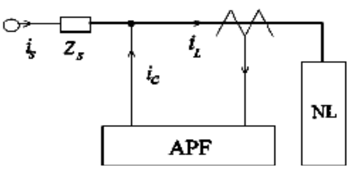

Fig.1 – Working block diagram of APF.

further decomposed into two terms, i.e.,

$$i_1(t) = I_1\cos(\theta_1)\sin(w_1 t) + I_1\sin(\theta_1)\cos(w_1 t)$$
$$= i_p(t) + i_q(t) \quad (3)$$
$$i_L(t) = i_p(t) + i_q(t) + i_h(t) = i_u(t) + i_c(t) \quad (4)$$

Where i_p active current component, which has identical frequency and phase with u_s;

i_q reactive current component;

i_u useful current component;

i_c compensating current component.

If simultaneously compensating both the reactive and the harmonic current, then i_c consists of i_q and i_h, and i_u consists of i_p. If only compensating harmonic current, then i_c consists of i_h, while i_u consists of i_1. After i_L flows through the current transformer, the desired current i_d that APF should compensate is first obtained by the detecting circuit of harmonic current. Then i_d controls the PWM inverter and i_c injected into the power system is attained. It can be seen that i_L is provided with both the supply power current i_s and the output current i_c of APF, that is, $i_L = i_s + i_c$. Since $i_c = i_q + i_h$, or $i_c = i_h$, the supply power only supplies i_p or i_1 . Hence i_s after compensation becomes a sinusoidal current which has identical frequency with u_s. This is just the basic operating principle of APF.

Some numbers of orders of harmonic currents only need to be detected for the general detecting circuits of power harmonic currents when the content of harmonics is analyzed. But the detecting circuit of harmonic current for APF is different. Each order of harmonics (or harmonics within some orders) usually does not need to be detected by it. Only the total harmonic current i_c except i_p or i_1 need to be detected. There are some higher requirements to detecting velocity and accuracy of the harmonic current detection circuit for APF can be obtained by a number of methods. The simpler one is that we are first trying to get i_u in frequency with u_s, then i_c can be attained by subtracting i_u from i_L. It is

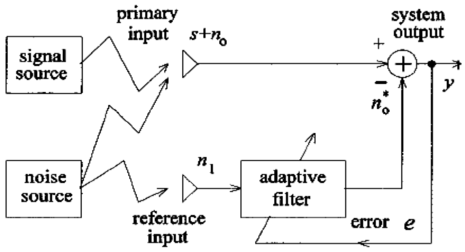

Fig.2 – Working block diagram of ANCT.

difficult to directly determine i_c because the amplitude and phase of i_p and i_q as well as each high-order harmonic current are not known before carrying out the analysis of harmonic currents. i_c can certainly be obtained by using the fixed frequency filter or the circuit containing low-pass or high-pass filter presented in [3] and [4], but i_c cannot be acquired accurately because of the restrictions of bandwidth and selectivity as well as the delay of phase and frequency drift, which exist in the fixed frequency filter. How the harmonic current can be obtained rapidly and accurately is one of the most important problems which should be solved in APF.

Widrow proposed a signal processing method—an ANCT in signal processing [10]. By using it, a signal can be separated from additive noise n_0 . Its principle is shown in Fig. 2. There are two inputs. They are the primary input $s + n_0$ and reference input n_1. s and n_0 are uncorrelated, and s and n_1 are uncorrelated, too. But n_1 and n_0 are correlated. n_1 is processed by the adaptive filter, and noise n_0^* which is identical to n_0 is attained, thus n_0 is canceled in the system output. In Fig. 2, system output y is simultaneously used as an error signal e to adjust the parameters of the adaptive filter. The priori knowledge of signal s and noise n_0 does not need to be known exactly. The adaptive filter can estimate n_0, and therefore s is obtained in the system output. ANCT is much better than the properties of Wiener's optimum filter because n_0 is subtracted, not filtered.

