Fuzzy-Logic-Control Approach of a Modified Hill-Climbing Method for Maximum Power Point in Microgrid Standalone Photovoltaic System

Bader N. Alajmi, Khaled H. Ahmed, Stephen J. Finney, and Barry W. Williams

***Abstract*—A new fuzzy-logic controller for maximum power point tracking of photovoltaic (PV) systems is proposed. PV modeling is discussed. Conventional hill-climbing maximum power-point tracker structures and features are investigated. The new controller improves the hill-climbing search method by fuzzifying the rules of such techniques and eliminates their drawbacks. Fuzzy-logic-based hill climbing offers fast and accurate converging to the maximum operating point during steady-state and varying weather conditions compared to conventional hill climbing. Simulation and experimentation results are provided to demonstrate the validity of the proposed fuzzy-logic-based controller.**

***Index Terms*—Fuzzy-logic controller (FLC), hill climbing, maximum power-point tracker (MPPT), photovoltaic.**

I. Introduction

RENEWABLE energy sources development has attracted research attention, especially after the energy crisis and environmental issues such as global warming and pollution. There has been significant progress in the development of renewable energy sources such as combined heat and power (CHP) applications, solar photovoltaic (PV) modules, small wind turbines, heat and electricity storage, where controllable loads are expected to play a significant role in future electricity supply. Microgrids are defined as systems that have at least one distributed energy source and associated loads and can form intentional islands in the electrical distribution systems [1]. In microgrids, loads and energy sources can be disconnected from and reconnected to the area or local electric power system with minimal disruption to local loads [2]. Microgrid technology offers improved service reliability, better economics, and a reduced dependency on the local utility. Advanced power electronic technology that includes power converters, pulsewidth-modulation (PWM) techniques, control algorithms, and electronic control units are required for the microgrids technology.

The microgrid should be able to operate in both grid-connected [3]–[5] and island modes [6]–[11]. Moreover, the transition between the two modes should be smooth to minimize any sudden voltage or current change between the local loads and the grid. Some control methods have been proposed [12]–[14]. PV systems are considered to be one of the most important renewable energy sources, because they are considered to be an effective and efficient solution to environmental problems [15]. The PV energy source system can operate in grid-connected [16]–[20] or standalone [21]–[24] mode under different loads and system conditions. Grid-connected PV systems are commonly used in a distributed generation system to inject energy into the grid. A standalone PV-based system is economically superior where other sources of energy are impossible or difficult to use, such as in mobile applications, transportation, and satellite systems. Unfortunately, PV systems suffer from three main problems: high fabrication cost, low conversion efficiency especially under variable weather conditions, and the nonlinearity between the PV array output power and current [25].

The PV array power and current characteristics are highly nonlinear and are affected by the irradiance and temperature variation. Therefore, a maximum power-point tracker (MPPT) is required to handle such problems and ensure that the PV system is operating at the maximum power point (MPP) [26]. Many different MPPT techniques have been proposed [25]. The existing techniques vary in simplicity, accuracy, time response, popularity, cost, and other technical aspects.

The voltage base MPP tracking method uses the fact that the ratio between the maximum power voltage and the open-circuit voltage under different weather conditions, are linearly proportional [27]. Since this method is based on an approximation of a constant ratio, the extracted power is most likely to be below the actual MPP, which results in significant loss of the available power. Moreover, this method fails to track the MPP if some of the PV array cells are partially shaded or damaged. A similar MPPT method, called current-based MPPT, has been proposed. This method approximates the ratio between the maximum power current and the short circuit current under different weather conditions [28]. The same limitations and disadvantages as the voltage base MPPT exist with this method.

The incremental conductive method is widely used because of implementation simplicity and high tracking efficiency. The method is based on the derivative of power over voltage being zero at the MPP, positive on the left of the MPP, and negative on the right. Complex computation is required to give good

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B. N. Alajmi, S. J. Finney, and B. W. Williams are with the Department of Electronic and Electrical Engineering, Strathclyde University, Glasgow, G1 1XQ, U.K. (e-mail: bader.alajmi@eee.strath.ac.uk).

K. H. Ahmed is with the Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria 21526, Egypt.

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performance under rapidly varying weather conditions. Moreover, the tracking time is relatively long since the step size is tuned to be small enough to reach the desired MPP [29].

Ripple correlation control (RCC) is an optimization technique that takes advantage of the converter signal ripple to track the MPP [30]. The optimal point is approached by changing the operating current according to its location. The tracking speed is comparatively fast in this method. However, since the differentiators are sensitive to noise and disturbance, the MPP accuracy is poorer than other MPPT methods.

Among the MPPT methods, hill climbing/perturbation and observation (P&O) are the commonly used algorithms because of simplicity, ease of implementation, and low cost [31]. Hill climbing works by perturbing the PV array system by changing the power converter duty cycle and observing its impact on the PV array output power, and then deciding the new direction of the duty cycle to extract maximum power. Similarly, P&O works by perturbing the PV array output current and observing its impact on output power. Many assumed both techniques are the same. The authors in [31]–[33] used duty cycle perturbation but term it P&O. On the other hand, in [34] a comparison between hill climbing and P&O proves that P&O is more efficient, especially under varying weather conditions. In general both techniques use the same concept for optimum operating point searching, but with different control structures.

