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REDUCED CURRENT STRESS BRIDGELESS CUK PFC CONVERTER WITH NEW VOLTAGE MULTIPLIER CIRCUIT

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Abstract— This paper presents a bridgeless CUK Converter with Voltage multiplier circuit and reduced current stress. The absence of bridge rectifier, transformer and the presence of only semiconductor switches in the current flowing path during each switching cycle results in less conduction losses and improved thermal management, reducing component count, size and cost of the converter compared to the conventional CUK PFC converter. In addition the proposed topology has semi-soft switching function of all active switches to reduce converter switching losses. Therefore, switch conduction losses and switch power losses all can be decreased due to the reduced current stress and semi-soft switching function. Unlike the existing converters the proposed bridgeless PFC CUK converter topology is able to achieve simple control structure with high efficiency, low Total harmonic Distortion (THD) and high input power factor. The proposed circuit configuration with BLDC motor drive load is designed in Matlab/simulation software and the performance of the system is analyzed.

Keywords:bridgeless; Cuk derived; AC/DC converter; power factor correction; semi-soft switching

I. INTRODUCTION

A new single phase ac-dc Cuk derived PFC bridgeless converter with voltage multiplier is introduced. The bridgeless topology with reduced switch current stress can increase the power rating and lifetime of the power converter. Although the four switches are utilized, the active switches all have semi-soft switching function, which implies there only exists one-half switching power losses of the four switches. In addition, the voltage gain also can be extended without extreme duty cycle operation which makes the proposed topology suitable for universal line voltage applications. The proposed bridgeless Cuk derived PFC rectifier with voltage multiplier cell. Where SW1 and SW2 is the PFC switch module and controlled by the PFC-controlled duty Dw, and So1 and So2 is the output voltage switch module and controlled by the output-voltage-controlled duty Do. Since the proposed circuit consists of two symmetrical configurations, the circuit is only analyzed in the positive half line cycle. First, assuming that the L1 inductor is operating in CCM and the L2 is operating in DCM, then the key waveforms of proposed bridgeless converter during one switching period Ts in a positive half-line period and the circuit operation can be divided into four distinct operating modes.a robust input filter must be adopted to suppress the high-frequency

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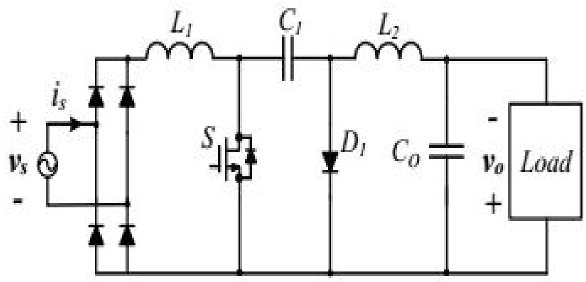
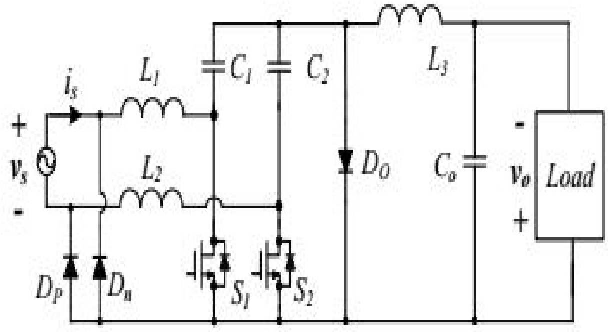
pulsating input current, which results in the weight and cost of the rectifier.To improve the drawbacks of a bridgeless PFC boost rectifier, the step up/step down AC-DC rectifiers [10]-[12] for Sepic and Cuk converter were proposed. However, the topologies all suffer from high current stresses of active switches due to the switch currents flowing together coming from input PFC current and output load current such as bridge [8] and bridgeless [10] Cuk derived AC/DC converters shown in Fig.3.1 (a) and Fig.3.1(b), respectively, which results in increasing conduction losses and switch current stresses so as to decrease the power rating and lifetime of the power converter.The bridgeless topology with reduced switch current stress can increase the power rating and lifetime of the power converter. Although the four switches are utilized, the active switches all have semi-soft switching function, which implies there only exists one-half switching power losses of the four switches. In addition, the voltage gain also can be extended without extreme duty cycle operation which makes the proposed topology suitable for universal line voltage applications. The Cuk converter has several advantages in power factor correction applications, such as easy implementation of transformer isolation, natural protection against inrush current occurring at start-up or overload current, lower input current ripple, and less electromagnetic interference(EMI) associated with discontinuous conduction mode topology. Thus for applications, which require a low current ripple at the input and output ports of the converter, Cuk converter is efficient [9-10].



