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Control of shunt active power filter for power quality improvements with PV system using MPC approach

Larouci Heguig[1], Nadhir Mesbahi[2], Yacine Guettaf[1]
[1]Laboratory of Instrumentation and Materials Applied (LIMA), Nour Bachir University Center, El Bayadh, Algeria
[2]Laboratoire de Génie Electrique et des Energies Renouvelablesd'El Oued (LGEERE), University of El Oued, El Oued, Algeria

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ABSTRACT

The major issue facing the electrical grid is the excessive use of non-linear loads, which pull distorted (non-sinusoidal) current from the grid. Considering this constraint, the objective is to remove any harmonic currents from the grid. The active filtering method has been selected, particularly focusing on the use of the shunt active filter, which provides numerous benefits. Therefore, in order to achieve effective harmonic compensation, a suitable and resilient control system is necessary for the shunt active filter. The system outlined in this study comprises a photovoltaic generator connected to the distribution electrical grid via a shunt active filter in order to simultaneously ensure the injection of renewable power generated by the photovoltaic generator into the grid and the improvement of the electrical energy quality. In this study, a model predictive current is introduced for shunt active power with fuzzy logic control to optimize the tracking of the maximum power point for the photovoltaic generator. The system was studied under various conditions, and the simulation was carried out using MATLAB/Simulink on the entire system.

Corresponding Author:

Nadhir Mesbahi
Laboratoire de Génie Electrique et des Energies Renouvelablesd'ElOued (LGEERE)
University of El Oued
El Oued, Algeria
Email: nadhir-mesbahi@univ-eloued.dz

1. INTRODUCTION

Environmental pollution is one of the major issues arising from non-renewable energies. This challenge has spurred the development of renewable energies, with solar power standing out as a top contender. What sets solar energy apart is its simple installation process and the absence of active moving components [1], [2]. To boost energy output from a solar power system, it is crucial to run the photovoltaic generator at its peak capacity. Employing maximum power point tracking (MPPT) techniques is essential in these systems to ensure optimal performance. Recently, extensive research has been concerned devising various MPPT methods aimed at maximizing the efficiency of solar energy production. These methods vary from smart techniques to those rooted in control theory [3].

One of the most popular algorithms used for tracking in MPPT is perturbation and observation or P&O algorithm. It is favored for its simplicity and low complexity. However, its drawbacks overshadow its benefits, with a significant issue being a consistent disturbance step in tracking the optimal point, along with its slow convergence to this point [4]. Fuzzy logic is the most efficient way to swiftly reach the perfect point without any complications or system modelling. This technology achieves good and stable results compared to the P&O algorithm. Moreover, it remains effective in all weather conditions, no matter the variations in temperature or shade [5].

On the other hand, with rapid advancement in power electronics, the widespread use of non-linear loads has caused significant disruptions like harmonics, unbalanced currents, and more to be introduced into the power grid. These harmonics lower efficiency, decrease the power factor, raise losses, and result in electromagnetic interference with nearby communication lines, leading to various adverse effects [6]. To tackle the issue of harmonic disturbances, various solutions have been suggested. Recent research efforts in this field have greatly aided in developing solutions and configurations based on single-phase and 3-phase diode rectifiers with special designs, passive filters, active filters and pulse-width modulation (PWM) rectifiers. Moreover, these methods rely on using passive filters, which are a common and viable solution. Specifically, inductor dan capacitor or LC passive filters act as traps for filtering out harmonic currents based on their harmonic orders [7]. They can also help offset reactive power. However, these devices have their drawbacks. For instance, they may struggle to adapt to changes in grid impedance or loads, potentially leading to resonance issues with the grid impedance [8].

