

Application of Modified High-Gain, Bridgeless, PFC-type CUK converter for Sustainable Energy Production - A Critical Review

Sayantan Banerjee¹, Pradip Kumar Sadhu¹, Anik Goswami², Sagnik Bhattacharya¹

¹ Department of Electrical Engineering, IIT (ISM), Dhanbad – 826004, India

² School of Electrical Engineering (SELECT), VIT, Chennai-600127, India

Corresponding Email: Sbim6065@gmail.com

ABSTRACT

This paper represents extensive study on different types of CUK converters such as the modified CUK converter where a boosting circuit is connected for high static gain compared to conventional CUK converter, bridgeless CUK converter, power factor corrected CUK converter & their different control strategies that have been developed during last several years for various applications like PV power integration in large scale or small scale, fuel cell's power injection, aircraft application, LED lighting solutions, Micro grid applications in low, medium or large voltage level, betterment of electric vehicle charging infrastructure, power factor correction for better power utilization of grid power, soft switching techniques for higher efficiency & any other aspects like those in renewable energy application or applications related to power industry or any other fields & research related to energy conversion. This review aims to serve as a resource for researchers and engineers seeking to understand and advance the development of CUK converters in modern power electronics applications.

Keywords: CUK converter, Modified CUK converter, High static gain, Power factor corrected & bridgeless Cuk converter, control strategies, soft switching, PV application, EV charging, renewable energy applications.

I. Literature Review

The study & analysis of more efficient modified CUK converter configurations for renewable energy applications have peaked during the last several years. The inherent nature of a CUK converter, which uses a capacitor rather than an inductor to transfer energy from the source side, makes it more suitable for applications requiring lower ripple. Conventional CUK or modified CUK converters overcome ripple-related difficulties and deliver higher output voltage with higher efficiency. A circuit configuration where two, three, or multiple input ports and one output port for a non-isolated CUK converter configuration can be created. This can be useful for interfacing renewable energy resources and delivering varying demands. The variation of the duty ratio of each individual input port, the continuous current-conduction mode of operation & sharing a single inductor as the common inductor at the output port make the converter require fewer passive components and are more suitable for varying load demand, a utilizable converter. Though "Falling-edge switching" & "Intermediate switching sequences have not been implemented or tested [1]. A Dual Isolated SEPIC or CUK (DISC) converter configuration, connected in series and acting as a Submodule (SM) in a Three-phase, multi-level Inverter, shows better results as

an energy conversion system for large-scale photovoltaic systems. It reduces the overall system size, provides flexibility to increase or decrease the level as user-defined & also provides better fault handling, where the faulty unit can be replaced with a new one without affecting the whole system. Further work remains, as soft-switching techniques haven't been employed; the design of a High-Frequency transformer, and the precise design of other elements on the secondary side of the isolated converter have not been considered [2]. The circuitry of the CUK converter integrated with the boost converter can be characterized by higher gain, making it suitable for photovoltaic applications where low-voltage solar panels are used. This circuit configuration makes it suitable for feeding the required high voltage to the inverter with a low-voltage panel. The single-controlled power switch makes it easy to control. It has fewer components and a configuration for the voltage-gain application, while the use of soft-switching techniques remains a scope for further work [3]. Soft-switching techniques such as Zero Voltage switching (ZVS), Zero Current switching (ZCS), and Zero Voltage Transition (ZVT) can be employed in addition to the common-ground structure, thereby eliminating the positive- and negative-half-line cycle detection for a bridgeless PFC CUK converter and improving efficiency. Operating in discontinuous conduction mode (DCM) can simplify the control circuit. But the mathematical analysis behind the design of ZVT cells, inductors & capacitors is not thorough and misses the relationship between the variances of the ratings of those elements and the converter ratings. [4], [28]. A fault-tolerant, wide-voltage-conversion DC/DC CUK converter circuitry arrangement can be constructed using a basic CUK converter circuit and "n" expendable units. By understanding the mutual redundancy between the basic CUK converter unit and the expendable units, the system can continue operating if a fault occurs in any expendable unit, thereby increasing reliability and making it more applicable to More Electric Aircraft (MEA) applications. Further work can be done to provide a rigorous mathematical approach or explanation for the optimal switching sequence & duty ratio under different loading conditions for the same NITPCC with two units working together [5]. A modified CUK converter circuit configuration can be made where the output of one cell of a conventional CUK converter can be used as input to the second stage of conversion and the output of the second stage can be used as input of the third stage voltage conversion and so on in a subsequent manner so that the voltage gain is much higher than the conventional DC-DC converter which doesn't use the cascaded topology. This three-level conversion configuration can provide a higher

output voltage, such as 380-400 volts DC. Though further scope of work is needed, otherwise the converter's efficiency will be low. Power losses in inductors and switches can be as high as 32% and 38% of the total power losses [6]. A PFC-bridgeless Cuk converter circuit can be implemented as a retrofit LED driver by resetting the mains power switch & operating the Cuk converter in DCM mode for low-power applications in households or other sectors. The implemented hardware solution for establishing the working circuitry & designing the elements of the CUK converter, which could trigger the color change from "warm white" to "Cool white" by resetting the main switch & also operating the CUK converter in DCM, is shown. Though the need for DCM or CCM for "warm white" or "Cool White" is not clearly explained & DCM is used for two types of lighting, it is also not explained. However, in DCM, the input & output inductor currents don't remain zero & also the input inductor current reverses, which contradicts the basic understanding of DCM mode. Although the same circuit provides both lighting modes, the power consumption of each mode has not been explained [7]. The key advantage of varying the duty ratio sinusoidally in the Cuk converter is that it produces an output voltage that varies sinusoidally over the DC offset of the output voltage. This advantage makes it well-suited for forming a three-phase inverter without the need for a conventional DC-AC inverter configuration & also eliminates the requirement for the AC side voltage to be higher & lower than the DC side voltage during standalone & grid-connected modes. Further work needs to be done cause the MPPT is not employed to fetch the maximum power from the PV system, & if some loads are served in a single-phase manner from this inverter system, they will face the DC offset voltage, which could damage the load & also, Lower-order harmonic rejection is not considered [8]. A modular DC-DC converter can be developed by connecting the inputs in parallel & outputs in series across multiple Cuk converter modules, with the input of those modules being a single DC source, multiple renewable energy resource voltage units, or a DC bus for Medium Voltage Direct Current applications, especially in Microgrid applications. Although the structure can be isolated or non-isolated, the isolated structure is chosen when ZVS & ZCS are applied, for the added benefit of lower switching losses. Further research is needed because the MPPT algorithm is not employed, the reduced-switch circuit configuration of the same converter is not implemented in hardware, the design of high-frequency transformers is not provided, and Conduction losses are a significant part of the total losses in the system [9]. An Adaptive Estimator-Based Sliding Mode control (AESMC) can be applied to develop a single-input double-output CUK converter from a conventional CUK converter configuration by inserting a switch & the output circuit of the CUK converter to serve multiple loads sourced from a single renewable source. The cross-coupling & cross-regulation issue arising because of this configuration can be solved by this (AESMC) [10]. The output circuitry of a CUK converter with an inductor, a capacitor & load can be integrated into a conventional CUK converter, so that the entire circuit operates as a single-input dual-output (SIDO)

