Harmonics Compensation of Grid-Connected PV Systems Using a Novel M5P Model Tree Control

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Abstract— **This paper proposes a new fast machine learning approach based on a mixed control of fuzzy logic controller designed under MATLAB and a pruned M5P model tree technique designed under WEKA software. An investigation of an innovative maximum power point (MPPT) method and equivalent dc-link controller for a grid-connected PV system was undertaken to evaluate the potential performances in both dynamic and steady operating conditions. In addition, an optional power quality enhancement can be benefited from integrating the shunt active power filter functionality (SAPF). This topology allows the system to be more effective, which means that the combined system can perform dual functions of harmonic mitigation and grid-connected photovoltaic system. Obtained results of simulations and real-time implementations indicate that the developed tree algorithm based on simple MATLAB code has clearly revealed significant role to replace controllers suffer from modeling complexity and a long hardware implementation time. According to the harmonic standard IEEE 519-1992 limits, the novel control would result in very low total harmonic distortion of the grid current and a successful power transaction along with near unity power factor.**

Keywords— Harmonics pollution, Photovoltaic generator PV, Pruned M5P model tree, Dynamic performance, SAPF.

I. INTRODUCTION

The fundamental objective of electrical grids is to provide customers with electrical energy with perfect continuity and a sinusoidal voltage shape which is characterized by a pre-established amplitude and frequency values. In recent years, the increasing use in both industrial and domestic world of controlled systems based on power electronic modules has led to more and more problems of harmonic pollution and disturbance in electrical grids [1]. However, these equipment's based on static converters have the advantage of better meeting needs such as flexibility of use, reliability, and high efficiency. Therefore, with the generalization of their use, the costs of these power electronic modules are constantly falling.

The disadvantage of these polluting devices is that they are composed like non-linear loads and absorb currents rich in harmonics with distorted waveforms and different from the supply voltages [2]. In this case, the evolution of the currents is not directly linked to the sinusoidal variations of the voltages. In terms of power quality, an electrical disturbance is interpreted as any deviation of the source voltage from its nominal value and form. By extension, we can also consider as disturbances the phenomena acting on the shape of the current, because they have a direct influence on the voltage. The various disturbances encountered are above all voltage fluctuations, imbalance, variation in source frequency, harmonics and transients [3]. Mention is made in particular of the problem of non-sinusoidal harmonic currents which circulate through the impedances of the grid and directly infect the source voltages. Harmonic currents consist of several harmonic components, the most dangerous are those of low odd order such as 3, 5,7,9,11,13 which can produce serious effects such as [4]:

- General loss of grid power.
- Heating and power loss in transformers.
- Disturbance and imbalance of the source voltage.
- High consumption of reactive energy.

Many national and international organizations such as IEEE 519-1992 impose limits on the injection of harmonic currents in order to ensure an acceptable power quality of the grid. They define the harmonic current levels expressed as a percentage of the fundamental with the harmonic distortion rate THD not to be exceeded. With this in mind, all distributors and users are required to comply with several standards and recommendations that comply with the rules relating to electromagnetic compatibility (EMC). Therefore, it is necessary to reduce these dominant harmonics below a THD specified in these standards. The appearance of new semiconductor components such as GTO thyristors and IGBT transistors has made it possible to consider new solutions for compensating harmonic currents. Shunt active power filters are an interesting alternative to conventional solutions. Flexible because self-adaptive, they are added to already existing structures of converters. The role of an active power filter is to compensate for disturbances in real time. In this paper, the voltage source inverter (VSI) considered as the main power device of SAPF is powered by a PV system through the DC-link side. This technique can make the SAPF system as a power source by injecting into the distribution grid both active and reactive powers. For the active power filtering control and harmonics identification systems, there are a large number of techniques proposed in the literature. In the main objective of optimization, these techniques are associated with several kinds of intelligent controls [5]-[6]. Fuzzy logic controller (FLC) is an efficient solution and considered as an alternative for conventional PI controller, it was proposed in several papers [7]-[9] for controlling the MPPT and the DC-link of inverter. Nevertheless, FLC efficiency is usually reduced due to the large capacity of computation time and its modelling complexity. Artificial neural network (ANN) and adaptive neural inference system (ANFIS) based control are also proposed as a solution that had a great impact on the dynamic side of the power quality field [8]-[11]. On the other hand, machine learning systems based on decision trees are largely developed due to its fast responses and good performances. Namely pruned M5P, this model tree controller which is developed by R. Quilan [9] is very effective and can yield the same performances as an ANN. Many researches in the literatures [10]-[23] are studies and compared this learning approach and finalise to conclude its robustness both for regression or classification tasks. In our case, we have designed a new control based on the M5P learning technique using WEKA and MATLAB software. The final controller was applied on both the MPPT algorithm and the dc-bus the VSI. Simulation and laboratory prototype will be shown and discussed in the last section to investigate the good performance of the proposed control when comparing with other recent research as in [17] and [18] especially in terms of dynamic time response of the dc-link voltage.

