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SEPIC Converter based-Drive for Unipolar BLDC Motor

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ABSTRACT

Front-end single-ended primary inductance converter (SEPIC) and a switch in series with each phase is proposed for driving a permanent magnet brushless dc (BLDC) motor with unipolar currents. All the switches are ground-referenced, which simplifies their gate drives. The available input voltage can be boosted for better current regulation, which is an advantage for low voltage applications. The SEPIC converter is designed to operate in the discontinuous conduction mode for operation with an ac supply. In this operation mode, the line current follows the line voltage waveform to a certain extent. The reduction in low-order harmonics and improved power factor is achieved without the use of any voltage or current sensors. The simplicity and reduced parts count of the proposed topology make it an attractive low-cost choice for many variable speed drive applications. The proposed topology is simulated and verified by using MATLAB/SIMULINK.

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1. INTRODUCTION

Brushless Direct Current (BLDC) motors are one of the motor types rapidly gaining popularity. 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, instead, they are electronically commutated. As compared to brushed DC motors and induction motors, BLDC motors have better speed versus torque characteristics, high dynamic response, high efficiency, noiseless operation, high speed ranges. Cost minimization is the key to the large volume manufacture and application of brushless dc (BLDC) motors in variable speed drives. The savings in converter cost opens up a lot of applications for variable speed drives such as HVAC, fans, pumps, and appliances which have been dominated by constant speed drives. BLDC motors are conventionally excited with bipolar currents which require a six-switch inverter but unipolar motor needs fewer electronic parts and use a simpler circuit. For these reasons, unipolar-driven motors are widely used in low-cost instruments.

The simplest unipolar drive consists of a single switch in series with each winding and a zener diode or dump resistor in the freewheeling path as shown in Fig. 1. This drive is inefficient because the stored energy in the phases is dissipated. Better performance can be obtained by using topologies such as the C-dump converter shown in Fig. 2, which offers full regenerative control. However, it has the disadvantage of requiring a complicated control for the dump capacitor voltage, the failure of which could be catastrophic. This topology requires a higher voltage on the dump capacitors than what is applied to the motor phases during turn-on.

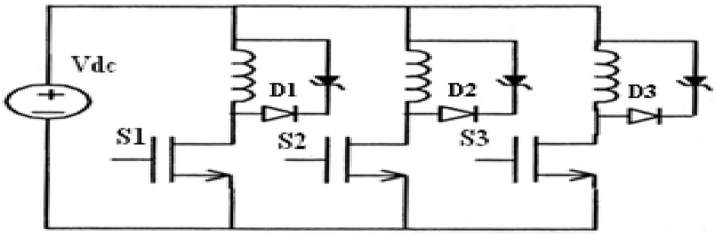


Figure 1. Simple unipolar converter for three-phase

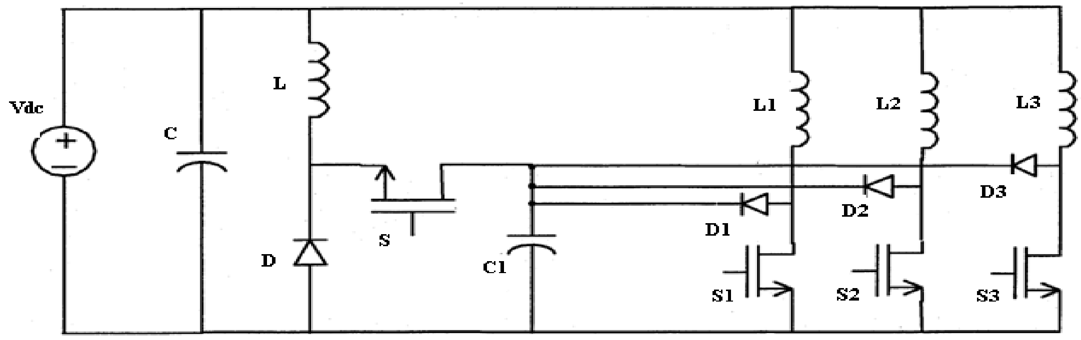


Figure 2. C-dump converter for unipolar BLDC motor drive.