(a)



(b)

Fig.1. Conventional single-phase (a) bridge [8] and (b) bridgeless Cuk derived AC/DC converters.

II. CIRCIT OPERATION

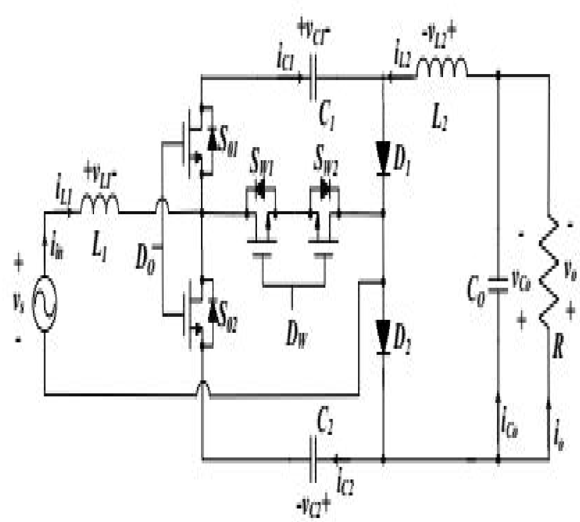


Fig.2 Proposed bridgeless single-phase Cuk derived PFC topology

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The proposed bridgeless Cuk derived PFC rectifier with voltage multiplier cell is shown in Fig. 3.2. Where SW1 and SW2 is the PFC switch module and controlled by the PFC-controlled duty Dw, and So1 and So2 is the output voltage switch module and controlled by the output-voltage-controlled duty Do. Since the proposed circuit consists of two symmetrical configurations, the circuit is only analyzed in the positive half line cycle. First, assuming that the L1 inductor is operating in CCM and the L2 is operating in DCM, then the key waveforms of proposed bridgeless converter during one switching period Ts in a positive half-line period are shown in Fig.3.3 and the circuit operation can be divided into four distinct operating modes as shown in Fig.3.4 (a)-(d), which can be described as follows.