The fuzzy-logic controller (FLC) has been introduced to elevate P&O or hill-climbing algorithm drawbacks. In most of the fuzzy-based MPPT algorithms [35]–[39], the optimum point is tracked after computing the slope of the power-current characteristic and the slope change. The drawback of this fuzzy controller, as shown in [35], is that the operating point moves away from the maximum point when the irradiance changes, since duty cycle variation is neglected. Therefore, the authors in [36] introduced a fuzzy controller with array power variation and duty cycle as inputs. This technique improves the dynamic characteristics in variable weather conditions; however steady-state error occurs in the PV output power. To improve the dynamic characteristic and power level accuracy, both techniques have been combined [37]. Three inputs are used for the fuzzy controller, the array power derivative over the array current derivative, the change of this derivative, and duty cycle variation. However, practically computing the slope is challenging, especially in a noisy environment. The author in [38] improved the proposed fuzzy-based MPPT method in [35] by adding fuzzy cognitive networks. The tracking speed is significantly improved compared to the conventional FLC; however, requires an additional switch in parallel with PV system and additional current sensor, to compute the short circuit current. Self-tuning fuzzy control for a PV inverter system is proposed in [40]. The scaling factor of both inputs and output are automatically tuned to improve system performance.

In this paper, a fuzzy-logic-based hill-climbing technique is proposed for MPPT in a microgrid standalone PV system. The drawbacks of conventional hill climbing are investigated. The proposed FLC is capable of exploiting the advantages of the hill-climbing searching method but eliminates its drawbacks. The FLC is designed by translating the conventional hill-climbing algorithm into 16 fuzzy rules, after the controller inputs and output have been divided to four fuzzy subsets. Simulation and experimental results are provided to evaluate the effectiveness and robustness of the proposed control method.

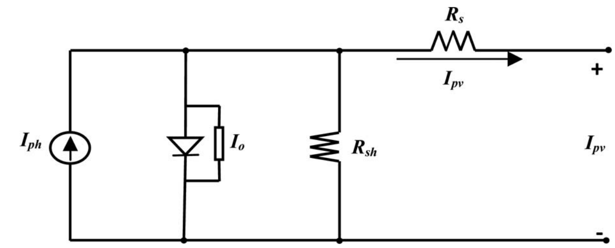


Fig. 1. Equivalent circuit of a PV cell.

II. PV Model

PV array consists of solar cells, where each cell is basically a p-n junction. The equivalent circuit of a solar cell is shown in Fig. 1.

PV array modeling can be implemented from the mathematical model in (1), which is derived from a cell's equivalent circuit where all cells are identical

$$I_{pv} = n_p.I_{ph} - n_p.I_o\left[e\left(\frac{q(V_{pv}+R_sI_{pv})}{AkTn_s}\right)-1\right] - np\frac{(V_{pv}+R_s.I_{pv})}{n_s.R_{sh}} \tag{1}$$

where V_{pv} and I_{pv} represent the PV array output voltage and current, respectively. R_s and R_{sh} are the solar cell series and shunt resistances. q is the electron charge $(1.6 \times 10^{-19}\ \mathrm{C})$; I_{ph} is the light generated current, I_o is the reverse saturation current, A is dimensionless junction material factor, k is Boltzmann constant $\left(1.38x\frac{10^{-23}J}{K}\right)$, T is the temperature (in Kelvin), and n_p and n_s are the number of cells connected in parallel and series, respectively. For a given PV array system, the power–duty cycle (P–D) characteristics under varying weather conditions are shown in Fig. 2.

G is the solar radiation and T is the absolute temperature. As shown in Fig. 2, the optimum power points are located at a specific duty cycle that varies according to weather conditions. Therefore, either direct or indirect coupling can be used to operate the PV array at its optimum power point. In direct coupling, the PV array is directly connected to the load and periodic fine-tuning is required [41]. In the other method, indirect coupling, automatically tracking of the optimum operating point is facilitated by connecting a power converter between the PV array generator and the load. The power converter switch is controlled by MPPT algorithm to draw array maximum output power.

III. Conventional Hill-Climbing Technique

Hill climbing operates by perturbing the system by changing the power converter duty cycle and observing its impact on the array output power. The hill-climbing MPPT method is the most commonly used algorithm in practice because of simplicity,