In certain cases, this resonance can cause a surge in harmonic current and voltage within the grid and the filter capacitor [9]. This limitation poses a significant challenge, especially in specific scenarios. Another solution to avoid drawbacks of passive filters involves implementing a system of active power filter (APF), which is an effective means of compensating current or voltage harmonics generated by non-linear loads. To best address industrial constraints, active filters are used in parallel, series, or combined configurations [10]. In this study, we have opted for a shunt active power filter (SAPF) designed for filtering harmonic currents. Currently, this filter represents the most suitable advanced solution for pollution control, whether at the production or distribution level [11]. Active filters rely on various control strategies for their performance. One of most famous methods proposed in literature is sliding mode control, direct power control, hysteresis current control and predictive control, main objective of all these strategies is to eliminate harmonic currents and improve power factor, despite their different operating principles [12]. For many years, model predictive control (MPC) has gained great popularity in the process and chemical industries, thanks to its complex models and slow-speed dynamics [13].

Unlike chemical processes, power electronics converters have faster dynamics and complex models, prompting need for enhancements in capabilities of microprocessor and separate model to be able to use MPC in such converters. High reliability and dynamic response of MPC attracted all the recent research to use it in different uses counting power converters and filtering as a result [14]. The distinctive feature of the MPC method compared to others is its ease of implementation. The process does not require linear or nonlinear controllers in the internal loops, nor does it require a carrier modulator, as in the case of PWM modulation. Furthermore, constraints are considered thanks to its flexibility, significantly reducing the overall cost of the drive system [15]. Three basic parts ensure the outstanding performance of the active filter in compensating harmonic currents: firstly, the strategy for extracting reference currents, secondly, controlling the voltage of the DC voltage, thirdly, and method of current control used to convert pulse generation for the inverter. The more advanced the techniques employed, the more precise and effective the outcomes [16], [17].

This paper sheds light on the topic of energy quality using cutting-edge techniques found in literature known for their precision and quick response. The detailed presentation of the shunt active power filter-photovoltaic or SAPF-PV included tracking the maximum point using fuzzy logic control (FLC) techniques and determining reference currents through a modified synchronous reference frame strategy. To manage the tracking of reference currents a predictive control strategy was implemented. Study was carried out in three cases. Case 01 is about performance SAPF-PV under the balanced condition of the grid voltages. Case 02 is about performance SAPF-PV under the unbalanced condition of the grid voltages while case 03 is about performance SAPF-PV under the distorted condition of the grid voltages.

2. GENERAL SYSTEM

The system analyzed in this study, as shown in Figure 1 (see Appendix), is primarily composed of four essential elements. Firstly, a 3-phase electrical grid; secondly, a combination of linear and non-linear loads; and thirdly, a photovoltaic system connected to a boost converter, whose maximum point is tracked by a fuzzy logic control. This process is intended to ensure a supply of suitable voltage to power the fourth element, which is a SAPF controlled by an MPC strategy.

3. PV SYSTEM

The photovoltaic power generation system relies on two main components. First, the solar panels, made from silicon junctions, are configured in either series, parallel, or a combination of both. They play a crucial role in the system by generating voltage. The second component is the boost converter, which not only enhances the input voltage but also regulates fluctuations in photovoltaic voltage. The direct current converter is controlled by an MPPT controller, which tracks the peak power under sudden changes in radiation [18].

3.1. PV panel

A solar panel is made up of a collection of solar cells that function as receivers for sunlight. These cells are interconnected within a specific frame and are connected either in series or in parallel. Solar panels form the essential element in a solar energy system [19]. The single-diode model is widely used in solar panel modelling because of its excellent performance. An equivalent circuit diagram is presented in Figure 2.

To find the load current the single-diode model can be characterized using Kirchhoff's law current as in (1).

$$I_{pv} = I_{ph} - I_D - \frac{v_{pv}+R_S \times I_{pv}}{R_p} \tag{1}$$

Where I_{ph} is the photo current; I_D is the current through diode; V_{pv} represents PV cell voltage; R_s is series; and R_p is the parallel resistance of the PV cell. The photocurrent, I_{ph} can be written as in (2).

$$I_{ph} = \frac{G}{G_{ref}}\left[I_{phref} + \mu_{sc}\left(T_{cell} - T_{ref}\right)\right] \tag{2}$$

Where T_{cell} and T_{ref} represent PV cell and standard temperatures in kelvin; G denotes isolation; and μ_{sc} represents temperature coefficient.

