Implementation of Recursive Least Square Method in Active Power Filters Control

Borisav Jovanović, Predrag Petković, Srđan Milenković

***Abstract*— This paper proposes implementation of Recursive Least Square (RLS) method in a self-adaptive technique for Active Power Filter (APF) control. APF are used to reduce the Total Harmonic Distortion (THD) in power system. Namely, APF compensate higher harmonics present in the power grid. In order to compensate, the higher harmonics should be identified, at first. The real truth is that nonlinear loads mainly distort the current. Therefore the distortion current is to be measured and all harmonic components identified. RLS method uses values of the sampled current to calculate the needed compensation for APF. Then APF (in shunt configuration) add to the grid the required higher harmonic components of current diminishing distortion on the grid. Simulations by SystemC verify the effectiveness of the method.**

***Index Terms*—Active power filters; Power grid; Power harmonics; Recursive Least Squares algorithm.**

I. INTRODUCTION

All loads connected to a power grid can be categorized as linear and non-linear loads. The linear load causes the current drawn from the power grid to be proportional to the applied voltage. If the load impedance changes with the applied voltage, the load is defined as non-linear. In this case, the current drawn from the grid does not follow the voltage linearly and it is not sinusoidal. It contains higher harmonics. Consequently, the distributed power, apart from active and reactive, receives another component, known as distortion power. This power is mainly nonvisible to the utility and is manifested as losses on the grid [1].

The number of nonlinear loads has been increased enormously in last few decades. Nonlinearity is typical for AC-DC converters, variable frequency drives, discharge lighting, etc. The problem has augmented with the effort to make much effective converters where active devices operate in switching mode. The good news is that contemporary electronics requires much less power per an appliance. However the bad news is that the number of electronic gadgets is huge. In total, the distortion part of the consumed power has become significant and reaches the same order of magnitude as active power [2]. Therefore it should be diminished. The main strategy in dealing with this problem is to strike at the point at which it is generated. The nonlinear loads introduce harmonics into the grid and they are *sources* of harmonics. Therefore it is natural to provide some kind of *drain* for harmonics, trying to compensate them.

The real answer to this challenge has come from using Active Power Filters (APF) [3]. Their role is to introduce new harmonics to the grid. In order to compensate existing harmonics, the new should have the same magnitude but the opposite phase. This can be done only if

1. magnitude and phase values of the presented harmonics are known,
2. there is possibility to add to the grid required harmonics.

Consequently, the system that compensate harmonics has to consist of a measuring module, some computing engine that calculate harmonics, control module that drives actuators capable to provide required harmonics to the grid.

Practically it means that one need to have a reservoir from which the loss that appears as the distortion power would be supplemented. The contemporary grid systems are enriched with such reservoirs. Basically, all alternative power sources like photovoltaic (PV) panels, wind farms, even any other DC supply are to be connected to the grid using DC/AC converters. The tricky part is how to control the converter in order to produce signal with required harmonics pattern.

This paper suggests implementation of Recursive Least Square (RLS) method in a self-adaptive technique for Active Power Filter (APF) control.

The following section describes principles of APF. The third section explains the use of RLS method for APF control. The idea is verifies by SystemC simulation. The obtained results are presented the fourth section that precedes to the concluding section.

II. ACTIVE POWER FILTERS

Active power filters (APF) are now relatively common in industrial applications for both harmonic mitigation and reactive power compensation [4]. The APF ensures the power grid current to be almost sinusoidal and in-phase with the source voltage signal [5]. Besides, the APF improves the power quality in order to impose a unity power factor. Shunt-connected APF, positioned in parallel with the nonlinear load, is the common configuration of the APF [6].

The APF is comprised of the IGBT bridge and DC bus architecture similar to that seen in alternating current pulse-width modulation drives. The direct current bus is used as an energy storage unit [6].

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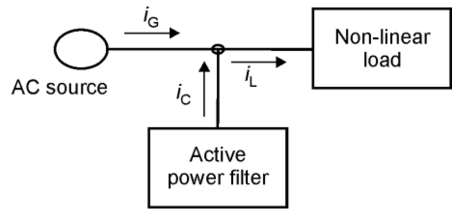

Fig. 1. Typical connections of Active power filter.

The APF operation is based on measured data of the distorted current drown from the nonlinear load. It is depicted in Fig. 1 as i_L. The measured results are fed to the embedded microprocessor to calculate harmonics and to generate the corresponding IGBT firing patterns that will provide the compensation current capable to cancel harmonics. This current is denoted as i_C in Fig. 1. As result, the total grid current (i_G in Fig. 1) is the difference of the distortion current and the compensation current. In order to make i_G cleared of harmonics, APF should add to the grid current that has the same amount of higher harmonics but with opposite phase of the distortion current [4].