While this is a requirement for the switched reluctance motor in order to achieve a fast turn-off of the phase current to avoid negative torque spikes, it is not so for the BLDC motor. By allowing the phase currents to overlap during the commutation intervals, the commutation torque pulsations can be reduced. The topology proposed in this paper takes advantage of this fact to use a smaller voltage on the dump capacitor. A three-switch converter for the unipolar BLDC motor for ac supply operation was investigated, but it requires a modification in the machine windings and a split-capacitor voltage balancing control scheme.

This paper makes use of the desirable properties of the single ended primary inductance converter (SEPIC) operating in the discontinuous conduction mode (DCM). At constant duty cycle, the average input current automatically tracks to some extent the sinusoidal shape of the input voltage. This is realized without the need of sensing and controlling the input current,thus simplifying the control circuit. Such a feature can be used to integrate the PFC stage with the output voltage regulation or inverter stage, which can lead to considerable cost reduction. The schematic of an ac motor drive with the PFC stage integrated with the inverter is shown in Fig. 3.

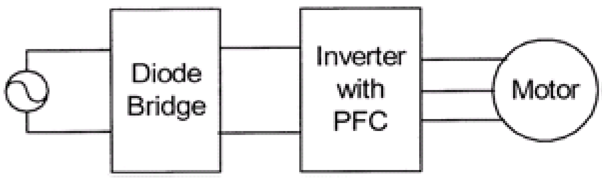


Figure 3. AC motor drive with integrated PFC stage and inverter.

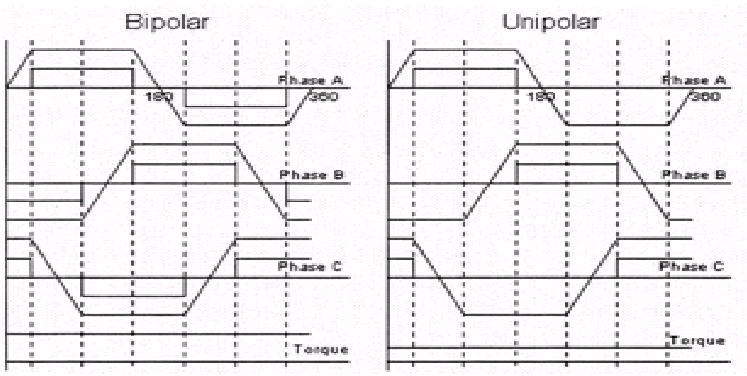
2. UNIPOLAR EXCITATION OF BLDC MOTORS:

Smooth torque production requires forcing a constant current through each phase winding when its back-emf is at its peak value and turning off the current when the back-emf is changing. For bipolar excitation, positive current is injected when the back-emf is positive and negative current when the back-emf is negative, with each conduction period lasting 120^{o}. This results in two phases conducting current and producing torque at any instant of time as shown in the waveforms of Figure 4(a). Unipolar current conduction limits the phases to only one direction of current as shown in Figure 4(b). Constant torque production is still possible because one phase is conducting current at any instant. It is of course possible to have an overlap in the phase conduction to have a smoother torque production.

The primary motivation for choosing unipolar excitation is that in practice, the inverter typically costs more than the motor and there is a great potential for reducing its cost and hence the overall cost of the drive. In addition to cost reduction, unipolar excitation offers the following advantages:

- There is only one device in series with each phase, minimizing conduction losses.
- The risk of shoot-through faults is eliminated.
- Switching of devices connected to the supply rails, which generally requires some isolation circuitry, can be avoided.

Another factor that has to be considered before choosing unipolar excitation is that the motor neutral has to be available because the phase currents are no longer balanced.