We can use the above principle of ANCT in harmonic current detection for APF. The adaptive filter in Fig. 2 can be substituted by an ANN or a neuron. i_L is used as the primary input, i_c is considered as the "signal" to be detected and i_u as the "noise." i_c and i_u as well as the output i_r of ANN must be (linear) uncorrelated so that i_c is not canceled by i_r. A sinusoidal signal, in frequency with u_s, must be selected as the reference input to make i_r approach i_u and counteract i_u. The u_s, whose distortion is usually very small in the power system, can be considered as a sinusoidal wave and is the same as i_u in frequency. So, $u^*{}_s$, a signal obtained after amplitude of u_s is reduced, is used as the reference input. After u_s^* (or u_s^* and its time lag terms) is processed by ANN, i_r approximates i_u. Finally, i_u is subtracted from i_L, and system output is i_d. Thus the harmonic current detection for APF is realized. Here, in order to show that the above idea is rational, we need to prove that i_c and i_u as well as i_r are uncorrelated, and i_r and i_u are correlated.

Definition [11]: Supposing $x_1(t)$, $x_2(t)$,…, $x_n(t)$ are finite functions (or signals) defined in the interval $[a, b]$. If there are constants $c_1, c_2, \ldots, c_n$ which are not all zero, and to all $t(a \le t \le b)$:

$$c_1x_1(t)+c_2x_2(t)+\ldots+c_nx_n(t)\equiv 0 \tag{5}$$

then the finite functions are known as being (linear) correlated. The tenability of (5) fails when:

$$c_1 = c_2 = \ldots = c_n \equiv 0 \tag{6}$$

then these finite functions $x_1(t)$, $x_2(t)$,…, $x_n(t)$ are known as being uncorrelated, that is, they are linear independent. The following theorem, according to the *Definition*, can be proven. *Theorem:* Supposing finite functions $x_1(t), x_2(t), \ldots, x_n(t)$, defined in the interval $[a \ , b]$, are mutually orthogonal, then they are linear uncorrelated. If the above *Definition* and *Theorem* are synthesized together and the orthogonal properties of the sinusoidal functions are considered, then it can be proven, on some condition, that i_c and i_u as well as i_c and i_r obtained after ANN processes u_s^* (or u_s^* and its time lag terms) are uncorrelated, and i_r and i_u are correlated (the proof is left out). So, the ANN adaptive detecting circuit of harmonic current constituted with the help of ANCT can separate i_u from i_L, and finally i_c in i_L is extracted.

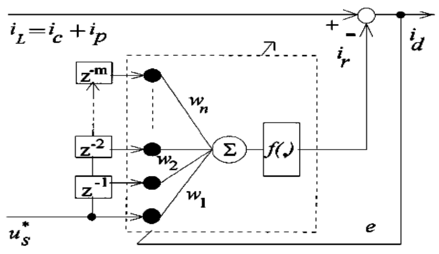

Fig.3 – Neuron adaptive detecting circuit of harmonic current.

III. NEURON ADAPTIVE DETECTING SYSTEM OF HARMONIC CURRENT

An adaptive detecting approach of harmonic current, by using the above theorem, can be formed after the adaptive filter in Fig. 2 is substituted by an ANN or a neuron. The mapping relationship between the input and output of ANN does not need to be too complicated, because the reference input is u_s^* and the output i_r of ANN should be in the same frequency with u_s^* when carrying out the detection of harmonic current. When considering the detecting velocity, the configuration of ANN should be as simple as possible. The neuron is not only simple to construct, but also it has a proper mapping ability and adaptive and self-learning properties [7], [11]. Thus we can substitute a neuron for the adaptive filter. From this, an adaptive harmonic current detecting system consisting of the neuron is formed. Its system configuration is shown in Fig. 3. The inputs, in terms of compensation, can consist of u_s^* or u_s^* and the time lag terms. The system output i_d is also used as an error signal e updating the weight w_j(j=0, …, n) of the neuron:

$$e(t)=i_d(t)=i_c(t)+i_u(t)-i_r(t) \tag{7}$$

$$e^2(t)=i_c^{\,2}(t)+2i_c(t)[i_u(t)-i_r(t)]+[i_u(t)-i_r(t)]^2 \tag{8}$$

If i_c and i_u as well as i_c and i_r are uncorrelated, then the mathematical desire can be obtained by (8) as follows:

$$E[e^2(t)]=E[i_c^{\,2}(t)]+E\left[[i_u(t)-i_r(t)]^2\right] \tag{9}$$

i_c which should be compensated is fixed, and so $E[i_c^{\,2}]$ is fixed, too. When w_j is updated to make $E[e^2]$ minimal, $E[(i_u-i_r)^2]$ is also minimal. We can attain from (7):

$$i_d(t)-i_c(t)=i_u(t)-i_r(t) \tag{10}$$

The above equation shows that when modifying w_j by e makes $E[(i_u-i_r)^2]$ minimal, $E[(i_c-i_d)^2]$ is minimal, too. At this moment, i_d is the approximate value of i_c. Under ideal circumstances if w_j is approximated to the optimum one after a number of iterations, then the neuron processes u_s^* into i_r, and it is thoroughly canceled out with i_u. Therefore i_d is just i_c, and the detection of harmonic current is completed.

