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Selection of non-isolated DC-DC converters for solar photovoltaic system

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ABSTRACT

Concerns over environment and increased demand of energy have led the world to think about alternate energy sources such as wind, hydro, solar and fuel cells. Out of these, photovoltaic (PV) power generation systems have become increasingly important all over the world due its availability, cleanness, low maintenance cost and inexhaustible nature. But power produced by the photovoltaic system is stochastic in nature due to the variation of solar irradiation and cell temperature throughout the day. In order to track the varying power, a DC-DC converter with maximum power point tracker (MPPT) is used. Different MPPT algorithms have been proposed for tracking peak power from the PV panel. Selection of adequate DC-DC converter is also an important factor since it has an influence on overall performance of the PV system. This paper presents a comparative study on the characteristics of different non-isolated DC-DC converters and highlights the various research works that has been done on DC-DC converters based MPPT PV system. Study shows that selection of converter also has an impact on the overall performance of the PV system. Based on the survey and comparative study, selection criteria to choose DC-DC converter for PV system is described in this paper.

1. Introduction

For economic development of any country energy is one of the major inputs. Number of industries, vehicles, domestic users has been increased by a large number in last decade; this in turn led to increase the global energy consumption also. Industries uses major share of energy produced in the world with a share of 33%, while residential, transport, service and other sectors follows with share of 29%, 26%, 9% and 3% respectively. Majority of energy is used in form of electricity and huge amount of electric energy is required by world to fulfill daily demand. By 2030 global electric energy demand is estimated to be doubled. Electric energy demands in fast developing countries are estimated to triple by this period. Majority of electric energy in the world is produced from coal with a share of 40.4% followed by natural gas, large hydro, nuclear, oil and renewable energy with a share of 22.5%, 16.2%, 10.9%, 5% and 5% respectively. Fossil fuel deposit on earth is depleting day by day and the atmospheric pollution and global temperature is increasing due to increased use of fossil fuels. Renewable energy tracking has become one of the interesting area in recent years due increased energy demand and issues related to environment. Out of all renewable energy sources, solar energy has gained much more attention due to its availability, cleanness and inexhaustible nature [1–4]. Tracking solar power is difficult due to non-linear current – voltage (I-V) characteristics of panel with a unique maximum power point (MPP) [5]. Power produced by PV panel varies with variation in atmospheric conditions such as solar irradiation and cell temperature. MPP of solar panel also varies with the variation in atmospheric conditions. So in order to extract maximum power, PV panel must be operated at a voltage corresponding to MPP (V_{MPP}). Maximum power point trackers are used to achieve this [6–10]. MPPT is an art of extracting maximum power from PV panel and it is regarded as the critical component of SPV system. Internal resistance of PV panel also varies with the variation in atmospheric conditions, but load resistance remains the same. Converter controlled with MPPT algorithm is used to achieve load matching and extracting maximum power from PV panel [11–13]. In order ensure that the PV system is operating near MPP, a DC-DC converter along with an MPPT controller is inserted in between the load and PV module [14]. Various MPPT algorithms such as short circuit current based [15,16], open circuit current based [17–21], ripple correlation control (RCC) [22–24], slide mode control technique [25–27], perturb and observe (P & O) [28–31], incremental conductance (INC) [32–37], fuzzy logic controller (FLC) [38–44], artificial neural network (ANN) based [45–49] approaches have been already proposed. DC-DC converters have drawn attraction these days, and are being used extensively with modern electronic systems. Since most of the renewable energy resources produce dc voltage, a DC-DC converter is used to transfer the power from source to load. For tracking solar and wind power, which are stochastic in nature,

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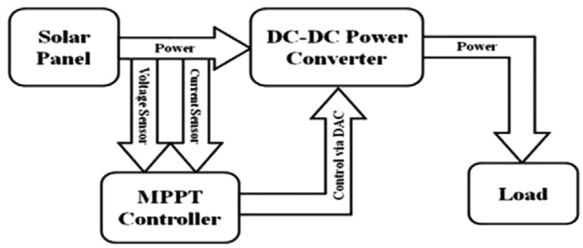

Fig. 1. SPV system with DC-DC converter and MPPT [51].

DC-DC converters are used as an impedance matching unit [50]. DC-DC converters act as an impedance matching unit in between the PV panel and load. By controlling converter duty ratio, input impedance of the converter is made equal to output impedance of the PV panel and load matching is achieved. Information regarding different converter topologies is mostly available on power electronics, simulation, and other electrical journals and detailed review on application of non-isolated DC-DC converter topologies on solar power tracking is not available. Since the application of non-isolated DC-DC converters on PV power tracking is increasing these days, it is the time to compile the work that has been already carried out in this area for the reference of researchers. This is the main motive behind this paper. This paper describes the working of different non-isolated DC-DC converters along with its merits and demerits on solar power tracking. At the end, a comparison of various converters is provided.

2. SPV system with DC-DC converter and MPPT

As shown in the Fig. 1, an SPV system consists of PV module, power conditioning unit (PCU) (in this case it is a DC-DC converter controlled by an MPPT tracker) and several loads. By varying the duty cycle of the DC-DC converter, load matching is achieved to transfer maximum possible power from PV panel to load. An MPPT controller with suitable algorithm is used to vary duty cycle of the converter. Current and voltage sensors are used to measure the value of panel voltage and current, and it is fed to the MPPT controller to determine the MPP [51].

3. PV characteristic curve

Characteristic curves of a PV panel are shown in Fig. 2. Both voltage-current (VI) and voltage-power (VP) curve of a PV panel is non-linear in nature. Open circuit voltage and short circuit current are two important points in VI characteristics of PV panel. Maximum voltage available from the solar cell is denoted by the open circuit voltage V_{OC} at this point, the PV current and power delivered from the panel is zero. V_{OC} of a particular solar cell depends on light generated current,

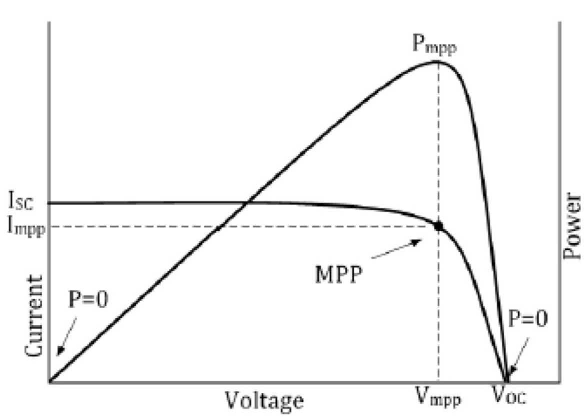

Fig. 2. Characteristics of PV module [52].

saturation current and temperature of the cell. I_{SC} is the maximum current available from the solar cell and it is due to the generation and collection of photo generated carriers. I_{SC} of a solar cell depends on total cross sectional area, intensity of light, light spectrum, optical properties of panel such as absorption and reflection and collection probability. Power delivered from the panel at these points is zero. The point at which product of voltage and current is maximum in VI characteristics of a solar cell is defined as maximum power point (MPP). MPP is unique and it is located at the knee of VI characteristics as shown in Fig. 2 [52].

4. DC-DC converter

DC-DC converter is an integral part of SPV system now days. It acts as impedance matching unit between the load and PV panel. Buck, boost, buck-boost, cuk, SEPIC and zeta converters are commonly used along with MPPT controller for peak power tracking. Comparative study and survey of various DC-DC converters are presented in coming sections.

4.1. Buck converter

Buck converter is a type of DC-DC converter in which the output voltage is lower than the input voltage [53–58]. Since the output voltage is less than the input voltage it is also called as step down converter. This topology is used to charging battery or powering loads connected to the PV modules with higher voltage than their ratings. Circuit topology of a buck converter is shown in Fig. 3.

When converter switch is turned ON, diode gets reverse biased and it stop conducting current and inductor stores energy in it. During this period, the inductor current rises from minimum value to maximum value. When switch is turned OFF, energy stored in the inductor is transferred to the capacitor and load through freewheeling diode. Inductor current falls from maximum value to minimum value during this period. Voltage transformation ratio and resistance transformation ratio of buck converter is given in Table 1. Input side impedance and load impedance are denoted by R_i and R respectively. By varying the duty cycle, converter input impedance can be varied and matching with optimum panel resistance can be achieved for maximum power transfer. Since the duty cycle can be only varied between zero and one, buck converter can only reflect R_i between load resistance and infinity. It cannot reflect R_i between Zero and R. Therefore, buck converter does not achieve values above I_{MPP} of the PV module. Hence, MPP tracking of buck converter is limited to a region where $R >= R_{MPP}$ as shown in Fig. 4.

Chew and Siek [59] proposed a quad input dual output buck converter with reduced number of components for PV system to fed resistive load and battery charging application. They designed converter for a standalone PV system and it tracks peak power of three PV modules connected to the converter simultaneously. The proposed topology eliminates the number of components required thereby increasing the efficiency-cost percentage. Zhang et al. [60] presented a variable inductance based buck converter topology for solar micro grid application. When the solar irradiance increases the light gener-

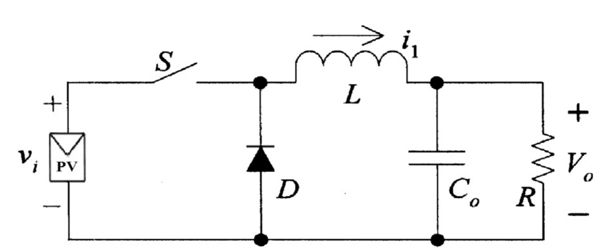

Fig. 3. DC-DC Buck converter.

Table 1
Summary of buck converter related work for MPPT.

Authors	Ref.	Control variable	MPPT type	Remarks
Chew and Siek	[59]	Voltage and current	Sliding mode	Quad input dual output buck converter with reduced number of components to fed resistive load and battery charging application.
Zhang et al.	[60]	Current	Variable inductance	When the solar irradiance increases the light generated current increase and the inductance value reduces. Inclusion of a variable inductance helps to maintain the current continuous under partial shading and low irradiation condition.
Veerachary	[61]	Voltage and current	P & O	Coupled inductor structure to reduce the ripple in source current and reduce the size of the core.
Yang et al.	[62]	Voltage and current	Single cycle	Doesn't require a current regulator and the required voltage regulator design are same for different operating conditions.
Pernia et al.	[63]	Current	Only current	Parallel connections of different sources are possible with the proposed control strategy which makes integration of new equipment easily.
Messenger et al.	[64]	Voltage and current	P & O	Designed linear current booster (LCB) for DC motor used for pumping application under low irradiation condition.
Oi et al.	[65]	Voltage and current	P & O and INC	Extended buck converter to convert high voltage, low current PV power to low voltage, high current power for driving the DC motor.
Masoum et al.	[66]	Duty cycle	FLC	Array current, duty cycle and power are used as the crisp inputs to FLC. Very robust under variable temperature and solar irradiance
Chiu et al.	[67]	Duty cycle	FLC	FLC-MPPT based on A Takagi–Sugeno (T–S) observer for state feedback to achieve asymptotic control. Unlike traditional MPPT, the proposed controller directly drives the system to MPP without searching the maximum power point and measuring irradiance
Alabedin et al.	[68]	Duty cycle	ANN	ANN is used as an optimizer for P & O MPPT controller. Improved performance in dealing with the fluctuations in the array power
Daraban et al.	[69]	Voltage and current	GA and P & O	Modified GA MPPT technique to track GMPP under PSC. Population size and number of iterations are reduced by integration GA with conventional P & O technique.

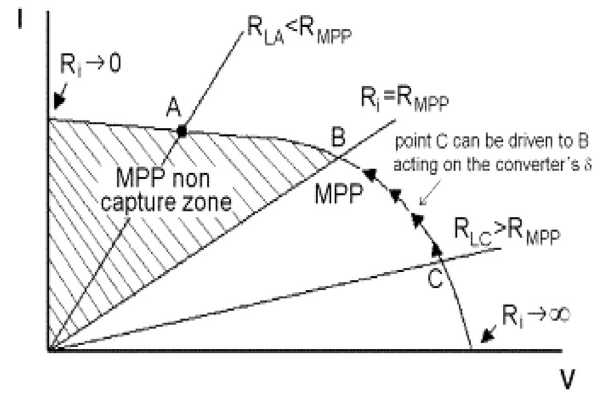

Fig. 4. Tracking and Non-tracking regions of a buck converter.

ated current increase and the inductance value reduces. On other hand when the solar irradiation decrease photo generated current decrease and inductance value increases to maintain the current continuous. Hence, inclusion of a variable inductance helps to maintain the current continuous under partial shading and low irradiation condition. The proposed topology reduces the inductor size up to 25%. Veerachary [61] presented an improved buck converter topology which reduces the source current ripple for solar power tracking. The proposed topology tracks peak power under all levels of solar irradiance. He used a coupled inductor structure to reduce the ripple in source current and reduce the size of the core. Experimental results show that the proposed topology increases the efficiency as well as reduces the input current ripple. Yang et al. [62] proposed a double input single output buck converter for SPV systems. They used single cycle control to simplify the control system design and eliminate control loop interactions. Main advantage of the proposed system is that it doesn't require a current regulator and the required voltage regulator design is same for different operating conditions. They made an experimental set up with an 800 W proto type and validated the results. Experimental proto type gave good dynamic response under different atmospheric conditions. Pernia et al. [63] proposed a buck converter with synchronous rectification for standalone SPV system. The proposed converter was designed to charge a 12 or 24 batteries from a PV panel. Parallel connection of different is possible with the proposed control strategy which makes integration of new equipment easily. They used a low cost PIC microcontroller for writing MPPT algorithm. They made an experimental proto type and efficiency has been improved up to 95%. Messenger et al. [64] presented an improved buck converter known as linear current booster (LCB) for DC motor designed for pumping application under low irradiation condition. They made a proto type and experimental results show that the proposed model is able to pump 20% extra fluid. Oi et al. [65] presented a new topology for water pumping application using SPV panels. They MPPT controller the used has two algorithms to track peak power under varying atmospheric conditions. They used an extended buck converter to convert high voltage, low current PV power to low voltage, high current power for driving the DC motor. Masoum et al. [66] presented a three input FLC MPPT technique using buck converter for standalone PV system. Array current, duty cycle and power are used as the crisp inputs to FLC. An experimental set up has been made to check the effectiveness of the proposed system. Experimental results show that the proposed system tracks MPP effectively under variable solar irradiance and cell temperature. Chiu et al. [67] proposed Takagi-Sogeno (T-S) based FLC MPPT controller using buck converter for a standalone PV system. For asymptotic control T-S fuzzy observer with state feedback system is used. The proposed controller drives operating point directly to MPP without searching or measuring solar irradiance. Controller and observer gains are obtained by solving two matrix equations. An experimental set up has been made to check the effectiveness of the proposed system. Experimental results show that the proposed system tracks MPP effectively. Alabedin et al. [68] presented two improved P & O MPPT technique using FLC and ANN for a standalone PV system. They used ANN and FLC to optimize the parameters of the conventional P & O MPPT to track MPP accurately and precisely. In ANN-P & O MPPT, ANN is used to determine reference power for P & O MPPT using solar irradiance and cell temperature. Hence ANN is trained initially with solar irradiance, temperature of the cell and corresponding power. In FLC-P & O MPPT, FLC is used to determine next increment in step size of duty cycle. Buck converter is used as PCU. A prototype has been made to verify the effectiveness of the proposed control strategy. Experimental results show that ANN MPPT controller provides better transient and steady state performance under varying atmospheric conditions. FLC is easy to implement as compared to ANN but has slow transient response with large fluctuations in power. Daraban et al. [69] presented a modified GA MPPT technique to track GMPP under PSC. Population size and number of iterations are reduced by integration GA with conventional P & O technique. A prototype has been made to check the effectiveness of the proposed system. Experimental results show that the proposed technique track MPP with lesser time.

