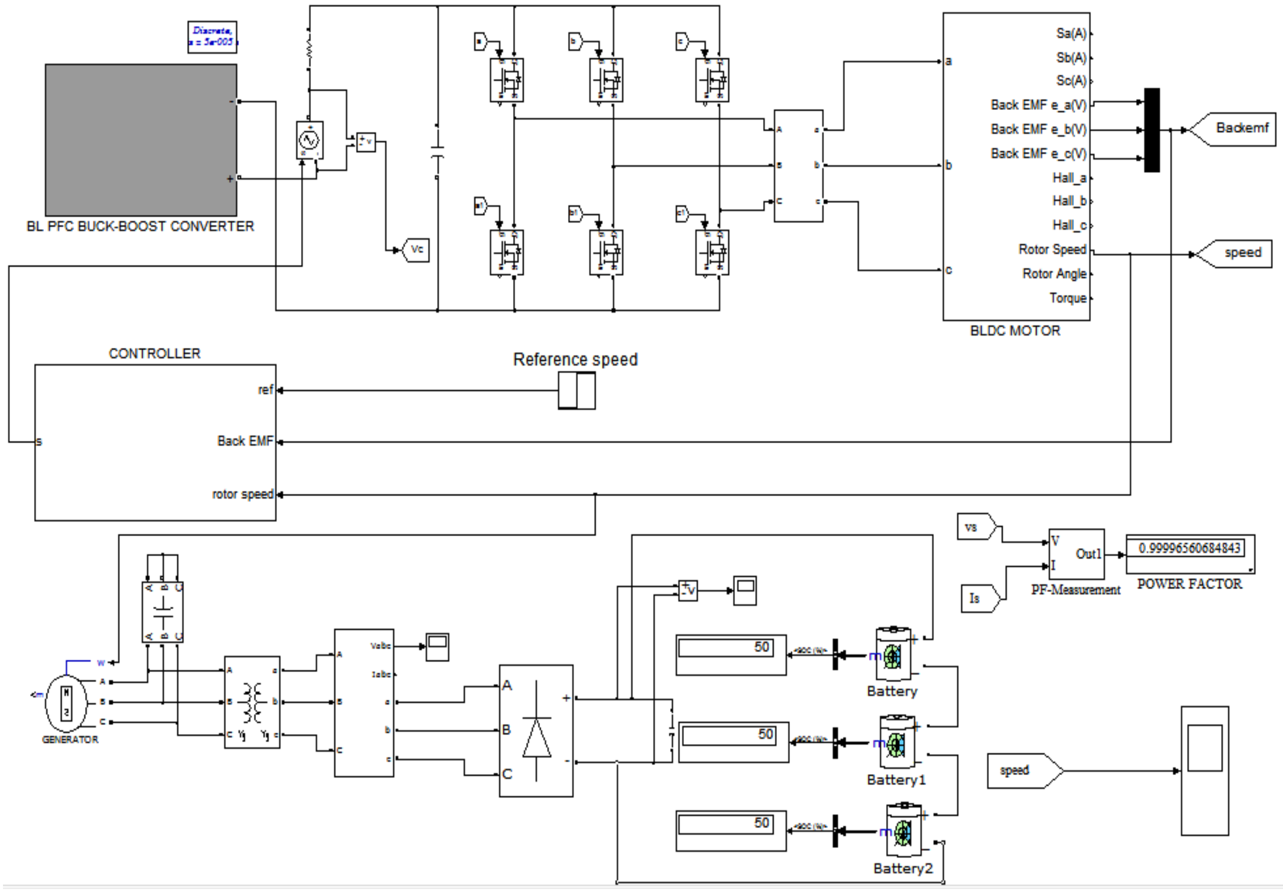

Fig: 5 Matlab/Simulink Model of Proposed Model

Now, the value of filter inductor is designed by considering the source impedance (L_s) of 4-5% of the base impedance. Hence the additional value of inductance required is given as,

Where fc is the cut off frequency of the designed filter which is selected as

$$f_l < f_c < f_{sw} \qquad \text{----- (11)}$$

Hence a value of fc is taken as fsw/10. Finally, a low pass filter with inductor and capacitor of 1mH and 100uF is selected for this particular application.

iii. Input Inductor's (L_{i1} & L_{i2}):

The value of inductance Lic1 to operate in critical conduction mode is given as,

$$L_{ic1} = [R (1\text{-}d)^2]/2f_s \qquad \text{------ (12)}$$

Where R is the equivalent load resistance and d is the duty ratio and fs are the switching frequency.

