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Power Quality Analysis of Vienna Rectifier for BLDC Motor Drive Application

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ABSTRACT

This paper presents the power quality improvements for a BLDC driver using Vienna rectifier as front end converter. The major drawbacks in the BLDC motor drive and non linear load applications are the line pollution and depreciation of the power factor. The conventional power factor correction method is not economical and efficient. It requires bulky components as load changes and produce high THD and less Power factor. The front end converter of BLDC bridge inverter drive is proposed by the Vienna rectifier, which can contribute more significantly in improving the power factor and reduce the line pollution. The Vienna rectifier topology is controlled by the constant switching frequency control technique for wide range of load variation and it reduces the THD, improve the power factor and provide a steady DC link voltage to the bridge inverter to drive the BLDC motor. The design calculation and performance characteristics of BLDC motor and Vienna rectifier are verified by using Matlab simulation.

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1. INTRODUCTION

In emerging markets the motor usage is more in the traction and industrial applications for rotational or moving objects [1]. There are different types of motors available in the market like induction motor, DC motor and servo motor. Based on the application requirement the motor will be selected. The Brushless DC (BLDC) motor is the best choice for application that requires high torque with varying speed, more precision, reliability and efficiency. BLDC motor is derived from the DC motor and Brushed DC motor. The major difference is that the BLDC motor doesn’t require the brushes for commutation, so there is no spark and wear out, hence the maintenance is less. This motor is lighter and more efficiency as compared to brushed DC motor or conventional DC motor for the same output power. The BLDC motor consists of a magnet as a rotor and surrounded by the stator windings. The stator windings are energized by the inverter output. The PWM control technique is used to control the three phase bridge inverter.

The three phase bridge inverter is used in order to drive the BLDC motor, but the inverter requires the steady boost DC voltage for the direct drive application. The conventional three phase Diode Bridge, the Bridge converter and chopper based converter will provide the dc link voltage but the biggest challenge is the pollution of the input line current due to the high current THD and low power factor.

In the paper [2] presented, hysteresis current control technique is used to control the switch in the boost converter to attain the unity power factor but this technique operates in variable switching frequency which cause the boost inductor design to become more complex and of bigger size for the low switching frequency and it performs only in the continuous conduction mode. In the paper [3] presented, the motor is driven by the voltage source inverter (VSI) which caused the non-sinusoidal voltage and current in the mains supply due to presence of the harmonics. To eliminate these harmonics, the active shunt filter is used along with VSI but this approach may increase the size and cost. In the paper [4] presented the Buck-Boost converter is used to drive the BLDC motor. This method has some drawbacks like to drive the high side switch, voltage stress is more on the switch, output capacitor size is large and it is suitable only in low power applications.

The Vienna rectifier is proposed to act as a front end converter to provide a steady boost DC voltage, high power factor with less THD. The Vienna rectifier consists of three phase diode bridge rectifier connected with three bidirectional semiconductor, the boost line inductor is connected in series with input supply and two equal value capacitance of capacitor is connected in series across the DC link. Due to the nature of the three level output voltage +E/2, 0, -E/2, the voltage stress across the semiconductor is reduced to half of the DC link voltage [5]. The Vienna rectifier is controlled by various control technique to achieve the high power factor and less THD to meet the IEC standards requirement. In the study of control system analysis the constant switching frequency control technique are more reliable than conventional feedback method and it is strong to reject source and load disturbance [6]. The constant switching frequency control method consists of less no of components like integrator with reset, comparator and flip-flop and it eliminates the multiplexer and voltage sensor. This control method is a non liner control for the switching circuit, which is operating at constant switching frequency modulation, it reduces the input boost inductor size and therefore it reduces the cost and size. The block diagram of Vienna rectifier fed BLDC drive system is as shown in Figure 1.

2. PRINCIPLE OF OPERATION OF BLDC MOTOR

The BLDC motor construction and operating principles are more similar to the AC induction motor and brushed DC motor [7]. BLDC motor also consists of stator and rotor. The brushless DC motor is a permanent magnet AC motor; the torque- speed characteristics are similar to the DC motor. In the brushed DC motor, brushes are used for commutating the armature current. The rotor position is sensed by mechanical commutator and brushes whereas in BLDC motor the electronics commutation is used and feedback is achieved by hall sensor or optical encoder so that the speed control is more precise.

