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Power Quality Enhancement Using Hybrid Power Filters with nonlinear controller

***Abstract**. This paper introduces a novel hybrid power filter (HPF) that combines a passive filter (PF) tuned to two harmonics (5th and 7th) with a series active power filter (SAPF). The HPF is designed to mitigate harmonic distortion, compensate for reactive power. Implemented as a three-phase voltage source inverter (VSI), the HPF is controlled by hysteresis control for the inverter and a backstepping controller for the DC bus, demonstrating how (PF) compensates for harmonic and reactive power, while the series power filter addresses voltage sag and short interruptions.*

***Streszczenie** W artykule przedstawiono nowatorski hybrydowy filtr mocy (HPF), który łączy filtr pasywny (PF) dostrojony do dwóch harmonicznych z szeregowym aktywnym filtrem mocy HPF ma na celu łagodzenie zniekształceń harmonicznych i kompensację mocy biernej. Zaimplementowany jako trójfazowy falownik źródła napięcia, HPF jest sterowany poprzez sterowanie histerezą falownika i sterownik krokowy dla szyny DC, demonstrując, w jaki sposób (PF) kompensuje harmoniczne i moc bierną, podczas gdy szeregowy filtr mocy adresuje zapady napięcia i krótkie przerwy (**Poprawa jakości zasilania przy użyciu hybrydowych filtrów zasilania z nieliniowym st**erownikiem)*

Keywords: Active filtering, Harmonics, Passive filter, Power Quality, Backstepping controller.
Słowa kluczowe: Aktywne filtrowanie, Harmoniczne, Filtr pasywny, Jakość zasilania, Backstepping con

Introduction

Power quality refers to the degree to which disturbances in both the utilization and distribution of electric power affect the efficiency of electrical equipment. These disturbances, known as power harmonics, contribute to electrical pollution, resulting in a degradation of power supply quality [1,2]. Therefore, it is essential to implement filtering processes to mitigate these harmonics and improve power supply quality.

Traditionally, passive filters have been employed to reduce Total Harmonic Distortion (THD) and compensate for reactive power. Passive filters are regarded as reliable, cost-effective, robust, and easy to maintain [3,4].

However, they suffer from certain drawbacks, such as creating resonance with the system, being bulky, and being tuned for specific harmonic frequencies [1,2,3]. Since the early 1980s, active power filters (APFs) have emerged as one of the most common compensation methods. A typical APF comprises a three-phase voltage source inverter and can be connected either in parallel or in series with the load [5]. Parallel configuration is particularly suitable for mitigating harmonics from loads known as harmonic current sources, whereas the series configuration is effective for compensating voltages sag, swell, and short interruption. However, active filters present challenges due to their relatively high costs, particularly for large-scale systems, and complexities in deployment within high-voltage grids. Therefore, leveraging a hybrid power filter emerges as a more advantageous solution in the realm of power quality enhancement [6].

In this study, we integrate two passive filters meticulously tuned at the fifth and seventh harmonic frequencies with a series active power filter. This synergistic combination enables passive filtering to effectively reduce the total harmonic distortion of current and compensate for reactive power, while the series active filter adeptly mitigates voltage perturbations and short interruptions, thus comprehensively improving power quality.

Topology of hybrid power filter

Figure 1 depicts the topology of the integrated system comprising a series active power filter and a shunt passive filter. The passive filter functions as a zero impedance for the fundamental frequency and as a high resistor for harmonic frequencies. Supplied by a three-phase inverter, the hybrid power filter (HPF) is linked in series with the primary supply and the nonlinear load via a current transformer. Additionally, the passive filter, connected in parallel with the load, serves to tune the 5th and 7th harmonics due to their elevated amplitudes.