The proposed method is focused on improving the quality of the power system. The method can be divided into two parts. In the first part, the distortion current is measured and processed. The outcomes are the amplitudes and phases of all harmonic components. In the second part, the compensation current signal is generated which is then subtracted from the distortion current to form harmonic-free grid current.

The aim of this paper is not to consider DC to AC converter and its driver that produces the compensation current. Instead, we want to prove a new concept of APF control based on RLS algorithm for harmonic detection and adaptive active filtering [5].

III. The Utilization of the Recursive Least Squares Method in Implementation of APF

When nonlinear loads are present in a power system, the load current waveforms are periodic but non-sinusoidal. According to Fourier series theory any periodic waveform can be represented as a sum of its harmonic components. Implemented in discrete domain when sampled with f_s, the n-th sample of the load current signal $i_L(n)$, can be expressed as follows:

$$i_L(n) = \sum_{i=1}^{K} A_i \cdot \sin(2\pi f n i + \varphi_i)\,, \tag{1}$$

where f=50/f_s is the fundamental frequency of 50Hz, which is normalized to sampling frequency value f_s. The A_i and φ_i represent the amplitude and the phase of the i-th harmonic of the load current signal. K is the order of the highest harmonic. Equation (1) can be transformed into the following equation:

$$i_L(n) = \sum_{i=1}^{K} \left[A_i \cos\varphi_i \cdot \sin\left(2\pi f n i\right) + A_i \sin\varphi_i \cdot \cos\left(2\pi f n i\right) \right] \tag{2}$$

It is practical to store components of expression (2) in form of two vectors sized as 2×K. One of them, denoted $\mathbf{x}(n)$, stores *sin(2πfni)* and *cos(2πfni)* pairs for each i=1,...,K:

$$\begin{aligned} \mathbf{x}(n) &= \left[x_j(n) \right]^T \Big|_{j=1,\dots,2K} \\ x_{2i-1}(n) &= \sin(2\pi f n i) \Big|_{i=1,\dots,K} \\ x_{2i}(n) &= \cos(2\pi f n i) \Big|_{i=1,\dots,K} \end{aligned} \,. \tag{3}$$

Another, denoted $\mathbf{w}(n)$, stores pairs of amplitudes related to cosine ($A_i \cos \varphi_i$) and sine ($A_i \sin \varphi_i$) components of harmonics for each i=1,...,K:

$$\begin{aligned} \mathbf{w}(n) &= \left[w_j \right]^T \Big|_{j=1,\dots,2K} \\ w_{2i-1}(n) &= A_i(n) \cos\varphi_i \Big|_{i=1,\dots,K} \\ w_{2i}(n) &= A_i(n) \sin\varphi_i \Big|_{i=1,\dots,K} \end{aligned} \,. \tag{4}$$

The scalar value $i_L(n)$ can be expressed as a product of the two vectors:

$$i_L(n) = \mathbf{x}(n)^T \mathbf{w}(n)\,. \tag{5}$$

In order to obtain all harmonic components of the load current one needs to know $\mathbf{w}(n)$. The amplitudes and phases of the i-th harmonic components are:

$$A_i = \sqrt{w_{2i-1}^2 + w_{2i}^2} = \sqrt{(A_i \cos\varphi_i)^2 + (A_i \sin\varphi_i)^2} \tag{6}$$

$$\varphi_i = \arctan \frac{w_{2i}}{w_{2i-1}} \tag{7}$$

If $\mathbf{w}(n)$ is known, any harmonic waveform can be easily reconstructed. For example, component of $i_{Li}(n)$ with frequency f, can be expressed as:

$$i_{Li}(n) = A_i \cos\varphi_i \cdot \sin\left(2\pi f n i\right) + A_i \sin\varphi_i \cdot \cos\left(2\pi f n i\right) \tag{8}$$

$$i_{Li}(n) = w_{2i-1} \cdot x_{2i-1}(n) + w_{2i} \cdot x_{2i}(n) \tag{9}$$

The elements of vector $\mathbf{x}(n)$ are considered as known because fundamental frequency, and frequency of all required harmonics, are known so that cosine and sine values for all harmonic components can be easily calculated. The elements of vector $\mathbf{w}(n)$, which contain information about amplitudes and phases of harmonic components, are unknown and have to be determined. For this purpose we suggest using adaptive filtering based on the iterative RLS method [7].

