International Journal of Advanced Technology and Engineering Exploration, Vol 9(93)
ISSN (Print): 2394-5443 ISSN (Online): 2394-7454
http://dx.doi.org/10.19101/IJATEE.2021.875193

Research Article

Adaptive neuro-fuzzy approach for maximum power point tracking with high gain converter for photo voltaic applications

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Received: 15-November-2021; Revised: 04-August-2022; Accepted: 09-August-2022

Abstract
Energy is essential for improving the management of the power systems. One of the major concerns in the power sector is increasing demand of power that tends to increase the demand for fossil fuels causing environmental problems. Thus, it is essential to use variable renewable energies for direct current (DC) micro grid applications. Solar photovoltaic (PV) is one of the phenomena where the solar irradiance is converted to electrical power through solar cell. A new high gain converter is implemented which is fed from solar PV to track the maximum voltage and power so as to elevate the output efficiency of the PV panel. The envisioned converter can be effectively worked in continuous conduction mode (CCM) with same gating pulse for the two switches that guarantees wide plying range. The preferred converter comprises least number of components and achieves a maximum gain of 25 for the switch on period of 0.8 which makes the control circuit simpler compared to other non-coupled inductor topologies. Presently, special maximum power point tracking (MPPT) procedures have been acquainted to track the maximum power point (MPP) viably of which adaptive neuro fuzzy inference system (ANFIS) based controller is used in this article and high efficiency of about 98.96% is attained with a good dynamic response. Over here, the potency of the system is endorsed by means of MATLAB/SIMULINK and compared with the other standard MPPT methods. Further, functioning and assessment of the conspired work are inspected carefully and verified effectively.

Keywords
Maximum power point tracking (MPPT), High gain DC-DC converter, Perturb and observe (P&O) and Fuzzy logic controller (FLC), Adaptive neuro-fuzzy inference system (ANFIS).

1.Introduction
Technology has served a number of ways to utilize the abundant resources. In recent years, renewable energy is considered as a green technology and yields the merits of inexhaustible, low maintenance and commercial source of energies. Now a days, renewable power innovation is transplanting the present world to clean energy solutions to offer the better practices of reduced fuel cost, lesser carbon emissions and pollution free environment. Some renewable energy sources like biomass and hydroelectric plants create several trade-offs with a great impact on wildlife, climatic changes and so on. Among various natural resources, solar and wind becomes major source of energy in today's energy sector providing zero greenhouse gas emissions. Hence, the energy from the sun is completely harnessed by virtue of the different converter topologies and exerted for direct current (DC) micro grid applications. Power electronic converters play a major role in conversion of power from one form of DC to other form of DC according to their applications. In this regard, the design and development of high gain DC-DC converters are gaining attraction towards many researchers.

This paper confers an exhaustive review of maximum power point (MPP) tracking strategies that are utilized for photovoltaic (PV) frameworks. The maximum power point tracking (MPPT) method is a vital part to revamp the efficiency of the network [1]. In order to maintain maximum power at all operating conditions, robust tracking of MPP is necessary. Therefore, this study implements perturb and observe (P&O) based fuzzy logic controller (FLC) to

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withstand the dynamic changes in sun illumination levels [2]. Moreover, it is essential to maintain the output voltage at MPP under various radiation conditions and hence, this proposed method displayed a block to calculate reference voltage of MPPT technique and FLC for applying pulse to the switch used. The same has been verified through MATLAB for a grid connected PV system attaining the precision of almost 99.5% to 99.9% and also acquiring MPP within 0.021s [3]. This paper adopts the combined highlights of both fuzzy logic and artificial neural network (ANN) to tackle the vagueness of the input parameters from solar PV panel [4].

The system design highlights the adaptive neuro-fuzzy inference system (ANFIS) for PV that generates the exact duty cycle for the boost converter. This ANFIS approach is more robust and feasible under all surrounding conditions. On best of that, this controller possesses added advantages of augmented efficacy and fast dynamic response when compared to other obsolete schemes. In [5−6], an overwhelming ANFIS structure with the assistance of error tuning methods is adopted to avoid the less oscillation at MPP, which optimizes the whole system. The plausible strategy was tested in different clime scenarios and compared with optimization techniques and the simulation results trots out the tracking of the propounded scheme under all environs. Fusing of sustainable energy sources viz. sun power and fuel cell are favored for the applications of DC micro grids.

The key intention of this paper is quoted as follows:
1.To grab the clean energy from sunlight effectively using different MPPT techniques.
2.To track the MPP efficiently by incorporating ANFIS based MPPT other than conventional methods.
3.To design a new high gain configuration with minimized number of components.
4.To upgrade the gain compared to other existing topologies present in DC microgrid applications.

The desire of this paper is specified as:
1.To design and develop the transformer less DC converter to reduce the size and cost.
2.To gain benefits from the combined features of FLC and ANN and implement ANFIS based MPPT method for tracking MPP.
3.To simulate and validate the performance of proposed technique in terms of high efficiency and fast-tracking response than conventional P&O and FLC based MPPT algorithms.

The contributions of this paper are notified as:
1.The operating principle of the converter is executed in continuous conduction mode (CCM) and achieved larger gain at particular duty cycle.
2.Performance characteristics and results of conventional P&O, FLC and ANFIS based MPPT techniques are analyzed and illustrated.

This study is organized in six modules. Module 1 delivers the introduction. In module 2, literature review is discussed followed by module 3, which confers the design methods and module 4 describes the Simulink outcomes. Thereafter, module 5 presents the comparative discussion of the results. Lastly, conclusion and future scope is discussed in module 6.