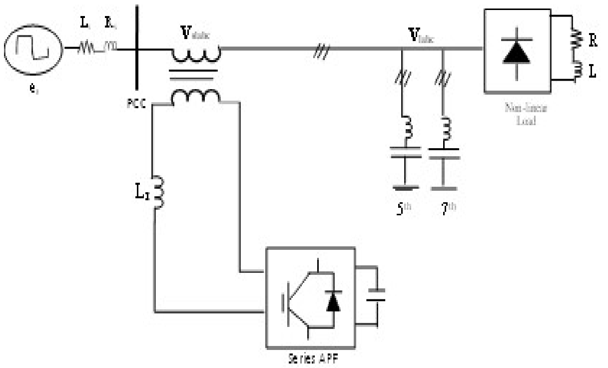

Fig.1. General structure of a hybrid power figure

The series APF acts as a voltage source and inject a compensating voltage in order to obtain a sinusoidal load voltage. The developments in digital electronics, communications and in process control system have made the loads very sensitive, requiring ideal sinusoidal supply voltage for their operation [6,7].

Modelling and control

Figure 2 Shows the per-phase equivalent scheme of the studied topology

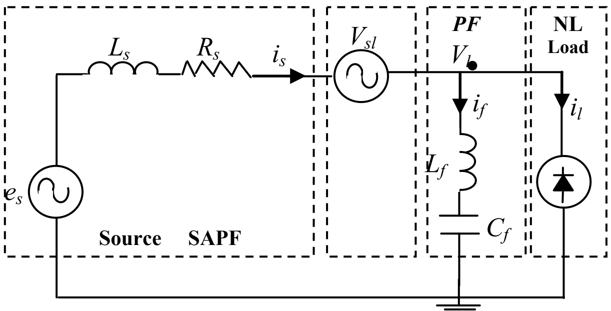

Fig.2. Per-phase equivalent scheme

where: e_s – Source voltage, i_s – source current, L_s – source inductance, R_s – source resistance, V_s – Line voltage, V_l – Load voltage, i_l – load current, V_{sl} – Controllable voltage source representing the series active power filter, i_f – Shunt passive filter current, C_f – passive filter capacitance, L_f – passive filter inductance.

This equivalent scheme is modeled by (1) and (2):

$$V_{sl} = V_s - V_l \tag{1}$$

$$i_s = i_f - i_l \tag{2}$$

Were

$$V_s = e_s - (R_s\ i_s) - (L_s \frac{di_s}{dt}) \tag{3}$$

The voltage error is given by:

$$\Delta V_{sl} = V_{slref} - V_{sl} \tag{4}$$

V_{slref} expressed by

$$V_{slref} = V_{sh} - V_{lh} \tag{5}$$

$$V_{sh} = k\ i_{sh} \tag{6}$$

V_{sh} – the harmonic components present in V_s, V_{lh} – the harmonic components present in V_l, i_{sh} – the harmonic components present in i_s, K a current sensor gain.

The harmonic component $V_{slh}$of V_{slh} is defined by:

$$V_{slh} = V_{sl} - V_{slf} \tag{7}$$

First, we extract the p-q components of V_{sl}

$$\begin{bmatrix} V_{slp} \\ V_{slq} \end{bmatrix} = C_{pq}\ C_{32} \begin{bmatrix} V_{la} \\ V_{lb} \\ V_{lc} \end{bmatrix} \tag{8}$$

C_{pq}, C_{32} representing the Park matrix and Concordia matrix given respectively by:

$$C_{pq} = \begin{bmatrix} sin(\omega t) & -cos(\omega t) \\ -cos(\omega t) & -sin(\omega t) \end{bmatrix} \tag{9}$$

$$C_{32} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{10}$$

Next, decomposition of V_{slp} and V_{slq} into continuous

Components $\overline{V}_{slp}$, $\overline{V}_{slq}$ and alternative components $\tilde{V}_{slp}$, $\tilde{V}_{slq}$.

$$V_{slp} = \overline{V}_{slp} + \tilde{V}_{slp} \tag{11}$$

$$V_{slq} = \overline{V}_{slq} + \tilde{V}_{slq} \tag{12}$$

$\overline{V}_{slp}$, $\overline{V}_{slq}$ are calculated through a second-order low-pass filter. Then, the three-phase fundamental components are obtained from this equation [8]:

$$\begin{bmatrix} V_{slfa} \\ V_{slfb} \\ V_{slfc} \end{bmatrix} = C_{23} C_{pq}^{-1} \begin{bmatrix} \overline{V}_{slp} \\ \overline{V}_{slq} \end{bmatrix} \tag{13}$$

Ultimately, the algorithm can be depicted through the block diagram illustrated in Figure 3.