(a) (b)

Figure 4. Back-emf, phase current and output torque waveforms with: (a) bipolar excitation and (b) unipolar excitation

3. PROPOSED CONVERTER

The proposed converter with four controlled switches and diodes is shown in Figure 5. The front-end consists of a SEPIC dc/dc converter comprised of inductors L1 and L2, switch S1, intermediate capacitor C1, diode D1 and output capacitor C2. The modification from the usual SEPIC configuration is that the diode D1 is placed in the return path instead of in the positive rail. This is to block the flow of current through the phases during the periods of negative back-emf. A, B, and C are the three machine windings and the currents through them are controlled by turn-on and turn-off of the switches S_A, S_B and S_C respectively. Since there is only one switch per phase, the currents through them are unidirectional. The diodes D_A, D_B and Dc serve to freewheel the winding currents when the switches are turned off during current regulation and phase commutation. The output of the converter is used to energize the three phases of the motor, and the voltage of capacitor C1 is used to demagnetize the phases during turn-off and for current control.

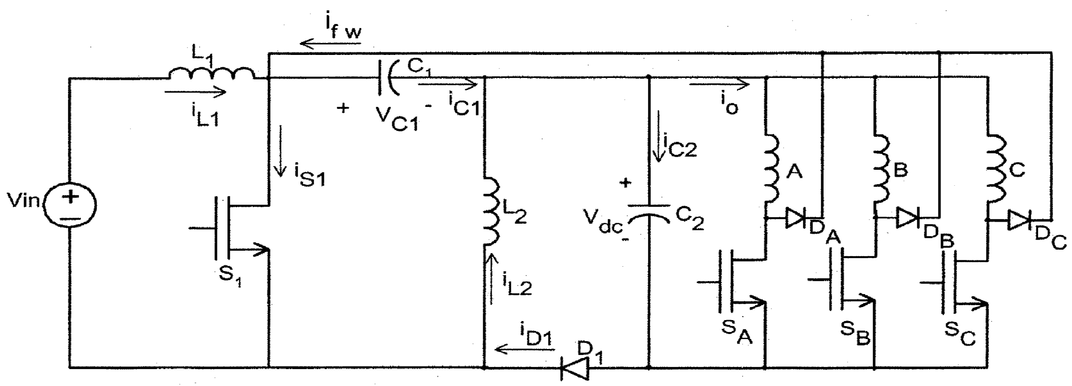


Figure 5. Schematic of SEPIC converter based BLDC motor drive.

For proper demagnetization of the phase after each conduction interval and to prevent conduction during periods of negative back-emf, the instantaneous value of V_{C1} should be greater than the peak value of the back-emf E, or

$$V_{C1} > E \qquad (1)$$

By applying Kirchhoff's voltage law to the SEPIC front-end, we obtain

$$V_{in} = V_{L1}+V_{C1}+V_{L2}$$

Since the average voltages in the two inductors are zero, we get

$$V_{in} = V_{C1} \qquad (2)$$

From equations (1) and (2), we obtain the peak back-emf at the maximum speed of the motor, which is given by, $E_{max} = V_{in}$ assuming that the ripple in the intermediate capacitor voltage is negligible. The maximum operating speed is then given by $\omega_{max}=V_{in}/K_e$, where K_e is the phase back-emf constant of the motor.

The front-end SEPIC converter can be designed for operation either in the continuous conduction mode (CCM) or in the discontinuous conduction mode (DCM). In CCM, its voltage conversion ratio is given by

$$m = \frac{Vdc}{Vin} = \frac{D}{1-D}$$

Where D is the duty cycle of the switch S_1
In DCM, its voltage conversion ratio is given by

$$m_d = \frac{V_{dc}}{V_{in}} = \frac{D}{\sqrt{K}}$$

where , $K=2L_1L_2/RT(L_1+L_2)$,R being the equivalent load resistance and T the time period of switch S1 .The boundary value of K between continuous and discontinuous conduction modes, K_{crit} can be calculated ($m=m_d$) as