Non-isolated CUK converter. Adaptive Estimator-Based Sliding Mode Control (AESMC) can be implemented in this configuration to regulate multiple outputs while effectively addressing challenges such as cross-coupling (CC) and cross-regulation (CR) issues inherent to this setup. Although optimal parameter tuning methods have not been employed, and a hit-and-trial approach has been used for selecting the control parameters, the voltage output at port-2, which is not entirely independent of port-1, presents an opportunity for further research and optimization [10]. A set of inductors & capacitors with switches & diodes can be integrated into a conventional CUK converter to form a new configuration called an Active Switched Inductor and Switched Capacitor CUK Converter, which provides higher voltage gain with the same duty ratio as a conventional CUK converter. The other advantages of this converter are a non-pulsating output current, low voltage & current stress on switching components & the ability to increase the switched capacitors as a cell or block according to the voltage gain required by the load demand or user. Further work is needed on this same converter regarding the Voltage stress on switches and diodes in both classical & interleaved modes, as is known. Also, the switch and diode ratings for different circuit combinations in the evaluation table have not been shown [11]. The integrated configuration of a CUK & Boost Converter, combined with a snubber capacitor & coupled inductor, can provide soft switching, resulting in higher efficiency & greater DC gain when a whole PV power system must be integrated through a DC-DC converter & grid-tied half-bridge inverter, as shown in [12]. Though Converter circulation losses are not considered, how to minimize that is not discussed & MPPT has not been implemented through hardware in the proposed system. However, it has highlighted the prohibition of that [12]. An energy-based approach can apply a dynamic voltage control loop to stabilize the BUS voltage & act as a constant DC BUS voltage to support constant power loads (CPLs), with the CUK converter operating as a grid-forming converter in DC microgrids. Further work is needed to implement MPPT when the same converter is used to inject maximum power from the PV panel into the microgrid system [13]. A buck-boost converter can be configured with two auxiliary switches, two snubber capacitors, one diode, and one coupled inductor to create a Zero-Voltage Transition (ZVT) condition that combines ZVS and ZCS in both buck and boost modes of operation, significantly reducing switching losses, as shown. However, it is not specified how auxiliary switches can be turned ON or OFF under this ZVT circuit configuration when MPPT is fed to this system. Also, the condition of C_{r1} in Boost mode & condition of C_{r2} in buck mode have not been shown [14]. In addition to the well-known fact that physical laws are used to determine the critical inductance for DCM and CCM, a symmetrical method can be proposed to design the elements of the CUK converter, as well as its output voltage ripple (OVR) and switch peak current (SPC) [15]. Relying on Power Factor Correction (PFC) converters to achieve better energy efficiency and improved power quality has increased nowadays, causing these converters to actively modify the

input current waveform to match the input nature of the input voltage waveform, thereby minimizing reactive power and reducing Total Harmonic Distortion (THD), which results in increasing Power Factor (PF). PFC converters are essential for applications involving different loads, such as EV battery charging, BLDC motor drives, Light Emitting Diode (LED) drivers, and medical equipment. Injecting harmonics into the power grid can cause uncompensated damage [4], [16], [17], [18], [24], [27]. For a bridgeless PFC converter, a modified circuit configuration, as shown in [16], [24], can be used in discontinuous conduction mode (DCM) to achieve natural PFC. the configuration allows for a single semiconductor switch for the entire operation. It eliminates the need to measure the output voltage and input current, reducing the number of components required to run the system. A bridgeless (BL) Cuk converter with a low component count can be constructed for front-end power factor correction (PFC) in an E-rickshaw battery charger, with a flyback converter used as the next stage of current control [17]. Including one additional inductor and one capacitor in the classical Cuk converter circuit gives a higher output voltage & improved efficiency compared to the normal output of a CUK converter [18]. A Cuk converter-fed isolated LLC resonant converter can be used for the electric vehicle (EV) battery charger (EVBC). The Cuk converter performs power factor correction by operating in CCM; the LLC resonant converter converts the DC link voltage to the isolated DC voltage required for (EVBC) [19]. A high-gain DC-DC converter with an additional injected DC voltage derived from the same input can be constructed, thereby achieving high voltage gain, a high boosting factor, and continuous input and output current compared to a classical CUK converter. Because of this injected voltage, the modified CUK converter can achieve a 40-volt-to-400-volt transformation with a lower duty cycle than the classical converter [20]. A Cuk converter can serve as a bridge between a bridge rectifier and a flyback converter in two-stage charging approaches for light electric vehicles. The Cuk converter also serves as an active power factor correction device to provide a resistive profile at the supply side & ripple-free charging on the battery side with reduced numbers of components and minimum cost [21]. [22] In this paper, the disadvantage of the classical CUK converter having inverted polarity has been resolved by modifying the circuit, applying a double-loop controller, and controlling the output voltage and input current. The control scheme is implemented by linearizing the small-signal model and analyzing the phase and gain margins. Inserting a boosting network consisting of two diodes, one inductor & one capacitor into the conventional CUK converter creates a modified high-voltage CUK converter topology for renewable energy applications. The combining arrangement makes the converter a controlled device for DC-DC topology. The voltage conversion ratio can be up to 10 times that of a normal classical converter at a duty ratio of 90% [23]. A Single-Phase Matrix Converter topology can be used as a CUK converter. Modified switching techniques, such as pulse width modulation (PWM), can drive the gate pulses and achieve the converter's required output as a CUK converter [25]. A

