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A novel combined Fuzzy-M5P model tree control applied to grid-tied PV system with power quality consideration

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ABSTRACT

A novel control strategy based on an effective combination of the fuzzy logic controller and the M5P decision tree algorithm (Fuzzy-M5P) for a grid-interfaced solar energy system is proposed in this paper. The aim is to benefit from fuzzy logic advantages using its resulting datasets along with the fast model tree functionality. This mixed control has the ability to cope effectively with the large computation time and complexity of fuzzy logic controllers especially when embedded systems or real-time implementation are considered. Using a photovoltaic (PV) inverter with active filtering capability, the primary objective is to provide a grid-solar topology with a maximum PV energy extraction and power quality enhancement. For the inverter control, the M5P model was tested in the indirect current technique. This harmonic generation method is very efficient and its performances are entirely dependent on the chosen dc-link controller. Moreover, a novel maximum power point tracking technique (MPPT) based on the M5P model tree is performed in which data inputs are collected from fuzzy logic-based MPPT. WEKA and MATLAB software are used to translate the model by formulating a simple hierarchical program structure. To validate the effectiveness of the proposed control, simulation, and experimental tests are done under steady and dynamic conditions. The final developed algorithm based on simple IF-ELSE rules shows promising results, it can reduce harmonic distortions to 2.77%, perfectly compensates reactive power with almost unity power factor, and enhances dynamic performances with fast transient response.

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KEYWORDS
M5P tree algorithm; machine learning; fuzzy logic; PV inverter; MPPT; power quality

Introduction

Fuzzy logic-based controls are widely applied in various domains due to their capability of mimicking human reasoning and judgments. These intelligent techniques have a good ability to handle the inaccuracy and incompleteness of information for nonlinear systems (Sun and Wang 2015). However, their internal complex process of fuzzification and defuzzification especially under real-time conditions presents a serious drawback, which results in a lower speed of implementation and inefficiency in some applications. In recent years, machine learning (ML) systems are seen as alternative solutions to cope with fuzzy logic issues. With high precision, MLs have the capability for classification and prediction using collected datasets of the basic trained model. The learning system with the artificial neural network (ANN) is one of the extensively used methods nowadays due to their timely responses and a good capacity for prediction (Soumya et al. 2021). Decision tree algorithms can fulfill another interesting forecasting solution to serve different purposes of regression and classification. Developed by R. Quilan (Fiedler 2019; Quilan 1992), the M5P algorithm is one of the decision tree models that can interpret systems in the form of a tree chart. Many research as in (Singh, Sihag, and Kumar 2014) and (Bhattacharya and Solomatine 2005) have studied this technique and finished to conclude that the M5P based learning approach can give the same

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performance as the ANN method. This proved robustness for learning from other systems pushed us to build a novel M5P model where the attribute data are extracted directly from the fuzzy controller.

In the last few years, the application of renewable energies has been extended to various engineering fields. Photovoltaic (PV) systems present one of the effective green solutions that offer the possibility of producing free active power in the utility grid. Therefore, the highly convenient way is to feed the dc-link of the voltage source inverter (VSI) via PV sources. These PV inverter systems have been widely adopted using many control strategies for both inverter and MPPT. On the other hand, with the continued enormous growth in the use of nonlinear loads, the crucial issues of power quality are always looming. One of the efficient solutions for enhancing the power quality in these grid-tied PV systems is to integrate the active power filter functionality (APF) (Boukezata and Chaoui 2014). The compensation principle of these harmonic compensators is to inject inverse harmonic components into the grid (Wamane, Baviskar, and Wagh 2013), which results in a sinusoidal source current shape and reactive power compensation (Du et al. 2012). Hence, the PV grid-connected topology is derived based on an active filter structure where the objective is to mitigate harmonics as well as power factor amelioration.

In this paper, the PV inverter is controlled by a modified indirect current technique (Adel, Zaid, and Mahgoub 2011). The simplicity and good correctness to generate harmonic currents are the main advantages of this method. In addition, this control technique is completely dependent on the dc-link controller and has the functional capability to handle dynamic disturbances (Gayadhar et al. 2013). By combining M5P algorithm and FLC, a new control is suggested through a very fast M5P learning approach and fuzzy logic outcomes. A simple MATLAB program using WEKA software and Excel computer tool can translate the final structure. Furthermore, the proposed control is also applied to the maximum power point tracking technique, a novel MPPT-M5P control is thus proposed. The main objective is to provide fast and effective control that allows smooth operation in both steady and dynamic situations. This might be used to replace controllers suffering from complex models and slow real-time implementation.

Literature review

Related works

In 2021, research published in a recognized journal (Chan et al. 2021) shows the effectiveness of combining fuzzy logic and a decision tree. The study focused on the field of computer sciences.

In 2020, the authors of (Mohammed et al. 2020) propose similar research that compares regression performances using the M5P and ANN algorithms. It was found that the training based on the M5P technique is accurate and effective.

In 2018, a new fast MPPT was proposed by the authors of (Blaifi, Moulahoum, and Benkercha 2018). The introduced control operates with the M5P algorithm along with a standalone PV system. Furthermore, an effective comparison has been performed with classical MPPTs.

Review

Recently, grid-connected PV systems have attained more attention and attracted many scholars since these on-grid systems offer many benefits especially their ability to provide free active power to the utility grid. Numerous MPPT techniques are suggested in the literature such as the classical P&O (Sera et al. 2013), the INC method (Hsieh et al. 2013), and the modified teaching MPPT using intelligent approaches based on ANN, ANFIS (Benhalima, Chandra, and Rezkallah 2019), and sliding mode control (Hou, Fei, and Chu Chen Chen 2019). Even though they provide accuracy and effectiveness, their complicated model and their large learning time limit these methods.

For the active filtering system, various strategies have been studied in the literature. The indirect current control (ICC) (Gayadhar et al. 2013), the direct power control (DPC) (Ouchen et al. 2020), the instantaneous active and reactive powers method (PQ), and the synchronous method (SRF) (Musa

Table 1. A review on the basis of recent research that highlights the novelty

Authors and Methods	Advantages	Challenges
Sabir Ouchen et al. (Ouchen et al. 2020) DPC-SVM method and H∞ regulator (2020)	-Offers a good THD value of 3.53%	-Complicated control -A large response time in a transient state
Yap hoon et al. (Hoon et al. 2016) Error deviation control (2016)	-Provides a good power quality of the system	-Suffers from high dynamic response [0.2s, 0.25s]
Azru Turksoy et al. (Turksoy et al. 2018) Adaptive switching method (2018)	-Focuses on the stability of the dc-link capacitor -Small dc voltage ripples	-No consideration of the source current waveform -Without real-time implementation
Sid-ali belaifi et al. (Blaifi, Moulahoum, and Benkercha 2018) M5P-MPPT (2018)	-Fast and efficient MPPT method	-Without grid integration -Need to consider power quality
Seghir Benhalima et al. (Benhalima, Chandra, and Rezkallah 2019) LMS-Adaline based ANFIS (2019)	-Efficient MPPT technique	-Without power quality consideration -Complicated control model -Can take a large time for training data since the ANFIS is employed
Adak S. et al. (Adak, Cangi, and Eid et al. 2021) A developed analytical expression for harmonic current (2021)	-A good THD of source current - High precision	-Complicated mathematical analytical model - No consideration of dynamic operating conditions
Suleiman Musa et al.(Musa et al. 2017) Modified synchronous reference frame control (2017)	-Enhancement of classical SRF using fuzzy logic control	-High THD of source current with 5.07% and 7.4% experimentally

et al. 2017) are the most used to find the reference current. In addition, the dc-link controller plays a very important role in guaranteeing the high performance of previously mentioned algorithms. Initially, the conventional proportional-integral PI based-control is the most used technique. Nevertheless, due to its less dynamic efficiency, other intelligent controllers have been proposed. The fuzzy logic controller (FLC) which was proposed in several research studies is an alternative solution for PI controller drawbacks. However, FLC performance is usually reduced due to its large computation time and complexity especially when embedded systems or real-time implementation needs to be performed. Other machine learning solutions (Benchouia et al. 2015) such as the artificial neural network and adaptive neural inference system prove to have a great significance on the overrunning and stability margin during the dynamic process. A space vector modulation (SVM) based DPC algorithm was proposed by the authors of (Ouchen et al. 2020). Their findings illustrate good harmonic mitigation of grid current with a THD value of 3.53%.

In 2016, the research (Hoon et al. 2016) suggested a new control based on the error deviation with a transient response time between 0.2 s and 0.25 s.

In 2019, LMS Adaline-based ANFIS method was suggested by Seghir Benhalima et al. (Benhalima, Chandra, and Rezkallah 2019), the study needs consideration of power quality and dynamic performance evaluations. Table 1 summarizes the review in light of previous contributions that found relevant results and novelty.

Proposed ML based on decision trees

Basic principle of the M5P algorithm

Decision trees are supervised learning algorithms that can be utilized for classification and regression tasks (Balouchi, Reza Nikoo, and Adamowski 2015). These predictive modeling tools use many algorithmic approaches that split datasets (training data) named 'attributes' in the form of tree charts using decision rules with if-then-else statements.

M5-Pruned is one of the commonly used tree algorithms proposed by Wong (Quilan 1992). Pruning is when removing unwanted branches in order to ameliorate the tree's form. Unlike other tree algorithms, the M5P has the possibility to introduce a linear regression to the classical model according to certain defined parameters.

