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Implementation of a cascaded fuzzy sliding mode control of hybrid power filter

***Abstract**. This paper provides an experimental analysis of a non-linear load-based disturbed system. The shunt hybrid power filter is proposed to avoid propagating the non-linear load-based harmonic current and giving compensation for reactive power. shunt hybrid power filter is a combination of a small-rating active power filter and a passive 5th, 7th harmonic tuned LC filter. In order to control a power shunt hybrid filter to minimize the total harmonic distortion, we use active and reactive instant power theory. In this article, we use the controller PI control technique in the first section and the second part, we use the flow logic and mode control sliding through the device, and we compared a theme. The output of shunt hybrid filter in reducing harmonic distortions and compensating for reactive power is defined in the experimental results. Through this research paper, we conclude that this type of hybrid filter had a significant role in reducing the THD ratio from 29 to 3.7*

***Streszczenie.** W artykule przedstawiono eksperymentalną analizę nieliniowego układu zaburzonego opartego na obciążeniu. Zaproponowano bocznikowy hybrydowy filtr mocy, aby uniknąć propagacji nieliniowego prądu harmonicznego opartego na obciążeniu i zapewnić kompensację mocy biernej. Hybrydowy filtr mocy bocznikowej jest kombinacją aktywnego filtra mocy o niskiej wartości znamionowej i pasywnego filtra LC dostrojonego do piątej i siódmej harmonicznej. Aby kontrolować hybrydowy filtr bocznikowy mocy w celu zminimalizowania całkowitego zniekształcenia harmonicznych, stosujemy teorię mocy czynnej i biernej chwilowej mocy. W tym artykule używamy techniki sterowania kontrolerem PI w pierwszej sekcji, a w drugiej części używamy logiki przepływu i sterowania trybem przesuwania się przez urządzenie i porównaliśmy motyw. Wydajność bocznikowego filtru hybrydowego w redukcji zniekształceń harmonicznych i kompensacji mocy biernej jest określona w wynikach eksperymentalnych. Na podstawie tej pracy badawczej dochodzimy do wniosku, że ten typ filtra hybrydowego odegrał znaczącą rolę w zmniejszeniu współczynnika THD z 29 do 3,7. (**Implementacja kaskadowego rozmytego sterowania ślizgowego hybrydowego filtra mocy**)*

Keywords: Power quality, Hybrid shunt filter, PQ theory, Fuzzy control, Sliding mode control.
Słowa kluczowe: Jakość energii, hybrydowy filtr bocznikowy, teoria PQ, sterowanie rozmyte, sterowanie trybem ślizgowym.

Introduction

In recent years, we have seen a decline in the quality of electrical power due to the widespread use of electronic energy components in manufactured electrical devices[1], which absorb sinusoidal currents, generate harmonic currents, and consume Energy [2,3]. This leads to heating in the lines of the electrical network. To reduce these problems, we have used the shunt hybrid power filter. It consisted of two filters: the passive and active filter. A capacitor connected in series with an inductor represented a passive filter that had a role in eliminating the higher order of harmonics [4] as the fifth and seventh harmonics. The shunt active filter is used to eliminate the remaining harmonicscurrent[5,6,7]. We present two types of control for the active power filter, the fuzzy logic with sliding mode control.The objective of our work is to evaluate the contribution of fuzzy logic-based control and the sliding mode control to make the filter control active and compared with the classical pi control and to study the effect of these controls to reduce the propagation of harmonic currents to the electrical network.

Structure and modelling

Figure 1 represents a inverter voltage with three arms used as FAP controlled by a three-phase electrical network, each arm of the inverter has two reversible switches current, controlled on closing and opening. The energy storage on the DC side is done via a C capacitor which acts as a DC voltage source Vdc regulated to a constant positive value. A coupling filter at the output of the inverter often from the first order Lf, R fis used to connect the voltage inverter and the power grid[8].

This inverter contains six sets(s1to s6) of switches of switches and three legs each leg has two switches.

The switches's type is an ICBT, depending on the iverter's DC operationg voltage. The switching (open-close) of switches depending on the state of the control signals(sa,sb,sc)[9-12].

