I J C T A, 9(2) 2016, pp. 1071-1082

A Bridgeless High Gain Cuk Converter for Power Factor Correction and Reduction of Harmonic Distortion in BLDC Motor

D. Saravanan[1*] and M. Gopinath[2]

ABSTRACT

In this paper a bridgeless Cuk converter is used for Power factor correction (PFC) for a BLDC motor. Bridgeless Cuk converter has only two semiconductor switches in the current flowing path. During each interval of the switching cycle it result in less conduction losses and an improved thermal management compared to the conventional Cuk PFC rectifier. To achieve almost unity power factor and to reduce the input current stress, the topologies are designed to work. This paper works on the limitations of the conventional PFC Cuk converter are resolved. The proposed Bridgeless High Gain CUK converter (BL-HG-CUK) for BLDC motor is simulated in MATLAB and the corresponding results show the better power quality indices such as power factor and Total Harmonic Distortion (THD).

Keywords: Bridgeless Cuk Converter, Power Factor Correction (PFC), BLDC Motor, Total Harmonic Distortion, Discontinuous Mode

1. INTRODUCTION

Nowadays, Cost and Efficiency are the critical issues in the design of low-power motor drives aiming at household applications like fans, water pumps, blowers, mixers, etc.1], [2]. Brushless direct current (BLDC) motor are finding large amount of usage in these applications because of the features with respect to huge efficiency, greater flux density per unit volume, lesser maintenance necessities, and lesser problems of electromagnetic-interference [1]. These BLDC motors are not restricted to household applications, also these are desirable for other applications including medical equipment, transportation, HVAC, motion control, and several other industrial instruments [2]–[4]. A BLDC motor consists of three phase windings on the stator and permanent magnets on the rotor [5], [6]. The BLDC motor is also referred to as an electronically commutated motor as an electronic commutation on the basis of the rotor position is employed instead of than a mechanical commutation that has drawbacks such as sparking, wear and tear of brushes as well as commutator assembly [5], [6].

Problems of Power quality have emerged to be significant issues to be taken into consideration because of the recommended limits of harmonics present in the supply current set by different international power quality standards inclusive of the International Electrotechnical Commission (IEC) 61000-3-2 [7]. For class-A equipment (<600 W, 16 A per phase) that contains household equipment, IEC 61000-3-2 limits the harmonic current of a different order in such a way that the total harmonic distortion (THD) of the supply current must be less than 19% [7]. A BLDC motor which when powered by a diode bridge rectifier (DBR) with a huge 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 [8]. Therefore, a DBR which is followed by a power factor corrected (PFC) converter is employed for enhancing the power quality at the ac mains.

[1] Research Scholar, Department of Electrical and Electronics Engineering, St.Peter's University, Chennai, Tamilnadu, India.
[2] Professor, Department of EEE, Dr.N.G.P. Institute of Technology, Coimbatore, Tamilnadu, India
[*] *Corresponding Author E-mail: saravanandrs16@gmail.com*

For the purpose of increasing the efficiency of the power supply, considerable research attempts have been targeted at the development of bridgeless PFC converter circuits, in which the number of semiconductors that are generating the losses are reduced through the removal of the full bridge input diode rectifier. Recently, different bridgeless PFC rectifiers have been introduced with the aim of boosting the rectifier power density and/or reduce the noise emissions by means of soft-switching methods [9]-[12]. Several bridgeless PFC rectifiers make use of a boost converter at their front end. But, the bridgeless boost rectifier [13]–[16] is put back with the same crucial real-time drawbacks similar to the conventional boost converter which are the dc output voltage being higher than the peak input voltage, the galvanic isolation being absent, and huge start-up inrush currents. Therefore, for supporting the applications that are involved with low-output voltage, just as in telecommunication or computer fields, an additional converter or an isolation transformer is required for the voltage step-down.

As an alternative usually in high output voltage applications, a boost-type dc–dc converter is added to the distributed power generation (DG) units for stepping up the dc voltage [17]–[19]. This type of topology, though simple, it might not have the ability to give sufficient dc voltage gain at the time when the input is very less, even in the presence of an extreme duty cycle. In addition, a large duty cycle operation can lead to severe reverse-recovery issues and thereby raise the ratings corresponding to the switching devices. Moreover, the converter that is added can also result in the deterioration of the system efficiency and increase in the size of the system, weight, and cost. The CUK converter renders multiple advantages in PFC applications, such as the easier implementation of the transformer isolation, natural safeguard against the inrush current which happens during the start-up or overload current, lesser input current ripple, easy accessibility towards high gain structure and low electromagnetic interference (EMI) with respect to the discontinuous conduction mode (DCM) topology [20], [21].

The selection of the operating mode of the PFC converter is a type of trade-off between the allowed stresses on the PFC switch and cost expense of the entire system. A PFC converter is designed in such a way to function in the two different modes of operation namely the Continuous conduction mode (CCM) and discontinuous conduction mode (DCM) of operation. A voltage follower approach is one of the control strategies used for a PFC converter which functions in the DCM. This voltage follower methodology requires a single voltage sensor for the regulation of the dc-link voltage having a PF close to unity at ac mains. Therefore, voltage follower control is more advantageous in having a current multiplier control of requiring a single voltage sensor. This yields the control of the voltage follower an easier way to gain PFC and output voltage control, but at the expense of huge stress over the PFC converter switch. On the other hand, the current multiplier approach gives less stress on the PFC switch, though three more sensors for PFC and output voltage control [22], [23] are required. In accordance with the design parameters, any one of the approach may force the converter to either function in the DCM or CCM.

2. PROPOSED PFC SCHEME OF BL-HG CUK CONVERTER FED BLDC MOTOR DRIVE

The new PFC bridge less-high gain CUK (BL-HG CUK) converter-fed BLDC motor drive is illustrated in Figure 1. The system proposed comprises of front end partly eliminated DBR, a PFC BL-HG CUK converter, and a voltage source inverter (VSI) fed BLDC motor drive. A BL-HG CUK converter is employed for PFC and speed regulation of BLDC motor. This converter functions in the DCM using a voltage follower approach i.e., the current which is flowing in either of the input or output inductor (Li and Lo) or else the voltage across the intermediate capacitor (C1) attempts to become irregular in a switching period. On the contrast, DCM requires a single voltage sensor for the control of output voltage, and the inherent PFC is accomplished at the ac mains.