IV. LEARNING ALGORITHM OF THE NEURON

It can be seen from Fig. 3 that the neuron model can be a processing unit of multi-input and single output. Its inputs consist of u_s^* and its delay time values. So the information of u_s^*, in accordance with compensation conditions, can be fully utilized for i_r to better approximate i_u. The input vector of the neuron is:

$$X(k) = \left[u_s^*(k), u_s^*(k-1), \ldots, u_s^*(k-m) \right]^T \tag{11}$$

The net input of the neuron is:

$$s(k) = \sum_{j=1}^{n} w_j(k) x_j(k) + \theta(k) \tag{12}$$

Its output is:

$$i_r(k) = f(s(k)) \tag{13}$$

where:

w_j weight of the neuron;

θ its threshold;

$f(x)$ its activation function.

Because i_r must finally be in keeping with the frequency of u_s^*, and the amplitude of (and its phase) need to be modified to make i_r approximate i_u, the relationship between the input and the output of the neuron does not need to be too complicated. Consequently, $f(x)$ is selected as a linear function, that is, $f(x) = x$. The neuron model which is used for the adaptive harmonic current detection is:

$$i_r(k) = \sum_{j=1}^{n} w_j(k) x_j(k) + \theta(k) \tag{14}$$

The delta learning rule [7] is used for the learning of the neuron. Weight w_j is updated by the error e. The corresponding amendment formulas of the weight and threshold are, respectively;

$$w_j(k+1) = w_j(k) + \eta^* e(k) x_j(k) \quad j = 1, 2, \ldots, n \tag{15}$$

$$\theta(k+1) = \theta(k) + \eta^* e(k) \tag{16}$$

where η^* is learning rate; $0 < \eta^* < 1$. η^* must be chosen appropriately; too large η^* is likely to affect the stability and too small η^* is likely to make the convergent velocity too slow. After a number of iterations, e approximates the minimum gradually, and w_j approaches the optimum. Hence i_r approximates i_u and the approximate value of i_c is attained in the system output. The harmonic current detection is completed.

In this paper, if simultaneously compensating both the harmonic and the reactive power by APF, then i_r must approximate i_p, when there is only an input u_s^* in the neuron inputs and there are no time lag terms. i_c (i_c consists of $i_q + i_h$) is finally obtained in the system output. From this, the simplest neuron adaptive detecting circuit of harmonic current can be formed.

V. ANALOG CIRCUIT REALIZATION OF THE DEVELOPED SYSTEM

Although it has a great number of distinguishing features and has found extensive use, the embodiment of ANN features and its wider use depend on design of ANN hardware circuits. So far, studies on ANN in many cases are mainly carried out by means of software and computer simulation. The study on design of ANN hardware circuits, especially analog circuits, is a weak link compared to its software and computer simulation. This cannot fully embody ANN specific properties, restricts the use of ANN and does not fully show the practical value of ANN. A great number of achievements in research show that actual operating neural network systems do not work discretely as digital logic circuits. Thus ANN realized by an analog circuit that works continuously can better simulate actual operating neural network systems, and analog circuit configurations are simpler and more convenient to design by VLSI technology. In a sense, the vitality of ANNs relies on design of their analog circuits.

The neuron adaptive detecting approach of harmonic current has been described above, and its algorithm is obtained. It can certainly be realized by using software, but in order to fully embody the distinguishing features of ANN and optimize its use in APF we should explore its design by analog circuits.