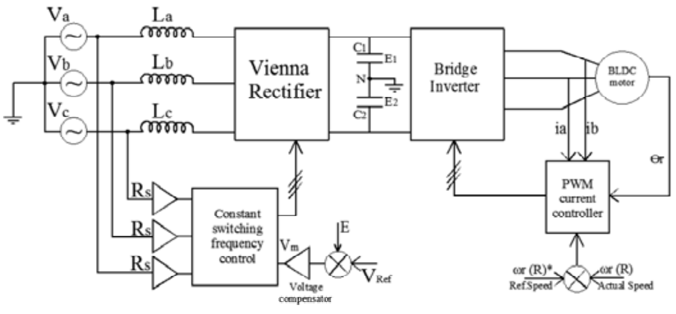


Figure 1. Vienna rectifier fed BLDC drive system

The hall sensor is fixed in the motor to generate the high or low signal when the magnetic poles pass the sensor which is used to determine the position of the rotor. The BLDC motor is classified as trapezoidal type and sinusoidal type based on the shape of the rotor magnet and stator winding. In the trapezoidal motor the back EMF induced in the trapezoidal shape and it requires the quasi-square currents for the ripple free torque operation. Similarly the sinusoidal motor induces the sinusoidal shaped back EMF and it requires the sinusoidal current for the ripple free torque operation. The stator coils are energized by the electronic commutation depending on the hall sensor signals. The stator coils are sequentially energized, a magnetic field is created and the rotor moves in a sequential manner.

The commutation electronic circuit consists of semi conductor switches and its drive control system to control the stator current. To complete one mechanical rotation, four pole BLDC motor requires four electrical cycles. The magnetic field determines the force and speed of the motor. The strength of the magnetic field is depending upon the current through the coil. The most popular PWM control technique is used for controlling the speed of the motor. The steady DC input voltage is fed to the bridge inverter and convert into controlled AC voltage by controlling the semiconductor switches in the inverter using PWM control technique and fed to the stator coil to energize. Therefore the stator coil current is varied, the speed and torque of the motor can be adjusted.

2.1. Control System of BLDC Motor Drive

The PWM technique is simple and more popular method in controlling the speed of motor [8]. This control system consists of outer loop speed and torque control and inner loop current controller [9]. The rotor position is sensed by hall sensor and the speed is derived by the integration of rotor position. In the speed control loop, the derived speed is compared with reference speed and fed to the controller to generate the reference torque. In the torque control loop, the actual torque is compared with the reference torque to generate the three phase reference current i_a*, i_b*, i_c*. In the inner current control loop, the measured i_a and i_b current signals are fed to the current controller and the i_c current value is calculated. These current signals are compared with reference current signal to generate the PWM to achieve the desired output by adjusting the PWM duty cycle.

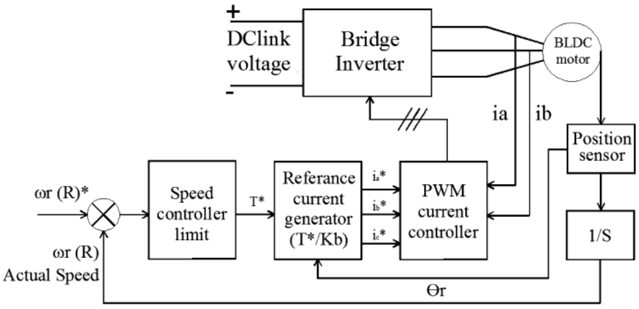


Figure 2. Block diagram of BLDC motor drive system

2.2. Advantages

- High Speed Operation under loaded and unloaded conditions.
- Responsiveness & Quick Acceleration.
- High Power Density – it is having the highest running torque per cubic inch of any DC motor.
- It doesn’t have brushes, it is more reliable.