The proposed BL-HG CUK converter is developed by a connection between two dc–dc Cuk converters, one for every half-line period (positive/negative half cycle) of the input voltage. In addition, Figure 1 shows that one of the rails of the output voltage bus is in connection with the input ac line at all times by

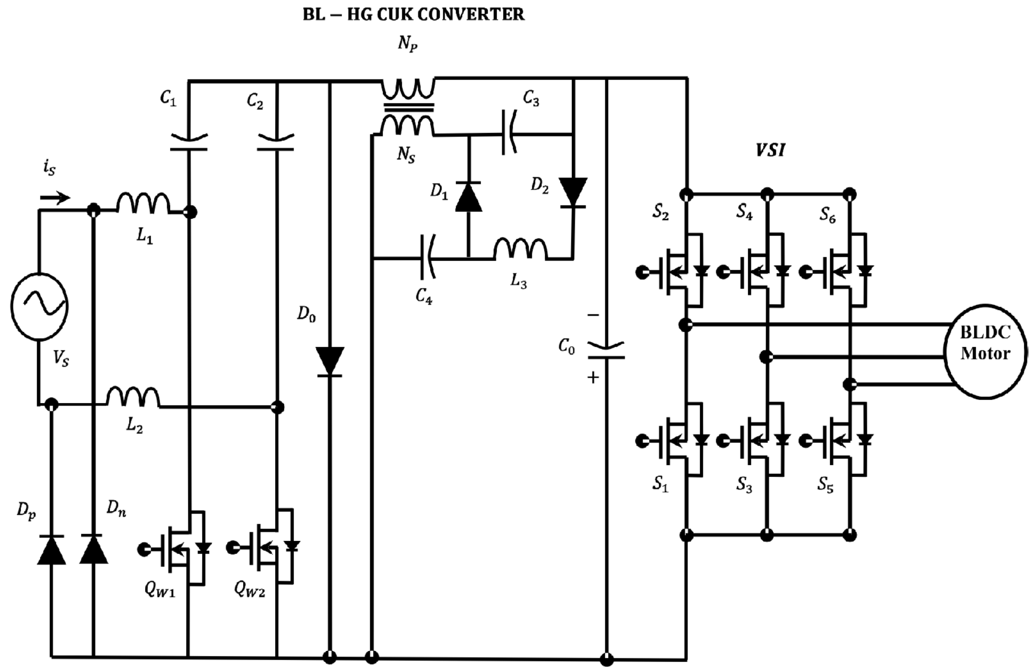

Figure 1: The Proposed PFC BL-HG CUK Converter

means of the slow-recovery diodes Dp and Dn. Hence, the topologies proposed do not suffer by the high common-mode EMI noise emission issue. Moreover the new converter exploits the use of two power switches (Q_{W1} and Q_{W2}). But yet, the same control signal can have control over the two power switches that significantly yields simplicity for the control circuitry.

As a result for achieving higher output voltage level in BL-HG CUK converter, the Coupled inductor's turn ratio can be controlled to regulating the boost gain. Hence, the output voltage can be controlled in a far and wide range and it can be stepped up to a higher value. At last, the bus voltage becomes equal to the sum of the capacitor voltages, and it is higher in comparison with every capacitor voltage. The bridgeless arrangement having coupled inductor is appropriate for applications in which the input voltage changes from a comparatively lower level to a higher level in a continuous manner when a stable dc voltage is provided as output having high power factor (PF). The operating principle of the new BL-HG CUK converter and the corresponding converter control loop is explained in sections that follow.

Operating Principle of BL-HG CUK Converter

The new BL-HG CUK converter is developed to operate with DCM such that the current in inductor L1 tends to become non-continuous for a switching period. Figure 2(a)–(c) shows the various modes of operation during an entire switching period for the corresponding positive and negative half-cycles of the supply voltage.

Operation during Positive Half-cycles of Supply Voltage

Mode 0

As shown in Figure 2(a), once the switch Q_{W1} is turned on, inductor L_1 on the input side starts to charge, and then current i_{L1} sees an increase, when the intermediate capacitor C_1 begins discharging through the switch Q_{W1} for charging the output capacitor C_0. Therefore, the voltage across the intermediate capacitor reduces, on the other side, the output voltage finds an increase. In addition, the energy on the secondary side of coupled inductor (N_S) transferred to the capacitors C_3 and C_4 thereafter the inductor L_3 by means of diode D_1. At that time, the capacitor C_4 voltage is transferred to the output capacitor C_0.