II. Modeling of the SAPF's Identification Algorithm

The objective of the compensation system is to produce at the output of the shunt active power filter a harmonic current as close as possible to the calculated reference and subsequently a better quality of the source current. For this reason, we will deal with the current harmonic disturbance problem and the compensation solution from a parallel active filter structure. SAPF has been performed by subsequently studying the different algorithms for identifying harmonic currents, namely the method of instantaneous real and imaginary powers (PQ) [12], the synchronous referential method (SRF) [13], the direct power algorithm (DPC) [14], and finally both direct and indirect current methods (DCC/ICC) [19]-[20].

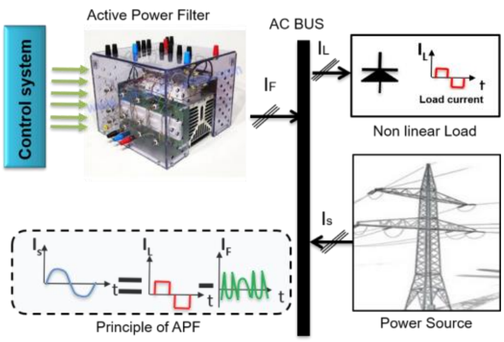

Fig. 1. SAPF connection and compensation principle

In this paper, we have used the simple ICC identification algorithm which can be modeled as follows: firstly, when assuming that the grid is without SAPF, the circulated load current can be written as:

$$i_{S(t)} = i_{L(t)} = i_{fund} + i_{har} \quad (1)$$

Where, i_{har} and i_{fund} denote respectively the harmonic and fundamental components of the circulated load current.

With the objective to describe the flow of powers, the Fourier development technique is used where the load current in (1) can be re-written as follows:

$$i_{L(t)} = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \quad (2)$$

Where Φ_n and I_n represent respectively the angle and amplitude with respect to the nth harmonic component, while Φ_1 and I_1 denote the angle and amplitude of the fundamental component.

In terms of powers, the load power $P_{L(t)}$ can be defined by the following equation [7]:

$$p_{L(t)} = v_{s(t)} * i_{L(t)} \\ = V_m \sin(\omega t) \times (I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)) \quad (3)$$

Consequently, three components of load power can be represented as in (4):

$$p_{L(t)} = p_{fun(t)} + p_{r(t)} + p_{h(t)} \quad (4)$$

Where the components $P_h(t)$, $P_r(t)$, $P_{fun}(t)$ drawn by the nonlinear load denote respectively the harmonic power, the reactive power, and the fundamental power.

Once the SAPF is connected at PCC, equation (1) can be re-written as follows [13]:

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

From equations (5) and (6), the shunt active power filter should supply all harmonic and reactive power demand of the nonlinear load as:

$$p_{F(t)} = p_{r(t)} + p_{h(t)} \quad (6)$$

In the case of ideal compensation, only fundamental power should be supply by the main utility, both harmonic and reactive components are provided by the active filter which results in a correction of the power factor and a reduction of a THD of the source current [14].

