New Control Algorithm to Compensate Harmonics, Unbalanced and Reactive Power in Three-Phase Four-Wire Power Systems

Arash Mahboobi¹, Behrooz Mohamadi², Mehdi Fallah³, Ali Sabouriasl⁴

¹Department of Electrical and Computer Engineering, Shabestar Branch, Islamic Azad University, Shabestar, Iran
²Faculty of Electrical Engineering, Shahid Beheshti University, Tehran, Iran
³Renewable Energy Research Center (RERC), Faculty of Electrical Engineering, Sahand University of Technology, Tabriz, Iran
⁴Department of Electrical and Computer Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran

*Corresponding Author’s E-mail: mfallah9090@yahoo.com

Abstract:

In this paper, a new method for harmonics, non-equilibrium and reactive power compensation based on the recursive least squares estimator with variable forgetting factor and fuzzy controller is proposed. For this purpose, first the fundamental harmonic components of the load current and then their positive sequence components are estimated by using the proposed algorithm. The precise performance, fast response and independency on the load current amplitude or order of harmonics are the features of the proposed method. So in the case of increase/decrease of load, sag/swell and grid voltage phase jumping, desirable compensation takes place in less than half a cycle with low total harmonic distortion. In compared with the previous control methods and regarding the structure of the proposed approach, the implementation of this method is easy. The simulation in the MATLAB/SIMULINK software and experimental results show the validity of the proposed method.

Keywords: Harmonic and Reactive Power Compensation; Fuzzy Logic Controller; Recursive Least Squares; Total Harmonic Distortion

1. Introduction

With increasing the application of power electronic converters and other nonlinear loads in the power system, the imposed harmonics on the power system are increased significantly (Sachin et al., 2014). The harmful effects of harmonics can be pointed out to increased losses, reduced capacity of power lines, and improper performance of power line equipment and reduced power quality (Yılmaz et
al., 2012- Ponnusamy et al., 2014). Passive filters are the first solution presented by researchers to eliminate the effects of harmonics. These filters have fixed compensation characteristic and it is possible to produce resonance with grid harmonic components. Therefore, for loads such as an electric arc furnace that has the time variable harmonic spectrum, the passive filters may amplify the harmonics and make the grid condition worse (Saikrishna et al., 2013- Grabowski et al., 2017).

Another solution proposed to eliminate the effects of harmonics, is the use of active filters (APF) with different control methods. Fig. 1 shows how to add an active power filter to a typical grid. One of the most important issues about active power filters, is their control methods. Control methods of active power filters are generally based on time-based computations such as Instantaneous Power Theory and Synchronous Reference Frame methods or based on computing in the frequency domain, such as the Fourier analysis method (Akagi et al., 2005- Fallah et al., 2016- Afonso et al., 2000). The disadvantages of these methods are the limitations of practical implementation in digital processors due to the heavy computation, the delay caused by it and inappropriate performance in different grid conditions, such as unbalanced load current with low-order harmonic components (third and fifth orders). Other various control methods based on time domain or frequency calculations are provided to improve the performance of active power filters by considering different network conditions (Acuna et al., 2014- Alberto et al., 2009- Biricik et al., 2013- Modarresi et al., 2016). These methods make it more difficult to control active power filters and make them very hard to implement. On the other hand, the performance of these methods is also limited.

Recursive Least Squares (RLS) is a mathematical tool and it is a useful for estimating real-time parameters of a signal (Ning et al., 2007). In this method, the estimation of signal parameters in the $t+1$ time sample, are performed by using the value of parameters in the $t$ time sample and the value of the measured signal in the $t+1$ time sample. Therefore, it requires less memory and can be easily implemented in DSP microcontrollers. For fast and accurate parameters estimation under transient and steady state of the signal, variable forgetting factor (VFF) is required for the covariance matrix resetting. Therefore, in this paper, a method based on fuzzy logic controller (FLC) and variable forgetting factor-recursive least squares (VFF-RLS) is proposed. The resulting estimator is called VFF-RLS based on FLC. In the VFF-RLS estimation method, when the signal parameters are invariant, forgetting factor value is tuned equal to the unit. But if the signal parameters are variable (For example, the change in the fundamental component of the load current), at the moment of change, forgetting factor should be reduced from the unit value and the estimation should be made. Then the value of this factor will be increased again to unit. When the signal parameters are changed, the VFF-RLS will reduce the amount of forgetting factor. Also after this reduction, the VFF-RLS has faster and accurate estimation process, if the time length of forgetting factor reduction will be lower. So in this paper, FLC is applied to VFF-RLS structure for the variation of the forgetting factor in transient and steady state conditions of the signal. The duration of the forgetting factor reduction by the proposed
method is equal to 0.1 ms, which is much less than the other methods (Beza et al., 2011). Therefore, the performance of the proposed control method of the active power filter is very accurate and fast. The effectiveness of the proposed method are shown by using the simulation in MATLAB/SIMULINK software and experimental results.