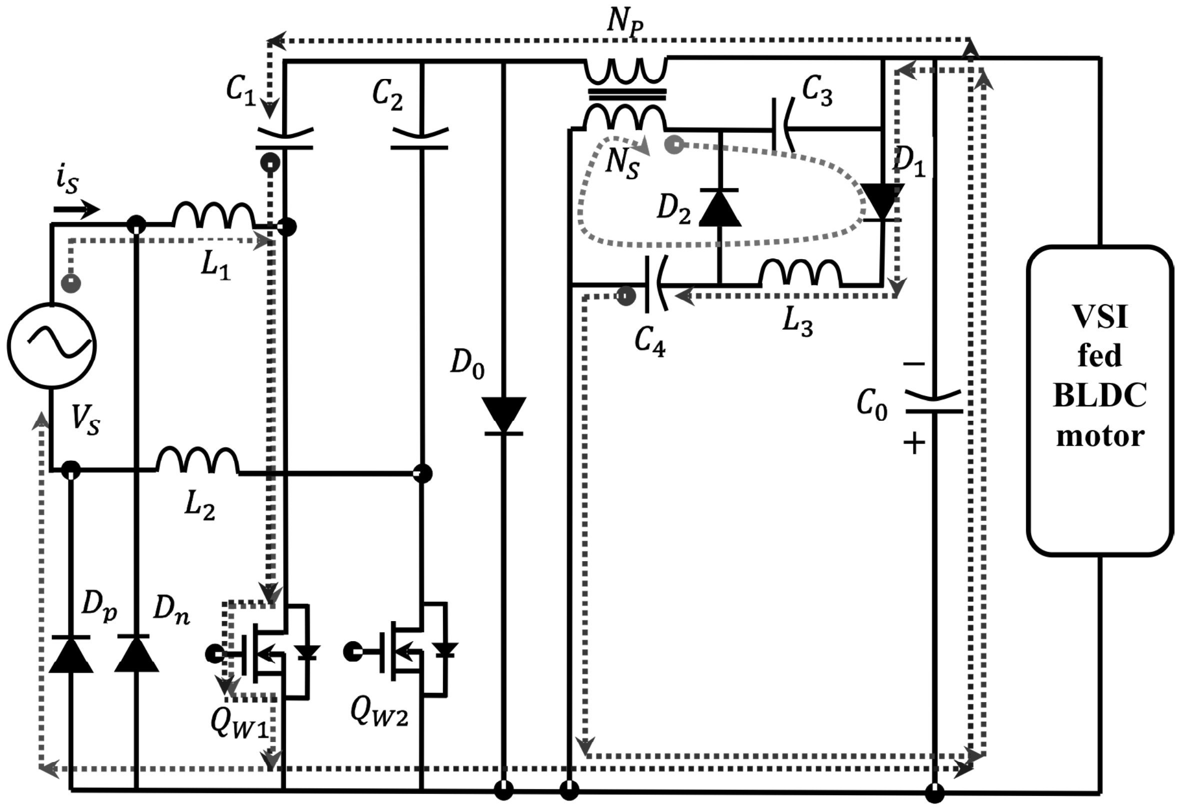

Figure 2(a): Mode 0

Mode 1

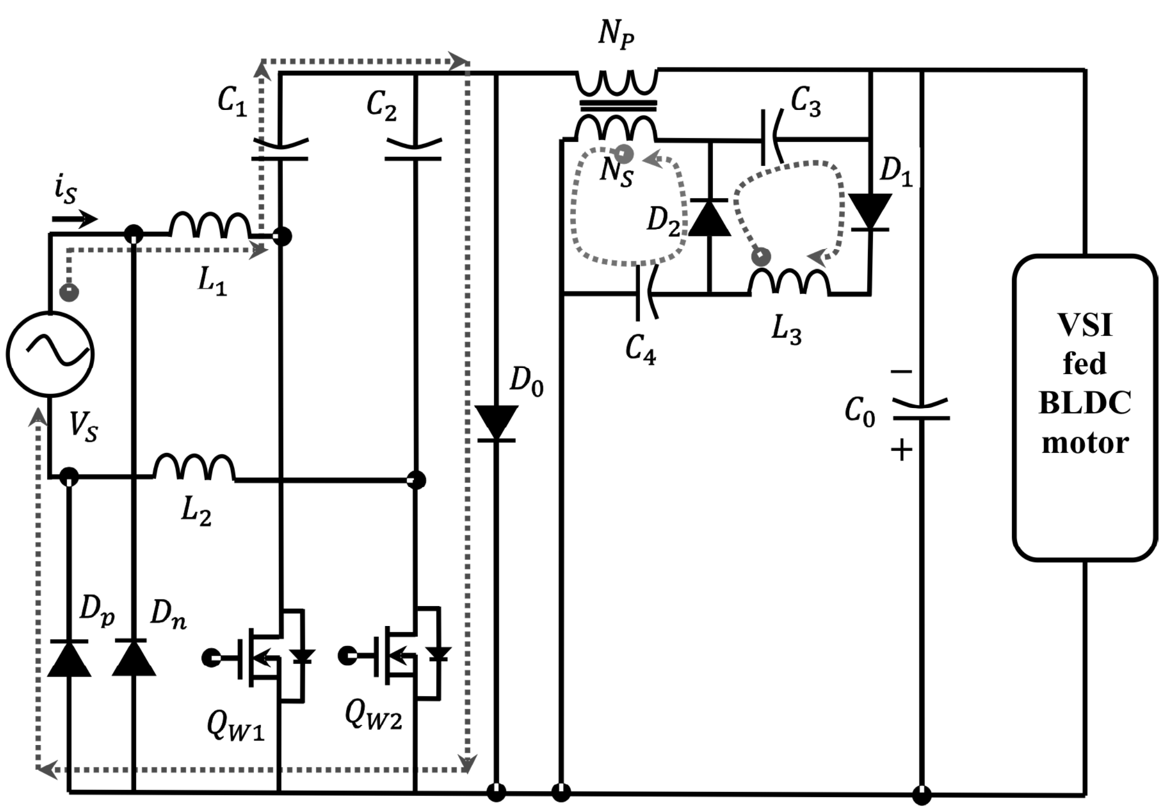

Figure 2(b): Mode 1

When the switch Q_{W1} is turned off, the energy which is stored in input inductor L_1 commences to discharge to the intermediate capacitor C_1 through diode D_0 and D_p, as shown in Figure. 2(b). The current i_{L1} sees a decrease, once the intermediate capacitor voltage tends to continue increasing in this mode of operation. Additionally, the output side inductor L_3 starts to discharge, and the capacitor voltage C_3 increases, as a result the secondary side of coupled inductor (N_S) for charging the capacitor C_4 as indicated in Figure 2(b).