Now the value of L_{ic1} is calculated at the worst duty ration d_{min}

such that the converter operates in CCM at very low duty ratio. At minimum duty ratio i.e., BLDC motor operates at 50V (V_{dcmin}) the power Pmin is given as 90W (i.e., for constant torque, load power is Proportional to speed). Hence from equation (13), the value of inductance Licmin corresponding to Vdcmin is given as

$$Licmin = [(V_{dcmin}^2)/P_{min}]*[(1-d_{min})^2)/2f_s] \quad \text{------ (13)}$$

$$= 142.67uF.$$

The values of inductances L_{i1} and L_{i2} are taken less than the 1/10th of the minimum critical value of inductance to ensure a deep CCM condition. The supply current at higher values of input side inductor is highly distorted due to inability of converter to operate in CCM at peak values of supply voltages. Hence the value of inductor L_{i1} and L_{i2} are selected around 1/10th of the critical inductance and are taken as 35μH. It reduces the size, cost and weight of the PFC converter.

XI. SIMULATED PERFORMANCE ANALYSIS

The performance of proposed BLDC motor drive is simulated in MATLAB/Simulink environment using the Sim-Power-System toolbox. The performance evaluation of the proposed drive is categorized in terms of performance of BLDC motor, Bridgeless converter and the achieved power quality indices obtained at AC mains. The parameters associated with BLDC motor such as speed (N), back Emf are analyzed for proper functioning of BLDC motor.

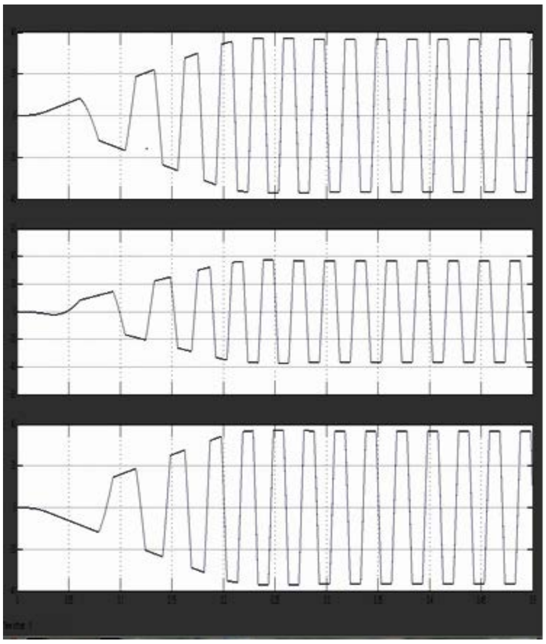

Fig: 6 Back-EMF Trapezoidal Output Voltage versus time

Parameters such as supply voltage (V_s), supply current (i_s), DC link voltage (V_{dc}), inductor's currents (i_{Li1}, i_{Li2}), switch voltages (V_{sw1}, V_{sw2}) and switches currents (isw1, isw2) of PFC BL buck boost converter are evaluated to demonstrate its proper functioning. Moreover, power quality indices such as PF (Power Factor), DPF (Displacement Power Factor) and THD (Total Harmonics Distortion) of supply current are analyzed for determining power quality at AC mains.