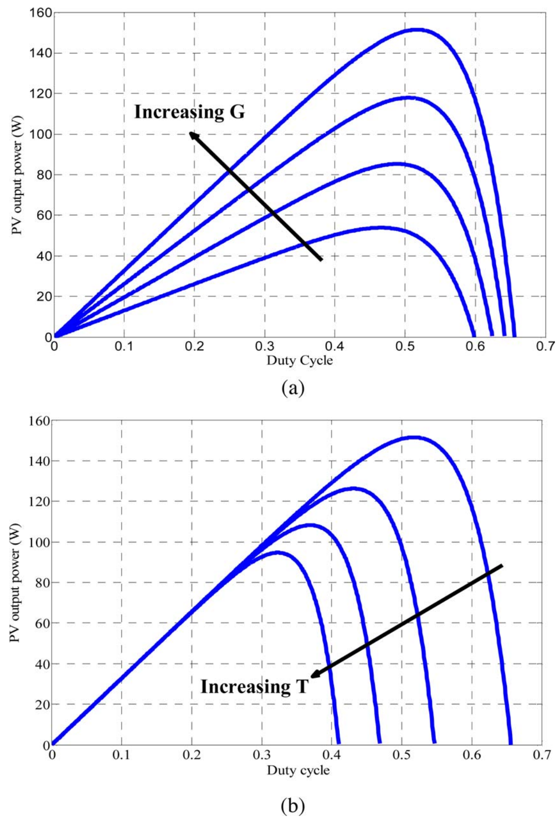


Fig. 2. Influences on P–D characteristics by (a) solar radiation (G) and (b) temperature (T) influence.

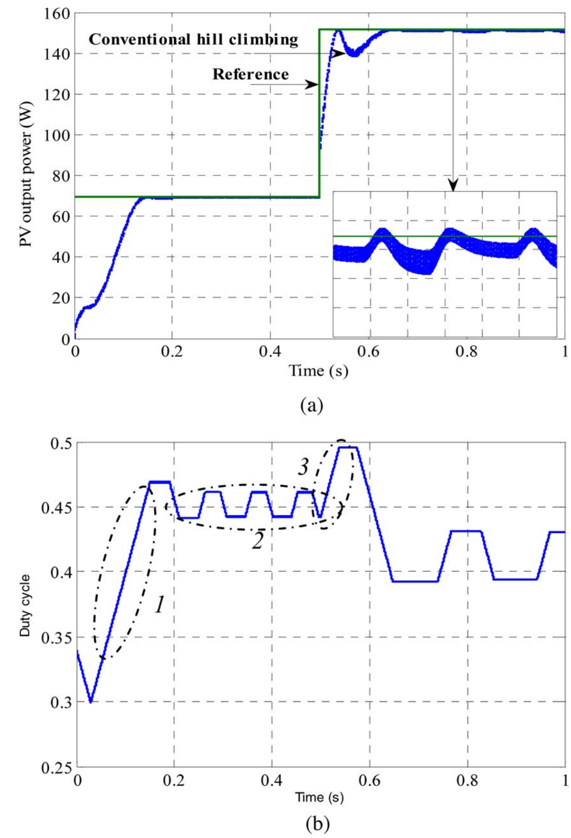


Fig. 3. Drawbacks of the hill climbing method: (a) PV output power and (b) duty cycle.

easy implementation, and low cost. However, it has three major drawbacks.

1) Slow converging to the optimum operating point.
2) At steady-state condition, the amplitude of the PV power is oscillates around the maximum point that causes system power losses.
3) During cloudy days when the irradiance varies quickly the operating point moves away from the maximum optimum point.

Fig. 3 is introduced to visualize the behavior of the PV system controlled by the conventional hill-climbing MPPT. In Fig. 3(a), the PV output power is forced to move toward the optimum point by a hill-climbing algorithm. After reaching the optimum point, the PV output oscillates around the MPP. At 0.5 s, the solar radiation is changed from $0.5\frac{kW}{m^2}$ to $1\frac{kW}{m^2}$, therefore the power moves to the new optimum point. The controller output in Fig. 3(b) is used to verify the aforementioned drawbacks of the hill-climbing algorithm. Ellipse 1 shows the required time for the controller to compute the optimum duty cycle, ellipse 2 shows the duty cycle oscillation around the optimum value, and ellipse 3 shows the duty cycle divergence from the optimum value.

Several techniques have been addressed in the literature to improve hill climbing. In [42], a technique has been developed to overcome oscillation around the MPP by optimizing the sampling time rate according to the converter's dynamics. A similar technique was implemented in [31] by customizing the duty-cycle perturbation magnitudes to the dynamic behavior of a specific dc–dc converter, to realize the adaptive algorithm. The second drawback with the hill-climbing algorithm is greatly reduced in [31] and [42]; however, the first and the third drawbacks remain in both proposals. Moreover, to improve hill-climbing performance, Weidong and Dunford [43] proposed an adaptive-based controller to enhance the steady-state and converging-speed performance. At steady state, the incremental step is small and during a transient stage the incremental step size is large. The following equation is used to tune the incremental step:

$$a(k) = M\frac{|\Delta P|}{a(k-1)} \tag{2}$$

The drawback of (2) is that M requires manual tuning for different radiation levels and PV system, which makes it commercially impractical. Femia *et al.* [44] enhanced variable step size techniques by designing a feedback compensator to minimize the oscillation problem. A new MPPT technique, called the β method, is proposed in [45]. This method uses conventional hill climbing and the approximated β MPP method simultaneously to extract the exact MPP. According to Jain and Agarwal [46], the β method offers faster convergence to the MPP than the conventional hill-climbing method. However, such a method depends on PV array configuration parameters, which make it impractical. Adaptive hill climbing has been proposed in [47], where a power window is added to the hill-climbing method.

