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Comparison of high gain power conditioners for photovoltaic applications with suitable maximum power point tracking

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Abstract

In this paper, a comparative study of high gain step-up converters of different topologies is taken place. Due to the increase in pollution, a shift towards a green energy is opted. The Photo Voltaic (PV) system is chosen as a source for the converters. To harvest maximum power from the PV, a suitable Maximum Power Point Tracking (MPPT) technique is adapted. The different converters taken into considerations are Conventional Boost converter, Full Bridge Converter, Dual Active Bridge Converter and Single- Ended-primary-Inductor Converter SEPIC. The major goal of this paper is to extract high gain from the converter with minimum PV output. The complexity among the converters is analyzed and this comparison reveals the best converter for the PV system. The converters are simulated using MATLAB/Simulink.

Keywords: *Photo Voltaic; Conventional Boost; Single- Ended-Primary-Inductor Converter; Full Bridge Converter; Dual Active Bridge Converter*.

1. Introduction

Recent times, due to the tremendous increase in population growth rate, the usage of electricity have been increased. The generation of power from the conventional resources such as fossil fuels and nuclear fuels will end up in scarcity one day. If that is the case, then the demand of electricity will be increased drastically. In order to meet the demand, a shift towards the renewable energy is necessary.
The renewable energy (i.e.) the non-conventional energy is abundant in nature. There are different types of renewable energy resources. Some of them are Photo Voltaic (PV) system, wind, tidal, geothermal, biomass etc. Energy can be retrieved easily and economically with the help of those renewable energy resources. Among them, a study of Photovoltaic system is to be seen in detail in this paper. The PV power generation provides green energy without any pollution; consequently, it becomes environmentally friendly. Hence, there is a drastic growth among the other renewable energy systems.
The PV and solar thermal heat technology exist separately, which is now combined due to increase in efficiency [1]. The Photovoltaic/Therrmal PV/T provides dual operations such as collection of photons which generates electricity and heat. The PV/T results in an increase in efficiency compared to the PV [1].
The PV/T technologies are classified into 3 major types, they are a flat plate, flexible and concentrated. The types of the PV panel the applications and the electrical and thermal efficiencies are described in Table1. [2].
The Table 1 illustrates the application of each PV/T type. For the concern of Flat-Plate are mounted on ground or roof top. The application focused on the flat plate [3] is to provide radiant floor heating and hot water supply, here the thermal efficiency is about 25.8% and electrical efficiency is about 14.5% [3]. Even the concentrated type has the same pattern of a roof top or

Table 1: PV/T Types Temperature and Efficiencies Ground Mounting. The Efficiency Is Quite Like That of the Flat Type [4], The Concentrated Type Can Sustain High Temperature

PV/T Types	Flat - Plate	Flexible	Concentrated
Temperature	Low-And-Moderate	Low-And-Moderate	High
Module's Electrical Efficiencies	6.7 - 15%	5 - 10 %	7 - 16%
Module's Thermal Efficiencies	22 - 79%	22 - 79%	39 - 70%

For the flexible type, roof top mounting or irregular building facades/tiles provide the installation. The all over efficiency is like that of the concentrated type [5].
The PV modules are selected: to provide a green energy in an efficient way. The selection of MPPT plays a vital role in harvesting the maximum power from the PV module. There are different algorithms present in extracting the maximum power. The lists of the different MPPT techniques are described in the Fig.1.

Maximum Power Point Tracking is a technique, which is used to harvest maximum power from the renewable energy sources such as photovoltaics and wind turbines. The MPPT technique has many different types of algorithm, they vary among each other in the aspect of tracking speed, convergence speed, whether can handle partial shading and level of complexity. Any hindrance of building or tree, bird droppings and low maintenance from dust particles lead to partial shading of the PV panel. The tracking system is improvising in the aspects of partial shading too.
Among the MPPT classifications of algorithim shown in Fig. 1., the conventional Incremental conductance algorithm is considered in this paper.