The following relations show the states of signals control that given by.

$$S_a\begin{cases}1: K_1 \rightarrow on, K_4 \rightarrow off\\ 0: K_1 \rightarrow off, K_4 \rightarrow on\end{cases}$$

$$S_b\begin{cases}1: K_2 \rightarrow on, K_5 \rightarrow off\\ 0: K_2 \rightarrow off, K_5 \rightarrow on\end{cases}$$

The inverter's output voltage (phase-phase) are given by the next equation:

$$(1)\quad \begin{bmatrix} V_{fa} & - & V_{fb} \\ V_{fb} & - & V_{fc} \\ V_{fc} & - & V_{fa} \end{bmatrix} = \begin{bmatrix} S_a & - & S_b \\ S_b & - & S_c \\ S_c & - & S_a \end{bmatrix} V_{dc}$$

$$J = \sum_0^\infty A^2 \sin \omega t + \int_0^\infty \sqrt{B_1^2 + C_2^2} + \frac{4\pi}{\mu_0}\int_V \frac{J \times r}{r^3} dv$$

Reference is been to the three rated output voltages (Vf a, Vfb, Vfc) relative to theNeutral network and confirms the equations below:

$$(2)\quad \begin{bmatrix} V_{fa} \\ V_{fb} \\ V_{fc} \end{bmatrix} = \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} - R_f \begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix} - L_f \frac{d}{dt} \begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix}$$

For equations it is recommended to use standard equation editor existing in Word editor (usually it is Math Type editor). The e It is assumed that the three network voltages are balanced, and knowing that the sum of currents injected by the inverter is zero, it can write:

$$(3)\quad \begin{cases} V_{sa} & + & V_{sb} & + & V_{sc} & = & 0 \\ i_{fa} & + & i_{fb} & + & i_{fc} & = & 0 \end{cases}$$

We can therefore deduce the following relation:

$$(4)\quad V_{fa} + V_{fb} + V_{fc} = 0$$

Where:

(5) $$\begin{bmatrix}V_{fa}\\V_{fb}\\V_{fc}\end{bmatrix}=\begin{bmatrix}2S_a & -S_b & -S_c\\-S_a & 2S_b & -S_c\\-S_a & -S_b & 2S_c\end{bmatrix}\frac{V_{dc}}{3}$$

Since the Sa, Sb, and Sc can each take two values (0 or 1), we, therefore, have eight possible configurations for the output voltages of the active filter (Vfa,Vfb,Vfc) referred to neutral n of the source[8].

Shunt hybrid power filter

The instantaneous reactive power theory (PQ theory) that used in this article since this theory is based on translating the reference coordinates from a-b-c to 0-α-β rotation coordinates using the Clark theorem to determine the active and reactive powers (P and Q)such as [13,14].

(6) $$\begin{bmatrix}V_0\\V_\alpha\\V_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2}\\1 & -1/2 & -1/2\\0 & \sqrt{3}/2 & -\sqrt{3}/2\end{bmatrix}\cdot\begin{bmatrix}V_a\\V_b\\V_c\end{bmatrix}$$

Where: va,vb, vc are the three phases network voltage.

(7) $$\begin{bmatrix}i_0\\i_\alpha\\i_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2}\\1 & -1/2 & -1/2\\0 & \sqrt{3}/2 & -\sqrt{3}/2\end{bmatrix}\cdot\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix}$$

Where:ia, ib, ic are the three phases of load current.

that the active and reactive power is presented by the following form[14,15]

(8) $$\begin{bmatrix}P\\Q\end{bmatrix}=\begin{bmatrix}V_\alpha & V_\beta\\-V_\beta & V_\alpha\end{bmatrix}\cdot\begin{bmatrix}i_\alpha\\i_\beta\end{bmatrix}$$

The powers (active and reactive) are composed of the fundamental and harmonics components.

Where:

(9) $$\begin{aligned}P &= \bar{p} + \tilde{p}\\Q &= \bar{q} + \tilde{q}\end{aligned}$$

There is a small amount of real power consumed by the parallel active filter, which must be in the following equation

(10) $$\tilde{p} = P - \tilde{p} + \bar{p}_{loss}$$

The transformation to coordinates a, b and c, it's necessary to generate the reference currents, after that go through the inverse transformation of these coordinates as shown in the following relations[14]:

(6) $$\begin{bmatrix}i_\alpha^*\\i_\beta^*\end{bmatrix}=\frac{1}{V_\alpha^2+V_\beta^2}\begin{bmatrix}V_\alpha & -V_\beta\\V_\beta & V_\alpha\end{bmatrix}\cdot\begin{bmatrix}\tilde{p}\\Q\end{bmatrix}$$

