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Bipolar DC output fed grounded DC-AC converter for photovoltaic application

***Introduction**. In recent years the usage of electricity has increased tremendously as the electrical needs and loads got increased. Hence the researchers focused on the electricity generation from renewable sources in order to promote sustainable green environment. Owing to the lesser cost and more reliable high efficiency system with reduced use of equipments became prominent for the grid connected photovoltaic single phase systems. The **novelty** of this proposed converters are to reduce total power loss and to analyze the performance of the converter under various modulation index and to have lesser harmonics using sinusoidal pulse width modulation technique for both T-type and F-type inverter. Interest of the work is to merge two DC-DC converters which have same output voltage in order to have transformer less utilization of power. This has given pathway to develop a new DC-DC converter network by merging the common input nodes of CUK and SEPIC converter. **Purpose.** This similar structure of both converters made it easy to combine the input stages of and to get bipolar output. **Methods.** Here we can get bipolar output without the utilization of transformer which minimizes the overall size of the proposed system. In this paper, a combined CUK-SEPIC based grid connected transformerless inverter for photovoltaic application is suggested. **Results.** The suggested converter is simulated using MATLAB and the results were discussed. Further the circuit is extended with a 1 kW F-type inverter to demonstrate grid connection of the converter. **Practical value.** This converter can be implemented for photovoltaic applications for obtaining the bipolar DC output from the DC source.* References 16, table 4, figures 12.

Key words: **combined CUK-SEPIC converter, bipolar inverter, T-type inverter, F-type inverter, maximum power point tracking, transformerless inverter, single phase photovoltaic systems.**

***Вступ**. В останні роки використання електроенергії значно зросло, оскільки потреби в електроенергії та навантаження збільшились. Тому дослідники зосередилися на виробництві електроенергії з відновлюваних джерел, щоб сприяти стійкому зеленому середовищу. Через меншу вартість та більш надійну високоефективну систему зі зменшеним використанням обладнання набули популярності фотоелектричні однофазні системи, підключені до мережі. **Новизна** пропонованих перетворювачів полягає у зниженні загальних втрат потужності та аналізі характеристик перетворювача при різних індексах модуляції, а також у зменшенні гармонік з використанням методу широтно-імпульсної модуляції синусоїдального типу для інверторів як T-типу, так і F-типу. Інтерес роботи полягає в об'єднанні двох перетворювачів постійного струму з однаковою вихідною напругою, щоб мати менше використання потужності трансформатора. Це дозволило розробити нову мережу перетворювачів постійного струму шляхом об'єднання загальних вхідних вузлів перетворювача CUK та SEPIC. **Мета**. Подібна структура обох перетворювачів дозволила легко поєднати вхідні каскади та отримати біполярний вихідний сигнал. **Методи**. Тут ми можемо отримати біполярний вихід без використання трансформатора, що мінімізує загальний розмір пропонованої системи. У цій статті пропонується комбінований безтрансформаторний інвертор на основі CUK-SEPIC, підключений до мережі, для фотоелектричних застосувань. **Результати**. Пропонований перетворювач моделюється за допомогою MATLAB, результати обговорюються. Далі схема розширена інвертором F-типу потужністю 1 кВт, щоб продемонструвати підключення перетворювача до мережі. **Практична цінність**. Цей перетворювач може бути реалізований для фотоелектричних застосувань для отримання біполярного виходу постійного струму джерела постійного струму.* Бібл. 16, табл. 4, рис. 12.

Ключові слова: **комбінований перетворювач CUK-SEPIC, біполярний інвертор, інвертор T-типу, інвертор F-типу, відстеження точки максимальної потужності, безтрансформаторний інвертор, однофазні фотоелектричні системи.**

Introduction.

A. DC-DC converters for photovoltaic application. Solar photovoltaic (PV) systems started ruling the recent era of power generation as its renewable and widely available resource. Hence the research started on that topic to increase the utilization of solar energy in an efficient way, which has given rise to wide varieties of DC-DC converter. Since the output whence the solar PV cell is DC we need to integrate the photovoltaic system with an efficient DC-DC converter topology. The non-isolated topology of DC-DC converter is of copious types [1]. The differentiation of copious DC-DC converter is presented in Table 1, which explains the count of devices used and expression for output voltage along with nature of output whether unipolar or bipolar.