4.2. Boost converter

A boost converter is a type of DC-DC converter which is able to generate an output voltage greater than the input voltage. Since the output voltage of a boost converter is greater than the input voltage, it is also known as step up converter [70–74]. According to the law of conservation of energy the input power must be equal to the output power. Since the output voltage of boost converter is greater than the input voltage, output current will be lesser than the input current. Circuit topology of a conventional boost converter is shown in Fig. 5.

When the switch is made ON input side inductor connected to the source stores energy in it. Current through the inductor rises from minimum level to maximum level during this period. Output voltage appears at the cathode and zero voltage appears at anode of the diode hence it is reverse biased and OFF. Hence load is isolated from source during ON period, so during this period load current is maintained continuous by the output side capacitor. When the switch is turned OFF, sum of voltage across the inductor and source voltage appear across the switch and at anode of the diode which is greater than the output voltage. Hence, the diode gets forward biased and starts conduction current. During this period inductor current falls from maximum level to minimum level and entire energy stored in it along with the source voltage is delivered to the load and output capacitor. Output current is always continuous in boost converter while input current can be continuous or discontinuous. High value of output capacitor is chosen to maintain the load current continuous. A boost converter does not reflect impedance at the input terminals. Hence, boost converter does not achieve values above V_{OC} of the solar PV panel. Boost converter track MPP in a region were the panel resistance is below or equal to load resistance ($R < =R_{MPP}$.) as shown in Fig. 6.

Kwon et al. [75] proposed a three level boost converter for a three phase SPV system with a simple power hysteresis loop based MPPT

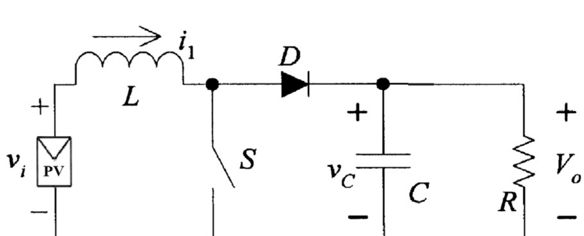

Fig. 5. DC-DC Boost converter.

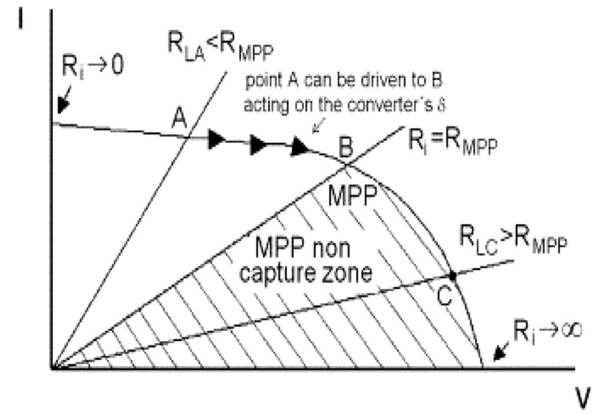

Fig. 6. Tracking and Non-tracking regions of a boost converter.

technique to track MPP. The proposed converter reduces the source ripple current, diode recovery losses and switching stress to a large extent. They made a 10 kW prototype to verify the effectiveness of the proposed method. Experimental results show that the proposed topology improves the power conversion and MPPT efficiency. Jung et al. [76] proposed a resonant soft switching interleaved boost converter topology for SPV system. They carried out numerical analysis for designing the converter. They made a 1.2 kW prototype to verify the feasibility of the proposed method. Experimental results show that the proposed topology improves efficiency by 1.5%. Agorreta et al. [77] presented a new control scheme for a boost converter used in a grid tied SPV system. They introduced a new inner loop strategy which performs mixed conduction mode to control inductor current. They designed an outer loop to control the voltage input and an FLC controller for switching operation. A 10 kW prototype has been made to verify the effectiveness of the proposed control strategy. Experimental results show that the proposed controller provides robust performance and tracks MPP quickly and accurately. Veerachary et al. [78] proposed a coupled inductor interleaved boost converter topology with feed forward MPPT technique for an SPV system. They used an FLC controller to generate the control pulse from for the converter. FLC controller generates a control signal based on the error and change in error values. Reference voltage for calculating the error has been determined using an artificial neural network trained offline. An experimental set up has been made to check the effectiveness of the proposed system. Experimental results show that the proposed system improves the efficiency and reduces the switching stress. Choi et al. [79] proposed a novel high gain boost converter topology with floating output for an SPV system. They proposed topology reduces the switching stress, lowers the input and output current ripple and lowers the current and voltage ratings of the components. An experimental set up has been made to check the feasibility of the proposed system. Experimental results show the proposed converter improves the conventional boost converter topology. Elshaer et al. [80] developed an FLC-genetic algorithm (GA) tuned PID controller for a boost converter used in SPV system. Parameters of the PID controller under different load conditions are tuned using GA and an FLC controller has been used to add intelligence to the tuning process. Experimental results show that the proposed controller is effective and reliable under various loading conditions. Park et al. [81] presented a resonant soft switching boost converter topology for SPV system. The proposed converter uses a simple auxiliary circuit to achieve and reduce the switching losses. They made an experimental setup to verify the effectiveness of the proposed topology. Experimental results show that zero current switching is achieved in all switches during turn ON and zero voltage switching during turn OFF. Efficiency of the converter improved due to reduced switching losses. Bratcu et al. [82] carried an investigation on power optimization issues associated with SPV system employing cascaded boost converter topology as PCU. They operated each converter module with separate MPPT controllers implemented by extreme seeking control. MATLAB simulink model of the proposed system has been made to study the effectiveness of the proposed system. Simulation results show that the proposed system provides a better solution to track peak power in a string illuminated with uneven solar irradiation. Naguchi et al. [83] developed a current controlled boost converter topology for SPV system employing short current pulse MPPT controller. They connected each PV panel in a string to individual boost converter controlled by separate MPPT controller. They used short current pulse amplitude based MPP technique to determine MPP. Experimental results show the proposed system improves the efficiency and flexibility. Pierre et al. [84] proposed a coupled inductor boost converter topology for SPV system. The proposed topology balances the voltage applied to the switch and eliminates the over voltage due to leakage inductance. Experimental results show the proposed system improves the efficiency. Nejabatkhah et al. [85] presented a novel three input boost converter topology for a hybrid system including PV panel, fuel cell and a battery charging system. PV and FC can deliver the output load or charge battery individually or simultaneously. Using four duty cycles four switches are controlled for setting FC power, tracking MPP of PV panel, regulating output voltage and controlling battery charging. Three duty ratios are used to control the converter and one for controlling the battery charging and discharging. Experimental results show the proposed converter is steady state and transient response. Simoes et al. [86] proposed an improved FLC MPPT controller using boost converter for a standalone PV system. They eliminated sensors and used duty cycle and power variation as crisp inputs to FLC. An experimental set up has been made to check the effectiveness of the proposed system. Experimental results show that the proposed topology is robust and precise. Chung et al. [87] proposed an improved FLC-MPPT controller using boost converter for standalone PV system. In order to reduce the time required for tracking and reduce the oscillations around MPP they designed FLC which works in coarse and fine mode. Coarse mode is used to move operating point quickly to MPP and fine mode to move operating point precisely to peak power. An experimental set up has been made to check the effectiveness of the proposed system. Experimental results show that the proposed system tracks MPP precisely. Khaehintung et al. [88] proposed an FLC-MPPT controller using a boost converter for a standalone PV system. In order to gave more importance to linguistic variables FLC membership functions are made less symmetric. Experimental result shows that the proposed algorithm improves the tracking speed and accuracy. An experimental set up has been made to check the effectiveness of the proposed system. Experimental results show that the proposed system tracks MPP quickly and precisely. Kottas et al. [89] proposed an improved FLC MPPT technique using boost converter for a standalone PV system. A fuzzy cognitive network (FCN) with solar irradiance, cell temperature, current and voltage are used as the nodes. To ensure the use of proposed topology with various PV systems, nodes are trained with wide range of atmospheric conditions. MATLAB simulink model of the proposed system has been made to study the effectiveness of the proposed system. Simulation results show that the proposed technique improves the tracking speed. Alamji et al. [90] proposed an FLC-hill climbing (HC) MPPT technique using boost converter for micro grid application. HC algorithm is translated into 16 fuzzy rules of FLC MPPT. An experimental set up has been made to check the feasibility of the proposed system. Experimental results show that the proposed system improves the efficiency and reduces the tracking speed. Patcharaprakiti and Premrudeepreechacharn [91] presented an adaptive FLC MPPT for a grid tied PV system. A boost converter followed by a single phase inverter is used to interfacing PV module with grid. Adaptive FLC allows tuning rule base and membership function constantly to achieve optimum performance. An experimental set up has been made to check the feasibility of the proposed system. Experimental results show that adaptive FLC technology tracks MPP quickly with high power factor and low harmonics. Jinbang *et al.* [92] proposed an improved INC MPPT technique to track peak power using boost converter for a standalone PV system. Using conventional INC MPPT technique duty cycle is determined and ANN is trained using this values. MATLAB simulink model of the proposed system has been made to study the effectiveness of the proposed system. Simulation results show that the proposed system tracks peak power effectively than conventional INC MPPT technique. Islam and Kabir [93] developed a novel ANN MPPT controller using boost converter for standalone PV system. They used 20 node hidden layer back propagation (BP) trained ANN to increase the execution speed and reduce complexity. MATLAB simulink model of the proposed system has been made to study the effectiveness of the proposed system. Simulation results show that the proposed system reduces the tracking time and improves the steady state performance. Purnama et al. [94] proposed a single fuzzy logic controller (*s*-FLC) using boost converter for a standalone PV system. S-FLC eliminates certain drawbacks of conventional FLC such as tuning of control rules, scaling factor and membership function. A prototype has been made to check the feasibility of the proposed system. Experimental results show that proposed control scheme has better convergence speed. Subiyanto et al. [95] presented a Hopfield neural network optimized (HNN) optimized FLC MPPT technique using boost converter for a PV system. Membership functions of FLS are tuned automatically using HNN. Linguistic variables for FLC are derived using a conventional P & O MPPT. MATLAB simulink model of the proposed system has been made to study the effectiveness of the proposed system. Simulation results show that the proposed technique improves the tracking MPP accurately. Kumar et al. [96] proposed GA-MPPT technique using a boost converter for a standalone PV system employing battery storage unit. MATLAB simulink model of the proposed system has been made to study the effectiveness of the proposed system. Simulation results show that the proposed method tracks peak power efficiently than conventional hill climbing methods. Rezvani et al. [97] proposed a GA-ANN based MPPT technique for a grid connected PV system. GA optimized data's are used to train the ANN. MATLAB simulink model of the proposed system has been made to study the feasibility of the proposed system. Simulation results show that the proposed method tracks peak power with less fluctuations. Ramaprabha and Mathur [98] proposed an ANN-GA MPPT technique to track peak power under PSC. Feed forward ANN network is trained with GA optimized power and voltage samples. MATLAB/simulink model of the proposed system has been made to study the effectiveness of the proposed system. Simulation results show that the proposed method tracks peak power efficiently under PSC. Badis et al. [99] presented a GA-PSO MPPT technique to track peak power effectively under PSC. MATLAB simulink model of the proposed system has been made to study the effectiveness of the proposed system. Simulation results show that the proposed method can solve multi extreme problem effectively. Kuo et al. [100] presented a dual mechatronic MPPT algorithm to track GMPP of an electric vehicle employed with a rotatable solar panel. A stepper motor is used to control the rotating angle of solar panel and an improved PSO MPPT technique is used for electric tracking. A prototype of solar powered electric vehicle has been made to check the effectiveness of the proposed system. Experimental results show that the dual mechatronic tracking increases the output and track peak power effectively under PSC. Miyatake et al. [101] proposed an MPPT technique to track peak power of a string of PV modules using PSO. For measuring the voltage and current of entire string only one pair of sensors are used this in turn reduces the cost and complexity of data acquisition system. A prototype of muli module PV system has been made to check the effectiveness of the proposed system. Experimental results show that the proposed system tracks GMPP effectively under PSC. Zhang et al. [102] proposed a dual MPPT search algorithm using dormant PSO (DPSO) to find global peak and an INC algorithm to track GMPP. When the particles in DPSO converge

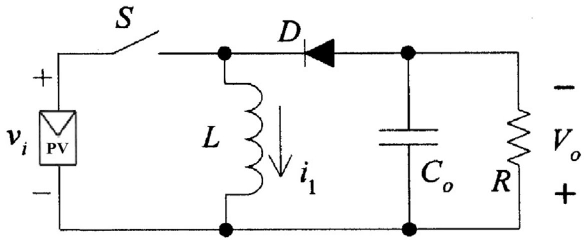

Fig. 7. DC-DC Buck-boost converter.

to certain point, it is made dormant and INC is activated to avoid repeated searching there by reducing the convergence time.