(11) $$\begin{bmatrix}i_a^*\\i_b^*\\i_c^*\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 0\\-1/2 & \sqrt{3}/2\\-1/2 & -\sqrt{3}/2\end{bmatrix}\cdot\begin{bmatrix}i_\alpha^*\\i_\beta^*\end{bmatrix}$$

The fuzzy logic controller

We introduce the fuzzy logic controller to boost the efficiency of SAFP linked to a non-linear load, as the latter is more versatile, powerful and reliable. Moreover, it does not rely on strict mathematical methods other than the classic PI and PID controller. There are two types of controllers in fuzzy logic. Mamdani, which alone includes 49 rules[18,19].The automatic system rules for fuzzy logic are shown in the table below, where we take the input variables, the difference between its reference and the measured current, and it's compared with a triangular signal. As the latter generates commands for the switches of the inverter[18-22].

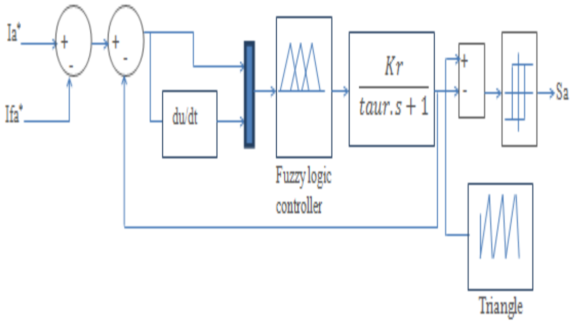


Fig.1. Fuzzy logic controller

Table 1. Fuzzy control rules

Vdc Vdc*	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
Z	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Where : NB (negative big), NM (negative medium), NS (negativesmall), ZE (zero), PS (positive small), PM (positive medium),and PB (positive big).

Sliding mode controller

The amplitude of the source reference current can be calculated by testing the continuous bus voltage using the sliding control mode. The following expression is used to give the error between the contained bus voltage and its relation[23-24].

(12) $$e_1 = V_{dc}^* - V_{dc}$$

The derivative of e1is:

(13) $$\dot{e}_1 = \dot{V}_{dc}^* - \dot{V}_{dc}$$

(14) $$\dot{e}_1 = \dot{V}_{dc}^* - \frac{1}{C_{dc}V_{dc}} * P_{dc}$$

On considering the design error as:

(15) $$Z_1 = c_1 e_1 + c_2 \int e_1 dt$$

Derivative of Z1is :

(16) $$\dot{Z}_1 = c_1\dot{e}_1 + c_2 e_1$$

(17) $\dot{Z}_1 = c_1\dot{V}_{dc}^* - C_1\frac{1}{C_{dc}V_{dc}}P_{dc} + c_2 e_1$

We define the following Lyapunov function:

(18) $V_1 = \frac{1}{2}Z_1^2 \geq 0$

Its derivative is:

(19) $\dot{V}_1 = Z_1\dot{Z}_1$

(20) $\dot{V}_1 = Z_1(c_1\dot{V}_{dc}^* - c_1\frac{1}{C_{dc}V_{dc}}P_{dc} + c_2 e_1)$

We can choose Pdc as a command to stabilize e1:

(21) $\dot{P}_{dc} = \frac{C_{dc}V_{dc}}{c_1}(k_1 z_1 + c_1\dot{V}_{dc}^* + c_2 e_1)$

(22) $\dot{P}_{dc} = \frac{C_{dc}V_{dc}}{c_1}\left[k_1 z_1 + c_2 e_1\right]$

$\dot{V}_{dc}^* = 0, c_1\rangle 0, c_2\rangle 0, k_1\rangle 0$

(23) $\dot{P}_{dc} = \frac{C_{dc}V_{dc}}{c_1}\left[k_1(c_1 e_1 + c_2\int e_1 dt) + c_2 e_1\right]$

(24) $\dot{P}_{dc} = \frac{C_{dc}V_{dc}}{c_1}\left[(k_1 c_1 + c_2)e_1 + k_1 c_2\int e_1 dt\right]$

The experimental results

The experimental test is performed in the SGRE laboratory. We study the performance of SHPF to compensate for the harmonics caused by the non-linear load. The system was executed on a dSPACE DS 1104 controller board and worked by a Matlab/Simulink Real-Time workshop environment. In this prototype, we used the PQ method, the control algorithm of SAPF [25].This study considered a three-phase diode rectifier connected a resistor in series with an inductor as a non-linear load; table 1 describes the system parameters.