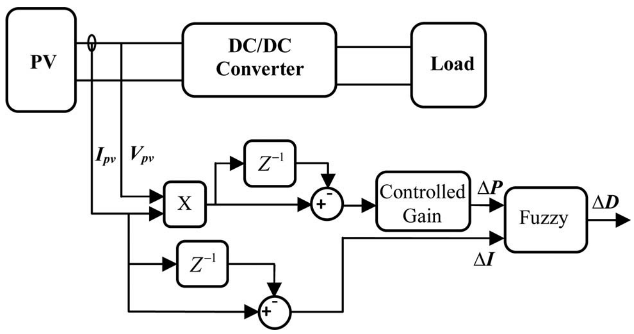


Fig. 4. Block diagram of the PV array system along with the proposed MPPT controller.

The operating point is kept within the window, just below the MPP. Once each iteration loop, the window size is adjusted until the optimum power is reached. In the conventional method, two points (the recent power and the previous power) are compared to choose the direction of the next incremental step. However, Ying-Tung and China-Hong [48] proposed a three-point comparison method, point A is the current operation, point B perturbed from point A, and point C is doubly perturbed in the opposite direction from point B. This method successfully eliminates the oscillation problem; however, slow convergence and divergence problems still exist. An improved perturbation and observation method is proposed in [49]. It is based on an adaptive algorithm, which automatically adjusts the reference step size and hysteresis bandwidth for power comparison. The algorithm shows better steady-state performance and total PV output power increases 0.5% over the classic case, under varying weather conditions.

IV. Modified Hill-Climbing Fuzzy-Based Technique

Modification of the hill-climbing searching method uses a FLC-based algorithm. The proposed controller is designed to take advantage of hill climbing simplicity and eliminate all the mentioned drawbacks. The PV system block diagram, along with the proposed controller, is shown in Fig. 4.

The inputs of the FLC are

$$\Delta P = P(k) - P(k-1) \tag{3}$$

$$\Delta I = I(k) - I(k-1) \tag{4}$$

and the output equation is

$$\Delta D = D(k) - D(k-1) \tag{5}$$

where ΔP is the PV array output power change, ΔI is the array output current change, and ΔD is the boost converter duty cycle change. To ensure that the PV output power does not diverge from the optimum point during varying weather conditions, ΔP passes through a gain controller to reverse its direction. The variable inputs and output are divided into four fuzzy subsets: positive big (PB), positive small (PS), negative big (NB), and negative small (NS). Therefore, the fuzzy rules algorithm requires 16 fuzzy control rules; these rules are based on the regulation of hill-climbing algorithm. To operate the

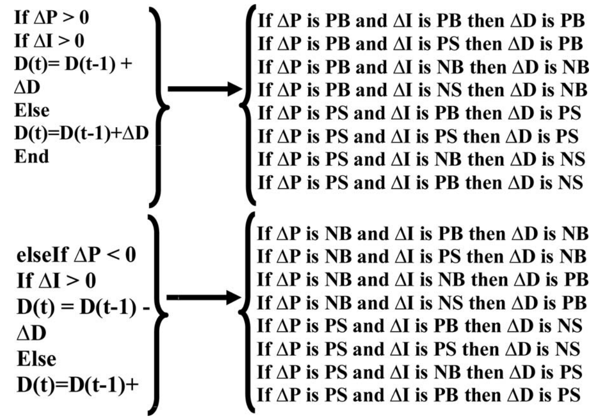


Fig. 5. Fuzzification of modified hill-climbing rules.

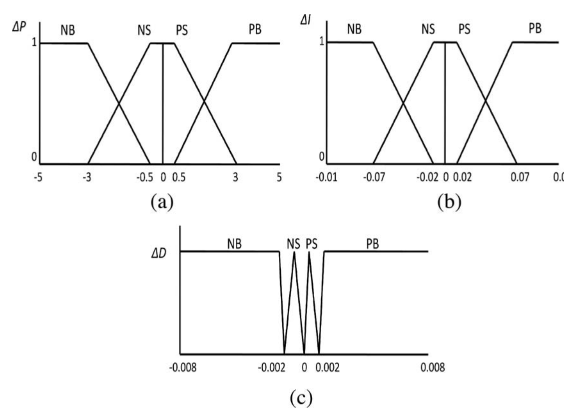


Fig. 6. Membership functions: (a) input ΔP, (b) input ΔI, and (c) output ΔD.

fuzzy combination, Mamdani's method with Max–Min is used. The fuzzifications of the hill-climbing rules are shown in Fig. 5.

After simulating the PV system and studying the behavior of the controller inputs and output, the shapes and fuzzy subset partitions of the membership function in both of inputs and output are shown in Fig. 6.

The last stage of the fuzzy controller is the defuzzification where the center of area algorithm (COA) is used to convert the fuzzy subset duty cycle changes to real numbers

$$\Delta D = \frac{\sum_i^n \mu(D_i) D_i}{\sum_i^n \mu(D_i)} \tag{6}$$

where ΔD is the fuzzy controller output and D_i is the center of max–min composition at the output membership function.