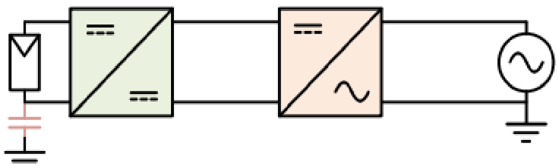
Table 1

Commonly used DC-DC converter

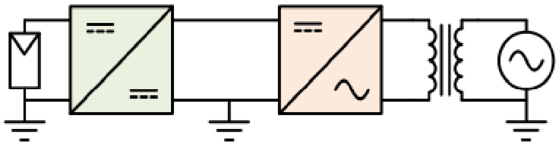
Converter	Voltage output	Input current	Voltage gain	No. of switches	No. of diodes	No. of inductors	No. of capacitors
Buck	Unipolar	Intermittent	D	1	1	1	1
Boost	Unipolar	Uninterrupted	$1/(1–D)$	1	1	1	1
Buck-Boost converter	Unipolar	Intermittent	$D/(1–D)$	1	1	1	1
CUK	Unipolar	Uninterrupted	$–D/(1–D)$	1	1	2	2
SEPIC	Unipolar	Uninterrupted	$D/(1–D)$	1	1	2	2
Combined Charging System	Bipolar	Uninterrupted	$2D/(1–D)$	1	2	3	4

The major building block of PV application is the DC-DC converter hence the proper choice of DC-DC converter is much needed for efficient utilization of resource. In PV applications, boost converters are widely employed for DC-DC conversion, but only with stepping-up voltages ratios [2-4]. Both the increased and decreased voltage conversion are feasible with the buck-boost converter but the main drawback is the discontinuous input current which stops the converter from optimal tracking of maximum power point tracking (MPPT) without decoupling capacitor [5]. The output voltage expression of CUK and SEPIC converter both are same but the only difference between them is the reversal of current. The input current in both these converter is continuous and have wide range of operating voltage in it. The main losses associated with DC-DC converters are losses associated with switches, inductor winding loss, diode conduction loss and inductor core loss. The minimization of the leakage current has been the main drawback in transformerless topology [6-9]. The proposed converter also has same number of switches like other DC-DC converter and in addition we can achieve a bipolar output from it with reduced current ripple [9]. The nature of high input current ripple limits the performance of MPPT. In order to enhance the PV system efficiency the input current ripple has to be minimized by using suitable modulation technique [10, 11]. The proposed converter reduces peak inductor current by minimizing input current ripple. This keeps the PV system to operate near MPP thereby improving the total power extracted.

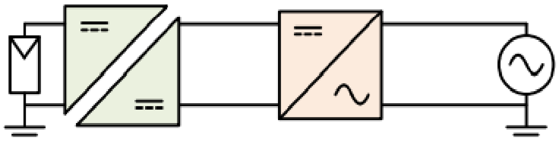
B. Configuration of PV system. Generally PV systems are used for configuring with the single phase AC grids with earth connection. Apart from the voltage boost or buck capability offered by the various DC-DC converters the main factor to be considered is the impact of the leakage current. There are various inverters out of which the H-bridge inverter which has been used widely introduces leakage current to pass through the PV panel parasitic capacitance [10, 11] as shown in Fig 1,*a*.