highly efficient bidirectional DC-DC converter, integrated with the CUK converter, can be employed in the main DC power conversion circuit of EVs. PI controlling and a combination of the CUK converter can provide the desired battery voltage for several applications in the EV circuitry [26]. The modified bridgeless CUK converter, shown in [27], can be used for a switch-reluctance motor drive and offers the added benefit of power-factor correction. Different floating solar systems can be integrated with the above-mentioned modified CUK converter circuit of high static gain & utilization of solar energy falling on a water body [30], [31]. However, validation through hardware implementation of the proposed modified bridgeless PFC CUK converter circuits mentioned in [17], [18], [27] is a further scope for research. For [18], [20], [22], [23], as these are the modified CUK converters to produce higher static gain than the conventional CUK converter, then how MPPT could be integrated with these modified CUK converter configurations for PV power injection needs to be investigated in simulation & also to be validated by hardware implementation as a future scope of research work. For the PFC converter explained in [19], [21], [27], the future scope of work is to implement it in hardware for practical validation & to determine whether other improvements are possible for various applications in the renewable energy sector.

II. VOLTAGE BOOSTED MODIFIED CUK CONVERTER FOR HIGH STATIC GAIN

Paper [1]:

In this paper, the Cuk converter is configured to operate with a multi-port input and a single-port output. The basic elements of a Cuk converter are the input, energy buffer & output port, which enables it to be configured as a multi-port device. N-port configuration consists of N input ports connected & operating in parallel & the output port is a common output port. At the same time, the energy buffer becomes an inherent part of each input port. For a better understanding of the configuration operating as a multi-port, a “Non-isolated Three-port Cuk converter” (NITPCC) is analyzed in this paper. The circuit configuration of NITPCC is shown in Fig. 1. The analysis of the configuration & operation of this three-port converter with two input ports helps clarify how a multiport converter with more than two input ports can operate. This Converter has two modes: 1. Single input Single output Mode (SISOM), 2. Dual Input Single Output Mode (DISOM). The operation of SISOM is the same as that of a conventional CUK converter; the shift from SISOM to DISOM depends on demand. If the single-input converter can't power the load, DISOM is employed. The DISOM application can be divided into three switching patterns: 1) Rising Edge, 2) Falling Edge, and 3) Intermediate Synchronization. In this paper, “Rising Edge” synchronization has been considered for switching & mathematical analysis. This synchronization pattern has three states: State 1: Where both switches are ON, State 2: One Switch of the two input ports is ON & the other is OFF, while the standard output diode is still off, State 3: Two controlled switches of the two input ports are OFF,

and the ordinary diode is on. Analysis of mathematical equations obtained from K.V.L in all modes & application of volt-second balance in every inductor for the whole switching period gives us the equation of output voltage to two different input voltages of NITPCC, as given by Eq. (1), where v_0 = output voltage, v_1 & v_2 Are two input voltages, d_1 & d_2 The duty ratio of two input converters connected in parallel. For “N” number of input ports having the same amount of input voltage v_i , the equation of the output voltage v_0 , is given by Eq. (2).

$$v_0 = \frac{d_1}{(1-d_1)} v_1 + \frac{d_2(d_2-d_1)}{(1-d_1)(1-d_2)} v_2 \quad (1)$$

$$v_0 = \left[\frac{d_1}{1-d_1} + \sum_{i=2}^n \frac{d_i(d_i-d_1)}{(1-d_1)(1-d_i)} \right] v_i \quad (2)$$

The voltage gain for different NITPCC duty ratios is plotted in Fig. 2.

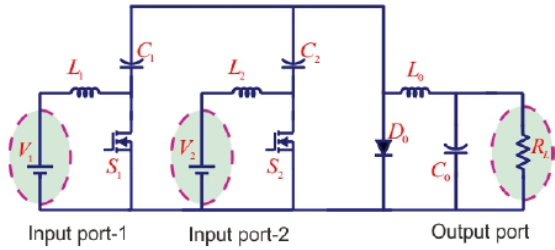


Fig.1. The Circuit configuration of NITPCC proposed in [1]

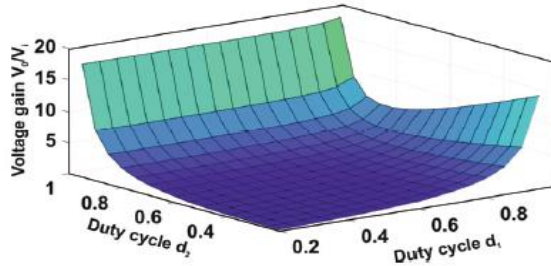


Fig. 2. Voltage gain of NITPCC for different duty ratios of two input ports having the same input voltage [1].

Paper [3]:

This paper proposes a hybrid converter that merges the inputs of the Boost & Cuk converters using a single control switch, divides the output capacitor, & doing other necessary circuit configurations to complete the working circuitry of the hybrid converter, as shown in Figure 3. The upper circuit works as a boost converter, and the lower circuit works as a Cuk converter. This hybrid converter configuration provides higher static gain than the usual boost or Cuk converter. The configuration of this circuit is made in such a way that the output of this converter becomes the sum of the Boost & Cuk converters. If they operate separately, the voltage gain of the two converters is given by Eq. (3) for Boost & Eq. (4) for CUK. Now, the voltage gain of this hybrid converter is given by Eq. (5).

$$\frac{v_{c1}}{v_i} = \frac{1}{(1-D)} \quad (3), \quad \frac{v_{c2}}{v_i} = \frac{D}{(1-D)} \quad (4), \quad \frac{v_0}{v_i} = \frac{(1+d)}{(1-d)} \quad (5)$$

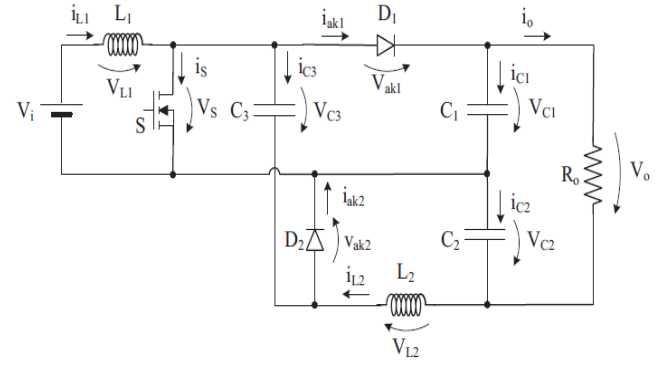


Fig 3. Circuit configuration of the proposed hybrid converter in [3].