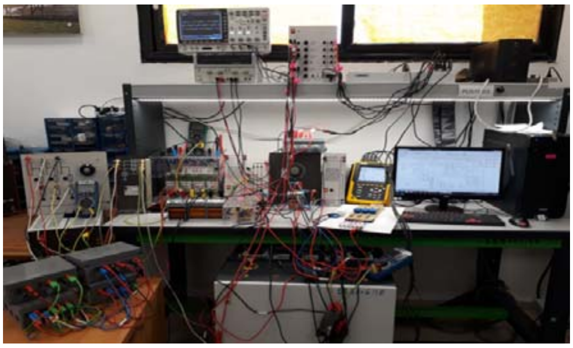


Fig.2. Shunt hybrid power filter experimental test

Table 1. The parameters system

Line to line source voltage(rms); and frequency		VSL-L=30V; fs=50Hz
Non-linear load		Rd=90Ω ; Ld=9mH
Shunt passive filter parameters	350Hz (h7)	Lpf= 0.00207H;Cpf=70μF;Rpf=120Ω
	250Hz (h5)	Lpf= 0.004068H ;Cpf =70μF; Rpf=120Ω
Shunt active filter parameters		Cdc=2200μF;Raf=20Ω;Laf=2mH; PWM switched frequency =20kHz.
DC bus voltage of SHAF		Vdc=85V
Damping coefficient ξ		0.707

The fig.2 presents the experimental, test of the three-phase source current before compensation and the THD of the three phase source current shows in Fig.19. We can observe for this current have a non-sinusoidal form.

The system before compensation

The fig.3 presents three-phase source voltage and the THD of three-phase source current respectively before compensation. We can observe for this current have a non-sinusoidal form.