The aim is to construct a learning model that can use to predict the target value (terminal node) by teaching simple rules inferred from prior collected datasets. Figure 1 shows a basic tree chart where the first attribute represents the root node followed by the splitting process of the node, which results in internal nodes (decision node) and a final leaf node (terminal node) that cannot be divided and holds the class label (nominal output). Many internal nodes are interconnected between to form a subsection called the sub-tree or branch (Onyari and Ilunga 2013).

Trained datasets from FLC

Fuzzy logic is an intelligent approach based on degrees of truth than the classical Boolean logic of true or false. This uncertainty reasoning can describe further types of linguistic variables such as very small, small, medium, and other criteria depending on the studied system. The fuzzy logic controller is one of the most important applications of fuzzy theory. It presents a type of expert system that uses fuzzy logic to make decisions. To solve a specified process problem, FLC uses a knowledge base represented in terms of fuzzy inference rules and fuzzy inference engine. Figure 2 shows the basic structure of FLC which is based on four modules that make up a general fuzzy controller named a fuzzy rule base, a fuzzy inference engine, a fuzzification module that provides fuzzy input sets, and a defuzzification module for producing quantifiable output results. FLC can be approached in two ways: The Mamdani method, Takagi and Sugeno's strategy (Sarabakha, Changhong, and Kayacan 2019). The Mamdani method is based on linguistic fuzzy modeling and is known for its great interpretability and low accuracy, while Takagi and Sugeno's technique uses accurate fuzzy modeling to achieve great accuracy at the expense of interpretability (Rezk and Fathy 2017).

The main process of generating datasets could be realized using the FLC model. Under run conditions with MATLAB/Simulink as shown in Figure 3, three essential parameters are collected: the reference input E, its derived ΔE, and the output signal.

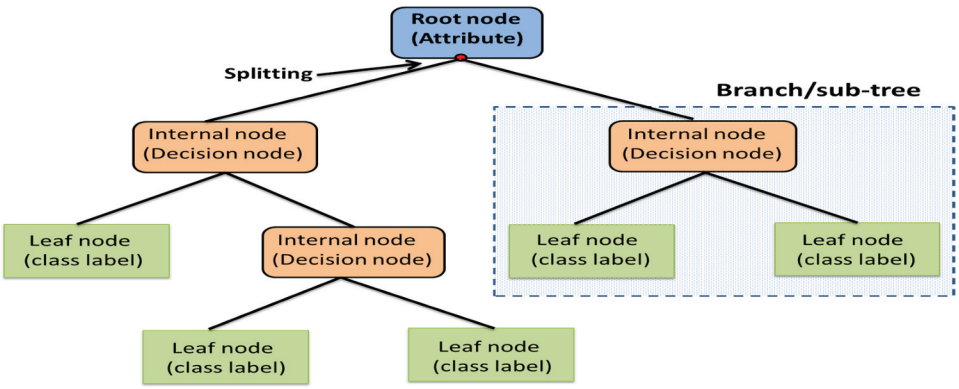


Figure 1. A basic tree chart with different nodes and splitting process

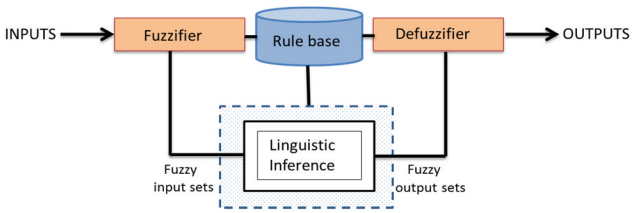


Figure 2. Components of a fuzzy logic controller.

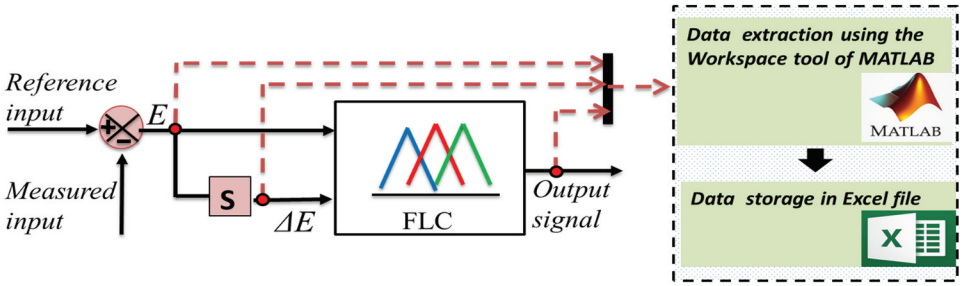


Figure 3. The mechanism of datasets extraction.

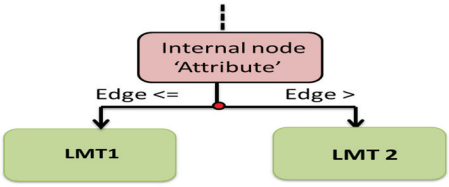


Figure 4. LMT outputs in the tree chart.

Building the proposed control under WEKA software

The proposed control is performed with WEKA software. This workbench can provide an equivalent model structure in the form of trees. As shown in Figure 4, the chosen M5P algorithm reproduces the output results at a called logistic model tree (LMT) (Huang, Wang, and Sun 2020). Figure 5 shows the followed research methodology to design the final MATLAB program (Solomatine 2004).

In order to evaluate the quality of the learning process, many statistical metrics should be taken into account (Balouchi, Reza Nikoo, and Adamowski 2015). The mean absolute error (MAE) is one of the most important accuracy parameters that can be calculated as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|Y_i - \hat{Y}_i\right| \tag{1}$$

Y and Ŷ represent the actual output value and the predicted output value respectively, while n is the number of data points. The root mean square error (RMSE) parameter can also be calculated through equation (2) as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right)^2}{n}} \tag{2}$$

For measuring how well Y (the actual output) is replicated by the training system, the correlation coefficient (R) can be represented mathematically as follows

$$R = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right)^2}{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}} \tag{3}$$

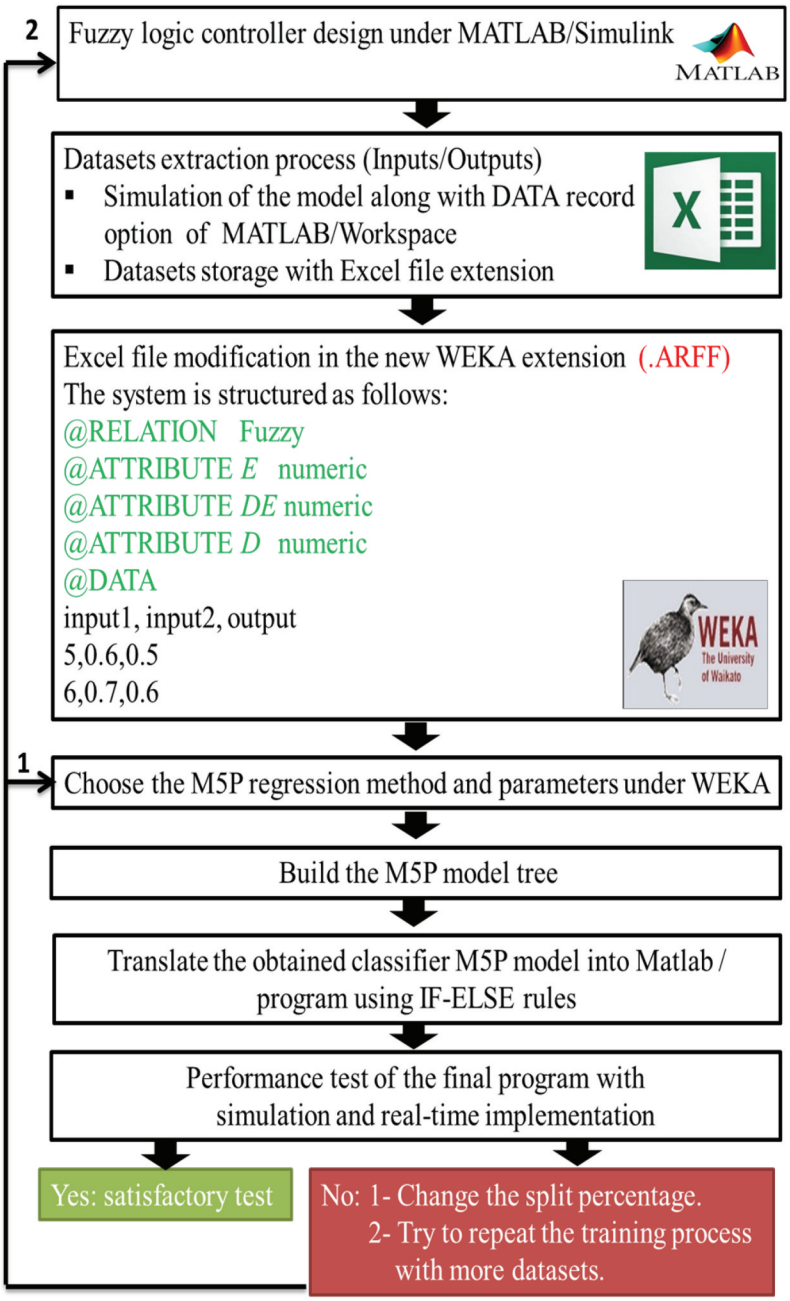


Figure 5. Research methodology to build the final controller.

In the case of our regression system using the M5P model tree, the previous statistical parameters can be quantified as shown in Table 2.

In WEKA software, the attribute data has been chosen from FLC's datasets in a new extension form (.ARFF). Data percentage split was taken as 66% for the training stage. Figure 6 represents the classifier output of the developed M5P model tree.