The working condition of this circuit is divided into three modes depending on switching, which are: Mode 1: Switch is made On, inductor L_1 charges from the input while the inductor L_2 charges from the stored energy C_3 , D_1 & D_2 remain in block state. Mode 2: When S is turned off, the Voltage across C_1 becomes smaller than that across C_3 ; this mode starts & D_1 stays in reverse bias & D_2 becomes forward biased, C_3 starts charging from the input & L_1 . Mode 3: This mode begins when C_1 voltage falls below C_3 's voltage & D_1 gets turned ON, while D_2 was ON from the previous.

Paper [2]:

This paper proposes a PV source-based dual-isolated Sepic CUK (DISC) converter, which is connected in series & acts as a Sub Module (SM) to the inverter, enabling it to operate as a multi-level inverter. Applying this DISC to the multi-level inverter reduces the requirement for filtering capacitance, large passive components, a line-frequency step-up transformer & additional conversion power stages & increases the inverter's scalability, lifetime, and resilience. This paper proposes a PV source-based dual-isolated Sepic Cuk (DISC) converter, which is connected in series & acts as a Sub Module (SM) to the inverter system, enabling it to operate as a multi-level inverter. Applying this DISC to the multi-level inverter reduces the requirement for filtering capacitance, large passive components, a line-frequency step-up transformer & additional conversion power stages & increases the inverter's scalability, lifetime, and resilience. The distinctive features of this converter system are 1) Addition of more SMs increases the scaling of voltage & current injected into the grid. A high-frequency transformer embedded in the module provides galvanic isolation, reduces inverter leakage current, and offers the flexibility to step the voltage up or down. 2) Continuous current flow path of this configuration, distributed MPPT operation & connection of each PV module to its own SM helps to extract maximum power from the PV module, even under partial shading conditions. 3) The current input is continuous in this configuration. Hence, a small capacitor is enough on the PV side, unlike the large electrolyte capacitor usually used in PV systems. Individual replacement of SMs is possible if one of them gets faulty. An SM is formed by combining a SEPIC and a CUK converter. Combining these two converters is likely

because they share a standard front structure and two output structures for dual-output voltages. In addition, integrating a High-Frequency Transformer (HFT) into this structure is easy to implement, helping achieve galvanic isolation and reduce leakage current in PV inverters. As both converters are inherently BUCK-BOOST types, the voltage conversion ratio of this converter is the sum of both converters and acts as a Buck-Boost type & the output gain is given by eq.6, Where D is the duty ratio of the primary circuit switch, S_{in} , and N is the HFT's transformation ratio. The output switches S_{01} and S_{02} operate in a complementary manner to the primary switch S_{in} , and the switches should be equipped with antiparallel diodes to cut off the negative current coming from the load side. The circuit configuration shown in Fig. 5 operates in two modes on the primary side: when switch S_{in} is ON and when it is OFF. The CCM operating mode is discussed here. State 1: The switch S_{in} is on, and I_{in} starts to flow. C_r starts to discharge to the HFT's inductor. The C_s and C_c charge the output inductors L_1 and L_2 , increasing their current. The output is driven by capacitors C_p and C_n and C_n . State 2: S_{in} is turned off, and S_{01} and S_{02} are turned ON. The input current flows through C_r , V_{in} , and L_{in} . C_s gets charged from the HFT's secondary winding in the secondary circuit. The load is driven by L_1 in the lower part of the secondary circuit, which operates as a CUK converter, driving the load via L_2 . Load side capacitors C_p and C_n get charged. The connection of SM's with PV is of two types: a) Separate PV modules relate to each SM, which helps to reduce the current of each PV module; b) One PV module is connected to two successive SMs, which eases the DC connection, but the current is increased. The control circuit is designed after forming the state-space model and analyzing the dynamic equations of the working circuit. The design of the various elements of this electronic power converter is explained in detail in the paper.

$$\frac{v_0}{v_{in}} = \frac{2ND}{(1-D)} \quad (6)$$

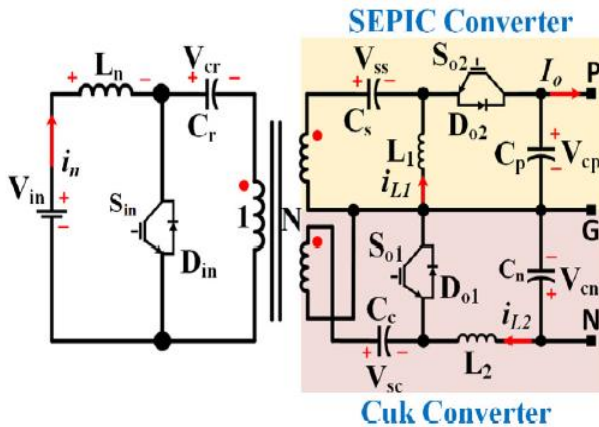


Fig 4. Circuit Configuration of the isolated SEPIC/CUK converter given in [2]

The sub-modules (SM) work in an integrated way with the inverter & PV system to make the system a modular multilevel inverter, as shown in Fig. 5.