3. PRINCIPLE OF OPERATION OF VIENNA RECTIFIER

The Vienna rectifier is mostly used for the power quality improvement in the grid side for various and wide load range. There are various control techniques used to control the Vienna rectifier to obtain the high power factor and less input current THD. The proposed constant switching frequency control method has more advantage compared to conventional control methods. The Vienna rectifier is used as front end converter for the BLDC drive application to avoid the line pollution and improving the power factor.

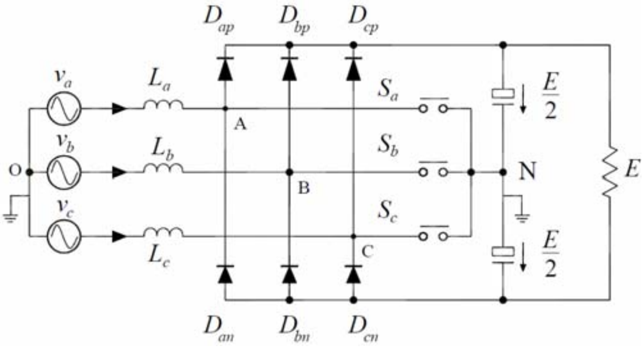


Figure 3. Three phase Vienna rectifier as front end converter

The Vienna rectifier topology consists of three bidirectional switch which corresponds to each phase which inturn is connected with three phase diode bridge rectifier. The DC bus output voltage is connected to the load (BLDC driver). The three bidirectional switch is switching continuously at constant switching frequency to draw the line current in phase with line voltage respectively; it ensures the unity power factor and less THD. The switching state and the sign of the input current define the rectifier input voltage. When the switch is turn on the input inductor starts charging and input current increases and when the switch is turn off the input inductor current discharge through the diode bridge rectifier. The Vienna rectifier bidirectional switch is switching On/Off state depends on the phase current of in each phase.

$$L_k \frac{di_k}{dt} = V_k - V_{kN} \tag{1}$$

Where k=a, b, c

When the phase current is positive,

$$V_{kN} = \left\{ \begin{array}{ll} \frac{+E}{2} & S_k = 0 \\ 0 & S_k = 1 \end{array} \right\} \tag{2}$$

When the phase current is negative,

$$V_{kN} = \left\{ \begin{array}{ll} \frac{-E}{2} & S_k = 0 \\ 0 & S_k = 1 \end{array} \right\} \tag{3}$$

3.1. Control System of Vienna Rectifier

The constant switching frequency control method is firmness for power disturbance, it excludes source and load disturbance. The OCC is very simple, desirable than conventional feedback control method. This control method is operating at constant switching frequency modulation of the output waveform instead of PWM; therefore magnetic size will be small. It consists of one or two integrator with reset, flip-flops, comparators, logic, linear devices. It doesn’t require any multipliers and the voltage sensor. It can operate by sensing either the inductor current or switching current. The important idea of one-cycle control is forcing the switched variable exactly equal to reference signal. Assuming that the Vienna rectifier is operated in continuous-conduction- mode (CCM), a general equation that relates the input phase voltage and duty ratio of switches is derived from an average model of the Vienna rectifier [10]. The block diagram of constant switching frequency control system as shown in Figure 4.

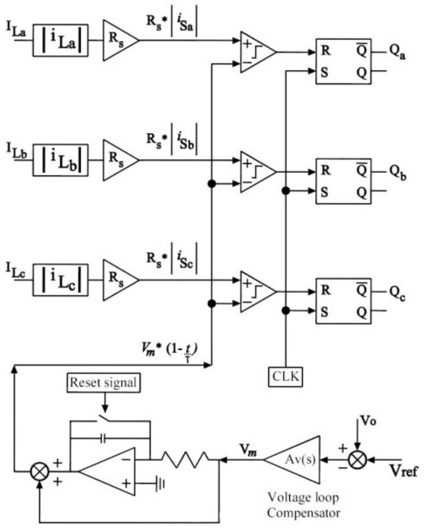


Figure 4. Unified switching frequency control system

The vector voltage at node A, B, C with respect to the neutral point O is equal to the phase vector voltage minus the inductor voltage La, Lb, Lc, where L is the inductance of the input inductors. The average node voltage in each switching cycle V_{AN}, V_{BN}, V_{CN} are given in equation (4).