4.3. Buck-Boost converter

Buck-boost converter is a type of DC-DC converter which is able to generate an inverted output voltage greater than or less than the input voltage [103–107]. Circuit topology of a buck converter is shown in Fig. 7. When the switch is turned ON diodes become reverse biased and stops conducting and the inductor store energy from the source. Inductor current rises from minimum value to maximum value during this period. During this period the load current is made continuous by the output capacitor. When the switch is turned OFF inductor current falls from maximum value to minimum value generating a negative voltage across the inductor, with lower side of inductor positive and upper side negative. This negative voltage across the inductor forward biases the diode and it starts conducting and the energy stored in the inductor is transferred to the load and output capacitor through the diode.

By cascading a buck converter and boost converter buck-boost converter is realized. Hence, voltage conversion ratio and resistance conversion ratio of buck-boost converter is product of voltage conversion and resistance conversion ratio of buck converter and boost converter. Resistance conversion ratio of buck-boost converter is given in Table 1. From the relation it is clear that buck-boost converter can track MPP over entire PV characteristics PV panel irrespective of the load resistance and atmospheric conditions. Reflection of load resistance at input side of the converter varies from zero to infinity which allows the operating to move all over the VI curve as shown in Fig. 8.

Peftitsis et al. [108] proposed a control strategy for an SPV system with buck-boost converter to operate at MPP with constant output voltage. They used a DSP controller for implementing MPPT algorithm.. An experimental set up has been made to check the effectiveness of the proposed control strategy. Experimental results show that the proposed control strategy tracks the peak power efficiently and accurately. Orellana et al. [109] developed a four switch buck-boost converter topology for solar power tracking application. When compared to conventional buck-boost converter proposed converter provides a non inverted output voltage. Similar to conventional buck-boost converter output voltage of the improved topology is also greater than or less than input voltage. Experimental results of the proposed converter show that the proposed converter has less switching stress and voltage ripple. Wu et al. [110] proposed single stage buck-boost converter with FLC MPPT for SPV powered street lighting system. Single stage buck-boost converter is an integration of buck-boost charger/discharger. Experimental verification shows that the proposed system is flexible, robust and simple to implement. Britto et al. [111] developed a buck-boost quadratic converter for a grid tied PV system. The proposed converter is able to carry a voltage ranging from 12 V DC from PV panel to 230 V AC from grid lines. Similar to conventional buck-boost converter their converter also has one switch and two operating modes. The proposed system is used for LED lighting. When the power produced by the PV panel is not sufficient power is drawn from grid lines for lighting. Veerachary and Yadaih [112] proposed an ANN based MPPT technique to track peak power of a standalone SPV system employed to feed a dc motor employed to drive two separate loads. Buck-boost converter is used as load matching unit and gradient descent algorithm is used to carry out ANN training using solar irradiation as a parameter. They made an experimental proto type and validated the results. Experimental result shows that the proposed algorithm improves the dynamic and steady state performance. Jie and Ziren [113] proposed a two level ANN based MPPT technique using buck-boost converter for a standalone PV system. First level ANN is trained using solar irradiance, temperature of the cell, I_{SC}, V_{OC}, junction temperature and position, while the output voltage of PV panel is used to train the second level. MATLAB simulink model of the proposed system has been made to study the effectiveness of the proposed system. Simulation results show that the proposed technique improves the tracking speed, accuracy and reduce power oscillations. Syafaruddin et al. [114] presented an MPPT controller which is combination of ANN and polar coordinated FLC. To track GMPP, three layer ANN is trained with several PSC data's. Voltage corresponding to GMPP obtained from ANN is used as reference by FLC with polar controller to generate control signal for the buck-boost converter. A prototype has been made to check the effectiveness of the proposed system. Experimental results show that proposed control scheme tracks global power effectively under partial shading conditions. Ishaque et al. [115] proposed a PSO MPPT controller using a buck-boost converter to track peak power under PSC. PI controller is eliminated by choosing duty cycle as a control variable. A prototype has been made to check the effectiveness of the proposed system. Experimental results show that proposed control scheme tracks GMPP effectively with an efficiency of 99.5%. Later they reduced the oscillations of operating around GMPP by improving conventional PSO [116]. Experimental results shows the improved technique reduce the oscillations of operating point around GMPP Tables 2–7.

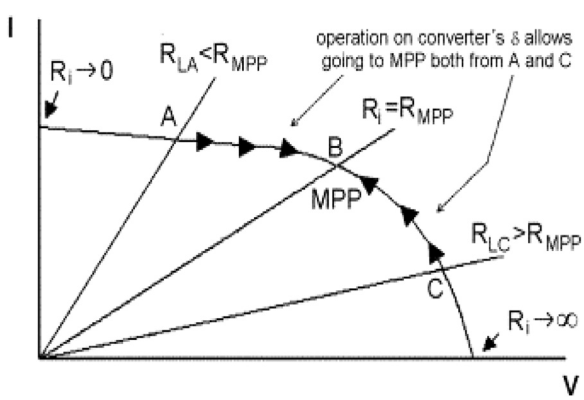

Fig. 8. Tracking and Non-tracking regions for a buck-boost, cuk, SEPIC and zeta converters.

4.4. Cuk converter

Cuk converter is a type of DC-DC converter which transfers energy from source to load during ON period and OFF period. Similar to buck-boost converter cuk converter also produces and inverted output voltage which is greater than or less than the input voltage [117–122]. Circuit topology of a cuk converter is shown in Fig. 9.

When the switch is turned ON negative polarity is applied to the anode of the diode by the capacitor (C) and it gets reverse biased and stop conducting current. Inductor, L_1 stores energy from the source and capacitor, C transfer energy from it to inductor, L_2, capacitor, C_0 and load. During ON period capacitors discharges and inductors stores energy simultaneously. Inductor current rises from minimum value to maximum value during this period. When the switch is turned OFF diode becomes forward biased and it starts conducting current. Energy

Table 2
Summary of boost converter related work for MPPT.

Authors	Ref.	Control variable	MPPT type	Remarks
Kwon et al.	[75]	Voltage	Hysteresis loop	A three level boost converter for a three phase SPV system with a simple power hysteresis loop based MPPT technique to track MPP. The proposed converter reduces the source ripple current, diode recovery losses and switching stress to a large extent.
Jung et al.	[76]	Voltage and current	P & O	Resonant soft switching interleaved boost converter topology for SPV system. The three-level boost converter reduces the reverse recovery losses of the diodes
Agorreta et al.	[77]	Voltage and current	FLC	The input voltage is controlled by the outer loop. The inductor current is controlled by an inner loop strategy which is able to perform in mixed conduction mode, owing to the fuzzy switching technique.
Veerachary et al.	[78]	Voltage	FLC with ANN	ANN is used as an optimizer for the feed forward FLC MPPT. The ANN is trained using the BP algorithm to estimation the reference voltage on-line. Tracking performance is improved. It also avoids the tuning of PI controller parameters
Choi et al.	[79]	Voltage and current	P & O	High gain boost converter topology with floating output which reduces the switching stress, lowers the input and output current ripple and lowers the current and voltage ratings of the components.
Elshaer et al.	[80]	Voltage and current	FLC-GA	FLC-GA tuned PID controller for a boost converter used in which PID controller under different load conditions are tuned using GA and an FLC controller has been used to add intelligence to the tuning process
Park et al.	[81]	Voltage and current	P & O	Soft-switching boost converter using a simple auxiliary resonant circuit, which is composed of an auxiliary switch, a diode, a resonant inductor, and a resonant capacitor.
Bratcu et al.	[82]	Voltage and current	Extreme seeking control	Cascaded boost converter topology is used as PCU. The most important disturbance occurs when the irradiance levels of modules are sensibly different because of various reasons – in this case, voltage-limitation requirements may be broken.
Naguchi et al.	[83]	Voltage and current	Hill climbing methods	Short-current pulse of the PV to determine an optimum operating current where the maximum output power can be obtained and completely differs from conventional hill-climbing-based methods.
Simoes et al.	[84]	Duty cycle	FLC	Eliminated sensors and used duty cycle and power variation as crisp inputs to FLC.
Chung et al.	[85]	Duty cycle	FLC	FLC which works in two modes. Coarse mode is used to move operating point quickly to MPP and fine mode to move operating point precisely to peak power.
Khaehintung et al.	[86]	Voltage	FLC	FLC membership functions are made less symmetric to give more significance to the specific linguistic variables
Kottas et al.	[87]	Duty cycle	FLC	A Fuzzy Cognitive Networks (FCN) with the voltage, current, temperature and solar irradiance used as the nodes. The weights of the nodes are trained using a wide range of different climatic condition to ensure it can used along with various PV system. It exhibits excellent tracking speed but at the expense of an additional switch and a sensor
Alajmi et al.	[88]	Duty cycle	FLC	Application of FLC to improve the performance of the conventional HC method. The FLC is developed by translating the HC algorithm into 16 fuzzy rules to ensure better tracking speed and efficient convergence
Patcharaprakiti and Premrudeepreechacharn	[89]	Duty cycle	FLC	Adaptive FLC MPPT for a grid tied PV system. A boost converter followed by a single phase inverter is used to interfacing PV module with grid. Adaptive FLC allows tuning rule base and membership function constantly to achieve optimum performance.
Purnama et al.	[90]	Duty cycle	FLC with ANN	FLC is optimized by Hopfield Neural Network which is proven applicable in partial shading. Convergence time is less than P & O and typical FLC controller
Subiyanto et al.	[91]	Voltage	FLC with P & O	Fuzzy P & O MPPT (FMPPT) is developed which is supported by offline tracking function to avoid local maxima. It shows better performance than traditional P & O method

Table 3
Summary of buck-boost converter related work for MPPT.

Authors	Ref.	Control variable	MPPT type	Remarks
Orellana et al.	[98]	Voltage and current	P & O	A four switch buck-boost converter topology which provides a non inverted output voltage.
Wu et al.	[99]	Voltage and current	P & O	Fuzzy-logic-controlled single-stage converter (SSC) for photovoltaic (PV)-powered lighting system applications. The SSC is the integration of a bidirectional buck–boost charger/discharger and a class-D series resonant parallel loaded inverter.
Britto et al.	[100]	Voltage and current	P & O	Able to carry a voltage ranging from 12 V DC from PV panel to 230 V AC from grid lines. Similar to conventional buck-boost converter their converter also has one switch and two operating modes.
Veerachary and Yadaiah	[101]	Voltage	ANN	ANN is used as the MPPT controller. The MPP is identified using gradient descent algorithm training. Work is extended for permanent magnet series motor
Jie and Ziran	[102]	Voltage	ANN	ANN used as the MPPT controller. The method uses a 2 level ANN, which has higher speed and accuracy compared to single level ANN
Syafaruddin et al.	[103]	Irradiance and temperature	ANN-FLC	To track GMPP, three layer ANN is trained with several PSC data's. Voltage corresponding to GMPP obtained from ANN is used as reference by FLC with polar controller to generate control signal for the buck-boost converter.
Ishaque et al.	[104]	Duty cycle	PSO	PSO is applied for MPPT specially in partial shading condition and showed that tracking efficiency is 99.5%
Ishaque et al.	[105]	Duty cycle	Dormant PSO	The random element of the velocity is replaced by constants. Faster tracking speed, zero oscillations at MPP. Able to locate MPP for any environmental variations including partial shading and large irradiance fluctuations

stored in the inductor, L_1 is transferred to capacitor C and energy stored in inductor L_2 along with source is transferred to capacitor C_0. Inductor currents fall from maximum value to minimum value during this period. Similar to buck-boost converter voltage conversion ratio and resistance conversion ratio of cuk converter is product of voltage conversion ratio and resistance conversion ratio of buck and boost converters. Hence, cuk converter operates all over the PV curve and tracks MPP. Input side inductor of the cuk converter filters source voltage and prevents harmonics from the supply. Cuk converter topology provides continuous input and output current. Safari and Mekhilef [123] developed a new control method to track MPP from PV panel using cuk converter. They used INC MPPT technique to track peak power and made the control loop simple by eliminating the proportional integral (PI) control loop. They made a prototype to verify the effectiveness of the proposed control method. Experimental results show that the proposed control method improves the efficiency and reduces the system cost. Bae and Kwasinski [124] presented a multiple input cuk converter for hybrid PV system. They used RCC MPPT technique to track peak power from PV panel. Since this method allows the integration of other generating system also individual MPPTs were preferred. They made a prototype in lab with PV panel connected to one leg and DC source on other leg of the converter. Experimental results show that the proposed topology is flexible, robust and simple to implement. Lin et al. [125] proposed an integrated cuk-forward converter based standalone PV system for LED lighting system. Cuk converter charges the battery during day time and forward converter drives the LED during discharge time. Thus charging is through cuk and discharging is through forward converters respectively. Both the converter topologies use the same switch for operation to reduce the component cost. They made a 200 W prototype to verify the feasibility of the proposed system. Experimental results show that the proposed system improves efficiency. Chung et al. [126] proposed a cuk converter based standalone PV system to track MPP under varying atmospheric conditions. The proposed converter operates in discontinuous capacitor voltage mode with continuous input current. MPP is located by injecting a sinusoidal pulse into the duty cycle and comparing variation in switching stress and input voltage variation. They made a 10 W prototype to verify the effectiveness of the proposed system. Experimental results show that the proposed system gave good response under varying atmospheric conditions. Torimbo et al. [127] developed a cuk/SEPIC converter based SPV system to feed a separately excited DC motor. They used linear reoriented coordinate method to determine MPP of the PV panel. By measuring the DC motor terminal voltage the velocity of motor is estimated. They made a prototype to verify the effectiveness of the proposed system. Experimental results show that the DC gave good performance when

Table 4
Summary of cuk converter related work for MPPT.

