Intelligent Tuned Hybrid Power Filter with Fuzzy-PI Control

Tzu-Chiao Lin (Associate Professor)*, Bawoke Simachew (4th year Ph.D. Candidate)
Department of Electrical Engineering, National Taipei University of Technology

Abstract

The increasing use of converters in today's power grid, driven by the integration of renewable energy sources, has significantly raised harmonic disturbances. These disturbances are likely to grow further due to the variability in renewable energy supply, potentially causing data loss in large data centers and overheating in industrial machinery due to chaotic signals. To address this issue, a novel intelligent harmonic elimination approach using a fuzzy-assisted PI controller is proposed, ensuring effective harmonic management in advanced power systems. The overall system was tested in MATLAB/SIMULINK® and demonstrated effectiveness in canceling harmonics.

Research Focus

Main Contribution

- ✓ A fuzzy-tuned PI controlled Hybrid Power Filter (HPF) is developed to enhance the performance of the PI controller during load variations and system resonance.
- ✓ The neutral voltage, in this article is treated as an induced voltage within the filtering circuit. Consequently, it addresses incoming phase voltage imbalances and their impact on the filter phase sequence.
- ✓ In addition to shunt active power filter (SAPF), this article also enhances the design of the passive filter to accommodate all limiting conditions, including resonance effects. Furthermore, it incorporates the smoothing inductor element from the active filter into the passive circuit design, with its values taken into account during the identification of maximum resonance.

Proposed Model

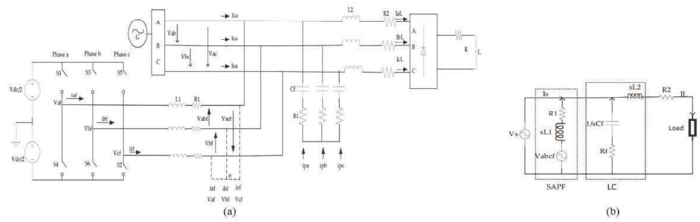


Figure 1. Hybrid Power Filter (a) LCL-HPF system structure. (b) Equivalent circuit of the LCL-HPF filter.

The design of the ***shunt active power filter (SAPF)*** starts with Figure 1(a), applying Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL). The phase-to-neutral voltage is given by:

$$V_{an} = i_{af}R_{af} + Ld\left(\frac{i_{af}}{dt}\right) + V_{fa} - V_n \tag{1}$$

where V_n is the unbalanced voltage on the phases of active filter acquired from grid phase imbalance. Applying on three phase line The derived voltage V_{abcf} can be computed from the converter is as (1). Thus, the values are either 0 or V_{DC} based on the sequence of switching.

$$[V_{abcnf}] = \frac{1}{3}[J][V_{abcf}] \tag{2}$$

where $[J] = \begin{bmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix}$.

Similarly first half three phase applied current can be given as (3):

$$[L_1]\left[\frac{di_{abcf}}{dt}\right] = [1 \quad R_1 \quad -1]\begin{bmatrix} V_{abcf-V_n} \\ i_{abcf} \\ V_{abcn} \end{bmatrix} \tag{3}$$

Hence the converter switching would be on the following conditions:

$$[V_{abcf}] = \begin{cases} 1, if\ S_k is\ ON\ and\ S_{k+3}\ is\ OFF \\ 0, if\ S_k is\ ON\ and\ S_{k+3}\ is\ ON \end{cases} \tag{4}$$

In ***passive filter design***, the resonant frequency limiting requirements is given in (5).

$$10f < f_{res} < 0.5f_{sw} \tag{5}$$

Based on equation (5), the resonance frequency derived from the transfer function of the LCL-HPF circuit shown in Figure 1(b) is given by equation (6).

$$L_2 = \frac{1}{R_f}\left[\frac{R_1}{(20\pi f)^2 C_f} - R_f L_1\right] \tag{6}$$

$$L_1 = \frac{-(L_{max}R_f - x + L_{max}) + \sqrt{(L_{max}R_f - x + L_T)^2 - 4(xR_f L_{max})}}{2R_f} \tag{7}$$

where $x = \frac{R_1}{(20\pi f)^2 C_f}$

Fuzzy Controller Design

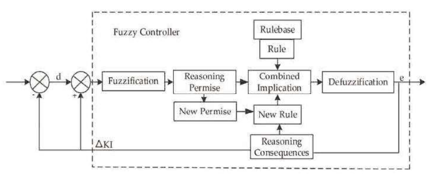


Figure 2. Fuzzy control model.