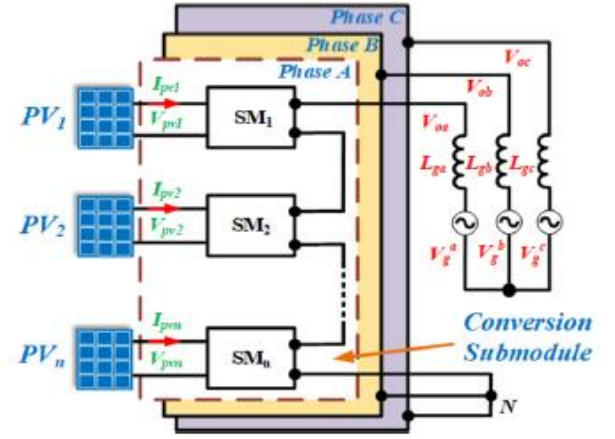


Fig 5. Integration of the SM's to form a multilevel inverter with the PV system shown in [2]

Paper [23]:

The arrangement of the modified CUK converter circuit is made in such a way that the extra circuit elements like two diodes, one inductor & one capacitor are connected & added in the conventional CUK converter in a manner shown in the figure, so that it acts as an extra boosting network which increases the static gain of the traditional CUK converter. The boosting network is connected between the input inductor & the energy-transfer capacitor to provide boosted output gain. Despite the capacitors, inductors, and diodes put as extra elements for voltage boosting, the converter is still a single-controlled topology. The converter has two operating modes, Mode I & II. Mode-I is considered the "ON" state & Mode-II is the "OFF" state. Diode D_1 & controlled switch "S" is ON in Mode I, 0 to DT_s . The Diodes D_2 & D_3 are on in mode-II during DT_s to T_s , where D is the duty ratio, and T_s is the switching period of the main controlled switch. Solving the K.V.L equations in both ON & OFF states, applying the volt-second balance in all inductors, and taking the drop elements of inductors, diodes, and Switches as zero, the relation between the input and output of the converter is given by Eq. (7).

$$v_0 = \frac{D}{(1-D)^2} v_{in} \quad (7)$$

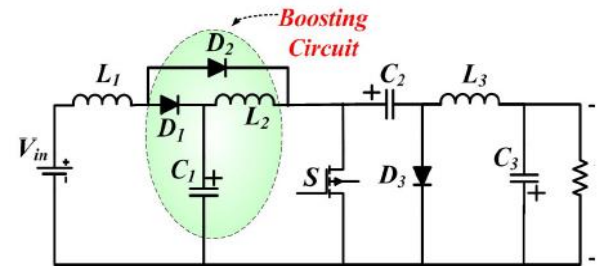


Fig 6. Circuit configuration of the modified CUK converter shown in [23].

III. BRIDGELESS CUK CONVERTER

Paper [16]:

This paper proposes modified Cuk converters, as shown in Fig. 10, which consist of one bidirectional switch, two diodes, two inductors, and three capacitors, for a total of eight essential components. This is fewer than the minimum of 10 components required by a conventional bridgeless Cuk converter. The distinction between this bridgeless converter and other bridgeless converters is that its positive and negative circuitry is not unified; a slightly different circuit-completion pathway is achieved during the positive and negative half-cycles. The conduction losses are reduced because either the switch or one diode provides the current flow path, and the voltage stress on the semiconductor devices decreases from $v_m + v_o$ to $v_m + \frac{v_o}{2}$. The DCM operation simplifies this converter's control loop, requiring only one voltage sensor. This converter has three modes of operation during two half-cycles of input. Mode 1: This mode starts with S turning ON, and the freewheeling of input current through V_{in} , L_{in} , C_t , and L_o ends. After S turns ON, the input inductor stores energy from V_{in} , and the energy stored in C_t is discharged into L_o . Mode 2: This mode begins after the input inductor and output inductor currents peak. The switch is OFF, and the total switch current is carried by the output diode D_{o1} . The input and output inductors are discharged through C_t and the output capacitors. Mode 3: In this mode, all the semiconductor devices are turned OFF, the load is supplied through the output capacitors, and the input current freewheels through V_{in} , L_{in} , C_t , and L_o . Through the output capacitors & the input current freewheels through V_{in} , L_{in} , C_t , & L_o .

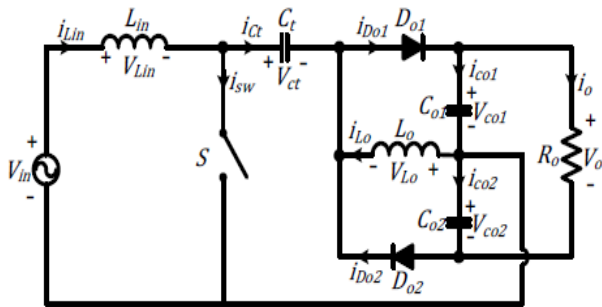


Fig. 7. Circuit configuration of the Bridgeless converter shown in the paper [16]

Paper [4]:

This paper proposes a switching circuit condition for a conventional bridgeless CUK converter. A conventional CUK converter uses two main switches for two-cycle operation, & a modified bridge CUK converter uses one main switch for positive & negative cycle operation, offering a lower component count advantage. However, switching losses become significant in both cases, particularly because the modified converter operates under hard switching despite having fewer components. This paper proposes a modified CUK converter that uses ZVT as a switching characteristic. A ZVT cell consists of a main switch, an Auxiliary switch, an inductor, and a capacitor for resonating operation. The auxiliary switch operates in ZCS condition & main switch operates in ZVS condition. The circuit configuration is shown in Figure 8.

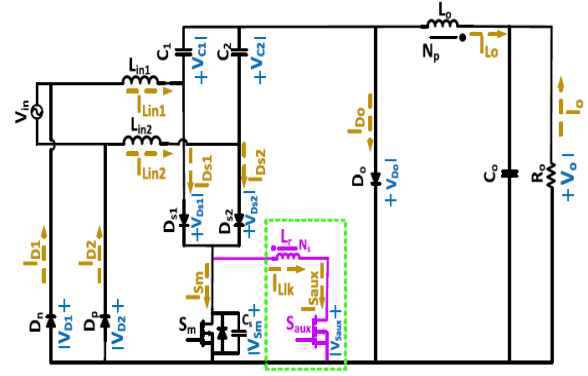


Fig. 8. Circuit configuration of the bridgeless CUK converter with ZVT cell shown in [4].