Let the $i_L(n)$ denote the referent input signal (the distortion current signal). In each iteration, for every new input sample $i_L(n)$, new elements of the vector $\mathbf{w}(n)$ should be calculated. Formally, when $\mathbf{w}(n)$ is substituted in (5) the obtained $i_L'(n)$

will differ from the referent value $i_L(n)$. The discrepancy indicates the calculation error $\varepsilon(n)$ expressed with:

$$\varepsilon(n) = i_L(n) - i_L'(n) = i_L(n) - \mathbf{x}(n)^T \mathbf{w}(n) \qquad (10)$$

The RLS method is implemented as an adaptive filter which recursively finds the coefficients that minimize a weighted linear least squares cost function relating to the input signals. The cost function $E(n)$, used for RLS minimization of error function $\varepsilon(n)$ is:

$$E(n) = \frac{1}{2}\sum_{m=0}^{n} \lambda^{n-m} \varepsilon(m)^2 \qquad (11)$$

where λ is the "forgetting factor" giving exponentially less weight to older error samples. The smaller λ is, the smaller contribution of previous samples. In practice, λ is usually chosen between 0.98 and 1 [7].

The cost function $E(n)$ given in (11) is in contrast to other algorithms such as the least mean squares (LMS) that aim to reduce the mean square error. Compared to the other recursive algorithms, the RLS manifests fast convergence. This benefit comes at the cost of high computational complexity [7]. Fortunately, today even complicated mathematics is easily handled at low-cost contemporary hardware.

The RLS iterative algorithm is derived by minimization of cost function E(n) which is achieved by taking the partial derivatives for all parameters w_i and setting the results to zero:

$$\frac{\partial E(n)}{\partial w_i} = 0 \qquad (12)$$

When RLS algorithm converge, the error function $\varepsilon(n)$ is zero and the signals $i_L(n)$ and $i_L'(n)$ become equal.

IV. The Implementation of APF in SystemC

The model of Harmonic Distortion Corrector, which is based on utilization of Recursive Least Squares algorithm, has been implemented in SystemC. The SystemC is a set of C++ classes which provide an event-driven simulation interface and can be applied to system-level modeling, functional verification and high-level synthesis [8]. SystemC can simulate real-time environments, using signals of all the datatypes offered by standard C++, additional ones offered by the SystemC library, as well as user defined libraries [8]. In certain respects SystemC has semantic similarities to hardware description languages such as VHDL and Verilog, but is more oriented to system-level modeling. The source code is compiled to an executable file.

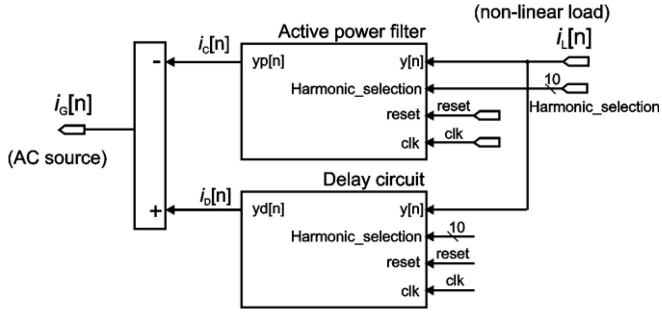

Fig. 2. The Active power filter simulation test-bench

The simulation test-bench is given in Fig.2. It consists of concurrent processes which are described using plain C++ syntax. The test-bench contains following instances:

- RLS based Active power filter,
- delay circuit having the same delay as APF, measured in number of clock cycles,
- subtraction circuit, producing grid current $i_G[n]$,
- current signal probes, storing these results into the binary log file.

The APF system takes at input the distortion current samples $i_L[n]$, sampled at frequency of 20 kHz. The distortion current is generated within the test-bench using data from Table 1. Beside, one of inputs of APF is harmonic selection bus, which is used for selection of those harmonic components which should be eliminated from the grid current $i_G[n]$. Therefore, we have an option to choose the harmonic content of the grid current. The width of this bus is K, where K is the harmonic order. In simulations, we have chosen K=10, meaning that the fundamental frequency and following nine higher harmonics are only identified. Besides, only the fundamental frequency of $i_G[n]$ is enabled and all higher harmonics are eliminated. The forgetting factor λ of RLS method is chosen to be equal to 0.98. The signal samples are defined with double C data type.

