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Design and Hardware Implementation of New Adaptive Fuzzy Logic-Based MPPT Control Method for Photovoltaic Applications

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ABSTRACT An adaptive fuzzy logic (FL)-based new maximum power point (MPP) tracking (MPPT) methodology for controlling photovoltaic (PV) systems is proposed, designed, and implemented in this paper. The existing methods for implementing FL-based MPPTs lack for adaptivity with the operating point, which varies in wide range in practical PV systems with operating irradiance and ambient temperature. The new proposed adaptive FL-based MPPT (AFL-MPPT) algorithm is simple, accurate, and provides faster convergence to optimal operating point. The effectiveness and feasibility verifications of the proposed AFL-MPPT methodology are validated with considering various operating conditions at slow and fast change of solar radiation. In addition, the simplified implementation of the proposed algorithm is carried out using C-block in PSIM software environment, wherein the proposed algorithm and system are simulated. Additionally, experimental results are performed using a floating-point digital signal processing (DSP) controller (TMS320F28335) for verifying the feasibility of the proposed AFL-MPPT methodology. The results of simulations and experimental prototypes show great consistency and prove the capability of the new AFL-MPPT methodology to extract MPPT rapidly and precisely. The new proposed AFL-MPPT method achieves accurate output power of the PV system with smooth and low ripple. In addition, the new proposed AFL-MPPT method benefits fast dynamics and it reaches steady state within 0.01 s.

INDEX TERMS DSP controller, energy efficiency, fuzzy logic (FL), MPPT, photovoltaic systems.

NOMENCLATURE

PV GENERATION SIDE

V_{pv}	Output voltage of the PV cell
I_{pv}	Output current of the PV cell
I_{ph}	Photocurrent of the PV cell
I_o	Saturation current of PV cell
V_t	Thermal-voltage of the PV cell
a	Ideality factor of the diode
R_{pm} and R_{sm}	The parallel and series resistances of the PV cell model, respectively
I_{rs}	Reverse saturated current of the PV cell
E_G	The bang-gap energy
V_{OC}	Open-circuit voltage of the PV
I_{SC}	Short-circuit current of the PV
N_S	Number of series cells in solar PV
N_P	Number of parallel cells in solar PV

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BOOST CONVERTER SIDE

V_{in}	Input voltage to the boost converter
V_{out}	Output voltage of the boost converter
D	Duty cycle of boost converter
D_{MPPT}	Duty cycle of boost converter at MPPT
V_{MPPT}	PV panel voltage to the boost at MPPT

P_{MPPT} PV panel power to the boost at MPPT
R_{load} Load resistance of the boost converter

AFL-MPPT CONTROLLER SIDE
P, ΔP The PV power and the change of power to MPPT controller, respectively
V, ΔV The PV voltage and the change of voltage to MPPT controller, respectively
E, ΔE The error and the change of error inputs to the AFL-MPPT controller, respectively

I. INTRODUCTION

Solar energy and other renewables like geothermal, biomass, photovoltaic (PV), and wind energy can minimize the emissions of the CO_2 and other harmful gases resulting from fossil fuel. Recently, the yearly growth rates of PV generation systems have been largely increased attaining total generation of 402 GW in 2017 compared with total generation of 303 GW in 2016. It is expected that the increase PV generation penetration levels continues and achieves between 1760 to 2500 GW by the year 2030 [1], [2]. Being available everywhere, continual decrease in their cost per watt, and environmental friendly have made wide spreading of PV system in comparison with the other renewable energy sources [3]–[5]. Concerns of energy efficiency and better energy harvesting have been arisen in order to maximize their power densities, and to reduce the cost of their generated kilowatt-hour. The most conventional and effective technique for better energy efficiency of PV systems is the maximum power point tracking (MPPT) control [6]. This is due to the fluctuating nature of PV generation. The output power of PV systems is highly dependent on their operating irradiance and ambient temperature.

Several MPPT extraction schemes have been developed in literature, including hill climbing, perturb and observe (P&O), incremental conductance and incremental resistance [7]–[12]. Surveys and comparison between MPPT methods have been introduced in [13]–[16]. The P&O represents the most widely used method because of its simplicity and generality. However, fast tracking has to be compromised with the steady state fluctuations in defining the proper step size for the P&O method. Generally, fixed step size MPPT methods have to consider the trade-off dilemma into consideration [17]. The situation becomes worse in case of fast and continuous changes in the operating environmental conditions, including solar irradiance and ambient temperature. Therefore, several variable step size MPPT methods have been developed for mitigating such dilemma [11]. Although, these methods suffer from dependence of step size on the data of PV panel, which is highly related to environmental operating point.

From another side, smart artificial intelligence (AI)-based schemes, such as the neural network, fuzzy logic (FL), neuro-fuzzy, and genetic algorithms were developed for MPPT extraction and for avoiding the associated problems to fixed and variable step size techniques [15]. Among AI-based MPPT methods, FL has proven itself as an effective solution for such nonlinear PV systems without the need for accurate system data [18]–[21]. In accordance, enhancing and achieving better performance of FL based MPPT methods has become an important research topic.

Several combinations and design methodologies for FL-based MPPT schemes have been introduced in literature. In [22], the FL was introduced for achieving MPPT of PV systems. The FL control has achieved a good operation of MPPT compared to conventional methods. A modified design of FL control has been proposed in [21] by using convergent distribution type of the membership functions (MFs) instead of the symmetrical distribution type of MFs. Higher precision and lower voltage fluctuations have been achieved. Although these design and implementation methods lack for adaptivity with various operating points of PV systems.

From another side, hybrid MPPT methods with FL have been introduced in the literature. These hybrid MPPT methods possess the best features of the combined methods. The FL control was combined with conventional P&O in [23]. A lower overshoot with a stable operation has been achieved. In [18], a combined approach of FL and hill climbing (HC) methods was presented. The FL control has enabled an accurate and better performance rather than conventional HC method. Additionally, dual MPPT method using fuzzy and P&O method was introduced in [19]. This method has achieved a good performance regarding adaptivity with the operating point. However, higher complexity and slower performance are obtained, especially in fast changing irradiance conditions. Additional techniques for FL-based MPPT combined with particle swarm optimization (PSO) have been presented in [24], [25]. The modified sine-cosine optimized MPPT method has been presented in [26] with using adaptive FL method integrated with the sliding mode control. However, their implementations lack for dynamic adjustment of FL membership functions boundaries and type.