Fig. 1. Active power filter connection to a sample grid

2. The Proposed Control Method

Fig. 2 shows the block diagram of the proposed approach to compensate three-phase four-wire systems by using active power filters. In this method, by estimating the positive sequence of the fundamental component of the load current and then calculating the compensation reference current, grid side current is modified and also reactive power of the load is compensated. In addition, the proposed method can also delete the unbalance load current.
Recursive least squares method is a strong mathematical tool for online estimating of a signal parameters. In this method, it is assumed that the estimation has been done until the moment of \( t \). Then by entering the data of the measured signal at the \( t+1 \) time sample, new estimation is done based on the previous estimation data at the \( t \) sample time and the data of the measured signal at the \( t+1 \) time sample. In other words, between the measured signal and the estimator there is an instantaneous communication, and with each new sample of the measured signal, the estimation will be updated. Therefore, with assuming the measured signal as (1), this method performs the estimation by using (2) and (3), which called estimation and update equations, respectively (Mostafa et al., 2012).

\[
y(t) = \Phi^T(t)\theta(t)
\]

\[
\hat{\theta}(t+1) = \hat{\theta}(t) + P(t+1)\Phi(t+1)[y(t+1) - \Phi^T(t+1)\hat{\theta}(t)]
\]

\[
P(t+1) = \frac{1}{\lambda(t)}[P(t) - P(t)\Phi(t+1)\Phi^T(t+1)P(t)]
\]

\[
1 + \Phi^T(t+1)P(t)\Phi(t+1)
\]

where \( \hat{\theta} \) is the estimation parameters matrix and \( \theta \) is the real value of the \( \hat{\theta} \). Also \( \Phi^T \) is the coefficient matrix or regressor matrix, \( P \) is the covariance matrix and \( \lambda \) is the forgetting factor. The value of \( \lambda \) is between zero and one and it is used to increase the convergence rate of the RLS method in the transient conditions of the signal. In other words, in the steady state condition of the signal, the value
of λ is equal to one, and the estimation has high accuracy. But in transient state of the signal, by decreasing this coefficient to less than one, the covariance matrix resets and as a consequence the convergence rate increases. By resetting the covariance matrix, the sampled data at the moment of t+1 will have more effect on the estimation process, and this will increase the estimation speed. On the other hand, by reducing the value of λ, the accuracy of the estimation decreases. Therefore, in transient state of the signal with fewer time length of forgetting factor reduction, the VFF-RLS estimator will have more accuracy and speed (Mostafa et al., 2012- Mebtu et al., 2016). In this paper, the fuzzy logic controller is used to control the forgetting factor in the proposed control structure, which reduces the length of this time to 0.1 ms. Based on this, (4) gives variable forgetting factor (Park et al., 1991).

\[
\lambda(t) = \lambda_{\text{min}} + (1 - \lambda_{\text{min}})2^{-|\rho \alpha^2(t)|}
\]  

(4)

where \( \lambda_{\text{min}} \) is the minimum value of the forgetting factor, \( \rho \) is the forgetting factor controller and \( \alpha \) is the estimation error which expressed by (5).

\[
\alpha(t) = y(t+1)-\Phi^T(t+1)\hat{\theta}(t)
\]

(5)

Rate of changes of the estimation error can be expressed by (6).

\[
\Delta \alpha(t+1) = \alpha(t+1) - \alpha(t)
\]

(6)

According to (4) and (5), and assuming that the value of \( \rho \) is constant, the forgetting factor will be changed only if the amount of estimation error (\( \alpha \)) is large. Therefore, when the signal is in transient state and the signal has a little change, fast and accurate estimate is not available. Thus in this condition and according to (4), the value of \( \rho \) must be increased and as a result by changing \( \lambda \) and resetting covariance matrix, the fast and accurate estimation will be done.

In this paper, a fuzzy logic controller has been used in the recommended control method to adjust the value of forgetting factor controller. Implementation steps of FCL are as follows.