Table 2. Statistical parameters of the training method.

Learning method	Attributes		Statistical parameters					
M5P model tree	Inputs	Output	Data	*R*	*MAE*	*RMSE*	Split	Training time
	E: Error	*Y*: *idc-link*	10001	0.9551	0.0427	0.1167	66%	0.75 s
	DE: Derived							

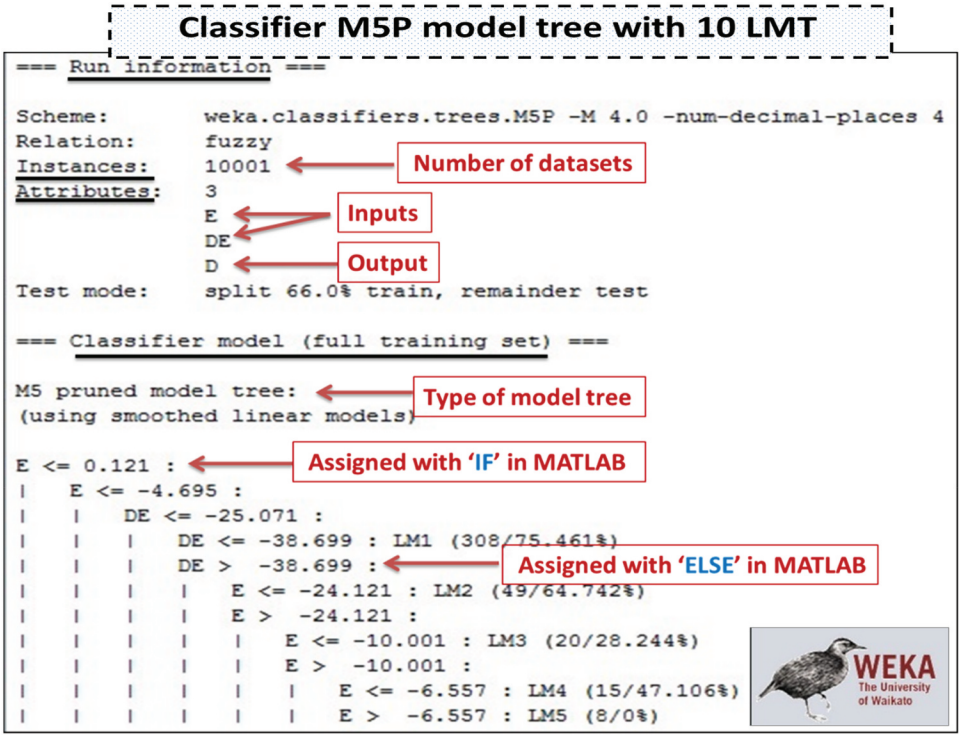


Figure 6. Classifier M5P model tree under WEKA software.

Grid interfaced PV inverter topology

Power quality is considered as a crucial parameter in power grids. For grid-interfaced PV energy systems (Adak, Cangi, and Eid et al. 2021), enhancing the power quality needs the consideration of more parameters and requires a reconfigurable control scheme. The extended configuration of PV inverter with active filter functionalities allows the system to be more reliable and effective. These implicit features of harmonic mitigation and photovoltaic maximum power transfer help to achieve optimal power control (Ouai et al. 2018). The proposed grid-PV system is illustrated in Figure 7, which includes (i) VSI inverter (ii) PV panels (iii) distorted grid with the power source and nonlinear load (iii) MPPT algorithm control (iv) dc-link voltage control.

For the PV inverter control system, the indirect current technique is used to mitigate harmonics while the hysteresis current control generates switching pulses (Sangwongwanich et al. 2018). Basically, the DC voltage controller generates a dc current while the PLL provides three synchronized grid voltage components (*sin (θ), sin (θ-120°), sin (θ + 120°)*) which are multiplied by the output current of the controller $i_{dc\text{-}link}$ (Sujatha, Chandra Sekhar, and Boppa 2014). The obtained source reference current is then compared with that measured through a hysteresis comparator. This theory can be mathematically modeled by equations as follows:

First, when assuming that the system is without compensation (without APF), the distorted load current can be defined as:

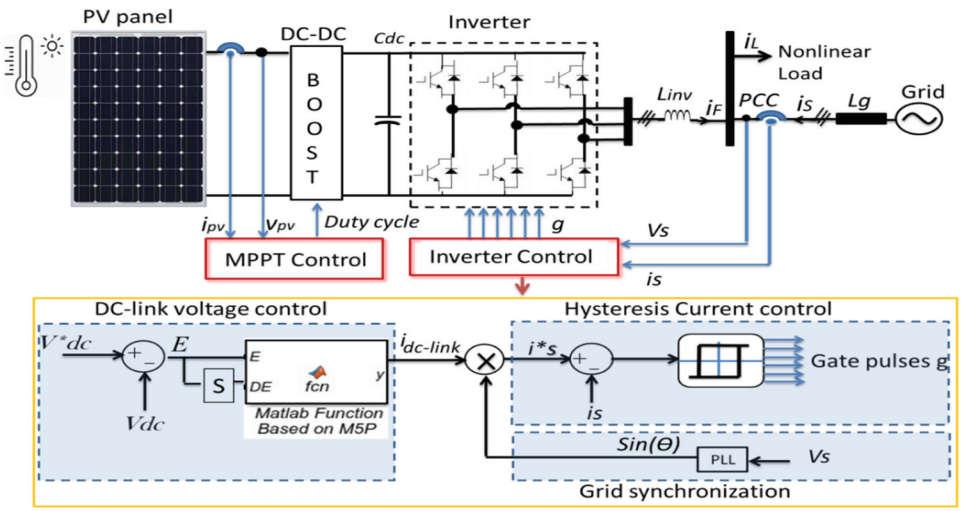


Figure 7. System configuration and control structure.

$$i_{S(t)} = i_{L(t)} = i_{fund} + i_{har} \tag{4}$$

where i_S,i_L denote, respectively, the source current and the load current, while i_{fund},i_{har} are the fundamental and harmonic components of the load current. Once the APF is connected at PCC, the equation (4) can be rewritten as follows:

$$i_{S(t)} = i_{L(t)} - i_{F(t)} = [i_{fund} + i_{har}] - i_{F(t)} \tag{5}$$

The main function of APF is to recover the sinusoidal shape of the source current i_s by injecting an appropriate filter current i_F in order to compensate i_{har} component. Hence, the source current will regain its sinusoidal form in phase with the source voltage.

From the identification scheme seen in Figure 7, the three reference currents can be expressed as (Rahmani, Al-Haddad, and Kanaan 2005):

$$\begin{cases} i^*_{Sa(t)} = i_{dc-link}\sin(\omega t) \\ i^*_{Sb(t)} = i_{dc-link}\sin(\omega t - 120^\circ) \\ i^*_{Sa(t)} = i_{dc-link}sin(\omega t) \\ i^*_{Sc(t)} = i_{dc-link}\sin(\omega t + 120^\circ) \\ i^*_{Sb(t)} = i_{dc-link}sin(\omega t - 120^\circ) \\ i^*_{Sc(t)} = i_{dc-link}sin(\omega t + 120^\circ) \end{cases} \tag{6}$$

where

$i_{dc\text{-}link}$ represents both the DC output current of the V_{dc} controller and the amplitude of the desired reference source current. With the PV system, the filter current will comprise a combination of the inverter current, PV current, and capacitor charging current. Equation (7) can justify the reduction of source current when a PV source is connected (Mohd Zainuri et al. 2018).

$$i_F = i_{inv} + i_{pv} \pm i_{dc-link} \tag{7}$$

DC-Link voltage control with M5P algorithm

Maintaining a constant dc-link voltage of the PV inverter is one of the more important tasks to be accomplished in both steady and dynamic operating conditions (Ahmed, Abdelrahem, and Farhan et al. 2021). Membership functions shown in Figure 8 are designed with a consideration of two inputs E and ΔE and one output $i_{dc\text{-}link}$. These fuzzy functions were set under a table of rules with zero, positive, negative, positive big, negative big linguistic labels (Turksoy et al. 2018).

On the other hand, the learning set using fuzzy data is reconstructed under WEKA software into three attributes, which are in our case the dc-link voltage error (E), its variation (ΔE), and the amplitude of source current ($I_{dc\text{-}link}$). Figure 9 shows the data extraction process under MATLAB/Simulink using an equivalent lookup table to collect fuzzy logic results.

Consequently, the network architecture of the linear model tree that includes 10 LMT can be represented as in Figure 10. After developing the M5P algorithm under WEKA, a hierarchical MATLAB program has been written to replace the fuzzy logic controller of the dc-link voltage. The final program is described in the section of Appendix.

A comparison between the M5P controller, FLC, and the anti-windup classical proportional-integral PI controller is modeled under the graphical environment of the MATLAB/Simulink to evaluate the performance of the proposed control. Figure 11 shows the superiority of the system under the M5P technique in terms of fast response time when a transient condition is applied by a sudden increase in the load (step load change at t = 1s by changing the resistance R_d of the PD3 bridge from 120 ohms to 200 ohms).

Even for the source current, Figure 12 shows a good sinusoidal shape using M5P-based control under a transient state condition at time t = 1 s. The THD always remains small with a value of 1.59% in a steady-state and 1.08% after a step change load from 2A to 2.77A, which shows clearly the efficiency of the suggested model tree method.

