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doi:10.15199/48.2022.03.11

Efficiency of fuzzy PWM control applied to an active filter series under a disturbed voltage source

***Abstract**. The purpose of this paper is to present and demonstrate the performance of a series active power filter (SAPF) with PI controller and Fuzzy controller associated by the pulse width modulation technique with simulation validations. This performance is manifested in the compensation of voltage sags and swells and distortions source voltage, the elimination of harmonic voltage and the regulation of the load terminal voltage by injecting a voltage component in series with the source voltage that is increased or decreased with respect to the source voltage, thus maintaining the load side waveforms as pure sinusoidal. The control method used in this work is not complex and is based on Synchronous Reference Frame (SRF) Theory, that is used to control the series active power filter. It is valid only in the phase system. The effectiveness of the suggested method is affirmed by the simulation results by MATLAB/Simulink® . These results show the capability of the proposed methods.*

***Streszczenie**. Celem niniejszej pracy jest przedstawienie i zademonstrowanie działania szeregowego aktywnego filtra mocy z regulatorem PI i regulatorem rozmytym powiązanym z techniką modulacji szerokości impulsu wraz z walidacją symulacyjną. Działanie to przejawia się w kompensacji spadków i wzrostów napięcia oraz zniekształceń napięcia źródłowego, eliminacji harmonicznych napięcia oraz regulacji napięcia końcowego obciążenia poprzez wstrzykiwanie składowej napięcia szeregowo z napięciem źródłowym, które jest zwiększane lub zmniejszane w odniesieniu do napięcia źródłowego, utrzymując w ten sposób przebiegi po stronie obciążenia jako czyste sinusoidalne. Metoda sterowania zastosowana w niniejszej pracy nie jest skomplikowana i opiera się na teorii synchronicznej ramy odniesienia (SRF), która jest wykorzystywana do sterowania filtrem aktywnym. Obowiązuje ona tylko w układzie fazowym. Skuteczność proponowanej metody potwierdzają wyniki symulacji w programie MATLAB/Simulink® . Wyniki te pokazują możliwości proponowanych metod. (**Skuteczność sterowania rozmytego PWM zastosowanego do aktywnej serii filtrów przy zakłóconym źródle napięcia**)*

Keywords: Filter active series ,Pulse width modulation,fuzzy logic controller,PI controller; Synchronous Reference Frame (SRF)
Słowa kluczowe: Filtr aktywny szeregowy Modulacja szerokości impulsu Regulator logiki rozmytej Regulator PI;

Introduction

Considering the demand for improving power quality, especially in the industry, where the sensitive loads are used largely and their power supply should not be disrupted. Here, an unbroken, clean and regulated power supply is needed to supply the loads that have important tasks. On the other hand, the most common voltage disturbances occur in AC equipment, resulting in a reduction in voltage amplitude, known as sag. Thus, sag and interruptions cause most industrial problems (90%) that affect power quality[1]. On the other hand, the problem of swell is also part of the perturbation that affects power quality, which is defined by an increase in the voltage amplitude over its nominal value[2]. In addition, harmonic distortions can cause considerable problems in the entire power conversion chain, such as heating of system components, mechanical oscillations, unpredictable behavior of protective devices, and can cause damage[3], [4].

Because of these difficulties, it is necessary to provide protection devices and an effective solution to resolve these disturbances. In this paper, we are concentrating on the series active power filter (SAPF) to minimize to mitigate sag-swell and harmonics [5]–[8] that affect our system. SAPF have the same topology as active filters, with an excellent dynamic ability to restore the load voltage to its nominal value within milliseconds, while providing a power interruption to the supplied loads In other research, the series topology aims to compensate the sag with active power [9]. In the power quality field, many papers have used classical and intelligent to improve the stability, robustness and excellent dynamic response of SAPF. SAPF as mentioned in [4],[10]–[12] .

A few years later, power semiconductor technology became active for harmonic compensation. In addition to the technology of pulse width modulation (PWM) control, the development of (PWM) control technology, the development of theoretical studies made it possible to materialize practical realization. At the beginning of the 1990, the active filter experienced a revival of interest. It has been demonstrated that its harmonic compensation performances are superior to those of a passive than those of a classical passive LC filter[13].Electrical turbulence reduces and damages the electrical equipment connected to the system. There are many systems that correct this problem. Among these systems, there is the SAPF which improves the quality of the power by correcting unbalanced and harmonic voltages and adjusting them in association with a PI or Fuzzy controller.