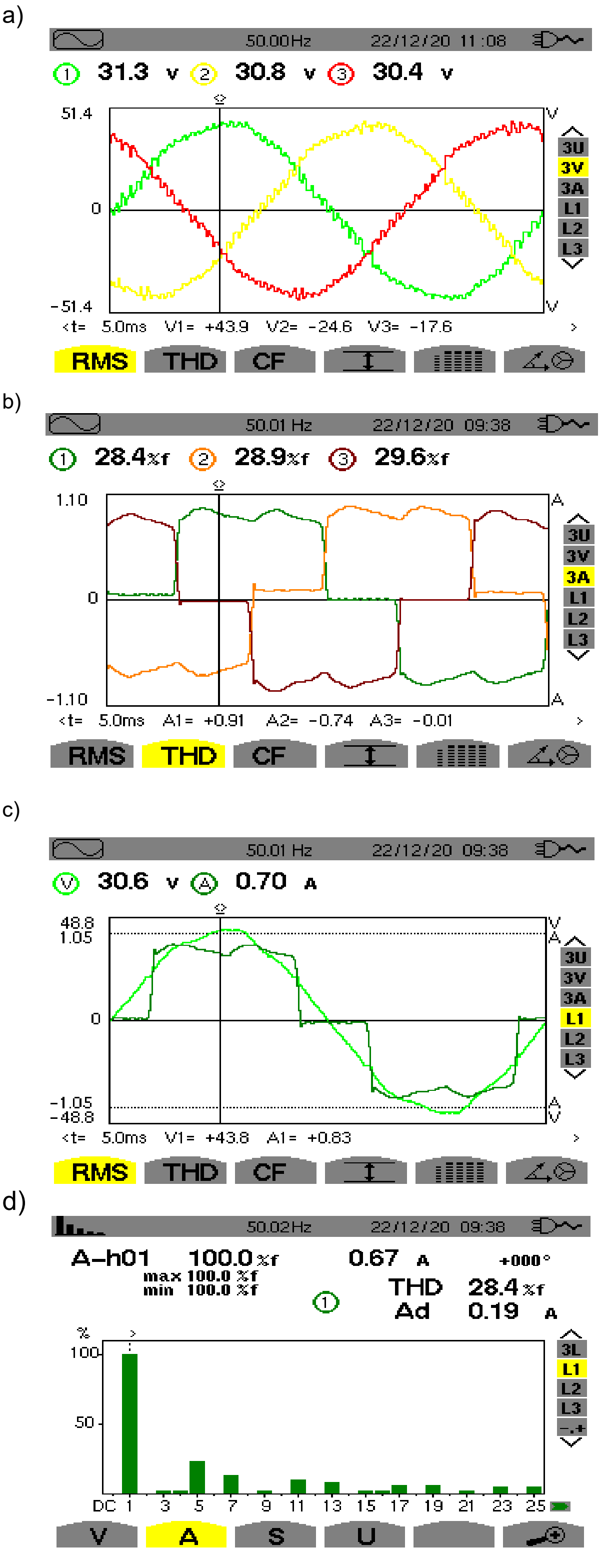


Fig.3.Source voltage (a, c) ,source current (b, c), harmonic spectrums of the source current before filtering (d)

Through the picture, we noticed that the value of THD is very high THD= 29%.

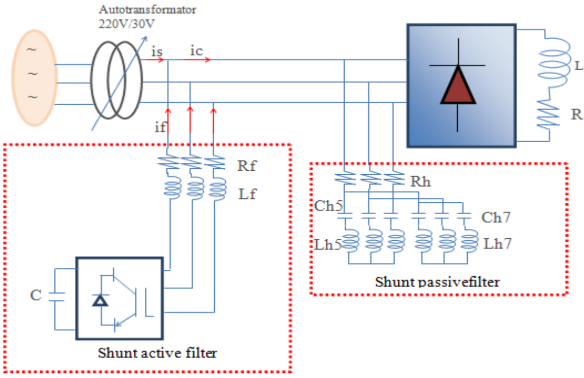


Fig.4.Configuration of studied system

PI controller compensation

In this work we use the classic control pi where we impose the DC capacitor voltage and compare it to the reference value of Vdc*.

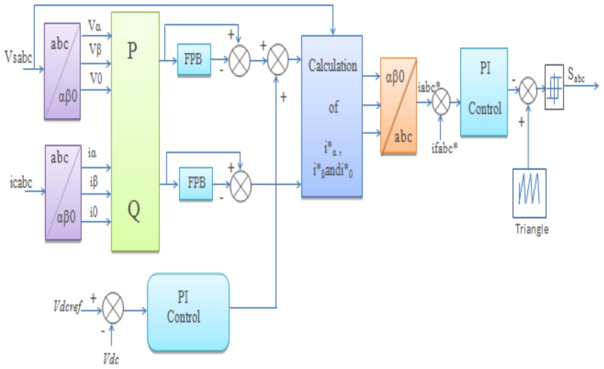
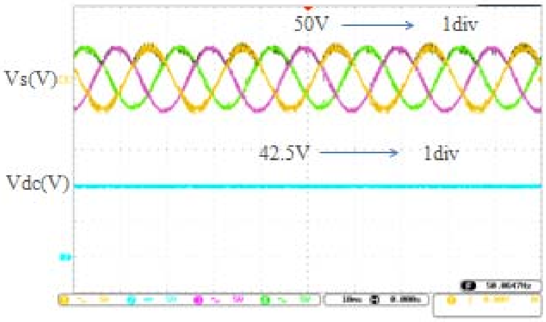


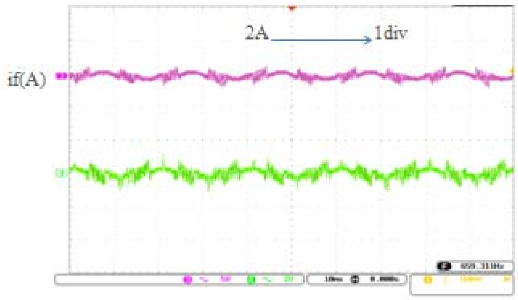
Fig.5. Shunt hybrid power filter control based PI-Controller

The output signal of the transformer PWM by comparing the source isabc currents with the reference currents isabc*, where the extracted error value is e = isabc - isabc* and this is by applying the control system pi with a triangular signal.