TABLE I
HARMONIC CONTENT FOR DIFFERENT SIMULATED NON-LINEAR LOADS

Harmonic order	Philips CFL lamp	Computer power supply	Power converter for variable speed motors
1	100/32°	100/-12°	100/0°
3	86/-107°	81/135°	9/60°
5	60/124°	61/-70°	70/70°
7	34/7°	37/83°	60/-150°
9	21.7/-82°	16/-115°	6/30°

Three different non-linear loads were simulated:

- the Philips CFL lamp
- for 6-pulse computer power supply
- pulse PWM controlled power converter for variable speed motors [9]

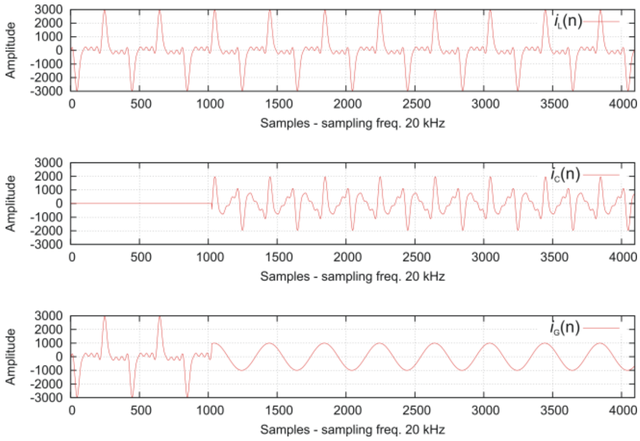

Fig. 3. The demonstration of harmonic compensation for Philips CFL lamp: top panel presents the non-linear load current $i_L[n]$, middle - compensation current $i_C[n]$ and bottom panel displays the grid current $i_G[n]$

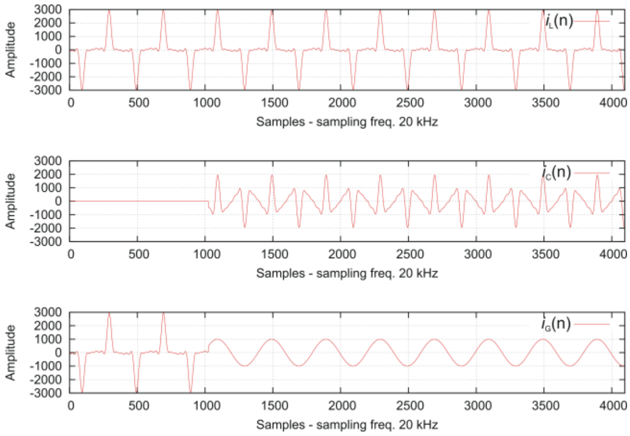

Fig. 4. The demonstration of harmonics compensation for 6-pulse computer power supply, top panel presents the non-linear load current $i_L[n]$, middle - compensation current $i_C[n]$ and bottom panel is the power grid current $i_G[n]$

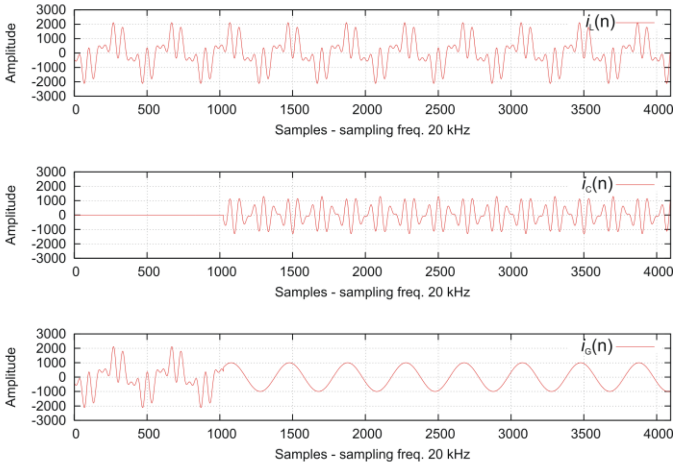

Fig. 5. The demonstration of harmonics compensation for 6- pulse PWM controlled power converter for variable speed motors, top panel presents the non-linear load current $i_L[n]$, middle - compensation current $i_C[n]$ and bottom panel is the grid current $i_G[n]$

The harmonic amplitudes and phases of input stimuli which are taken from [1], are defined in Table 1 and the results are presented in Figures 3 to 5. The top panel presents original distortion current waveform, the middle presents the compensation current and the bottom panel displays the resulting grid current. As it can be seen in figures, during the RLS training period, lasting 1000 data samples, the elements of vector $\mathbf{w}[n]$ are calculated. After the training period is finished, the compensation current is calculated and applied to distortion current. Then, the resulting grid current becomes sinusoidal.

The proposed method manifests adaptive behavior; the system is able to continuously track changes of distortion current and automatically update the coefficients of vector $\mathbf{w}[n]$.

V. Conclusion

The Active power filter (APF) is used for harmonics mitigation. This paper suggests using the iterative Recursive Least Square method for APF implementation. First, the harmonic components of distortion current signal are determined. After that, the higher harmonics are reconstructed and subtracted from distortion current. The resulting grid current becomes pure sinusoidal. We have built the SystemC simulation model of the APF system. Simulation results show that the method is feasible and works in real-time. The superior performance and the good dynamic response have been assured by simulation results, but there is still a lot of experimental research to do in the future.

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