In this work, the fuzzy logic control method of nonlinear systems has been applied in the control of a serial active filter to correct the disturbance problems more efficiently than the classical control using a PI controller.

The advantage of the proposed system over other is that it can compensate for the voltage interruption, as well as the voltage sag and swell and harmonics. The operation of the proposed system has been verified by simulations with MATLAB/Simulink.

Description system

The active series filter is a solution to protect sensitive loads against voltage disturbances of the electrical network. It is inserted between the disturbed network and the load to be protected via a voltage injection transformer. The most commonly used series active filter structure, shown in Fig. 1, consists of a power part and a control part.

The power part consists of a three-phase PWM-controlled voltage inverter,

- Energy storage elements with a DC power supply system, a second order output filter, three filter, and three single-phase voltage injection transformers.
- The control and command part includes the identification of the disturbing voltages, the regulation of the injected voltages and the control of the inverter switches, often in PWM.

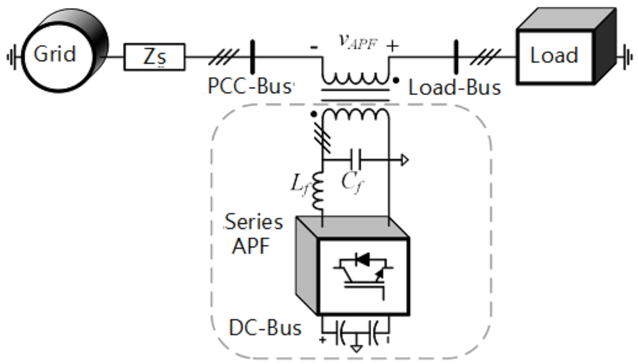

Fig.1. Conventional Series FAS structure.

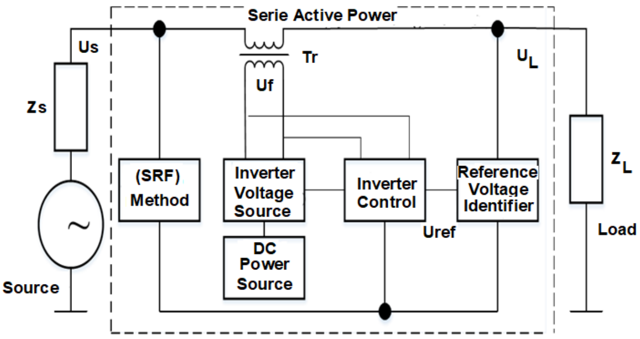

Fig.2. Series active power filter – block diagram

Reference voltage identification method based on the calculation of disturbances in Synchronous Reference Frame (SRF) Theory

The control strategy for the (SAPF) is based on the Synchronous Reference Frame (SRF) Theory[14], [15]. The supply voltage Vsabc is transformed as dq-0 by using the Transformation matrix T given by

$$(1)\quad \begin{bmatrix} V_{So} \\ V_{Sd} \\ V_{Sq} \end{bmatrix} == T \begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix}$$

$$(2)\quad T = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sin(\omega t) & \sin(\omega t - 2\pi/3) & \sin(\omega t + 2\pi/3) \\ \cos(\omega t) & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \end{bmatrix}$$

The inverse transformation matrix $T^{-1}$is used for producing the reference load voltage by the average component of source voltage and ωt produced by PLL.

$$(3)\quad T^{-1} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \sin(\omega t) & \cos(\omega t) \\ \frac{1}{\sqrt{2}} & \sin(\omega t - 2\pi/3) & \cos(\omega t - 2\pi/3) \\ \frac{1}{\sqrt{2}} & \sin(\omega t + 2\pi/3) & \cos(\omega t + 2\pi/3) \end{bmatrix}$$