It has six modes of operation per half-cycle. The operation in the positive and negative half-cycles is symmetrical, so the operation in one half-cycle is as follows: Mode 1: S_{aux} is turned on under ZCS conditions, and the resonant current starts to flow between L_{lk} and C_s . The capacitor voltage begins to vary sinusoidally, facilitating the transition to Mode 2. This mode finishes when the capacitor voltage reaches zero. Mode 2: This mode starts by turning ON S_m under ZVS conditions when the capacitor voltage reaches zero. The current through L_{lk} decreases linearly, allowing S_{aux} to be turned off under ZCS conditions when I_{lk} reaches zero in the subsequent stage. The current through the inductors L_{in1} and L_o increases in the same and opposite directions, while the capacitors begin to discharge to the load. Mode 3: This mode starts with turning S_{aux} off under ZCS condition when I_{lk} reaches zero, while S_m remains ON, & current in L_{in1} & L_o keep on increasing with the same slope, the combined time duration of this mode 3 & mode 2 defines the "Duty Ratio" of the main switch, Mode 4: This mode starts by turning S_m off under ZVS, as it was already in On condition, the current through D_{s1} diode starts flowing through C_s capacitor. Mode 5: When C_1 voltages drop to a specific value, the input voltage exceeds the C_1 voltage, and D_0 turns on. The C_1 gets charged & L_o drives the load. Mode 6: This mode leads the path to mode 1. Here, in this mode, the voltage at L_o rises to a level that turns D_0 off & input current free-wheels through V_{in} , L_{in1} , C_1 , L_o , and C_o .

IV. PFC CUK CONVERTER

Paper [19]:

This paper proposes an Electric Vehicle battery Charger (EVBC) configured with a PFC CUK converter & an LLC Half-Bridge converter. AC input is applied to the back end of the PFC CUK converter, which operates in CCM, maintaining the sinusoidal AC input. The PFC Cuk converter charges the high-voltage DC link capacitor, which is converted to a low-voltage rectified DC output voltage V_0 through the LLC converter operating under resonant conditions. Two-loop control structures & PWM operations help eliminate unwanted harmonics. Loop control is the key factor of this converter operation. Control of the DC link voltage & output voltage is the outer loop, and the inductor current feedback forms the inner loop of control. The advantage of using a CUK converter is its

ability to “Buk” or “Boost” the output voltage, which enables the LLC converter to work under low DC link voltage at high lines. The circuit configurations of the intermediate CUK converter, integrated with the DC link capacitor and the LLC converter, under different switching conditions are shown in Fig. The circuit configuration of the PFC CUK converter integrated with the LLC converter is shown in Fig. 9.

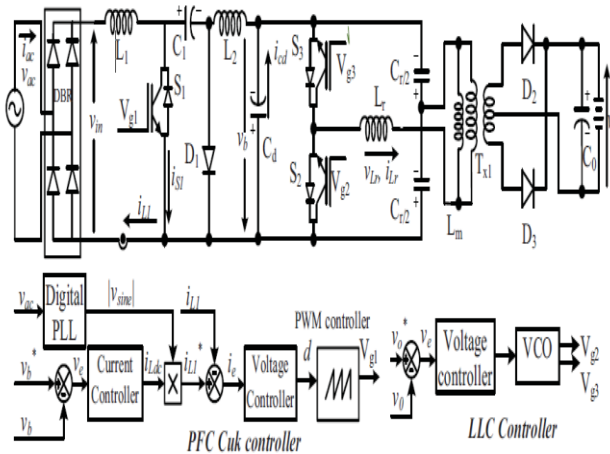


Fig. 9. Shows the circuit configuration of the PFC CUK converter with loop control mentioned in [19].

TABLE I
COMPARISON TABLE OF MERITS & LIMITATIONS OF THE
WORK OF DIFFERENT PAPERS REVIEWED SO FAR

Ref. No.	Merits of the work	Limitation of the work
Voltage Boosted Modified CUK Converter for High Static Gain		
[1]	A multiple-input, single-output, non-isolated CUK Converter circuit configuration has been created, & Rising edge switching sequence has been implemented.	Falling-edge and Intermediate switching sequences have not been implemented or tested.
[2]	Created a PV-based dual isolated SEPIC-CUK converter as a submodule to make a multi-level inverter, increasing its scalability & reliability.	Soft-switching and precise secondary-sides' elements design, including the high-frequency transformer, were not considered.
[3]	A Boost & CUK converter is integrated to form a hybrid converter, thereby enhancing the static gain relative to the outputs of the individual converters.	Soft switching techniques are not employed, and MPPT is not integrated.
[5]	This paper proposes a CUK converter with “N” expandable units for wide voltage conversion, load sharing, and fault tolerance, ensuring continuous load supply during faults.	N expandable components, the redundancy and dependency of different units under different modes of operation
[6]	This converter uses a cascaded CUK topology to correct polarity and achieve higher voltage gain than the classical design.	The converter's efficiency is low, with inductors and switches accounting for up to 32% and 38% of total losses, respectively.
[9]	Developed a medium voltage modular isolated DC-DC converter that uses a CUK configuration in	MPPT is not used, the reduced-switch converter is not hardware-implemented, the