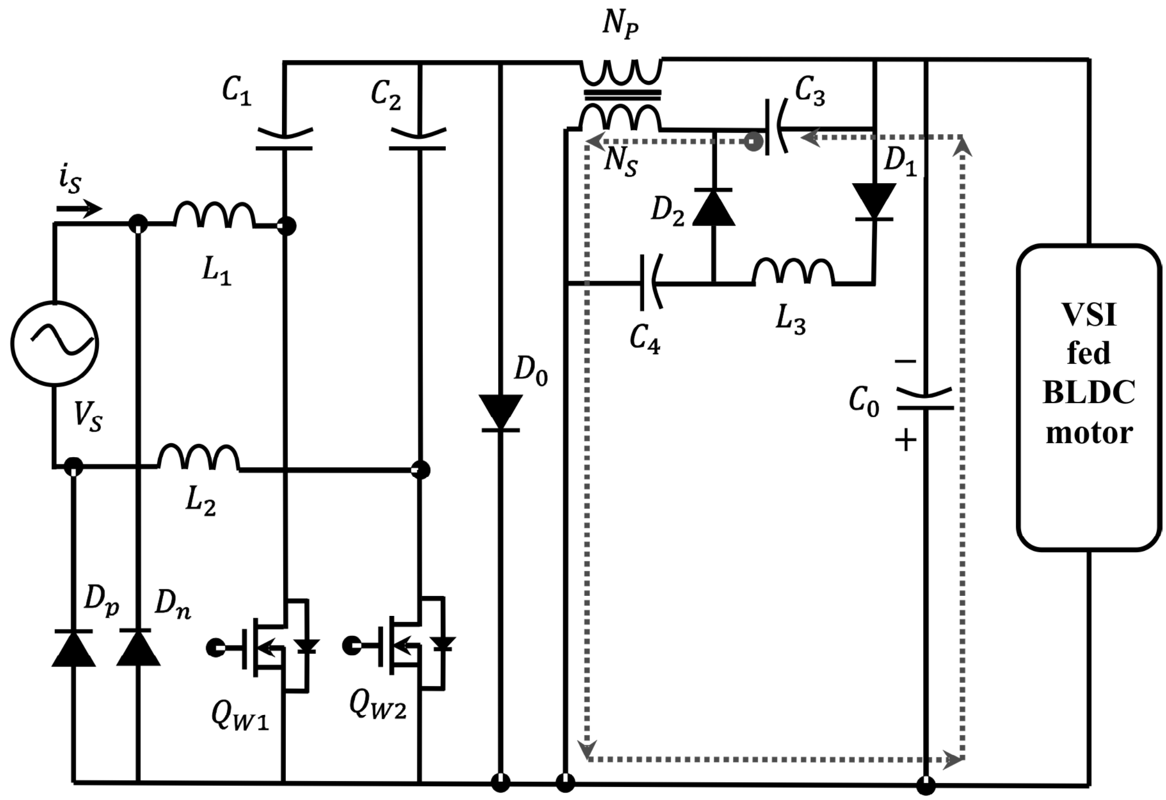

Figure 2(c): Mode 2

Mode 2

This mode refers to the DCM of operation since the current in the input inductor L_1 comes to zero; the output side coupled inductor commences to discharge, and the output capacitor voltage also increases, as illustrated in Figure 2(c), whereas the output capacitor C_0 provides the required energy to the load.

Operation during Negative Half-cycles of Supply Voltage

Same kind of behavior of the converter is seen for the supply voltage's the other negative half-cycle. An input inductor L_2, switch Q_{W2}, an intermediate capacitor C_2, diodes D_n and D_0, output side coupled inductor and output capacitor C_0 conduct in a similar way, just that there is a difference in the direction of current flow.

Control (Voltage Follower Approach) of BL-HG CUK Converter Fed BLDC Motor Drive

A. Control of PFC Converter

The Control unit of BL-HG CUK converter is illustrated in Figure 3. The control of the front-end PFC converter produces the PWM pulses for the PFC converter switches (Q_{W1} and Q_{W2}) for the control of dc link voltage along with PFC operation at the ac mains. A single voltage control loop (voltage follower approach)

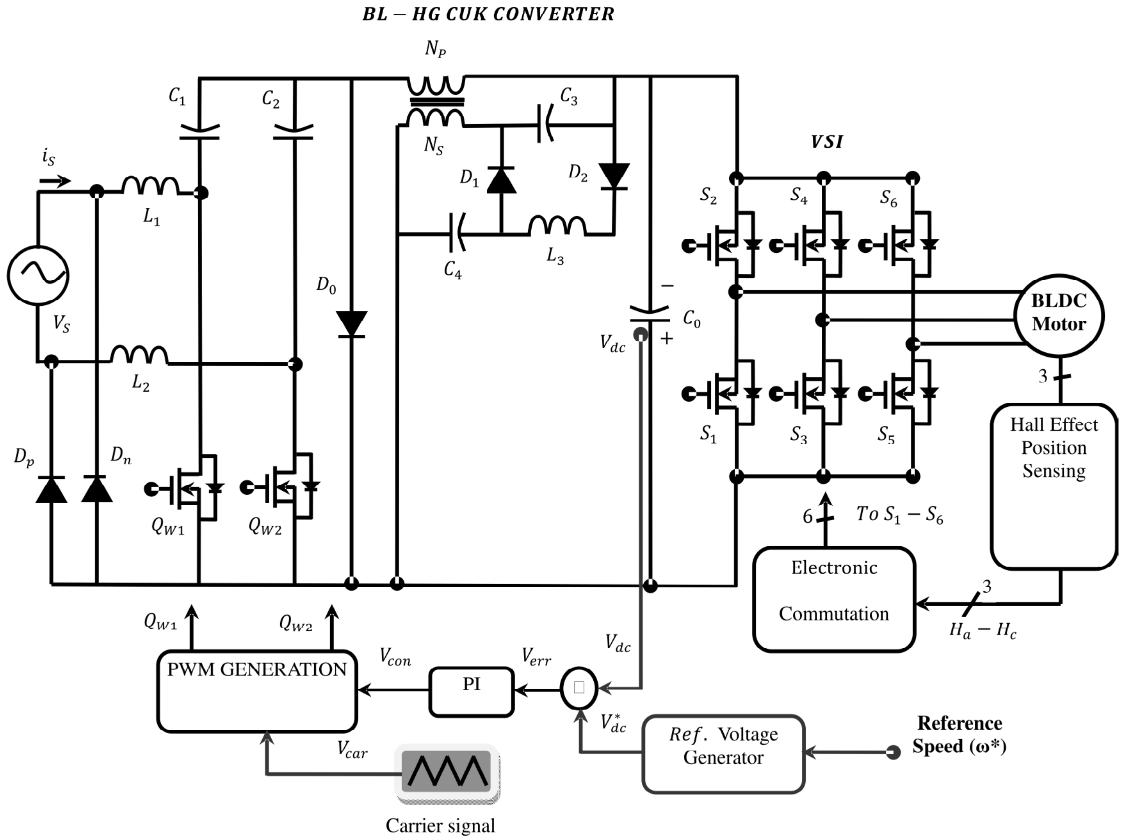

Figure 3: Control Unit (Voltage Follower Approach) of BL-HG Cuk Converter

is used for the BL-HG CUK converter which functions in DCM. A reference dc link voltage (V^*_{dc}) is produced as

$$V^*_{dc} = k_{volt} * \omega^* \tag{1}$$

In which k_{volt} and ω^* refer to the corresponding motor's voltage constant and the reference speed.

The voltage error signal (V_{err}) is generated by the comparison of the reference output voltage (V^*_{dc}) with the sensed output voltage (V_{dc}) as

$$V_{err}(k) = V^*_{dc}(k) - V_{dc}(k) \tag{2}$$

Where k stands for the kth sampling instant. This error voltage signal (V_{err}) is provided as input for the voltage proportional–integral (PI) controller for the generation of a regulated output voltage (V_{con}) as

$$V_{con}(k) = V_{con}(k-1) + k_p\{V_{err}(k) - V_{err}(K-1)\} + k_i V_{err}(k) \tag{3}$$

Where k_p and k_i refer to the respective proportional and integral gains of the voltage PI controller. Finally, the voltage controller output is then compared with a high frequency sawtooth signal (V_{car}) for generating the PWM pulses in the form of Q_{W1} and Q_{W2},

$$\begin{aligned}
&For\ V_S > 0; if\ V_{car} < V_{con}\ then\ Q_{W1} = "ON" \\
&For\ V_S > 0; if\ V_{car} \geq V_{con}\ then\ Q_{W1} = "OFF" \\
&For\ V_S < 0; if\ V_{car} < V_{con}\ then\ Q_{W2} = "ON" \\
&For\ V_S < 0; if\ V_{car} \geq V_{con}\ then\ Q_{W2} = \text{OFF}
\end{aligned} \tag{4}$$

where Q_{W1} and Q_{W2} represent the corresponding switching signals to the switches of the PFC converter.