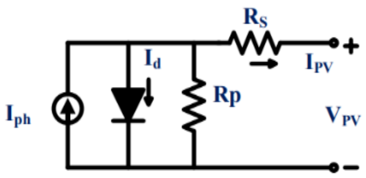


Figure 2. Equivalent circuit of a solar cell

3.2. MPPT controller design

FLC is one of the most famous artificial intelligence-based schemes in control units due to its high and excellent performance and low complexity in program implementation. It is based on three important steps: fuzzification, rule evaluation, and defuzzification. In the fuzzification stage, the measured changes in the photovoltaic output current and voltage are used to determine the membership functions (MFs) of the FLC-based MPPT control unit. During the rule evaluation stage, the control procedure is determined depends on the linguistic rules of FLC, as illustrated in the Table 1 [20], [21]. In the defuzzification stage of the FL control unit, the expected value of the MF output is obtained and fed into the rest of the system. A fuzzy controller is designed with two inputs and one output. Figure 3 illustrates the mechanism of fuzzy logic. The input variables are the error (*E*) and the error change (*CE*), as defined in (3) and (4) for the sampling times (*k*).

$$E(K) = \frac{P(K)-P(K-1)}{V(K)-V(K-1)} \tag{3}$$

$$CE(K) = E(K) - E(K-1) \tag{4}$$

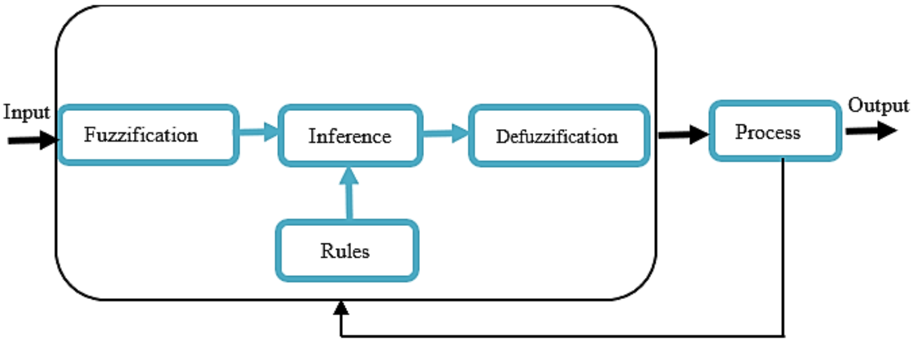


Figure 3. Fuzzy logic structure

Table 1. The rules of fuzzy logic controller

CE/E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NM	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PB	PB	NS
PM	NS	ZE	PS	PM	PB	PB	ZE
PB	PB	ZE	PS	PM	PB	PB	PB

Note: Change of Error/Error (CE/E) Négatif-Big (NB), Négatif-Medium (NM), Négatif-Small (NS), Zero (ZE), Positif-Big (PB), Positif-Medium (PM), Positif-Small (PS)

4. GENERATING REFERENCE HARMONIC CURRENTS (MSRF-METHOD)

This method is based on the SRF technique and involves the simplified generation of unit vectors rather than a phase-locked loop (PLL) circuit for synchronization purposes [22], [23]. This method has been shown to achieve better performance even when the grid is disturbed or unbalanced. It involves the transition from a balanced 3-phase system (abc) to a 2-phase system (dq). The transition from the real (abc) system to the (dq) system is achieved through the Clark transformation in the fixed and orthogonal ($\alpha\beta$) reference frame, followed by axis rotation. Based on the Park transformation, this method transitions the currents (i_α, i_β) from the load to currents (i_d, i_q) in a 2-phase (dq) reference frame. This transformation is achieved by the electrical angle θ. Here, we use low-pass filters (LPF) to minimize the voltage harmonics of the input signals, as they are central to the control [24]. The basic configuration of the multi-spatial receptive field or MSRF method is shown in Figure 4.

