



Fuzzy Logic with PI Controller and Multivariable Filter for Harmonic Reduction Based Hybrid Active Power Filter

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Abstract—In this paper, a Fuzzy Logic used with Proportional Integral (PI) controller to regulate the DC bus voltage of Hybrid Power Filter (HPF) in order to improve power quality of the three-phase distribution system. The electricals and electronics equipment generate a large quantity of harmonics currents which effects several problems in the supply system. The principal goal of this study is to improve the efficiency of HPF, suppress harmonics currents and consequently reduce Total Harmonic Distortion (THD) under 5%. The suggested control mechanism is d-q theory based on Multivariable Filter (MF) and Fuzzy Logic for extracting reference currents. The efficiency of combined fuzzy logic and PI controller is evaluated by the simulation study using Matlab/Simulink software and the obtained results are presented.

Index Terms—fuzzy logic controller, PI controller, hybrid filter, harmonic currents, multivariable filter.

I. INTRODUCTION

The development of power electronics and the flexibility of the use of semiconductors in the electronic devices has led to a negative impact on the power quality. These devices act as a nonlinear load that generates harmonic currents. In addition, they consume reactive power and hence the source current waveform loses its sinusoidal form and the power factor deteriorates. As a result, the energy distributors and electrical engineers have been developed various solutions in order to reduce harmonic currents and solve this problem. One of the used solutions is a filtering technique such as an LC filter (called passive filter), an active filter and a hybrid filter with several types of control strategies [1]-[3]. In this paper, the hybrid filter is selected regarding its performance in compensating harmonic currents, it offers an economic advantage over active filters [4]-[7]. This filter consists of a three-phase active filter connected with LC passive filter. The main role of active filter is helping passive filter absorb harmonic currents as well as improve filtering performance.

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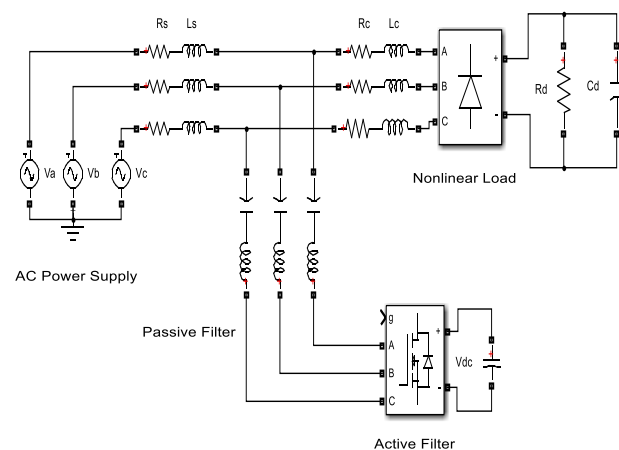


Figure 1. General System Configuration.

Many types of control methods for HPF have been studied in the literature in order to generate switching patterns for the inverter, based on the accuracy of the reference's current extraction and on the current control technique. Therefore, in our study we propose a control technique based on d-q theory companion with fuzzy logic with a PI regulator and a multivariable filter to reduce harmonic distortion. Fig 1, show the general configuration of the studied system, which consists of a three phase AC power supply and hybrid filter connected to the system between the power source and the nonlinear load. This hybrid filter consisted of an active filter connected in series with an LC passive filter [8]. The nonlinear load is a three-phase bridge diode rectifier feeding a RC load.

II. CONTROL TECHNIQUE AND DC VOLTAGE REGULATION.

The applied control strategy in this paper based on d-q theory to generate reference currents, and fuzzy logic with PI controller to regulate the DC voltage of source inverter (V_{dc}) and provide a real power to compensate the system losses [9][10].

Fig 2, presents the diagram of d-q theory. The control technique is split into two stages, the first one for creates the harmonic currents and the second focuses on creating the switching signals of voltage inverter.