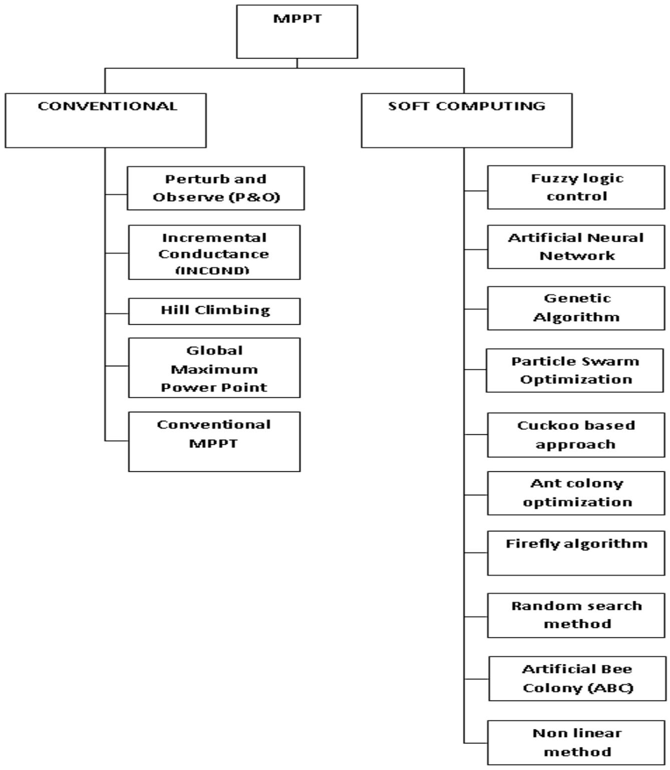

Fig. 1: Comparison of MPPT Techniques.

The MPPT technique is implemented for the converter since the source is PV. It is wise to choose best DC-DC converter to implement and to regulate the voltage. The converter's duty ratio is varied as per the maximum power on the panel.
The DC-DC converters can be classified as a buck, boost, buck-boost, forward, flyback, SEPIC, and CUK. Since the source of the paper is photovoltaic, a converter which regulates as a step up is alone considered and implemented. So higher gain converters are chosen such as Conventional boost converter, SEPIC converter, Modified SEPIC converter, Full bridge converter and Dual active bridge converter. Thus, comparison of their performance is carried out.
The sections of the paper can be summarized as: section I deal with the design of the photovoltaic system. In order to harvest maximum power from the PV, MPPT technique modeling equations and flowcharts of the suitable algorithm are discussed in section II. Then Section III involves the theoretical comparison of high gain DC-DC converters. Finally, the simulation result of the converters comprises section IV.

2. Photo voltaic system

In the year 1950's, researchers incorporate the development of PV [6-7]. As a panel PV is classified into three types as shown in Table 1[2]. The PV is utilized effectively when it relates to the converter either with or without a controller. So that it can be connected to the load side easily.
The photovoltaic cell is a semiconductor diode consisting of the p-n junction. The light can incident in the cell, which generates carriers that originate the electrical current [8]. This process of generating charge carriers incorporate when the cell is short-circuited. The most common single cell model [9] is combined to form arrays and then arrays are grouped to form modules.
Describing the fabrication of PV cell is out of scope in this paper because this paper concentrates on the regulation of the PV output. Converter's input depends on the output of the PV. Thus, the PV modeling is accomplished.

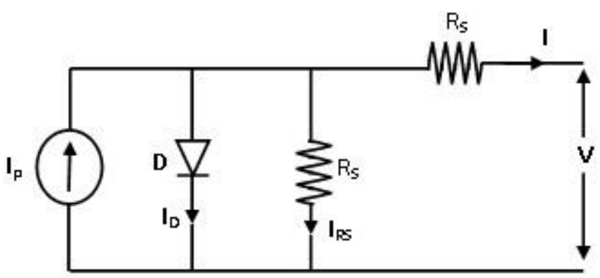

Fig. 2: The Equivalent Circuit of A Photovoltaic Cell Using the Single Exponential Model.