A novel M5P- MPPT

The energy delivered by PV cells depends mainly on their sensitivity to the irradiance variations. So, due to the variability of the solar irradiance and temperature, it is necessary to track permanently the maximum available power from PV cells through an adequate control of a boost converter by applying the maximum power point tracking technique. The basic principle of this tracking method is to extract the maximum power from PV panels using different control algorithms such as perturb and observe (P&O) (Sera et al. 2013), incremental conductance (INC) (Hsieh et al. 2013), and many other intelligent controls (Sameh et al. 2018, 2019). In addition, it is necessary to keep a good power quality of the grid-tied PV system according to the variable irradiance and temperature environment conditions. At very low irradiation, the combined system keeps its principal task and operates only as a harmonic compensator. Figure 13 shows

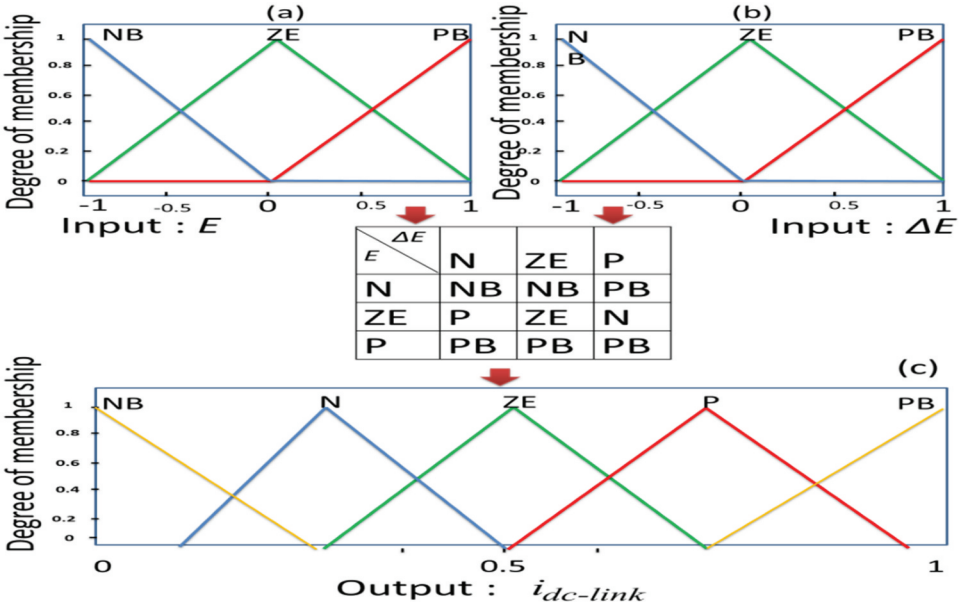


Figure 8. Membership functions and rules of FLC.

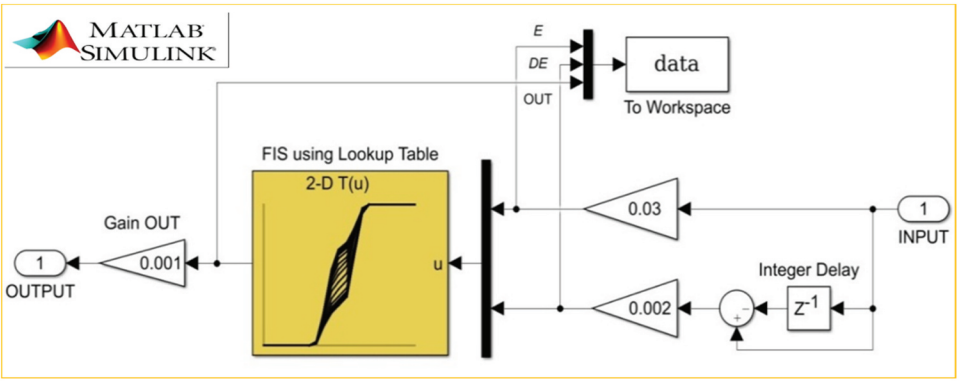


Figure 9. Data extraction process under MATLAB/Simulink.

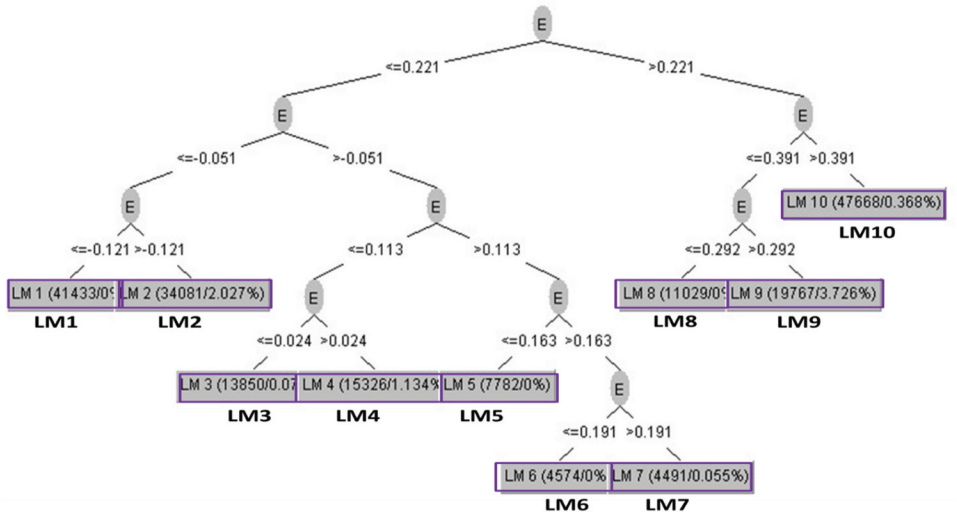


Figure 10. Final M5P model tree with WEKA.

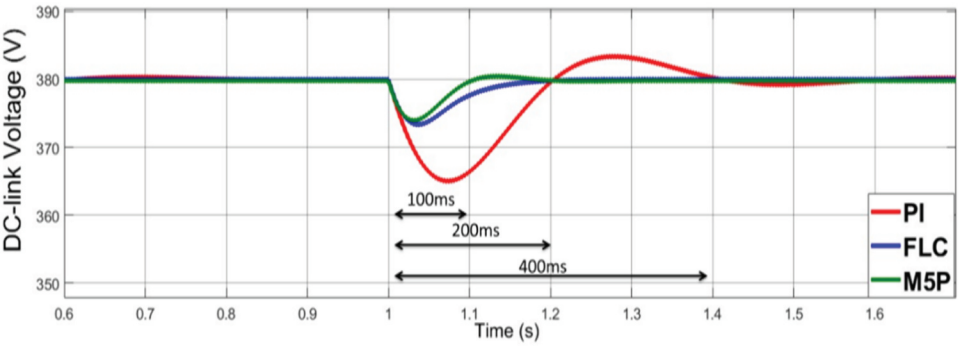


Figure 11. Dynamic performance of different controllers with simulation.

the principal characterization of P/V and I/V curves of the photovoltaic cell where P_{mpp}, I_{sc}, and V_{oc} represent, respectively, the maximum power point and its coordinate [I_{mpp},V_{mpp}], the short circuit current, and the open circuit voltage.

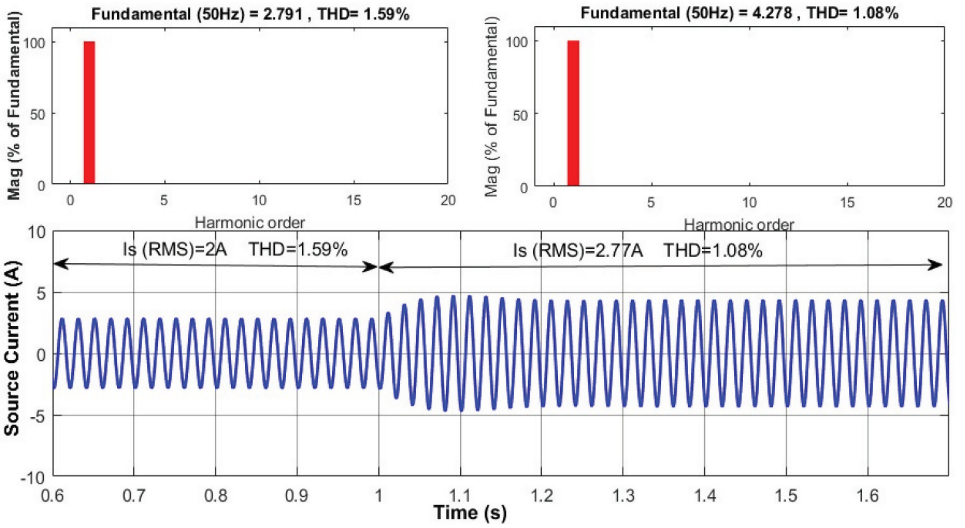


Figure 12. Source current waveform using M5P control with simulation (under transient condition).

In addition, the PV system that includes a boost converter is controlled with the MPPT algorithm (Srinivasarao et al. 2021). This configuration allows the system to boost the dc-link voltage from 100 V to 380 V using two PV panels of 47 V each. The boost converter can be represented by a classical chopper which consists of an IGBT transistor, an inductance L, and a diode. Its output voltage V_{dc} serves to supply the VSI's dc-link voltage. With a variable duty cycle, the boost converter uses the MPPT technique to extract automatically the maximum powers from PV panels (McCandless, Haupt, and Young 2015). Figure 14 shows the fuzzy logic membership system that uses seven 7 fuzzy variables linguistic for inputs and 49 fuzzy inference rules. Figure 15 displays the block diagram of FLC modeled under the Simulink environment.