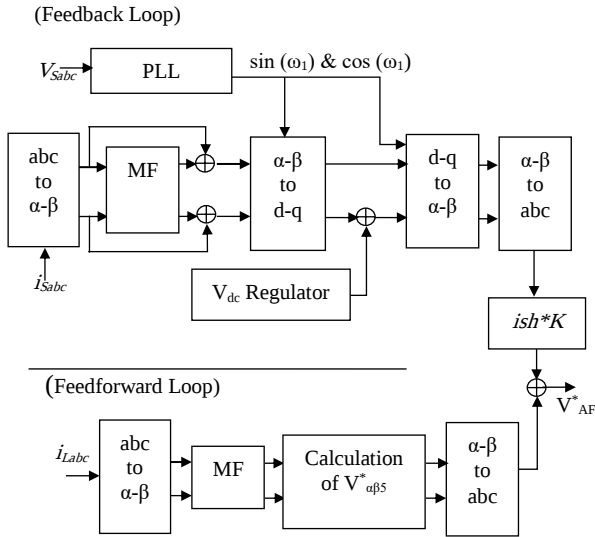


Figure 2. Diagram of Control Scheme.

As presented in the Fig 2, the control scheme has two loops (feedback loop and feedforward loop).

The feedback loop is used to extract the three harmonic currents i_{Shabc} from source currents i_{Sabc} at fundamental frequency, here we need three source sinusoidal voltages (V_{Sabc}) to be detected and transformed into α - β plane in the PLL circuit in order to produce sine and cosine signals:

$$\begin{bmatrix} V_{S\alpha} \\ V_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix} \quad (1)$$

Additionally, three phase source currents (i_{Sabc}) are recognized and converted into α - β in order to execute the d-q transformation:

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} \quad (2)$$

In the output of this loop, we can obtain the three harmonic currents (i_{Shabc}), then by multiply these currents by the gain K , the voltage references have been generated.

$$V_{Sh}^* = i_{Sh} \times K \quad (3)$$

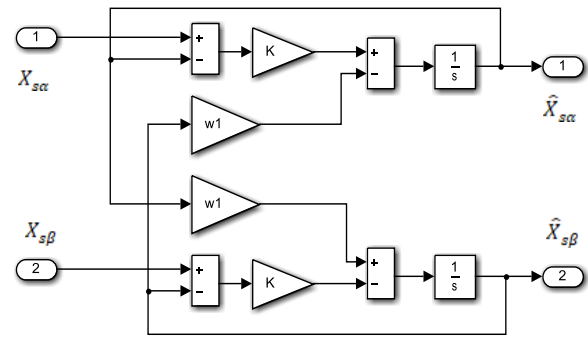


Figure 3. Multivariable Filter.

The objective of using Multivariable Filter (MF) in the control method is to optimize the performance of the control method. From Fig.3, following expressions can be obtained:

$$\hat{X}_{s\alpha}(s) = \frac{K}{s} [X_{s\alpha}(s) - \hat{X}_{s\alpha}(s)] - \frac{\omega_1}{s} \hat{X}_{s\beta}(s) \quad (4)$$

$$\hat{X}_{s\beta}(s) = \frac{K}{s} [X_{s\beta}(s) - \hat{X}_{s\beta}(s)] + \frac{\omega_1}{s} \hat{X}_{s\alpha}(s) \quad (5)$$

where (ω_1) is the fundamental frequency.

For the feedforward loop and with the aid of multivariable filter which presented in Fig 3, the three load currents (i_{Labc}) are detected and transformed into α - β in order to produce the three voltage references at 5th harmonic frequency. We tuned the MF at the 5th harmonic frequency by changing (ω_1) to (ω_5) in equations (4) and (5) in order to compute the dc components $\bar{i}_{\alpha 5}$ and $\bar{i}_{\beta 5}$ at the output of the MF, as follows:

$$\bar{i}_{\alpha 5} = \left(\frac{K}{s} [i_{\alpha}(s) - \bar{i}_{\alpha 5}(s)] - \frac{\omega_5}{s} \cdot \bar{i}_{\beta 5}(s) \right) \quad (6)$$

$$\bar{i}_{\beta 5} = \left(\frac{K}{s} [i_{\beta}(s) - \bar{i}_{\beta 5}(s)] + \frac{\omega_5}{s} \cdot \bar{i}_{\alpha 5}(s) \right) \quad (7)$$

where ($\omega_5 = -5\omega_1$) is the 5th-harmonic frequency, and ω_1 is the fundamental frequency. Note that the minus sign of ($-5\omega_1$) means the negative sequence.