(B) Control of BLDC Motor Drive with Electronic Commutation

An electronic commutation of the BLDC motor comprises of the proper switching of VSI in such a manner that a symmetrical dc current is obtained from the dc link capacitor for 120° and then placed in a symmetrical manner at the center of every phase. A Hall-effect position sensor is employed for sensing the rotor position on a span of 60° that is necessary for the electronic commutation of the BLDC motor.

Table 1
Switching States on the Basis of the Hall Effect Position Signals

θ^0	*HALL SIGNALS*			*SWITCHING STATES*					
	H_a	H_b	H_c	S_1	S_2	S_3	S_4	S_5	S_6
NA	0	0	0	0	0	0	0	0	0
0-60	0	0	1	1	0	0	0	0	1
60-120	0	1	0	0	1	1	0	0	0
120-180	0	1	1	0	0	1	0	0	1
180-240	1	0	0	0	0	0	1	1	0
240-300	1	0	1	1	0	0	1	0	0
300-360	1	1	0	0	1	0	0	1	0
NA	1	1	1	0	0	0	0	0	0

A line current is obtained from the dc link capacitor whose magnitude is dependent on the dc link voltage which is applied, back electromotive forces, resistances, and self-inductance and mutual inductance of the stator windings. Table 1 tabulates the various switching states of the VSI powering a BLDC motor on the basis of the Hall-effect position signals (*Ha* – *Hc*).

3. RESULT AND DISCUSSION

The performance of the proposed BLDC motor driver based BL-HG CUK converter is modelled in a MATLAB/Simulink environment making use of the SimPower-System Toolbox. The proposed BL-HG CUK converter performance is assessed for both rated and dynamic situations and the attained power quality indices obtained at ac mains.

Parameters like supply voltage (V_S) supply current (i_s), input inductors L_1 and L_2 current (i_{L1}) and (i_{L2}), dc link voltage (V_{dc}), Speed (N), Torque (T_e), Stator Current (i_a) Stator voltage (e_a), power switches Q1 and Q2 current (i_{Q1}) and (i_{Q2}), of the proposed system are investigated for demonstrating its proper functioning. In addition, power quality indices like power factor (PF), Total Harmonic Distortion (THD) of supply current are evaluated for deciding power quality at ac mains. The converter specifications that are utilized for the simulations are provided in Table 2.

Table 2
Specification

V_{s_peak}	36 V
$V_{s\text{-}RMS}$	52 V
I_{s_peak}	10 A
I_{s_RMS}	7.07 A
Rated Load Power	250 Watts
Rated (dc link) Voltage	200 V
Rated Torque	1.2 Nm
Rated Speed	1500 rpm
Power Factor (PF)	0.9999

(A) Steady-State Performance

Figure 4(a)-(e) illustrates the proposed converter operating at rated supply voltage of (36 V) and rated torque of BLDC motor 1.2 Nm, respectively to maintain a dc link voltage of 200V. As observed in these figures, the BLDC motor runs at the speed of 1500 rpm, and its corresponding stator are indicated in Figure 4(b) respectively.

Then the converter performance is analyzed, in which positive switch Q1 is ON, the current passed through the inductor L1 and it gets charged. Similarly, when negative switch Q2 is ON, the current passed through the inductor L2 and it gets charged are indicated in the figure 4 (g)(h). By this way the stress gets reduced across switches due to bridgeless operation.