Authors	Ref.	Control variable	MPPT type	Remarks
Safari and Mekhilef	[112]	Voltage and current	INC	INC MPPT technique to track peak power and made the control loop simple by eliminating the proportional integral (PI) control loop.
Kwasinski and Sugwoo	[113]	Voltage and current	RCC	Method allows the integration of other generating system also.
Lin et al.	[114]	Voltage and current	P & O	Cuk converter charges the battery during day time and forward converter drives the LED during discharge time. Thus charging is through cuk and discharging is through forward converters respectively.
Chung et al.	[115]	Duty cycle	Injecting sinusoidal pulse	Operates in discontinuous capacitor voltage mode with continuous input current. MPP is located by injecting a sinusoidal pulse into the duty cycle and comparing variation in switching stress and input voltage variation.
Torimbo et al.	[116]	Voltage and current	Linear reoriented coordinate	Cuk converter based SPV system to feed a separately excited DC motor. They used linear reoriented coordinate method to determine MPP of the PV panel. By measuring the DC motor terminal voltage the velocity of motor is estimated.
Rathge and Mecke	[117]	Voltage and current	P & O	Changes level of generated DC voltage to charge the battery system. A snubber circuit is also designed to protect the switch from voltage peaks occurring during turn OFF period.
Mahmoud et al.	[118]	Voltage	FLC	Converge in all solar irradiance with good efficiency and robustness. This method does not need any modification in membership functions and rules while testing with different resistive loads

Table 5
Summary of SEPIC converter related work for MPPT.

Authors	Ref.	Control variable	MPPT type	Remarks
Veerachary	[125]	Voltage	v^2 based	Coupled inductor structure reduces the ripple current, magnetic core requirements and thereby improves the performance of the converter.
Duran et al.	[126]	Voltage and current	P & O	Parallel connected SEPIC converter operating in interleaved mode to measure and display VI and PV characteristics of a PV module.
Santos et al.	[127]	Voltage and current	P & O	A triple active bridge (TAB) converter interfaces PV panel, main voltage source and load together using a multi winding transformer. SEPIC converter with MPPT to interface PV panel to TAB.
Chiu et al.	[128]	Voltage and current	Pulse-current-charging	SEPIC power factor correction converter with high accurate, high efficiency MPPT algorithm to track peak power and charge battery. Overcharging of battery is avoided by applied a pulse charging scheme with a rest period.
Tse et al.	[129]	Voltage	RCC	For locating the MPP a small sinusoidal perturbation is injected into switching pulse and average value of panel voltage is compared with ac component.
Chen et al.	[130]	Voltage	FLC	FLC MPPT control is activated if the solarization is insufficient. FLC controller is to maintain a charged current so as that the battery voltage can reach to desired value.
Seyedmahmoudian et al.	[131]	Voltage and current	GA-DE	Combined DE and PSO algorithms to avoid the locking of operating point in local maxima under PSC's. Using the differential information DE algorithm overcomes the locking of operating in local maxima. PSO algorithm helps in the convergence the operating point towards optimal point.

powered from a PV panel. Rathge and Mecke [128] presented a bidirectional cuk converter topology for integration of energy storage system into a PV plant. The proposed converter changes level of generated DC voltage to charge the battery system. A snubber circuit is also designed to protect the switch from voltage peaks occurring during turn OFF period. Experimental results show that the proposed topology works well with the PV system. Mahmoud et al. [129] presented a cuk converter based standalone PV system employing FLC MPPT technique to track peak power. They made a prototype in lab to verify the feasibility of proposed system. They compared the experiment results of PV system with and without cuk converter. The comparison show that the MPP tracking efficiency improves with inclusion of converter.

4.5. Single ended primary inductor (SEPIC) converter

SEPIC converter also provides an output voltage which is greater than or less than the input voltage [130–136]. Main advantage of a SEPIC converter when compared to buck-boost and cuk converter is that it provides a non inverted output voltage. Circuit diagram of a SEPIC converter is shown in the Fig. 10. When the switch is turned ON negative polarity is applied to the anode of the diode by the capacitor C and it gets reverse biased and stop conducting current. Inductor L_1 stores energy from the source and the energy from the capacitor C is transferred to the inductor L_2. Load current is made continuous by the output capacitor C_0. Inductor currents rise from minimum value to maximum value during this period. When the switch is turned OFF, diode becomes forward biased and it starts conducting. Energy stored in the inductor L_1 is transferred to capacitor C and energy stored in the inductor L_2 along with source is transferred to capacitor C_0 and load. Inductor currents fall from maximum value to minimum value during this period. Capacitors and inductors are used to transfer energy in SEPIC converter and switching stress is much less than cuk converter. Voltage conversion ratio and resistance conversion ratio of SEPIC converter is same as that of buck-boost converter and cuk converter. Hence, operating point of SEPIC converter is also spread all over the PV curve as shown in Fig. 8.

Veerachary [137] presented a coupled inductor SEPIC converter with v^2 based MPPT technique for SPV system. Coupled inductor structure reduces the ripple current, magnetic core requirements and thereby improves the performance of the converter. He implemented the proposed system using DSP evaluation module. Experimental results show that the proposed tracks MPP within 200 ms. Duran et al. [138] implemented a parallel connected SEPIC converter operating in interleaved mode to measure and display VI and PV characteristics of a PV module. They made a hardware model to verify the results. Experimental results show that the proposed system reduces the source ripple current, improves the response time and reduces the cost of implementation. Santos et al. [139] proposed a triple active bridge (TAB) converter which interfaces PV panel, main voltage source and load together using a multi winding transformer. They used a SEPIC converter with MPPT to interface PV panel to TAB. Simulation results show that the proposed system maintains reliability in power supply with less input current and output voltage ripple. Chiu et al. [140] implemented a SEPIC converter based PV system for street lighting system. They used a SEPIC power factor correction converter with high accurate, high efficiency MPPT algorithm to track peak power and charge battery. In order to avoid the overcharging of the battery they applied a pulse charging scheme with a rest period. And when the battery voltage goes down power from grid line is drawn to avoid over discharging of the battery. They implemented a laboratory prototype to check the effectiveness. Experimental results show that the proposed topology is feasible. Chiang et al. [141] presented modeling and controller design for a SEPIC converter based stand alone PV battery charging system. Voltage command generated from battery control loop and MPPT control is used for generating current command for peak current mode control of SEPIC converter. They made an 80 W prototype to verify the effectiveness of the proposed system. Experimental results proved that the proposed system is effective in power balance and MPPT controls. Tse et al. [142] proposed a PWM SEPIC converter with RCC MPPT for extracting power efficiently from a PV panel. For locating the MPP a small sinusoidal perturbation is injected into switching pulse and average value of panel voltage is compared with ac component. They made a 10 W prototype to verify the feasibility of the proposed system. Experimental results proved that the proposed system tracks MPP quickly and accurately. Chen et al. [143] presented an FLC MPPT controlled SEPIC converter SPV system for battery charging. They implemented MPPF algorithm using a DSP controller. They made a 120 W prototype to verify the effectiveness of the proposed system. Experimental results show that the circuit design and proposed charging strategy are effective and feasible. Seyedmahmoudian et al. [144] proposed a hybrid evolutionary algorithm which employs differential evolution (DE) and PSO, hence called as DEPSO. They combined DE and PSO algorithms to avoid the locking of operating point in local maxima under PSC's. Using the differential information DE algorithm overcomes the locking of operating in local maxima. PSO algorithm helps in the convergence the operating point towards optimal point. DE and PSO algorithms together ensure the convergence of operating point towards global maximum.

Table 6
Summary of zeta converter related work for MPPT.

Authors	Ref.	Control variable	MPPT type	Remarks
Antonio et al.	[138]	Voltage and current	P & O	Converter is designed to ensure low ripple and limited charging current, as well as voltage regulation when the batteries are fully charged.
Zanotti et al.	[139]	Voltage	Input impedance	Doesn't use knowledge of previous resistance value to determine the MPP; hence no memory is required for storage.
Lopez et al.	[140]	Voltage	Linearization	Zeta converter and full bridge integrated topology for grid integration of renewable sources such as wind and solar. Grid synchronized sinusoidal current waveform is produced by the zeta converter operating in DCM mode. Full bridge inverter is used reverse the current waveform by 108 degrees before it is fed to the grid.
Kumar et al.	[141]	Voltage and current	INC	INC MPPT technique controls the zeta converter to provide a low current during starting of the motor to ensure soft starting.
Adhikari et al.	[142]	Voltage and current	P & O	Includes an isolated zeta converter, energy storage system, voltage source inverter (VSI) and a filter. Output voltage of the proposed system is maintained constant using a PID controller.
Satapathy et al.	[143]	Voltage and current	P & O	Small signal analysis and switch averaging techniques has been used to analyze the effect changes in input voltage on zeta converter.
Antonio et al.	[144]	Voltage and current	P & O	P & O MPPT technique to track peak power and constant voltage/constant current method to control charging and discharging of battery.
Salenga et al.	[145]	Voltage and current	P & O	A two input zeta converter topology for hybrid solar, wind power system. Controller is designed based from the transfer functions derived from the dynamic analysis conducted.
Priya et al.	[146]	Voltage and current	P & O	Perturbation step size is made adaptive. Perturbation step size is large during the initial stage of tracking but once the operating point reaches MPP step size decreases gradually.

4.6. Zeta converter

Zeta converter also provides a non inverted output voltage which is greater than or less that the input voltage similar to SEPIC converter [144–150]. Circuit topology of a zeta converter is shown in Fig. 11.

Operation of the converter can be explained in two modes. Switch ON mode and switch OFF mode. When the switch is turned ON, diode gets reverse biased due to the negative potential applied across it and it blocks current. Energy stored in the capacitor C is transferred to the inductor L_2 and inductor L_1 stores energy from the source. Inductor currents rise from minimum value to maximum value during this period. When the switch is turned OFF, diode becomes forward biased and it starts conducting. Energy stored in the inductor L1 is transferred to the capacitor c and energy stored in the inductor L_2 is transferred to the capacitor C_0 and load. Inductor currents fall from maximum value to minimum value during this period. Voltage conversion ratio and resistance conversion ratio of zeta converter is same as that of buck-boost, cuk and SEPIC converters. Zeta converter can also track MPP all over PV curve of solar PV panel. Antonio et al. [151] presented a novel Zeta-boost integrated converter for PV system with battery storage capability. The proposed topology reduces input and output current ripple, has high voltage conversion ratio and operates effectively in both CCM and DCM modes. Experimental and simulation results show proposed charging strategy is effective and feasible. Zanotti et al. [152] validated the effectiveness of input characteristics impedance (ICI) for PV system employing zeta converter as PCU. The proposed method doesn't use knowledge of previous resistance value to determine the MPP; hence no memory is required for storage. They made a prototype of the proposed system in laboratory to check the effectiveness under different irradiation and temperature condition. Experimental results show that the proposed topology track peak power efficiently. Lopez et al. [153] proposed a novel zeta converter and full bridge integrated topology for grid integration of renewable sources such as wine and solar. Grid synchronized sinusoidal current waveform is produced by the zeta converter operating in DCM mode. Full bridge inverter is used reverse the current waveform by 108 degrees before it is fed to the grid. They made a 100 W prototype of the proposed system in laboratory to check the effectiveness Experimental results show that the proposed topology track peak power efficiently. Kumar et al. [154] developed an INC MPPT controlled zeta converter SPV system for water pumping application. They coupled the shaft of centrifugal water pump with a brushless DC motor. INC MPPT technique controls the zeta converter to provide a low current during starting of the motor to ensure soft starting. MATLAB simulink simulation results show that the proposed system is able to work under low irradiation condition too. Adhikari et al. [155] proposed an SPV system for rural electrification which includes an isolated zeta converter, energy storage system, voltage source inverter (VSI) and a filter. Output voltage of the proposed system is maintained constant using a PID controller. They made a MATLAB simulink model to check feasibility of the proposed system. Simulation results show that the proposed topology give good performance under varying consumer load and irradiation conditions. Satapathy et al. [156] compared the performance of an SPV system employing zeta converter with different MPPT techniques. They compared the effectiveness of the topology with P & O, INC and an improved P & O MPPT. Small signal analysis and switch averaging techniques has been used to analyze the effect changes in input voltage on zeta converter. They used MATLAB simulink to carry out analysis. Antonio et al. [157] carried out a complete analysis of a zeta converter based SPV system for battery charging application. They used P & O MPPT technique to track peak power and constant voltage/constant current method to control charging and discharging of battery. An experimental set up has been made in the laboratory to check the effectiveness of proposed topology. Experimental results show that the proposed topology is reliable. Salenga et al. [158] proposed a two input zeta converter topology for hybrid solar, wind power system. They used

Table 7
Comparison of various non-isolated DC-DC converters.

Characteristic	Buck	Boost	Buck-boost	Cuk	SEPIC	Zeta
Static Gain	α	$\frac{1}{1-\alpha}$	$-\frac{\alpha}{1-\alpha}$	$-\frac{\alpha}{1-\alpha}$	$\frac{\alpha}{1-\alpha}$	$\frac{\alpha}{1-\alpha}$
Resistance Conversion ratio	$\frac{1}{\alpha^2}$	$1-\alpha^2$	$\frac{1-\alpha^2}{\alpha^2}$	$\frac{1-\alpha^2}{\alpha^2}$	$\frac{1-\alpha^2}{\alpha^2}$	$\frac{1-\alpha^2}{\alpha^2}$
O/P Voltage polarity	Invert	Non-invert	Invert	Invert	Non-invert	Non-invert
Input current	Pulsating	Non-pulsating	Pulsating	Non-pulsating	Non-pulsating	Pulsating
Minimum load inclination angle (degrees)	$\theta = 0$	$\theta = a\tan(\frac{1}{R})$	$\theta = 0$	$\theta = 0$	$\theta = 0$	$\theta = 0$
Maximum load inclination angle (degrees)	$\theta = a\tan(\frac{1}{R})$	$\theta = 90$	$\theta = 90$	$\theta = 90$	$\theta = 90$	$\theta = 90$
Minimum voltage across PV module	$V_{PV} = V_{bus}$	$V_{PV} = 0$	$V_{PV} = 0$	$V_{PV} = 0$	$V_{PV} = 0$	$V_{PV} = 0$
Maximum voltage across PV module	$V_{PV} = V_{OC}$	$V_{PV} = V_{bus}$	$V_{PV} = V_{OC}$	$V_{PV} = V_{OC}$	$V_{PV} = V_{OC}$	$V_{PV} = V_{OC}$
Complexity	Medium	Medium	Medium	High	High	High
Number of switch	1	1	1	1	1	1
Relationship between D and V_o	Linear	Non-linear	Non-linear	Non-linear	Non-linear	Non-linear
Switch drive	Floated	Grounded	Floated	Grounded	Grounded	Floated
Output current	High	Low	Low-High	Low-High	Low-High	Low-High
Energy transferring elements	Inductor	Inductor	Inductor	Inductor and capacitor	Inductor and capacitor	Inductor and capacitor

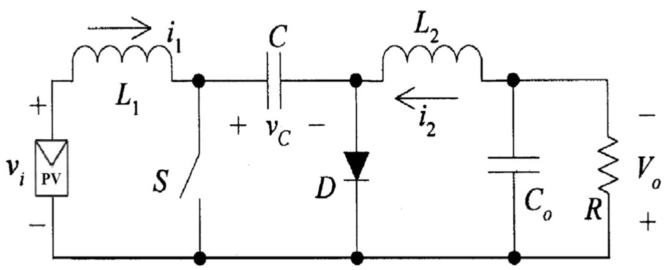

Fig. 9. DC-DC cuk converter.