By equalizing (3) and (4), the fundamental power absorbed by the load can be expressed as:

$$p_{fun}(t) = V_m I_1 \sin^2(\omega t) * \cos(\phi_1) = v_s(t) * i_s(t) \quad (7)$$

Subsequently, the current supplied by the source after compensation is defined as:

$$i_{s(t)} = p_{fun(t)} \div v_{s(t)} = I_{sp} \sin(\omega t) \quad (8)$$

I_{sp} represents the amplitude of the desired reference source current provided by the Vdc controller, while "sin(ωt)" can be provided with a synchronized PLL. Moreover, the principle of this identification algorithm can be portrayed graphically as in Figure 2 [15]- [16].

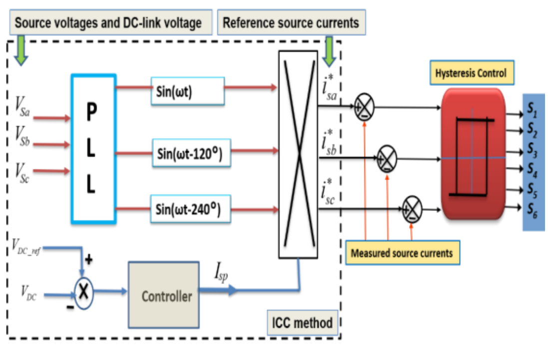

Fig. 2. Schematic diagram of the ICC algorithm associated with Hysteresis method

In the case when the PV generator is connected on the dc-link, the provided filter current as in equation (9) will comprise a combination of the inverter current, PV current, and capacitor charging current [21].

$$i_F = i_{inv} + i_{pv} \pm i_{dc} \quad (9)$$

Thus, active power is injected from PV panels to the nonlinear load which results in a significant reduce of the source current from its normal value.

III. GRID-CONNECTED PV SYSTEM TOPOLOGY

Recently, solar energy attracts more attention and has become as one of the most important and promising electric power sources in various fields due to the abundance of sunlight and respect of the environment. On the other hand, because of the intensive presence of non-linear loads NL in the electrical grids, a solution consists in deploying a photovoltaic (PV) inverter with an active filtering capacity of harmonics [24]. The main objective is to provide an Active Filter-PV topology with maximum solar energy extraction while keeping the power quality at acceptable levels. The energy delivered by PV cells mainly depends on their sensitivity to variations in irradiance. Thus, due to the variability of solar irradiance and temperature, it is necessary to continuously track the maximum available power of the PV cells through adequate control of an often boost converter by applying the point tracking technique of maximum power. The basic principle of this tracking method is to extract the maximum power from the PV arrays using different control algorithms such as perturb and observe (P&O), incremental conductance (INC), PSO and other intelligent MPPT based on neural networks or adaptive like the ANFIS technique [11]. In some applications, the use of a chopper is essential in order to maximize the output voltage of the photovoltaic module. This DC-DC converter is controlled by the MPPT tracking technique while maintaining the highest possible converter efficiency (greater than 90%). The transistor (MOSFET) and the storage components, in particular the boost inductance and the capacitors, present the main factor relating to the efficiency of the converter. Figure 3 illustrates the configuration of the network-active filter-PV generator system assembly.

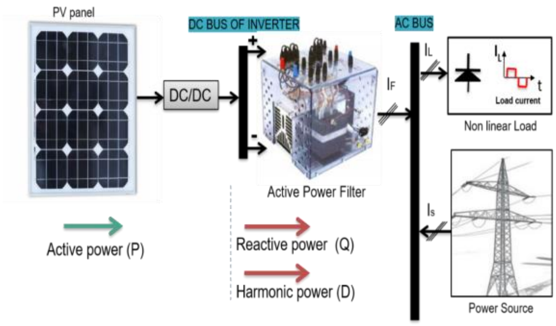

Fig. 3. SAPF and PV generator association

This combination known also by PV inverter is very beneficial in several terms, namely the possibility of supplying the grid with free active power alongside the option of active filtering. In this way, the active compensator now performs several functions, by compensating reactive energy, by eliminating harmonic currents, and finally by covering part of the active power of the NL load [24].