The fractional order (FO) was combined with FL MPPT in [20], wherein the robustness of FL is added to the accuracy of fractional order so as to enhance the performance of their tracking efficiency. The alpha factor of fractional order control is set to large or small value based on the dynamic range of the fuzzy controller operation. Therefore, wide or narrow range of the input MFs of the FL controller is obtained through adapting the alpha factor of fractional order control. Nevertheless, the complexity of implementing the fractional order controller limits this type of MPPT controllers. Additionally, there are several complexities in the calculations of the required alpha factor for the PV operating point.

Motivated by the aforementioned weaknesses of existing MPPT methods in the literature, a new adaptive FL-based MPPT (AFL-MPPT) methodology is proposed in this paper. The proposed design and implementation features the high accuracy of extracting MPPT, low fluctuation in the PV voltages, and adaptivity with wide range of operating point of PV systems. Moreover, a simplified implementation of

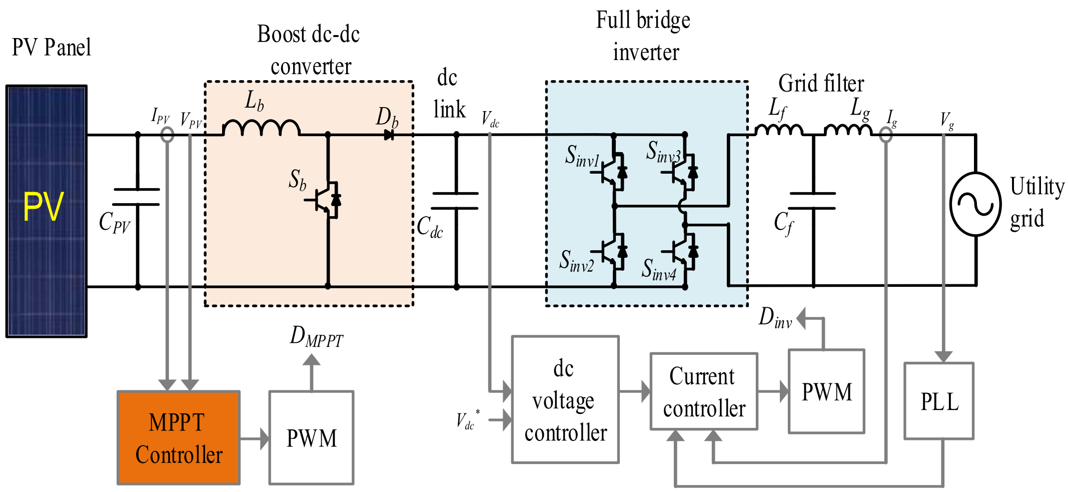


FIGURE 1. Schematic diagram of PV system and control method.

the proposed controller is achieved using PSIM program in order to provide an adaptive scheme of the input MFs of the proposed AFL-MPPT controller.

The main contribution of this paper can be summarized as following:

- A new adaptive MPPT control methodology is proposed, designed, and implemented based on fuzzy logic control method.
- A simplified implementation of adaptive algorithm for fuzzy logic based MPPT method is presented using the C-block programming in PSIM simulation program.
- A generalized implementation of fuzzy logic-based MPPT controllers is presented. The membership functions can be shaped in static or dynamic manner, whether they are symmetrical or asymmetrical types.

The rest of paper is prepared as following: Section II explains various PV system components and its control method. The design procedures for the implementation of the new proposed AFL-MPPT technique are presented in details in Section III. The simulation and experimental obtained results for validating the AFL-MPPT technique under different conditions are introduced in Section IV. The outlines of the research conclusion are highlighted in Section V.

II. DESCRIPTION OF PV SYSTEM

The PV power system (PVPS) is mainly composed of PV panels, which are often connected in series and/or parallel in order to increase their generated voltage and output power. The existing PV systems in the literature can be mainly sectioned into two categories; 1) Single stage-based PV systems, wherein only one dc-ac converter stage is employed; 2) Two-stages-based PV systems, in which series cascaded dc-dc converter stage and dc-ac converter stage are utilized to connect the PV system with the utility grid [27]. According to the various published papers in literature to distinguish and compare the two PV systems, considering efficiency, voltage boost ratio, and system cost, the two stages PV systems are considered in this paper [28], [29]. The configuration of the two stages PV system and controller are illustrated in Fig. 1.

The boost dc-dc power converter represents the first stage, wherein the maximum available energy is harvested from the PV module. The boost power converter possesses the benefits of voltage boosting, less component, and continuous current of the solar PV panel side. The control of this stage is composed of the MPPT and the PWM modulator that transfers the MPPT signal to gating pulses for the boost dc-dc converter.

The full bridge dc-ac converter is usually utilized in the second power stage. This stage is responsible for modulating the dc output of the first stage into ac output to the utility grid. By this process, the extracted maximum power is harvested and injected to the utility grid. The reference current for the current controller is calculated according to the MPPT power in addition to the demanded reactive power by the grid system. Additionally, a phase locked loop (PLL) is employed for synchronizing the PV system with the utility grid. There are several approaches that were developed in the literature to achieve the current control of the dc-ac power inverter stage [30], which is not covered in this paper as it is out of scope of this paper.

The 75-watt PV module is selected in this paper as a case study and the PV module characteristics are tabulated and listed in Table 1. The simulation of the PV panel is performed using PSIM program using 110 series connected solar PV cells. The mathematical models and detailed analysis of PV modeling can be found in [13], [31]. The component and the controller for the first power stage using the boost dc-dc power converter are presented in the following:

A. PV ARRAY MODEL

The single diode-based PV cell model has been widely used in the literature for modeling PV cells, as shown in Fig. 2 [13]. The PV output current I_{PV} can be represented

TABLE 1. PV system parameters employed in the selected case study.