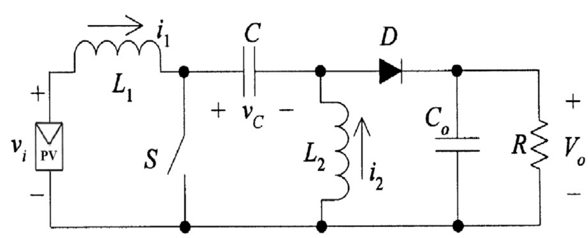

Fig. 10. DC-DC SEPIC converter.

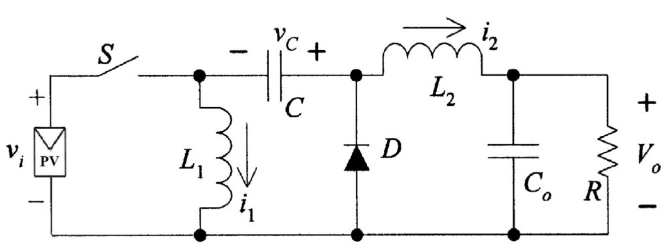

Fig. 11. DC-DC Zeta converter.

state space averaging (SSA) technique to carry out the dynamic modeling and controller design. They made a MATLAB simulink model to check effectiveness of the proposed system. Simulation results show that the proposed topology provide better transient and steady state performance. Priya et al. [159] proposed a zeta converter with adaptive P & O MPPT for SPV system. Peak current control technique has been used to track MPP under rapidly changing atmospheric conditions. Perturbation step size is large during the initial stage of tracking but once the operating point reaches MPP step size decreases gradually. They made a MATLAB simulink model to check effectiveness of the proposed system. Simulation results show that the proposed system track MPP quickly and more precisely Figs. 12–18.

5. Comments and remarks on various non-isolated DC-DC converters

Comparison of various non-isolated DC-DC converters are carried out based on cost, efficiency, input and output current ripple, number of passive elements used for energy transfer, tracking and non-tracking zones, driver circuit requirements, complexity, minimum and maximum load inclination angle, output voltage polarity, resistance conversion ratio, minimum and maximum voltage across the PV panel and static gain. Table 1 depicts comparison of different non-isolated DC-DC converters converter topologies. Buck-boost, cuk, SEPIC and zeta converter provides an output voltage greater than input voltage and can track MPP all over the PV curve. Buck, boost and buck-boost converters are less complex when compared to other converter topologies.

Based on the comparative study and survey on various non-isolated DC-DC converters following key points can be made:

(1) When compared to buck converter, boost converter requires a high value of inductor to achieve same value of inductor ripple current.
(2) High value of input capacitor is required for a buck converter to smooth discontinuous input current from the PV panel.
(3) Complex high side switch driver circuit is required for buck, buck-boost, and zeta converters while simple low side switch driver circuit is only required for boost, SEPIC and cuk converters.
(4) An additional blocking diode is required for buck, buck-boost, cuk and zeta converters to avid the reverse flow of current from battery to PV panel during night time, while in case of boost and SEPIC converter freewheeling diode which in series with the PV panel performs the blocking action too.
(5) When compared to other converter topologies boost converter

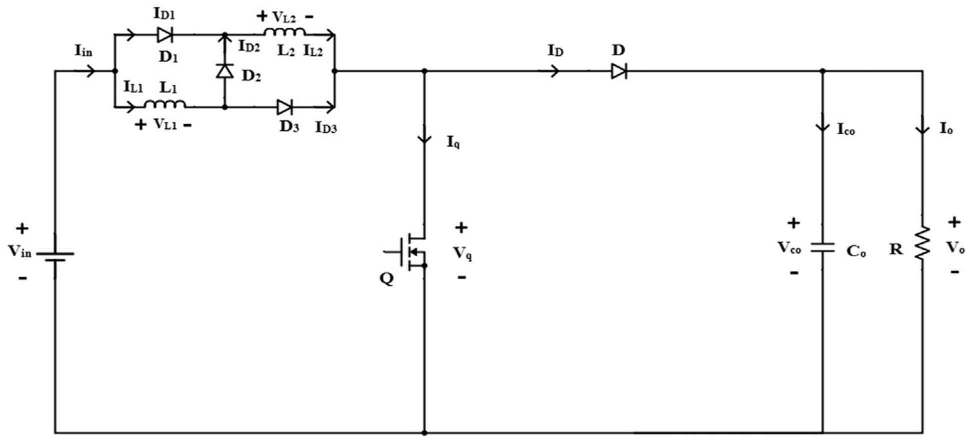

Fig. 12. Single switch coupled inductor boost converter (SSCBC).

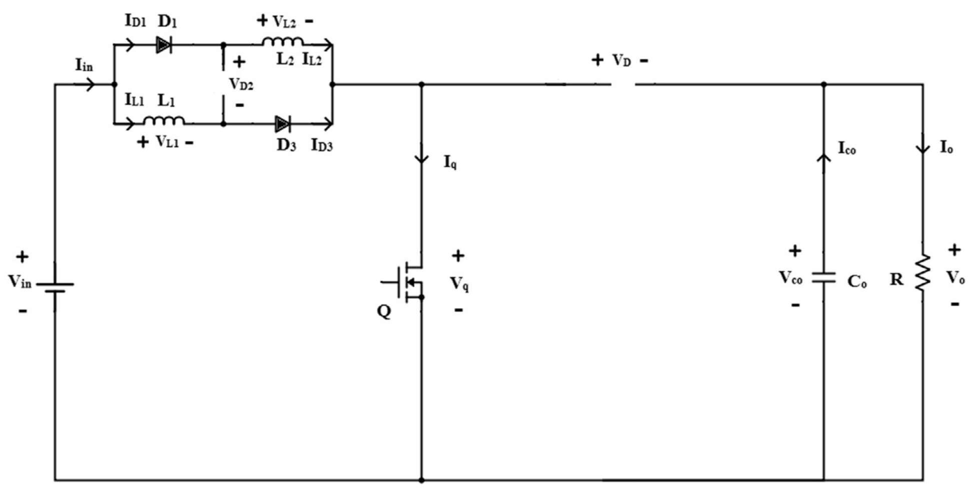

Fig. 13. Mode 1 when switch is ON.

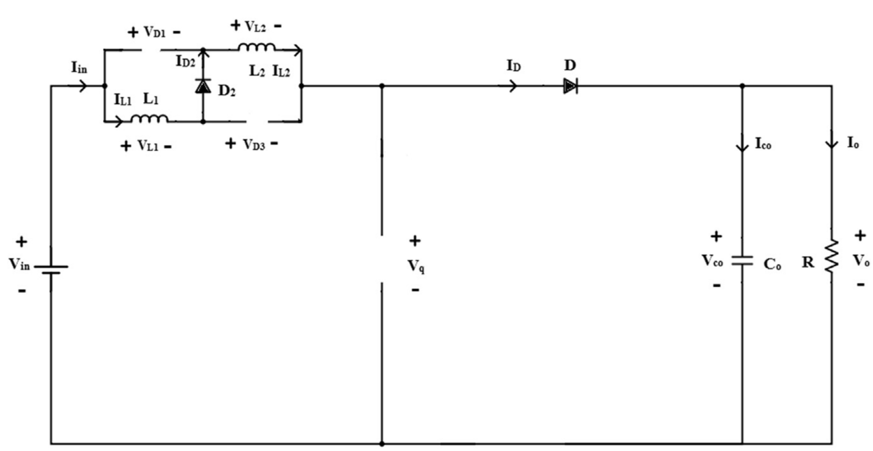

Fig. 14. Mode 2 when switch is OFF.

does not track MPP efficiently under low irradiation condition.

(6) Buck and boost converter fails to track MPP efficiently under all irradiance, temperature and load conditions.

(7) Cost of buck, boost and buck-boost converters are less as compared to cuk, SEPIC and zeta converters. But the cost of driver circuit for buck, buck-boost and zeta converter is more than that of boost, cuk and SEPIC converters.

(8) Number of passive components required for cuk, SEPIC and zeta converters is more than buck-boost and buck-boost converters. Energy transferred from source to load using inductors in buck, boost and buck-boost converters, while inductors and capacitors are used in cuk, SEPIC and zeta converters for energy transfer.

(9) Buck-boost, cuk, SEPIC and zeta converters can track MPP all over the VI curve while buck and boost converters tracking zone

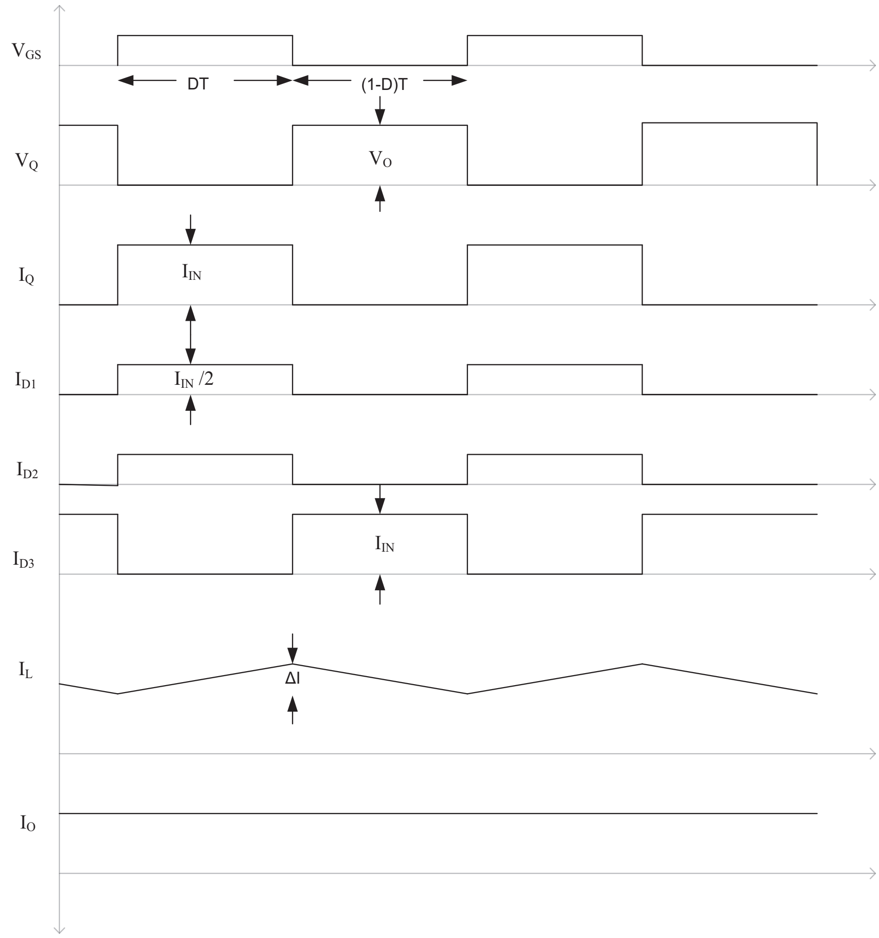

Fig. 15. Switching waveforms of SSCIBC.

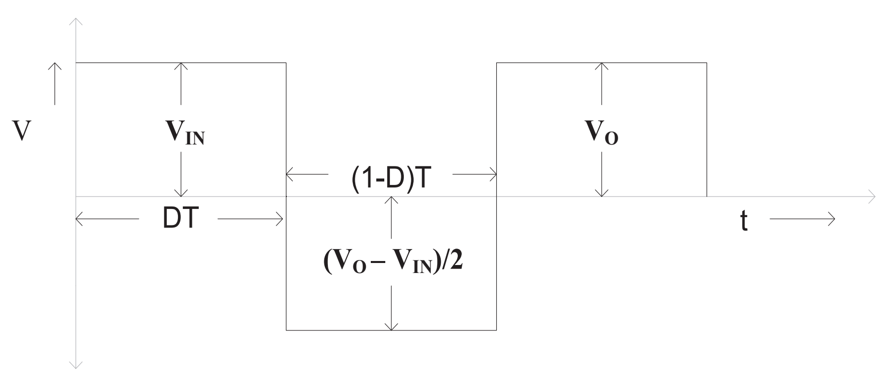

Fig. 16. Voltage across inductor.

is limited to particular zones, this affects the MPP tracking adversely.

(10) Buck converter has a linear relationship between voltage and duty cycle, while all other converters have a non-linear voltage-duty cycle relationship.

(11) Minimum load inclination angle of a boost converter is tangent of reciprocal of load resistance while that of other converter is zero. Maximum load inclination angle of buck converter is tan of reciprocal of load resistance while that of other converter is 90 degree. From this it is clear that the load inclination angle of buck and boost converters are limited to a region while that of other converters are spread all over the first quadrant.