The FLC computes variable step sizes to increment or decrement the duty cycle, therefore the tracking time is short and the system performance during steady-state conditions is much better than with conventional hill-climbing algorithm. Moreover, divergence problem no longer exist since the controller input, change of power (*dP*), reverses its direction in response to atmosphere condition variation.

TABLE I
DESIGN SPECIFICATION AND CIRCUIT PARAMETERS

Item	Value
PV array rated Power, *P(W)*	150
Boost inductor, *L (H)*	0.3
Smoothing capacitor, *C (mF)*	2
Output voltage, *V (V)*	85
Switching frequency, f_s *(kHz)*	4

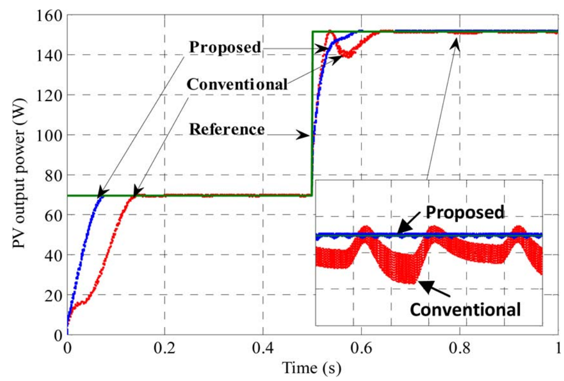


Fig. 7. PV output power characteristic for conventional and the proposed modified hill-climbing method.

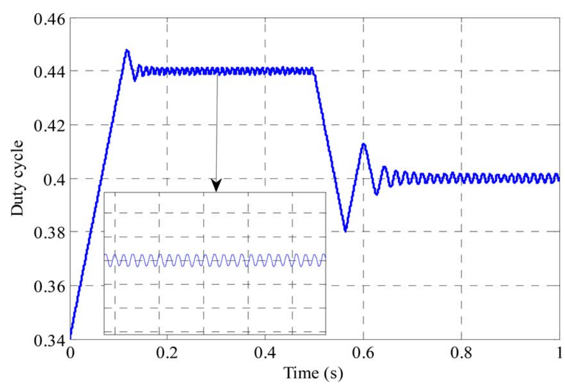


Fig. 8. Advantages of modified hill-climbing based on FLC.

V. RESULTS AND DISCUSSION

The tested PV array is composed of three series models with rated power of 150 W, where the design specification and circuit parameters are shown in Table I. Fig. 7 shows a comparison of the PV output power characteristics that demonstrates the effectiveness of the proposed FLC compared to conventional hill climbing.

From Fig. 7, the proposed MPPT performs better than conventional hill climbing. The proposed MPPT convergence time is faster, has no oscillation at steady state, and the MPP is directly extracted under varying weather conditions.

To verify the advantages of the proposed controller, Fig. 8 represents the controller output, which is the duty cycle against time. The optimum duty cycle is reach within an acceptable time and the oscillation around the optimum value is small compared to the hill-climbing algorithm. Moreover, during solar radiation changes, the duty cycle moves toward the optimum value.

The first two drawbacks of the hill-climbing searching method are inherently eliminated via the FLC, since the increment and

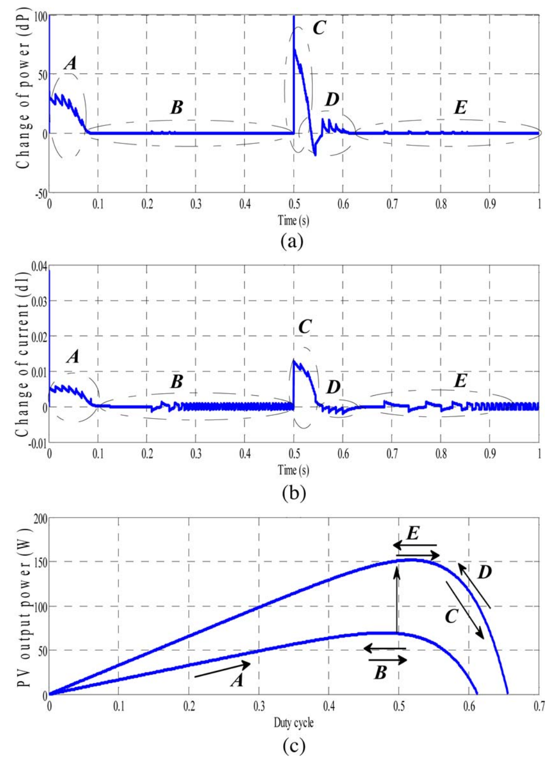


Fig. 9. Power direction of PV array system under varying irradiance: (a) power change. (b) Current change. (c) P–D characteristic under two different irradiance conditions.

decrement step size is varied according to the location of ΔP and ΔI. The fuzzy rules force the step size to increase as long as the system is operating away from the optimum point and vice versa. However, the third drawback remains, where the explanation of the phenomena can be understood from Fig. 9, which represents the behavior of the FLC inputs and output at different operation periods; namely initial, steady state and under new weather conditions at both initially and in steady state.