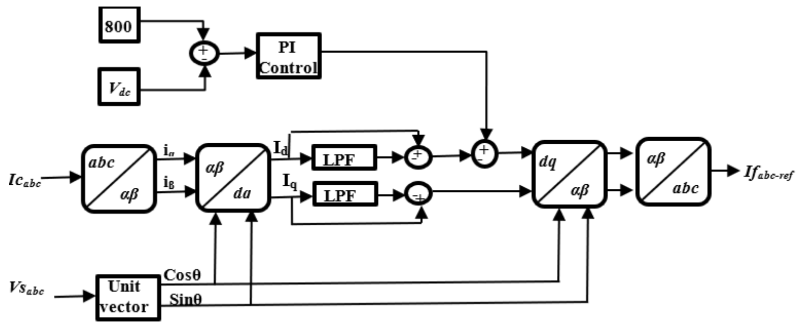


Figure 4. Block diagram of MSRF diagram

5. MPC STRATEGY FOR CURRENT CONTROL

The MPC depends on only a finite number of possible switching states can be generated by an inverter and that system models can be utilized in predicting the behavior of the variables at each switching state. To apply the proper switching state, a selection criterion must be defined. This selection criterion is expressed in the form of a cost function, which will be determined for the expected values of the variables under control [25], [26]. The switching state which minimizes the cost function is chosen. A functional scheme of the MPC used on current control for a 3-phase inverter is illustrated in Figure 5. The fundamental steps of this control approach can be limited to three steps: i) Creating a model for predicting the future behavior of variables throughout time; ii) Creating a cost function to compute the difference between the model and its reference value; and iii) Finally, the best performance is achieved by reducing the cost function.

5.1. Inverter model

The 2-level insulated-gate bipolar transistor (IGBT)-based 3-phase voltage inverter are composed of six bidirectional current switches (controlled for turn-on and turn-off) conducting current in both directions through anti-parallel diodes. Usually, it is connected to two passive stages—one on the AC side and one on the DC side. The passive stage on the AC side primarily serves for filtering and is composed of output inductance [27]. The output voltage can be described as a space vector in a stationary frame ($\alpha\beta$) according to the (5).

$$v_{\alpha\beta} = R_f i_{\alpha\beta} + L_f \frac{di_{\alpha\beta}}{dt} + e_{\alpha\beta} \tag{5}$$

Where R_f and L_f refer to the values of the filter's resistance and inductance, $i_{\alpha\beta}$ refers to the current passing through the filter, $v_{\alpha\beta}$ is the voltage carrier output by the SAPF, and $e_{\alpha\beta}$ is the estimated back-emf.

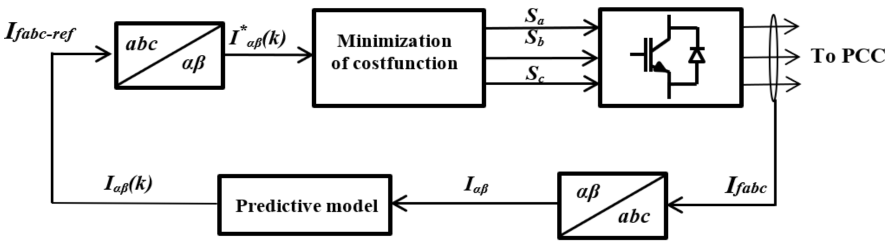


Figure 5. Predictive current control functional diagram

5.2. Discrete-time model for prediction

The key of MPC technique lies in understanding the proper mechanism to track the measured current of the filter and its reference throughout the sampling period. To achieve good results and high precision performance, a discrete-time model is required [28], by applying a discrete time model during the sampling time T_s and depends on the Euler approximation of (5), the future value of the filter current at time ($k+1$) can be predicted as in (6).

$$i_{\alpha\beta}(k+1) = \left(1 - \frac{R_f T_S}{L_f}\right) i(k) + \frac{T_S}{L_f}\left(v_{\alpha\beta}(k) - \hat{e}_{\alpha\beta}(k)\right) \tag{6}$$

From (6), we extract the estimated back-emf as in (7):

$$\hat{e}_{\alpha\beta}(k-1) = v_{\alpha\beta}(k-1) - \frac{L}{T_s} i_{\alpha\beta}(k) - \left(R - \frac{L}{T_s}\right) i_{\alpha\beta}(k-1) \tag{7}$$

where $\hat{e}_{\alpha\beta}(k-1)$ is the estimated value of $\hat{e}_{\alpha\beta}(k)$.