	parallel input, series output mode, with two film capacitors for energy transfer	transformer design is missing, and conduction losses are significant
[10]	Transforming a CUK converter into a SIDO setup enables powering multiple loads from a single source, enhancing utility in distributed systems. The AESMC manages cross-coupling and maintains a stable output under dynamic loads.	AESMC parameters are tuned by trial and error rather than optimally. The dependence of Port 2 voltage on Port 1 output suggests scope for further research.
[11]	Higher voltage gain, non-pulsating current, reduced switch stress, and scalability with switched capacitors.	Voltage stress on switches and diodes in classical and interleaved modes is not shown, nor are their ratings for different circuit combinations in the evaluation table.
[12]	Soft switching improves efficiency, while CUK-Boost Integration provides high voltage gain, making it ideal for PV applications.	Converter circulation Losses are not addressed, and MPPT is not hardware-implemented, with its exclusion noted.
Bridgeless CUK Converter		
[4]	This paper implements ZVT switching using an auxiliary switch, a main switch, an inductor, and a capacitor, achieving ZCS for the auxiliary switch and ZVS for the main switch, thereby significantly reducing switching losses.	The mathematical analysis underlying the design of ZVT cells, the inductor, and the capacitor is not thorough. Misses the relation of the variance of ratings of those elements concerning converter ratings.
[5]	This paper proposes a Cuk converter with “N” expandable units for wide voltage conversion, load sharing, and fault tolerance, ensuring continuous load supply during faults.	N expandable components, the redundancy and dependency of different units under different modes of operation.
PFC & other Types of CUK converter		
[7]	This paper presents a CUK converter-based lighting solution that delivers dual-color output by varying its conduction mode.	The paper is unclear on DCM/CCM use for 'Warm White' and 'Cool White' lighting; inductor currents contradict DCM principles, and power consumption per mode is not detailed.
[8]	The CUK converter's buck-boost capability produces a sinusoidal output with a DC offset by adjusting the duty ratio, eliminating the need for a traditional inverter. The output voltage adapts to grid demand for grid-connected or islanded operation.	"MPPT is absent, risking power loss from the PV system. Single-phase loads may face harmful DC offset, and lower-order harmonics are not addressed.
[13]	The energy-based approach enables dynamic voltage control, stabilizing the DC bus voltage for CPLs and allowing the CUK converter to act as a grid-forming converter, thereby ensuring stability in DC microgrids.	The MPPT algorithm is not implemented, even though grid-forming converters attempt to inject maximum power from the PV panel using the same approach.
[14]	ZVT operation, which combines ZVS and ZCS, reduces switching losses, enabling bidirectional soft switching and enhancing efficiency, reliability, and component lifespan.	The ZVT circuit's control of auxiliary switches with MPPT input is not explained, and the conditions for Cr1 in Boost mode and Cr2 in Buck mode are not shown.

V. CONCLUSION

This rigorous review of the various categories of CUK converters is sufficient for understanding recent advancements in the renewable energy sector. This could inspire many researchers or engineers to pursue the next phase of research on the CUK converter, whether applied in renewable energy or other areas of electrical engineering related to energy conversion. The limitations mentioned in the papers studied so far in this review could serve as a research gap and a first step for any researcher's future research journey.

REFERENCES

- [1] Balaji Chandrasekar, N. Chellammal, and Bhargavi Nallamothe, "Non-Isolated Unidirectional Three-Port Cuk-Cuk Converter for Fuel Cell/Solar PV Systems", *Journal of Power Electronics*,
- [2] Saud Alotaibi, Ahmed Darwish a, Barry W. Williams Vol. 19, No. 5, pp. 1278-1288, September 2019.c, "Three-phase inverter based on isolated SEPIC/CUK converters for large-scale PV applications", Elsevier, *International Journal of Electrical Power and Energy Systems*, vol. 146, Arti. 108723, 2023.
- [3] V. Fernão Pires, Daniel Foito, F.R.B. Baptista, J. Fernando Silva, "A photovoltaic generator system with a DC/DC converter based on an integrated Boost-Cuk topology", Elsevier, *Solar Energy*, vol.136, pp. 1-9, 2016.
- [4] Atefe Shameli, Hosein Farzanehfard, "Bridgeless Cuk PFC converter with full load range soft switching operation by using a simple auxiliary circuit", Elsevier, *Computers and Electrical Engineering*, vol. 122, Art. 109905, 2025.
- [5] Binxin ZHU, Jiaxin LIU, Yu LIU, Kaihong WANG, "Fault-tolerance wide voltage conversion gain DC/DC converter for more electric aircraft", Science Direct, *Chinese Journal of Aeronautics*, Vol.36, iss. 7, pp. 420-429, 2023.
- [6] Anam Rais Assidiq, Andriazis Dahono, Arwindra Rizqiawan, Jihad Furqani, "High ratio DC-DC converter based on cascade modified Cuk converter topology", Elsevier, *e-Prime - Advances in Electrical Eng., Electronics and Energy*, Vol-9, 100654, 2024.
- [7] Somnath Pal, Bhim Singh, and Ashish Shrivastava, "A Novel Cost-Effective Dual-Colored LED Lighting in Household Applications", *IEEE Trans., Journal of Emerging & Selective Topics in Power Electronics*, vol.10, No. 4, August 2022.
- [8] Ahmed Darwish, Derrick Holliday, Shehab Ahmed, Ahmed M. Massoud, and Barry W. Williams, "A Single-Stage Three-Phase Inverter Based on Cuk Converters for PV Applications", *IEEE Trans., Emerging & Selected topics in Power Electronics*, vol.10, no.4, August 2022.
- [9] Abudlgafor Alfares, Brad Lehman, and Mashid Amirabadi, "A Cuk-Based Modular DC-DC Converter For Medium Voltage Direct Current (MVDC) Applications", *IEEE Trans., Open Journal of Power Electronics*, August 2022.
- [10] Laxmidhar Senapati, Anup Kumar Panda, Man Mohan Garg, and Rajesh Kumar Lenka, "An Adaptive Estimator-Based Sliding Mode Control of Non-Isolated Single-Input Double-Output Cuk Converter", *IEEE Trans., Journal of Emerging & Selected Topics in Industrial Electronics*, Vol. 4, No. 2, April 2023.
- [11] António Manuel Santos Spencer Andrade, Tiago Miguel Klein Faistel, Ademir Toebe, and Ronaldo Antonio Guisso, "Family of Transformerless Active Switched Inductor and Switched Capacitor Cuk DC-DC Converter for High Voltage Gain Applications", *IEEE Trans., Emerging and Selected Topics in Industrial Electronics*, Vol.2, No. 4, October 2021.
- [12] Reza Heidari, Ehsan Adib, Kwang-Il Jeong, Jin-Woo Ahn, "Soft-Switched Boost-Cuk-Type High Step-Up Converter for Grid-Tied with Half-Bridge Inverter", *IEEE Trans., Emerging and Selected Topics in Power Electronics*, Vol. 11, no.1, February 2023.
- [13] Marco Guerreiro, Pedro dos Santos, and Steven Liu, "Voltage Control of the Cuk Converter for Grid-Forming in DC Grids: An Energy-Based Approach", *IEEE Trans., Emerging and Selected Topics in Industrial Electronics*, Vol. 5, No. 4, October 2024.
- [14] Mahdi Rezvanyvardom and Amin Mirzaei, "Zero-Voltage Transition No isolated Bidirectional Buck-Boost DC Converter with Coupled Inductors", *IEEE Trans., Emerging and Selected Topics in Power Electronics*, Vol. 9, no.3, June 2021.
- [15] Ebrahim Babaei, Mir Esmaeel Seyed Mahmoodieh, "Systematical method of designing the elements of the Cuk converter", Elsevier, *Electrical Power and Energy Systems*, vol. 55, pp. 351-361, 2014.
- [16] Sukanya Dutta, Akshay Kumar Rathore, and Vinod Khadkikar, "Single-Phase Bridgeless Converter for On-Board EV Charger With Flexible Charging Capabilities", *IEEE Trans., Emerging and Selected Topics in Industrial Electronics*, Vol. 4, No. 4, October 2023.
- [17] Bhim Singh, Radha Kushwah, "A High Power Quality Battery Charger for Light Electric Vehicle based on Improved BL Cuk Converter with Low Component Count", 9th Power India International Conference, IEEE, March 2020, Sonapat, India.
- [18] Adepouju Webstar Oluwafeni, Emre Ozsoy, Sanjeevikumar Padmanaban, Mahajan Sagar Bhaskar, Vigna K Ramchandramurthy, Vilian Fedak, "A modified High Output Gain Cuk converter for Renewable application- A comprehensive Investigation", Conference on Energy Conversion (CENCON), IEEE, October 2017, Kuala Lumpur, Malaysia.