Dividing both sides of (15) and (16) by the sampling period T_s of the signal, respectively, we can get:

$$\frac{w_j(k+1) - w_j(k)}{T_s} = \frac{\eta^* e(k) x_j(k)}{T_s} \tag{17}$$

$$\frac{\theta(k+1) - \theta(k)}{T_s} = \frac{\eta^* e(k)}{T_s} \tag{18}$$

η^* and T_s can be merged into a single term and stood for by mark $\eta (= \eta^* / T_s)$. If T_s is sufficiently small, then a discrete quantity can be considered as a continuous one. So we substitute continuous quantity for discrete quantity and the above two equations can be changed into differential form, i.e.,

$$\frac{dw_j(t)}{dt} = \eta\, e(t) x_j(t) \tag{19}$$

$$\frac{d\theta(t)}{dt} = \eta\, e(t) \tag{20}$$

where

$$0 < \eta < \frac{1}{T_s} \tag{21}$$

Learning rate η is likely very large because T_s is very small. In accordance with η^*, η must be chosen appropriately, too. Under the precondition of assuring system stability, η should be as large as possible.

Integrating both sides of (19) and (20), we have:

$$w_j(t) = \int \eta\, e(t) x_j(t) dt \tag{22}$$

$$\theta(t) = \int \eta\, e(t) dt \tag{23}$$

It is thus clear that the adjustment of the neuron weights and threshold can be achieved by integrating the term multiplying e by the neuron input x_j and by integrating e, respectively. The corresponding analog circuit of the neuron adaptive detecting system of harmonic current, in accordance with (15) and (16) as well as (22) and (23), can be formed. When the neuron has only one single input, that is, with no the time lag terms, an analog circuit of the neuron adaptive detecting system of harmonic current can be attained. Its block diagram is shown in Fig. 4. There is a neuron threshold in Fig. 4(a), while there is not one in Fig. 4(b). In order to explain the method, PSIM simulation studies of the circuit shown in Fig. 4(b) and the performance of the proposed control method will be discussed.

VI. PSIM SIMULATION STUDIES OF THE ANALOG CIRCUIT AND APF

In this paper we shall utilize PSIM software, simulation software which has excellent properties. The integrator, ratio amplifier, and adder as well as multipliers in Fig. 4 are realized by operational amplifiers, resistors, and capacitors, thus forming the experimental analog circuit of the neuron adaptive detecting system of harmonic current.

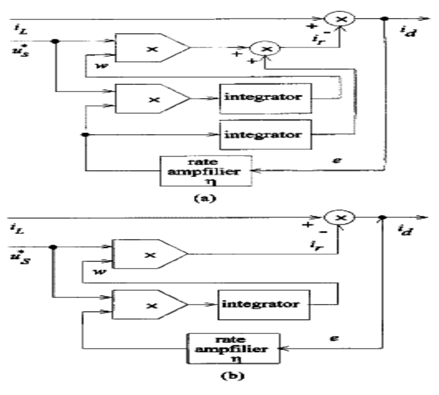

Fig.4 – Analog circuit block diagram of neuron adaptive detecting system of harmonic current (a) with neuron threshold and (b) without neuron threshold.

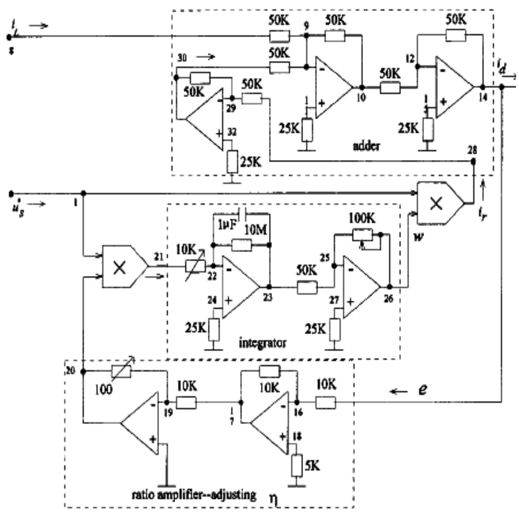

Fig.5 – Experimental circuit of neuron adaptive detecting system of harmonic current.

In Fig. 5 experimental circuit of neuron adaptive detecting system of harmonic current is shown. In Fig. 6 the typical single phase power system and a shunt APF with neuron adaptive control method using PSIM software is given. The load is a diode rectifier and APF is realized with full-bridge MOSFET switches with a DC capacitor. Performance of APF and control method is simulated with capacitive and inductive rectifier loads. The capacitive rectifier load is a parallel capacitor and a resistor with $C = 1000\ \mu F$, $R = 470\ \Omega$ and the inductive rectifier load is a series inductor and a resistor with $L = 10\ mH$, $R = 10\ \Omega$. Instead of a large inductor in connecting APF to power system a series small inductor and a capacitor with $L = 200\ \mu H$, $C = 33\ \mu F$ are used.