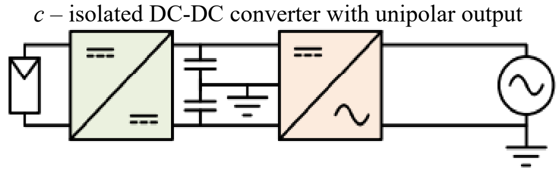
a – unipolar DC output without transformer causing leakage currents



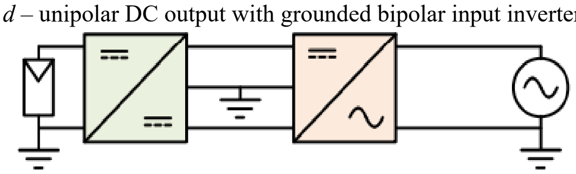
b – unipolar DC with line frequency transformer



c – isolated DC-DC converter with unipolar output



d – unipolar DC output with grounded bipolar input inverter



e – bipolar DC output with grounded bipolar input inverter

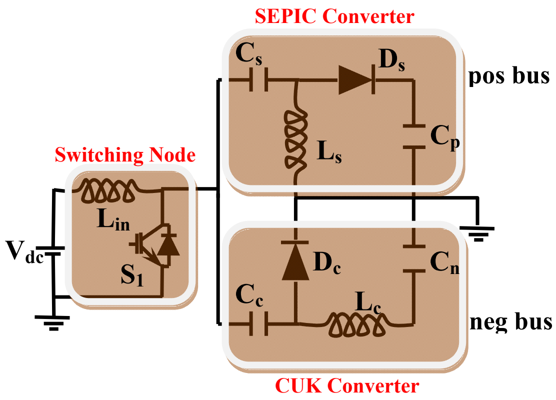
Fig. 1. Variety of grounding choices for PV systems

This leakage current problem can be mitigated easily using a transformer operating at line frequency between the PV system and grid in order to provide ground connection as shown in Fig. 1,*b*, but the main drawback with this method is that the system becomes bulky, costly and heavy [12]. Hence this problem is met by utilizing the concept of isolated DC-DC converter topology as shown in Fig. 1,*c* but the drawback over here is it provides the unipolar output. This condition can be met by introducing a grounded bipolar input inverter as shown in Fig. 1,*d*. It makes no difference whether a low- or high-frequency transformer is used, topologies without owing transformer are having more efficiency, lighter in weight, and less expensive than isolated inverters. However, by making use of non-isolated PV inverters, ground leakage currents because of parasitic capacitance are a major concern [13]. The decoupling method will tend to boost the efficiency of systems by chopping the complexity and losses of the system. In view to eliminate the decoupling issues and to eliminate the usage of transformer the alternate solution is the use of an inverter with the grounded bipolar DC output. The configuration as shown in Fig. 1,*e* eliminates all the problems discussed above and mitigate the leakage current issues without the use of transformer. Hence the system becomes less complex and more reliable. This DC output has to be fed with DC-AC converter for which many inverters are available. To have lesser harmonics cascaded multilevel inverters can be utilized [14]. But main drawback is the need of bipolar inverter [15].

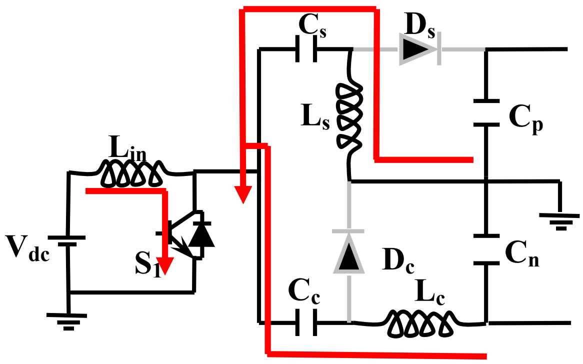
C. Proposed CUK-SEPIC converter. The suggested converter used the benefits of both CUK and SEPIC converter in order to produce a bipolar output. The proposed CUK-SEPIC converter has been in investigation recently and it's found to be the best solution for a reliable and efficient PV systems. Since, both the CUK and the SEPIC converter's input stages are same it made an idea to combine both the converters input stage. Thus by having the common input switching stages both the converters is connected. Since the voltage expression for the output is same in case of CUK and SEPIC it paved a way of generating DC bus. Since the polarity of output is reversed in CUK and SEPIC the SEPIC produce a positive voltage bus and CUK produces a negative voltage bus and both are of same magnitude. As a result, the output generates a bipolar DC bus. The configuration of this proposed combination of CUK-SEPIC converter is shown in Fig. 2,*a*. The suggested structure has the one single common switching node.