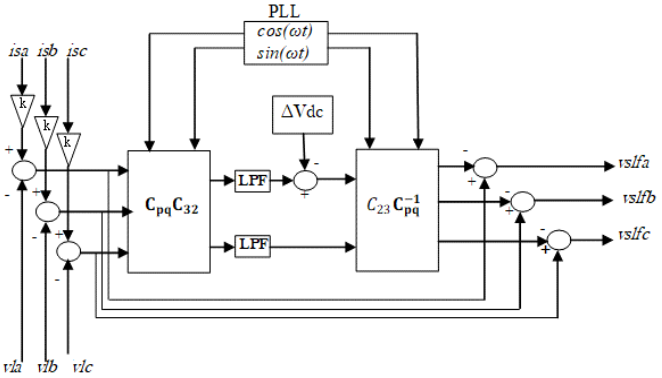

Fig. 3. Block diagram of voltages references determination

Hysteresis control

Switching control of the current-controlled voltage source inverter VSI is mandatory to acquire the necessary current waveform. Thus, the hysteresis controller also known as the bang-bang controller is used. This technique ensures robustness and a very rapid dynamic response along with unconditioned stability [9,10]. His role is to force the series active power filter voltage V_f reimbursement signal to follow its estimated reference signal $V_{f\text{-}ref}$ within a fixed tolerance acceptable band [11,12].

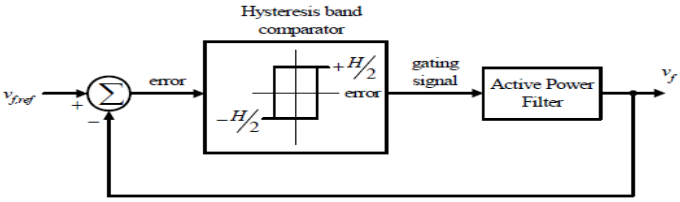

Fig. 4. Conventional hysteresis band current controller

DC Voltage Control

By using Backstepping Controller : [13]

$$\frac{dv_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc} = -\frac{P_{dc}}{C_{dc}.v_{dc}} \tag{14}$$

v_{dc} , P_{dc} : Voltage and power across the capacitor.

We give the error e by this formula:

$$e = v^*_{dc} - v_{dc} \tag{13}$$

$$\frac{de}{dt} = \frac{d}{dt} v^*_{dc} - \frac{d}{dt} v_{dc} = 0 - \frac{P^*_{dc}}{C_{dc}.v_{dc}} \tag{14}$$

Reference voltage:

$$\frac{d}{dt} v^*_{dc} = 0 \tag{15}$$

Reference power:

$$P_{dc} = P^*_{dc} \tag{16}$$

The Lyapunov function is written as follow:

$$v = \frac{1}{2} e^2 \tag{17}$$

The derivative will be given by:

(18) $$\frac{dv}{dt} = e\,\frac{de}{dt} = e\left[-\frac{P^*_{dc}}{C_{dc}.v_{dc}}\right] = -K.e^2$$

If we achieve the quality of the equation below, we obtain better stability of the system [10] by choosing the constant K positive.

(19) $$\frac{dv}{dt} = -\frac{P^*_{dc}}{C_{dc}.v_{dc}} = -K.e$$

K – Constant positive.