From the comparative study and literature survey it is clear that the tracking zone of buck and buck-boost converters are limited to a small area within the first quadrant. This affects the MPP tracking adversely. Tracking zone of buck-boost, cuk, SEPIC and zeta converter is spread all over the first quadrant, hence MPP can be tracked efficiently tracked using any of these converters under all temperature and irradiation condition. Buck, buck-boost and converter provides an inverter output voltage while boost, SEPIC and zeta converters provide an output with same polarity. Buck-boost, cuk, SEPIC and zeta converter provides an output voltage greater than or less than input voltage, while buck and boost converter cannot perform these two actions together. Switch is directly connected to the PV panel in buck, buck-boost and zeta converter. When this switch is continuously operated PV panel will

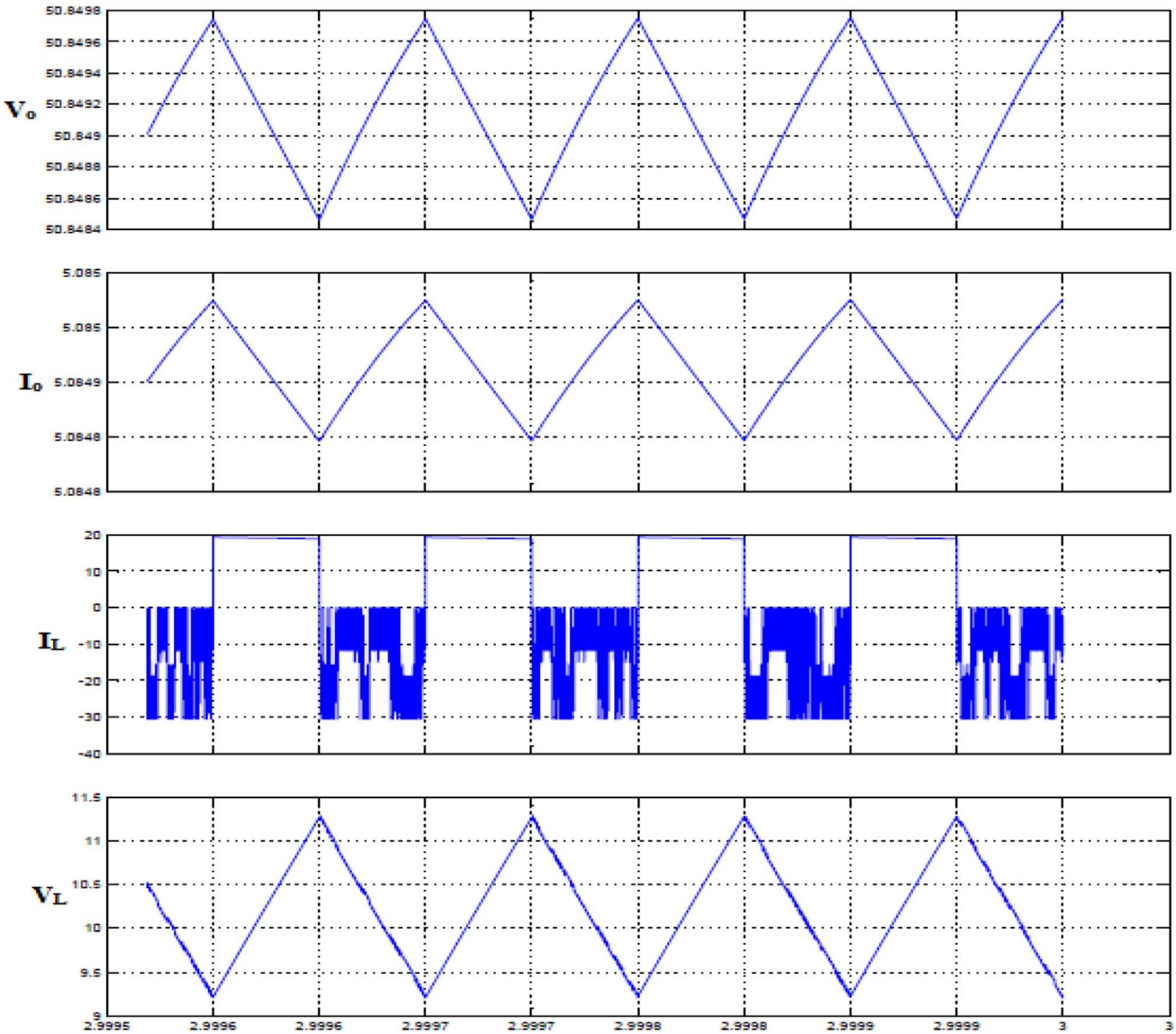

Fig. 17. Simulation results.

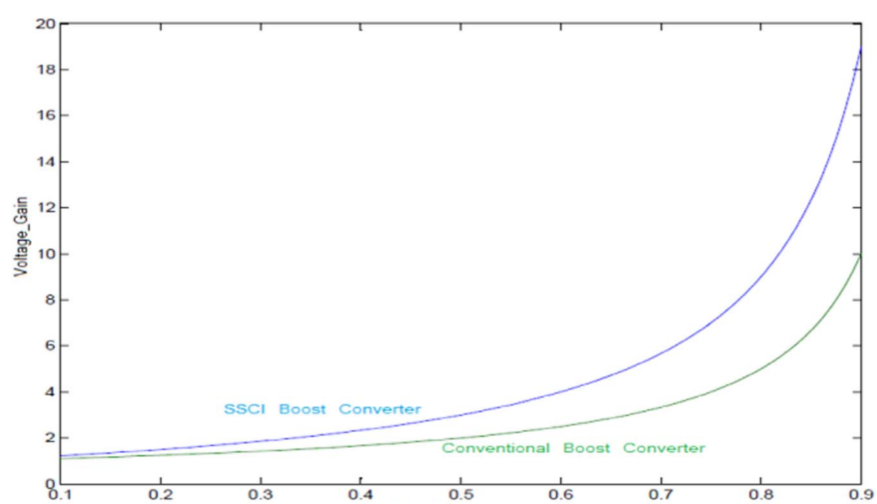

Fig. 18. Gain comparison of SSCI Boost converter and Conventional Boost converter.

be isolated during OFF period and during this period no power will be drawn from PV panel. Continuous operation of input side switch increases the input current ripple and a floating high level complex driver circuit is required for these converters. One terminal of switch is grounded and it is not directly connected to the PV panel in boost, cuk and SEPIC converters. Hence, operation of switch doesn't isolate the PV panel and the input current ripple will be also less. Grounded, low level simple driver circuit is only required for these converters. Based on the comparative study it was found that buck-boost, cuk, SEPIC and zeta converters are more suited for MPP tracking, out of these SEPIC converter is best one due to low input ripple current, simple driver circuit requirement, non-invert output voltage, tracking zone available all over the first quadrant, and it provides best performance under all atmospheric conditions.

6. Selection of non-isolated DC-DC converters for MPPT of PV system

Selection of DC-DC converter for SPV system can be done based on the following points:

(1) Cost of the converter: Initial cost of SPV system is generally on higher side so it is better to chose a converter with low cost for residential applications. High cost converters with better performance can be chosen for industries and large solar power plants were cost is not an issue.
(2) Efficiency of the converter: Converters with high efficiency cost ratio can be preferred for SPV applications.
(3) Input current ripple: Input current ripple of the converter must be on lower side under all conditions. Input current ripple of boost, SEPIC and cuk converters are less than that of buck, buck-boost and zeta converters.
(4) Load inclination angle: It's better to choose a converter with load inclination angle ranging from 0 to 90 degrees. Load inclination angle of buck-boost, cuk, SEPIC and zeta converters are in range of 0–90 degrees. Load inclination angle of buck converter is within a range of zero to tangent of reciprocal of load resistance and for boost converter it falls in a range of tangent of reciprocal of load resistance to 90 degrees.
(5) Tracking and non-tracking zone: A converter which tracks MPP all over the PV curve during all temperature, irradiance and load conditions are preferred for MPPT. Buck-boost, cuk, SEPIC and zeta converters can track MPP all over the PV curve while buck and boost converter can track MPP on left hand side and right hand side of PV curve respectively.
(6) Input-output energy flow: A converter with continuous input-output energy flow is preferable for SPV systems. Input-output energy flow of boost, SEPIC and cuk converters are continuous while it is discontinuous in case of buck, buck-boost and zeta converters.
(7) Output voltage polarity: A converter which provides an output with same polarity can be preferred for SPV systems. Boost, SEPIC and Zeta converters provides a non-inverted output voltage, while buck, buck-boost and cuk converters provides an inverted voltage at output.
(8) Driver circuit requirement: Converter with simple, grounded driver circuit can be preferred for SPV system. High side driver circuit is required for buck, buck-boost and zeta converters while a low side, low cost driver circuit is only required for boost, SEPIC and zeta converters.
(9) Output voltage ripple: Converter with less output voltage ripple can be chosen for SPV systems. Output voltage ripple of buck, buck-boost and zeta converters are lees as compared to SEPIC, boost and cuk converters.

Selected converter may not satisfy all the conditions mentioned above, there must be tradeoff while choosing a converter for SPV system. A converter which is able to perform both bucking and boosting action can be selected for SPV systems. Selected converter must track MPP all over the PV curve and the load inclination angle must lie between 0 and 90 degrees. Converter must provide continuous input-output power flow with fewer ripples in input current, output current and output voltage. Buck-boost, SEPIC, cuk and zeta converters are best for solar power tracking purpose. As mentioned in survey slight modification of a conventional converter can address the issues and make the converter more attractive.

7. Conclusion

This paper provides a comprehensive study on various non-isolated DC-DC converters which are used for MPPT of solar power. Non-isolated DC-DC converters are found attractive due to the ability it to step up the low voltage produced by PV panel and the ability achieve load matching between PV panel and load. Selection criteria for choosing an adequate converter for solar power tracking has been also presented based on the study and survey. Advantages and disadvantages of each converter are discussed in detail. To determine the characteristic of each converter different parameters are analyzed. Working principle, merits and demerits of various non-isolated DC-DC converters are described in detail and are compared against each other based on the certain parameters like static gain, resistance conversion ratio, O/P voltage polarity, input current ripple, load inclination angle, voltage across PV module, complexity, number of switches used, relationship between D and V_o, switch drive requirement, energy transferring elements and output current ripple. Buck converter must be used with a load impedance less than or equal to R_{MPP} while boost converter must be used with a load impedance greater than or equal to R_{MPP}. Buck-boost, cuk, SEPIC and zeta converters can be used with load resistance greater than or less than R_{MPP}. Selection of proper converter is an important factor in designing an MPPT system for SPV system. Tabular comparison on various non-isolated DC-Dc converters are provided at the end of the paper, which will help the researchers to choose a particular converter.

References

[1] Saif-Ul-Rehman M. Economic competitiveness of solar energy with conventional fuels and electricity. Sol Energy 1976;18:577–9.
[2] Tani Tatsuo, Sawata Shinji, Horjgome Takashi. A terrestrial solar energy system. Sol Energy 1976;18:281–5.
[3] Bertrand H. Chatel, New Potentialities for international co-operation in the field of solar energy, 18; 1976, p 69–71.
[4] John W. Andrews, energy storage requirement reduced in coupled wind-solar generating systems. Sol Energy 1976;18:73–4.
[5] Nagayoshi Hiroshi. I-Vcurve simulation by multi-module simulator using I2V magnifier circuit. Sol Energy Mater Sol Cells 2004;82:159–67.
[6] Dasgupta Nivedita, Pandey Ashish, Mukerjee Ashok K. Voltage-sensing-based photovoltaic MPPT with improved tracking and drift avoidance capabilities. Sol Energy Mater Sol Cells 2008;92:1552–8.
[7] Salas V, Olı´as E, La´zaro A, Barrado A. Evaluation of a new maximum power point tracker (MPPT) applied to the photovoltaic stand-alone systems. Sol Energy Mater Sol Cells 2005;87:807–15.
[8] Kawamura T, Harada K, Ishihara Y, Todaka T, Oshiro T, Nakamura H, Imataki M. Analysis of MPPT characteristics in photovoltaic power system. Sol Energy Mater Sol Cells 1997;47:155–65.
[9] Muhidaa Riza, Park Minwon, Dakkak Mohammed, Matsuura Kenji, Tsuyoshi Akira, Michira Masakazu. A maximum power point tracking for photovoltaic-SPE system using a maximum current controller. Sol Energy Mater Sol Cells 2003;75:697–706.
[10] Kobayashi Kenji, Takano Ichiro, Sawada Yoshio. A study of a two stage maximum power point tracking control of a photovoltaic system under partially shaded insolation conditions. Sol Energy Mater Sol Cells 2006;90:2975–88.
[11] Matsukawaa Hiroshi, Koshiishib Koukichi, Koizumi Hirotaka, Kurokawa Kosuke, Hamada Masayasu, Bo Liu. Dynamic evaluation of maximum power point tracking operation with PV array simulator. Sol Energy Mater Sol Cells 2003;75:537–46.
[12] Salas V, Olı´as E, La´zaro A, Barrado A. New algorithm using only one variable measurement applied to a maximum power point tracker. Sol Energy Mater Sol Cells 2005;87:675–84.
[13] Mun˜oz FJ, Almonacid G, Nofuentes G, Almonacid F. A new method based on