In Fig. 9, during period A, the change of power and current is PB; therefore, the change of duty cycle is also PB. As the PV power reaches maximum power, during period B, both the changes of power and current are almost zero; therefore, the change of duty cycle is very small, approaching zero. During varying weather conditions, the PV operating power moves from period B to C and continues to move until the change of power becomes negative, period D, at which point the control system detects that operation is diverging from the MPP. Therefore, the duty cycle change is reversed to the correct direction, to reach period E, which is the maximum operating point.

By inspection, ΔP becomes (PB) under two conditions only: initial system operator and varying weather conditions. Therefore, to prevent diverging from MPP, the sign of ΔP should only be reversed under varying weather conditions. Therefore, the proposed FLC has a controlled gain on the fuzzy ΔP input. The controlled gain neglects the first "PB" value of ΔP since this represents the initial operating condition; subsequently, the controlled gain will change the ΔP sign to negative. In this

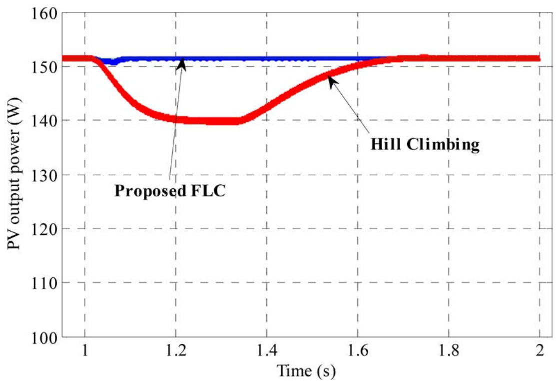


Fig. 10. Proposed and conventional technique responses during load change.

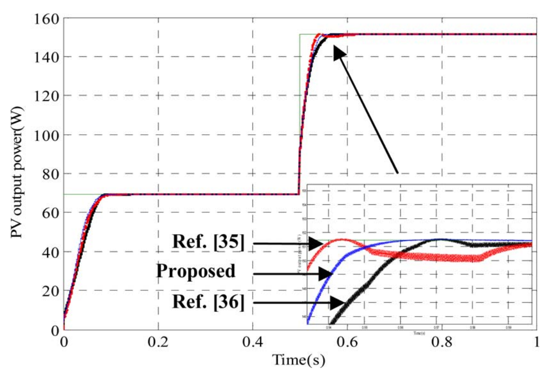


Fig. 11. Simulation results of the propose technique and two other existing fuzzy tracker.

case, the power direction shown in Fig. 9(c) will move from B directly to D under irradiance changes.

The load-variation effect on the PV output power for the proposed technique and the conventional hill-climbing technique is verified in Fig. 10. Unlike conventional hill-climbing, the proposed technique is not significantly affected by the load variation since the FLC quickly locates the new optimum duty cycle. On the other hand, conventional hill climbing tracks in the wrong direction for the new optimum duty cycle for some time; then corrects its direction.

To validate the robustness of the proposed technique, the comparison in Fig. 11 between the proposed method and two other existing FLCs is presented. All techniques provide a good tracking speed and less variation around the MPP. However, during varying weather conditions, the FLC in [35] miss to track the new optimum point, which could result in failing to track the MPP under quickly varying weather conditions. Moreover, the FLC functions by computing the PV power derivative over the current derivative and the change of the derivative as inputs, which could result in a difficulty in practical implementation of the controller, especially in a noisy environment. The FLC in [36] is proposed to improve the MPPT dynamic performance under varying weather conditions in [35], by considering the duty cycle in the FLC input. Nevertheless, the tracking accuracy is limited, as shown in Fig. 11. Further validation of the considered techniques is shown in Table II by comparing the proposed technique with existing FLCs for MPPT. As shown

TABLE II
COMPARISON BETWEEN THE PROPOSED ALGORITHM AND THE PREVIOUS LITERATURE

	Dynamic performance	Tracking accuracy	Number of Fuzzy rules	Execution speed time	Practical validation
Proposed	Good	Good	16	Low	Yes
[35], Won	Bad	Good	25	Medium	Yes
[36], Simoes	Good	Bad	15	Low	Yes
[37],Masoum	Good	Good	74	Large	Yes
[38], Kottas	Good	Good	25	High	No
[39], Cheikh	Good	Good	25	Medium	No

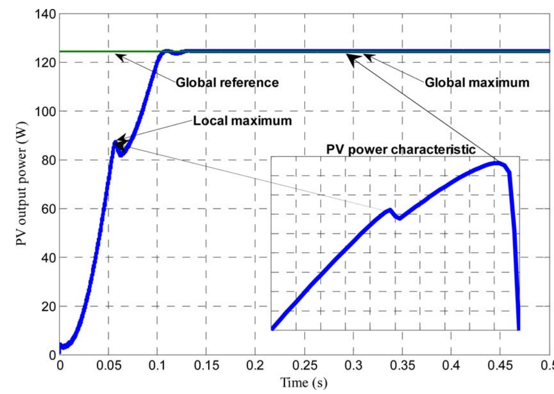


Fig. 12. Simulation result of the propose technique under partial shadowing conditions.

in Table II, the proposed technique gives good tracking speed, small oscillation, good accuracy, fewer fuzzy rules, and no PI controller is needed.