Rated power of PV panel	75 W
Voltage at MPPT (V_{MPPT})	17.6 V
Current at MPPT (I_{MPPT})	3.69 A
Voltage of open-circuit condition (V_{OC})	21.7 V
Current of short-circuit condition (I_{SC})	3.99 A
Number of series cells in solar PV (N_s)	110
Series resistance (R_{sm})	0.008 Ω
Shunt resistance (R_{pm})	1000 Ω
Ideality factor	1.2
Temperature coefficient	0.0004

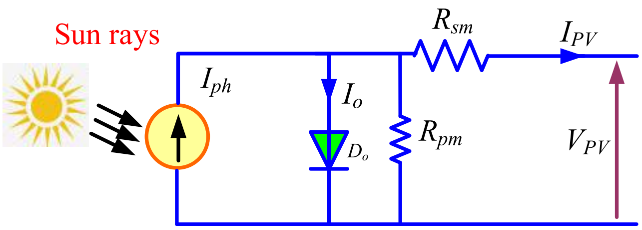


FIGURE 2. Single diode model for PV equivalent circuit.

as fellows [32], [33]:

$$I_{PV} = I_{ph} - I_o \left[\exp\left(\frac{V_{PV} + R_s I_{PV}}{V_t a} \right) - 1 \right] - \frac{V_{PV} + R_{sm} I_{PV}}{R_{pm}} \quad (1)$$

where V_{pv} and I_{pv} denote to the output voltage and current of the cell; I_{ph} and I_o represent the photocurrents and saturation; V_t represents the thermal-voltage of the PV cell; a is the diode's ideality factor. Whereas, R_{pm} and R_{sm} are the parallel and series resistances of the PV cell.

The photocurrent is mostly dependent on the solar PV radiation intensity and the PV cell temperature. It can be formulated as fellow:

$$I_{ph} = \left(I_{sc} + k_i \left(T_c - T_{ref} \right) \right) R \quad (2)$$

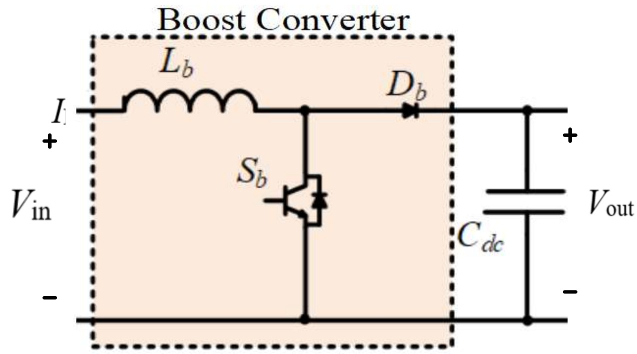
Moreover, the following relation can be used to estimate the diode saturation current [34]:

$$I_o = I_{rs} \left(\frac{T_c}{T_{ref}} \right)^3 \exp\left(\frac{qE_G}{kA} \left(\frac{1}{T_{ref}} - \frac{1}{T_c} \right) \right) \quad (3)$$

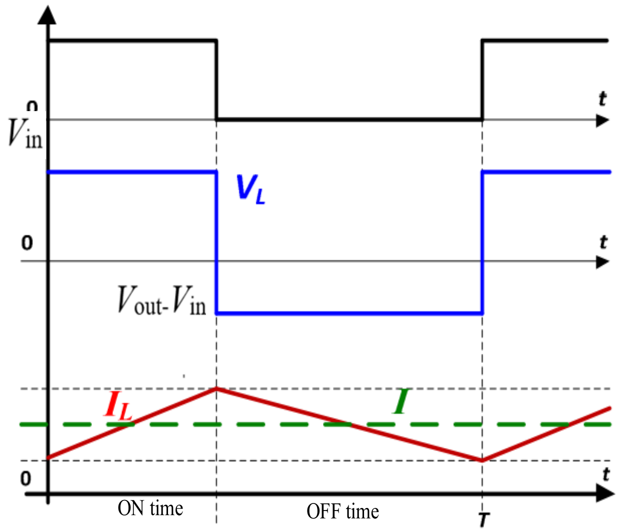
where I_{rs} denotes to the reverse saturated current, and E_G denotes to the bang-gap energy.

B. BOOST DC-DC POWER CONVERTER

Fig. 3(a) illustrates the ideal circuit of the boost dc-dc converter. It is powered by a dc voltage source from the photovoltaic solar panels. The circuit output is controlled through the duty cycle of the power semiconductor MOSFET device, which is controlled through the pulse-width modulation (PWM) [35]. The converter duty cycle D is the most



(a) Circuit



(b) Waveforms

FIGURE 3. Circuit and operation of boost dc-dc converter.

important key element for selecting the boost converter components and for controlling of the dc-dc power converter to maximize the output harvested power of the solar PV system. The output and input voltages are related as following:

$$V_{out} = \frac{1}{1 - D} \times V_{in} \quad (4)$$

where V_{in} denotes to the input voltage to the converter from the PV system, and V_{out} is the output voltage of the boost dc-dc power converter [37]. The duty cycle corresponding to MPPT D_{MPPT} of the boost converter can be estimated as following [36]:

$$D_{MPPT} = 1 - \frac{V_{MPPT}}{\sqrt{P_{MPPT} \times R_{load}}} \quad (5)$$

where, V_{MPPT} denotes to the PV panel voltage that corresponds to MPPT operating point, P_{MPPT} is the PV panel power of at MPPT, R_{load} is the equivalent resistance for the boost power converter output load and D_{MPPT} represents operating duty-cycle for the boost power converter at the MPPT operating point.