2. Literature review

Owing to low power generation, highly prominent converters are entailed to couple with the DC micro grid. A non-isolated converter without a boosting voltage multiplier cell (VMC) or hybrid switched capacitor (HSC) is enunciated in this paper [7]. The voltage is augmented in single switch non-confined converter with boosting capacitor which is concatenated with switched inductor (SL) and switched capacitor (SC) structures. Moreover, the hassle on the switch and diodes are minimized up to V0/2 [8]. A non-isolated converter with an eccentric feature treating solar as the input is highlighted in this paper. An off-centered converter is entrusted to procure exalted gain. Huge filters are not deployed due to continuous nature of currents. The converter functions with a sole switch and therefore results in slighter voltage burden [9]. A novel non-coupled inductor based single-ended primary-inductor (SEPIC) converter is displayed with continuous supply current for fuel cell applications. Without the absence of transformer, coupled inductor and ancillary clamping circuit, the voltage overshoot amid the commutation process is evaded [10]. Compared with the classical boost, the additional two capacitors and diodes included in the capacitor cell doubles the voltage gain. Over and above, unlike SC topology there's no huge current spike on the capacitors subsequently lessening the cost of capacitors [11]. This composition is proffered with model predictive control based MPP algorithm along with step-up converter for solar applications. The gain is boosted and efficacy is sustained to 93%. This control strategy could be well suited under varying and stable conditions [12]. The author employed a push-pull topology with FLC based MPP algorithm. In addition to, closed loop control is assessed with inductive-capacitive-inductive (LCL) filter [13]. As of now, numerous analysts have transposed towards distributed energy sources for viable advancement. This paper discusses a converter that renders high efficacy, uplifted gain even with a least number of passive elements. This requirement is meet out by the new SL network named doubled switch DC-DC converter [14]. Though the size of the system is compact, the converter reveals lower efficiency at low input voltage leading to higher conduction losses. To face the wavering low voltage grabbed from the sun powered PV cluster, a SC converter topology is accomplished. Moreover, fuzzy tuned proportional-integral (PI) controllers are utilized to overcome the drawbacks of customary PI controller in terms of steady state voltage [15].

In [16], a transformer-less DC-DC converter providing higher variable voltage gain with low stress on the passive components is revealed. A single switch converter accomplished with non-coupled inductor is flaunted here, that fulfills the objectives without utilizing any additional components and it also favors high proficiency with reduced control complexities. It offers low current ripple and becomes pertinent towards green energy applications [17]. This paper discusses about a modified VMC with SL network. The converter operation is simple with a single switch. The stress analysis across all the components along with the efficiency of the converter is analyzed and compared with other existing structures. But this converter possesses more component count owing to the system bulkier, so the researchers are looking forward to provide the high gain even with light weight boosting topology [18]. To procure the maximum power from panel, many of the authors are focusing on to the various hybrid MPPT controllers. This article highlights the novel grey wolf optimization (GWO) based FLC method as a MPPT controller. This work implements the non-isolated boost converter (NIBC) system with LC3D3 network for improving the gain of the converter. However, in the same way this topology also comprises of a greater number of passive components which makes system cost high [19]. Furthermore, the different switching methods can also be adopted for high gain converters to achieve the highest voltage gain at different duty cycles. The two types of switching schemes like simultaneous and complementary is presented with maximum gain of 11.25 for the maximum duty cycle of 80% and the proposed converter design suits for low voltage applications as presented in [20]. Despite many researchers face the problem of various consequences in their converters, they have moved towards transformer less DC-DC converter for green energy applications. This paper also includes a high gain converter employing FLC to attain the maximum efficiency of 97.4% [21]. In [22−25], it was reported that the boosting cell utilizes SL, SC and VMC networks to improve the gain. Since these networks have several diodes and capacitors, which in turn gives rise to conduction losses. Irrespective of the various networks implemented in recent studies, the addition of coupled inductor along with a VMC cell is proven to achieve ultra-high gain without operating the switch at the extreme duty ratios. Even though the switch stress is minimized, the input and magnetizing inductors are facing high dissipation losses than other elements [26]. This study discusses about ultra-voltage gain DC-DC converter with an active impedance network to reduce the switch burden. However, there are significant advantages present in this topology but limits its operation only at high voltage low power applications [27]. By integrating the boost and quadratic boost topologies in [28, 29] the high gain with increased efficiency even at low duty cycle is achieved. In [30−32], a non-isolated high gain boost converter is presented, by integrating the coupled inductor with SC topology to attain reduced voltage stress and conduction losses on the power switches at moderate duty cycle. On account of considering the losses, the efficiency is decreased at high output power. Therefore, the converters in the above said literatures is applicable to low to medium power applications. So far, the papers have been listed out showcased various topologies to improve the voltage gain, a new transformer-less boost converter with two active switches have been designed to reduce the switch voltage stress to half. Additionally, this configuration has a wider operating range of the duty cycle that imposes low current ripple along with a continuous input current as in [33−35]. Moreover, some converters have introduced a symmetrical configuration by having a VMC twice in the circuit and provides low stress on the switch. This configuration makes the component selection easier and simpler. Hence, the non-isolated boost high gain topology along with SC network is proposed for fuel cell applications. Both configurations possess high gain without operating converter at extreme duty ratio. In addition, these configurations also provide high efficiency and low voltage stress [36−38]. From [39, 40], it is noted that the cascaded configuration of boost converters exhibits ultra-high gain with an elimination of diode reverse recovery loss. At the same time, it is capable of achieving desired operating characteristics required for renewable applications.

Therefore, to overcome the above said limitations, this paper focuses on the development of high gain converter that operates in CCM for DC microgrid applications. The motive of this study is to track the maximal power from the solar panel using an intelligent soft computing technique called ANFIS as an MPPT technique for the proposed converter. The PV characteristics of the ANFIS based MPPT is further compared with other techniques like P&O and fuzzy methods.

The key features of this article are as follows:

- The goals of extreme gain, efficiency and power density are ensured with least component count.
- Owing to the less component count, the design becomes more compact.
- The control methodology of ANFIS based MPPT is accomplished to acquire the MPP from PV.

The robust tracking capability of MPPT controller is verified through MATLAB Simulink for various irradiation levels with good PV characteristics.

3.Design methods

Figure 1 shows the outlined working mechanism of renewable energy source based high gain configuration. However, to obtain the radiation from the sun, a study of various MPPT methods is executed to assess the performance of controllers such as P&O, FLC and ANFIS for fast tracking of PV power. Moreover, the output from the high gain converter is integrated with DC microgrid network to feed the various DC loads. In this aspect, it is difficult to change the solar panel after installation and hence the use of MPPT controllers is intended as the easiest way to strengthen the characteristics of the solar PV system. Numerous online approaches were imparted to fulfill the control requisites. The panel criterions are delineated in *Table 1*. A PV array with a maximum capacity of 350 W at standard atmospheric condition (1000 W/m^2, 25℃) is favored as per the ratings of the devised converter. Based on insolation and temperature levels of the sun, the voltage and current of the panel differs. *Figure 2* pictured the characteristics of V_{PV} versus P_{PV} and I_{PV} for distinct sun irradiation levels at the temperature of 25℃. *Figure 3* portrays the characteristics of the V_{PV} versus P_{PV} and I_{PV} for several temperatures at same irradiation level of 1000W/m^2.