The Series converter has the function of compensating the Voltage Problems like Sag. The series controllers have the PLL which supplies the sine and cosine value to the abc to dq0 and dq0 to abc transformation. In series control the reference signal is generated by the use of abc to dq0 and dq0 to abc. The reference signal generated is compared with the PCC point voltage and using the pulse width modulation signals are generated. The generated signals are given as gate pulse to the converter. The simulation diagram for the serial controller is shown in Fig.3.[16]

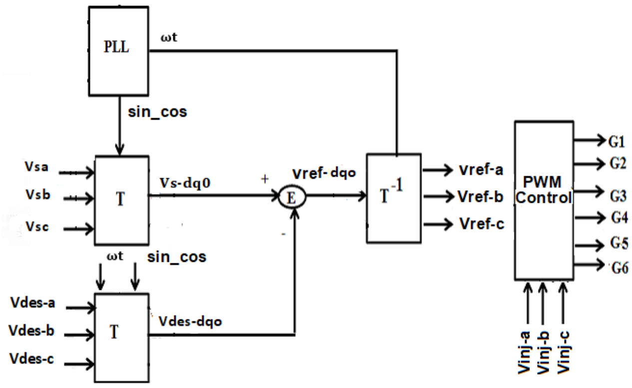

Fig.3. Series Active Power Filter (SAPF) configuration

Control of a series active filter

In this paper, a simple control approach is proposed and its effectiveness in frequent cases is evaluated by simulation. Voltage distortion and voltage sag and swell are simulated and compensated using an active filter in series with a simple control method (fuzzy logic based PWM and PI controller based PWM). In addition, a Synchronous Reference Frame (SRF) is used to extract the voltages references.In this paper, the phase-locked loop is a suitable choice for such easy structures where the voltage at the load terminal, the voltage produced by the active filter is injected in series using the device through transformer. Because in such cases, high quality voltage is important, the DC voltage of the active filter is provided by a low power diode rectifier. Fig. 4 shows the control approach for the active filter. The reference voltage is used by a pulse width modulator to produce it through the active filter.

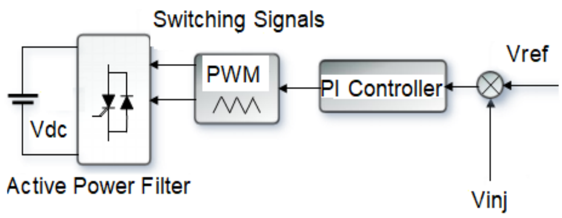

Fig.4. Active filter controller

The presence of an internal current control loop allows us to decouple the dynamic effects of the second order output filter from the series filter. The internal current control loop will be driven by an external voltage control loop. It is best if the external loop model is first order, simple and accurate enough to produce the system dynamics in a reasonable and reliable way.

Due to the fact that the series filter is considered to be a compensation voltage generator, the load current causes voltage drops in the output filter and consequently a larger deviation between the set point and the output voltage. To compensate for the error produced by the LC filter, we can close the voltage loop and based on the filter model, develop voltage correctors [17]. Thus the Ich contribution will be eliminated during the designation of the PI corrector of the voltage control loop.

The output filter model will be modified to have a structure of two nested loops, one internal in current and the other external in voltage as shown in Fig. 5.

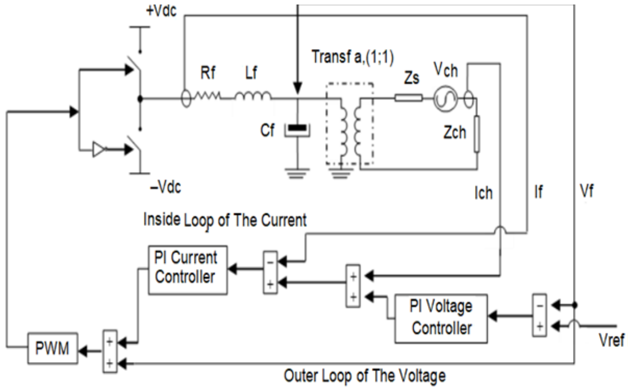

Fig.5. Principle of the two-loop control (current and voltage).