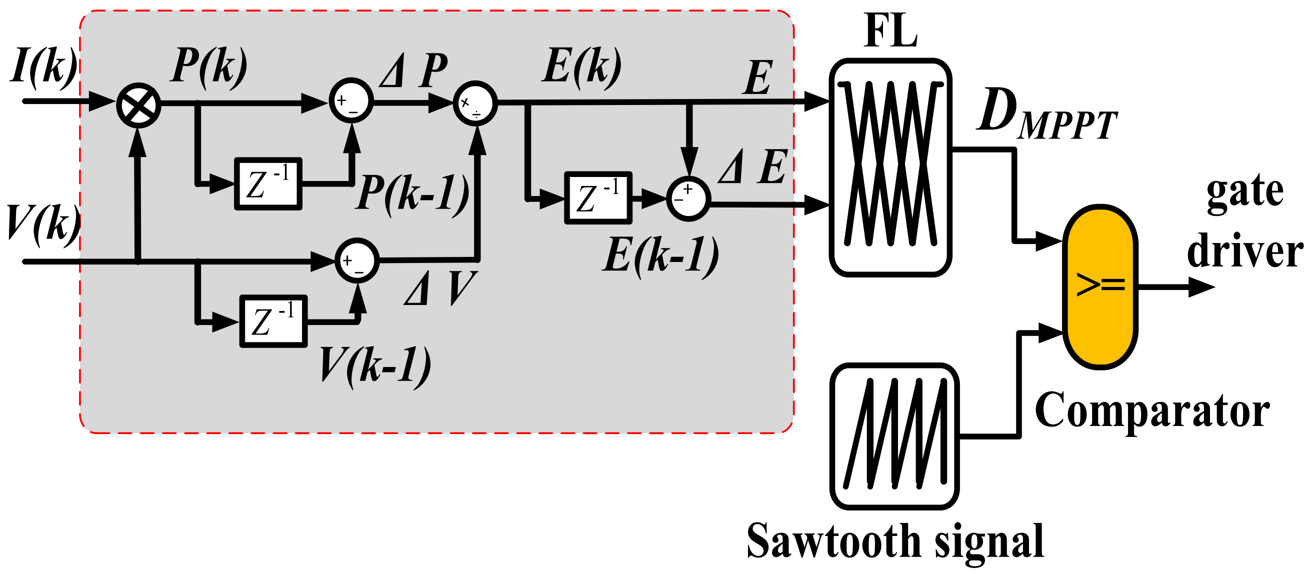


FIGURE 4. Circuit Schematic diagram for the new proposed AFL-MPPT method for PV systems.

III. THE PROPOSED AFL-MPPT METHOD

Employing FL control methods in several applications has been increased because it is simple, does not require data regarding mathematical modeling, and can address the nonlinearity of systems. The nonlinear nature of solar PV panels and the climate conditions result in quite complicated tracking behavior. Therefore, FL-based MPPT methods can be employed for tracking the MPP in the solar PV system with simplified implementation and less required data [21]. There are several FL algorithms have been developed in literature for extracting the MPPT in PV systems [18]–[21].

The operation and design of the FL controller can be summarized by three main stages. These stages include fuzzification, rule evaluation, and defuzzification steps. During the fuzzification stage, the measured changes in the PV output voltage and current are employed for determining the input membership functions (MFs) of the FL-based MPPT controller. The MFs are assigned for each input of the FL controller in order to convert the measured change into suitable inputs for the FL MPPT controller. The number of input MFs, which are assigned to the FL MPPT controller, defines the accuracy of the FL control system. In the rule evaluation stage, the control action is determined based on FLC linguistic rules, which link the logic functions between the input and output MFs. Result of the rule evaluation step is a fuzzy output MF for every type of the consequent action of input MFs. In the defuzzification stage of FL controller, the predictable value of an output MF is obtained and outputted to the rest of the system.

The inputs to the FL MPPT controller include the error (E), and the change of error (ΔE) quantities. The error signal can be estimated as the change in the PV extracted output power divided by the change in the PV output voltage. The error signal and ΔE are estimated, respectively, as follows:

$$E\left(n\right)=\frac{P\left(i\right)-p\left(i-1\right)}{V\left(i\right)-V\left(i-1\right)} \tag{6}$$

$$\Delta E\left(i\right)=E\left(i\right)-E\left(i-1\right) \tag{7}$$

where $P(i)$, and $P(i-1)$ represent the current and previous samples of the PV measured output power, respectively. Whereas, $V(i)$, and $V(i-1)$ denote to the measured current and previous samples of the PV output voltage, respectively. $E(i)$, and $E(i-1)$ represent to the current and previous samples of the error variable, respectively. Then, the E and ΔE values are estimated using the measured output power and voltage of the solar panel based on (6) and (7).

In the proposed AFL-MPPT method, there are two input MFs belonging to the estimated E and ΔE. The variable inputs and output MFs are divided to seven different fuzzy subsets: Pos3 (denotes to Positive and Big subset), Pos2 (denotes to Positive and Medium subset), Pos1 (denotes to Positive and Small subset), Zer0 (denotes to Zero Error subset), Neg1 (denotes to Negative and Small subset), Neg2 (denotes to Negative and Medium subset), and Neg3 (denotes to Negative and Big subset). Therefore, there are total 49 fuzzy control rules in the proposed AFL-MPPT method in implementing the algorithm. Once the proposed algorithm estimates the values of E and ΔE, the FL interface converts these values into linguistic variables. Lastly, the proposed AFC-MPPT method outputs the duty cycle demand as the output MF of the system. The rules that links the input and output MFs for the proposed AFL-MPPT method are shown in Table 2. The schematic diagram for the new proposed AFL-MPPT method is shown in Fig. 4. Fig. 5 shows the three-dimensional (3D) surface (surface function) representation of the input-output MFs for the proposed AFL-MPPT method.

TABLE 2. The FL rules between the input and output MFs in the proposed AFL-MPPT method.

Input MFs		ΔE						
		Neg3	Neg2	Neg1	Zer0	Pos1	Pos2	Pos3
E	Neg3	Neg3	Neg3	Neg3	Neg3	Neg2	Neg1	Zer0
	Neg2	Neg3	Neg3	Neg3	Neg2	Neg1	Zer0	Pos1
	Neg1	Neg3	Neg3	Neg2	Neg1	Zer0	Pos1	Pos2
	Zer0	Neg3	Neg2	Neg1	Zer0	Pos1	Pos2	Pos3
	Pos1	Neg2	Neg1	Zer0	Pos1	Pos2	Pos3	Pos3
	Pos2	Neg1	Zer0	Pos1	Pos2	Pos3	Pos3	Pos3
	Pos3	Zer0	Pos1	Pos2	Pos3	Pos3	Pos3	Pos3

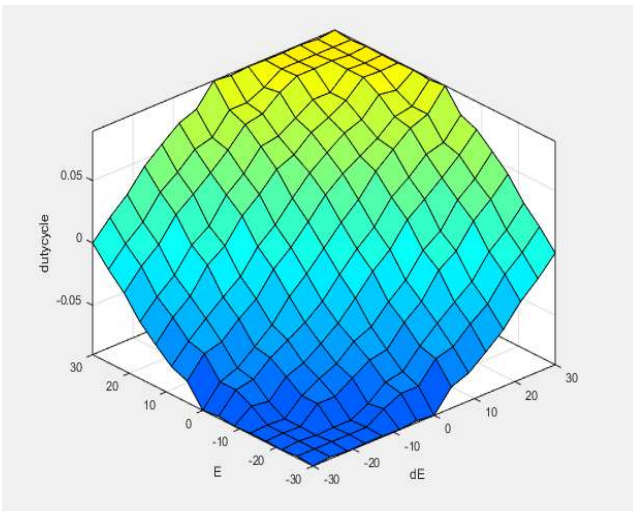
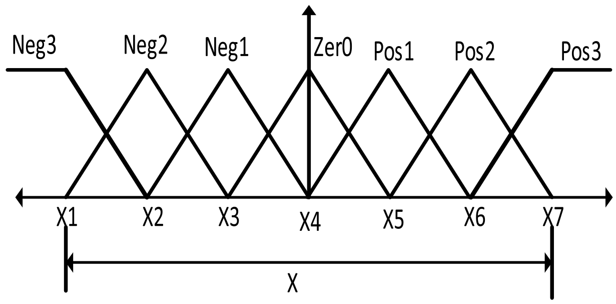