- Selecting the variables as inputs of FCL (\( \alpha \) and \( \Delta \alpha \) are the estimation error and the rate of variation of the estimation error)
- Set fuzzy levels to convert exact and numeric values to linguistic values \{(PB: Big Positive),(P: Positive),(Z: Zero),(N: Negative),(NB: Big Negative)\} and \{(S: Short),(M: Medium),(L: Large)\} are Fuzzy output levels.
- Determine member functions and draw charts (The member function is a curve that shows how each point of the input space is mapped to a member value (Member grade) between 0 and 1).
In Fig. 3, member functions are plotted. The member grade of the inputs is obtained from (7).

\[
\mu_{N,Z,P} (x) = \begin{cases} 
1 - \frac{|x-m|}{0.5w} & x > m \\
1 & x \leq m
\end{cases}
\]

(7)

\[
\mu_{NB, PB} (x) = \begin{cases} 
1 - \frac{|x-m|}{0.5w} & x > m \\
1 & x \leq m
\end{cases}
\]

where \( w \) is the domain width of the function, \( x \) is the value of the input variable, and \( m \) is the space which its member degree’s is equal to one. Note that the fuzzification of the rate of changes of the estimation error is done based on Fig. 3(a).

Figure 3. Member functions (a) fuzzification of estimation error, (b) estimation error, (c) rate of changes of the estimation error, (d) forgetting factor controller gain or output signal of FCL (\( \rho \))

- Setting rules and forming rules table

When the inputs are fuzzificated, then there is a degree for each section of the "if". If the preceding rule is more than one, then we use fuzzy operators to obtain one number that represents the precedence
of that rule. Then this number is used in the output function. Here, due to using operator, the preceding (coefficient of weight) of each law is calculated from (8).

\[
W_i = \min \left\{ \mu_{F_{\text{Error}}} (\alpha), \mu_{F_{\text{Error}}} (\Delta \alpha) \right\}
\]

(8)

When we attribute proper weight to each of the rules, the signifying method is used. The input of the signifying process is a number and the output is a fuzzy set which defined by a member function, and this function is multiplied by the corresponding weight. The signifying process is executed for each of the rules, and finally, weighted average of the output of all the rules is obtained from (9), which indicates the output of the FLC.

\[
\rho = \frac{\sum_{i=1}^{N} W_i C_i}{\sum_{i=1}^{N} W_i}
\]

(9)

where \( N \) is the total number of rules, \( C_i \) is coordinates corresponding to the output of each rule and \( \rho \) is the output of the FLC. The set of rules is defined in Table 1.

<table>
<thead>
<tr>
<th>Rate of changes of the estimation error (( \Delta \alpha ))</th>
<th>P</th>
<th>L</th>
<th>M</th>
<th>S</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>S</td>
<td>M</td>
<td>L</td>
<td>M</td>
<td>S</td>
</tr>
<tr>
<td>N</td>
<td>S</td>
<td>L</td>
<td>M</td>
<td>L</td>
<td>S</td>
</tr>
<tr>
<td>NB</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>

Table 1. FLC rules

To increase the response speed, the “sugeno” type is selected as the fuzzy inference system.

2-1- Estimation of Fundamental Component of Load Current

The Fourier series of the load current obtained as (10).

\[
y(t) = y_{dc} + \sum_{j=1}^{J} \left( a_j \sin(j \omega t) + b_j \cos(j \omega t) \right)
\]

(10)
Based on the (1) and (10), the estimation parameter matrix and the regressor matrix can be formed as (11) and (12), respectively.

\[
\theta^T (t) = [y_{dc} \ a_1 \ b_1 \cdots a_j \ b_j]
\]

\[
\Phi^T (t) = [1 \ \sin (\omega t) \ \cos (\omega t) \ \sin (3\omega t) \ \cos (3\omega t) \ \cdots \ \sin (J\omega t) \ \cos (J\omega t)]
\]

For other two phase load currents, the regressor matrixes can be obtained with considering 120 degree phase difference. Finally, by using (2) and (3), the matrix of the estimation parameters for each phase of the load current can be calculated. By considering the feature of the load current, the values of \(y_{dc}\) and \(b_j\) are zero and (13) shows the fundamental component of load current of phase “a”.

\[
I_{a1} (t) = a_1 \sin (\omega t)
\]

Therefore, the fundamental components of the load current can be obtained using RLS estimator (in the equations the subtitles 1 or f are devoted to the fundamental component of the current).

