Adaptive Fuzzy Logic Control of Hybrid, Active Power Filters, for Harmonic Mitigation

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Abstract: In industrial applications which include power systems, it notices that, harmonics which generated due to nonlinear load (power electronic switches) cause issues for the power quality. Generally, the rectifiers accounted as one of the main elements which produce currents harmonics, where these harmonics will transmit through power system and the generated harmonic distortion will be led to enormous issue and damage for the equipment’s. This study deals with hybrid active filter that consist of shunt active power filter (APF) and passive power filter (PPF) in series with grid based on the instantaneous active and reactive current component ($i_d$–$i_q$) control strategy to calculate the reference signal of compensation current which is needed to cancelled the non-linear load current. Furthermore, this new technique method handles with adaptive fuzzy logic control with proportional integral control (PI) to obtain perfect controllable dc input of the inverter across capacitor. Therefore, ac output voltage of active power filter with assist of passive power filter is the desirable value in magnitude and frequency, this led to achieve a perfect attenuation of harmonics, where both harmonics and reactive power are compensating. The simulation results show that, the new control method is very effective to reduce harmonic and improve power quality.

Keywords: hybrid active power filter, series passive power filters (SPPF), adaptive fuzzy, harmonic reduction.

1. Introduction
In the last years, the development in Industrial applications and usage incensement of power electronic and non-linear loads has given rise to numerous challenges in power systems which implies has negative side effect of power quality. One of the most important power quality (PQ) problems is Harmonic distortion. The main causes of this problem can be classified as soft start rectifiers and augmentation of semiconductor circuitry devices. Non-linear loads cause uniform distortion within current and voltage waveform in the power system. Harmonics lead to many problems such as high-temperature power systems low power factor electrical appliances and transformers [1]. There are many types of methods for solving harmonics issues the conventional method is Passive Power Filter (PPF). PPF is simple structure and consist of inductor capacitor and resistor. Re-arrangement of these elements give a new order, each order solve specific harmonic (3th, 5th, 7th, 9th, etc.) [2]. These filters shave many drawbacks such as resonance and instability. Therefore, it is not encouraging for implementing [3].

Another method to mitigate harmonic problems is Active Power Filters (APF), which got a lot of attention, since the 1970s [4]. The APFs are connected in series or in parallel with grid a Shunt Active Power Filters (SAPFs) used to cancel harmonic current distortion while a series active power filters
used to cancel harmonic voltage distortion. SAPFs are commonly used and it was proposed by H. Sasaki, and T. Machida in 1971 [5]. SAPFs are often used to absorb current harmonics, as well as compensate reactive power for the grid and regulate the dc-link voltage [6]. However, they are restricted by high cost, not has flexible with high voltage system and deal with low power application [7]. Hybrid active power filters (HAPFs) are represented a good solution for the harmonics. HAPFs can be classified into passive and active filter connected in parallel with the grid passive filter in series and active filter in parallel with grid and the active filter is connected in series with passive filter where it connected in parallel with grid [8]. Parallel passive filters are more suitable to compensate for non-linear loads of the current source. In addition, it is suitable to compensate for the current source type of non-linear loads. The series passive filter can be used to compensate for the voltage source type of non-linear loads [9].

A Hybrid Passive Filter (HPF), consist of a parallel passive filter and a series passive filter. It can be used for all types of non-linear loads. The HPF is also not sensitive to source impedance. Although HPF has been largely implemented for harmonic mitigation, this filter cannot be quite effectiveness to compensate for the reactive ability to suddenly change nonlinear loads. These techniques (APF) are considered as an important way to reduce harmonics with a relatively low capacity. Depending on path of current the current control can be divided into two categories: linear and non-linear each of them has basic operation principle depend of use. linear current control contains proportional integral (PI) state feedback controllers and ramp comparison control. nonlinear control includes hysteresis controllers and predictive control ...etc. [10]. The ramp technique circuit is easy to design and its cost is low. But for implementation need more software or hardware as well as suffers from various limitations [7]. To diagnoses the behavior of APF for various harmonic current and under different voltage conditions, method of control for extraction of reference current signal must be known.

An instantaneous, active and reactive power (p-q) theory is a method for current control and it is simple and completely frequency independent, but the implementation is unsuitable under unbalanced source voltage conditions [11]. This paper proposes the hybrid passive and active filters configuration which composed of series passive filters and a parallel active filter. As well as, the I-dq control method that include of an adaptive PI control with fuzzy adjustor controls is used to eliminate many synchronization problems and it can deal with unbalanced and non-sinusoidal voltage conditions. The Simulation results based on this method shows the effectiveness and efficient in reducing. harmonics.