$$
\begin{gathered}
\left\{ v_{AN} = \begin{cases} (1-d_a)*\frac{E}{2} & when\ \ i_a \geq 0 \\ -(1-d_a)*\frac{E}{2} & when\ \ i_a < 0 \end{cases} \right\} \\
\left\{ v_{BN} = \begin{cases} (1-d_b)*\frac{E}{2} & when\ \ i_b \geq 0 \\ -(1-d_b)*\frac{E}{2} & when\ \ i_b < 0 \end{cases} \right\} \\
\left\{ v_{CN} = \begin{cases} (1-d_c)*\frac{E}{2} & when\ \ i_c \geq 0 \\ -(1-d_c)*\frac{E}{2} & when\ \ i_c < 0 \end{cases} \right\}
\end{gathered}
\tag{4}
$$

The clock pulse generator is set the switching frequency of the converter and the integration time constant is also equal to the switching frequency. The clock pulse sets the SR flip-flop at starting of each switching cycle. The three phase inductor current i_{La}, i_{Lb}, i_{Lc} pass through the full wave rectifier circuit to convert absolute value of the Rs*i_{La}, Rs*i_{Lb}, Rs* i_{Lc} and fed to the input of the three comparator. The voltage loop compensator generates the Vm signal by comparing the output dc voltage and reference voltage. The Vm signal is integrated and subtracted from the Vm which is fed to another input of the comparator. The slope of ramp signal changes according to the error voltage [11]. The SR flip-flop resets, by the output of the comparator for the respective phases and it turns off the semiconductor switches. The comparator is comparing the current reference signal and integrated error voltage signal, therefore based on the clock pulse and comparator output decides the duty cycle of the corresponding switches for the each switching cycle

3.2. Advantages

- The Vienna rectifier has continuous sinusoidal input current.
- Number of IGBTs is less and manufacturing cost is also less.
- The blocking voltage stress on power semiconductor is reduced to half of the DC link voltage.
- The control system is simple and reliable and it doesn’t require any multipliers, voltage sensors.
- The boost inductance will be reduced due to unified constant switching frequency.
- The control system is simple and more reliable.
- This control method can be achieved by sensing either the inductor currents or the switching currents.

4. DESIGN CALCULATION

The Vienna rectifier is supplying power to the inverter to drive the BLDC motor. The losses considered for both Vienna rectifier and inverter are approximately 500W. In the simulation analysis, the critical components values are calculated and semiconductors are considered in the general simulink blocks.

The input power taken from the supply is 7.5kW, the phase peak voltage is 100V, Dc link voltage is 600V, input current ripple is 15% and assumed power factor is 0.98,

Input power $P_{in} = 3*V_{ph}*I_{ph}*\cos ø$

$$I_{ph} = \frac{P_{in}}{3*V_{ph}*\cos ø} = \frac{7500}{3*70.7*0.98}$$

$$I_{ph} = 36A$$

$$I_{peak} = \sqrt{2} I_{rms}$$

$$I_{peak} = 51A$$

The input inductor ripple current is as [12]

$$I_{ripple\max} = 0.15*51 = 7.65A$$

The input boost inductor L is as [12]

$$L = -\frac{0.866*V_{ph,pk}}{E/2} * \frac{(0.866*V_{ph,pk} - E/2)}{I_{ripple\max} * F_{sw}}$$

$$L = -\frac{0.866*100}{300} * \frac{(0.866*100 - 300)}{7.65*10000}$$

$$L = 805uH$$

Where E is DC link voltage

The DC link capacitor C1 and C2 are equal value capacitance and the capacitor value is determined using simulation model by trial and error method which is less than 4700uf. The ripple voltage across capacitor is less than 2%.