PWM control based on a PI controller

The difference between the reference voltage and the injected voltage is the final result that will be the input of the PI controller, which operates an error signal. While the output is considered as the angle that Leads to the PWM signal generator. The PWM generator then makes the pulse signals to the IGBT gates of voltage source converter (VSC). The PI controller cannot react to sudden changes in the error signal (Ɛ).

It analyses the instantaneous value of the error signal left out the rise and fall of the error. Mathematically, this practice is called the derivative error signal and characterized as Δε.

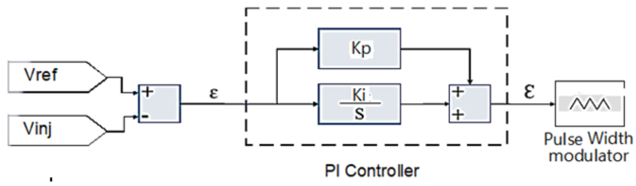

Fig.6. PI controller with PWM

PWM control based on a fuzzy logic controller

logic controller was first introduced by Professor Zadeh Lotfi of University California Berkeley in 1965. He proposed a technique of how to process an imprecise data with complex input. The idea of Zadeh's was fully utilized after the introduction and availability of modern computers and controllers applications. Fuzzy logic controllers gain interest by many researchers and system engineers in the application of control system analysis, as well as in the control algorithm for shunt active power filter applications. Fuzzy logic controller has advantages of simplicity in design procedures that does not need any accurate mathematical modeling, can work with an imprecise input of the system and it can also work with non-linearity. This fuzzy controller is very robust than classical controllers such as PI and PID controllers. In this study, a Mandani fuzzy controller was chosen and designed with linguistic term "if then". The linguistic variables for the rule base was selected as, positive Big (PB), positive medium (PM), positive small (PS), negative Big (NB), negative medium (NM), negative small (NS) and zero (ZE). However, fig. 7 depicts the general structure of fuzzy logic controller[18].

The operating principle of the fuzzy controller has been presented in this control, where the inputs of the fuzzy controller are the error and its derivative resulting from the difference between the reference harmonic voltage and the voltage generated by the active filter.

The control law of the system is a function of the error and its variation:

(4) $$\Delta u = f(e, \Delta e)$$

The most general form of this control law is defined as following

(5) $$\Delta u(k+1) = \Delta u(k) + G_s \Delta u$$

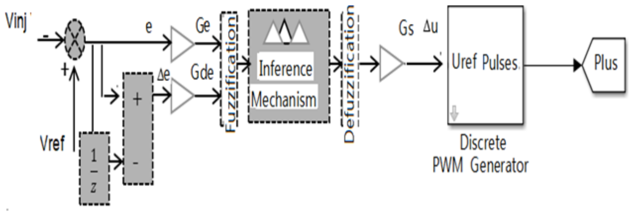

Fig.7. Fuzzy controller model built with Matlab-Simulink.

The error and its variation are defined as follows:

(6) $$\begin{cases} e(k) = G_s\left(V_{ref}(k) - V_{inj}(k)\right) \\ \Delta e(k) = G_{\Delta e}\left(e(k) - e(k-1)\right) \end{cases}$$

k: Iteration number, Δu =command signal.

Table 1. Inference table of the PWM control based on a fuzzy logic controller

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	PM
PS	NM	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PM	PB	PM	PB	PB

Results and discussion

The simulation results were obtained under the Matlab \ Simulink environment and also using the Fuzzy toolbox.In order to show the advantages of applying fuzzy logic control to adjust the switching frequency of SAPF inverter,two comparative studies have been carried out in this section: On the one hand, between the PI controller structured in PWM technique, and on the other hand between a fuzzy logic controller of a PWM strategy in order to stabilize the modulation of series active filter inverter. the aim of checking further the effectiveness of the proposed control techniques, one type of disturbed source voltage (voltage sag, voltage swell, voltage distortion (Fig.8)) is presented in this work. Figures 9 and 10 and 11 show the frequency spectrum of the disturbed source voltage respectively according to its distribution types.