When the switch is turned on in the manner depicted in Fig. 2,*b* the inductors present in the circuit L_{in}, L_s and L_c will be in charging state whereas the capacitors C_s and C_c discharges and the direction of the current will be as shown in the Fig. 2,*b*. During the turn off of the switch the vice versa will happen. The inductors present in the circuit L_{in}, L_s and L_c will be in discharging state whereas the capacitors C_s and C_c starts charging and the direction of the current will be as shown in the Fig. 2,*c*.

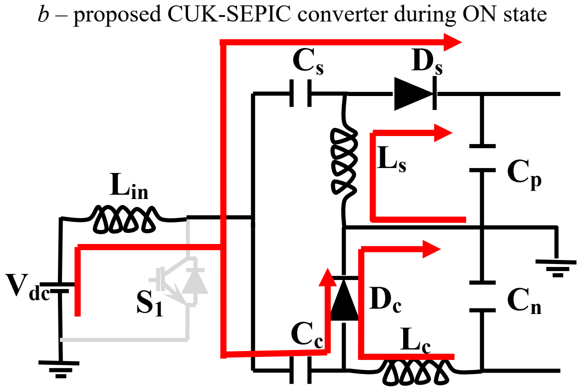
The proposed converter is having ability of providing both enlarged and reduced voltage ratios since the gain when it comes to voltage is $2D/(1–D)$. This implies that if the duty ratio (D) which is the proportion of switch turn on time to complete time period is less than 0.5 the suggested converter operates in step down or buck mode and if the duty ratio (D) is greater than 0.5 then the suggested converter will operate in the step-up or buck mode of operation. Thereby achieving an output voltage in wide range is possible to get achieved using this proposed combination of CUK and SEPIC converter. As we take into account the output voltage gain across both converter together, the voltage gain will be $2D/(1–D)$ which regulates wide variation in input voltages. In reality, the capacitor of enough capacitance should be connected before coupling with inverter in order to decouple the PV array from the 100 Hz ripple, allowing for continuous power output and keeping the PV panel operating at its MPP.



a – proposed CUK-SEPIC converter topology



b – proposed CUK-SEPIC converter during ON state



c – proposed CUK-SEPIC converter topology during OFF state

Fig. 2.

Bipolar inverter grid integrated with PV solar.

A. MPPT. The prerequisite of the input current of the converter, which controls the output current of the PV system and hence power, is explained by the *P-V* and *I-V* curves [1]. In order to make the maximum power and for the purpose to handle system efficiently and effectively we need to steer the PV panel at its optimum operating point. There are several algorithms which helps us to operate the panel at its MPP which makes system efficient one. The Perturb and Observe (P&O) algorithm is used here. The flowchart of the P&O algorithm is as shown in the Fig. 3. The MPPT controller sends an updated reference value to a PI current controller, which receives it. In most cases, the MPPT's reference would vary smoothly [1].

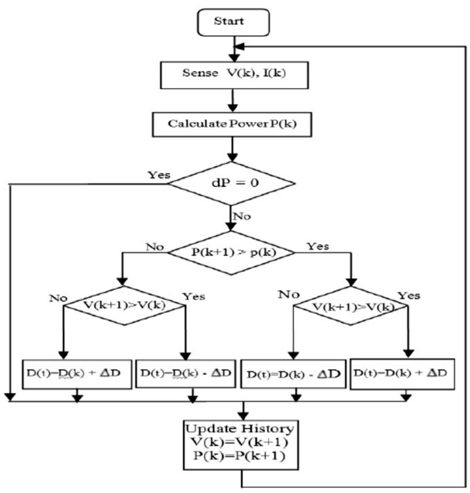


Fig. 3. Flowchart of P&O algorithm

B. Bipolar T-type inverter. As we need to export this DC into the grid we need to integrate our system with an inverter configuration for converting DC power from the solar panel into AC power. Inverters can be of unipolar DC input type or bipolar DC input type. The main disadvantage of the unipolar type is that it cannot provide the leakage current elimination. Hence we need to opt for the bipolar DC input structure type inverter. The bipolar inverter likes half bridge inverter, T-type inverter, flying capacitor/capacitor-clamped inverter [1]. In this paper we have simulated for T-type inverter. The pattern in which switches need to be triggered is shown in Table 2.