This filter can be tuned at any frequency by changing the fundamental frequency (ω_1) to the desired frequency [11]-[13].

In order to generate the active filter voltage references, we lastly added the feedback voltage references to the feedforward voltage references. The switching signals for the inverter are then produced by comparing these voltage references with a triangular waveform.

III. REGULATION OF DC BUS VOLTAGE (V_{dc})

The regulation of DC capacitor voltage in this control method is very important part because it allows to obtain the better performance of the hybrid filter and stability of the system. For this reason, two types of controllers are used in our study, PI controller and fuzzy logic controller.

Firstly, by simulation study, the DC bus voltage will be controlled by using only PI controller, then we will repeat the same steps using both controllers PI and fuzzy logic and the obtained results will be compared [14].

As known, fuzzy logic theory was presented in the first time by Professor Lotfi Zadeh in 1965, it makes possible to obtain an effective way of control without need to apply any important or complex calculation steps, need only to take into account the experiences acquired by users and operators of process to be controlled [15]-[17].

The fuzzy controller receives as input an observation of the system to infer a command to be applied based on a table of decisions (rules).

The general structure of this controller can be presented into 3 parts (Fuzzification, Inference system and Defuzzification) as shown in the Fig 4.

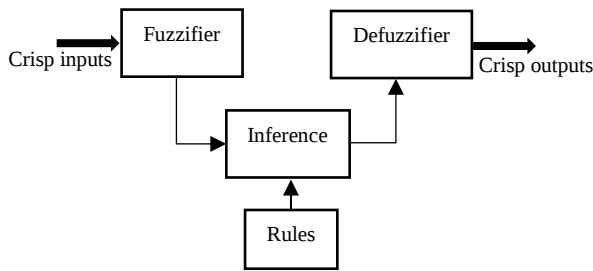


Figure 4. General Structure of Fuzzy System.

When designing a fuzzy logic step, we need to studying the system to be adjusted and making an adequate description of it, then determining the adjustment strategy and implementing it. Generally speaking, this approach should be changed in order to identify an appropriate behaviour [21]. Fig. 5, shows the block diagram of DC bus voltage regulator which has two inputs and one output. The reference value V_{dc}^* (105V) is compared with the measured value V_{dc} , the resulting error (e) is used as a first input to the fuzzy logic controller while its derivative (Δe) used as a second input.

$$e(K) = V_{dc}^*(K) - V_{dc}(K) \quad (8)$$

$$\Delta e(K) = e(K) - e(K-1) \quad (9)$$

In the fuzzification step, the two digitals' inputs error (e) and (Δe) are transformed into fuzzy variables and defined as seven triangular memberships shown in Fig. 6: negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB). As a result, the inference stage defines the fuzzy output as seven triangular memberships and determines the fuzzy output based on the categories of inputs based on the rule table: negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB) [18]-[20].

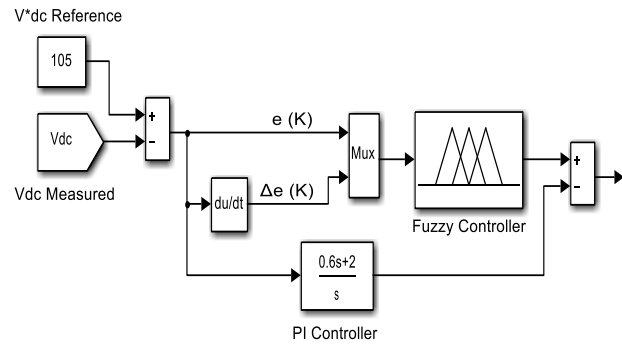


Figure 5. Regulation of Inverter Voltage (Vdc).