2. Configuration of Power System:

2.1 A. a hybrid. active power
The hybrid active power filter (HAPF) as shown in figure 1 where (SPPF) with Active. Power Filter (APF) are connected in shunt with grid. The main aim of HAPF is to compensate reactive power and mitigation harmonics in the grid as well as all the reactive power current which that controlled through, passing via APF. Ideal inverter has sinusoidal output voltage waveform but, in the fact, it is non-sinusoidal because it has harmonics which is generated from switching operation (transistor/thyristor) therefore the output voltage of inverter must be controlled for the following reasons:
1. To deal with the variation of dc input.
2. Regulate voltage of inverter and
3. To obtain control of constant voltage and frequency. Generally, the aim of APF part is used to hold on DC link voltage that only requires for harmonic compensation, while SPPF part is used to provided high impedance to block harmonics current of non-linear load.
2.2 Series Passive Power Filter

Both capacitor and a reactor are represented the real elements of Series passive power filter (SPPF) as shown in Figure 2a. The SPPF prevent the harmonic current of nonlinear load from passing towards the source voltage side by providing high impedance path for all type of harmonics. At the same time (SPPF) provide low impedance path for the fundamental frequencies because the significant impedance may be cause drop voltage for the system as shown in Figure 2b [9].

![Figure 1. Hybrid Active Filter System Diagram](image1)

![Figure 2. Equivalent circuit of passive power filter (a) structure (b) frequency response](image2)

3. Control Strategies

The active power flow which that pass through active power filter must be controlled to achieve regulate and maintained of DC link voltage capacitor this led to the DC link voltage which can be maintained at, the desired value as well as the control circuit support to reduce the losses which implies producing from switching inside the filter as shown in Figure 3. The control strategy it is represented very important part in hybrid active power filter because it plays an important role in contributing to the attenuation of harmonics. In general, control strategies including four important sections are represented detection of signals generation of compensating signals dc link voltage control and generation of firing signals. To get better performance active power filter this depend on the methods of detection harmonic to produce compensating reference current signal. Also, this study
deal with (id–iq) theory in order to maintain DC link voltage where, constant PI branch is added to the d-axis theory to calculate compensating reference current signal.

![Harmonic detection circuit](image)

**Figure 3.** The architecture of current control of active power filter

### 3.1. direct and quadrature current (id–iq) theory

The APF compensate performance is based on the way of calculation the compensation current signal reference and the method which can be used in this study which deals with (id–iq) theory. The advantage of using this theory are the fast reaction to fast current transitions as well as the fundamental active and reactive harmonic the current or voltage can be easily calculated in d-q frame. The load currents (i_La, i_Lb, i_Lc) are converted depending on park transformation to obtain corresponding, d-q axes currents i_Ld and i_Lq (the new current) i_Ld, i_Lq, i_L0 (which are obtained from transformation equation in term) i_Lα and i_Lβ as shown in figure 4 which can be represented by the following equations:

\[
\begin{bmatrix}
i_Ld \\
i_Lq \\
i_L0
\end{bmatrix} =
\begin{bmatrix}
\sin \varphi & \cos \varphi & 0 \\
-\sin \varphi & \cos \varphi & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
i_Lα \\
i_Lβ \\
i_L0
\end{bmatrix}
\]

(1)

where the angle (θ) is calculated directly, from main voltages: \( \varphi = \tan^{-1}(v_β / v_α) \)

\[
\begin{bmatrix}
V_α \\
V_β \\
V_c
\end{bmatrix} = \sqrt{\frac{2}{3}}
\begin{bmatrix}
1 & -1 & 1 \\
0 & \frac{\sqrt{3}}{2} & 0 \\
0 & 0 & \frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
V_α \\
V_β \\
V_c
\end{bmatrix}
\]

(2)

\[
\begin{bmatrix}
i_Lα \\
i_Lβ \\
i_L0
\end{bmatrix} = \sqrt{\frac{2}{3}}
\begin{bmatrix}
1 & -1 & 1 \\
0 & \frac{\sqrt{3}}{2} & 0 \\
0 & 0 & \frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
i_α \\
i_β \\
i_c
\end{bmatrix}
\]

(3)