Table 2

T-type inverter switching states

State	V_{out}	S_1	S_2	S_3	S_4
P	$+V_{DC}/2$	1	1	0	0
0	0	0	1	1	0
N	$–V_{DC}/2$	0	0	1	1

The overall converter composition is as shown in the Fig. 3. The converter is designed as per the specification given in Table 3. The main drawback in T-type inverter is increased voltage stress across the switches.

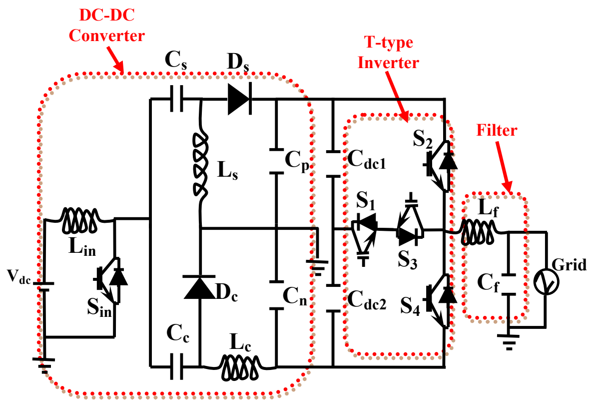


Fig. 4. Overall proposed system with T-type inverter

Table 3

Converter specification

Component	Values	Component	Values	Component	Values
L_{in}	545 μH	C_p	5 μF	L_c	891 μH
C_s	1.5 μF	C_n	0.33 μF	L_f	330 μH
C_c	0.47 μF	L_s	891 μH	C_f	1 μF

C. Bipolar F-type inverter. Figure 5 depicts the F-type inverter's phase-leg power circuit. It is a topologically modified T-type inverter circuit in which the bidirectional switch's common-emitter node is explored in order to reduce voltage stress in the forming power switches. It operates in the same way as its neutral point clamped. As a result, it can generate three output voltages with reference to the neutral-point n: $0.5 \cdot V_{dc}$, $0 \cdot V_{dc}$, and $-0.5 \cdot V_{dc}$ [16]. Table 4 shows the switching states of the power switches as well as the generated inverter output voltages. The letters P, O, and N in this table reflect the inverter's positive, zero, and negative voltage states, respectively. The logic states 1 and 0 indicate the ON and OFF switching states of the power switches, respectively.

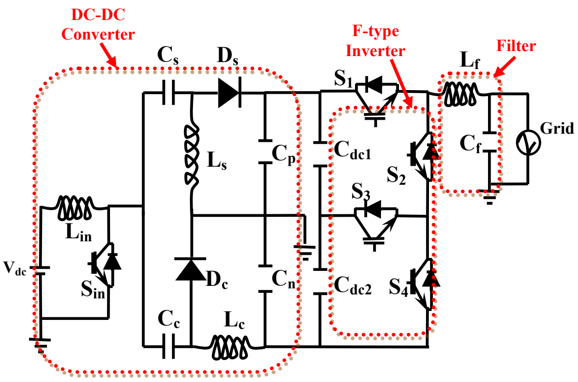


Fig. 5. Overall proposed system with F-type inverter

Table 4

The F-type inverter switching states

State	V_{out}	S_1	S_2	S_3	S_4
P	$+V_{DC}/2$	1	0	1	0
0	0	0	1	1	0
N	$-V_{DC}/2$	0	1	0	1

D. Sinusoidal pulse width modulation (SPWM) technique. SPWM is a phase modulation technology that uses an inverter phase-leg based operational basis to generate gating signals. The phase angle shift is the only control parameter that differs. Its expansion to a multiphase multilevel system provides minimal computational problems when compared to space vector modulation. When pure sinusoidal references are used in the modulation process, the SPWM approach has the drawback of underutilizing the dc-link voltage in power converters. One strategy for extending the modulation index range in the linear modulation area beyond unity with SPWM is to add the zero-sequence component in accordance with the min–max function principle.