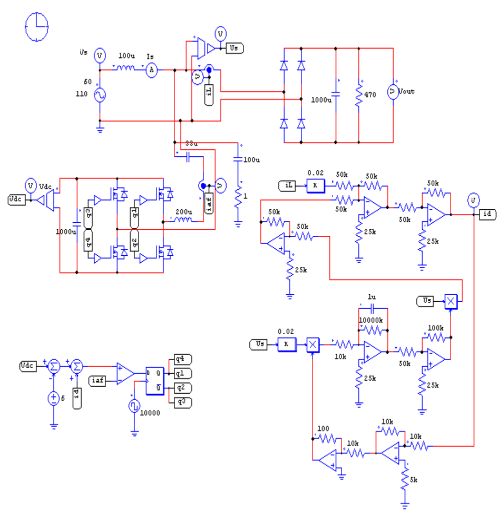

Fig.6 – Single phase power system with a shunt APF and neuron adaptive control.

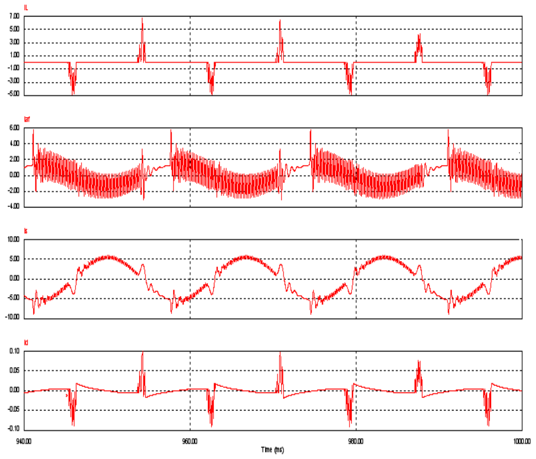

Fig.7 – Waveforms of i_L, i_{af}, i_s, i_d for the capacitive rectifier load.

Waveforms of i_L, i_{af}, i_s, i_d for capacitive and inductive rectifier loads have been shown in Fig. 7 and Fig. 8 respectively.

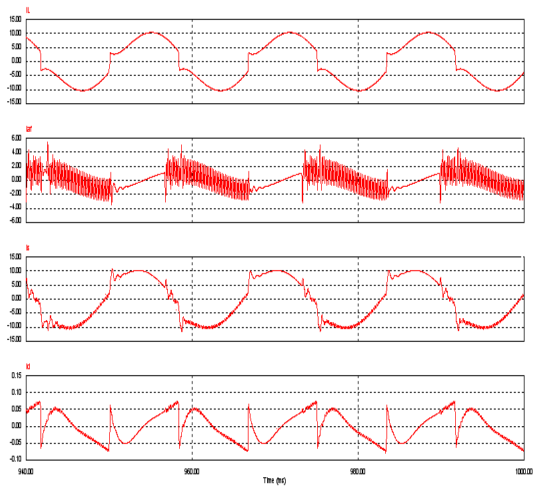

Fig.8 – Waveforms of i_L, i_{af}, i_s, i_d for the inductive rectifier load.

VII. CONCLUSIO

In this paper according to the fundamental properties of a neuron, and combining the ANCT in signal processing, the neuron is used for the harmonic current detecting system of APF. First the tentative idea using ANCT for the harmonic current detection is analyzed. Then the neuron is used for the adaptive filtration, and a neuron adaptive detecting approach of harmonic current is formed. The learning algorithm of the neuron adaptive detecting system of harmonic current is discussed. The system configuration which is made up of the proposed approach is simple, and its algorithm is easy and convenient to realize by using an analog circuit. The design of the analog circuit is a difficult point and weak link in studying ANN. If the difficult point is not resolved better, then the extensive use and further development of ANN are restricted. In this paper, based on the neuron adaptive detecting approach of harmonic current for APF, a design method of the analog circuit is explored, and the adaptive continuous adjustment of neuron weights is implemented. The design scheme of the analog circuit for the detecting system, based on this method, is presented. An experimental circuit is formed. The more detailed simulation studies of the analog circuit for the neuron adaptive detecting system of harmonic current are done by using PSIM software. The simulation results indicate that the proposed analog circuit is not only simple in configuration, but also its detecting velocity is fast and its following effect is good and its adaptive ability is strong.

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