In the end we found the command as follow:

(20) $$p^*_{dc} = C_{dc}\ v_{dc}\ K\ e$$

(21) $$i^*_{dc} = C_{dc}\ K\ e$$

Table 1. System parameters

Source	Vs	220 V
	L_s	5.5 mH
	R_s	3.6 Ω
Load	R	25 Ω
	L	55 mH
Passive filter	L_{f5} ; C_{f5}	13.5 mH ; 30 µF
	L_{f7} ; C_{f7}	6.75 mH ; 50 µF
DC Link	DC Voltage reference	800V
	Capacitor	2200 µF
Turns Ratio of Coupling Transformer		1:1
Switching Frequency		10 KH
Current sensor gain k		5

Simulation results

The simulation is carried out using a program working in MATLAB/SIMULINK environment. For nonlinear load we use a three-phase diode rectifier with RL load. The simulation parameters are shown in the table 1.

A. Without filtering

In figures 6, 7, 8, and 9 we present the results before using filtering.

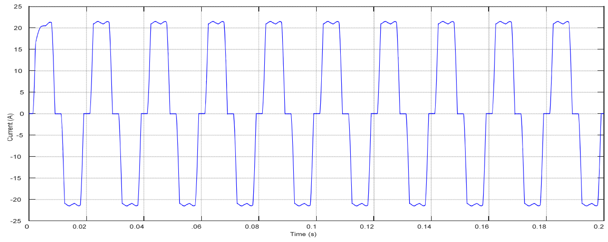

Fig. 6. Load current

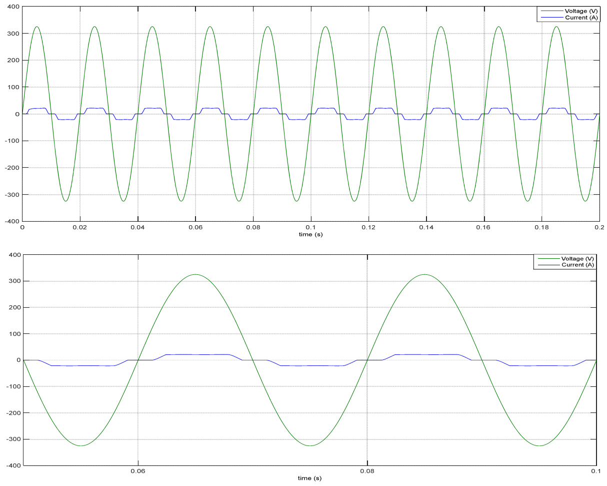

Fig. 7. Delay phase between Waveforms of load (current, voltage)

Figure 6 shows the load current which is too degraded due to the presence of non-linear load

In Figure 7, we present the delay between voltage and current which represents the existence of reactive power which explains a poor power factor.

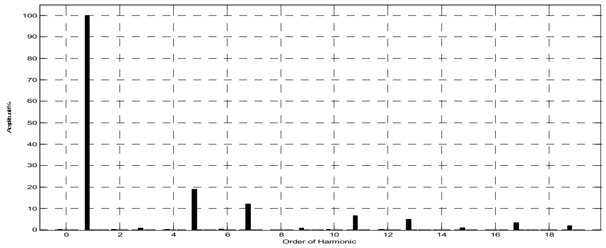

Fig. 8. Harmonic Spectrum of current

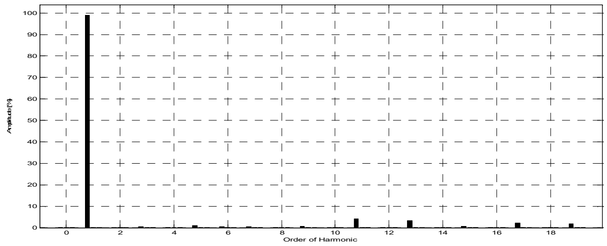

Fig. 9. Harmonic Spectrum of voltage

The current harmonic spectrum reveals that the most predominant harmonics are of orders 5, 7, 11, 13, etc., with larger amplitudes. This predominance occurs due to their characteristic nature as harmonics, following the pattern of 6K ± 1, where K is an integer. This pattern is directly related to the nonlinear load being used, specifically the Three-phase rectifier PD3 (see figures 8 and 9)

B. With Hybrid Power Filter (HPF)

In figures 10, 11, and 12 we present the results before using filtering.