The novel M5P-MPPT-based control is illustrated in Figure 16. The proposed strategy uses the recorded fuzzy datasets of the Fuzzy-MPPT control, which are converted into a tree form via the WEKA software. Figure 17 shows the obtained M5P algorithm with 8 LMT.

As a final step, the M5P-MPPT controller can be translated with the MATLAB programming language as depicted in the section of Appendix.

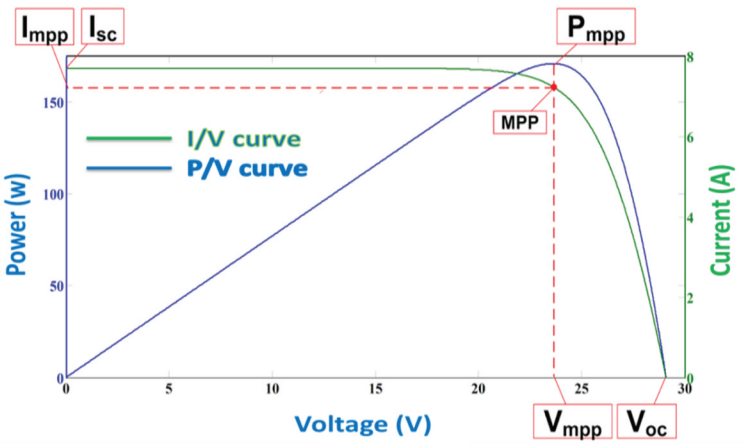


Figure 13. P/V and I/V curves of the photovoltaic cell.

As shown in Figure 18, the M5P-based system is simulated and compared with FLC outputs under various scenarios considering the constant and variable irradiances conditions (Patro et al. 2021) . Under dynamic operating conditions, the temperature is kept constant at 25°C while the irradiance is changed according to the ramp-up/down shown in Figure 19. Comparatively, the proposed M5P-MPPT tracks perfectly its fuzzy trained model and can yield better results by small ripples in the case of variable irradiance especially during the ramp-down period.

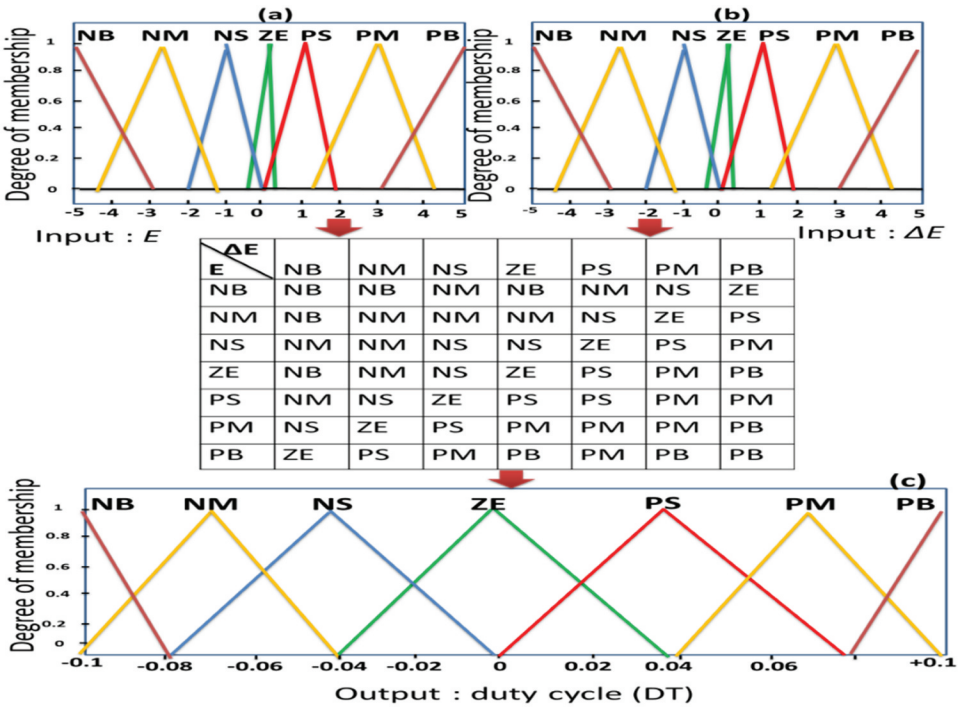
The hysteresis current control

The six switching pulses of the inverter are generated using the hysteresis control. Characterized by its fast response, the fixed hysteresis band is a very simple technique and easy to implement for the shunt active filtering system. The method is based on the principle of the called hysteresis band (HB) which provides switching pulses through a comparison between source current and its reference. Figure 20 illustrates the functionality of the hysteresis-based control.

Experimental results and discussions

The hardware validation aims to confirm the effectiveness of the suggested control. The entire system, including the active power filter interfaced with a PV system in both static and dynamic conditions, has been implemented under MATLAB/Simulink environment and dSPACE 1103 hardware. The experimental results were obtained using a compiled Simulink model as shown in Figure 21. The system consists of PLL, three current sensors, five voltage sensors, dc-link controller, PV system with MPPT strategy, and lastly hysteresis band controller.

Figure 22 shows the designed laboratory prototype where the two PV panels are fixed under real weather conditions of ambient temperature and irradiance. As listed in Table 3, the entire system is conducted in a manner where the voltage utility is set as 120 V/50 Hz and the dc-link voltage is set as 380 V.



E \ ΔE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NB	NM	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PM	PB	PM	PB	PB

Figure 14. Membership functions and rules of FLC based MPPT.

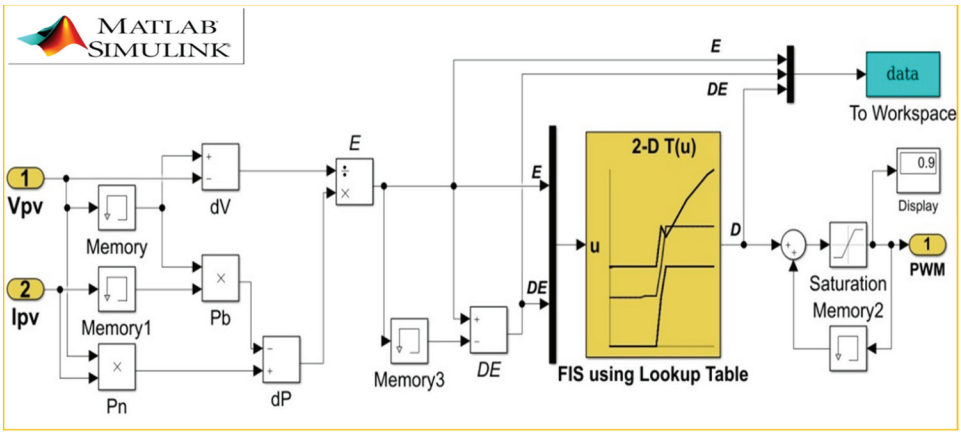


Figure 15. Data record process from Fuzzy-MPPT system.

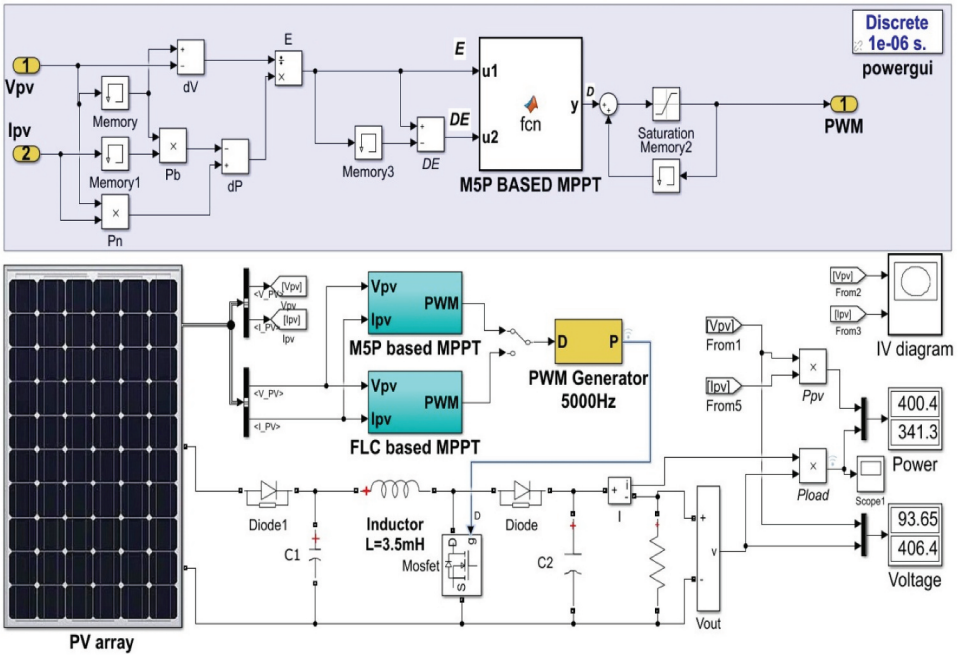


Figure 16. Simulink control block of the PV system.

Figure 23 shows the initial source current without APF characterized by a high THD value of 24.9%. Whereas Figure 24 demonstrates that the source current with the RMS value of 2A can reach a good THD value of 2.77%.

In the case of grid-PV configuration, it has been revealed by Figures 26 and 27 that the applied Fuzzy-M5P model for both MPPT and dc-link control regulates well the system and gives a good THD of 4.12% as well as a remarkable decrease of the source power from 246 W to 192 W under a real irradiance condition of about 500 w/m^2 and an ambient temperature of 30°C.