The equivalent circuit and the basic equations of the PV cell/ module in Standard Test Conditions (STC) are formulated [10-11]. STC is to measure PV cells or modules nominal output power.
STC condition:
Irradiance level = 1000 W/m^2
Temperature = 25° C

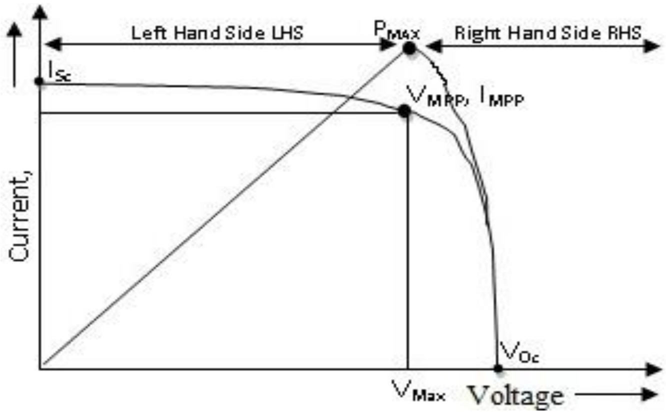

Fig. 3: I-V Characteristics of PV Module [17].

Therefore, the governing equation for the equivalent circuit is derived using Kirchoff's current law for current I.

$$I = I_{Ph} - I_D - I_{Sh} \tag{1}$$

I_{Ph} → photocurrent
I_D → diode current
I_{Sh} → shunt resistor current
In single diode module, I_D is modeled using the Shockley equation for an ideal diode.

$$I_D = I_o \left[\exp\left(\frac{V + I R_S}{n V_T}\right) - 1\right] \tag{2}$$

n → diode ideality factor
I_D →saturation current
V_T → thermal voltage
I_o → diode reverse saturation current
R_S → Series Resistance

We know that, $V_T = \frac{kT_c}{q}$ (3)

Where, k→ Boltzmann's constant (1.381 X 10^{-23} J/K)
q → Elementary charge (1.602 X 10^{-19} C)

$$I_{Sh} = \frac{(V + I R_S)}{R_{Sh}} \tag{4}$$

R_{Sh} → Shunt resistance.
Substituting equation 2 and 3 in 1

$$I = I_{Ph} - I_o\left[exp\left(\frac{V + IR_S}{nV_T}\right) - 1\right] - \frac{V + IR_S}{R_{Sh}} \tag{5}$$

- Short Circuit Point

Equation (4) can be written as

$$I_{Sc} = I_{Ph} - I_o\left[exp\left(\frac{V_{Sc} + I_{Sc}R_S}{nV_T}\right) - 1\right] - \frac{V_{Sc} + I_{Sc}R_S}{R_{Sh}} \tag{6}$$

W. K. T, At short circuit point, V_{Sc} =0,
Therefore,

$$I_{Sc} = I_{Ph} - I_o\left[exp\left(\frac{I_{Sc}R_S}{nV_T}\right) - 1\right] - \frac{I_{Sc}R_S}{R_{Sh}} \tag{7}$$

- Open Circuit Point

The equation for open circuit point can be expressed as

$$I_{Oc} = I_{Ph} - I_o\left[exp\left(\frac{V_{Oc} + I_{Oc}R_S}{nV_T}\right) - 1\right] - \frac{V_{Oc} + I_{Oc}R_S}{R_{Sh}} \tag{8}$$

W.K.T, At open circuit point, I_{Oc} =0, therefore,

$$0 = I_{Ph} - I_o\left[exp\left(\frac{V_{Oc}}{nV_T}\right) - 1\right] - \frac{V_{Oc}}{R_{Sh}} \quad (9)$$

- Single Cell Equation For A Module Or Array Becomes

I_{module} =I_{cell}
V_{module} = N_S X V_{Cell}
Thus,

$$I_M = I_{Ph} - I_o\left[exp\left(\frac{V_M+I_M N_S R_S}{nN_S V_T}\right) - 1\right] - \frac{V_M+I_M N_S R_S}{N_S R_{Sh}} \quad (10)$$

Where I_M and V_M are voltage and current of modules or array.

- Maximum Power Point

At maximum power point tracking V=V_{MPP} and I=I_{MPP} , therefore,

$$I_{MPP} = I_{Ph} - I_o\left[exp\left(\frac{MPP+I_{MPP}R_S}{nV_T}\right) - 1\right] - \frac{V_{MPP}+I_{MPP}R_S}{R_{Sh}} \quad (11)$$

3. Maximum power point tracking

Maximum Power Point Tracking (MPPT) is used to provide the desired output at any circumstance apart from weather abnormalities. An algorithm is framed for the converter's duty cycle ratio, in order to track the Maximum Power Point (MPP). In literature, there are various algorithms as shown in table 2, among them Incremental Conductance (INCOND) is concentrated due to its higher efficiency [12].