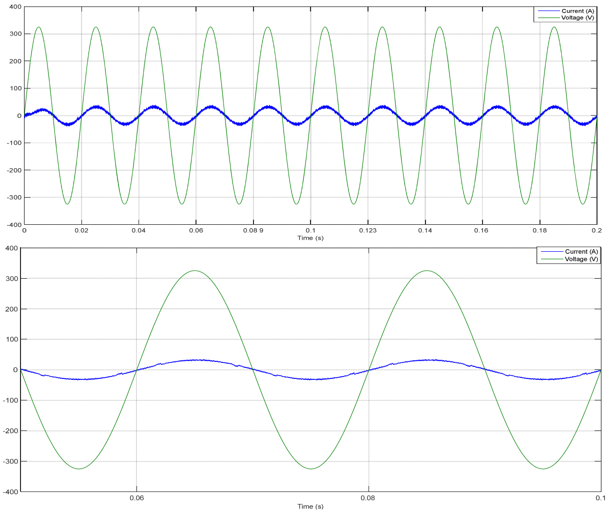

Fig.10. Delay phase between Waveforms of source (current, voltage)

Figure 10 illustrates that the phase shift between the source current and the voltage disappears; which explains reactive power compensation and power factor correction

Figures 11 and 12 show the harmonic spectrum of the current and the voltage after the insertion of the hybrid power filter where we notice the great reduction of all the harmonics as well as the rate of harmonic distortion (THD) is reduced.

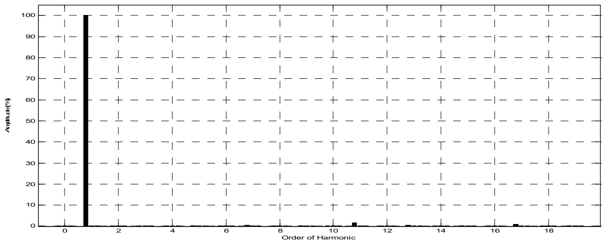

Fig. 11. Harmonic Spectrum of current

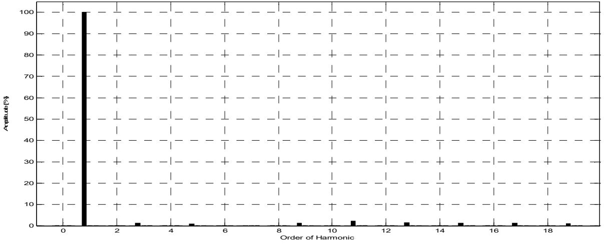

Fig. 12. Harmonic Spectrum of voltage

Table 2: Simulation results of harmonics currents

THD	Before Filtering	After filtering
THDi	25.46 %	1.40 %
THDv	9.49 %	2.77 %

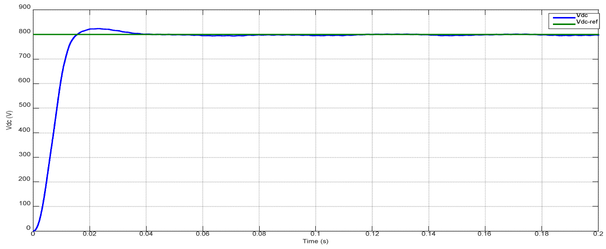

Fig .13. DC Bus control with Backstepping Control

To test the performance of our proposed filter we created a short interruption problem and a voltage sag between 0.4 and 0.6 s(see the figures 14 and 15).