2-2-Estimation of the Positive Sequence of the Fundamental Component of Load Current

The symmetric sequences of the fundamental components of the load current can be calculated by (14).

\[
\begin{bmatrix}
I_{a1} \\
I_{b1} \\
I_{c1}
\end{bmatrix} = T
\begin{bmatrix}
I_0 \\
I_+ \\
I_-
\end{bmatrix}
\]

(14)

where \(T\) is the transpose matrix and defined by (15).

\[
T = \begin{bmatrix}
\sin (\omega t) & \sin (\omega t) & \sin (\omega t) \\
\sin (\omega t) & \sin (\omega t - 120) & \sin (\omega t + 120) \\
\sin (\omega t) & \sin (\omega t + 120) & \sin (\omega t - 120)
\end{bmatrix}
\]

(15)

For compensating of the load current harmonics, unbalances and reactive power, the positive sequence of fundamental components of load current is used to generate reference signals. In order to decrease the computation burden of positive sequence estimation and as a result to increase the speed of response of the proposed control method, the zero sequence of fundamental components of load current is subtracted from the fundamental components of the load current for each phase. According to (16), the zero sequence is equal to average of the fundamental components of load current. So a new equation to estimate the positive and negative symmetrical sequences will be (17).
$$I_0(t) = \frac{I_{a1}(t) + I_{b1}(t) + I_{c1}(t)}{3}$$  \hspace{1cm} (16)$$

\[
\begin{bmatrix}
i_{a1}(t) - I_0(t) \\
i_{b1}(t) - I_0(t) \\
i_{c1}(t) - I_0(t)
\end{bmatrix} =
\begin{bmatrix}
sin(\omega t) & sin(\omega t) \\
sin(\omega t - 120) & sin(\omega t + 120) \\
sin(\omega t + 120) & sin(\omega t - 120)
\end{bmatrix}
\begin{bmatrix}
I_+ \\
\dot{\phi}(t)
\end{bmatrix}
\]  \hspace{1cm} (17)$$

With considering (17) in the matrix form of (1) and by using (2) and (3), positive sequences of the fundamental components of load current ($I_{abc(f+)}$) are estimated. Finally, by using (18) the reference compensation currents ($I_{abc(ref)}$) of the active power filter are obtained.

$$I_{abc(ref)} = I_{abc(h)} - I_{abc(f+)}$$  \hspace{1cm} (18)$$

where $I_{abc(h)}$ is load current components. In estimating fundamental components of the load current and also their positive sequence components, the vectors of the regressors are obtained by using the reference phase ($\omega t$), which is extracted by the PLL.

### 3. Simulation Results

Fig. 4 shows the power system studied in MATLAB / SIMULINK software. This three-phase, four-wire power system is composed of a constant unbalanced load and a diode rectified load that at the moment $t=0.2s$ connected to the grid. The diode rectified load is used for analysis the dynamic response of the proposed active power filter control method at the moment of the connecting the load to the grid. Table 2 shows the parameters of the studied power system.
Table 2. Simulated power system parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_s$</td>
<td>Power system voltage</td>
</tr>
<tr>
<td>Rectified Load</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>L</td>
</tr>
<tr>
<td>Unbalanced load</td>
<td>Lag</td>
</tr>
<tr>
<td>$R_s$</td>
<td>1 mΩ</td>
</tr>
<tr>
<td>$L_s$</td>
<td>0.1 mH</td>
</tr>
<tr>
<td>$C$</td>
<td>8 mF</td>
</tr>
<tr>
<td>$L$</td>
<td>1 mH</td>
</tr>
<tr>
<td>$\lambda_{\text{min}}$</td>
<td>0.88</td>
</tr>
<tr>
<td>$f$</td>
<td>Power system frequency</td>
</tr>
</tbody>
</table>

Figs. 5(a) and 5(b) illustrate the distortion load current waveform and the compensated grid side current by the proposed active filter, respectively. Based on Fig. 5(b), the compensated grid side current has a very high accuracy (THD≈1%) and is less than the standard determined by IEEE-519. Also, the response time of the active filter is very low and equal to 5 ms. In addition, the amount of current unbalanced ratio (CUR) is 45% and 1.8% before and after compensation, respectively.