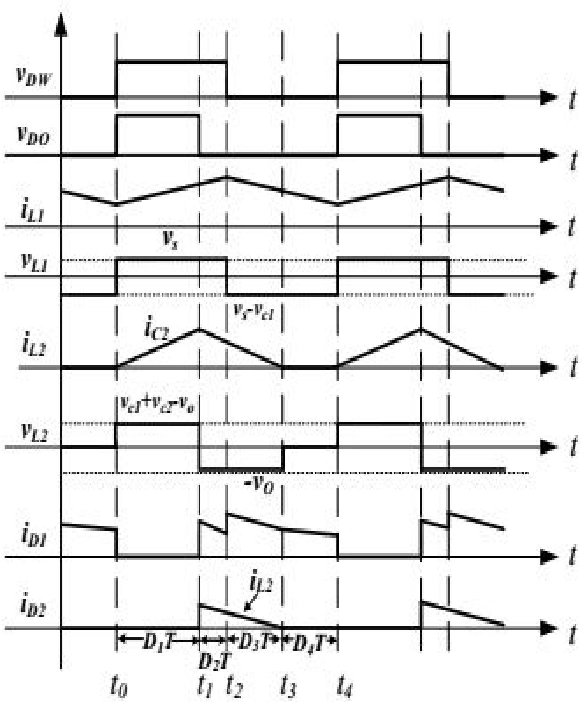
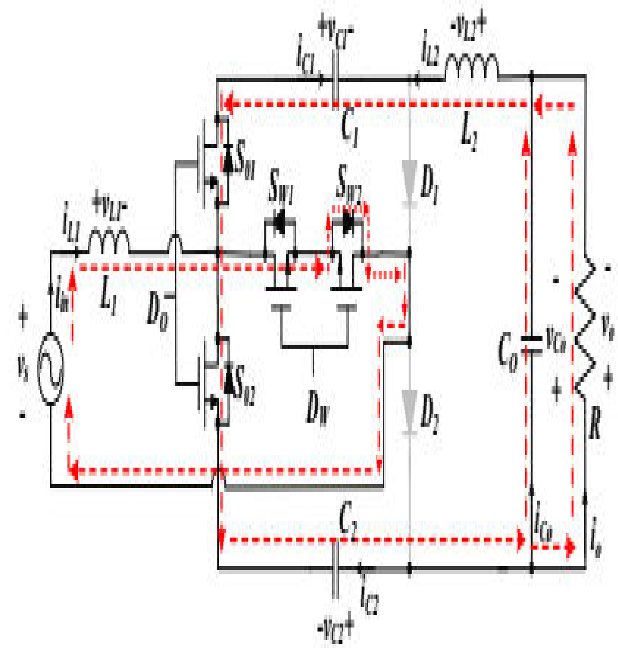
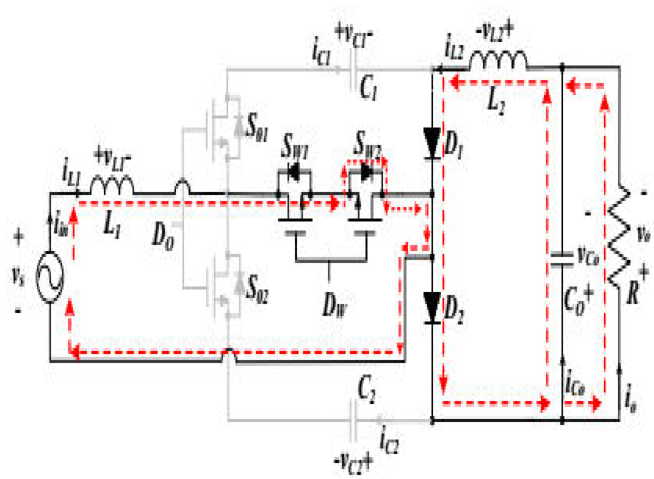


Fig.3 The key waveforms of proposed bridgeless converter during positive half-line period.

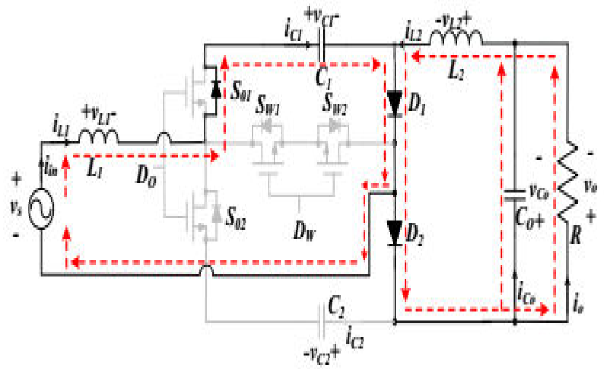
1) **State 1** (t0<t<t1): In this stage, as shown in Fig.3.4 (a), the PFC switch module and output-voltage switch module are turned on. Inductor current iL1 is increasing to store energy. Capacitors C1 and C2 release their energy to the inductor L2 and output. The state and output equations can be expressed as follows.