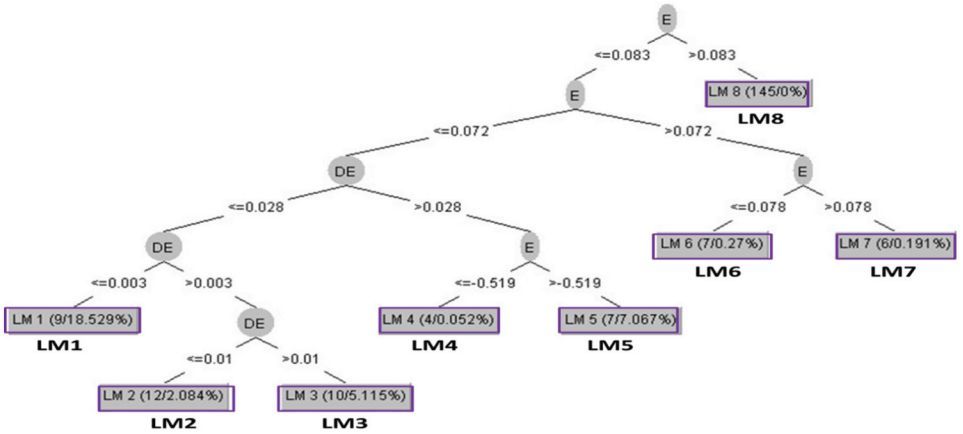


Figure 17. The obtained M5P-MPPT model tree with WEKA.

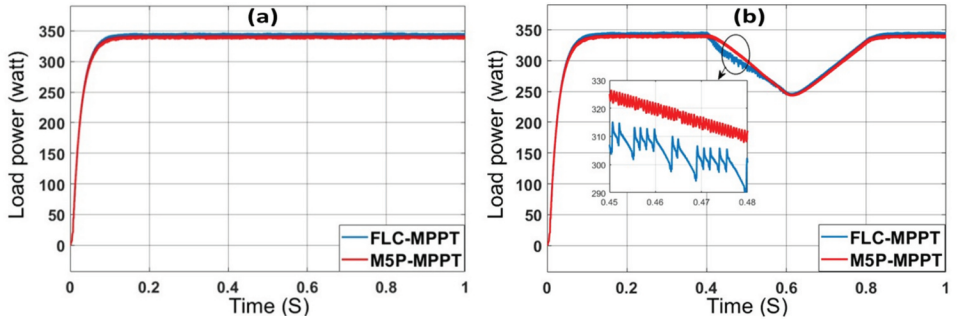


Figure 18. M5P-MPPT and FLC-MPPT comparison (a) with constant irradiance (b) with variable irradiance.

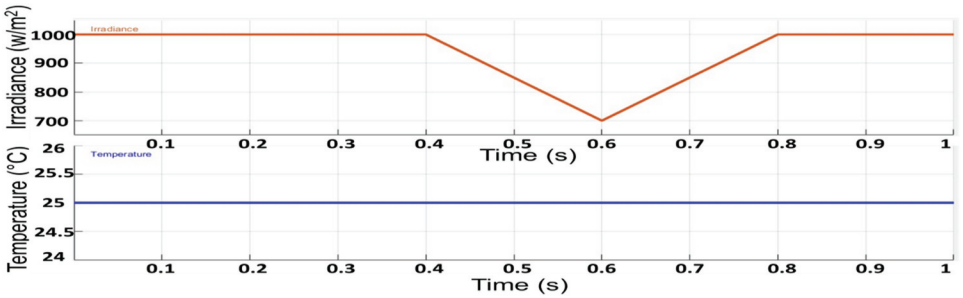


Figure 19. Variable irradiance conditions with ramp-up/Dawn.

In addition, Figure 28 depicts the output results of the M5P-MPPT technique under dynamic conditions. Less oscillation is shown from the green dc-link voltage shape when rapid shading conditions are applied.

As shown in Figure 29, the proposed control is compared with fuzzy logic outcomes for the purpose to evaluate performance under rapid variable shading.

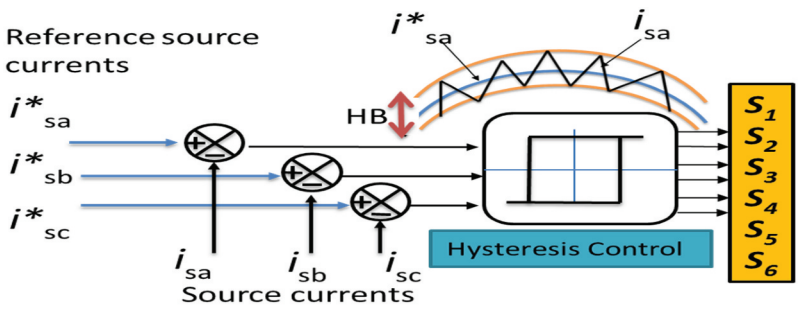


Figure 20. The basic principle of the hysteresis control.

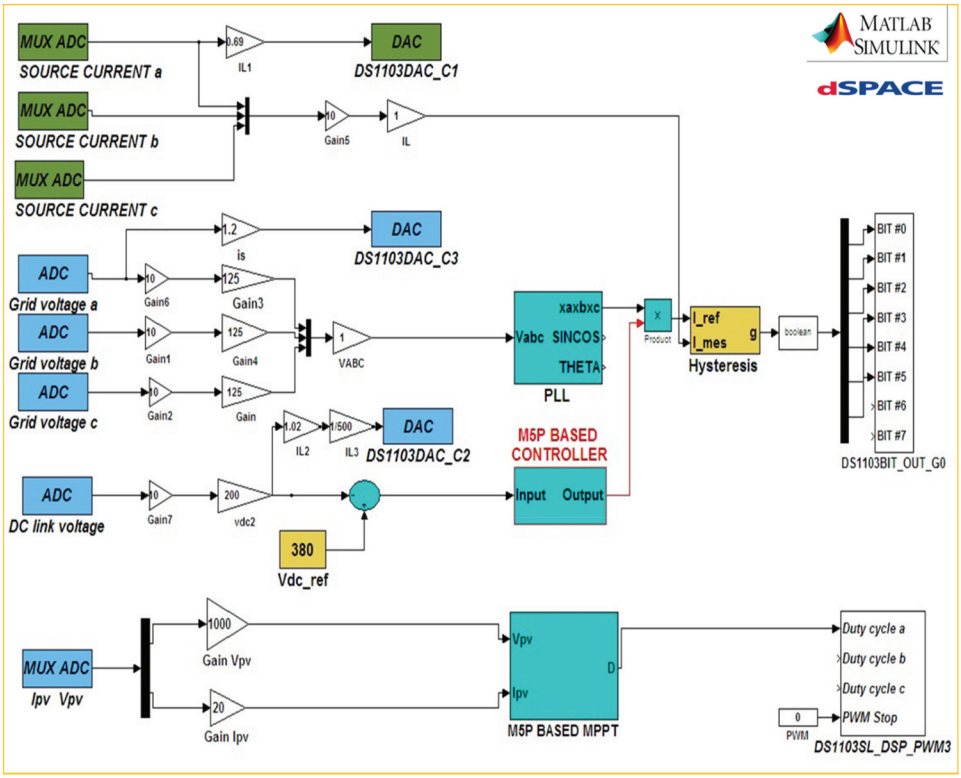


Figure 21. The compiled MATLAB block.

Results interpretation

Firstly, with MATLAB simulation, Figure 11 shows the superiority of the suggested technique. Compared with FLC and conventional PI outcomes, a fast response time of 100 ms was obtained under a transient condition. In terms of harmonics distortion, Figure 12 illustrates a good sinusoidal waveform of the source current with a low THD value of 1.08%. Moreover, the novel M5P-MPPT is verified under Simulink environment, the system has been tested

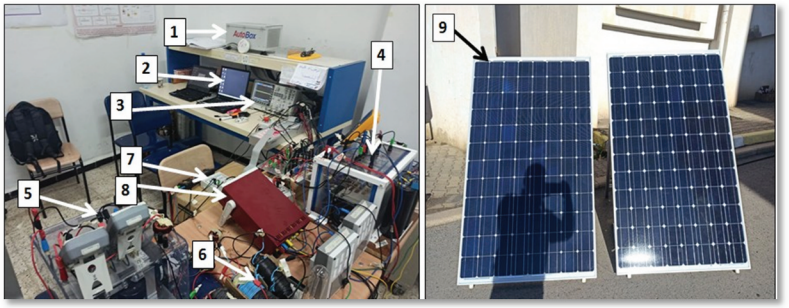


Figure 22. The laboratory prototype. 1-dSPACE 1103 type AUTOBOX 2-Laptop with MATLAB /Simulink and Controldesk 3-Scope GWinstek with power analyzer function 4-Inverter and rectifier converters 5- DC/DC converter 6- Filter inductances L_{inv} 7- PWM control box for MPPT 8-Second power analyzer 9- PV panels.

Table 3. System parameters.