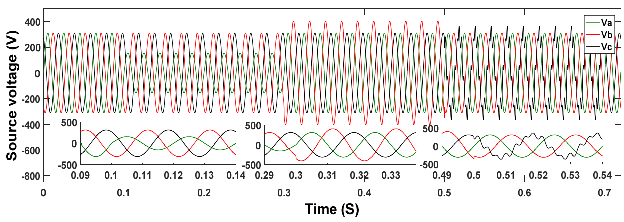

Fig.8. waveform of the disturbed source voltage of sags and swells and harmonics

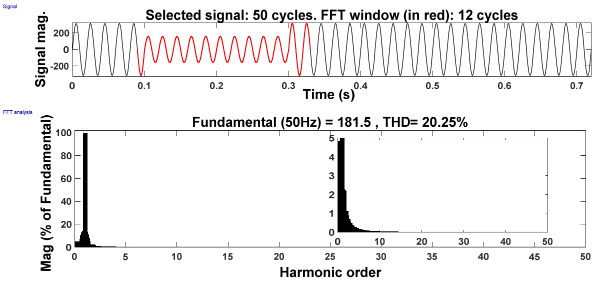

Fig.9. Spectral analysis for source voltage sags disturbed

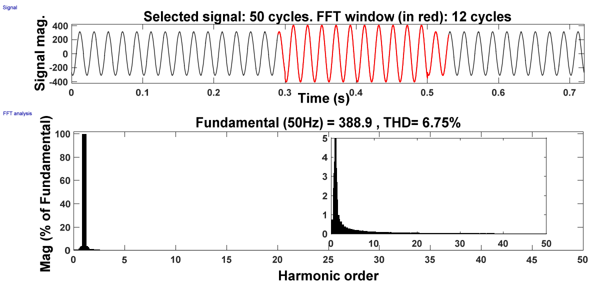

Fig.10. Spectral analysis for source voltage swells disturbed

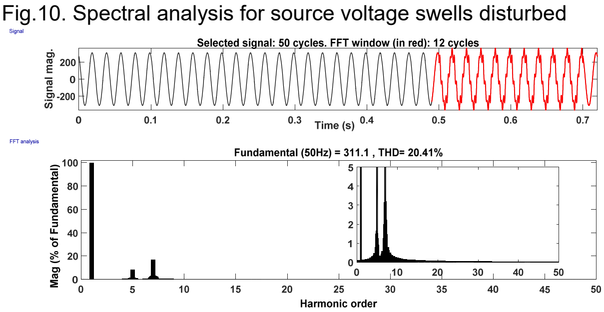

Fig.11. Spectral analysis for source voltage harmonics disturbed

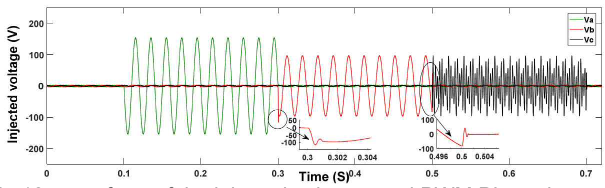

Fig.12. waveform of the injected voltage used PWM PI regulator

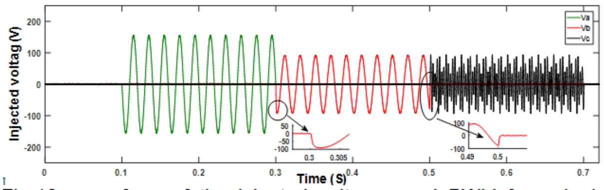

Fig.13. waveform of the injected voltage used PWM fuzzy logic controller

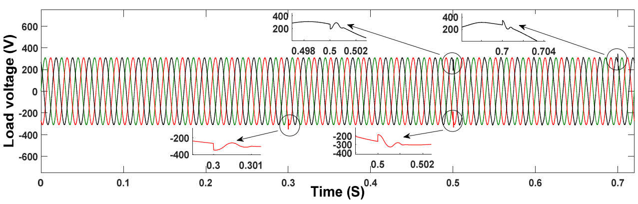

Fig.14. waveform of the load voltage with PWM method used PI controller

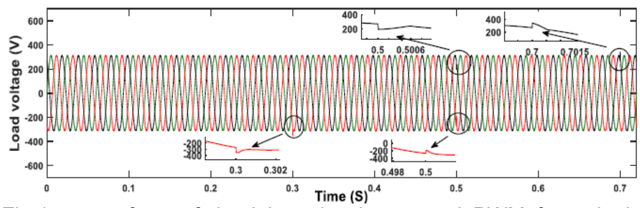

Fig.15. waveform of the injected voltage used PWM fuzzy logic controller

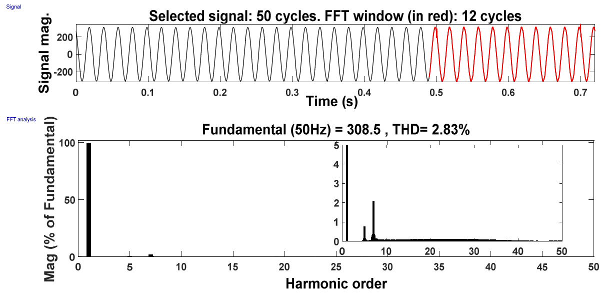