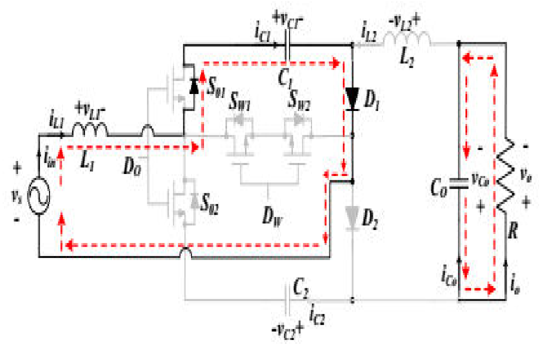
(a)



(b)



(c)



(d)

Fig. 4 Operation circuits of the proposed bridgeless Cuk derived converter under (a)State 1 (b)State 2 (c)State 3 (d)State 4 during positive half-line period.

$$\frac{dx}{dt} = A_1 x + B_1 u \quad (1)$$

$$y = C_1 x \quad (2)$$

Where the state and output vectors are defined as

$$x = \begin{bmatrix} i_{L1} & i_{L2} & v_{C1} & v_{C2} & v_{CO} \end{bmatrix}^T, \ y = \begin{bmatrix} i_{in} & v_o \end{bmatrix}^T$$

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & \frac{1}{L_2} & -\frac{1}{L_2} \\ 0 & -\frac{1}{C_1} & 0 & 0 & 0 \\ 0 & -\frac{1}{C_2} & 0 & 0 & 0 \\ 0 & \frac{1}{C_o} & 0 & 0 & -\frac{1}{RC_o} \end{bmatrix}, \ B_1 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix},$$

$$C_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \ u = v_s$$

2) **State 2** (t1<t<t2): In this stage, as shown in Fig.3.4(b), the PFC switch module remains on and output-voltage switch module is turned off. Inductance current iL1 continues increasing to store energy. The inductor L2 releases its current to output load. The state and output equations can be described as follows

$$\frac{dx}{dt} = A_2 x + B_2 u \quad (3)$$

$$y = C_2 x \quad (4)$$

Where

$$A_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_2} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_0} & 0 & 0 & -\frac{1}{RC_0} \end{bmatrix}, \ B_2 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \ C_2 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

3) **State 3** (t2<t<t3): In this stage, as shown in Fig.3.4(c), the PFC switch module turns off and output-voltage switch module remains off. The inductor L1 releases its current to the capacitor C1. The inductor L2 continues to release its current to output load. The state and output equations can be expressed as follows.

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$$\frac{dx}{dt} = A_3 x + B_3 u \quad (5)$$

$$\frac{dx}{dt} = A_3 x + B_3 u \quad (6)$$

Where

$$A_3 = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_2} \\ \frac{1}{C_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_o} & 0 & 0 & -\frac{1}{RC_0} \end{bmatrix}, B_3 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, C_3 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

4) **State 4** (t3<t<t4): In this stage, as shown in Fig.3.4(d), the PFC switch module remains off and output-voltage switch module remains off. The inductor L1 continues to release its current to the capacitor C1. The inductor current iL2 had dropped to zero. The output voltage is supplied from the output capacitor Co. The state and output equations can be expressed as follows.

$$\frac{dx}{dt} = A_4 x + B_4 u \quad (7)$$

$$y = C_4 x \quad (8)$$

Where

$$A_4 = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{RC_0} \end{bmatrix}, B_4 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, C_4 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

III. STEADY-STATE ANALYSIS

The analysis of voltage gain and switch current stress of the proposed converter operated in steady state. Furthermore, the comparison of conventional Cuk converter [8], bridgeless Cuk converter [10], and the proposed converter are also discussed to verify the validity of proposed converter.