The Eq. 3 can be reformulating in terms of \(v_α\) and \(v_β\) and the reference signal can of compensation current obtain by the inverse park’s transformation as follows:
\[
\begin{bmatrix}
i_{Ld} \\
i_{Lq} \\
i_{L0}
\end{bmatrix} = \frac{1}{\sqrt{v_{\alpha}^2 + v_{\beta}^2}} \begin{bmatrix}
v_{\alpha} & v_{\beta} & 0 \\
-v_{\beta} & v_{\alpha} & 0 \\
0 & 0 & v_{\alpha\beta}
\end{bmatrix} \begin{bmatrix}
i_{Ld} \\
i_{Lq} \\
i_{L0}
\end{bmatrix}
\]
(4)

\[
\begin{bmatrix}
i_{ca}^* \\
i_{cb}^* \\
i_{c0}^*
\end{bmatrix} = \frac{1}{\sqrt{v_{\alpha}^2 + v_{\beta}^2}} \begin{bmatrix}
v_{\alpha} & v_{\beta} & 0 \\
-v_{\beta} & v_{\alpha} & 0 \\
0 & 0 & v_{\alpha\beta}
\end{bmatrix} \begin{bmatrix}
i_{ca}^* \\
i_{cb}^* \\
i_{c0}^*
\end{bmatrix}
\]
(5)

\[
\begin{bmatrix}
i_{ca}^* \\
i_{cb}^* \\
i_{cc}^*
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & 0 & \frac{1}{\sqrt{2}} \\
-\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
-\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \begin{bmatrix}
i_{ca}^* \\
i_{cb}^* \\
i_{c0}^*
\end{bmatrix}
\]
(6)

\[e(t) = v_{dc} - v_{dc}\]
(7)

\[i_{dh} = kp \cdot e(t) + ki \int e(t) \, dt\]
(8)

By using park transformation to convert three phase current to as like dc component the result (i_{ld}, i_{lq}) then the currents are allowed to pass through low pass filter to reduce the dc components in the non-linear load currents.

\[i_{ld2h} = i_{ld1h} - i_{ld}\]
(9)

\[i_{lq2h} = i_{lq1h} - i_{lq}\]
(10)

The d-q load current, i_{ld} and i_{lq} has \text{ DC} component and both \text{ d-q load, current} (i_{ld} and i_{lq}) has \text{ DC} and \text{ ac component}.

\[i_{ld} = i_{ld} + i_{ld} , \text{ and } i_{lq} = i_{lq} + i_{lq}\]
(11)

By using inverse park transformation to obtain three phase reference signals current. The signal current reference was calculated so the stage of detection of harmonic is done. the next stage of control is represented Comparison operation between current reference and sensed actual currents of APF for
each phase and the Error which that produce will pass through hysteresis band width as shown in Figure 5.

![Figure 5](image)

**Figure 5.** The tracing of error through hysteresis PWM

### 3.2. B-adaptive Fuzzy Adjuster and adaptive PI control

The important thing that distinguishes fuzzy logic controller on another controller is that, it is can cope with imprecise input. The purpose of fuzzy logical controls to adjust proportional control ($k_p$) and generalized integral control ($k_i$) by based on the error ($e$) and change of error ($ec$).

$$k_p=k_p^*+\Delta k_p$$  \hspace{1cm} (12)  

$$k_i=k_i^*+\Delta k_i$$  \hspace{1cm} (13)  

where ($k_p^*$) and ($k_i^*$) represented reference value of adaptive PI controller. A membership function of $\Delta k_p$ and $\Delta k_i$ Figure 6. In this technique, the system appears more coherent with small overshoot and a fast dynamic response. The process of building the variable rules is to be setting $\Delta k_p$ and $\Delta k_i$ parameters as shown in table 1 and 2 respectively.

| CHANGE OF ERROR | NB | NM | NS | 0 | PS | PM | PB |
|-----------------|----|----|----|---|----|----|----|
| ERROR           | NB | PM | PB | NB | PM | PS | PM | PS | 0  |
| NB              | NM | PM | PB | NM | PM | PS | PM | PS | 0  |
| NS              | PS | PS | PS | 0  | NS | NM | NM | NM | 0  |
| 0               | PM | PS | 0  | 0  | NS | NM | NM | NM | 0  |
| PS              | PM | 0  | NS | NM | NM | NM | NM | NM | NB |
| PM              | 0  | NS | NM | NM | NM | NM | NM | NM | NB |
| PB              | 0  | NS | NM | NM | NM | NM | NM | NM | NB |

| CHANGE OF ERROR | NB | NM | NS | 0 | PS | PM | PB |
|-----------------|----|----|----|---|----|----|----|
| ERROR           | NB | PM | PB | NB | PM | PS | PM | PS | 0  |
| NB              | NM | PM | PB | NM | PM | PS | PM | PS | 0  |
| NS              | PS | PS | PS | 0  | NS | NM | NM | NM | 0  |
| 0               | PM | PS | 0  | 0  | NS | NM | NM | NM | 0  |
| PS              | PM | 0  | NS | NS | NS | NM | NM | NM | NB |
| PM              | 0  | NS | NS | NS | NS | NM | NM | NM | NB |
| PB              | 0  | NS | NS | NS | NS | NM | NM | NM | NB |
Figure 6. Membership function of Δkp and Δki