5.3. Cost function

The error between the reference currents and predicted currents at sampling time is evaluated through the cost function. This function can be expressed by several analytical expressions [29]. In our study, we introduce an expression for this function, which is defined by using the form in (8):

$$g = |i_\alpha^*(k+1) - i_\alpha(k+1)| + \left|i_\beta^*(k+1) - i_\beta(k+1)\right| \tag{8}$$

where $i_\alpha^*(k+1)$ and $i_\beta^*(k+1)$ represent the real and imaginary components of the reference current, and $i_\alpha(k+1)$ and $i_\beta(k+1)$ also represent the real and imaginary components of the predictive current. The flowchart of the algorithm of MPC for the SAPF is shown in Figure 6.

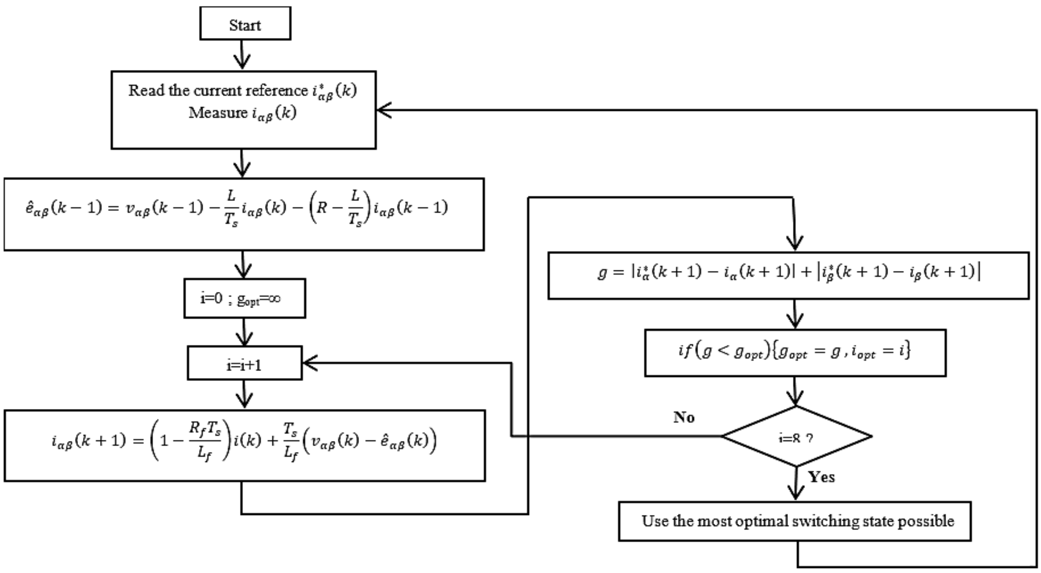


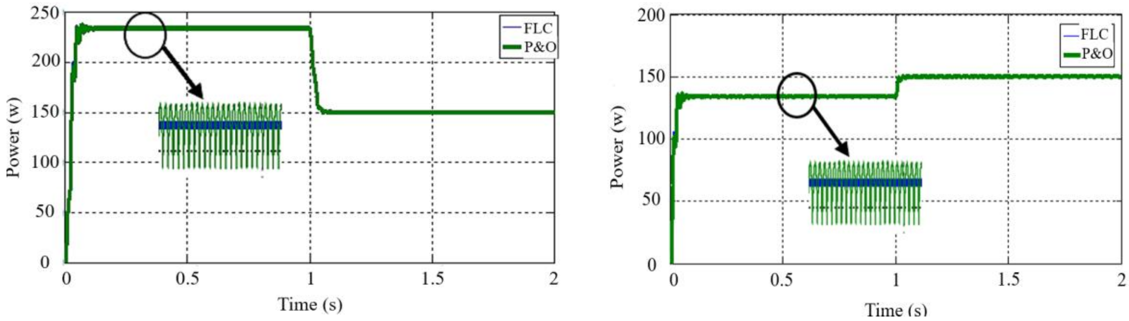
Figure 6. Steps of the predictive current control

6. RESULTS AND ANALYSIS

To evaluate the efficiencies of the SAPF powered by a PV generator using the MPC approach, we utilized MATLAB/Simulink software to present in detail the results of our work with parameters listed in Table 2. We will begin by comparing the performance of fuzzy control with the traditional P&O method under the influence of sudden changes in shade and temperature as in Figures 7(a) and 7(b). Also, the system's overall performance will be demonstrated under several operating conditions, as shown in Figures 8(a)-8(c).