a) Voltage gain

Consider the converter is operating in one switching period during positive half-line period. By utilizing state-space averaged technique and voltage second balance theory in the inductor L1 during the Dw duty period, one can obtain the relationship as follows:

$$v_{C1} = \frac{v_s}{(1 - D_W)} \quad (9)$$

Similarly, for the inductor L2 during the Do duty period, the voltage relationship can be obtained

$$v_O = (v_{C1} + v_{C2}) D_0 \quad (10)$$

Next, Consider the converter is operating in one switching period during the negative half-line period, and one can obtain the following equations:

$$v_{C2} = \frac{-v_s}{(1 - D_W)} \quad (11)$$

$$v_0 = (v_{C1} + v_{C2}) D_0 \quad (12)$$

According to the equations (9)-(12), the voltage gain of proposed converter can be derived as follows:

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$$v_o = D_0(v_{c1} + v_{c2}) = D_0(\frac{|v_s|}{1-D_W} + \frac{|v_s|}{1-D_W}) = \frac{2D_0}{1-D_W}|v_s| \quad (13)$$

For convenient comparison, assume that DO=DW. Fig. 3.5 shows the comparisons of voltage gain as a function of duty ratio for the three converters. As can be seen from Fig.3.5, the proposed converter has twice the voltage gain compared with the conventional bridge [8] and bridgeless [10] AC-DC Cuk derived converters.

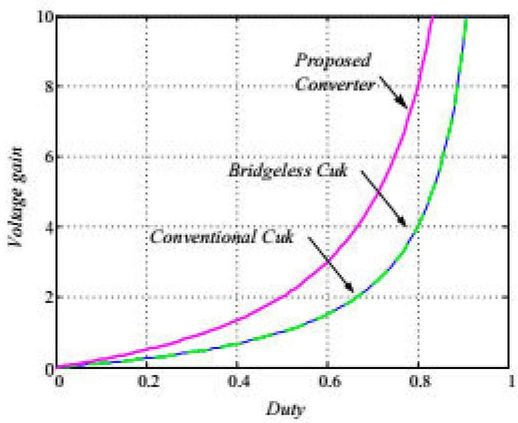

Fig. 5 Comparisons of voltage gain for the conventional Cuk [8], bridgeless Cuk [10],and the proposed converter.

b)Current stresses of active switches

According to the circuit operation, the current stress of PFC switch module and OV switch module is iin or io. Compared with the conventional Cuk [8] and bridgeless Cuk [10], consider the converter is operated at the same input voltage Vs and output load Io. The switch current stress of the conventional Cuk and bridgeless Cuk is iin + io as shown in Fig.3.6 for illustration. Although the proposed converter needs four switches, the proposed converter has lower switch current stress and lower cost of each switch. Therefore, it can be utilized for higher input current application compared to the conventional Cuk and bridgeless Cuk. Table 3.1 is provided to summarize comparisons of the switch/diode/inductance number, current stress, voltage gain for the conventional bridge [8], bridgeless [10], and the proposed Cuk derived rectifiers.

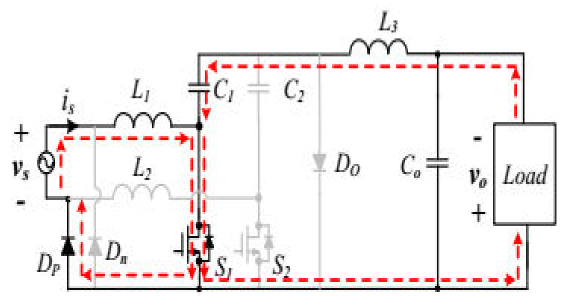

Fig. 6 The illustration of switch current stress of conventional bridgeless Cuk converter