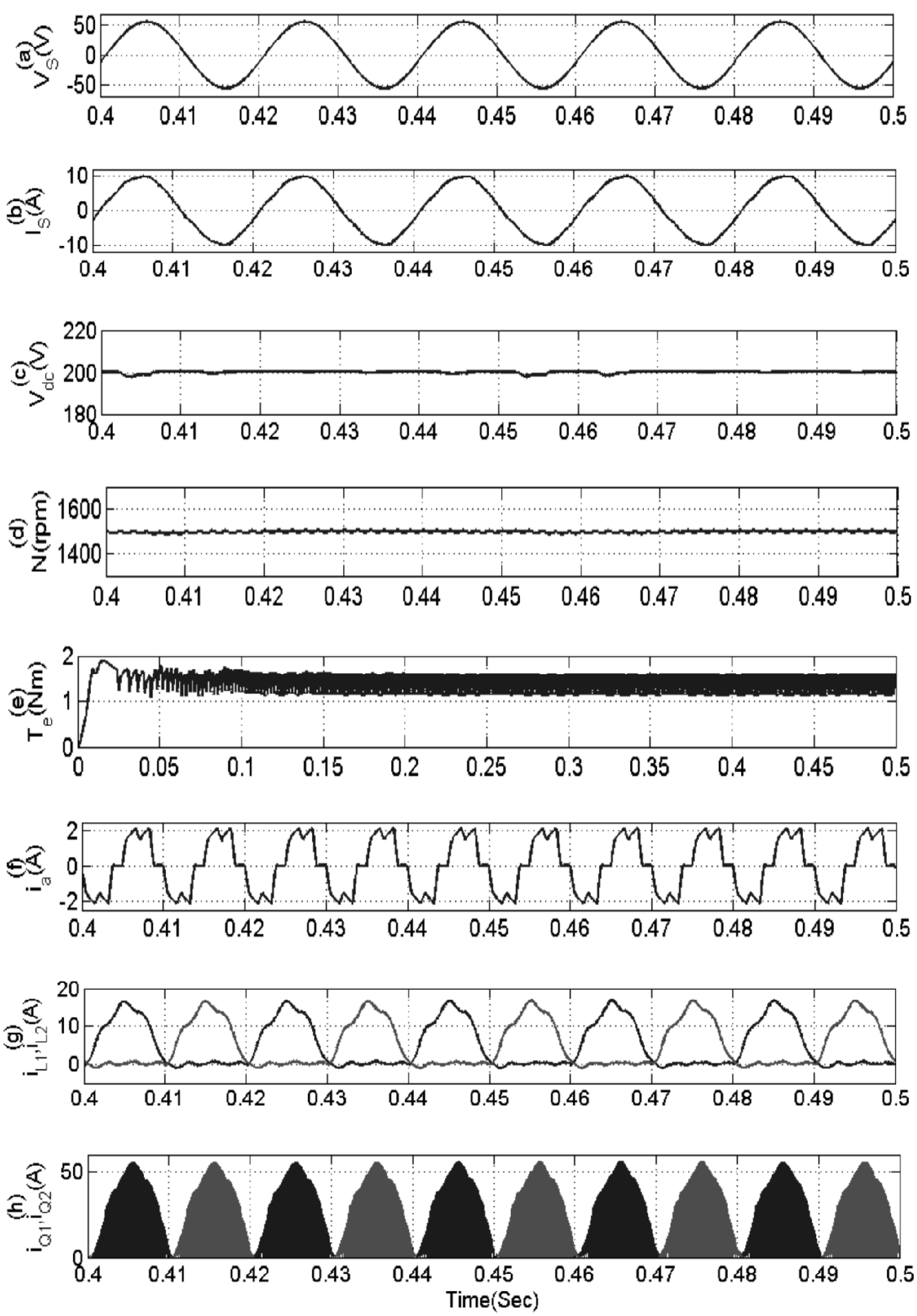

Figure 4(a)-(h): The Proposed Converter Operating at rated Supply Voltage of 36 V)

Performance Evaluation

The dynamic performance of the proposed converter during different values of output voltage is illustrated in Figure 5. It depicts the dynamic performance of the proposed converter during brightness control related to the step change in speed of the BLDC motor from 1100 to 1500 V at a peak supply voltage of 52V, torque of 1.2Nm and the respective stator current and stator voltage current variation is shown in figure 5(b), and 5(c). Also, magnitude of the stator current and the stator voltage shows variation for the constant supply voltage 36V, torque 1.2Nm and 1500 rpm where it shows the proposer functioning of closed loop operation.

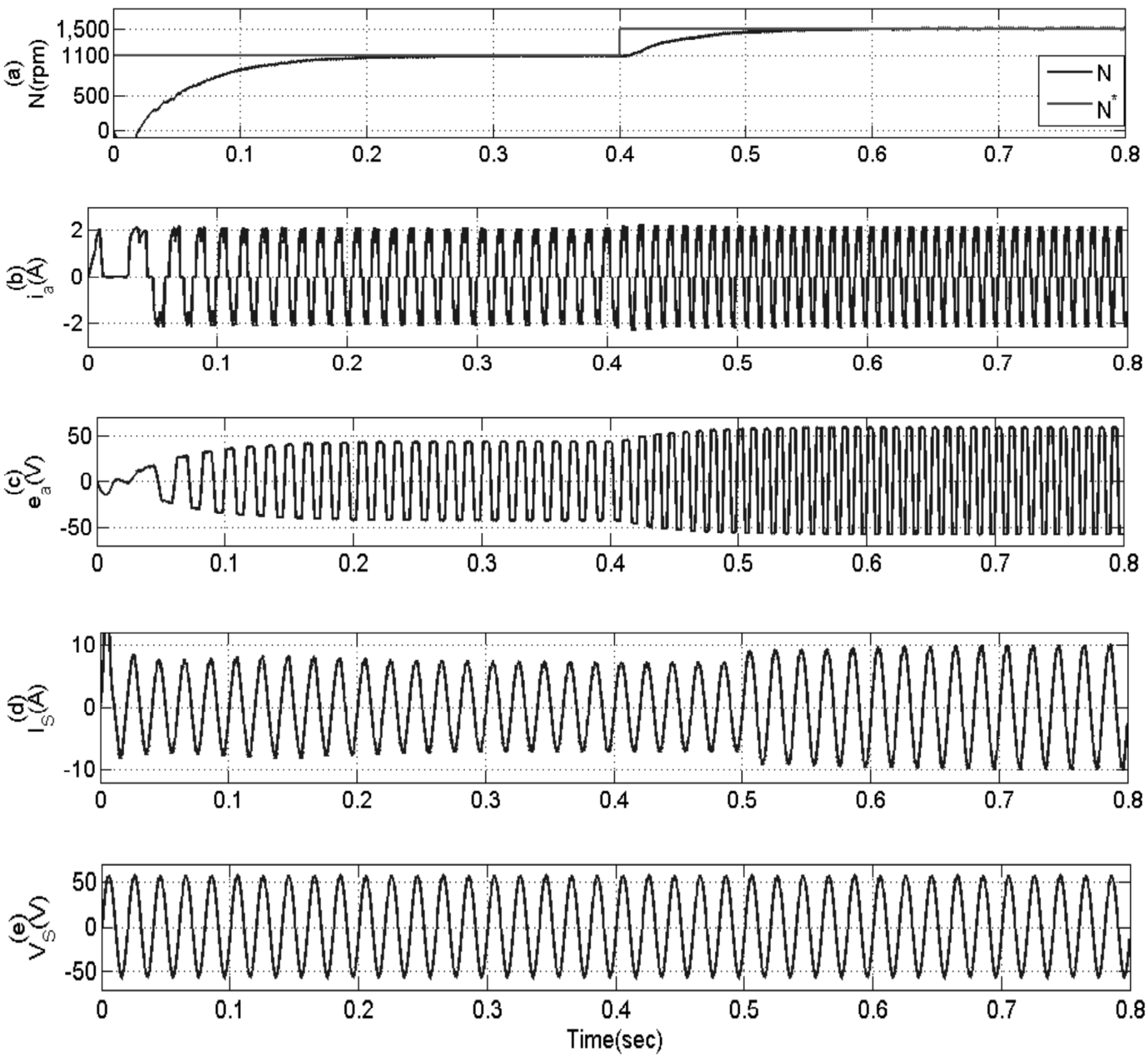

Figure 5: The Dynamic Performance of the Proposed Converter during Different Values of Output Voltage

This section involves the obtained power quality indices at the ac mains for the operation of the proposed converter at various values of output voltages. As in figure 6 the gained power quality indices received at ac mains when the speed is varied between 1100 to 1500 rpm. The corresponding Total Harmonic Distortion(THD) are also shown below.