charge parameters to analyse the performance of stand-alone photovoltaic systems. Sol Energy Mater Sol Cells 2006;90:1750–63.
[14] Chowdhury Shubhajit Roy, Saha Hiranmay. Maximum power point tracking of partially shaded solar photovoltaic arrays. Sol Energy Mater Sol Cells 2010;94:1441–7.
[15] Giustiniani A, Petrone G, Spagnuolo G, Vitelli M. Low frequency current oscillations and maximum power point tracking in grid-connected fuel cell based systems. IEEE Trans Ind Electron 2010;57(6):2042–53.
[16] Toshihiko Noguchi, Shigenori Togashi, Ryo Nakamoto. Short-current pulse- based maximum-power-point tracking method for multiple photovoltaic and-converter module system. IEEE Trans Ind Electron 2002;49(1):217–23.
[17] Weidong Xiao, Dunford William G, Palmer Patrick R, Antoine Capel. Application of centered differentiation and steepest descent to maximum power point tracking. IEEE Trans Ind Electron 2007;54(5):2539–49.
[18] Kobayashi K, Takano I, Sawada Y. A study on a two stage maximum power point tracking control of a photovoltaic system under partially shaded insolation conditions. : IEEE Power Eng Soc General Meet 2003:2612–7.
[19] aaaa
[20] Masoum Mohammad AS, Dehbonei Hooman, Fuchs Ewald F. Theoretical and experimental analyses of photovoltaic systems with voltage- and current based maximum power-point tracking. IEEE Trans Energy Convers 2002;17:514–22.
[21] Mummadi Veerachary, Tomonobu Senjyu, Uezato Katsumi. And. voltage based maximum power point tracking control of PV system. IEEE Trans Aerosp Electron Syst 2002;38:262–70.
[22] Trishan Esram, Kimball Jonathan W, Krein Philip T, Chapman Patrick L, Pallab Midya. Dynamic maximum power point tracking of photovoltaic arrays using ripple correlation control. IEEE Trans Power Electron 2006;21(5):1282–91.
[23] Kimball Jonathan W, Krein Philip T. Discrete-time ripple correlation control for maximum power point tracking. IEEE Trans Power Electron 2008;23(5):2353–62.
[24] Domenico Casadei, Gabriele Grandi, Claudio Rossi. Single-phase single-stage photovoltaic generation system based on a ripple correlation control maximum power point tracking. IEEE Trans Energy Convers 2006;21(2):562–8.
[25] Yang Zhixun. DC/DC converter sliding mode control. Electra Technol J 2000;2:13–5.
[26] Il-Song Kim, Myung-Bok Kim, Myung-Joong Youn. New maximum power point tracker using sliding-mode observer for estimation of solar array current in the grid-connected photovoltaic system. IEEE Trans Ind Electron 2006;53(4):1027–35.
[27] Aghatehrani R, Kavasseri R. Sensitivity-analysis-based sliding mode control for voltage regulation in microgrids. IEEE Trans Sustain Energy 2013;4(1):50–7.
[28] Quamruzzaman M, Rahman KM. A modified Perturb and observe Maximum power point tracking technique for single-stage grid-connected photovoltaic inverter. WSEAS Trans Power Syst 2014;9.
[29] Femia N, Petrone G, Spagnuolo G, Vitelli M. Increasing the efficiency of P & O MPPT by converter dynamic matching. IEEE 2004, [0-7803-8304-4/04/$20.00@i].
[30] Jung Youngseok, So Junghun, Yu Gwonjong, Choi Jaeho. improved perturbation and observation method (IP & 0) of MPPT control for photovoltaic power systems. IEEE 2005, [0-7803-8707-4/051$20.00].
[31] Liu Xuejun, Luiz , Lopes AC. An improved perturbation and observation maximum power point tracking algorithm for PV arrays. 35th Ann IEEE Power Electron Spec Conf 2004, (Aachen, Germany).
[32] Ishaque Kashif, Salam Zainal, Lauss George. The performance of perturb and observe and incremental conductance maximum power point tracking method under dynamic weather conditions. Appl Energy 2014;119:228–36.
[33] Tey Kok Soon, Mekhilef Saad. Modified incremental conductance MPPT algorithm to mitigate inaccurate responses under fast-changing solar irradiation level. Sol Energy 2014;101:333–42.
[34] Radjai Tawfik, Rahmani Lazhar, Mekhilef Saad, Gaubert Jean Paul. Implementation of a modified incremental conductance MPPT algorithm with direct control based on a fuzzy duty cycle change estimator using dSPACE. Sol Energy 2014;110:325–37.
[35] Lin Chia-Hung, Huang Cong-Hui, Duc Yi-Chun, Chen Jian-Liung. Maximum photovoltaic power tracking for the PV array using the fractional-order incremental conductance method. Appl Energy 2011;88:4840–7.
[36] Sivakumar P, Kader Abdullah Abdul, Kaliavaradhan Yogeshraj, Arutchelvi M. Analysis and enhancement of PV efficiency with incremental conductance MPPT technique under non-linear loading conditions. Renew Energy 2015;81:543e550.
[37] Carrasco JM, Franquelo LG, Bialasiewicz JT, Galvn RGE, Prats M, Leon J, Moreno-Alfonso N. Power-electronic systems for the grid integration of renewable energy sources: a survey. IEEE Trans Ind Electron 2006;53(4).
[38] Noppadol Khaehintung, Chaiboon Kangsajian, Kunakorn Anatawat Sirisuk Phaophak. Grid-connected photovoltaic system with maximum power point tracking using self-organizing fuzzy logic controller. IEEE PEDS 2005:517–21.
[39] Mummadi Veerachary, Tomonobu Senjyu, Katsumi Uezato. Feed forward maximum power point tracking of PV systems using fuzzy controller. IEEE Trans Aerosp Electron Syst 2002;38(3):969–81.
[40] Chian-Song Chiu. T–S fuzzy maximum power point tracking control of solar power generation systems. IEEE Trans Energy Convers 2010:6–10.
[41] Al Nabulsi A, Dhaouadi R, Rehman H.Single input fuzzy controller (SFLC) based maximum power point tracking. In: Proceedings ICMSAO'11, Malaysia.
[42] Salhi Mohamed, El-Jouni Abdeslam, El-Bachtiri Rachid. Maximum power point tracker using fuzzy control for photovoltaic system. Int J Emerg Res Manag Technol (IJRRECE) 2013, [ISSN 2278-9359].
[43] Ibrahim HEA, Ibrahim Mahmoud. Comparison between fuzzy and P & O control for MPPT for photovoltaic system using boost converter. J Energy Technol Policy 2012;2(6).
[44] Krishna Ganesh SM, Muthuvel L. FLC based maximum power point tracking of solar photovoltaic system. TIJCSA 2012;1(6), [ISSN-2278-1080].
[45] Mummadi Veerachary, Tomonobu Senjyu, Katsumi Uezato. Neural-network based maximum-power-point tracking of coupled-inductor interleaved-boost converter-supplied PV system using fuzzy controller. IEEE Trans Ind Electron 2003;50:4.
[46] Syafaruddin Karatepe E, Hiyama T. Artificial neural network-polar coordinated point tracking control under partially shaded conditions. Power Gener 2009 2008;3(2):239–53.
[47] Younis MA, Khatib T, Najeeb M, Ariffin AM. An improved Maximum power point tracking controller for PV systems using artificial neural network. Przegląd Elektrotech (Electr Rev) 2012, [ISSN 0033-2097, R. 88 NR 3b/3b/].
[48] Hatti M, Meharrar A. Novel approach of MPPT for photovoltaic module neural network based. Int Symp Environ Friendly Energ Electr Appl, EFEEA'10, 2010.
[49] Ramaprabha R, Mathur BL. Intelligent controller based maximum power point tracking for solar PV system. Int J Comput Appl (0975 – 8887) 2011;12(10), [January].
[50] Singh GK. Solar power generation by PV(photovoltaic) technology: a review. Energy 2013;53.
[51] Jain S, Agarwal V. Comparison of the performance of maximum power point tracking schemes applied to single-stage grid-connected photovoltaic systems. IET Electr Power Appl 2007;1(5):753–62.
[52] Barth Nicolas, Jovanovic Raka, Ahzi Saïd, Khaleel Mohammad A. PV panel single and double diode models: optimization of the parameters and temperature dependence. Sol Energy Mater Sol Cells 2016;148:87–98.
[53] Norbert JL, Philips , Francois Guido E. Necessary and sufficient conditions for the stability of buck-type switched-mode power supplies. IEEE Trans Ind Electron Control Instrum 1981;vol(3), [August].
[54] Samosir Ahmad Saudi, Yatim Abdul Halim Mohd. Dynamic evolution control for synchronous buck DC-DC converter: theory, model and simulation. Simul Model Pract Theory 2010;18:663–76.
[55] Xu Shen, Sun Fengfeng, Yang Miao, Han Caixia, Sun Weifeng, Shengli Lu. A wide output range voltage-mode buck converter with fast voltage- tracking speed for RF power amplifiers. Microelectron J 2015;46:111–20.
[56] Tsai J-F, Chen Y-P,Sliding mode control and stability analysis of buck DC-DC converter. International Journal of Electronics.
[57] Lin BR, Chen PL, Shih KL,Analysis, design and experimentation of an interleaved active-clamping buck-type converter. International Journal of Electronics.
[58] Lee CS, Kim NS, MGendensuren, Choi JH, Choi JH, Integrated on-chip 0.35 μm BiCMOS current-mode DC–DC buck converter. International Journal of Electronics.
[59] Chew KWR, Siek L. Single inductor quad-input-dual-output buck converter for photovoltaic systems. : Proc IEEE IECON 2010 – 36th Annu Conf Ind Electron Soc 2010:704–9.
[60] Longlong Z, et al. A new approach to achieve maximum power point tracking for PV system with a variable inductor. IEEE Trans Power Electron 2011;26:1031–7.
[61] Veerachary M. Fourth-order buck converter for maximum power point tracking applications. IEEE Trans Aerosp Electron Syst 2011;47:896–911.
[62] Yang D, et al. One-cycle control for double-input DC/DC converter. IEEE Trans Power Electron 2011:1.
[63] Pernı´a AM, Jorge A, Prieto MJ, Martı´nez JA. A modular strategy for isolated photovoltaic systems based on microcontroller. Renew Energy 2009;34:1825–32.
[64] Smrithi R, Venugopal LV, Vanitha M. Hardware implementation of linear current booster for solar pumping applications. ARPN J Eng Appl Sci 2016;11(2), (January).
[65] Taufik AO, Anwari M, Taufik M. Modeling and simulation of photovoltaic water pumping system. Proc Third Asia Int Conf Model Simul, AMS '09 2009:497–502.
[66] Masoum MAS, Sarvi M. Design, simulation and implementation of a fuzzy based maximum power point tracker under variable irradiance and temperature conditions. Iran J Sci Technol 2005;29:27–32.
[67] Chian-Song C. T–S fuzzy maximum power point tracking control of solar power generation systems. IEEE Trans Energy Convers 2010;25:1123–32.
[68] Alabedin AMZ, El-Saadany EF, Salama MMA. Maximum power point tracking for Photovoltaic systems using fuzzy logic and artificial neural networks. : IEEE Power Energy Soc General Meet 2011:1–9.
[69] Daraban S, Petreus D, Morel C. A novel MPPT (maximum power point tracking) algorithm based on a modified genetic algorithm specialized on tracking the global maximum power point in photovoltaic systems affected by partial shading. Energy 2014;74:374e388.
[70] Yang JW, Do HL. Analysis and design of a high-efficiency zero-voltage-switching step-up DC–DC converter. Sadhana 2013;38(Part 4):653–65.
[71] Lingle JohnT. Reliable energy conversion power systems for space flight, Supplement to IEEE transactions on aerospace, June; 1965.
[72] Krithiga S, Ammasai Gounden N. Investigations of an improved PV system topology using multilevel boost converter and line commutated inverter with solutions to grid issues. Simul Model Pract Theory 2014;42:147–59.
[73] Li W, He X. An interleaved winding-coupled boost converter with passive lossless clamp circuits. IEEE Trans Power Electron 2007;22(4):1499–507, [Jul].
[74] Zhao Q, Lee FC. High-efficiency, high step-up DC–DC converters. IEEE Trans Power Electron 2003;18(1):65–73, [Jan].
[75] Henn G, Silva R, Prac¸a P, Barreto L, Oliveira D. Interleaved boost converter with high voltage gain. IEEE Trans Power Electron 2010;25(11):2753–61, [Nov].
[76] Kwon JM, et al. Three-phase photovoltaic system with three-level boosting MPPT control. IEEE Trans Power Electron 2008;23:2319–27.
[77] Doo-Yong J, et al. Interleaved soft-switching boost converter for photovoltaic