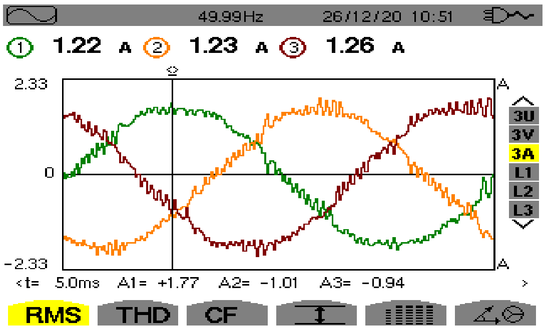
a)



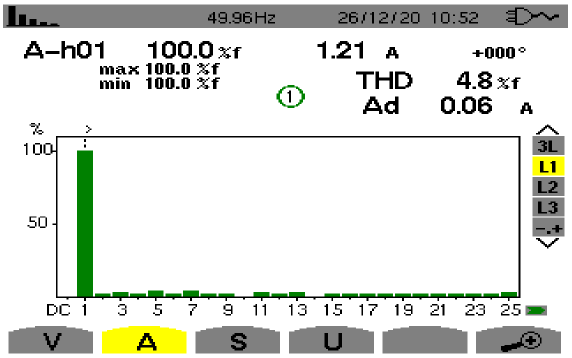
b)



c)



d)



e)

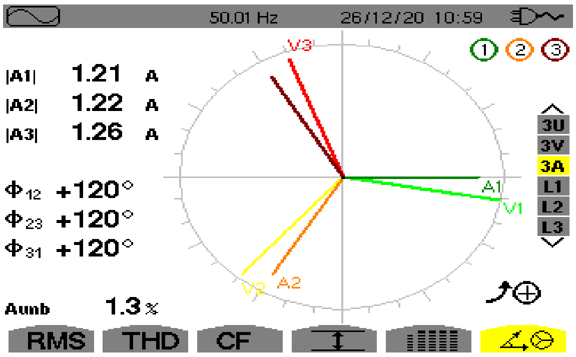
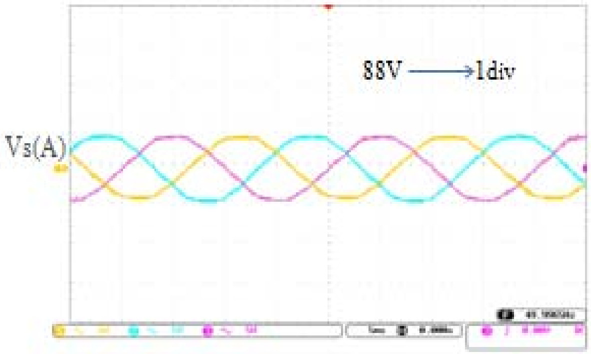


Fig.6. Experimental results for balanced sinusoidal grid voltage and dc capacitor voltage(a), the injected filter current(b), source current after filtering and its spectrum (c,d),vector diagram of source current(e)

Compensation using cascaded fuzzy logic controller and sliding mode control

We increase in this stage the value of voltage to 50V, and to keep currents in the same range we introduce a variable resistance in series. The following fig.7 show the supply voltages and the load current which are the same for the network.

a)



