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Application of Adaptive Neuro-Fuzzy Logic Method of Noised Electrical Signals for Correction

Aplicación de un Método Neuro-Difuso Adaptativo de Señales Eléctricas con Ruido Para Corrección

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ABSTRACT. In this article, the correction of the distorted electrical signal with an adaptive neural fuzzy logic (ANFIS) is discussed due to noise forming at the electrical signal. A sinusoidal signal is widely used both in load supply and in modulation techniques for control and information transport. While the deterioration in a structure of the sinusoidal signal causes energy losses on the power system, it also causes damage to the control signals in the circuit and information transmission signals in telecommunication. Therefore, after considering the structure of the pure reference signal equation, a noise that can occur in the sine structure is included in the reference signal structure. So, an interference signal is formed with the unknown nonlinear process from another noise source for creating the information signal because of an interference signal needs. After an interference signal is generated, the measuring signal is given in the sum of the pure reference signal and the interference signal. For the correction stage of the signals, at inputs of the adaptive fuzzy logic system in the Matlab toolbox, the source signal with noise and the measuring signal values are entered. Then, the experiment is performed via a 3-triangular membership function. When the results are observed, it is seen that the signal which is distorted after the correction operations is very close to the reference signal.

keywords: ANFIS, clear reference signal, energy losses, information transmission, noise forming, sine structure.

RESUMEN. En este artículo, se discute la corrección de la señal eléctrica distorsionada con una lógica difusa neural adaptativa (ANFIS) debido al ruido que se forma en la señal eléctrica. Una señal sinusoidal se usa ampliamente tanto en el suministro de carga como en las técnicas de modulación para el control y el transporte de información. Si bien el deterioro en una estructura de la señal sinusoidal causa pérdidas de energía en el sistema de energía, también causa daños a las señales de control en el circuito y a las señales de transmisión de información en las telecomunicaciones. Por lo tanto, después de considerar la estructura de la ecuación de señal de referencia pura, se incluye un ruido que puede ocurrir en la estructura sinusoidal en la estructura de señal de referencia. Entonces, se forma una señal de interferencia con el proceso no lineal desconocido de otra fuente de ruido para crear la señal de información debido a las necesidades de una señal de interferencia. Después de que se genera una señal de interferencia, la señal de medición se da en la suma de la señal de referencia pura y la señal de interferencia. Para la etapa de corrección de las señales, en las entradas del sistema de lógica difusa adaptativa en la caja de herramientas de Matlab, se ingresan la señal fuente con ruido y los valores de la señal de medición. Luego, el experimento se realiza a través de una función de membresía triangular 3. Cuando se observan los resultados, se ve que la señal que se distorsiona después de las operaciones de corrección está muy cerca de la señal de referencia.

Palabras clave: ANFIS, señal de referencia clara, pérdidas de energía, transmisión de información, formación de ruido, estructura sinusoidal.

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1 | INTRODUCTION

With the development of industry and technology, both the energy sector and information technologies are becoming very rapid advances. The sinus voltage sources used as energy sources are widely used to feed the load. And, these sources need to protect the sinus shape structures and not produce harmonics while feeding the load [1][2]. The sinus voltage source can include noises because the sinus source feeds nonlinear load or has environmental effects such as a high electromagnetic field. In this case, sinus welding performance on the load will decrease and energy losses will occur. Also, the deterioration of the sinus and similar signals used in modulation techniques affects the full formation of control signals at the circuit and information signals at the telecommunication. The deterioration of signals causes deterioration in the output values and an unwanted performance of the controlled load. In order to avoid all these unwanted situations, the loss of time and cost to create extra hardware occurs. Sliding mode control and fuzzy logic control for improving signals have been used frequently in some studies so far [3, 4, 5, 6, 7, 8, 9]. The artificial neural network (ANN) is used at the design of the weighting factors for a multilevel converter while artificial neural network provides a reliable technique for protection of multi-terminal high voltage direct current system systems [10, 11]. Also, lighting estimation has been made with ANN in building and environment [12, 13] while Adaptive Neuro-Fuzzy "ANFIS" has been used for Maximum Power Point Tracking Control for photovoltaic system in some studies [14, 15, 16, 17] although modulation signal regulation has been provided by fuzzy logic control in a multilevel inverter [14], it is necessary to use a higher-level application such as ANFIS to correct a signal that contains too much noise. To demonstrate the correction effect of ANFIS in this study, after the electrical signals which are a pure reference signal and a noised signal can be expressed with a mathematical equation, adaptive fuzzy logic is to be applied to correct on a distorted electrical sinusoidal.
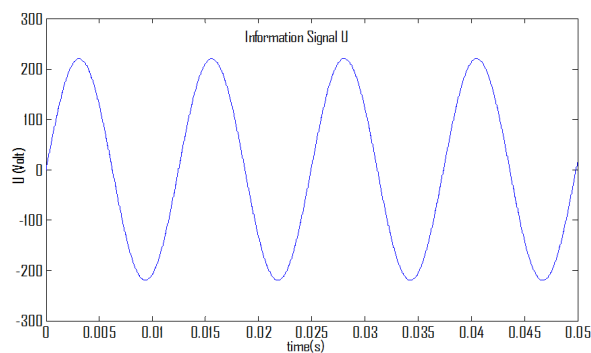

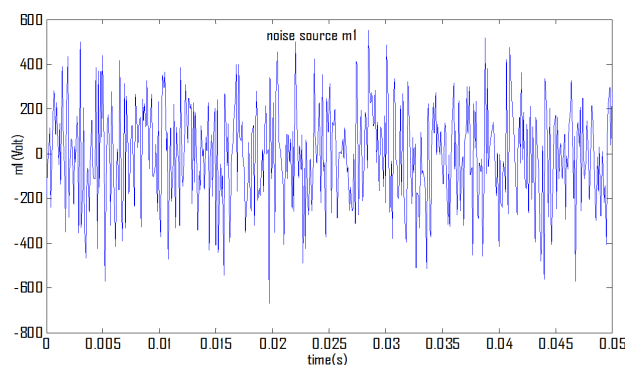**FIG. 1** Sinusoidal information signal sampled at $80Hz$ in 0.05 seconds

FIG. 2 Noise source signal m_1.