E. Estimation of power loss. Because it has a direct impact on the converter's efficiency, the converter's loss calculation is an important factor for assessing its performance. Conduction and switching losses are the two most typical types of losses in a converter. The conduction current, $i(t)$, and the turn-on resistance, R_S and R_D, where S and D stand for switch and diode, respectively, are linked to conduction losses. Because a switch consists of both a transistor and an anti-parallel diode, both are considered for computing losses. Both of these are calculated as follows:

$$P_{con(S)}(t) = [V_s + R_S I \wedge \beta(t)] \cdot I(t); \quad (1)$$

$$P_{con(D)}(t) = [V_D + R_D I \wedge \beta(t)] \cdot I(t), \quad (2)$$

where specification can be found in the Datasheet.

The sum of (1) and (2) is the overall conduction losses of a switch. The number of transistors (N_S) and diodes (N_D) that conduct instantly determine the average conduction loss of a converter.

The quantity of energy dissipated during each phase determines the switching losses, which are classified into two categories: turn-off losses and turn-on losses. The following formula (3) and (4) is used to calculate these losses:

$$E_{off}(S) = \int_0^{t_{off}} v(t) \cdot i(t) dt ; \quad (3)$$

$$E_{on}(S) = \int_0^{t_{on}} v(t) \cdot i(t) dt . \quad (3)$$

During the turn-on and turn-off times, energy is lost across each switch. Energy lost across s^{th} switch are $E_{off,\,s}$ and $E_{on,s}$, respectively. And t_{off} and t_{on} represent the time it takes for the switch to turn on and off, respectively, while t represents the period. The power loss is calculated for various modulation indexes and shown in Fig. 6. It is clear from Fig. 7 that the losses in F-type converter are less compared to T-type inverter.

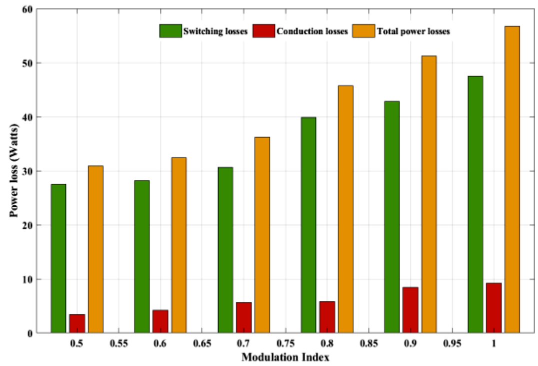


Fig. 6. Power loss for varying modulation index

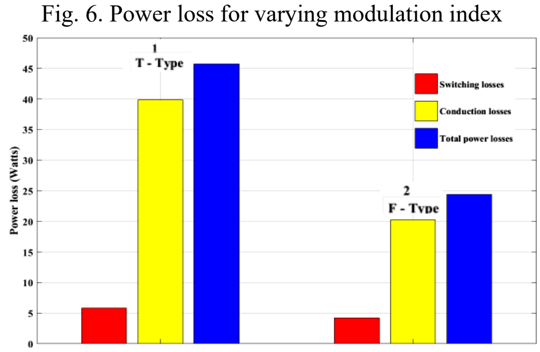


Fig. 7. Total power loss for T-type and F-type configuration

F. Simulation results. The proposed CUK-SEPIC converter is combined with the bipolar F-type inverter in place to analyze the waveform and its operation. The converter's DC input is supplied by a solar PV panel, which is then monitored by an MPPT controller. The P&O algorithm is used in the MPPT controller and simulated. The LC filter is been chosen for this purpose. The converter utilizes a decoupling capacitor of 100 µF in order to remove the 100 Hz ripple in the system. A 1 kW F-type inverter has been designed to serve this proposed DC-DC converter [1]. The switching frequency is around 100 kHz, and the rated input voltage is 360 V DC. The suggested converter can achieve a wide variation in the output voltages gain of the converter. It can dispense both expanded and shrunken voltage ranges. The complete setup of the network is shown in Fig. 8.