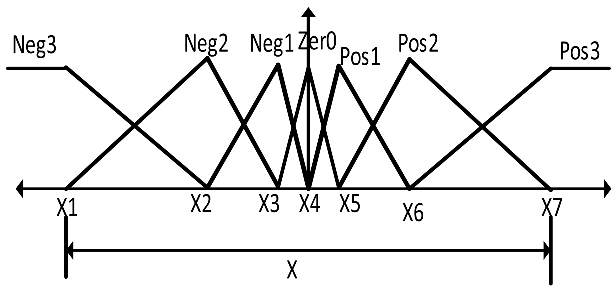
FIGURE 5. Three-dimensional 3D surface function for the proposed AFL-MPPT method.

In the proposed AFL-MPPT algorithm, triangular membership functions are used for both inputs and output MFs due to their implementation simplicity using low cost digital controller systems. Linguistic variables, which are assigned for the ΔD at various combinations of the E and ΔE input MFs, are relying on the rating and type of the employed power converter, in addition to the user knowledge. The last stage of the proposed AFL-MPPT method is the defuzzification, wherein the output of the proposed controller is transformed to numerical output variable using the controller linguistic output variable. The output of this stage is analog signal that denotes to the duty cycle command ΔD for the boost converter.

The output of the fuzzy logic controller is compared with sawtooth triangular signal, and the comparator generates the operating duty cycle for the power converter in accordance. Based on Table 2, there are 49 IF-THEN fuzzy rules have been employed in the proposed AFL-MPPT method to



(a) Symmetrical membership function.



(b) Asymmetrical membership function.

FIGURE 6. The main types of membership functions for the Fuzzy MPPT controller.

describe the relationship relating both the input and output MFs. In case of partial shading condition of series connected PV modules, the new proposed AFL-MPPT method can be integrated with existing global MPPT searching algorithms in literature [24], [37]. The integration of the moth-flame, artificial bee colony (ABC), particle swarm optimization (PSO), ant colony optimization algorithm (ACO), and other optimizers [38], [39] with the new proposed AFL-MPPT method would provide enhanced performance at steady state for global MPPT methods in series-connected PV modules.

Fig. 6 shows the symmetrical and asymmetrical Fuzzy membership function for the inputs and outputs of the Fuzzy controller. The boundaries and shapes of the membership functions in fuzzy logic-based MPPT methods are usually defined by the power level and parameters of the power conversion system. The new proposed implementation using the C-code enables the easy adaptivity of the type of the membership function. In particular, the points X1, X2, ..,X7 can be adjusted in a static or dynamic manner according to the required response. This in turn enables the adaptive implementation for the MPPT controller.

Fig. 7 shows the flowchart of the new proposed AFL-MPPT implementation. In stage 1, the parameters for the new AFL-MPPT control method are calculated using the measured current and voltage of the PV module. In stage 2, the membership functions types and boundaries (X for inputs and Y for outputs) are defined according to the system parameters and the required system response. In stage 3, the estimated parameters and the defined membership

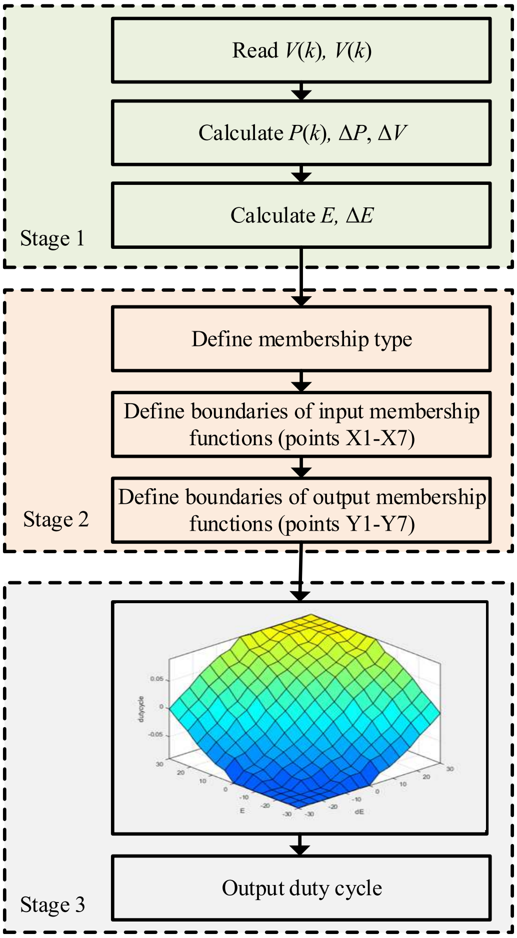


FIGURE 7. The flowchart of the new proposed AFL-MPPT controller implementation.

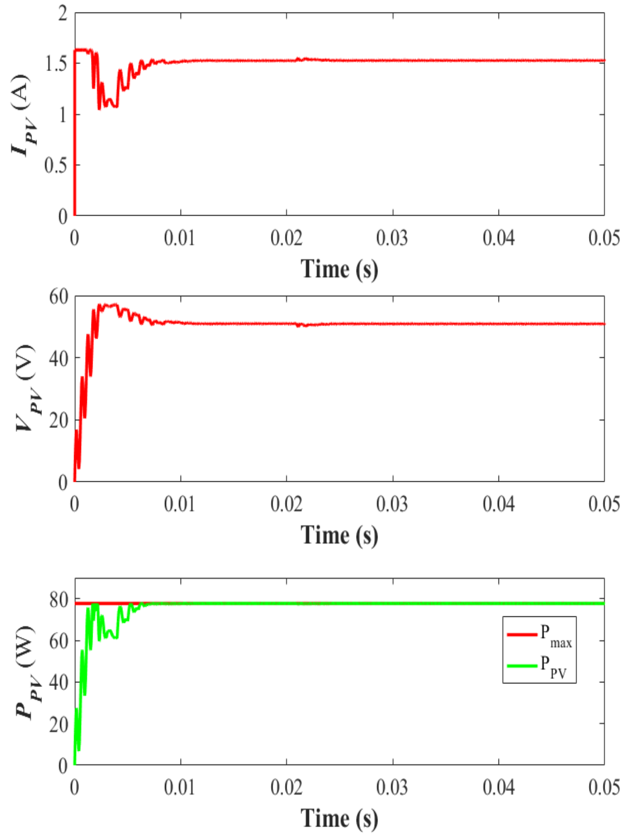


FIGURE 8. Simulation results for the new proposed AFL-MPPT method at transient starting.

functions are fed into the proposed AFL-MPPT controller, which outputs the duty cycle for the boost converter.