The BLDC motor torque T_e is calculated by multiplying the torque constant T_k and stator current I_a. The stator current is measured at no load and the reference speed condition. The measured torque and stator current at no load condition is shown in Figure 5 and Figure 6 respectively.

$$T_e = T_k * I_a$$

$$T_e = 1.05*1.2 = 1.26\ Nm$$

5. SIMULATION RESULTS

The simulation is carried out for BLDC motor drive with Vienna rectifier. The Vienna rectifier DC link reference voltage is 600V and reference speed of BLDC motor is 1500 rpm. The measured speed of the motor in the simulation model is as shown in Figure 7.

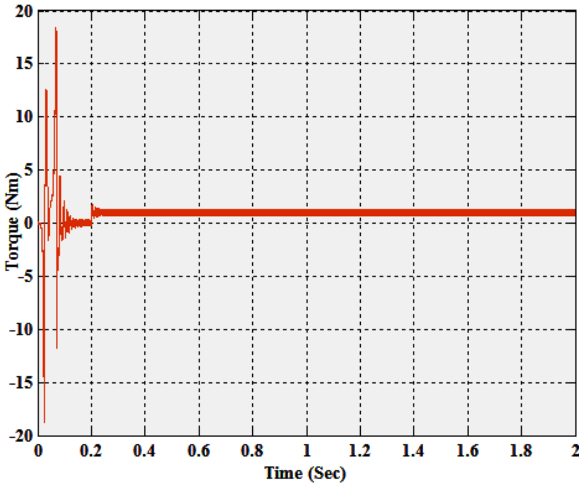


Figure 5. Torque characteristics of BLDC motor

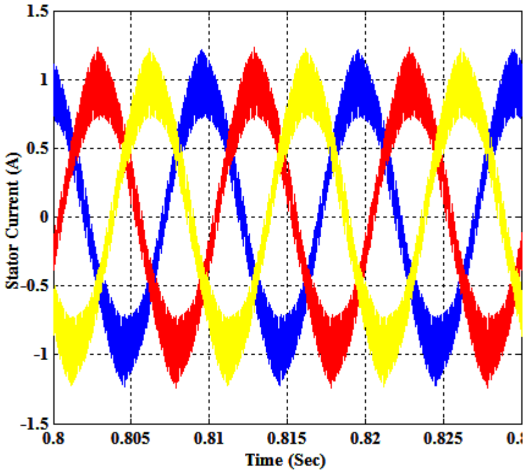


Figure 6. Stator input current of BLDC motor

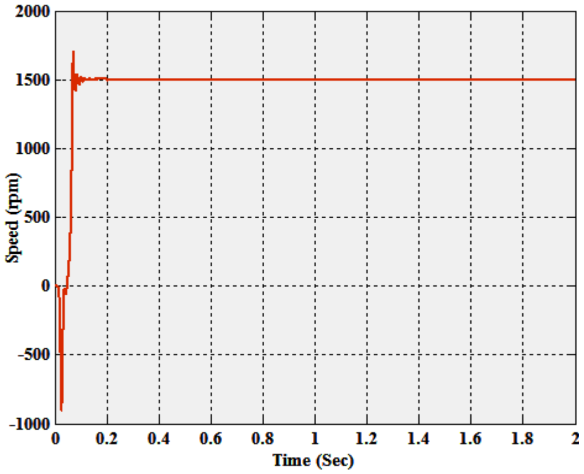


Figure 7. Speed characteristics of BLDC motor

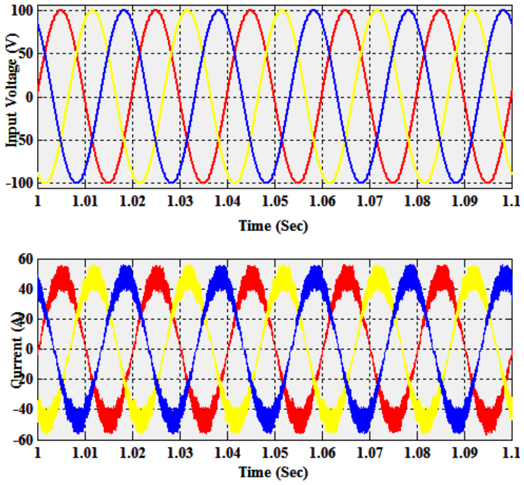


Figure 8. Input voltage and Input current signal

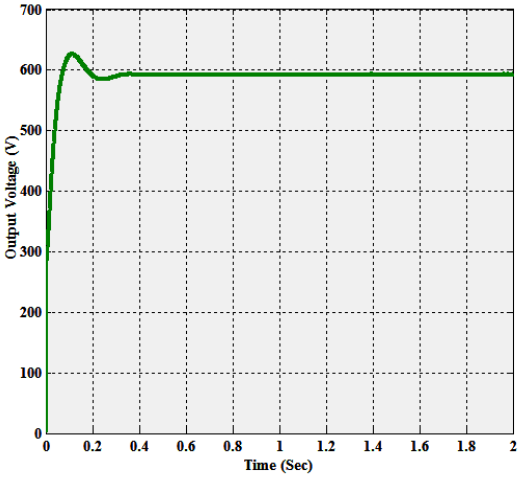
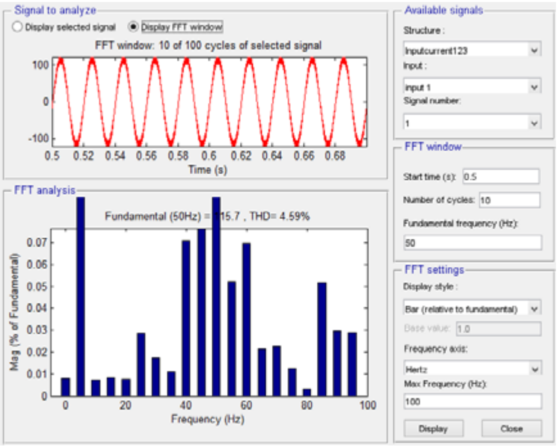


Figure 9. DC link voltage fed to inverter


Signal to analyze
○ Display selected signal ● Display FFT window

Available signals
Structure : Inputcurrent123
Input : input 1
Signal number: 1

FFT window
Start time (s): 0.5
Number of cycles: 10
Fundamental frequency (Hz): 50

FFT settings
Display style : Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz
Max Frequency (Hz): 100