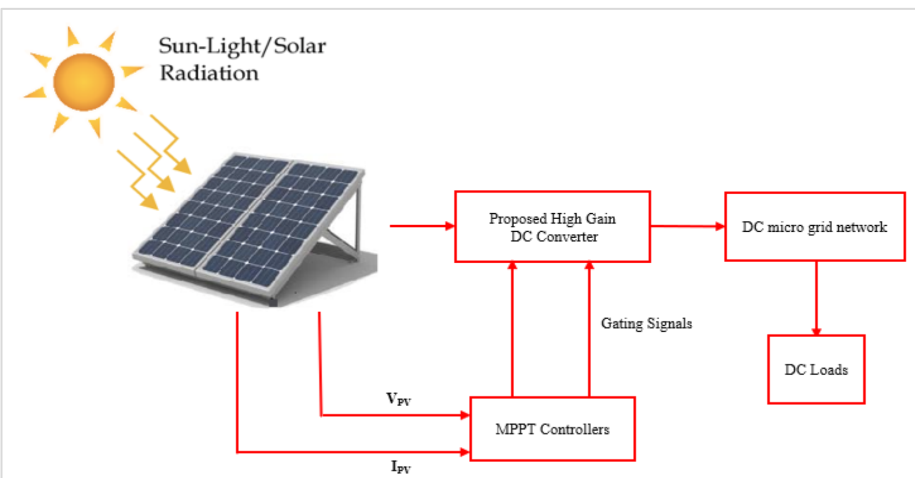


Figure 1 Outlined model of solar PV system

Table 1 Solar PV array specifications

Specifications of PV module	
Panel power P_{PV}	350W
Open circuit Voltage V_0	51.5V
Short circuit Current I_{SC}	9.4A
MPP Voltage V_M	43V
MPP current I_M	8.13A
Current temperature Coefficient	0.09(%/℃)
Voltage temperature Coefficient	-0.36(%/℃)

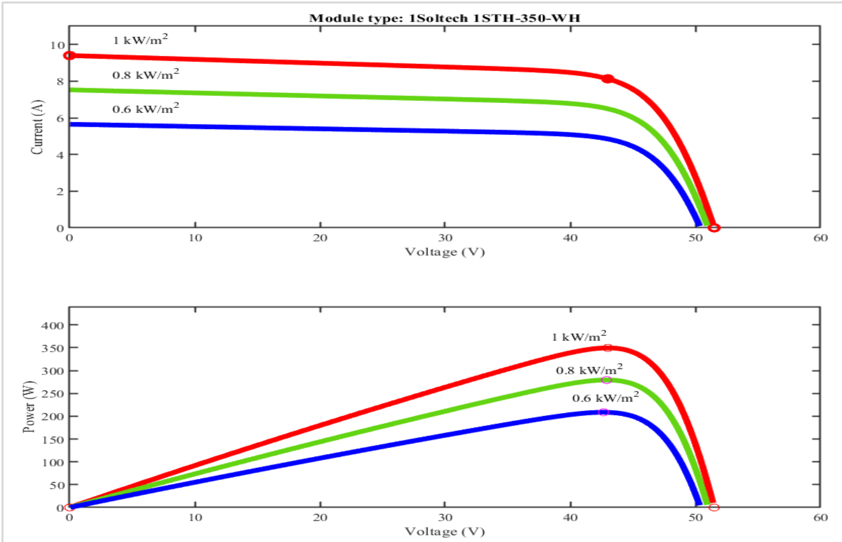


Figure 2 V_{PV} versus I_{PV} and P_{PV} at various irradiation levels

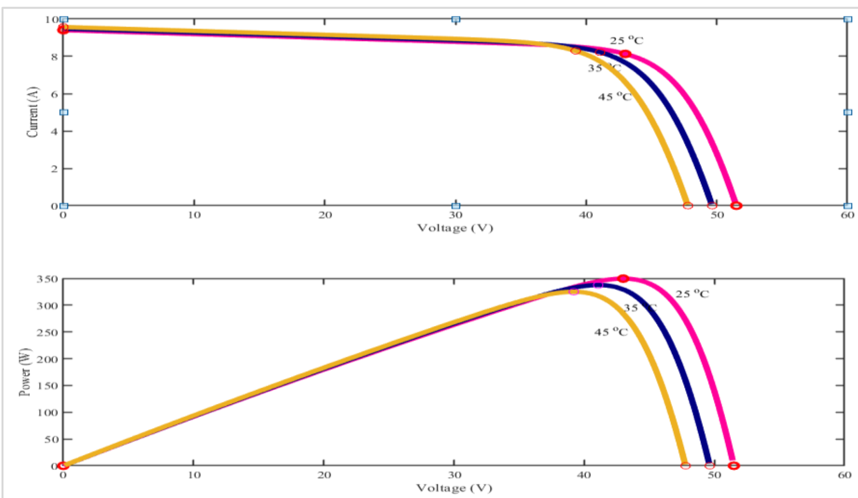


Figure 3 VPV versus IPV and PPV with at various temperature levels

PV cluster has only one working point where, the maximum power can be extricated. These maximum points are reached only when the PV's operating point is set at the knee point of the IPV (VPV) curve. The MPPT controller is incorporated to attain extreme power from the panel. In this study, the distinctive MPPT techniques like P&O, I&C, FLC and ANFIS-based controls are showcased along with its performance.

3.1 Functioning of the circuit configuration

The presented schematic of high gain DC-DC converter is illustrated in *Figure 4.* This circuit encompasses with four energy storage components (L_1, L_2, C_1, and C_2), two diodes (D_1 and D_2) and two dynamic control switches (S_1 and S_2). Equal control signals are synchronically applied for both the switches. The converter takes the supply voltage of V_S with switching frequency of f_S as 20 kilo hertz (kHz).

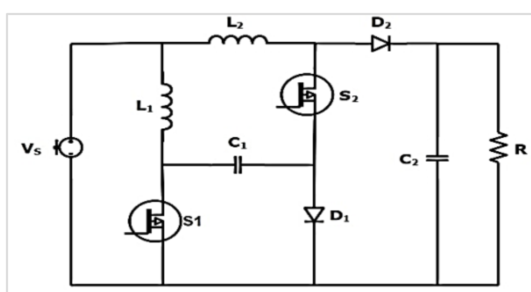


Figure 4 Propounded augmented gain converter

The working principle and steady state analysis of the proffered converter in CCM is discussed below.
The initial assumptions made are as follows:
1. All the devices are in ideal state.
2. All the capacitors are examined to be huge in order to maintain their voltages constant in each switching cycle.

There exist two viable modes 1 and 2 that are confessed below. The functional modes are depicted in *Figure 4(a)* and *Figure 4(b).* The *Figure 5* pictured the chopping waveforms of CCM of the suggested converter. The switches S_1 and S_2 lasts for on period of DT_S and off period of $(1\text{-}D)T_S$ where, T_S is the switching period with D as the duty ratio.