3.1. Incremental conductance

From the derivative of the PV module, power is zero at MPP, positive at the left of MPP and Negative at the right of the MPP.

$\frac{dP}{dV} = 0$ at MPP

$\frac{dP}{dV} > 0$ at left of MPP (i.e.) $\frac{dP}{dV}$ is negative (12)

$\frac{dP}{dV} < 0$ at right of MPP (i.e.) $\frac{dP}{dV}$ is positive

The incremental conductance method overcomes the limitations of P&O by dealing with the signs of dP/dV [13-14]

Therefore, $\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V}$ (13)

For MPP, $\frac{dP}{dV}$ = 0, we obtain

$$I + V\frac{\Delta I}{\Delta V} = 0 \quad (14)$$

$At\ MPP, \frac{\Delta I}{\Delta V} = -\frac{I}{V}$

$At\ left\ of\ MPP\ \frac{\Delta I}{\Delta V} > -\frac{I}{V}$

$At\ Right\ of\ MPP\ \frac{\Delta I}{\Delta V} < -\frac{I}{V}$

By comparing the $\frac{I}{V}$ to $\frac{\Delta I}{\Delta V}$, the MPP can be tracked.
Where, $\frac{I}{V}$ → instantaneous conductance
$\frac{\Delta I}{\Delta V}$ → incremental conductance.
The PV array operates at V_{REF} , At that instant V_{REF} =V_{MPP}. V_{REF} remains same until there is any change in atmospheric conditions, therefore rapid computation is involved in the controller. The parameter V_{REF} is altered to maintain the MPP as shown in the Fig. 3 [15-16].

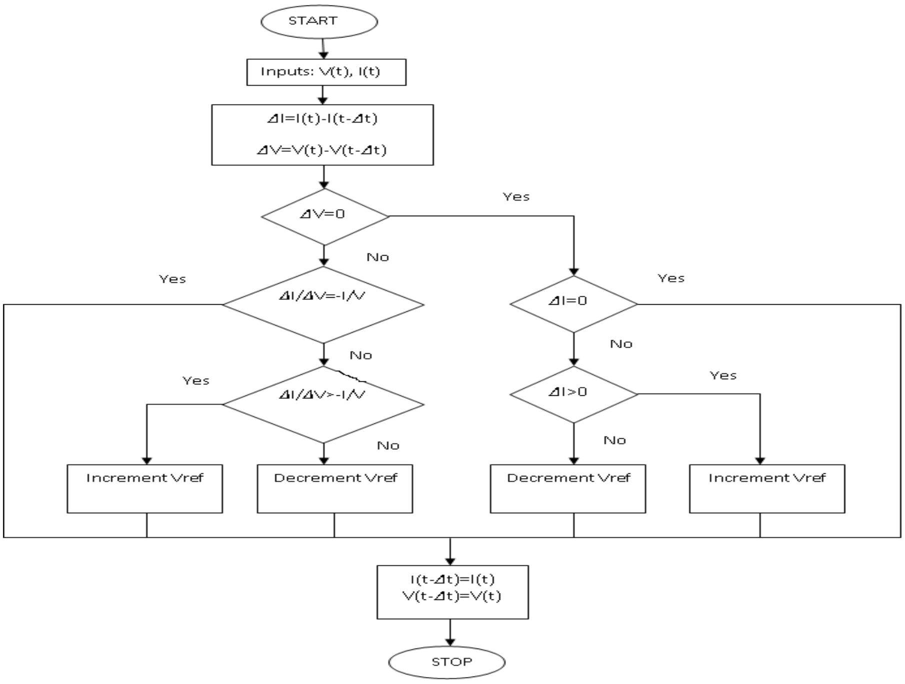

Fig. 3: Flowchart of Incremental Conductance (INCOND) Method [15-16].

The INCOND algorithm is advantageous than P&O, due to the ability to track rapid change in atmospheric conditions [13]. The dynamic tracking and steady tracking are high compared to the P&O technique. The limit faced by INCOND technique is the algorithm complexity is high. But due to the preciseness in tracking change in atmospheric conditions, the high in complexity is almost negligible.