Description	Parameters	Values
Solar PV array	Number of panels	2
DC/DC Boost converter	Maximum power P_{max}	200 W /Panel
	Voltage at P_{max}	47.06 V
	Current at P_{max}	4.26A
	Open circuit voltage V_{oc}	57.6 V
	Short circuit current I_{sc}	4.6A
	Boost inductance	3.5 mH
Power Supply (3 Phases)	Nominal voltage (PH-N)	120 V RMS
	Source voltage inductance	0.1 Ω, 0.1mH
DC-link	dc voltage	380 V
	dc capacitor	2350 µF
NL Load (Rectifier PD3)	R_d L_d Load	120 Ω, 2mH
Inverter (VSI)	Coupling Inductance L_{inv}	10 mH
Inverter Current Control	Hysteresis Band	0.01 (1%)
Sampling Time	Ts	2e-5 s for experiment 1e-6 s for simulation

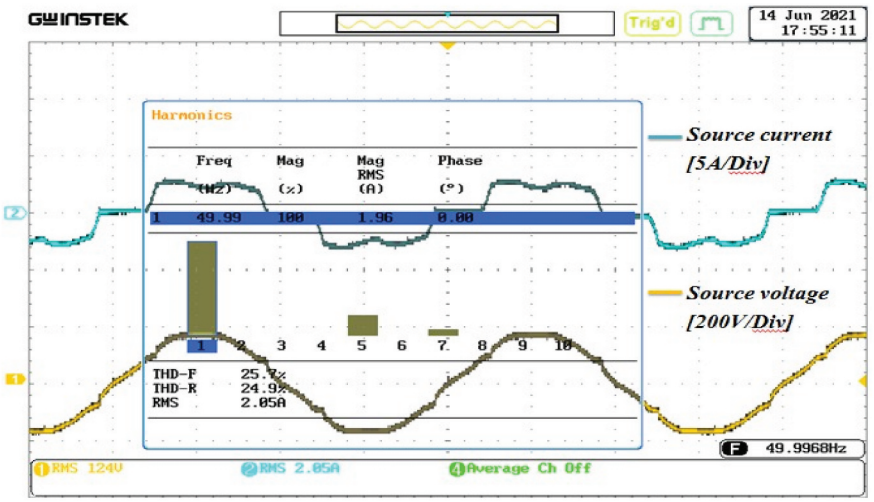


Figure 23. THD source current of the grid without PV inverter.

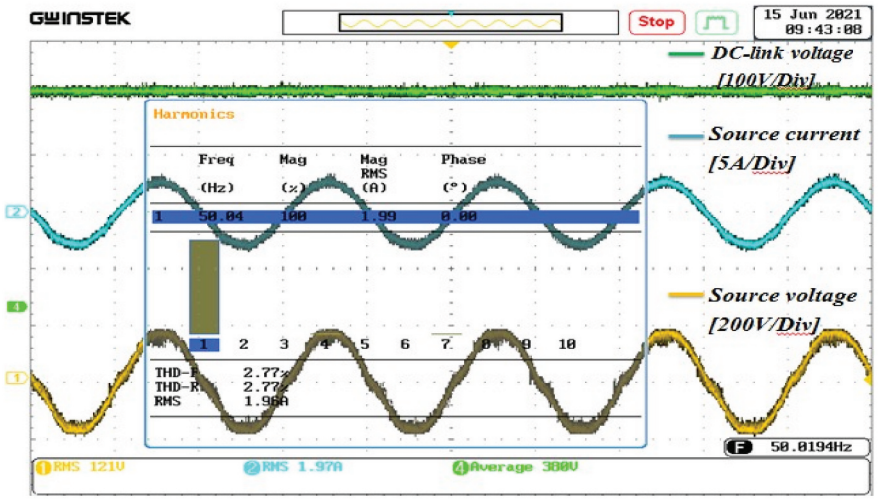


Figure 24. Harmonics mitigation without PV system (APF control with the M5P algorithm).

with a constant and variable irradiance as shown in Figures 18 and 19. Obviously, the Fuzzy-M5P method can yield satisfactorily harmonic mitigation and a good maximum power tracking without ripples when compared with fuzzy logic-based MPPT.

Experimentally, Figure 23 shows the deformed waveform of the source current before compensation. After APF connection, it has been observed from Figures 24 and 25 that the THD of the source current reaches a low value of 2.77% along with the Fuzzy-M5P strategy in the dc-Link control. The power source consumption was 246 W without a connected PV source. From Figures 26 and 27, the complete grid-connected PV source system revealed that the applied method for both MPPT and dc-link control can achieve a low THD of 4.12% and a remarkable decrease of power source until 192 W. In addition, the proposed control is compared with FLC outcomes under rapid variable shading as shown in Figures 28 and 29. By introducing a step-change in the load current, the dynamic performance is reconfirmed. It can be seen from Figure 30 that the applied algorithm regulates well the dc voltage with a fast response time of 100 ms. It is clear that the obtained results both in steady and transient states indicate a close agreement between simulation and experiment. By merging decision tree with fuzzy logic, many promising performances and objectives are achieved, which can be summarized as follows

- Simple structure of the controller based on MATLAB program.
- Fast learning approach with a remarkable time of 0.75s.
- Offer accurate training with a good correlation coefficient and a minimum error especially the root mean square error.
- Can yield both improved MPPT and a purely sinusoidal grid current.
- A control that exhibits superior dynamic performance when compared to other techniques as in research papers (Ouchen et al. 2020) and (Hoon et al. 2016).
- Can offer a low THD of a source current that meets IEEE-519 harmonic standards.
- Many motivated tuning parameters can be investigated such as the pruning factor and the percentage of the training split.
- The capacity to learn from a variety of different controllers.
- A possibility to use a variety of tree models such as the C4.5 technique.

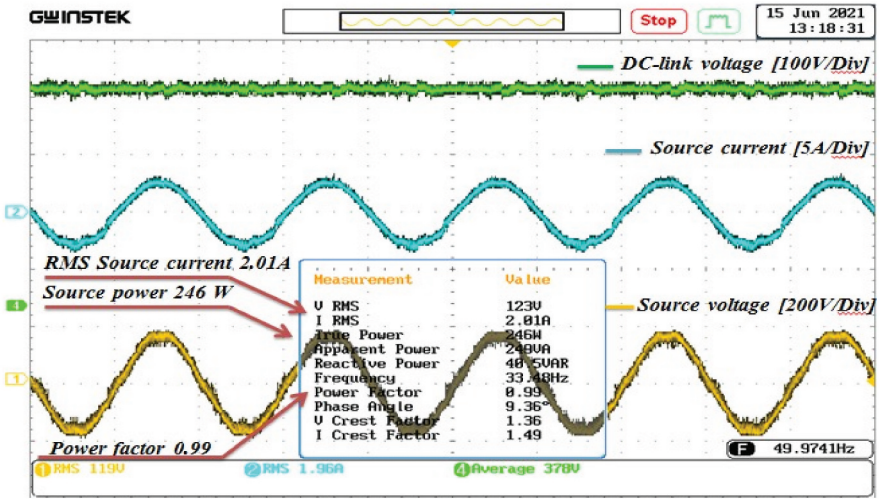


Figure 25. Power supply measurements without PV system (APF control with the M5P algorithm).

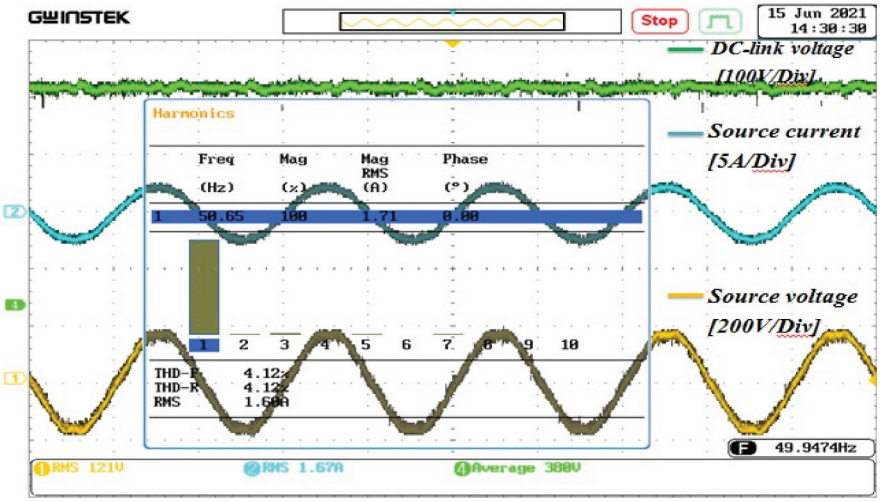


Figure 26. Harmonics mitigation using the M5P algorithm for both MPPT and APF control.

According to the literature evidence base summarized in Table 1, the adopted control can guarantee an alternative solution for systems suffering from complex structure and low performances during the transient process.

Conclusion

The paper has presented a novel mixed control in the form of a MATLAB program based on the M5P tree algorithm and fuzzy logic applied to a grid-tied PV inverter with active filter capability. The fuzzy logic-based controller is very common in control systems due to its robustness and good performance, especially under dynamic conditions. However, this previous advantage points out also that fuzzy logic is not the perfect solution due to its lower real-time implementation speed and complicated modeling under embedded systems.