3.2 CCM operation

3.2.1Mode I [0<t<DT_S]

During the time interval [0-DT_S], S_1 and S_2 are turned ON whereas the operation of diodes D_1 and D_2 are in blocked state as per the equivalent circuit shown in *Figure 4(a).* The current through the inductors L_1 and L_2 starts rising due to the energy drawn from the source. Meanwhile, the capacitor C_1 is discharging via the switch S_1. The output capacitor C_2 supports the load. Hence, the voltage across L_1 and L_2 are illustrated as in Equations 1 and 2.

$$VL1 = VS \quad (1)$$

$$VL2 = VS + VC1 \quad (2)$$

Where, $V_{L1}$and V_{L2} is the voltage across the input inductors $L_1$and L_2.V_{C1} represents voltage across the capacitor C_1.

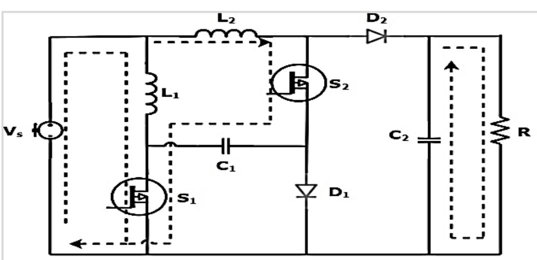


Figure 4(a) Mode I operation

3.2.2 Mode II [DT_S<t<T_S]

This mode begins when both the switches S_1 and S_2 are in OFF state as depicted in *Figure 4(b).* The energy in the inductor L_1 begins to release its energy through diode D_1 as it is in the conducting state and also capacitor C_1 is simultaneously charging at this interval. Other inductor L_2 is discharged via D_2 and the output capacitor C_2 supports the load. Thus, the voltage across L_1 and L_2 are elucidated as in Equations 3 and 4.

$$VL1 = VS - VC1 \quad (3)$$

$$VL2 = VS - V0 \quad (4)$$

Where, V_0 denotes output voltage across the load resistor R.

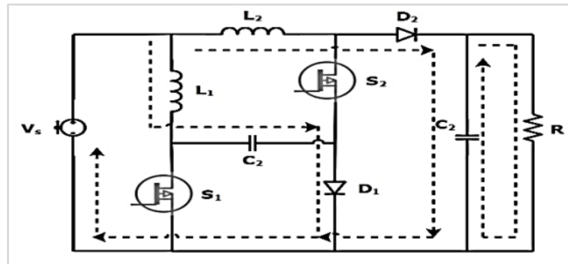


Figure 4(b) Mode II operation

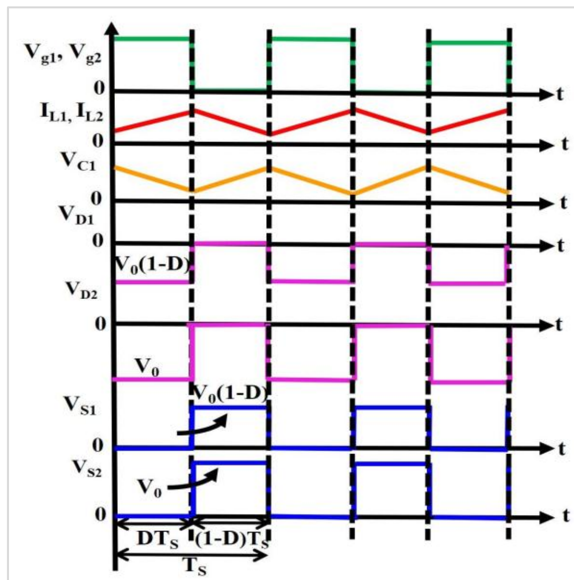


Figure 5 Chopping waveforms under CCM operation

$$\int_0^{DTS} VSdt + \int_{DTS}^{TS} (VS - VC1)dt = 0 \quad (5)$$

$$\int_0^{DTS} (V_S + V_{C1})dt + \int_{DTS}^{TS} (V_S - V_0)dt = 0 \quad (6)$$

Based on the above mathematical expressions as enumerated in Equations 5 and 6, the expression for V_{C1} and the voltage gain of the preferred converter is obtained as given in Equations 7 and 8.

$$VC1 = \frac{VS(1-2D)}{(1-D)} \quad (7)$$

$$G = \frac{V0}{VS} = \frac{1}{(1-2D+D^2)} = \frac{1}{(1-D)^2} \quad (8)$$

Where, G depicts the voltage gain of the converter.

3.3Expropriate design parameters of converter

3.3.1 Design of Inductors (L_1 and L_2)

The two inductors are coextensive with same inductance value and they fetch the equal current. Considering the ripple current of inductors L_1, L_2during on and off time intervals, the expression for the inductors isobtained as in Equations 9 and 10.

$$\frac{\Delta iL1}{VS} L1 + \frac{\Delta iL1}{VS - VC1} L1 \qquad (9)$$

$$L1 = L2 = \frac{VS \times D}{fs\Delta iL1{,}2(2D-1)} \qquad (10)$$

By assuming ripple current $\Delta i_{L1,2}$ as 30% and to ensure CCM operation the inductor value is selected as 1mH.

3.3.2 Design of intermediate and output capacitors (C_1 and C_2)

The design equation of the intermediate capacitor C_1 and output capacitor $C_2$are derived as in Equations 11 and 12.

$$C1 = \frac{VC1 \times D}{fs\Delta VC1(2D^2 + 3D + 1)} \qquad (11)$$

$$C2 = \frac{V0DTs}{R\Delta VC2} \qquad (12)$$

Where, ΔVC1 is the ripple voltage of capacitor C_1 with an assumption of 20% and to ensure CCM operation the capacitor value is selected as 50μF. The ripple voltage of the capacitor C_2 with an assumption of 3% and the selected value of capacitor is 250μF.

3.4Performance evaluation of converter

This subsequent section discusses the performance comparison of the presented topology with the other structures in terms of component count, stress and voltage gain as referred in *Table 2*. *Figure 6* depicts the graphical illustration of different topologies with their respective voltage gain. Referring to *Figure 6* and *Table 2*, the suggested topology provides high gain than other existing converters in [11, 12, 20].