IV. RESULTS AND DISCUSSIONS

A. SIMULATIONS RESULTS

Simulation programs and experimental prototypes are employed for verifying the superior performance of the new proposed AFL-MPPT controller for PV systems. The PSIM software is employed for designing and investigating the simulation performance for the proposed AFL-MPPT method. The PVPS, shown in Fig. 1, is simulated using one solar PV panel with 75 W maximum output power. The dc/dc boost power converter is designed so as to operate in the continuous conduction current mode, and the switching frequency is selected to be 30 kHz. The parameters of the boost power converter are as follows: the input inductance L_B is 1 mH, the boost output capacitor C_{dc} is 47 μF, and output load is 50 Ω resistive loads. For achieving MPPT of the solar PV panel, the panel voltage and the current are sensed and employed as inputs for the MPPT controller block, as shown in Fig. 4. The output of the MPPT controller block represents the gating pulse, which is employed for driving the IGBT switch of the boost dc-dc converter.

Firstly, the proposed AFL-MPPT method is tested under the transient response condition at starting the PV systems. Fig. 8 shows the simulated waveforms of the PV output current I_{PV}, voltage V_{PV}, and power P_{PV} at starting from zero irradiance level to 1000 W/m^2 irradiance level. The new proposed AFL-MPPT controller reaches the steady state operating point in less than 0.01 seconds. In addition, it has become clear that the proposed AFL-MPPT tracks accurately the reference maximum output power of the solar PV system. The extracted power in the solar PV system is also smooth without fluctuations in the steady state operating point. This is superior performance for the new proposed AFL-MPPT controller in comparison with the widely used conventional MPPT methods in the literature.

The proposed AFL-MPPT method has been tested at sudden change in the radiance in order to verify its tracking ability of the operating point of the PV system. Fig. 9 shows the simulation results at sudden decrease of the solar PV irradiance from 1000 W/m^2 to 600 W/m^2 at the time of 0.1 seconds. The results show that the new proposed AFL-MPPT achieves fast transient response in addition to accurate tracking for the maximum output power operating point. This in turn verifies the tracking efficiency in the proposed AFL-MPPT for PV systems with fast changing irradiance. The proposed AFL-MPPT achieved low fluctuations at the sudden change

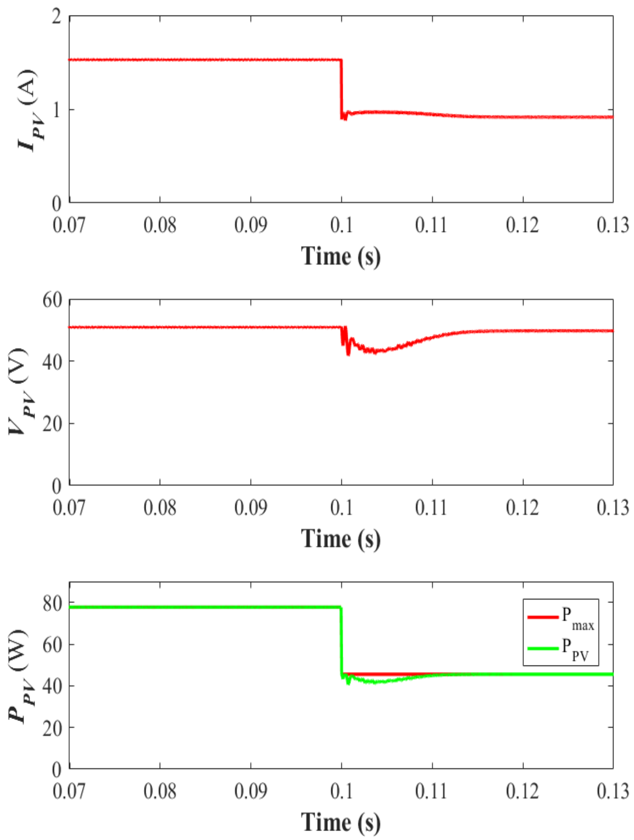


FIGURE 9. Simulation results for the new proposed AFL-MPPT method at step change in the radiance.

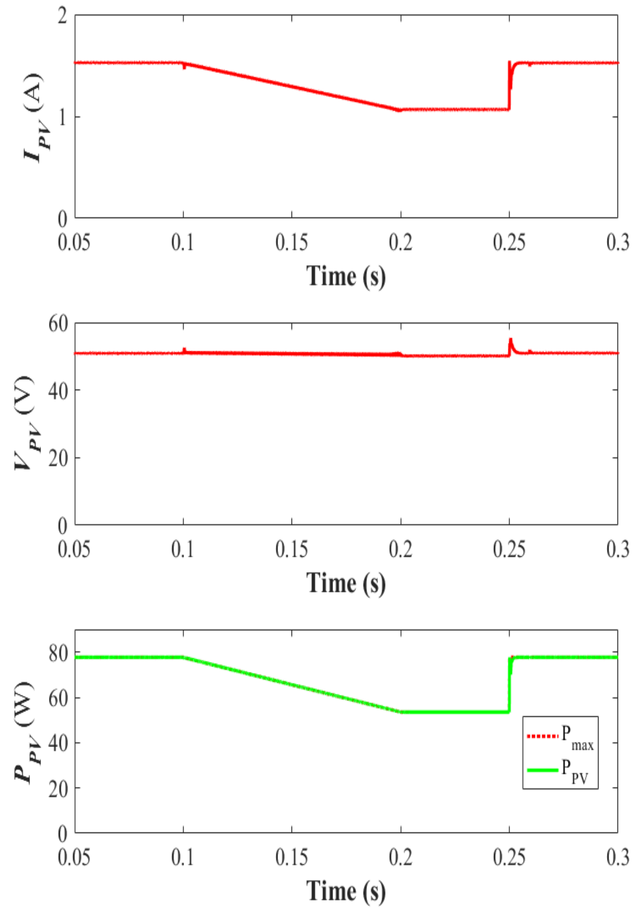


FIGURE 10. Simulations results of the new proposed AFL-MPPT method at slow tracking response of the radiance.

in addition to elimination the power fluctuations at steady state operating point, regardless of the irradiance level.