The output of a fuzzy controller given in Figure 2, is computed by exchanging the rule base membership functions with the universe of discourse [−0.6, 0.6]& [-6, 6] as shown in Figure 3. The notations mentioned are divided into positive and negative membership functions. The negative and positive domains, where {NL, NB, NM, NS, ZO} represent negative very large, negative large, negative medium, negative small, and zero, respectively; and {PL, PB, PM, PS} represent positive very large, positive large, positive medium, and positive small, respectively.

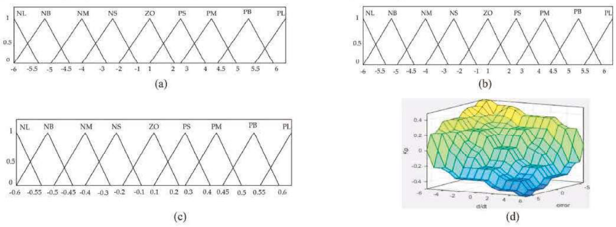


Figure 3. The input–output membership and output surface for a fuzzy control system **(a)** the membership function of the input VDC error control; **(b)** the membership function of the fuzzy controlled change ($\frac{d}{dt}$) input; **(c)** the membership function of the fuzzy controlled errors; and **(d)** the membership function rules of the fuzzy control output 3D surface view.

Experimental Results

Figure 4(a) shows that the DC voltage of the PI-controlled HPF starts with a delay and is affected by load variations. During load changes, the DC voltage waveform produces spikes, which in real cases can become chaotic at higher levels and may damage customer equipment. In contrast, Figure 4(b) demonstrates that the fuzzy-tuned PI controller maintains a stable and smooth waveform. This stability indicates that the feedback mechanism has learned from prior conditions, allowing the fuzzy logic to adapt its decisions immediately with each load variation.

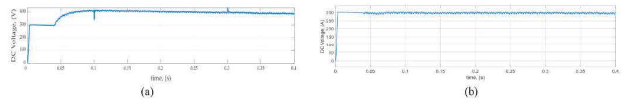
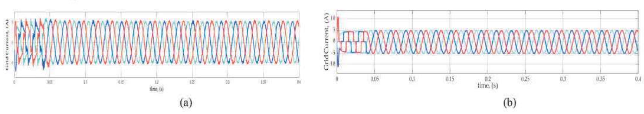


Figure. 4. The switching current and DC voltage performance **(a)** the PI controller filtering output current, **(b)** the fuzzy-tuned PI controller filtering current wave shape

- Figure 5(a) shows that the current output waveform is stable, with only a small ripple caused by shunt capacitor switching and the PI controller's limitations under nonlinear variations. Achieving this stability requires careful parameter sizing.
- Increasing the filtering capacitor could further reduce THD; however, this would lead to excessive current, system heating, and increased losses.
- In contrast, the waveform in Figure 5(b) shows that the fuzzy-tuned PI controller reduces ripple, improves load imbalance, and remains stable under all conditions. By leveraging feedback control, the fuzzy-tuned PI continuously readjusts the output error, which enhances fuzzy decision-making.

As a result, the THD of the fuzzy-controlled output in Figure 5(c) is lower than that of the standard PI-controlled output.



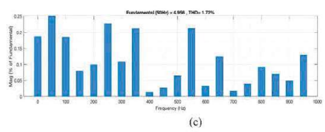


Fig. 5. Grid current and the THD after HPF. (a) Grid current waveform, (b) the grid current output wave shape after incorporating the fuzzy-tuned PI controller into the HPF circuit, and (c) the THD of the fuzzy-assisted PI controlled HPF.

Publications

1. T.C. Lin and **B. Simachew**, "Intelligent Tuned Hybrid Power Filter with Fuzzy-PI Control," *Energies*, vol. 15, no. 12, p. 4371, Jun. 2022.