Table 2 Performance comparison of various converter topologies

Topology		**Boost**	**[11]**	**[12]**	**[20]**	**Proposed**
No. of Switches		1	2	2	2	2
No. of Diodes		1	3	3	3	2
No. of inductors		1	1	2	2	2
No. of capacitors		1	3	2	3	2
Total device count		4	8	9	10	8
Continuous input current		Yes	Yes	Yes	Yes	Yes
Current Ripple		High	High	Moderate	Moderate	Low
Voltage Gain		$\frac{1}{(1-D)}$	$\frac{2}{(1-D)}$	$\frac{(1+D)}{(1-D)}$	$\frac{1+D}{D(1-D)}$	$\frac{1}{(1-D)^2}$
Switch stress	S_1	$V0$	$\frac{V0}{2}$	$\frac{(V0-Vin)}{2}$	$\frac{Vin}{(1-D)}$	$V0(1-D)$
	S_2	***NA***	$\frac{V0}{2}$	$V0$	$\frac{Vin}{D(1-D)}$	$V0$
Diode Stress	D_1	$V0$	$\frac{V0}{2}$	$\frac{(V0+Vin)}{2}$	$\frac{Vin}{(1-D)}$	$V0(1-D)$
	D_2	***NA***	$\frac{V0}{2}$	Vin	$\frac{Vin}{(1-D)}$	$V0$
Duty Cycle		**Voltage Gain**				
0.5		2	4	3	6	4
0.8		5	10	9	11.25	25

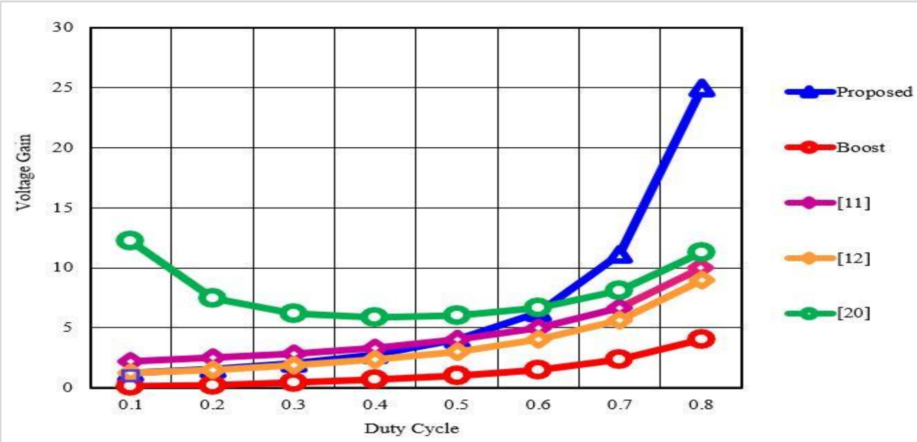


Figure 6 Graphical Illustration of various topologies

3.5MPPT controls for PV clusters

Many researchers have proffered to harness the maximal power from the PV board. For acquiring maximum power even for spontaneous climatic changes, the dynamic MPP controller is suggested. To oversee with ceaseless temperature and sun-oriented radiation, the MPP also changes. In this section, weeded ANFIS method is implemented and compared with other algorithms. In expansion, the viability of the propounded outline work is validated on MATLAB/SIMULINK.

3.5.1 Perturb and observe method (P&O)

A PV panel requires a technique to track the MPP at all times independent of the variations in temperature, irradiation levels and climatic conditions. The P&O strategy intermittently increments or diminishes the PV voltage and compares the panel response with that of the past cycle. Hence, this perturbation leads to track the maximum power in the same/opposite direction in which the MPP is followed appropriately. This method of tracking encounters the following demerits of susceptibility towards the environmental changes, oscillations around steady state and presents incorrect or sluggish response in tracking of MPP.

3.5.2 Fuzzy logic control (FLC)

Dealing with an imprecise data, is one of the best attractive features of fuzzy logic and it is utilized to attain the MPP here. It can also handle the nonlinearities in the system in which it is incorporated. Fuzzification, rule base creation and defuzzification are the simple steps in FLC. Hinged on to fuzzy rules, the maximum power can be harnessed even for the change in temperature and irradiation levels of PV clusters. The output surface for the FIS is displayed in *Figure 7*.

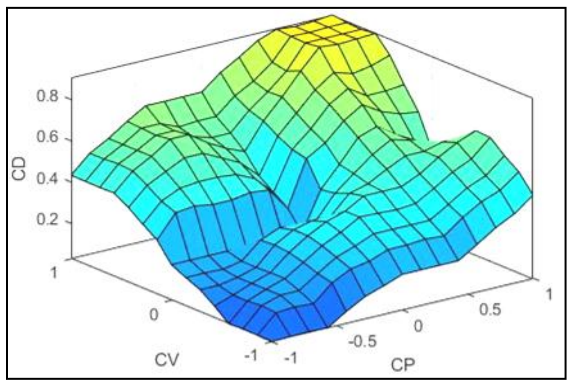


Figure 7 Output surface of FIS

3.5.3ANFIS controller for MPPT tracking

The intended controller is embedded in the PV framework as outlined in *Figure 8*. The PV cluster, MPP tracker, along with a converter together forms the overall system. The aforementioned ANFIS controller endows a reference power which is compared with panel power (P_{PV}) and error signal is pertained to the controller to procure the control signals for the power switches. The hastened pulse width modulated signals control the switches of the augmented gain converter to modify the working of solar clusters. An advanced Neuro-Fuzzy based consummate tracking methodology is endorsed to achieve the extreme power from PV module for spontaneous climatic conditions. The system input components are PV voltage (V_{PV}), current (I_{PV}) and cell temperature (T_{PV}).