Fig.16.Spectral analysis correction for source voltage harmonics disturbed (PWM PI regulator)

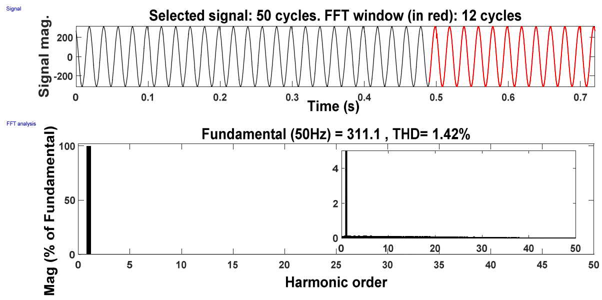

Fig.17.Spectral analysis correction for source voltage harmonics disturbed (fuzzy logic controller)

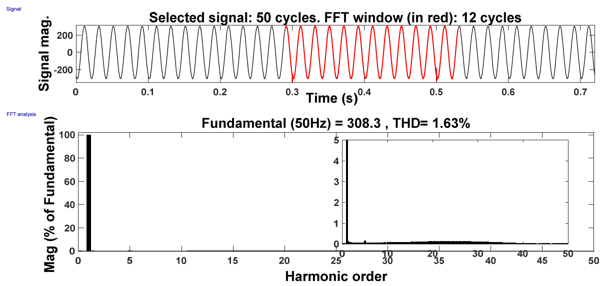

Fig.18.Spectral analysis correction for source voltage swells (PWM PI regulator)

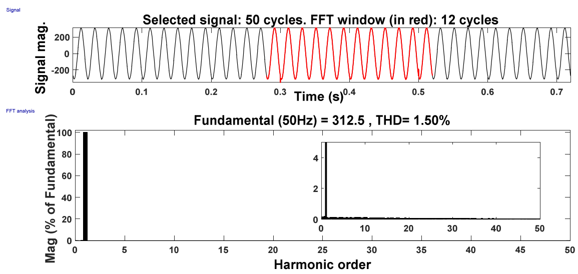

Fig.19.Spectral analysis correction for source voltage swells (fuzzy logic controller)

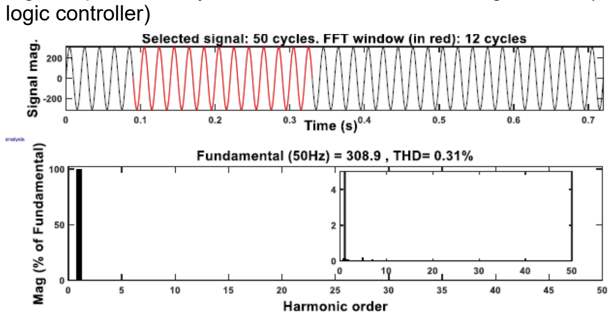

Fig.20.Spectral analysis correction for source voltage sag (PWM PI regulator)

we can see that from the instants t=0.1s, t=0.3s, t=0.5s (figs. 9,10,11) the series active power filter starts to correct the types of voltage disturbances, by injecting compensating voltages having waveforms well synchronized and in phase opposition with the source voltage (figs. 8,14,15).