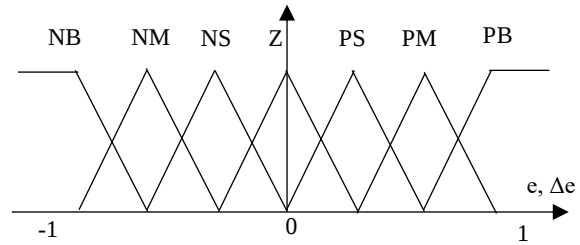


Figure 6. Inputs Variables of Fuzzy Controller (e , Δe).

Defuzzification step, because unable to using fuzzy variable (linguistic variable) directly as fuzzy output. Therefore, we need to converts it to crisp output, defuzzification step ensure this converting process [22][23]. The Table 1, shows the 49 fuzzy rules that will be required for the fuzzifier and defuzzifier phase.

TABLE 1. FUZZY RULES TABLE.

$e \backslash \Delta e$	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

IV. SIMULATION RESULTS

Simulation results of the studied system are achieved by using MATLAB/Simulink tool box. The main objective of this study is to evaluate the effectiveness of the hybrid filter and the control method with two different kinds of capacitor voltage regulation. The system parameters are shown in Table 2.

In order to remove undesired harmonic currents, the hybrid active power filter under study is made up of a three-phase pure active filter and an LC passive filter that is adjusted at the seventh harmonic frequency. A diode rectifier coupled to an RC parallel load is regarded as a nonlinear load.

The diode rectifier can be playing the role of converter the power from ac to dc. The main goal of feedforward loop in control scheme is to suppress the fifth harmonic frequency which is the most influential harmonic component, while the feedback control loop is used for the rest of harmonics currents.

TABLE 2. STUDIED SYSTEM PARAMETERS.

Power supply parameters	
System voltage	480 V
System frequency	60 Hz
Inductor: L_s	0.15mH
Filter parameters	
Passive filter Inductor: L_F	2.5mH
Passive Filter Capacitor: C_F	57.6 μ F
Inverter Capacitor: C_{dc}	1500 μ F
DC bus capacitor voltage: V_{dc}	105 V
Load parameters	
Resistor: R_d	21 Ω
Capacitor: C_d	1500F
Gain: K	20

Firstly, the system is studied with the regulation of dc capacitor voltage that achieved by only proportional integral PI controller, this regulation is done by comparing between the measured DC bus capacitor voltage V_{dc} with its reference voltage V_{dc}^* , the resulted error is used as input to controller (controller gain set to $K_p = 10\Omega-1$ and $K_i = 0.3\Omega-1s-1$).

Fig. 7 and 8, illustrate the response of the three-phase hybrid filter, we present in particular the source voltage, load current, filter current, source current, active filter voltage and capacitor voltage (V_{dc}).

Table 3 shows the total current harmonic distortions (THD) of load current and source current, and the ratio of each harmonic current with respect to the fundamental current. We can see that the load current contains a large amount of the 5th harmonic current, so that its current THD reaches 25.75% before filtering.

The obtained results present that source current became sinusoidal waveform. With regard to the waveform of Dc bus voltage V_{dc} , we can notice that it has some difficulty to follow its reference voltage and it take some time to reduce the ripples and reaches the reference value (105V).