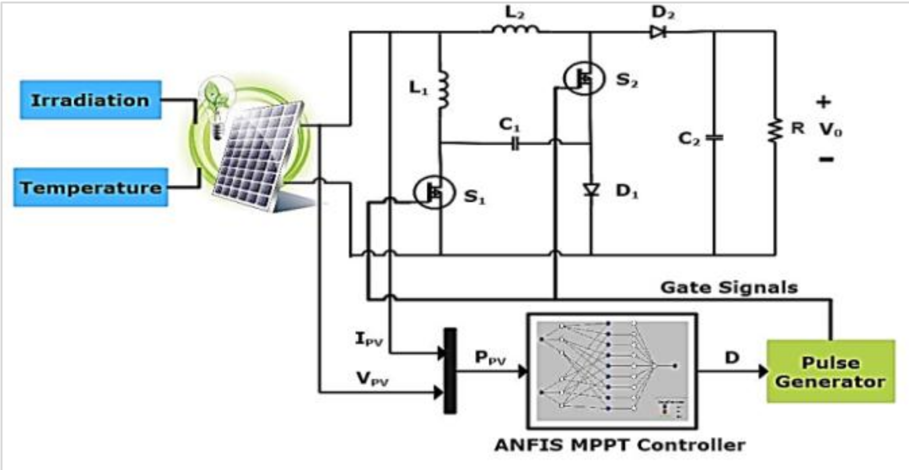
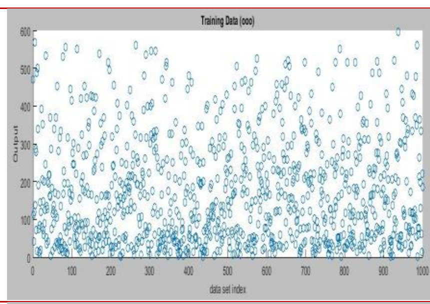
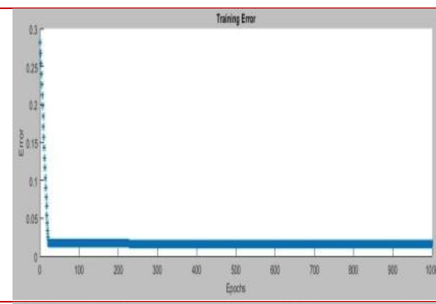
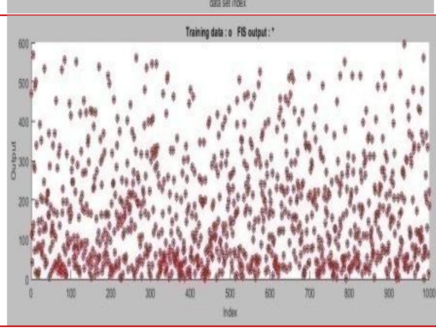
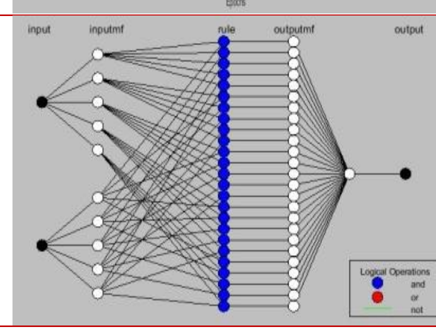
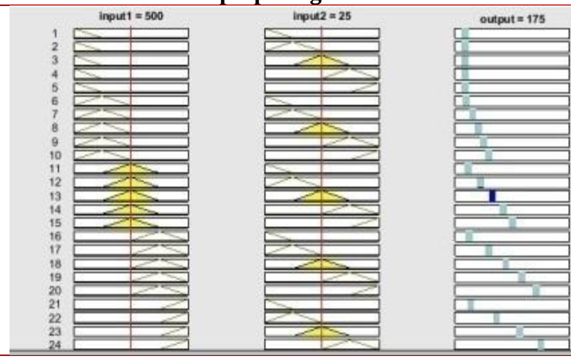


Figure 8 Outlined ANFIS controller for PV panel

ANFIS network creates the Fuzzy rules and membership functions with a help of input and output information. ANFIS network is trained for most extreme number of 1000 epochs and training error is visualized in *Table 2*. The data is collected to train and hence, controlled utilizing the MATLAB code. Neuro-Fuzzy Control Logic has five layers with two inputs (Irradiation and temperature) and one output (Power). Each input parameter owns five triangular membership functions, which are learned through neural network. Hence, 25 fuzzy rules are provoked to deliver output control for every insolation and temperature values. The stages of ANFIS training, structure, rule base for ANFIS controller is showcased in *Table 3*.

Table 3 ANFIS training stages

Stages of preparing	Exemplification of training in MATLAB	Stages of preparing	Exemplification of training in MATLAB
Response details of the ANFIS controller		Plot for 1000 iteration of training error	
Trained data testing		Structure of trained ANFIS controller	

Stages of preparing	Exemplification of training in MATLAB	Stages of preparing	Exemplification of training in MATLAB
Rule base for trained data			

4. Simulink out comes

The envisioned ANFIS based MPPT controller with high gain converter is modelled and mimicked in MATLAB Simulink as disported in *Figure 9*. The prompted frame work entails the PV cluster, converter with elevated gain and ANFIS based MPP tracker. The PV board utilized here is 1Soltech 1STH-350-WH. The consummate power point voltage, current, power of the preferred panel at 25℃ is given as 43V, 8.13A and 349.59W respectively. The favoured converter is validated and tested with the ANFIS based MPPT tracker and is compared with classical algorithms. The converter simulated with P&O and fuzzy based MPPT is tested under distinct sun-powered illumination conditions and finally compared with a proposed ANFIS based MPPT strategy.

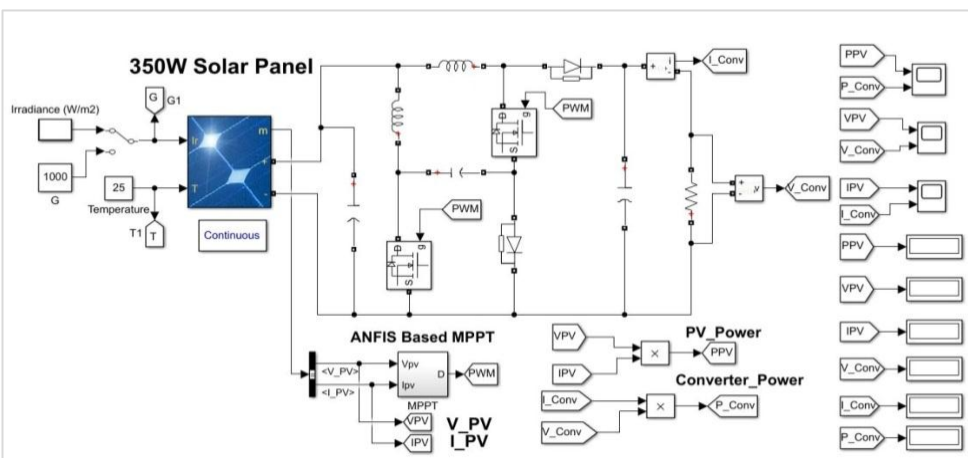
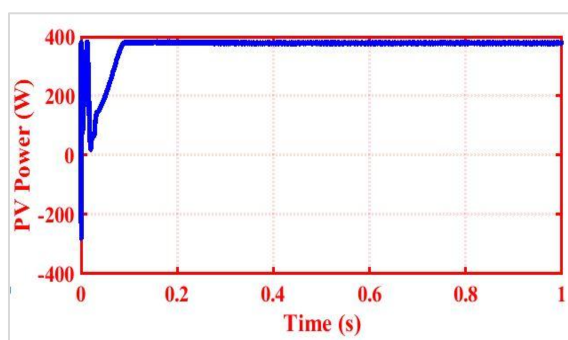