Table 3.1. Comparisons Of Cuk Derived Ac/Dc Converters

	Conventional Cuk [8]	Bridgeless Cuk [10]	Proposed
Slow diode	4	2	0
Fast diode	1	1	2
Inductance	2	3	2
Switch count	1 switches (Hard switching)	2 switches (Hard switching)	4 switches (All switches with semi-soft switching)
Switch current stress	$i_{in}+i_o$	$i_{in}+i_o$	i_{in} or i_o
Voltage gain	$v_O = \frac{D}{1-D} \cdot \lvert v_{sin} \rvert$	$v_O = \frac{D}{1-D} \cdot \lvert v_{sin} \rvert$	$v_o = \frac{2D_0}{1-D_W} \lvert v_{sin} \rvert$
Bridgeless	No	Yes	Yes

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IV. BLDC MOTOR

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 com- mutated. BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

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

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors. In this application note, we will discuss in detail the construction, working principle, characteristics and typical applications of BLDC motors.

MAIN CHARACTERISTICS BLDC MOTOR

Brushless DC motors consist of two coaxial magnetic armatures separated by an air gap. In certain types of motor,

- The external armature, the stator, is fixed.
- The internal armature, the rotor, is mobile (the rotor can also be external in certain cases).
- The stator is the induced part of the machine.
- The rotor is the inductor of the machine.
- In brushless DC motors, the internal armature, the rotor, is a permanent magnet. This armature is supplied by a constant current (DC).
- The external armature (stator) is poly phased (3 phases in our case) and is covered by poly- phased currents.

In a Brushless DC motor, the rotor is a permanent magnet, this type of motor has almost the same properties and physical laws as a DC current machine. An electric motor transforms electrical energy into mechanical energy. Two main characteristics of a brushless DC motor are:

- It has an electromotive force proportional to its speed
- The stator flux is synchronized with the permanent magnet rotor flux.

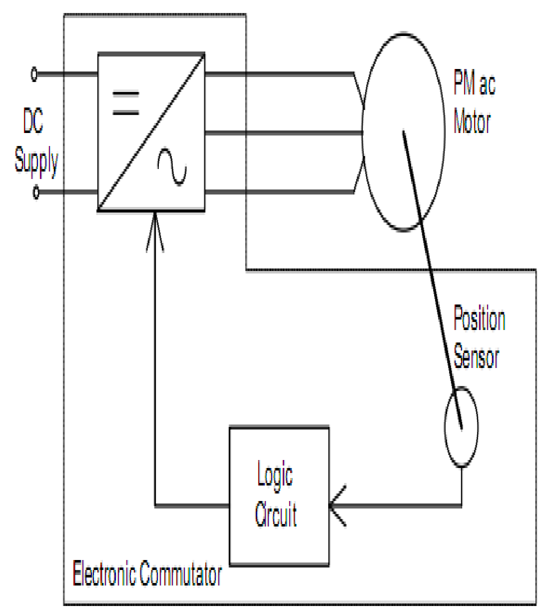

Fig.7. Brushless dc motor = Permanent magnet ac motor + Electronic commutator

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V.MATLAB/SIMULINK RESULTS

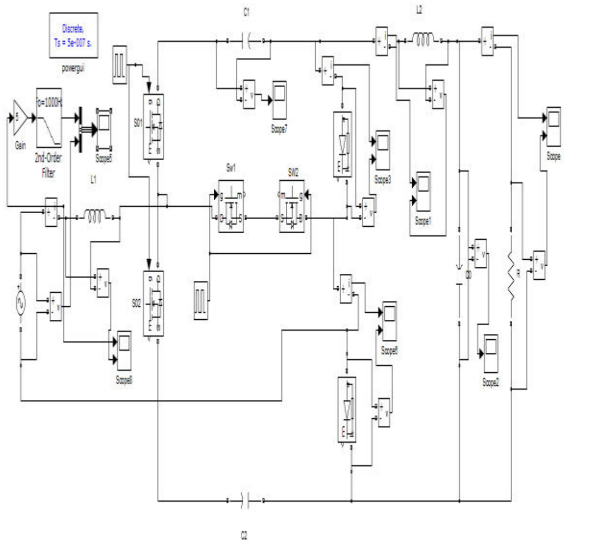

Fig.8. Simulink model of Proposed bridge-less single phase CUK derived PFC topology