IV. SUGGESTED PRUNED M5P MACHINE LEARNING

Recently, the rapid development of artificial intelligence (AI) technologies has made possible its practical application in many technical fields. Due to its advantage of being able to work with vague aspects of human judgment and perception, the fuzzy logic approach has been widely used in various electrical applications. This clever "if-then" fuzzy rule-based system has attracted a lot of attention due to its many features such as the ability to be used effectively for nonlinear systems with imprecise inputs and undefined mathematical models. However, in some applications, complex fuzzification and defuzzification processes can take a long time, which results in lower processing speed and lack of responses under real-time implementation. Machine learning systems offer an effective solution to overcome the disadvantages of fuzzy systems. Its ability to classify, predict and analyze systems is based on large datasets obtained from trained base models. Since 1989, and thanks to the development of computer science, the learning method based on artificial neural networks (ANN) has been widely used in electrical systems [22]. These smart forecasting solutions offer a good alternative to controlling complex systems due to their timely response and prediction capability.

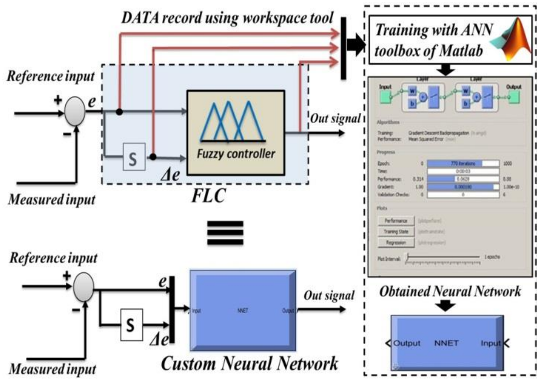

Figure 4. Principle of the neural network training system under MATLAB

Another interesting learning solution can be achieved by decision tree (DT) algorithms. These solutions can serve different classification and regression purposes on supervised data with acceptable performance. Control techniques based on decision tree algorithms are considered to be the most powerful and useful supervised machine learning strategies. Its rapid modeling tools can be applied in many areas of engineering for regression and classification purposes. Based on sets of input data called “attributes”, DT splits the input attributes in different ways through an algorithmic approach in the form of trees. Pruned M5 (M5P) is an extended version of the M5 tree [23]. It splits the training attributes (data) into subset values based on some defined parameters to build the final model tree with efficient class label prediction. The M5P model combines a classical model tree and gives the possibility of introducing linear regression performances at the nodes. Pruned M5P is one of the model tree algorithms used to produce and identify interpretable tree such as models that are intuitive and easy for humans to learn. R. Quinlan [9] developed this extended version of the original M5 model where tree building does not require any system parameter tuning or domain knowledge. In several researches, it has been found that the M5P algorithm is quite robust and gives the same predictive accuracy as an ANN with the same data sets. More efficiency can be achieved by combining fuzzy logic with decision tree algorithms [24]. The goal is to gain the benefits of fuzzy logic using its resulting datasets along with the fast model tree functionality. By using a photovoltaic (PV) inverter with active filtering capability, the primary objective is to provide an Active Filter-PV topology with maximum PV energy extraction and improved power quality. For the control of the inverter, the M5P model was tested in the indirect current technique ICC. This method of generating harmonics is very efficient and its performance depends entirely on the DC bus controller chosen. In addition, a new maximum power point tracking technique based on the M5P algorithm is realized in which data is collected from the fuzzy logic-based MPPT. The main process of generating datasets could be done using the FLC model. Under MATLAB/Simulink as shown in Figure 4, three essential parameters are collected: the reference input E, its derivative ΔE, and the output signal.