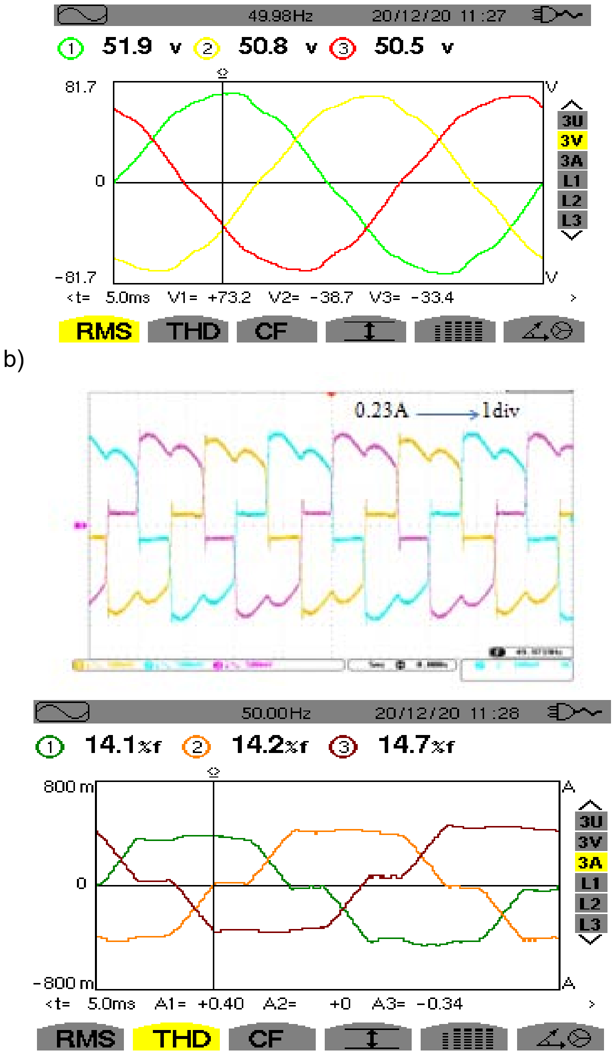


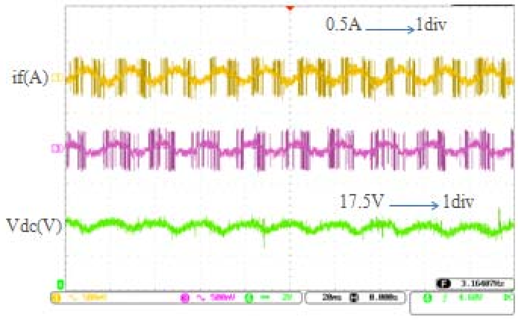
Fig.7. Experimental results for balanced sinusoidal grid voltage (a) ,source current and its spectrum before filtering(b)

In this party we change the classic PI control with the fuzzy logic and sliding mode controllers. We use the sliding mode controlto implement the DC capacitor voltage and compare it with the reference value Vdc_{ref}. And we propose the fuzzy logic control the output signal of the transformer PWM by comparing the source currents isabc with the reference currents isabc*where the extracted error value is e = isabc-isabc* by applying the PI control system with a triangular signal.

The injected filter current and the DC link voltage are mentioned in fig.8(a)

The shape of the current becomes sinusoidal in fig.8(b). The spectrum of the network current represents a harmonic rate of 3.7%, which makes it possible to have a balanced three-phase system.

a)



b)

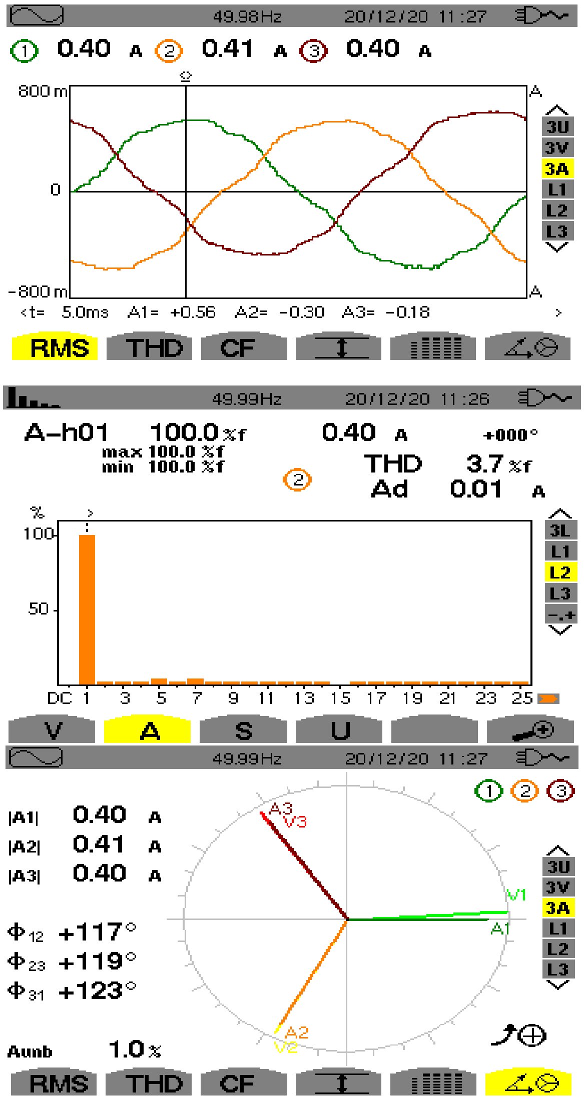


Fig.8. Experimental results for injected filter current and the dc link voltage(a),the source current and its spectrum and vector diagram after filtering (b)

Conclusion

From the best results that we obtained, we conclude that the hybrid filter had the ability to control the spread of harmonics produced from the loading is non-linear, but it includes two types of filter, the passive filter and the active filter. As for the control side of the active filter side, the result was that the use of modern control systems fuzzy logic and sliding mode controls as was Faster response, more flexibility and lower THD obtained 3.7% than using the classic control systems PI, where the THD=4.8%.

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