power-generation system. IEEE Trans Power Electron 2011;26:1137–45.
[78] Agorreta JL, et al. Fuzzy switching technique applied to PWM boost converter operating in mixed conduction mode for PV systems. IEEE Trans Ind Electron 2009;56:4363–73.
[79] Veerachary M, et al. Neural-network-based maximum-power-point tracking of coupled-inductor interleaved-boost-converter-supplied pv system using fuzzy controller. IEEE Trans Ind Electron 2003;50:749–58.
[80] Choi S, et al. Analysis, design and experimental results of a floating-output interleaved input boost-derived DC–DC high-gain transformer-less converter. IET Power Electron 2011;4:168–80.
[81] Elshaer M, et al. Smart optimal control of DC–DC boost converter in PV systems. IEEE/PES Transm Distrib Conf Expo, Lat Am (TD-LA), 2010:403–10.
[82] Sang-Hoon P, et al. Design and application for PV generation system using a soft-switching boost converter with SARC. IEEE Trans Ind Electron 2010;57:515–22.
[83] Bratcu AI, et al. Power optimization strategy for cascaded DC–DC converter architectures of photovoltaic modules. Proc IEEE Int Conf Ind Technol, ICIT 2009:1–8.
[84] Noguchi T, et al. Short-current pulse-based maximum-power-point tracking method for multiple photovoltaic-and-converter module system. IEEE Trans Ind Electron 2002;49:217–23.
[85] Petit P, et al. New architecture for high efficiency DC–DC converter dedicated to photovoltaic conversion. Energy Procedia 2011;6:688–94.
[86] Nejabatkhah F, et al. Modeling and control of a new three-input DC–DC boost converter for hybrid PV/FC/battery power system. IEEE Trans Power Electron 2011:1.
[87] (a) Simoes MG, Franceschetti NN, Friedhofer M. A fuzzy logic based photovoltaic peak power tracking control. : Proce Indust Electron IEEE Int Symp 1998;1:300–5;
(b) Chung-Yuen W, Duk-Heon K, Chen KS. A new maximum power point tracker of photovoltaic arrays using fuzzy controller. : Power Electron Spec 25th Annu IEEE Conf 1994;1:396–403.
[88] Khaehintung N, Pramotung K, Tuvirat1 B, Sirisuk P. RISC-microcontroller builtin fuzzy logic controller of maximum power point tracking for solar-powered light-flasher applications. IEEE 30th Annu Conf Indust Electron Soc, IECON 2004;3:2673–8.
[89] Alajmi BN, Ahmed KH, Finney SJ, Williams BW. Fuzzy-logic-control approach of a modified Hill–Climbing method for maximum power point in microgrid standalone photovoltaic system. IEEE Trans Power Electron 2011;26:1022–30.
[90] Patcharaprakiti N, Premrudeepreechacharn S. Maximum power point tracking using adaptive fuzzy logic control for grid-connected photovoltaic system. IEEE Power Eng Soc Winter Meet 2002;1:372–7.
[91] Wu TF, Yang CH, Chen YK, Liu R. Photovoltaic inverter systems with self-tuning fuzzy control based on an experimental planning method. IEEE 34th IndAppl Annu Meet Conf 1999;3:1887–94.
[92] Jinbang X, Anwen S, Cheng Y, Wenpei R, Xuan Y. ANN based on IncCond algorithm for MPP tracker. : bio-inspired sixth Int Conf on Comput: Theor Appl (BIC-TA) 2011:129–34.
[93] MA Islam, MA Kabir, Neural network based maximum power point tracking of photovoltaic arrays, In: TENCON 2011–2011 IEEE region 10 conference; 2011, p. 79–82.
[94] Subiyanto Mohamed A, Hopfield Shareef H. Neural network optimized fuzzy logic controller for maximum power point tracking in a photovoltaic system. Int J Photoenergy 2012:6–13.
[95] Chin CS, Neelakantan P, Yoong HP, Yang SS, Teo KTK. Maximum power point tracking for PV array under partially shaded condition. 3rd Int Conf Comput Intell, Comm sys Net 2011:72–7.
[96] Kumar P, Jain G, Palwalia DK. Genetic algorithm based maximum power tracking in solar power generation. IEEE 2015, [978-1-4799-8371-1/15/$31.00_c].
[97] Rezvani Izadbakhsh M, Gandomkar M, Vafaei S. Investigation of ANN-GA and modified perturb and observe MPPT techniques for photovoltaic system in the grid connected mode. Indian J Sci Technol 2015;8(1):87–95, [January].
[98] Ramaprabha R, Mathur BL. Intelligent controller based maximum power point tracking for solar PV system. Int J Comput Appl (0975–8887) 2011;12(10), [January].
[99] Badis A, Mansouri MN, Sakly A. PSO and GA-based maximum power point tracking for partially shaded photovoltaic systems. IEEE 2016, [978-1-4673-9768-1/16/$31.00 ©].
[100] Kuo JL, Chao KL, Lee LS. Dual mechatronic MPPT controllers with PN and OPSO control algorithms for the rotatable solar panel in PHEV system. IEEE Trans Ind Electron 2010;57(2), [February].
[101] Miyatake M, Veerachary M, Toriumi F, Fujii N, Ko H. Maximum power point Tracking of multiple photovoltaic arrays: a particle swarm optimization approach. IEEE Trans Aerosp Electron Syst· 2011, [January].
[102] Zhang⁎ Shi, Wen, Zhang Yongge, Xue Fei, Yang Ting. MPPT for PV systems based on a dormant PSO algorithm. Electr Power Syst Res 2015;123:100–7.
[103] Rick Hayner TK Phelps JohnA Collins, Middlebrook RD. The venerable converter: a new approach to power processing. IEEE transactions on industrial electronics and control instrumentation, vol. ieci- 24, no. 4, November; 1977.
[104] Krishna CM, Saritha B, Narayanan G. Computationally efficient models for simulation of non-ideal DC–DC converters operating in continuous and discontinuous conduction modes. Sadhana 2015;40(Part 7):2045–72.
[105] Samavatian Vahid, Radan Ahmad. A high efficiency input/output magnetically coupled interleaved buck–boost converter with low internal oscillation for fuel-cell applications: small signal modeling and dynamic analysis. Electr Power Energy Syst 2015;67:261–71.
[106] Soon Tey Kok, Mekhilef Saad, Safari Azadeh. Simple and low cost incremental conductance maximum power point tracking using buck-boost converter. J Renew Sustain Energy 2013;5:023106.
[107] Hauser H, Himmelstoss F, Wurm P. Flux measurements and modeling of the magnetic hysteresis for a zero- voltage switching dc-to-dc converter. J Appl Phys 2003;93:8790.
[108] Peftitsis D, et al. Photovoltaic system MPP tracker investigation and implementation using DSP engine and buck–boost DC–DC converter. Proc Power Electron Motion Control Conf, EPE-PEMC 2008:1840–6.
[109] Orellana M, et al. Four switch buck–boost converter for photovoltaic DC–DC power applications. Proc IECON 2010 36th Annu Conf IEEE Ind Electron Soc 2010:469–74.
[110] Tsai-Fu W, et al. A fuzzy-logic-controlled single-stage converter for PV-powered lighting system applications. IEEE Trans Ind Electron 2000;47:287–96.
[111] de Britto JR, et al. Proposal of a DC–DC converter with wide conversion range used in photovoltaic systems and utility power grid for the universal voltage range. : Proc 2010 Twenty-fifth Annu IEEE Appl Power Electron Conf Expo (APEC) 2010:2258–63.
[112] Veerachary M, Yadaiah N. ANN based peak power tracking for PV supplied DC motors. Sol Energy 2000;69:343–50.
[113] Jie L, Ziran C. Research on the MPPT algorithms of photovoltaic system based on PV neural network. In: chinese control and decision conference; 2011.
[114] Syafaruddin Karatepe E, Hiyama T. Artificial neural network-polar coordinated fuzzy controller based maximum power point tracking control under partially shaded conditions. IET Renew Power Gener 2009;3(2):239–53.
[115] Ishaque K, Salam Z, Amjad M, Mekhilef S. An improved particle swarm optimization (PSO)–based MPPT for PV with reduced steady-state oscillation. IEEE Trans Power Electron 2012;27(8), [August].
[116] Ishaque K, Salam Z. A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition. IEEE Trans Ind Electron 2013;60(8), [August].
[117] Lin Bor-ren, Huang Tsang-sum. Zero current switching cuk converters for power factor correction. Electr Power Syst Res 1997;41:91–8.
[118] Zhou D, Pietkiewicz A, Cuk S. A three-switch high-voltage converter. IEEE Trans Power Electron 1999;14(1):177–83, [Jan].
[119] Babaei Ebrahim, Mahmoodieh Mir Esmaeel Seyed. Systematical method of designing the elements of the Cuk converter. Electr Power Energy Syst 2014;55:351–61.
[120] Lin B-R, Huang C-L, Tsao F-P, Integrated Cuk-forward converter for photovoltaic-based LED lighting. International Journal of Electronics.
[121] Kavitha A, Uma G, Reesha M Beni. Analysis of fast-scale instability in a power factor correction Cuk converter. IET Power Electron 2012;5(8):1333–40.
[122] Selwan Elias, Park Gunhyung, Gajic Zoran. Optimal control of the Cuk converter used in solar cells via a jump parameter technique. IET Control Theory Appl. 2015;9(6):893–9.
[123] Safari A, Mekhilef S. Simulation and hardware implementation of incremental conductance MPPT with direct control method using cuk converter. IEEE Trans Ind Electron 2011;58:1154–61.
[124] Sungwoo B, Kwasinski A. Maximum power point tracker for a multiple-input Cuk dc–dc converter. Proc 31st Int Telecommun Energy Conf, INTELEC 2009:1–5.
[125] Lin BR, et al. Integrated Cuk-forward converter for photovoltaic-based LED lighting. Int J Electron 2009;96:943–59.
[126] Chung HSH, et al. A novel maximum power point tracking technique for solar panels using a SEPIC or Cuk converter. IEEE Trans Power Electron 2003;18:717–24.
[127] Jimenez-Toribio EE, et al. Sensorless control of SEPIC and Cuk converters for DC motors using solar panels. Proc IEEE Int Electr Mach Drives Conf, IEMDC '09 2009:1503–10.
[128] Rathge C, Mecke R. Converter for energy storage integration in photovoltaic plants. Proc 2002 IEEE Int Symp Ind Electron, ISIE 2002;3:959–63.
[129] Mahmoud AMA, et al. Proceedings of the 26th annual confjerence of the IEEE fuzzy logic implementation for photovoltaic maximum power tracking in industrial electronics society. ECON 2000;1:735–40.
[130] Do Hyun-Lark. Soft-switching SEPIC converter with ripple-free input current. IEEE Trans Power Electron 2012;27(6), [June].
[131] Babaei E, Seyed Mahmoodieh ME, Sabahi M. Investigating buck dc-dc converter operation in different operational modes and obtaining the minimum output voltage ripple considering filter size. J Power Electron 2011;11(6):793–800.
[132] Babaei E, Seyed Mahmoodieh ME, Mashinchi Mahery H. Operational modes and output voltage ripple analysis and design considerations of buck-boost DC-DC converters. IEEE Trans Ind Electron 2012;59(1):381–91.
[134] Mahdavi Mohammad, Farzanehfard Hosein. Bridgeless SEPIC PFC rectifier with reduced components and conduction losses. IEEE Trans Ind Electron 2011;58(9), [September].
[135] Yang Jae-Won, Do Hyun-Lark, SEPIC Bridgeless. Converter with a ripple-free input current. IEEE Trans Power Electron 2013;28(7), [July].
[136] Melo Priscila Facco de, Gules Roger, Romaneli Eduardo Felix Ribeiro, Annunziato Rafael Christiano. A modified SEPIC converter for high-power-factor rectifier and universal input voltage applications. IEEE Trans Power Electron 2010;25(2), [February].
[137] Veerachary M. Power tracking for nonlinear PV sources with coupled inductor SEPIC converter. IEEE Trans Aerosp Electron Syst 2005;41:1019–29.
[138] Dura´n E, et al. Methodology and experimental system for measuring and displaying I–V characteristic curves of PV facilities. Progress Photovolt: Res Appl 2009;17:574–86.
[139] dos Santos WM, et al. Application of the voltage fed TAB converter as energy source coupler. IEEE Lat Am Trans (Rev IEEE Am Lat) 2011;9:510–5.

[140] Chiu Huang-Jen, Lo Yu-Kang, Yao Chun-Jen, Cheng Shih-Jen. Design and implementation of a photovoltaic high-intensity-discharge street lighting system. IEEE Trans Power Electron 2011;26(12), [December].

[141] Huang-Jen C, et al. Design and implementation of a photovoltaic high intensity-discharge street lighting system. IEEE Trans Power Electron 2011;26:3464–71.

[142] Tse K, et al. A novel maximum power point tracker for PV panels using switching frequency modulation. IEEE Trans Power Electron 2002;17:980–9.

[143] Ta-Tau C, et al. Proc IEEE Int Conf Des Digit Battery Charg Syst Based PV-Modul Fuzzy Syst (FUZZ) 2011:1860–5.

[144] Seyedmahmoudian M, Rahmani R. Simulation and hardware implementation of new maximum power point tracking technique for partially shaded PV system using hybrid DEPSO method.. IEEE Trans Sustain Energy 2015;6(3), [July].

[145] Narula Swati, Singh Bhim, Bhuvaneswari Gurumoorthy. power factor corrected welding power supply using modified zeta converter. IEEE J Emerg Sel Top Power Electron 2016;04(2), [June].

[146] Wu Tsai-fu, Ljang Shih-an, Chen Yaow-ming. Design optimization for asymmetrical ZVS- PW M zeta converter. IEEE Trans Aerosp Electron Syst 2003;39(2), [April].

[147] Bist Vashist, Singh Bhim. Reduced sensor configuration of brushless DC motor drive using a power factor correction-based modified-zeta converter. IET Power Electron 2014;7(9):2322–35.

[148] Shikha Singh Bhim Singh, Bhuvaneswari G, Bist Vashist. power factor corrected zeta converter based improved power quality switched mode power supply. IEEE Trans Ind Electron 2015;62(9), [September].

[149] Murthy-Bellur Dakshina, Kazimierczuk Marian K. Isolated two-transistor zeta converter with reduced transistor voltage stress. IEEE Trans Circuits Syst: Express Briefs 2011;58(1), [January].

[150] Lin Jong-Lick, Yang Sung-Pei, Lin Pao-Wei. Small-signal analysis and controller design for an isolated zeta converter with high power factor correction. Electr Power Syst Res 2005;76:67–76.

[151] Andrade Antonio MSS, Beltrame Rafael C, Schuch Luciano, Martins Mario L da S. PV module-integrated single-switch DC/DC converter for PV energy harvest with battery charge capability. IEEE 2014, [978-1-4799-5551-0/14/$31.00 ©].

[152] Zanotti Jefferson William, Martins Denizar Cruz. Input characteristic impedance technique of power converters circuits applied to the maximum power point tracker of photovoltaic panels. IEEE 2014, [978-1-4799-5230- 4/14/$31.00_c].

[153] Lopez Henrique F, Viero Renan C, Zollmann Cesar A, Reckzielgel Lucas L, Tonkoski Reinaldo, dos Reis Fernando S. Low power solar system grid-Tied with MPPT based on temperature compensation. IEEE Electr. Energy Conf. 2009, [978-1-4244-4509-7/09/$25.00 ©].

[154] Kumar Rajan, Singh Bhim. BLDC motor-driven solar PV array-fed water pumping system employing zeta converter. IEEE Trans Ind Appl 2016;52(3), [May/June].

[155] Neha Adhikari Bhim Singh, Vyas AL. Design and performance of low power solar-PV energy generating system with zeta converter. IEEE 2012.

[156] Satapathy Samresh, Dash K Mahesh, Babu B Chitti. Variable step size MPPT algorithm for photo voltaic array using zeta converter – a comparative analysis. IEEE 2013, [978-1-4673-5630-5//13/$31.00 ©].

[157] Andrade Antonio MSS, Schuch Luciano, Mário , da L, Martins S. Photovoltaic battery charger based on the zeta converter: analysis, design and experimental results. IEEE 2015, [978-1-4673-7554-2/15/$31.00 ©].

[158] Salenga Jane S, Magsino Elmer R. Dynamic analysis of a two-input zeta converter topology for modular hybrid PV-wind microgrid system. IEEE 2015, [978-1-4799-8641-5/15/$31.00 ©].

[159] Sivasakthi Priya R, Inayath Bathul I. Adaptive P & O MPPT method using zeta converter for solar PV systems. Int J Res Appl Sci Eng Technol (IJRASET) 2016;4(III), [March].