According to Fig. 5(b), the proposed control method has high speed and high accurate response. These advantages are caused by the applying FLC in VFF-RLS structure. When load current changes, the estimation error is high and as a result the rate of change of the estimation error will be also high. Then the FLC determines the value of forgetting factor controller gain based on predefined rules. According to (4), (3) and (2), the estimation of desired parameters can be done after changing the forgetting factor controller gain. In other words, in this condition, the proposed estimator using FLC
reduces the forgetting factor to very short time. With this reduction the covariance matrix will be reset and increases instantaneously based on (3) and as a result the measured data at \( t+1 \) time sample have more effect than data at \( t \) time sample in the estimation process. Figs. 6(a) and 6(b) show the changes in the covariance matrix and the forgetting factor of fundamental components estimator when the load current changes, respectively. Also Fig. 7 depicts the estimation values of zero and positive sequences. In this paper the VFF-RLS estimator is proposed based on FLC. This estimator can be self-tune the value of the forgetting factor controller using estimation error and rate of the change of it. The high accuracy and speed response are the prominent features of the proposed estimator which caused by self-tuning characteristic of it. Fig. 8 shows compensated grid side current using VFF-RLS estimator with constant value of forgetting factor controller (without FLC). According to this figure, without FLC, the time response of compensation is very high. This is due to the resetting failure in the covariance matrix by the forgetting factor. So for resetting the covariance matrix, the value of the forgetting factor controller gain must be tuned manually. In other words, for any variation in the estimation parameters, there is a specific value of the forgetting factor controller gain which it must be set manually. The proposed estimator is an adaptive method, and it has self-tuning ability for the forgetting factor controller gain in any working point.

![Waveforms of the (a) covariance matrix and (b) variable forgetting factor](image)

Figure 6. Waveforms of the (a) covariance matrix and (b) variable forgetting factor
According to this figure, when the load changing is occurred, the compensation process is failed due to the lack of suitable control of the forgetting factor. Figs. 9(a) and 9(b) demonstrate the active and reactive power of source and load sides, respectively. According to Fig. 9(a), the proposed method compensates the reactive power. This is due to application of phase locked loop (PLL) method for active power filter synchronization with grid (construction of regressor matrixes).
Figure 9. Waveforms of the active and reactive power, (a) source side and (b) load side

Table 3 summarizes the performance comparison of the proposed control method (VFF-RLS with FLC) with the control method without FLC under various load change conditions.

<table>
<thead>
<tr>
<th>Amount of load increasing (or decreasing)</th>
<th>Accuracy and delay by compensation method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VFF-RLS with FLC</td>
</tr>
<tr>
<td>%20</td>
<td>THD (%)</td>
</tr>
<tr>
<td>%40</td>
<td>1.5</td>
</tr>
<tr>
<td>%60</td>
<td>1.3</td>
</tr>
<tr>
<td>%80</td>
<td>1.2</td>
</tr>
</tbody>
</table>

4. Experimental results

In order to verify the simulation results, the laboratory prototype of the APF based on the proposed control, is implemented. To this end, the proposed control method is simulated in MATLAB/SIMULINK Real-Time Windows Target (RTWT) toolbox and then the reference signals are obtained. So, these reference signals are applied to digital signal processor (DSP) through advanced data acquisition card (DAQ) which is the interface between software and DSP. In this prototype, Texas TMS320F2812 and PCI-1716 are used as the DSP and DAQ respectively. DSP generates the 10 KHz PWM switching pulses using reference signals. Generated PWM signals lead to act the converter IGBTs. Power section of APF is formed by DC capacitor link, inductors and three half bridge semikron SKM 75GB128D IGBT modules as the converter. Also LEM-LV25-P voltage...
transducer is used to measure and generate a suitable feedback system. The schematic diagram of the implemented prototype is depicted in Fig. 10.

![Schematic diagram of the implemented prototype](image)

**Figure 10.** Schematic diagram of the implemented prototype

Transient and steady state response of the APF are the very important criterion to analysis of its performance. Therefore, Fig. 11(a) shows the load current. According to this figure, load is increases at a certain time. Fig. 11(b) demonstrates the injected current by APF which contains wide spectrum of load current harmonics. By injection of this current, the grid side current is compensated as Fig. 11(c). Based on Fig. 11(c), transient response of the APF with proposed control method is less than half cycle of power system frequency and it is acceptable by IEEE 519 standard limitation. Also, in this figure, the red curve shows the harmonic spectrum of the waveform. In other words, according to red curve in the Fig. 11(c), the steady state response of the proposed method is good. Note that, in Figs. 11(a), (b) and (c) the waveforms of two phases are illustrated.
Figure 11. Waveforms of the (a) load side current, (b) injected current by APF and (c) compensated grid side current. (50 mV/A-10 ms/div)
5. Conclusion

In this paper, a new control algorithm for active power filters is introduced using the recursive least squares method with variable forgetting factor based on fuzzy controller. The proposed control method can be compensate unbalanced, harmonics and reactive power of the load. Since the proposed method is entirely based on numerical signal processing methods, so there is no dependency on the amplitude and frequency of load current harmonics. The simulation and experimental results confirmed that the proposed method has fast, accurate and acceptable compensation performance based on the limitation defined by the IEEE-519 standard.

6. References