4. High gain DC-DC converters-objective

For the purpose of high gain converter comparison, four different topologies of step up converters are analyzed. The converters are Conventional Boost converter, Full bridge converter, Dual active bridge converter and SEPIC converter.

4.1. Boost converter

Initially, in 1960's, the step-up circuit was operated by means of a transistor. The usage of the transistor in converters is to boost the low voltage level to higher level [18]. Due to the generation development, the boost converters are operated with semiconductor devices. The duty ratio of the converter can be calculated by (15). Duty cycle ratio is directly proportional to the gain of the converter.

$$V_{out} = \frac{V_{in}}{1-D} \tag{15}$$

4.2. SEPIC converter

The SEPIC converter has the capability of step down and step up like the buck-boost converter [44], [45], here the step-up operation is discussed. In comparison with the boost and SEPIC converter, SEPIC converter comprises of 2 inductors and 2 capacitors. Hence due to the additional passive element there will be a slight increase in the gain of the converter [46].

$$D = \frac{V_{out}}{V_{out}+V_{in}} \tag{16}$$

4.3. Modified SEPIC converter

The modified SEPIC converter consists of additional capacitor and diode compared to the SEPIC converter [47]. There are more number of improvement in the converter by correcting the power factor [48], adding controllers for closed loop operation [49].

$$D = \frac{V_{out}-V_{in}}{V_{out}+V_{in}} \tag{17}$$

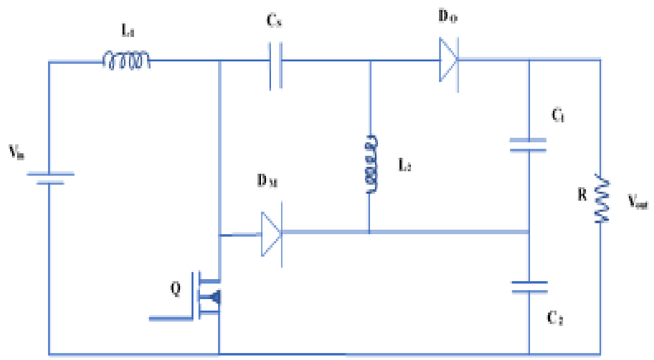

Fig. 4: Schematic Diagram of Modified SEPIC.

The modified SEPIC converter shown in fig. 4. comprises two operating modes, when the switch is on and off. When switch conducts the diodes D_M and D_O are reverse biased. The converter has an ability to boost the output more than ten times and above with suitable design procedure. In this paper, the converter has designed and simulated successfully, and arrived gain of the converter is 11.8 times to that of the input.

4.4. Full bridge converter

The full bridge converter topology varies according to the number of switches, passive components and diodes. A full bridge DC-DC converter with MPPT based on INCOND algorithm [17] highlights the pros of the tracking system. The topologies may adopt different techniques such as Zero Voltage Switching (ZVS), Zero Current Switching (ZCS), Zero Voltage Zero Current Switching (ZVZCS), Zero Voltage Transition (ZVT) and Zero Current Transition (ZCT). The snubber circuit is provided to perform tasks in the circuit. Auxiliary circuit may also play vital roles in increasing the efficiency of the circuit by decreasing the conduction losses.
Techniques are adopted to decrease the losses present in the system such as tailing current problem. By resonance the zero-voltage switching is established. In ZVS wide range papers, the advantages are said to be low primary conduction loss, less output inductance and the power transferring is accomplished within the whole switching cycle [19]. The author has implemented a passive snubber at secondary side of the full bridge converter to reduce the primary current at the freewheeling state. The output inductor size is reduced as well [19], [20]
The output inductor is to smooth down the spikes whereas the transformer satisfies the task without output inductor [21]. The resonant operation for the switch is attained by the resonant inductors and may be with parasitic capacitor. The parasitic capacitor acts as a snubber as well [22], [23]. The inductance of the transformer may also be the reason to perform zero crossing voltage or current operation.
The full bridge converter can also be implemented without transformer, which is also known as dual full bridge converter. The topology comprises of 6 switches with three legs, shares 1 leg due to integration topology. This integration reduces current stress of the power components [24], [25]. The current ripple may reduce by accomplishing interleaved topology. The ZVS for primary switches and ZCS for secondary diodes are implemented [26]. The ripple is reduced with the aid of interleaved topology [27]. For the two interleaved buck boost converters, ZVS is applied for both the primary and the secondary switches resulting to the reduced ripple current [28]. Bi-directional converter is also possible in full bridge DC-DC converter [38] which enables the power to flow in both the directions.
The Dual Active Bridge converter (DAB) topology doesn’t provide a high gain output voltage, which leads to research of dual full bridge converter with transformer known as DAB converter.