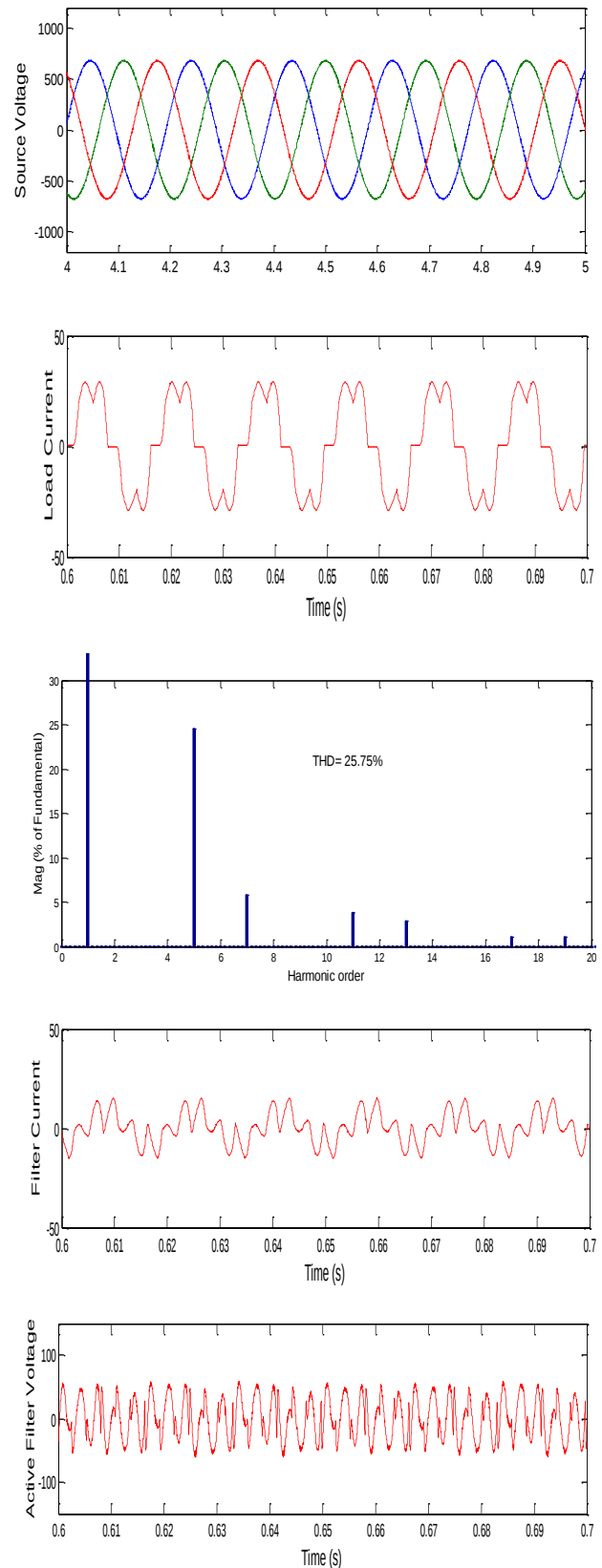


Figure 7. Simulation Results with PI Controller, from top to bottom (three ac source voltage, load current, harmonic order of load current, filter current and active filter voltage)

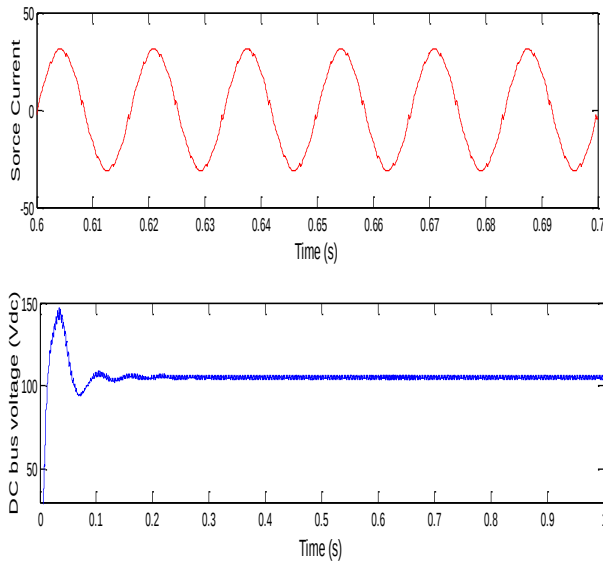


Figure 8. Simulation Results with PI Controller (source current and DC bus capacitor voltage V_{dc})

Secondly, Fig. 9 and 10, shows the obtained results when the regulation of Dc bus voltage V_{dc} carried out by using fuzzy logic controller with PI controller (we used the same proportional-integral controller gain $K_p = 10\Omega-1$, $K_i = 0.3\Omega-1s-1$).