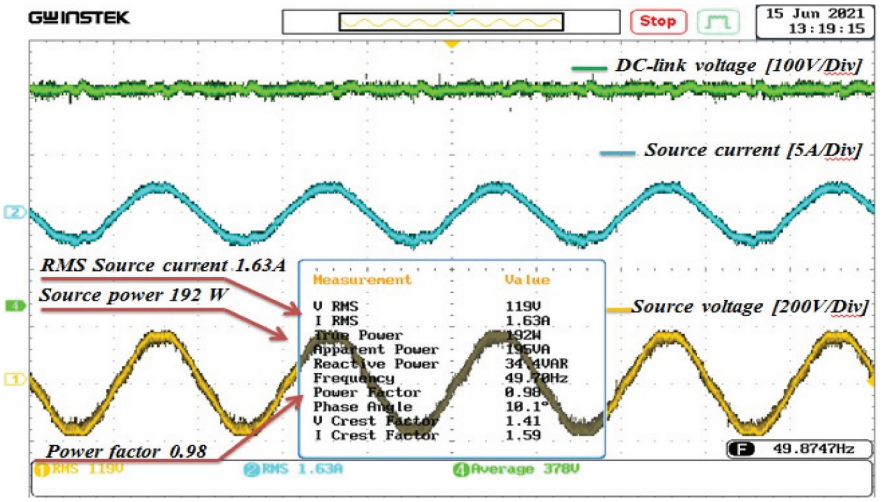


Figure 27. Power supply measurements of the grid-connected PV system (under a constant irradiance)

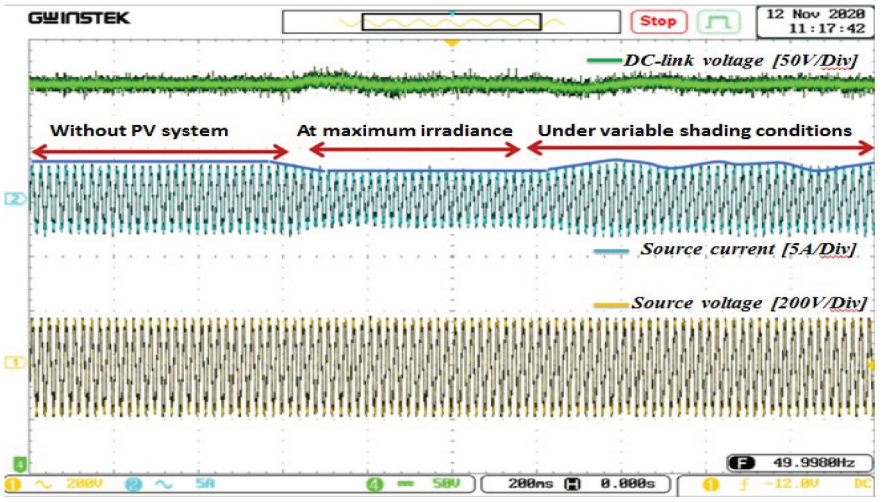


Figure 28. Dynamic performances using Fuzzy-M5P model tree

Based on a deep literature review, the main purpose is to provide a simple and efficient control under both steady and dynamic operating conditions. Computational simulations completed by real-time implementations have been conducted in order to investigate the system behavior and performances. The obtained results for both MPPT and dc-link voltage control demonstrate a significant enhancement of the power quality with a good THD of grid current of 2.77% and a remarkable decrease of the active power of the main source. Moreover, the proposed methodology shows an attractive efficiency in terms of fast learning speed of 0.75s for 10000 attributes, accurate training method with a minimum *RMSE* error, and a fast response time of 100 ms during transient state. The proposed mixed control appears to be an

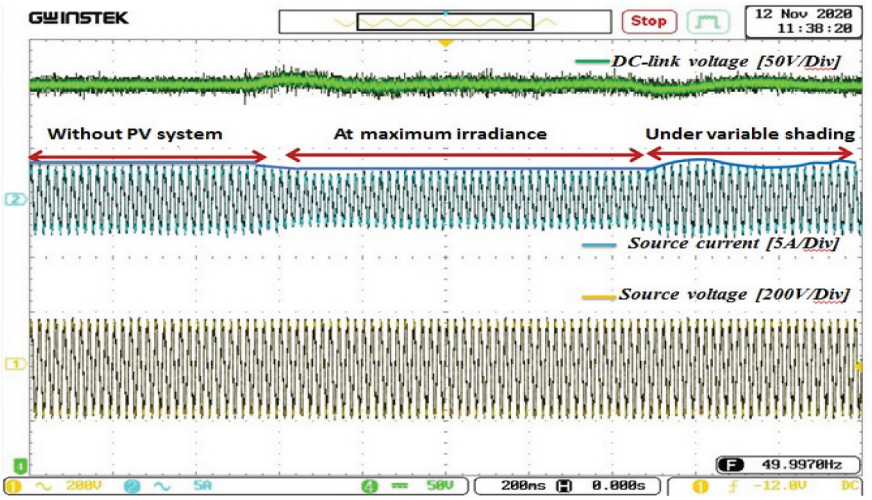


Figure 29. Dynamic performances using FLC

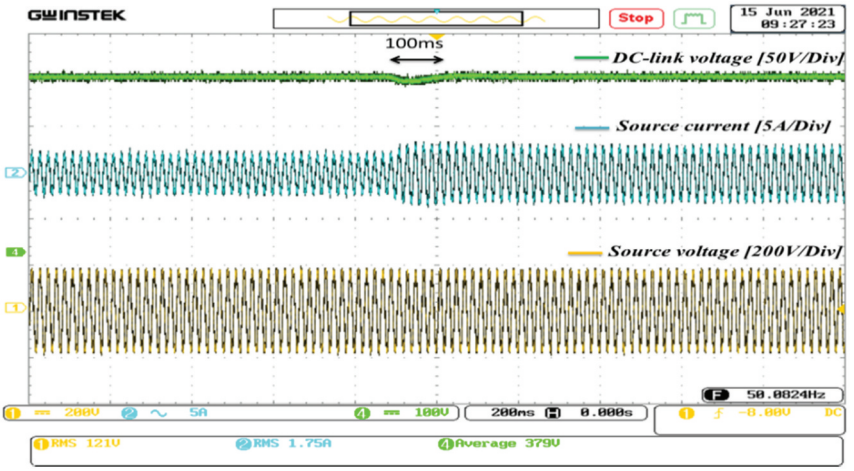


Figure 30. Fuzzy-M5P dynamic performances on the grid side under nonlinear load variation.

interesting guiding tool to design simple controllers and therefore deserves further exploration using a variety of tree methods.

List of symbols and abbreviations

T_s	Sampling-time
PV	Photovoltaic system
M5P	Pruned M5 model tree
MPPT	Maximum power point tracking
FLC	Fuzzy logic control

ANN	Artificial neural network
APF	Active power filter
ICC	Indirect current control
THD	Total harmonic distortion
PLL	Phase locked-loop
VSI	Voltage source inverter
$i_{dc\text{-}link}$	Output dc current from the regulator
i_S	Source current
i_F	Filter current
i_L	Load current
V_s	Source voltage
V_{dc}	DC-Link voltage
P	Active power
Q	Reactive power
D	Harmonic power
C	DC bus capacitor
NL	Nonlinear load
PI	Proportional-Integral
L_{inv}	Filter inductance
L_g	Source inductance
R_d	Resistance of NL
L_d	Inductance of NL
LMT	Logistic model tree
DT	Decision tree
LUT	lookup table
PO	Perturb & observe technique
INC	Incremental conductance technique
MAE	The mean absolute error
RMSE	The root mean square error
R	The correlation coefficient

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix

A. The Fuzzy-M5P based program for the dc-link control and MPPT

Fuzzy-M5P based program for the dc-link inverter

```
function y = fcn(E,DE)
LM1=3.5001 * E + 0.2234;
LM2=1.9305 * E + 0.0528;
LM3=1.24 * E - 0.0013;
LM4=1.3121 * E - 0.0077;
LM5=3.4216 * E - 0.2253;
LM6=3.4215 * E - 0.2253;
LM7=3.2909 * E - 0.1995;
LM8=3.2551 * E - 0.01917;
LM9=0.002 * E + 0.8066;
LM10=0.0006 * E + 0.8404;
if E <= 0.221
if E <= -0.051
if E <= -0.121
S=LM1; %(41433/0%)
else %DE > -0.121
S=LM2; %(34081/2.027%)
end
else %DE > -0.051
end
if E <= 0.113
if E <= 0.024
S=LM3; %(13850/0.078%)
end
else %DE > 0.024
S=LM4; %(15326/1.134%)
end
else %DE > 0.113
end
if E <= 0.163
S=LM5; %(7782/0%)
else %DE >  0.163
if E <= 0.191
S=LM6; %(4574/0%)
end
S=LM7; %(4491/0.055%)
end
if E <= 0.391
if E <= 0.292
S=LM8; %(11029/0%)
else %DE > 0.292
S=LM9; %(19767/3.726%)
end
else %DE > 0.391
S=LM10; %(47668/0.368%)
end
y = S;
```

Fuzzy-M5P based program for the MPPT control

```
function y = fcn(u1,u2)
E=u1;
DE=u2;
LM1=-0.0273 * E + 0.0005 * DE + 0.5253;
LM2=-0.0425 * E + 2.2177 * DE + 0.4639;
LM3=0.1233 * E + 3.5636 * DE + 0.467;
LM4=-0.0282 * E + 0.0004 * DE + 0.5395;
LM5=-0.0539 * E + 0.0004 * DE + 0.5298;
LM6=0.09706 * E + 0.0003 * DE - 0.0418;
LM7=0.02149 * E + 0.0003 * DE - 0.0608;
LM8=-0 * E + 0.0001 * DE + 0.89;
if E <= 0.083
if DE <= 0.072
if E <= 0.028
if E <= 0.003
S=LM1; %(12/2.084%)
end
end
else %E > 0.003
S=LM2; %(12/2.084%)
S=LM3; %(10/5.115%)
end
if DE <= -0.519
S=LM4; %(4/0.052%)
else %E >  -0.519
S=LM5; %(7/7.067%)
end
if E > 0.072
if E <= 0.078
S=LM6; %(7/0.27%)
End
else %E > 0.078
S=LM7; %(6/0.191%)
end
else %E >0.083
S=LM8; %(145/0%)
end
y = S;
```