4.5. Dual active bridge

The DAB converter provides higher gain compared to the conventional boost, SEPIC and full bridge converter. The onset classification of the topology is shown in fig . The dual active bridge DC- DC converter [34-37] can be of Single Phase Dual Active Bridge Converters (SPDABC) [38], [39] and Three-Phase Dual Active Bridge Converters (TPDABC) [40-42]. TPDABC are lower peak current in power semiconductors, filter effective current is low and transformer usage factor is high compared to (SPDABC).
The Transformer selection in the DAB converter carries the merit to fullfil the goal of the DAB converter. The author has meticulously presented the selection of transformer’s accordingly [29]. Majorly, The DAB converter has conduction and switching losses. Sum of the semiconductor (conducting P_{CD} and switching P_{TSW}) losses and the transformer losses provides the total losses of the DAB converter. It may be represented as P_T, depends on the step up or step down converter, switching mode of each operating zone such as hard or soft switching and the parameters of the DAB [30]. Equation (18) explains the losses involved in the DAB circuit.

$$P_{Tcond} = P_{Tcond} + \mathrm{P_{Tsw}} + \mathrm{P_{Ttr}} \tag{18}$$

Where,

$$\mathrm{P_{Tcond}} = \mathrm{P_{CT}} + \mathrm{P_{CD}}$$

$$\mathrm{P_{Tsw}} = \mathrm{P_{OFF}} + \mathrm{P_{ON}}$$

$$\mathrm{P_{Ttr}} = \mathrm{P_{cu}} + \mathrm{P_{core}}$$

Dual Active Bridge is prefered not only due to the high gain, but also due to its efficient power transfer in Bidirection [31]. Hard switching at light loads provide tailing of current and so ZVS technique implementation will increase the low load effieciency. And so the transformer core losses can also be reduced [31]. By optimum trajectory using lagrange multiplier method, the peak current is minimized. The efficiency is said to be increased upto 40% [32]. The usage of the switch is high and so the conduction ande the switching losses will also be high in Dual Active Bridge. The voltage multiplier can be implemented at the secondary side to reduce the voltage stress and it has the ability to step up the voltage for four times [33].

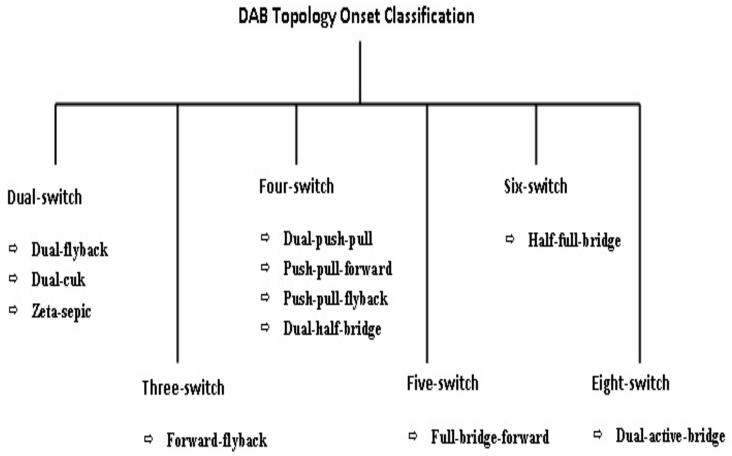

Fig. 3: DAB Topological Classifications.

The technique ZVS and ZCS can be implemented to reduce the conduction and switching loss [37], [41-42]. The classification of techniques can follow same as for the full bridge converters such as ZVS, ZCS, ZVZCS, ZVT and ZCT. The auxiliary circuits may be utilized to reduce the losses with the power semiconductors in TPDABC, either by adding auxiliary circuit [40-41] and/or by using different modulation strategies [42-43].