The final level of proposed control strategy is represented by adaptive PI controller as shown in Figure 7. Adaptive PI support to produce change coefficients of PI parameters (Δkp and Δki).

Figure 7. The architecture of adaptive PI control

4. propose technique of control
With the hybrid active filter, the system is implemented by the two-control technique of DC link voltage.

1. Traditional method by use fuzzy logical control.
2. Propose method control by adaptive fuzzy and adaptive PI.

Figure 8. Implementation circuit : (a) traditional method (b) proposed method

As show in Figure 8, the pervious technique is presented by fuzzy logic control to regulate DC input of inverter and to control the current and reactive compensator. This will have led to attenuation the harmonic process and thus improve power quality while the propose method which used fuzzy with
two input, one of error and another for derivative of errors comparable. As shown in the simulation result in table 3, the proposed system it may be more effective through comparison the result of THD%.

5. Numerical Results

The results of the simulation have been obtained by using three phases power system in mat- lab. with hybrid active power filter and control strategy as shown in Figure 1. The results are set for: (a) Without compensation before adding filters Figure 9. (b)Compensation with series passive filter Figure 10. (c)The compensation process through active filter with proposed control technique Figure 11. The results obtained after the insertion of a filter on the AC load side at PCC has proven them to be effective. It was found that filters had a high effect on the dropping of the harmonic voltage and in turn on the injected harmonic current reductions as well on the supply AC side. After connecting the filters, the three-phase supply currents become near to sinusoidal and harmonics are decreased. From FFT spectrum that shown in Figure 12, the observed results of THD% for each case are comparable. The effectiveness of hybrid active filter with proposed technique of control on DC link voltage gives better performance results for control DC link voltage with small ripple, and it is more efficiency than previous control methods as shown in table 3. on other hand, the error that produce from the comparison between filter current and signal reference current Processed with two methods, (1)-SPWM (2)-The hysteresis PWM both of them are responsible of performed on the error signals. The control in hysteresis technique is more effective than SPWM by giving the result of relatively little harmonic distortion (THD%) as shown in the simulation result in table 3.

| Table 3. Comparison results of THD% |
|-----------------------------------|
| THD% of the grid current | THD% of the load current |
|---------------------------|---------------------------|
| Before adding filters | 21.34 | 21.34 |
| Comparison between SPWM, hysteresis PWM Techniques | 3.26 | 8.55 |
| Just with SSPF hybrid with conventional technique control | 3.86 | 3.86 |
| Propose technique Hybrid active filters with proposed control | 1.88 | 2.55 |
Figure 9. Waveform before adding filters for: (a) Source voltage (b) Load current (c) Source current

Figure 10. Waveform just with SPPF: (a) Source voltage (b) Load current (c) Source current
Figure 11. Waveform hybrid filters with proposed technique control for: (a) source voltage, (b) source current (c) DC link voltage (d) filter current (e) load current.
Figure 12. FFT spectrum for: (a) before add filters (b) just with SPPF (c) with hybrid filters and propose technique control.

6. Conclusion
In this paper, a new technique adaptive fuzzy logic control of shunt APF and adaptive PI controller with (id–iq) theory to calculate signal harmonic current reference in order to control APF under unbalanced mains voltage, also which are can promise perfect results it can observed from the input of inverter (dc voltage) is approximate constant and the ripple is nearly disappear as well as output voltage sinusoidal after control of gate pulses. The current THD is reduced from (21.34) % to (2.55) % which impels confirms the performance of the filters is perfect and good compensation reactive power which that leads to enhancement the power quality and improve the performance of the system.

Appendix A. parameter of circuit

|                          |            |
|--------------------------|------------|
| AC supply voltage        | 400 V      |
| DC voltage of inverter   | 220 V      |
| Cdc capacitor            | 500 uF     |
| Fundamental frequency    | 50 Hz      |
| Lsf                      | 33.7 mH    |
| Csf                      | 30 uF      |

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