Once the data is collected, the learning operation can be performed using the WEKA software. Developed at the University of Waikato in New Zealand, WEKA is free software under the GNU General Public License, this very powerful and fast tool is used to perform machine learning and classification tasks. First, we need to choose the basic template to extract the data from. In our case, we chose the fuzzy logic controller, because we noticed that this intelligent controller suffers from a significant computation time under an experimental environment [24]. Under MATLAB/Simulink, we start the simulation process with the option of saving data using the MATLAB/Workspace tool. The next step is to transfer all the previous data into an Excel file. From a modified extension of this Excel file, WEKA can provide an equivalent model structure in the form of trees. The chosen M5P algorithm reproduces the output results with logistic instruction models called LMT (Logistic model tree). Figure 5 shows the steps to follow in order to obtain the final control model. In the last step, the obtained results are interpreted in the form of a very simplified MATLAB code based on IF/ELSE rules [25].

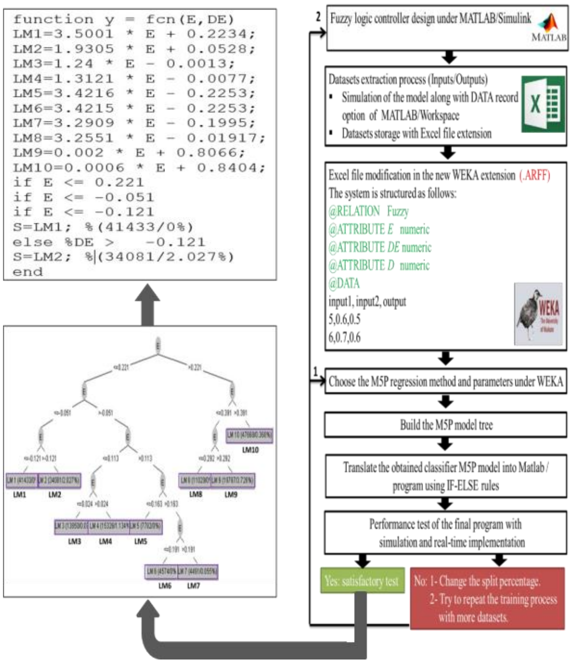

Fig. 5. Chart methodology for building the final tree controller

In our system, the identification of harmonics is performed using the indirect current ICC technique, while the current control is ensured by the hysteresis technique which will generate fast switching pulses. Figure 6 shows the general topology of the studied system.

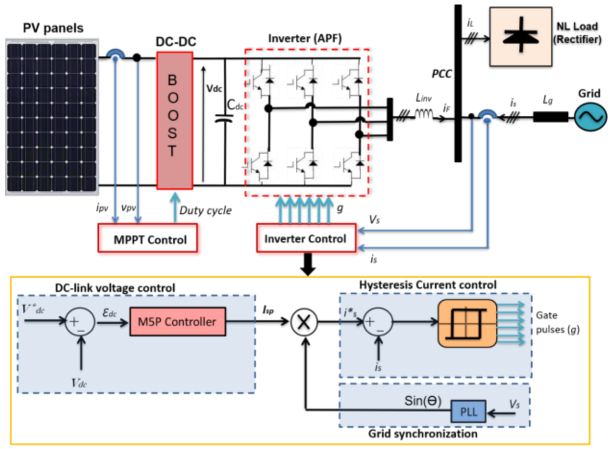

Fig. 6. General topology of the studied system

V. SIMULATION AND HARDWARE IMPLEMENTATION RESULTS

First, a comparison between the M5P controller, FLC, and the classical anti-windup proportional-integral PI controller is done under the graphical environment of MATLAB/Simulink to evaluate the performances both in static and dynamic conditions. As in Figure 7 and Figure 8, the results show the superiority of the DC bus voltage regulation system using the proposed M5P controller. A fast response time of 100 ms is achieved when a transient disturbance is applied by a sudden increase in load current (changing the load at t=1s by changing the resistance Rd of the PD3 bridge from 120 ohms to 200 ohms).