5. Results and discussions

The converter topologies are simulated using MATLAB/Simulink and the results of the four topologies are tabulated in table II.

Table 2: Results Comparison

TYPE OF CONVERTER	INPUT VOLTAGE V_{IN}	OUTPUT VOLTAGE V_{OUT}	GAIN
Conventional boost converter	24 V DC	79.53 V DC	3.3
Modified SEPIC converter	24 V DC	283.3 V DC	11.8
Full Bridge Converter	24 V DC	420 V DC	17.5
Dual Active Bridge Converter	24 V DC	420 V DC	17.5

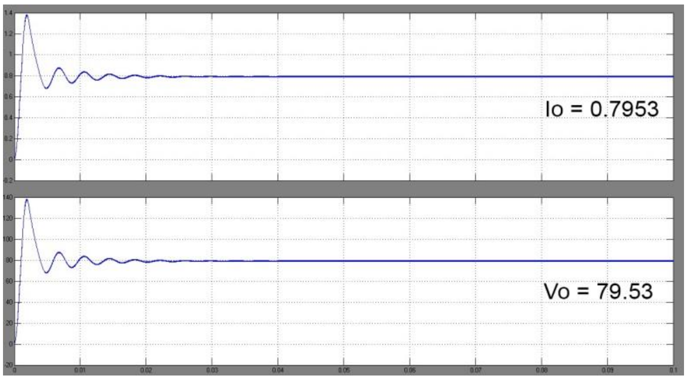

Fig. 4: Output Current Io and Voltage VO of Conventional Boost Converter.

The conventional boost converter waveform Fig. 4 has a settling time of about 0.025, the peak time is 0.0025. The gain of the converter is 3.3 and the converter is less complex with single switch

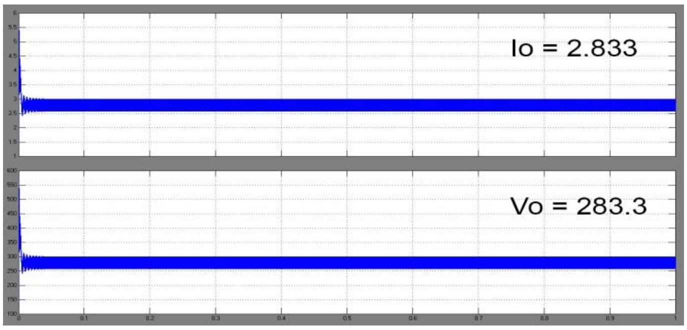

Fig. 5: Output Current and Voltage of Modified SEPIC Converter.

The SEPIC converter result as shown in Fig.5 has higher gain when compared to that of the conventional boost converter. The settling time is also less when compared to the conventional boost converter. The SEPIC converter has a gain of about 11.8.

Table 3: Complexity of the Converters

Type of converter	Complexity	Switching Loss	Gain
Con. Boost	Low	Low	Low
SEPIC	Low	Low	Moderate
Mod. SEPIC	Low	Low	High
FB	Moderate	Moderate	High
DAB	High	High	High

Full bridge converter FB and Dual Active Bridge converter DAB has a greater number of switches and their gain is also high. For higher gain applications FB and DAB can be preferred. Both the converters have gain of 17.5.

The converters complexity and the gain of the converter prove the specialty of the converter to be chosen for the PV applications as shown in table III. Due to the comparison, we have come to an idea that the converters which are less complex has less gain and more complex has more gain.

So, selection of converters may be carried over depending on domestic or industrial PV applications. If it is for industries higher gain can be chosen and for domestic lower can be preferred. Apart from the general preference, this paper narrow down to the Modified SEPIC is to be more efficient than the topologies discussed later.

6. Conclusions

A comparative study of high gain step-up converters of different topologies was analyzed. The PV was chosen as a source and INDCOND was preferred for maximum power point tracking. The simulated results were compared and concluded that the modified SEPIC converter is more efficient than the converters discussed later. The converter is designed majorly for microgrid applications with the usage of PV as a renewable source. Thus, the goal of the paper was accomplished successfully.

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