Figure 9 Simulink model of converter with ANFIS based MPPT controller

4.1 Virtual results of P&O based MPPT approach

To validate the capability of the propounded controller, we have considered the customary P&O and FLC based MPPT strategy for comparative performance investigation. *Figure 10(a)* and *10(b)* follows the output power of PV module, converterwith P&O is realized at irradiance of 1000W/m^2 and temperature of 25℃. The power of PV panel and its variations for irradiation level from 1000W/m^2 to 800W/m^2 at 0.3s to 0.7s is portrayed in *Figure 10(c).*



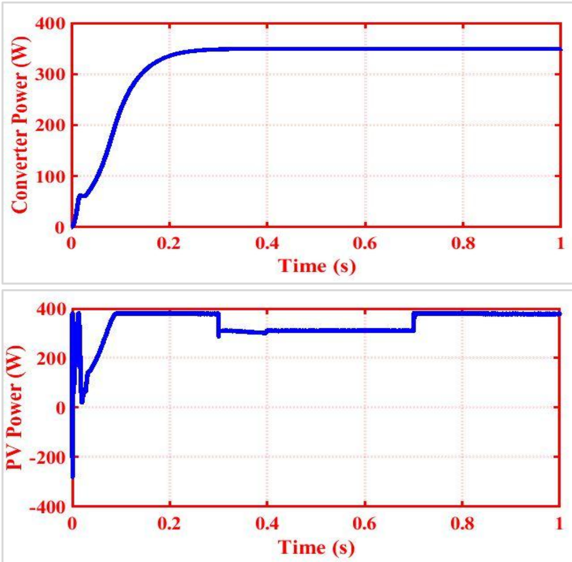


Figure 10 Waveforms secured for P&O approach (a) Panel Power at 1000W/m^2/25℃ (b) Converter Power at 1000W/m2/25℃ (c) PV power for irradiation change from 1000W/m^2 to 800W/m^2 at 0.3s to 0.7s

4.2Virtual results of fuzzy based MPPT approach

Here, *Figure 11(a)* and *11(b)* presents the output power of PV module and converter with FLC based MPPT is accomplished at irradiance of 1000W/m^2 and temperature of 25℃.The power of PV panel and its variations for irradiation level from 1000W/m^2 to 800W/m^2 at 0.3s to 0.7s is displayed in *Figure 11(c).*

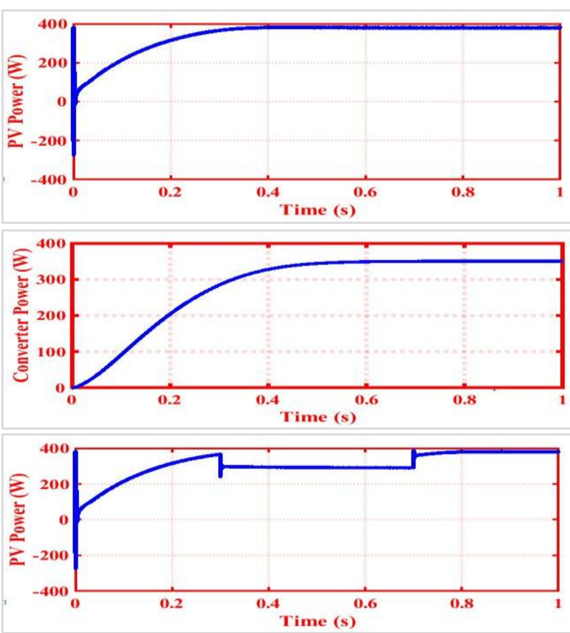


Figure 11 Waveforms acquired for FLC approach (a) Panel Power at 1000W/m^2/25℃ (b) Converter Power at 1000W/m^2/25℃ (c) PV power for irradiation change from 1000W/m^2 to 800W/m^2 at 0.3s to 0.7s.

4.3Virtual results of ANFIS based MPPT approach

The *Figure 12(a)* and *12(b)* interprets the output power of PV module and converter with ANFIS based MPPT is effectuated at irradiance of 1000W/m^2 and temperature of 25℃. The power of PV panel and its variations for insolation level from 1000W/m^2 to 800W/m^2 at 0.3s to 0.7s is revealed in *Figure 12(c).*

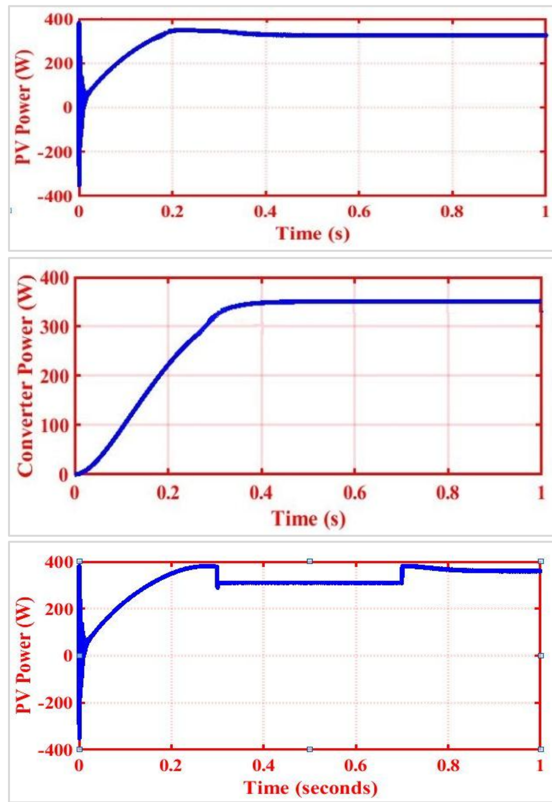


Figure 12 Attained Waveforms for ANFIS based MPPT (a) Panel Power at 1000W/m^2/25℃ (b) Converter Power at 1000W/m^2/25℃ (c) PV power for irradiation change from 1000W/m^2 to 800W/m^2 at 0.3s to 0.7s.

5. Discussion

5.1 Comparative analysis of power at various temperature levels for all methods

In this section, the preferred topology is collated on the prospects of power at various temperature levels. *Figure 13* depicts the variation of PV power for different temperature conditions. It is observed that the ANFIS based MPPT control tracks the exact maximum power at various temperature levels.