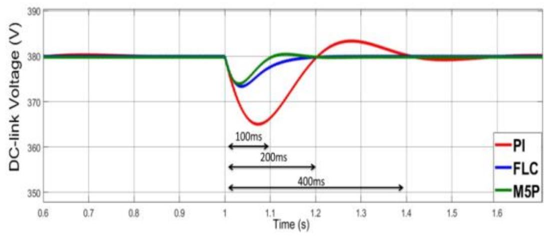

Fig. 7. Dynamic comparison of controllers

Similarly, for MPPT control of the boost converter, Figure 9 shows the system controlled by M5P and compared to FLC results under various scenarios considering both constant and variable irradiance conditions. In the case of dynamic operation, the temperature is kept constant at 25°C while the irradiance is modified. Comparatively, the proposed tree MPPT can perfectly follows its training model and can even give better results characterized by small ripples under variable solar irradiances.

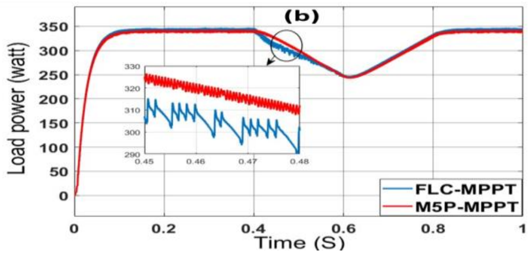

Fig. 8. Dynamic performance of the proposed tree MPPT

In addition, experimental validation aims to confirm the effectiveness of the proposed controls and techniques. The whole system, including the active power filter interfaced with a PV system under static or dynamic conditions, was implemented under the MATLAB/Simulink environment and the dSPACE 1103 numerical control board. The system mainly consists of a PLL system for voltage synchronization, an inverter DC bus voltage regulator, a PV system consisting of two solar panels, a boost converter monitored by MPPT, and finally a hysteresis band controller for switching commands. Figure 9 shows an overview of the used test bench.

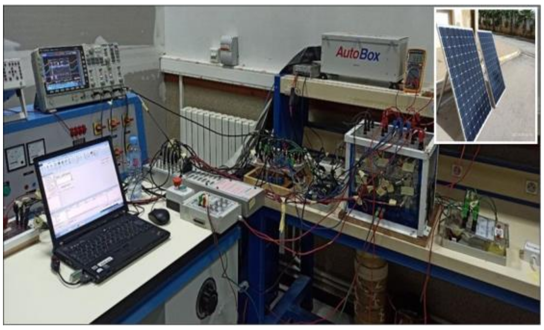

Fig. 9. Test bench

It should be noted that the ICC identification method is used for the rest of all the practical tests in view of its simplicity and its reduced number of sensors (three for the source currents and four for the source voltages and the DC bus). At the beginning, the system is studied without active filtering in order to visualize the shape of the source current. Figure 10 clearly shows the distortion of the source current with a THD value of 24.9%.

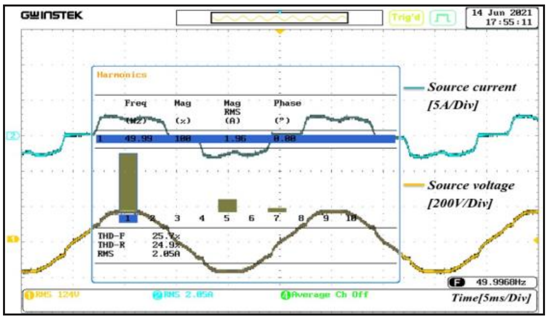

Fig. 10. Source current form before compensation

After the connection of active power filter to the grid, we can see a very remarkable improvement in the shape of the source current as in Figure 11.