$$K_{crit} = (1-D)^2$$

The converter operates in CCM when $K > K_{crit}$ and in DCM when $K < K_{crit}$. In both modes of operation, V_{dc} can be regulated at a value higher (Boost operation) or lower (Buck operation) than the input voltage V_{in} . From the controls viewpoint, it is advantageous to have the converter operating in the same mode under all load conditions. In addition, the size of the inductors and hence the overall converter can be reduced if it is operated in DCM. Hence it is proposed that the converter be designed for operation in the critical conduction mode at maximum load, so that it operates in DCM at rated load and all values less than rated load.

4. AC SUPPLY OPERATION

For applications requiring operation from an ac supply, it is desired to obtain improved power factor by using the proposed topology as shown in Figure 6. The converter works as a voltage follower, meaning that the input current naturally follows the input voltage profile and the theoretical power factor is unity.

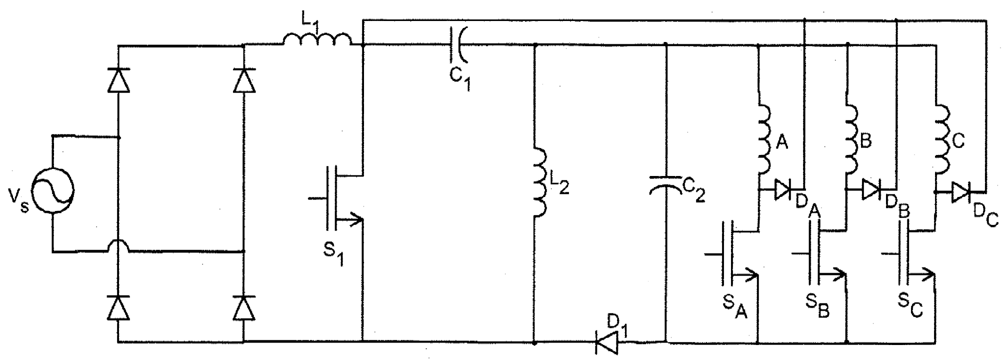


Figure 6. Schematic of the proposed converter operating from an ac supply.

With a unipolar BLDC motor load, the intermediate capacitor voltage has to be greater than the phase back-emf for proper demagnetization of the phases. This causes a distortion of the input current waveform around his zero-crossings of the input voltage. This is acceptable because the input current shaping is achieved at no cost to the drive, and as will be seen, the resulting power factor is better than with the conventional circuit configuration.

There is a practical limit to the power level up to which dc/dc converters can be operated in DCM. This limit is reached around 300W. The use of unipolar excitation for BLDC motors beyond this power rating is also not recommended, as bipolar excitation would better utilize the machine windings. So the proposed topology is well-suited to low-power, low-performance applications where cost is a major consideration.

5. SIMULATION RESULTS

The operation of the proposed topology has been verified by simulation using MATLAB/SIMULINK. A block diagram of the drive system implementation is shown in Figure 7. The rotor position is sensed by means of three hall sensors, and the position information is used to determine the phase winding to be excited. The motor speed is derived from the position inputs and is compared with the speed reference to generate the current references. Hysteresis control is used to regulate the phase currents to the reference current. The dc bus voltage is regulated by PWM control of the switch S1. The motor shaft is coupled to a hysteresis brake acting as a load