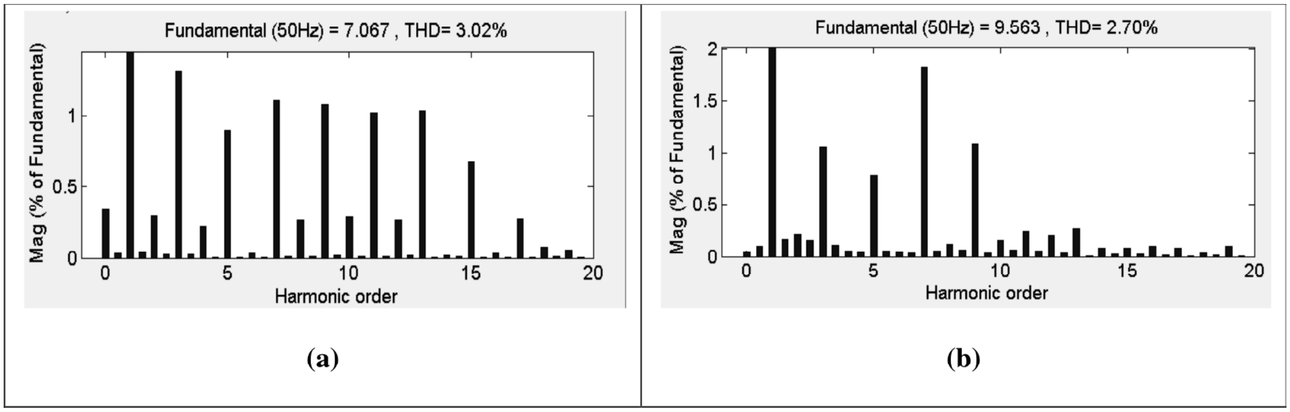

Figure 6: Harmonic Spectra of Speed at rated Input Supply on BLDC Motor (a) 1100 rpm and (b) 1500 rpm

Performance Comparison

The performance of the proposed BL-HG-CUK converter and the existing BL-CUK is analyzed based on the dc link voltage and the power factor value. The existing BL-CUK attains a constant dc link voltage of 110V, whereas the proposed BL-HG-CUK converter reaches upto 182 V. It can be said that the proposed converter attains high gain when compared with the existing converter.

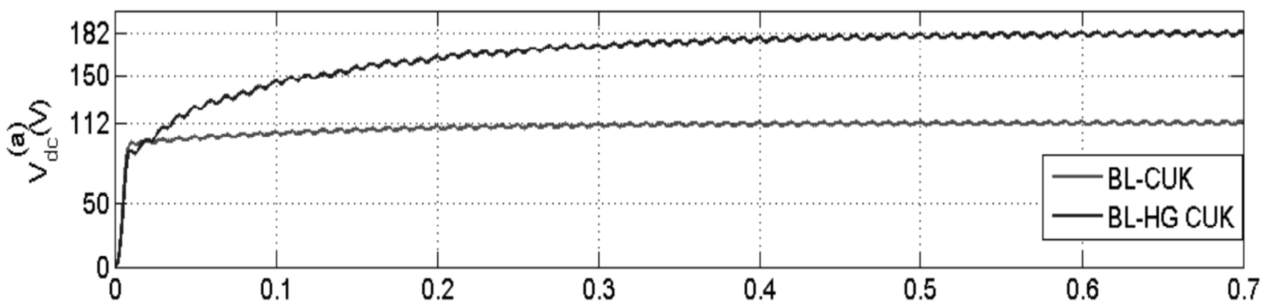

Figure 7: dc Link Voltage Comparison

The power factor comparison of the proposed BL-HG-CUK converter and the existing BL-CUK is analyzed. The existing BL-CUK attains a 0.97 power factor value, whereas the proposed BL-HG-CUK converter attains 0.999 nearer to unity power factor value. It can be said that the proposed converter attains better power factor value when compared with the existing converter. In addition the corresponding THD is also measured when the converter is connected with the BLDC motor.

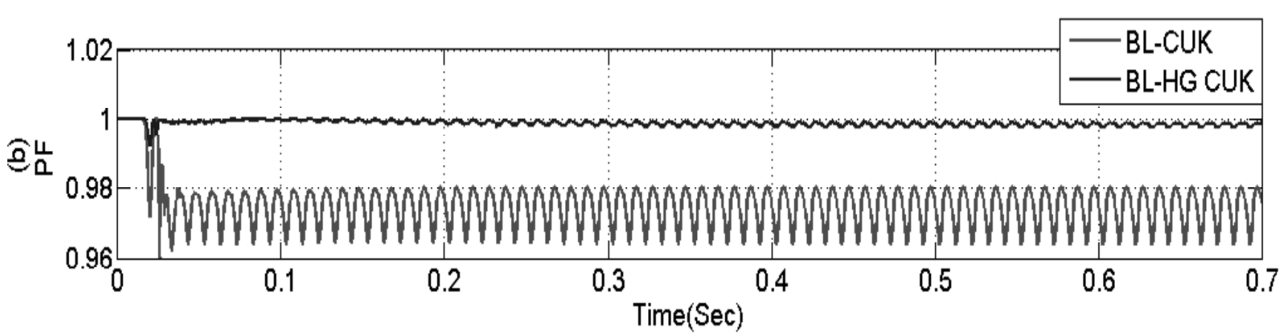

Figure 8: Power Factor Comparison

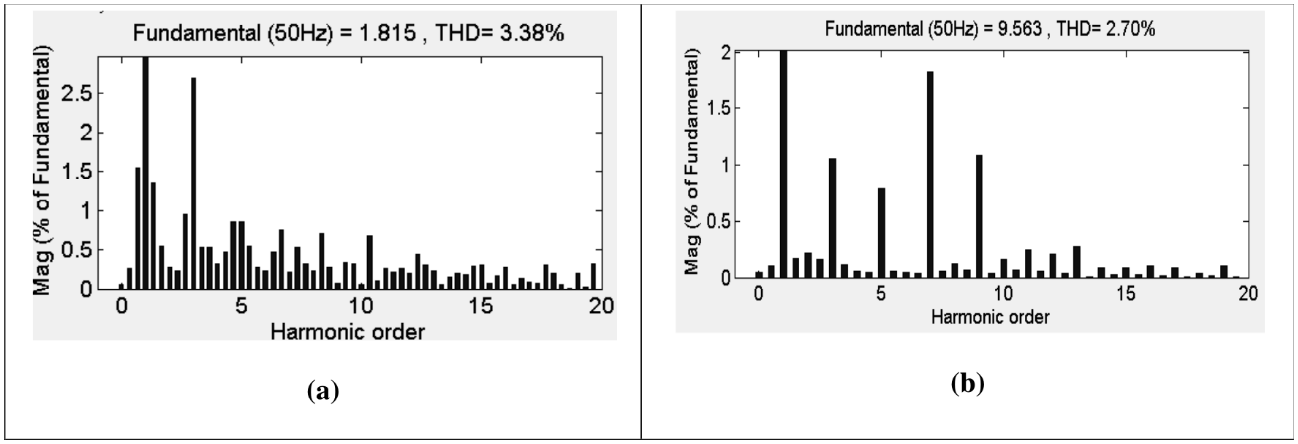

Figure 9: Corresponding THD is also Measured when the Converter is Connected with the BLDC Motor

4. CONCLUSION

This paper proposed a novel BL-HG-CUK converter design for BLDC motor. The proposed Bridgeless Cuk converter overcomes the limitations of the conventional PFC converter. The proposed BL-HG-CUK converter focused on providing the better performance when compared with existing converters. The simulation results clearly show that the proposed work resulted in minimal THD 2.70% and 0.999 nearer to unity power factor.