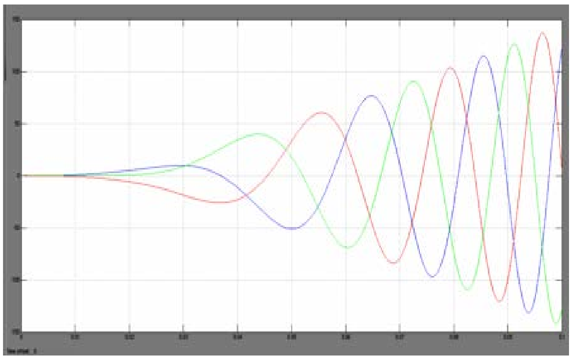

Fig: 7 Three phase Ac output voltage from Generator

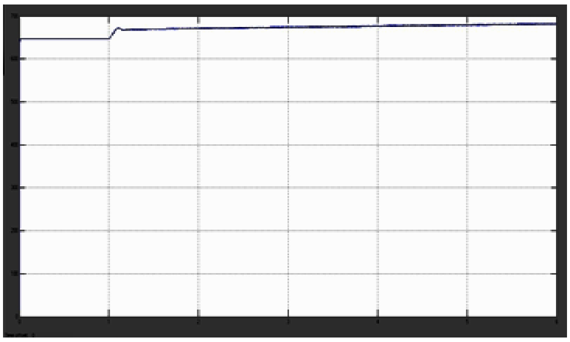

Fig: 8 Battery output voltages versus time curve

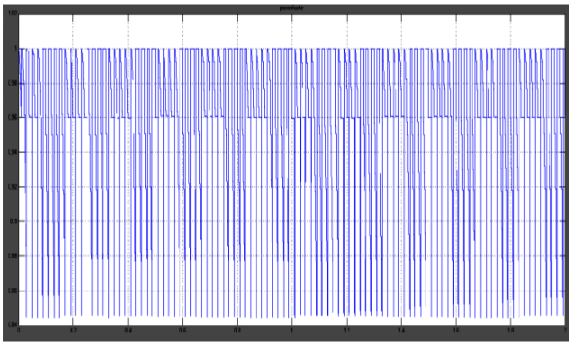

Fig: 9 Power Factor at Input mains

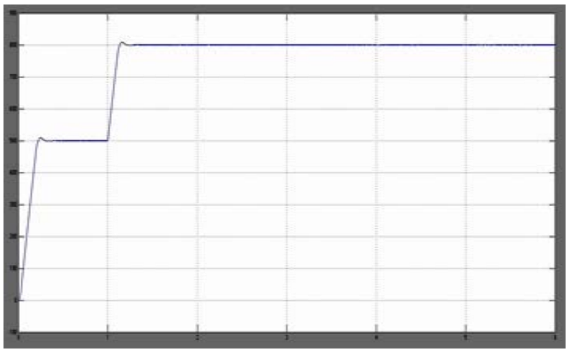

Fig: 10 BLDC motor Speed versus time

X. PMSM GENERATOR

Here, A Permanent Magnet Synchronous generator (PMSM) is connected with the BLDC motor Drive. The PMSM act as a generator when the BLDC motor speeds exceed the rated speed. When this achieved, then the generator set will produce electrical energy which is further converted and stored in battery storage. In this mechanism, the battery can store up to 600VAh. The battery has a configuration of 50% state of charge.

XI. CONCLUSION

Here, A Start line Power Factor Correction using Bridgeless Buck-Boost Converter fed BLDC motor drive with Sensor-less Speed Control is achieved. Also, it is possible to generate the electric power using generator when the BLDC drive exceeds the rated speed can be examined. A novel method of sensor-less speed control has been utilized by controlling the voltage at DC bus and operating the VSI at fundamental frequency for reducing the switching losses. The front end Bridgeless Converter has been operated in Continuous Current mode for achieving an integral power factor correction at AC mains. An acceptable performance has been achieved for power quality indices within the acceptable limits of IEC 61000-3-2. Moreover, Energy Regeneration is achieved above the rated speed of BLDC which can be derived by connecting a PMSM. This generated voltage is further converted and stored in the battery storage. The graph shows the performance of the overall system which satisfies the required target. The proposed scheme has shown satisfactory performance and it is a recommended solution applicable to low & medium power BLDC motor drives.

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