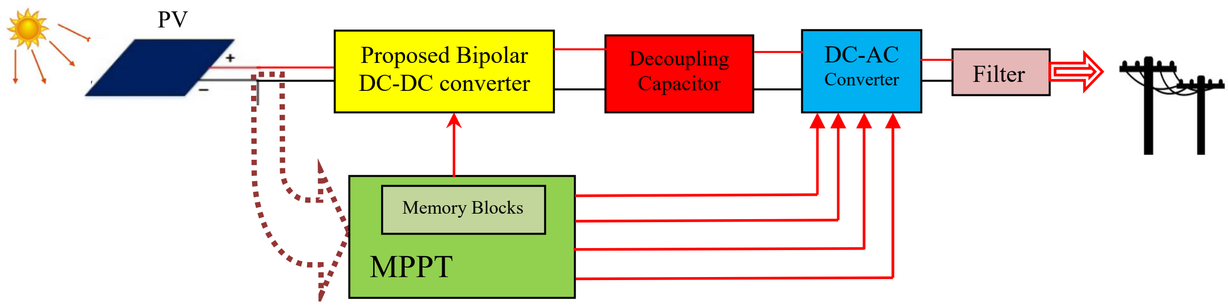
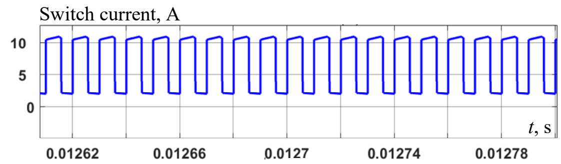
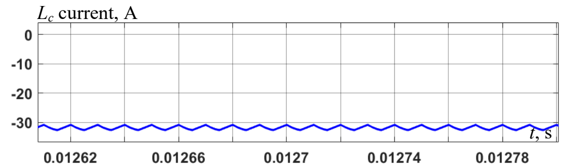


Fig. 8. Overall system of proposed network

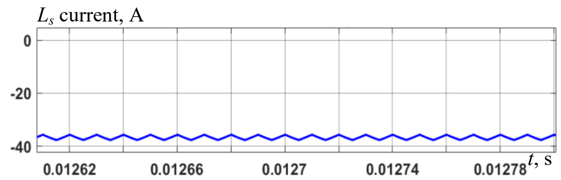
The common switching node at the input side provides the possibility of bipolar output at the DC-DC converter side. Figure 9,*a* shows the switching current waveform in the common input node. The CUK converter provides the negative output and the SEPIC converter provides the positive output this necessitates the possibility of occurrence of bipolar DC bus. Figures 9,*b*,*c* depict the current through L_C and L_S. Figures 9,*d*,*e* show the current obtained through the positive and negative bus.



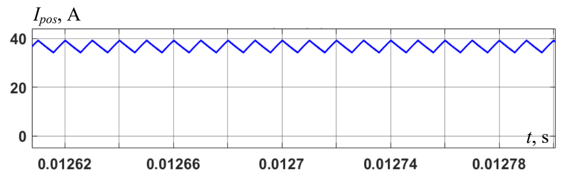
a – common node switching current



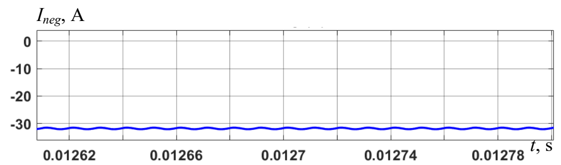
b – current through CUK side inductor



c – current through SEPIC side inductor



d – current through positive bus



e – current through negative bus

Fig. 9

Figure 10 represents the bipolar DC voltage obtained at the result of the above said converter.