REFERENCES

[1] C. L. Xia, Permanent Magnet Brushless DC Motor Drives and Controls. Hoboken, NJ, USA: Wiley, 2012.

[2] J. Moreno, M. E. Ortuzar and J. W. Dixon, “Energy-management system for a hybrid electric vehicle, using ultracapacitors and neural networks,” IEEE Trans. Ind. Electron., Vol. 53. No. 2. pp. 614–623, Apr. 2006.

[3] Y. Chen, C. Chiu, Y. Jhang, Z. Tang and R. Liang, “A driver for the singlephase brushless dc fan motor with hybrid winding structure,” IEEE Trans.Ind. Electron, Vol. 60. No. 10. pp. 4369–4375, Oct. 2013.

[4] X. Huang, A. Goodman, C. Gerada, Y. Fang and Q. Lu, “A single sided matrix converter drive for a brushless dc motor in aerospace applications,” IEEE Trans. Ind. Electron., Vol. 59. No. 9. pp. 3542–3552, Sep. 2012.

[5] H.A. Toliyat and S. Campbell, DSP-Based Electromechanical Motion Control. Boca Raton, FL, USA: CRC Press, 2004.

[6] P. Pillay and R. Krishnan, “Modeling of permanent magnet motor drives,” IEEE Trans. Ind. Electron., Vol. 35. No. 4. pp. 537–541, Nov. 1988.

[7] International Electrotechnical Commission. Limits for harmonic current emissions (equipment input current< 16 A Per Phase). Tech. Rep., IEC61000-3-2, 1995.

[8] S. Singh and B. Singh, “A voltage-controlled PFC Cuk converter based PMBLDCM drive for air-conditioners,” IEEE Trans. Ind. Appl., Vol. 48. No. 2. pp. 832–838, Mar./Apr. 2012.

[9] W.Y. Choi, J.M. Kwon, E.H. Kim, J.J. Lee and B.H. Kwon, “Bridgeless boost rectifier with low conduction losses and reduced diode reverse-recovery problems,” IEEE Transactions Industrial Electronics, Vol.54. No.2. pp 69-780, 2007.

[10] Y. Jang and M. Jovanovic, “A bridgeless PFC boost rectifier with optimized magnetic utilization,” IEEE Trans. Power Electron., Vol. 24. No. 1. pp. 85–93, 2009.

[11] L. Huber, Y. Jang and M. Jovanovic, “Performance evaluation of bridgeless PFC boost rectifiers,” IEEE Trans. Power Electron., Vol. 23. No. 3. pp. 1381–1390, May 2008.

[12] B.Su and Z. Lu, “An interleaved totem-pole boost bridgeless rectifier with reduced reverse-recovery problems for power factor correction,” IEEE Trans. Power Electron., Vol. 25. No. 6. pp. 1406–1415, 2010.

[13] H. Ye, Z. Yang, J. Dai, C. Yan, X. Xin and J. Ying, “Common mode noise modeling and analysis of dual boost PFC circuit”, in Proc. Int. Telecommun. Energy Conf., pp. 575–582 , 2004

[14] W.Y.Choi, J. M.Kwon, E. H.Kim, J. J.Lee and B.H. Kwon, “Bridgeless boost rectifier with low conduction losses and reduced diode reverse recovery problems,” IEEE Trans. Ind. Electron., Vol. 54. No. 2. pp. 769– 780, 2007.

[15] B. Su, J. Zhang and Z.Lu, “Single inductor three-level boost bridgeless PFC rectifier with nature voltage clamp,” IEEE Int. PowerElectron. Conf., pp. 2092–2097, 2010.

[16] M. Mahdavi and H. Farzanehfard, “Zero-current-transition bridgeless PFC without extra voltage and current stress,” IEEE Trans. Ind. Electron., Vol. 56. No. 7. pp. 2540–2547, 2009.

[17] M. Mohr, W.T. Franke, B. Wittig and F. W. Fuchs, “Converter systems for fuel cells in the medium power range—A comparative study,” IEEE Trans. Ind. Electron., Vol. 57. No. 6. pp. 2024–2032, Jun. 2010.

[18] R.J. Wai, W.H. Wang and C.-Y. Lin, “High-performance stand-alone photovoltaic generation system,” IEEE Trans. Ind. Electron., Vol. 55. No. 1. pp. 240–250, Jan. 2008.

[19] B. Yang, W. Li, Y. Zhao and X. He, “Design and analysis of a gridconnected photovoltaic power system,” IEEE Trans. Power Electron., Vol. 25. No. 4. pp. 992–1000, Apr. 2010.

[20] M.Brkovic and S.Cuk, “Input current shaper using Cuk converter,” in Proc. Int. Telecommun. Energy Conf., pp. 532–539, 1992.

[21] D.S.L. Simonetti, J. Sebastian and J. Uceda, “The discontinuous conduction mode Sepic and Cuk power factor preregulators: Analysis and design,” IEEE Trans. Ind. Electron., Vol. 44. No. 5. pp. 630–637, 1997.

[22] B. Singh, B.N. Singh, A. Chandra, K. Al-Haddad, A. Pandey and D.P. Kothari, “A review of single-phase improved power quality AC-DC converters,” IEEE Trans. Ind. Electron., Vol. 50. No. 5. pp. 962–981, 2003.

[23] B. Singh, S. Singh, A.Chandra and K. Al-Haddad, “Comprehensive study of single-phase AC-DC power factor corrected converters with high frequency isolation,” IEEE Trans. Ind. Inf., Vol. 7. No. 4. pp. 540–556, 2011.