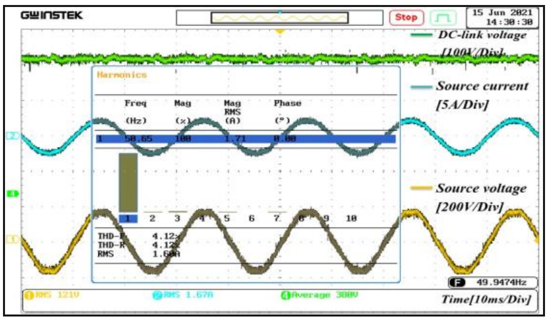

Fig. 11. Power quality with active filter and PV generator

Under the whole system including active filter and PV generator, as shown in Figures 11 and 12, the results revealed that the proposed pruned M5P method applied for both MPPT and DC bus regulator can achieve a low THD of 4.12% and a remarkable decrease in power source from 246W to 192W. It is clear that the system controlled by the new technique can fulfil twine objectives of attenuation of harmonics and power supply simultaneously.

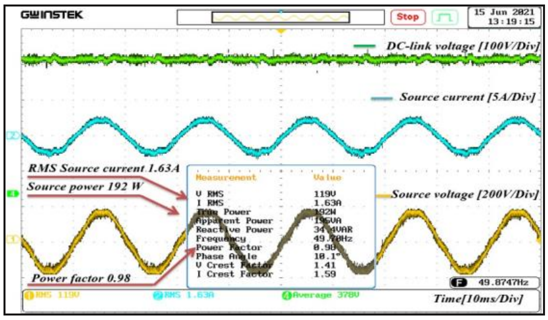

Fig. 12. Different measurements taken with PV system

The results obtained for both the MPPT control and the inverter DC bus regulation demonstrate a significant improvement in power quality and a remarkable decrease in the active power of the main source. In addition, the proposed system has proven its efficiency under transient conditions, by varying the nonlinear load as in Figures 13.

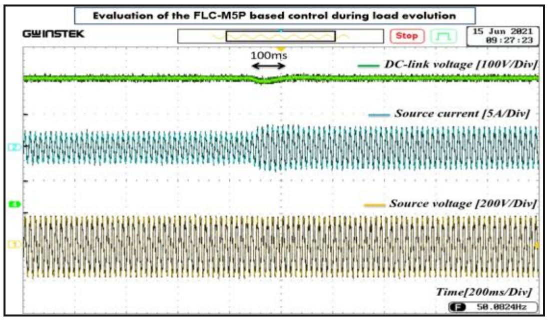

Fig. 13. Dynamic performance test under sudden change of NL load

VI. Interpretation of Results

By combining the M5P algorithm and fuzzy logic, a new control is proposed through a very fast M5P learning approach and datasets collected from a fuzzy logic controller. The proposed MATLAB code is tested in both maximum power point tracking technique and dc-link controller. In the light of the results obtained from simulation and experimental prototyping, it was revealed that the suggested tree control mode is appear to be very interesting solution. As shown in Figure 11, a good THD of 4.12% can be obtained, which is well within the 5% limit set by the IEEE Std 519-1992 standard. This solution also makes it possible to correct the power factor of the installation in parallel with the reduction in the power supplied by the main source from 246W to 192W under a real lighting condition of approximately 500W/m² and an ambient temperature of 30°C. Finally, in addition to a multifunction system configuration, we also aim to provide a new fast and efficient control that allows smooth operation in static and dynamic situations of the system. At the end, several perspectives emerge. The results summarize that the proposed technique could replace controllers suffering from complex modeling or slow real-time implementation. As future projects, we will direct our research to explore this combination of control through the use of other decision algorithms such as the C5.0 technique. The basic model (FLC) can also be replaced by collecting our basic data from other control approaches such as the ant colony optimization algorithm.

VII. Conclusion

An advanced control algorithm based on decision tree for a grid-connected photovoltaic system with active power filter capability is performed under simulation and real-time implementation. The proposed tree control appears to be an efficient solution for providing active and reactive power besides wiping out the harmonic currents at the grid side. The paper also focuses on the dynamic of the system by considering the scenarios of a sudden grid load variation. Experimental results under real conditions reveal that the pruned M5P based control is able to perform effectively resulting in a low THD of source current of 4.18% and an acceptable active power transaction with the grid utility. We can conclude that the established controller increases efficiency, which makes it an interesting alternative for the conventional or complex controller.

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