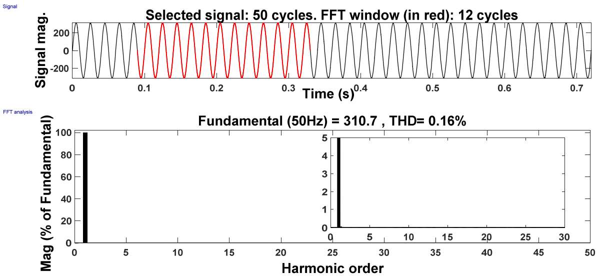

Fig.21.Spectral analysis correction for source voltage sag (fuzzy logic controller)

The load voltage (case sag voltage) has a total harmonic distortion rate equal to 0.31% with PWM-PI and equal to 0.16% with PWM-fuzzy logic (figs. 20, 21), where the source voltage has a THD equal to 20.25% (fig. 9) .In this part of the simulation, we will analyze the robustness in terms of speed and accuracy of SAPF compensating for voltage sags.

The load voltage (cas swell voltage) has a total harmonic distortion equal to 1.63% with PWM-PI and equal to 1.50% with PWM-fuzzy logic (figs. 18, 19), where the source voltage has a THD equal to 6.75%(fig. 10).SAPF starts to compensate and correct perfectly the swell voltages produced on the connection point, injecting through the transformer compensating voltages that are well synchronized and in phase opposition with the source voltage.

Table 2.THD values of the load voltage for the different techniques used

before filtering	After filtering with PWM-fuzzy logic Controller	After filtering with PWM-PI regulator
Case of the voltage sag THD=20.26%	THD= 0.16%	THD =0.32%
Case of the voltage swell THD= 6.75%	THD= 1.50%	THD=1.63%
Case of the harmonics voltage THD=20.41%	THD=1.42%	THD=2.83%

Table 3. Parameters of the studied system

Power grid					
Parameter	Source voltage	Frequency	source resistor	source inductance	
Values	380 v	50 Hz	0.0001 Ω	3e-6 H	
Non-linear load					
Parameter	Rectifier resistor	Rectifier inductance	Load inductance	Load resistor	
Values	12 Ω	3e-3 H	3e-3 H	1 Ω	
Series active power filter					
Parameter	filter inductance	Filter resistor	PI current and voltage Controller parameters	Capacitor C1=C2	Filter Capacitor
Values	1.4814e-04 H	0.0020 Ω	Kp= 5,3818/ 27,6039 Ki= 3,5480e−4/ 1,003e3	0.0860 F	150.2773e-05 F

The voltage at the terminals of the load (case of the harmonics voltage) has a total harmonic distortion rate equal to 2.83% with PWM-PI and equal to 1.42% with PWM-fuzzy logic(figs 16,17), where the source voltage has a THD equal to 20.41%(fig. 11). The load is therefore well protected against voltage harmonics.

As can be seen in (figs 12, 14), in both cases the active power filter in series successfully compensated for the voltage harmonics. For the PWM strategy structured by PI regulator represents in the load voltage curve very complicated disturbance amplitudes, but the PWM technique based on fuzzy logic (fig. 13, 15), it regulates and cancels the disturbances during the filtering operation by using its fuzzy set that makes the system act in a very reasoned and flexible way, we see in the load voltage.

Conclusion

In this paper, influence of the PWM method based on fuzzy logic has been presented with results agreeable and much validated than the PWM technique based on the PI regulator. The main objective of the proposed control strategies is to obtain a quasi-sinusoidal load voltage under the constraints of the disturbed voltage of sags and swells and harmonics. The simulation results confirmed the excellent performance of the suggested Fuzzy controllers and the good PI effect, even in transient and steady state conditions. The control strategy using classical controllers gives satisfactory results, but they are more and more defeated by the lack of robustness due not only to poor modeling but also to operating conditions, such as the effect of load variation or active filter parameters. The most important advantage of the adaptive fuzzy logic control technique over other tuning strategies is that the controller structure can be improved by acting on a number of factors constituting the internal configuration of this type of controller (input and output gains,fuzzification, inferences and defuzzification block).

Acknowledgement

This project was financially supported by the Directorate General for Scientific Research and Technological Development - Algerian Ministry of Higher Education and Scientific Research of Algeria.

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