Table 2. Parameters of the simulation SAPF

Parameter	Value	Parameter	Value
V_s, f_s	220 V, 50 Hz	R_f, L_f	5 mΩ,5 mH
R_s, L_s	25 mΩ, 19.6 µH	R, L	26 Ω,5 mH
R_c, L_c	1.2 mΩ,0.3 mH	K_i, K_p	0.56, 0.52
V_{dc}, C_{dc}	800 V, 2350 µF		



(a) (b)

Figure 7. Power of the photovoltaic generator with P&O and FLC controls for:
(a) T=25 °C; E=500-1000 W/m² and (b) T=25-50 °C; E=1000 W/m²

(a) (b) (c)

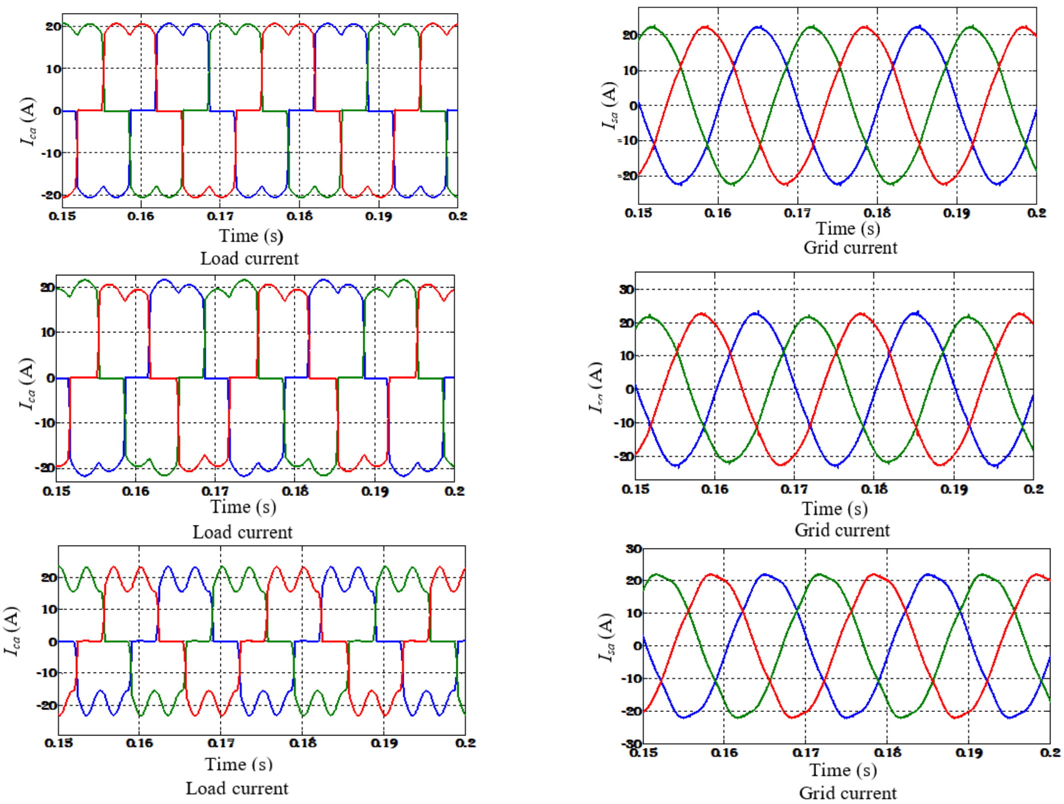


Figure 8. SAPF simulation results: (a) balanced sinusoidal grid voltage, (b) unbalanced grid, and (c) distorted grid