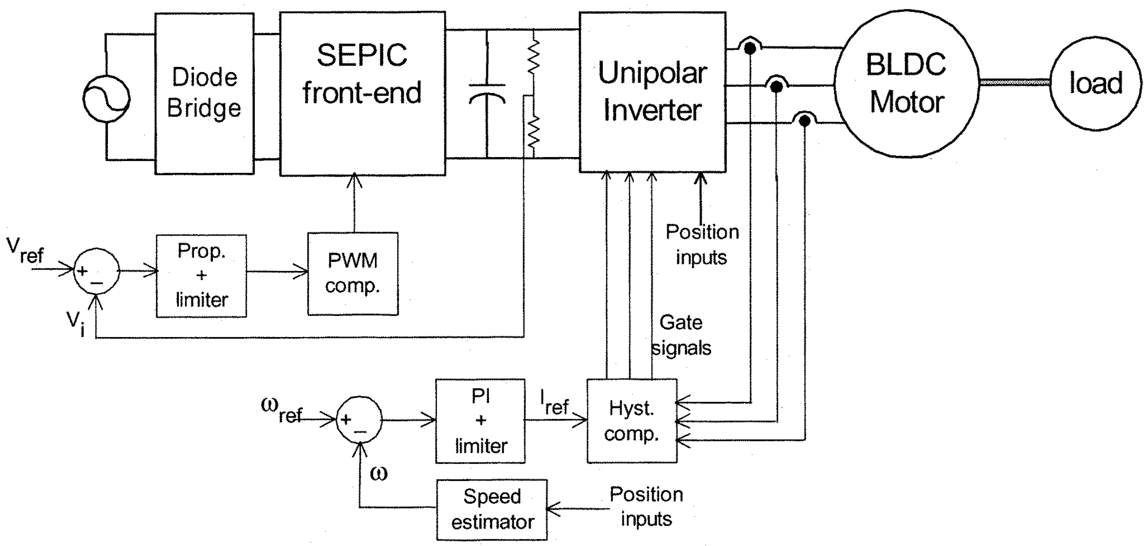


Figure 7. Block diagram of the drive system

A PI controller is used to compare the reference and actual speed and generate the current reference. The performance improvement achieved by using the proposed topology is evident.