PI controller yields the same results for waveforms such as source voltage, load current, filter current, and active filter voltage.

Moreover, it appears clearly from the Fig. 9 that the waveform of the source current after compensation is pure sinusoidal and the THD is reduced to a low value equal to 2.4% and the fifth harmonic current is reduced to 0.75%. These results also verify that the hybrid filter with control method applied can achieve satisfactory performance.

TABLE 3. LOAD CURRENT AND SOURCE CURRENT THD AND HARMONIC-TO FUNDAMENTAL CURRENT RATIO (%)

	5 th	7 th	11 th	13 th	17 th	19 th	THD
Load current	24.5	5.81	3.86	2.85	1.11	1.06	25.75
Source current	0.78	0.54	1.23	1.11	0.64	0.67	2.4

Also, due to fuzzy controller, the DC bus voltage (V_{dc}) reaches its reference value (105V) rapidly with the disappearance of the high peak or ripples as shown in Fig 10.

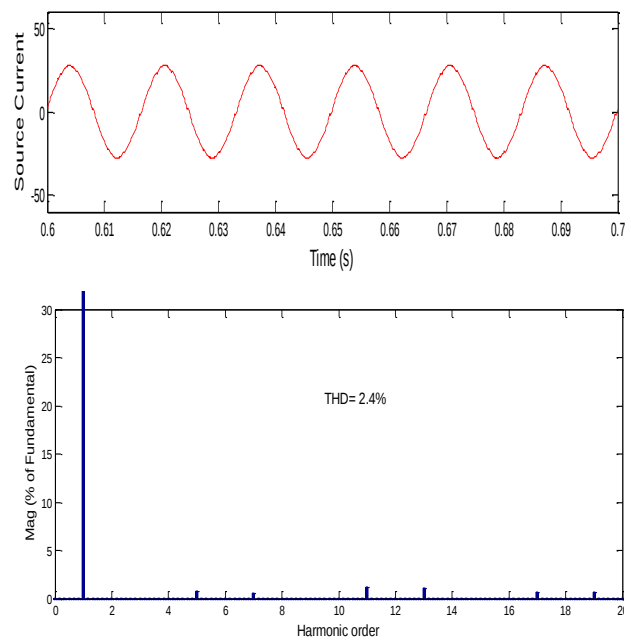


Figure 9. Simulation Result for Source Current and Harmonic Spectrum with Fuzzy and PI Controller.

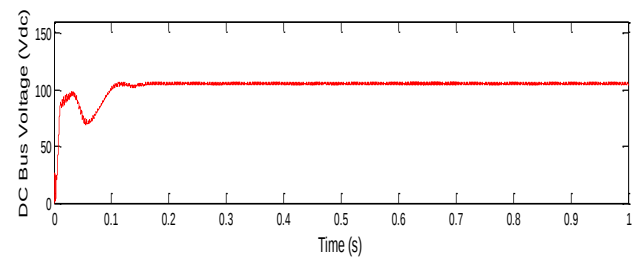


Figure 10. Simulation Result for DC bus Capacitor Voltage (V_{dc}) with Fuzzy and PI Controller.

V. CONCLUSION

This paper has studied three phase system consisted of ac power supply, a diode rectifier which plays a role of nonlinear load and hybrid filter that composed in passive filter tuned to seventh harmonic frequency and active filter. In this study, we have been described and compared by simulation study two types of voltage controller, PI controller and Fuzzy logic with PI controller and illustrated that the three phase hybrid filter has high capability to compensate harmonic currents and reduce the THD value to 2.4%.

In addition, Multivariable Filter (MF) is used in the control scheme instead of classical extraction filters like low pass and high pass filters in order to simplify calculation steps and to get the best performance of hybrid filter.

However, we have showed that the control mechanism with both controllers is able to eliminate harmonic currents generated by the nonlinear load. Also, the obtained results and the comparison that we made between two controllers validate the efficiency of the fuzzy controller with PI and demonstrate that is better for suppress the ripples from the capacitor voltage waveform (V_{dc}) and make it stable at 105V.

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