The simulation results were obtained for a PV module unit with the characteristics (P_{max} = 150 W, V_{max} = 35.5 V, I_{max} = 4.34 A, I_{sc} = 5.5 A, and V_{oc} = 45 V) and demonstrated that the P&O algorithm is relatively easy to apply, but it tends to oscillate around the maximum power point due to its perturbative nature. This behavior can cause system instability and reduce the efficiency of MPPT. On the other hand, fuzzy control has shown remarkably impressive results compared to P&O, offering a better response time than P&O control. Furthermore, if the maximum point is achieved, fuzzy control remains closer to the maximum power point than P&O control in both cases (a and b). This stability ensures a constant voltage supply for powering the inverter used in filtration.

The results show a noticeable distortion in the load current due to the non-linear load. However, when the SAPF current is injected into the grid, the grid current regains its original shape across all our cases (a, b, and c) as shown in Figures 8 and 9. Furthermore, in Figure 10, the voltage of the DC-DC converter V_{dc} precisely follows its reference, with very little deviation from the reference value. Additionally, the analysis of the spectrum in Figure 11 indicates a significant decrease in the total harmonic distortion (THD) of the grid current. Grid current THD has been minimized from 28.56% to 1.61%, it can be noted from this value that THD of grid current is restricted as per IEEE-519 standard. It can therefore be concluded that, under these conditions, this method is suitable and allows for the correct identification of the harmonic components of the load currents.