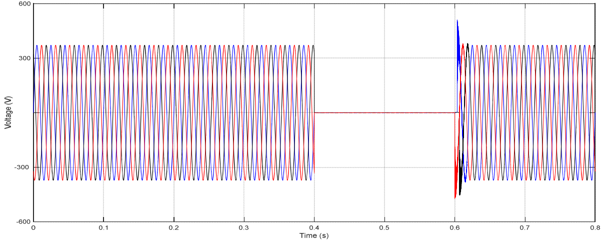

Fig. 14. Voltage short interruption

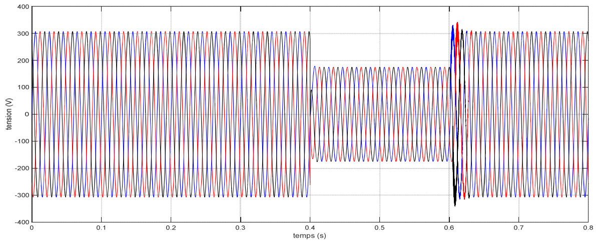

Fig.15. Voltage sag between 0.4 and 0.6 s

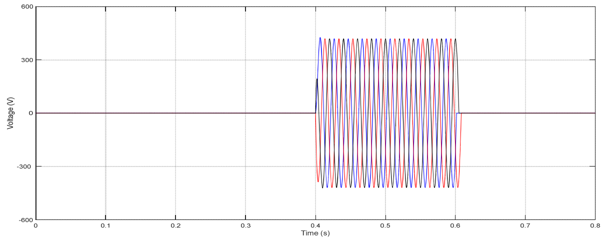

Fig.15. Injection voltage for voltage short interruption compensation

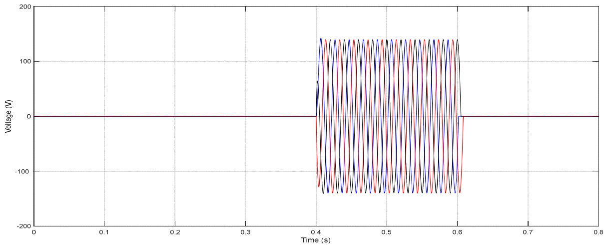

Fig.18. Injection voltage for voltage sag compensation

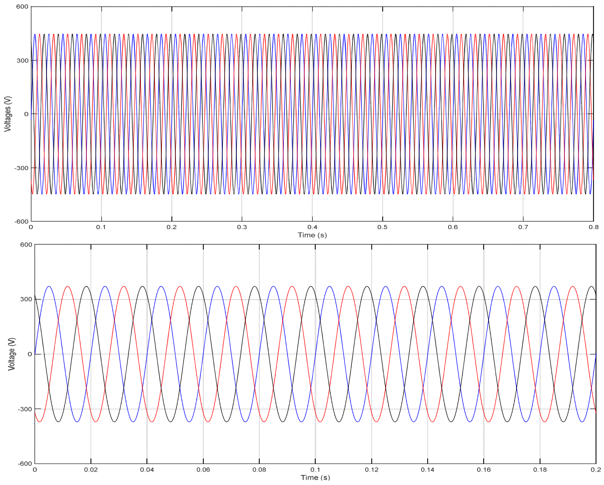

Fig .16. Source voltage after compensation (using HPF) and its Zoom

In Figure 8 we see that it to be disruptive phenomena associated with voltage as imbalance and flicker and after use a Hybrid Filter we note that these phenomena are reduced (Figure 16) and this because the injected voltage by this filter.

Conclusion

In this study, we present a novel three-phase hybrid active power filter aimed at improving power quality. Our methodology incorporates two nonlinear controllers: hysteresis control for a three-phase voltage source inverter and backstepping control for the DC bus. The system is meticulously modeled and simulated using the MATLAB/SIMULINK environment.

Simulation results demonstrate a significant reduction in total harmonic distortion for both supply current and voltage, aligning with the rigorous harmonic standards set by IEEE 519. Notably, our system achieves not only the reduction of harmonics to acceptable levels but also minimizes transient response times.

Furthermore, successful utility power factor correction, mitigation of voltage sag and flicker, and resolution of short interruptions underscore the achievement of the primary objectives of our research endeavor.

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