The overall system topology of integrated proposed CUK-SEPIC converter with MPPT controller connected with the bipolar F-type inverter is illustrated in Fig. 5. The following circuit was built, simulated and the results were obtained using MATLAB. Figure 11 depicts the output voltage and current waveforms obtained across the inverter output. In order to visualize the output waveform *R* load is considered as 100 Ω.

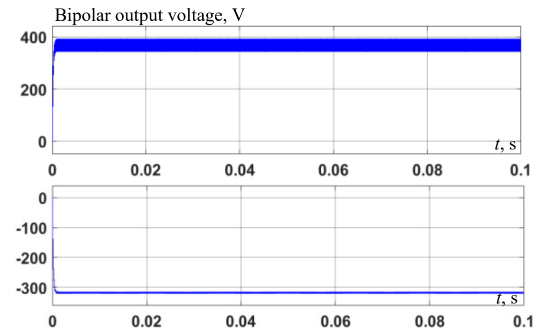


Fig. 10. Bipolar DC bus voltage

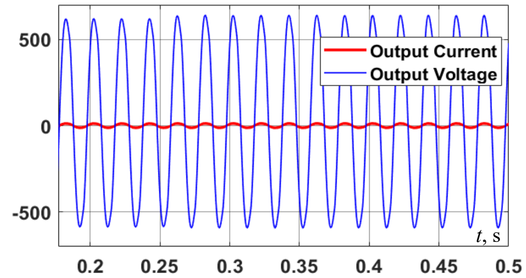


Fig. 11. AC grid output voltage and current

The overall system topology of hardware setup with PV integrated proposed CUK-SEPIC converter with MPPT controller connected with the bipolar F-type inverter is illustrated in Fig. 8 and the developed module in MATLAB/Simulink environment is depicted in Fig. 12 which has CUK-SEPIC converter fed DC-AC inverter.

Conclusions. The similarity in the structure of the CUK and SEPIC converters' input stages made the development of this proposed converter with the single common switching node and as the CUK converter imparts the negative voltage and the SEPIC converter imparts the positive voltage and both the voltage is of same magnitude which added advantage of obtaining the bipolar DC voltage at the terminal of the DC-DC converter. The transformerless utilization of this converter paves the way of lesser cost and complexity. Because of the bipolar inverter utilised in the circuit, the converter's input current ripple is reduced and leakage current is removed. When compared to T-type converter the F-type converter, F-type converter reduces the total conduction losses by 47.8 %. Thus F-type inverter produces lesser switching and conduction losses paying the way for the better efficient inverter topology.

Conflict of interest. The authors declare that they have no conflicts of interest.

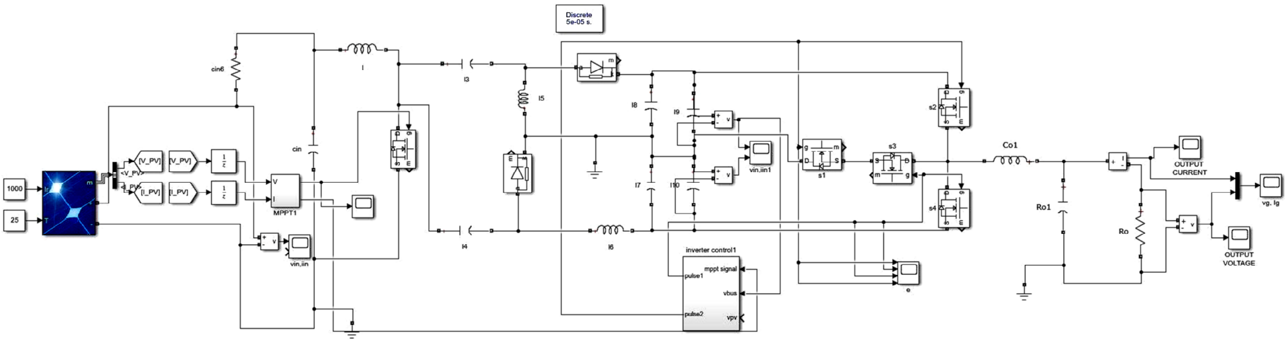


Fig. 12. Overall system of proposed network

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