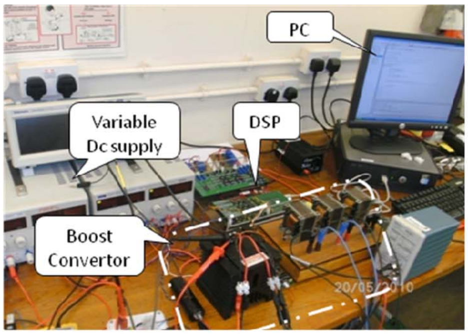
A. Partial Shadow

Partial shadowing is expected in PV arrays, where the radiation intensities are unequally distributed around the PV module or some parts of the PV module go out of service. Under partial shadowing conditions, multiple maxima exist in the PV power characteristics; therefore, the proposed method, as well as conventional hill climbing and existing fuzzy-logic-based controllers, tracks one of these maxima. However, the proposed method can track the global maximum by increasing the search range; however, a wider search range will cause a significant loss in power. The effect of partial shadow on the PV output power for the proposed technique is shown in Fig. 12.

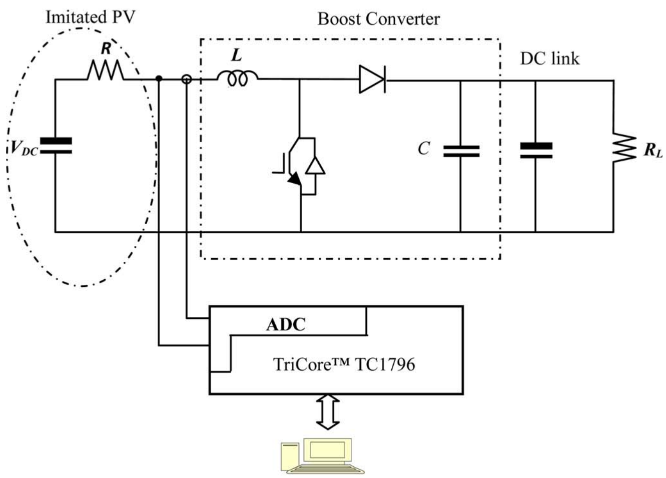
By increasing the scale factor, the first maximum point is ignored to search for any other maxima; otherwise, the operating point returns back to the first maximum. As shown in Fig. 12, the controller makes a wide search of the PV power locus, and then locates the global maximum, with a small oscillation.

VI. EXPERIMENTAL RESULTS

The performance of the proposed fuzzy-logic-control approach is verified experimentally with the configuration shown in Fig. 13. The system consists of a variable dc supply in series with variable resistor and a dc–dc boost converter with a 4 kHz switching frequency. The PV source is emulated by a DC voltage supply plus a series resistor, where in the DC supply voltage level changes represent the radiation variation and temperature variation is represented by changing the resistor value.

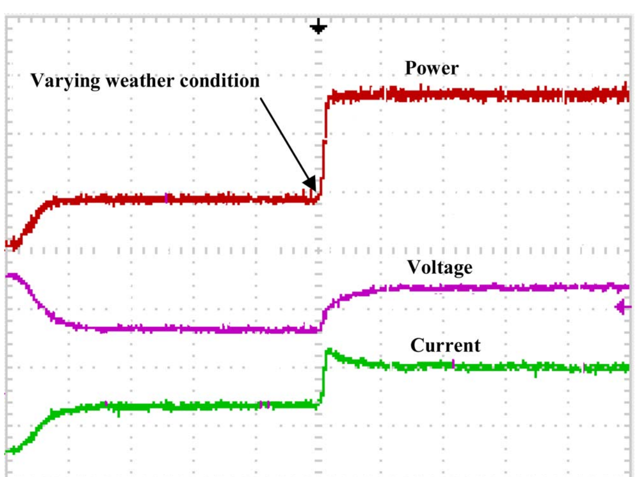


(a)



(b)

Fig. 13. (a) Test rig photograph, and (b) hardware diagram arrangement.

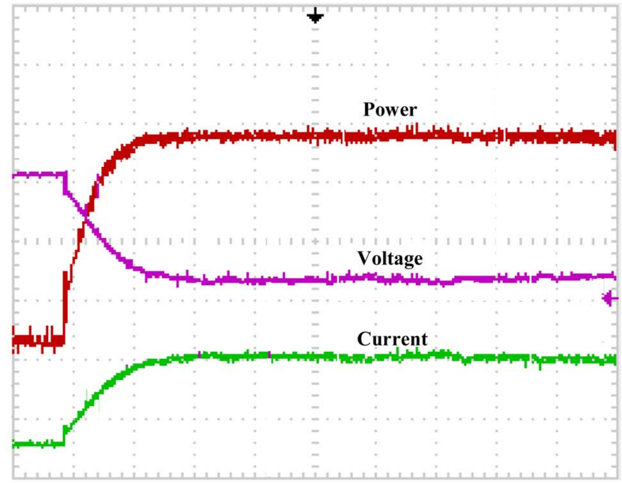


Time: 5s/div, P_o: 10 W/div, V_o: 10 V/div, i_o: 1 A/div

Fig. 14. Experimental results of the proposed MPPT.