Figure 10. Input current harmonic distortion bar

The Vienna rectifier input voltage and current waveform as shown in Figure 8 at full load condition; measured DC link voltage is 600V as shown in Figure 9. The measured input current harmonics is less than 4.59% and power factor is phase A 0.99, phase B 0.99 and phase C 0.99 are shown in Figure 10 and 11 respectively at full load condition.

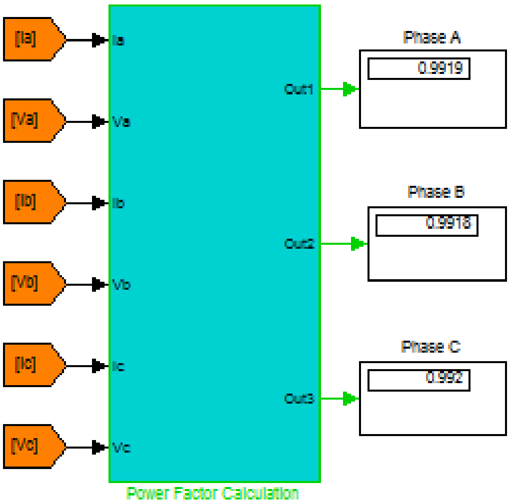


Figure 11. Measured power factor

6. CONCLUSION

The simulation analysis is carried out for the BLDC driver with Vienna rectifier as front end converter using Matlab simulink. The design is implemented and performance of BLDC motor and Vienna rectifier is verified with the simulation model. Constant switching frequency control system is implemented for the Vienna rectifier to drive the bridge inverter driver of BLDC motor. The Vienna rectifier supplies the steady DC link voltage from the utility supply to the bridge inverter to drive the BLDC motor. The performance characteristics of BLDC motor like speed, torque and stator current are observed. The Vienna rectifier input line current harmonics distortion and power factor is verified in the Matlab simulation analysis. The cumulative benefits of the Vienna rectifier and the control techniques are utilized by the BLDC motor driver which inturn results in exorbitant improvement of the power quality.

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