- [19] Rahul Pandey, Bhim Singh, "A Power Factor Corrected LLC Resonant Converter for Electric Vehicle Charger Using Cuk Converter", International Conference on Power Electronics, Drives and Energy Systems (PEDES), IEEE, December 2018, Chennai, India.
- [20] Burle Tulasi Rao, Dipankar De, "Additional Voltage Assisted High Gain DC-DC Converter with Modified Cuk Configuration", International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020), IEEE, January 2020, Cochin, India.
- [21] Bhim Singh, Jitendra Gupta, Radha Kushwaha, "An Improved Power Quality Charger for Electric Vehicle with Cuk PFC Converter", Transportation Electrification Conference & Expo (ITEC), IEEE, August 2020, Chicago, USA.
- [22] Sofyan M. Ilman, Andriazis Dahono, Muhammad Aji K Priambodo, Bintang Antares, Arwindra Rizqiawan, Pekik A. Dahono, "Analysis and Control of Modified DC-DC Cuk Converter", 2019 2nd International Conference on High Voltage Engineering and Power Systems (ICHVEPS), IEEE, October 2019, Bali, Indonesia.
- [23] Pandav Kiran Maroti, Sanjeevikumar Padmanaban, Patrick Wheeler, Frede Blaabjerg, Marco Rivera, "Modified High Voltage Conversion Inverting Cuk DC-DC Converter for Renewable Energy Application", Southern Power Electronics Conference (SPEC), December 2017, IEEE, Puerto Varas, Chile.
- [24] Sivanagaraju Gangavarapu, Akshay Kumar Rathore, Santanu K. Mishra, Rajeev K. Singh, "Analysis and Design of a Single-Phase Bridgeless Cuk-based PFC Converter as On-Board Charger with Reduced Number of Components and Losses", Transportation Electrification Conference (ITEC-India), IEEE, April 2020, Bengaluru, India.
- [25] Mr. Chandra Sekhar Tripathy, Mr. Sumant Kumar Dalai, Miss. Tamanna Samal, "Modeling and Simulation of Cuk-Converter Using Single-Phase Matrix Converter Topology", 2021 1st Odisha International Conference on Electrical Power Engineering, Communication and Computing Technology(ODICON), IEEE, May 2021, Bhubaneswar, India.
- [26] Md. Mizanur Rahman, M. Nasir Uddin and Md. Khurshedul Islam, "Performance Enhancement of a Bi-Directional DC-DC Converter using a CUK Converter for Electric Vehicle Applications", Proceedings of the 28th Canadian Conference on Electrical and Computer Engineering, IEEE, May 2015, Halifax, Canada.
- [27] Aniket Anand, Bhim Singh, "Cuk-SEPIC Based Bridgeless PFC Dual Output Converter Fed SRM Drive", 8th India International Conference on Power Electronics (IICPE), IEEE, December 2018, Jaipur, India.
- [28] Bor-ren Lin, Tsang-sum Huang, "Zero current switching CUK converter for power factor correction", Proceedings of IEEE International Symposium on Industrial Electronics, June 1996, Warsaw, Poland.
- [29] K. Balachander, A. Amudha, M. Siva Ramkumar, G. Emayavaramban, S. Divyapriy, P. Nagaveni, "Design and analysis of modified CUK converter for electric hybrid vehicle", Proceedings of Materials Today, Elsevier, 2021, vol.45, pp. 1691–1695.
- [30] Nimesh Kumar Singh, Anik Goswami, Pradip Kumar Sadhu, "Parameter extraction of floating solar PV system with war strategy optimization for sustainable cleaner generation", Microsystem Technologies, Springer Nature, vol.30, pp. 481-488, November 2023.
- [31] Nimesh Kumar Singh, Pradip Kumar Sadhu, "The investigation of energy and economy for floating solar PV system on saline water", Microsystem Technologies, vol.30, pp. 1079-1086, July 2024.

Cite this article as:

Sayantan, Pradip and et. al. "Application of Modified High-Gain, Bridgeless, PFC-type CUK converter for Sustainable Energy Production - A Critical Review", *Special Proceedings of Applied Energy System and Computer Science*. Displayed as online in October 2026.

AOI: 10.100.234512.00046

Link: <https://actsoft.org/science/act2025-pro/77-esda2024.pdf>

@Copyright to 'Applied Computer Technology', Kolkata, WB, India. Website: <https://actsoft.org>, Email: info@actsoft.org,