In several applications, there are gradual increase/decrease of the solar irradiance, which requires proper design of the MPPT algorithm. Therefore, the proposed AFL-MPPT controller has been tested at gradual change of the irradiance, by linear decrease of the solar PV irradiance level from 1000 W/m^2 to 600 W/m^2 in 0.1 seconds. The results in Fig. 10 show that the proposed AFL-MPPT method can track the slow changing irradiance at high efficiency, which makes the PV system capable of producing the maximum available power in the whole operating period of the solar PV system.

The proposed controller can achieve MPPT with eliminating power fluctuations, which disadvantages most of the existing MPPT methods in the literature. In addition, the proposed AFL-MPPT method has been tested at sudden increase of the solar irradiance at time 0.25 seconds from 600 W/m^2 to 1000 W/m^2. It is clear that the proposed controller achieved fast transient tracking of the irradiance increase with high amount in short time. In addition, the proposed controller can mitigate the fluctuated power of the conventional MPPT method. Therefore, the simulations results confirm that the new AFL-MPPT controller and design method achieve fast MPPT with low fluctuations during the steady state. In addition, to the ability to track the various fluctuated operating pointing of practical PV system.

B. EXPERIMENTAL RESULTS

Experimental prototype was developed in laboratory to validate the tracking performance for the new AFL-MPPT method, as illustrated in Fig. 11. The AFL-MPPT controller algorithm has been implemented by using floating point digital signal processor (TMS320F28335) DSP unit. The Agilent PV simulator is used experimentally for emulating the solar PV system and the changes in the irradiance levels. The output voltage and current quantities of the PV system are measured using LEM sensors with LEM LA 50-P, and LEM LV 25-P transducers, respectively.

The new AFL-MPPT controller has been tested experimentally for transient starting operating point with starting solar radiation from 0 W/m^2 level to 1000 W/m^2 level. Fig. 12 displays the obtained experimental results for the new AFL-MPPT controller at transient starting point. It has become clear that the proposed AFL-MPPT controller achieves fast and accurate tracking of the operating point of the solar PV system. The steady state point has been reached after 0.03 seconds with small power fluctuations and stable operation of the system. The results of the transient starting coincide with the simulated test case study of the PV system.

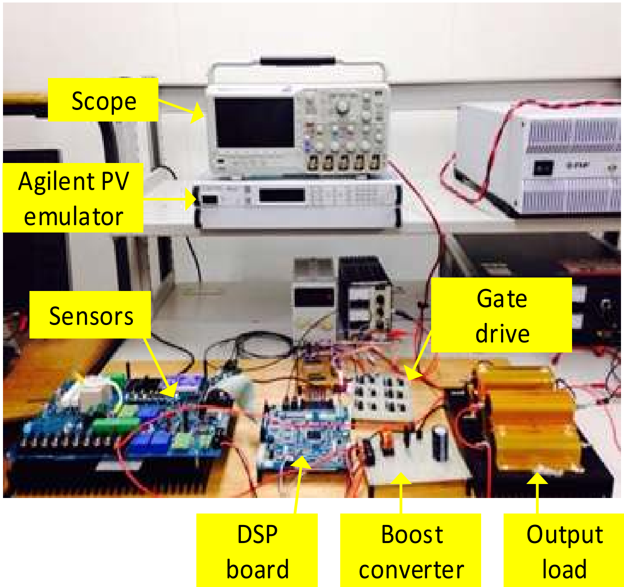


FIGURE 11. Experimental setup of PV system with new AFL-MPPT and controller.

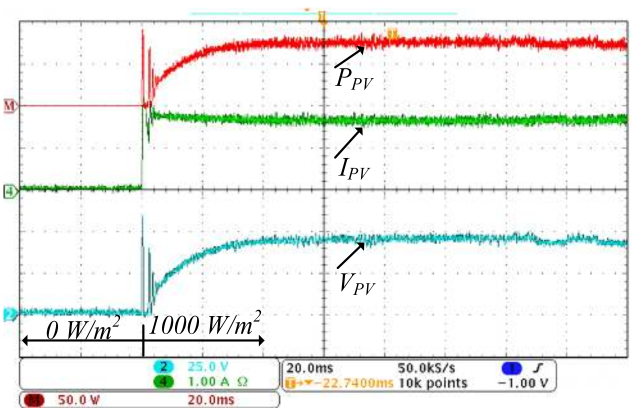


FIGURE 12. Experimental results of the proposed AFL-MPPT method at transient starting.

In addition, the smooth operation with small power fluctuations of the new proposed AFL-MPPT is experimentally investigated. Zoomed-in results of the output power, voltage, and current waveforms of the PV system are illustrated in Fig. 13(a) at steady state 1000 W/m^2 irradiance level. The results confirm that steady state operating performance of the new AFL-MPPT algorithm achieves the maximum theoretical output power for the solar PV system. Moreover, mitigated power fluctuations are obtainable using the new proposed AFL-MPPT method compared to traditional design methods in the literature. Moreover, the stable and prober design of the boost power stage are investigated experimentally. The input and output waveforms of the deigned boost dc-dc converter are illustrated in Fig. 13(b). It can be seen the stepping up ability for the boost converter with low ripple in the output voltage. The proposed PV system and power converter can also achieve stable operation of the PV system.