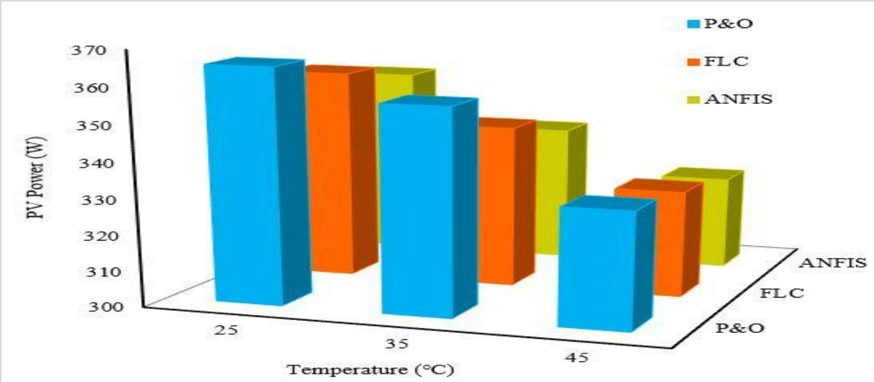


Figure 13 Comparison of power and temperature for various MPPT methods

5.2 Comparison of ANFIS strategy with classical methods

The suggested control method exactly tracks the maximum power and its value equals to 353.2W, which corresponds to the MPP. In addition, this control method is compared with other traditional methods like P&O and FLC. By examining the *Table 4*, it is observed that this control method is more effective in tracking the MPP with high efficacy, robustness and dynamic response. The implications from the above discussion involve huge voltage gain for the previously mentioned converter with an achievement of 98.96% efficiency.

Table 4 Trailing efficacy of MPPT strategies at 1000W/m^2/25°C

MPPT techniques	PMP (W)	VMP (V)	IMP (A)	Efficacy (%)
P&O	365.3	44.08	8.55	95.69
FLC	358.5	43.86	7.85	97.51
ANFIS	353.2	43.05	8.2	98.96

5.3Theoretical and simulation outcomes of preferred converter for varying duty cycles

This section discusses about the performance of the aforementioned converter for the range of duty cycle from 0.1 to 0.8. The converter offers maximum gain of 25 for the duty cycle of 0.8, which is viable for DC micro grid integration. The open loop verification of the proposed converter, that is presented in the table below includes the theoretical and simulation results of voltage and power. *Figure 14* shows the comparison plot for output voltage and power for duty cycle variations.

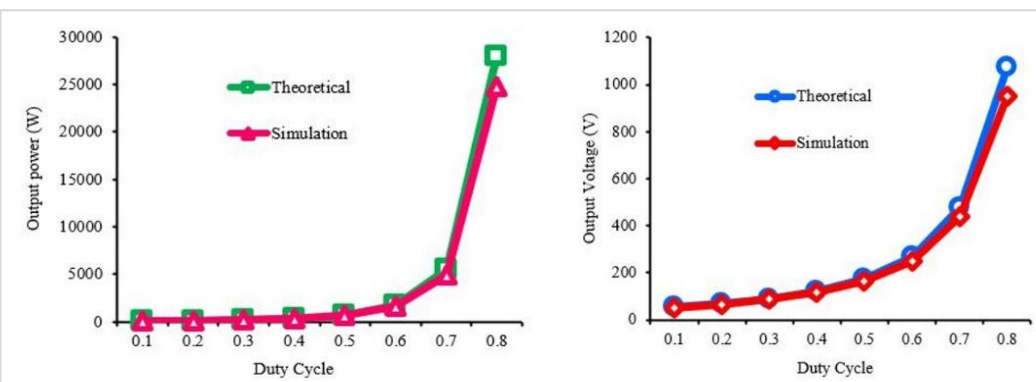


Figure 14 Comparison of voltage and power

Limitations of our study

From the study of this paper, it seems that the presented high gain converter is restricted to operate in discontinuous conduction mode (DCM). Our preferred converter exhibits maximum gain of 25 for the duty ratio of 0.8. Henceforth, it is not possible to operate the switch at maximum duty ratio for a longer time. Our future scope is to modify this topology to exhibit high gain at minimum duty cycle.

A complete list of abbreviations is shown in *Appendix I*.

6. Conclusion and future work

This scope has shown the investigation of the solar powered DC converter with its specific highlights, comparison of different MPPT controllers and Simulink results for the preferred system. The favored converter produces maximum lifted voltage gain of up to 25 for the maximum duty ratio of 0.8. This converter consolidates lesser number of components that leads to simpler circuit. This topology caters merits like high voltage gain, high efficacy, and minimal cost with reduced switch burden. Potency of the proposed strategy is scrutinized and compared with standard P&O and FLC based MPPT. ANFIS based intelligent controller proffers faster tracking speed, higher output stability and robustness. The execution of the sun-powered system is reenacted for consistent irradiation and step change in insolation levels. This intelligent technique is competent to track the MPP aptly, when compared with other classical techniques of MPPT. The efficiency is achieved around 98%. Inevitably, the ANFIS based tracking schema for sun-powered converter is prudent for green energy and DC micro grid applications. However, this topology is limited to CCM operation. The proposed converter can also be modified and recent optimization techniques will be implemented in future.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

S. Narthana: Conceptualization, investigation, data curation, writing – original draft, writing – review and editing. **P. Muthu Thiruvengadam:** Data collection, conceptualization, writing – original draft, analysis and interpretation of results. **J. Gnanavadivel**: Data collection and design. All authors reviewed the results and approved the final version of the manuscript.

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Appendix I

S. No.	Abbreviation	Description
1	ANFIS	Adaptive Neuro-Fuzzy Inference System
2	ANN	Artificial Neural Network
3	ASL	Active Switched Inductor
4	CCM	Continuous Conduction Mode
5	DCM	Discontinuous Conduction Mode
6	DC	Direct Current
7	FLC	Fuzzy Logic Controller
8	GWO	Grey Wolf Optimization
9	HSC	Hybrid Switched Capacitor
10	I_{PV}	PV Current
11	LCL	Inductive-Capacitive-Inductive
12	MPPT	Maximum Power Point Tracking
13	MPP	Maximum Power Point
14	NIBC	Non-Isolated Boost Converter
15	PI	Proportional-Integral
16	P&O	Perturb and Observe
17	PV	Photo Voltaic
18	P_{PV}	PV Power
19	SC	Switched Capacitor
20	SEPIC	Single-Ended Primary-Inductor
21	SL	Switched Inductor
22	SU2C	Step Up Two Capacitor
23	T_{PV}	PV Temperature
24	VMC	Voltage Multiplier Cell
25	V_{PV}	PV Voltage