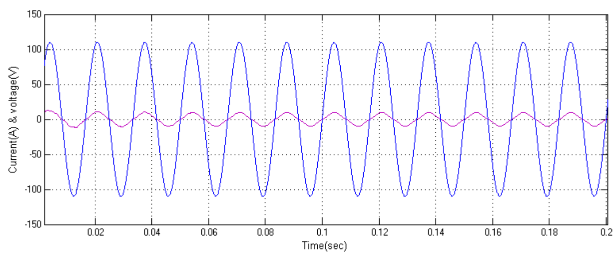

Fig.9. Supply Voltage and current

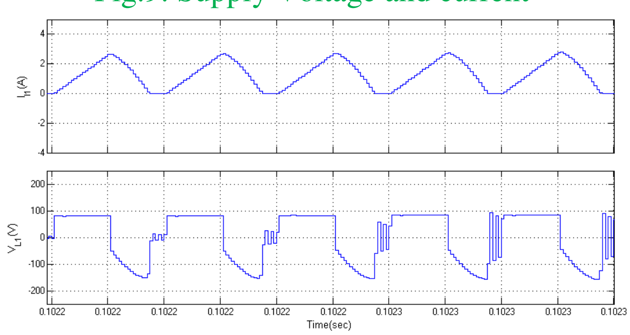

Fig.10. Inductor L1 Voltage and current

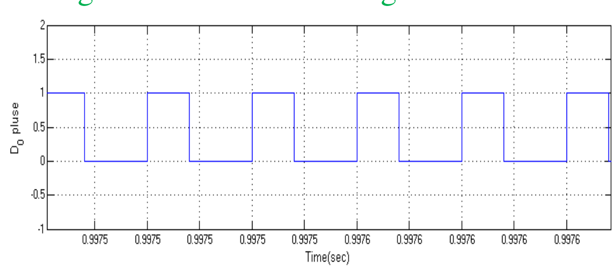

Fig.11. Switching Pulse D0

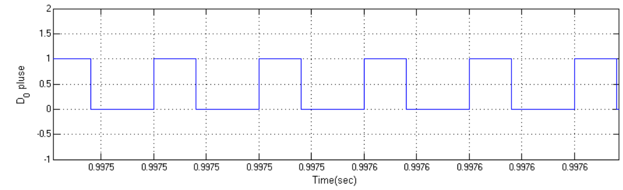

Fig.12. Switching pulse Dw

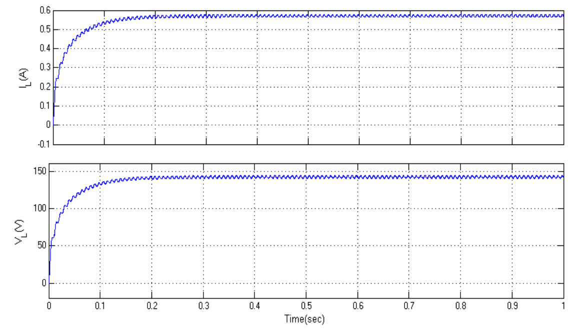

Fig.13. Output Voltage and Current

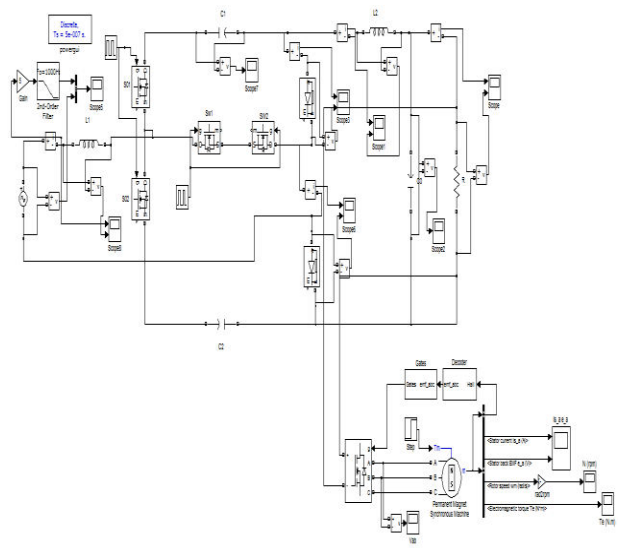

Fig.14. Simulink model of proposed bridge-less single phase CUK Derived PFC topology with BLDC Motor Load

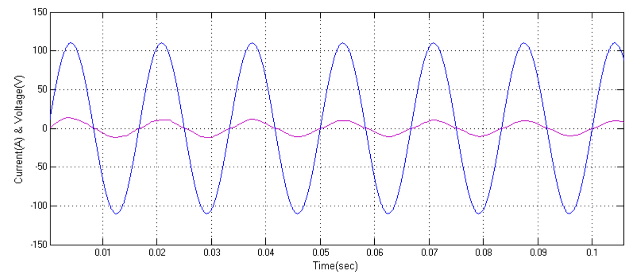

Fig.15. Input voltage and current with Motor load

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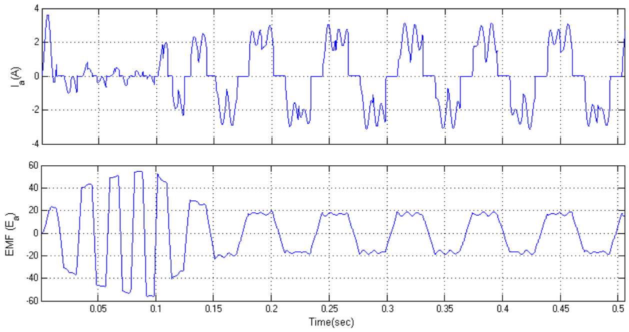

Fig.16. Stator current and Back EMF

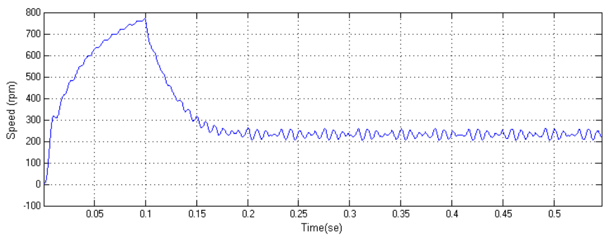

Fig.17. Speed

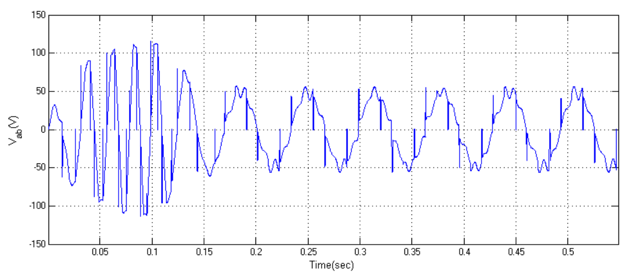

Fig.18. Inverter Voltage Vab(V)

VI.CONCLUSION

In this project a new single phase ac-dc Cuk derived PFC bridgeless rectifier with voltage multiplier is introduced. The bridgeless topology with reduced switch current stress can increase the power rating and lifetime of the power converter. Although the four switches are utilized, the active switches all have semi-soft switching function, which implies there only exists one-half switching power losses of the four switches. Also absence of bridge rectifier, transformer results in less conduction losses, reduced component count, less size and cost. Due the lower conduction losses and switching losses the proposed topology can further improve the conversion efficiency and also improves the input power factor when compared with the conventional CUK PFC converter.

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