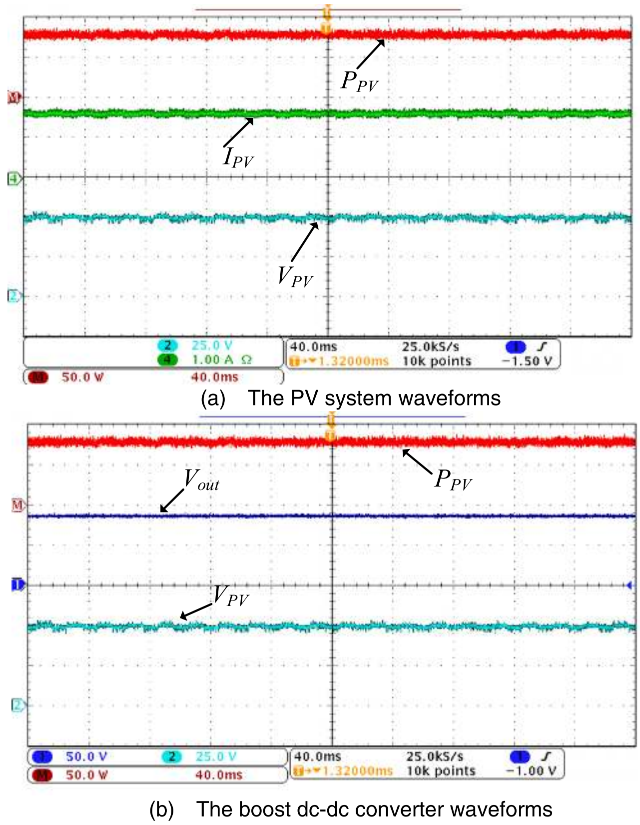


FIGURE 13. Experimental results for the new proposed AFL-MPPT method at steady state irradiance.

TABLE 3. Circuit and PV parameters for the selected case study.

Rated power of PV panel	75 W
PV Simulator	Agilent E4360 PV simulator
Experimental Implementation	(TMS320F28335) DSP unit
Simulation platform	PSIM 11
Boost inductor (L_b)	1 mH
Boost capacitor (C_{dc})	47 µF
Switching frequency (F_{sw})	30 kHz
Load resistance (R_o)	50 Ω
PV capacitor (C_{PV})	10 µF
Current sensor	LEM LA 50-P
Voltage sensor	LEM LV 25-P

The new proposed AFL-MPPT method has been tested experimentally at changing irradiance levels from 1000 W/m^2 to 600 W/m^2 using the Agilent PV emulator. Fig. 14 shows the experimental results of the output voltage, current, and extracted output power of the PV system at different irradiance levels. The new proposed AFL-MPPT controller achieves fast and accurate tracking of optimal operating point. In addition, the proposed controller possesses smooth steady state output performance with eliminating the fluctuated

TABLE 4. Performance comparison of MPPT methods.

Performance	Methodology	Implementation	Generalization	Training necessity	Adaptivity
Ref [15]	Artificial intelligence (AI)-based MPPT	Complex	Sym. / Asym. membership	√	X
Ref [21]	Asym. FL-based MPPT	Simple	Asym. membership	X	X
Ref [22]	Sym. FL-based MPPT	Simple	Sym. membership	X	X
Ref [23]	FL + P&O MPPT	Complex	Sym. membership	X	X
Ref [18]	FL + HC MPPT	Complex	Asym. membership	X	X
Ref [20]	FL + FO MPPT	Complex	Sym. membership	X	X
Proposed	AFL- based MPPT	Simple	Sym. / Asym. membership	X	√

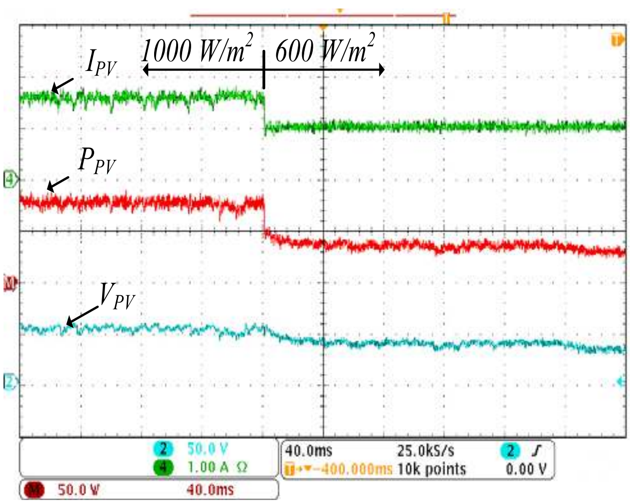


FIGURE 14. Experimental results for the new proposed AFLC-MPPT method at step change in solar irradiance.

power output, which exists in the conventional tracking methods. The obtained experimental results match with the simulated results of the new AFL-MPPT controller for the various test cases and operating conditions.

C. PERFORMANCE COMPARISON

Table 4 presents performance comparison of the new proposed AFL-MPPT with the MPPT methods in the literature based on the fuzzy logic principle. The comparison includes the principle of operation, implementation complexity, application to symmetrical (Sym.) and/or asymmetrical (Asym.) membership functions, training necessities, and adaptivity. In the traditional fuzzy based MPPT methods in the literature, a compromise between the implementation complexity and generalization is required. However, the new proposed AFL-MPPT method benefits simple, accurate and provides faster convergence to optimal operating point. It has become clear that the new proposed AFL-MPPT method possesses superior performance over the existing fuzzy logic methods in the literature.

The main advantages of the new proposed AFL-MPPT controller over the traditional methods in the literature can be summarized as following:

- The new proposed controller is simple, accurate and provides faster convergence to optimal operating point.
- In addition, the simplified implementation of the proposed algorithm is carried out using the C-block, which makes the new proposed algorithm general, and adaptive.
- The shapes of input and output membership functions for the AFL-MPPT method can be adjusted in static and dynamic manner in the proposed algorithm for achieving specific system response.

V. CONCLUSION

This paper presented a new modified controller and design method for FL-based MPPT tracking for PV systems. The new proposed method represents an adaptive FL-based MPPT (AFL-MPPT method). The main advantages in the proposed AFL-MPPT method are accurate and adaptive tracking performance of the operating maximum power extraction point of the solar PV system, and the mitigation of power fluctuations in transient and steady state operating points. Moreover, the proposed AFL-MPPT method achieves faster MPPT convergence with simple implementation. The proposed AFL-MPPT controller can effectively overcome the demerits of the existing MPPT methods in the literature. The proposed AFL-MPPT method has been implemented using C-block in PSIM environment and verified by experimental prototyping of 75-watt PV module. The obtained experimental results coincide with the obtained simulation results, which verify the superior performance for the new proposed control method and design procedures over the conventional MPPT extraction schemes in the literature. The new proposed

AFL-MPPT method benefits high tracking efficiency and fast dynamics by reaching steady state point within 0.01 seconds. Additionally, the new proposed implementation method can be easily integrated with the existing global MPPT searching algorithms.

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