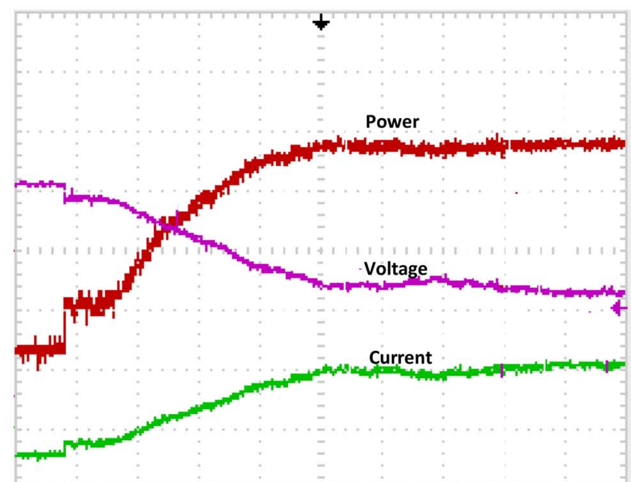
An Infineon TriCore TC1796 is used to realize the proposed controller.

The experimental system is tested under different stepped operating conditions. Fig. 14 shows the result of the proposed MPPT. In each operating condition, the MPP is attained in a relatively short time and has a small oscillation in steady state. Moreover, when the weather conditions are changed, the proposed FLC forces the power to move directly to the new optimum point.



Time: 5s/div, P_o: 5 W/div, V_o: 10 V/div, i_o: 0.5

(a)



Time: 5s/div, P_o: 5 W/div, V_o: 10 V/div, i_o: 0.5

(b)

Fig. 15. Experimental results: (a) proposed MPPT, and (b) conventional hill-climbing MPPT method.

The practical results of the proposed MPPT and the conventional hill climbing are shown in Fig. 15(a) and (b), respectively. The responses in Fig. 15(a) confirm the effectiveness of the proposed MPPT method over hill climbing. It is observed that the maximum power in the proposed MPPT is obtained faster and has smaller oscillation than with conventional hill climbing.

VII. Conclusion

In this paper, the hill-climbing search method has been modified based on fuzzy logic control for MPPT under rapidly changing weather conditions. The proposed MPPT approach was implemented by fuzzifying the rules of hill-climbing search methods to reduce its drawbacks, with a relatively simple approach. Simulink model and practical experiments were used to verify the outcome of both conventional hill-climbing and the proposed approach. The results of the proposed MPPT exhibit a faster converging speed, less oscillation around the MPP under steady-state conditions, and no divergence from the MPP during varying weather conditions. The feasibility and effectiveness of the proposed method were evaluated with different simulation studies and compared with the existed FLC MPPT techniques.

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Bader N. Alajmi received the B.Sc. and M.Sc. degrees from the California State University, Fresno, in 2001 and 2006, respectively. He is currently working toward the Ph.D. degree in electrical engineering in the Electrical and electronic Department, Strathclyde University, Glasgow, U.K.

His research interests include digital control of power electronic systems, microgrids and distributed generation, photovoltaic inverters, and dc–dc converters.

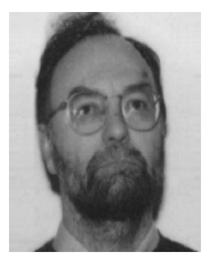
Khaled H. Ahmed received the B.Sc. (first-class honors) and M.Sc. degrees from the Faculty of Engineering, Alexandria University, Alexandria, Egypt, in 2002 and 2004, respectively, and the Ph.D. degree in electrical engineering from the Electrical Department, Strathclyde University, Glasgow, U.K., in 2008.

Since 2009, he has been a Lecturer at the Alexandria University. He has authored or coauthored more than 21 technical papers in refereed journals and conferences in the past 3 years. His current research interests include digital control of power electronic systems, power quality, microgrids, and distributed generation.

Dr. Khaled is a reviewer for the IEEE Transactions and several conferences.

Stephen J. Finney received the M.Eng. degree from Loughborough University of Technology, Loughborough, U.K., in 1988, and the Ph.D. degree from Heriot-Watt University, Edinburgh, U.K., in 1995.

For two years, he was with the Electricity Council Research Centre Laboratories, Chester, U.K. He is currently a Reader at Strathclyde University, Strathclyde, U.K. His current research interests include soft-switching techniques, power semiconductor protection, energy recovery snubber circuits, and low-distortion rectifier topologies.



Barry W. Williams received the M.Eng.Sc. degree from the University of Adelaide, Adelaide, SA, Australia, in 1978, and the Ph.D. degree from the Cambridge University, Cambridge, U.K., in 1980.

For seven years, he was a Lecturer at the Imperial College, University of London, London, U.K. In 1986, he was appointed as the Chair of electrical engineering at Heriot-Watt University, Edinburgh, U.K. He is currently a Professor at University, Strathclyde, U.K., where he is engaged in teaching power electronics (in which he has a free internet text) and drive systems. His current research interests include power semiconductor modeling and protection, converter topologies, soft-switching techniques, and application of ASICs and microprocessors to industrial electronics.