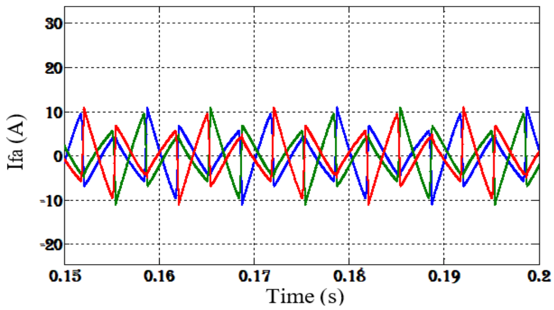


Figure 9. Filter current

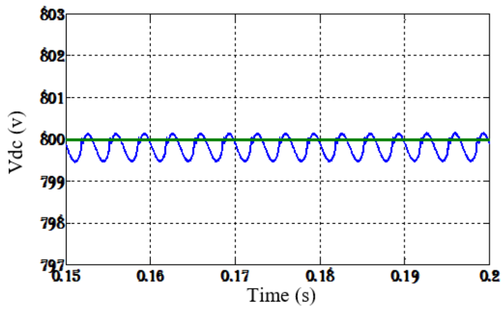


Figure 10. DC-link voltage

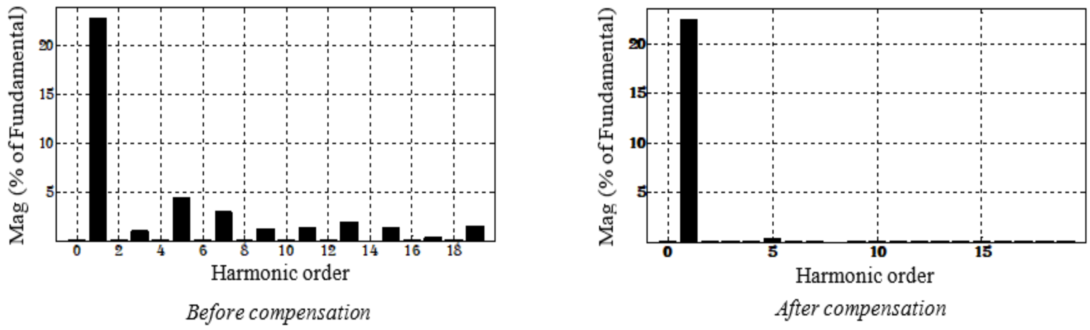


Figure 11. Harmonic spectrum of grid current phase-a

6. CONCLUSION

This paper proposed a photovoltaic (PV) interface two-level voltage source inverter-based 3-phase shunt active power filter to enhance power quality under ideal as well as non-ideal grid voltage conditions. The interest of this system lies in the minimization of environmental pollution by adding a renewable energy source PV to an SAPF to assure good power quality in this installation. To enhance the performance of the SAPF, MSRF theory and PI regulator are incorporated. The reference current for compensation is generated using MSRF theory, and the control for the maintenance of smooth DC link voltage is provided by the PI regulator. In addition, for the purpose of suppressing the harmonics in the system, the MPC approach is employed to control shunt active power filter due to its simplicity. The simulation results obtained confirm the effectiveness and performance improvement of the proposed scheme under various grid voltage conditions.

APPENDIX

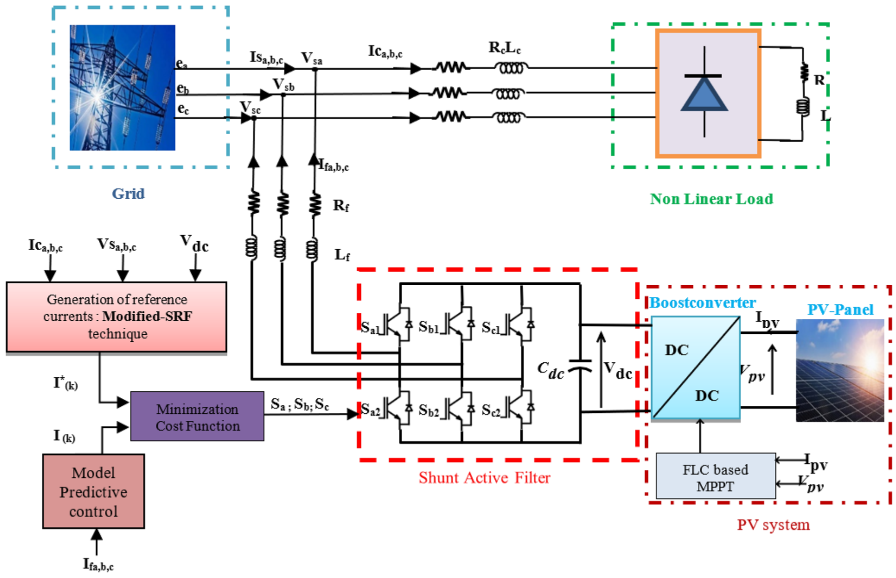


Figure 1. Comprehensive system plan

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BIOGRAPHIES OF AUTHORS

Larouci Heguig was born on 5 August 1995 in El Oued, Algeria. He received a master's degree in electrical engineering from the University of El Oued in 2019. He is currently working toward his Ph.D. thesis in Electrical Energy at Nour Bachir University Center, El Bayadh. His fields of interest are control technology of photovoltaic systems, improving power quality, and model predictive control. He can be contacted at email: l.heguig@cu-elbayadh.dz.

Nadhir Mesbahi received the Eng., M.Sc., and Ph.D. degrees in Electrical Engineering from the Department of Electrical Engineering, Badji Mokhtar–Annaba University, Annaba, Algeria, in 2000, 2007, and 2014, respectively. He is currently a full professor with the Department of Electrical Engineering, University of El Oued, Algeria. Since 2021, he has been a research member of the El Oued Electrical Engineering and Renewable Energy Laboratory (LGEERE). His research interests include control of power converters, active power filters, and model predictive control. He can be contacted at email: nadhir-mesbahi@univ-eloued.dz.

Yacine Guettaf was born in Tiaret, Algeria, in 1986. He received the magister and the Ph.D. degrees respectively, in 2012 and in 2016 from the University of Sciences and Technology of Oran (USTO MB), Algeria. His main research interests include modelling and simulation of the power electronics' devices: more specifically the analysis and design of switched mode power supply at the Instrumentation and Applied Materials Laboratory (LIMA), who is also the head of his research team from among his four teams. He is a full professor of electrical engineering in Nour Bachir University Center, El Bayadh, Algeria. He can be contacted at email: y.guettaf@cu-elbayadh.dz.