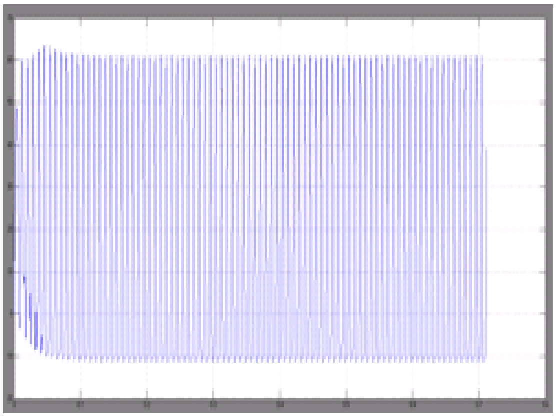


Figure 8. Output DC Voltage waveform before boosting

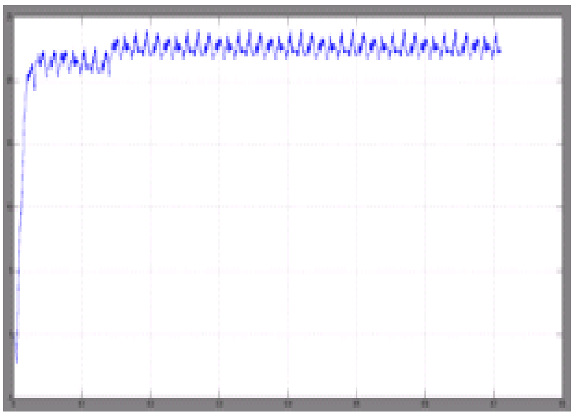


Figure 9. Output DC Voltage waveform after boosting

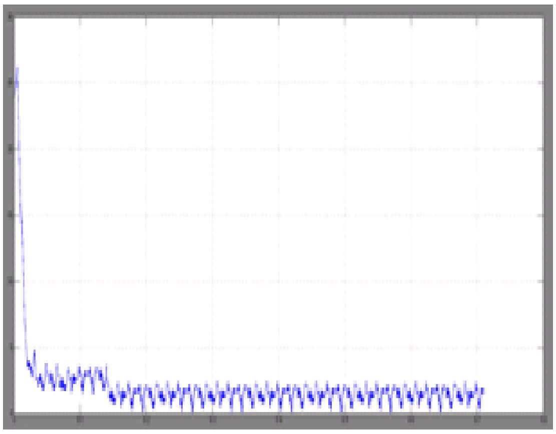


Figure 10. DC Error Voltage waveform

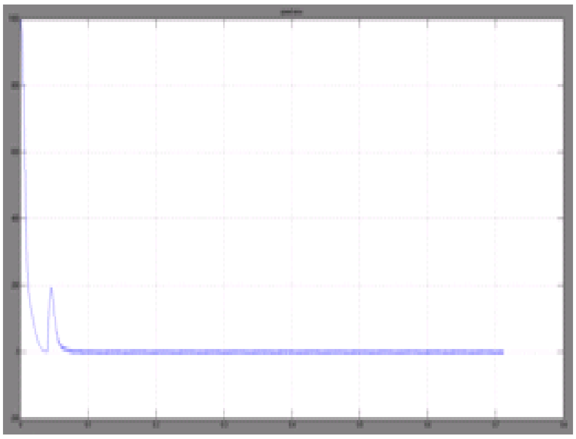


Figure 11. Speed Error waveform

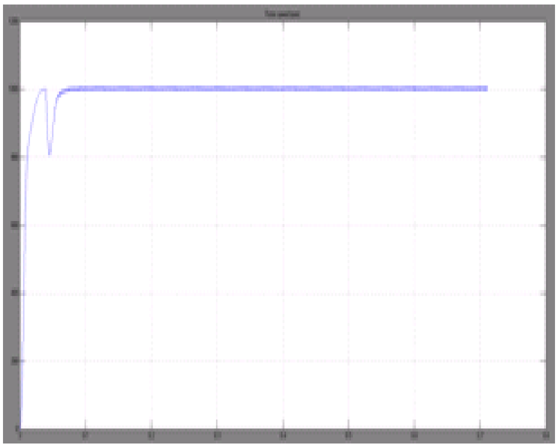


Figure 12. Rotor Speed waveform

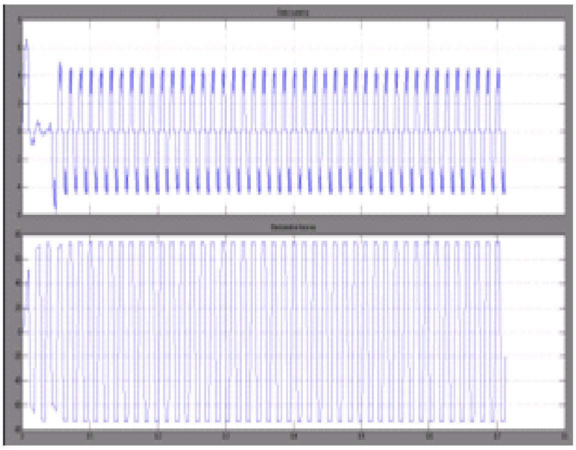


Figure 13. Stator Current Ia and EMF Ea waveform

6. CONCLUSION

A new converter topology based on a SEPIC converter operating in DCM has been proposed for unipolar excitation of brushless dc motors. The proposed scheme has the following advantages.

1. The proposed converter uses only four controlled switches, all of which are referenced to ground. This considerably simplifies their gate drive circuitry and results in low cost and compact packaging.
2. It is capable of bucking or boosting the available input dc voltage to maximize the current-regulated operation of the drive.
3. The input current naturally follows the input voltage to a certain extent, reducing the amount of low-order harmonics and resulting in a high power factor.
4. Eliminates the possibility of shoot-through faults which could occur in bipolar converters.
5. Lower conduction and switching losses because of the presence of only one switch and diode per phase as opposed to two in the bipolar case.

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