ANFIS is referred to in the literature by adaptive neural fuzzy inference system, Adaptive Neural Fuzzy Inference System or Adaptive Network-Based Fuzzy Logic Inference System. ANFIS is an adaptive network in which the topology of artificial neural networks can be used together with the principles of fuzzy logic. This method has the features of fuzzy logic and artificial neural network methods and eliminates some disadvantages when these two methods are used together according to used alone. It allows optimizing the values of the rule base and membership function to model fuzzy logic of known systems with input and output values. In ANFIS, it is provided to optimize the rule base and membership function values for modeling the systems with certain input and output values using fuzzy logic. In the application stage, firstly hypothetical reference signal equation $x(t)$ is determined and clean signal views are obtained. The interference signals m_2 appearing in the measuring signal is considered to be formed with an unknown nonlinear mathematical equation. After that, necessary noised signal equations $m(t)$ are formed by adapting the noise signal $m_2(t)$ to the hypothetical reference signal. The measuring signal m is calculated from the original information signal x and the interference $m_2(t)$. The only signals are the signal with noise m_1 and the measuring signal m are known. m is the sum of $x(t)$ and $m_2(t)$. The aim is to recover the polluted information signal $x(t)$. So, after general signal

properties are determined, ANFIS finds the nonlinear correlation between $m_1(t)$ and $m_2(t)$. Although $m_2(t)$ is not directly known, m is considered as the contaminated model of $m_2(t)$ for practice at the ANFIS. Thus $x(t)$ is used as the noise of this kind of nonlinear. ANFIS with 2-inputs is employed for practice. Three triangular membership functions are employed to inputs of ANFIS. So, the total number of fuzzy rules is 9 for learning. Also, the step size is set to 0.01. All the training information is observed with receiving in command window of the MATLAB.
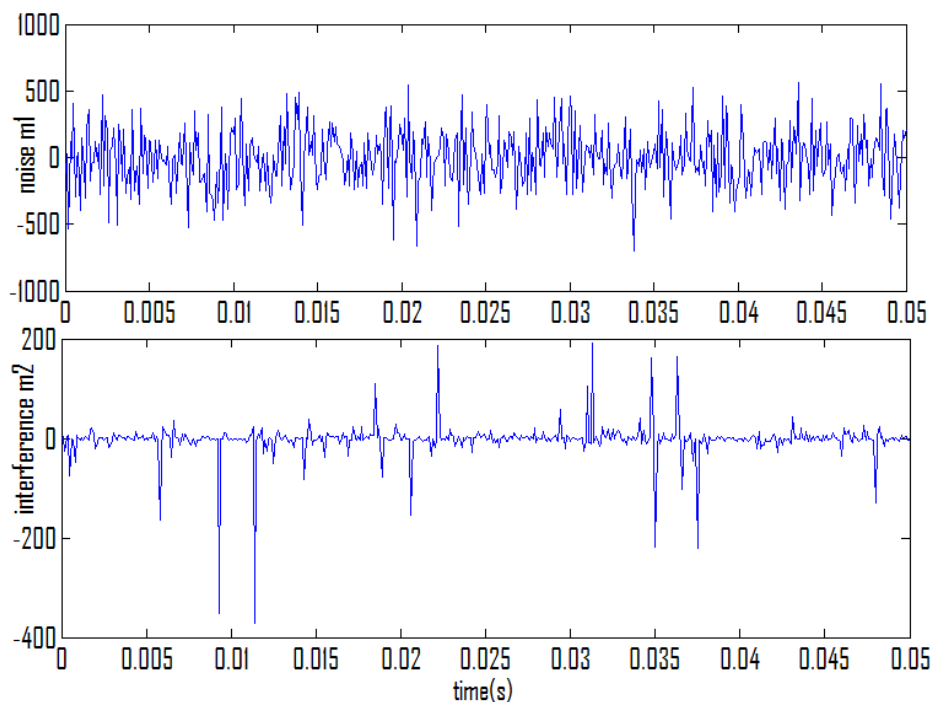

FIG. 3   Noise source m_1 and interference m_2.

The results obtained show that the distorted signal approaches the clean reference signal with ANFIS. At the end of the first ANFIS study, the distortion value of the distorted signal is reduced from 18.11% to 4.32%. At the end of the second ANFIS study, the distortion value of the distorted signal is reduced from 18.11% to 1.21%. This value is much more ideal for power electronics applications and energy quality improvement applications and other signal processing and generation applications in [18, 19]. So, ANFIS performs very good work. These results demonstrate that ANFIS can be used effectively on electrical signals, which means that it can be used as an effective option in preventing unnecessary hardware additions, preventing energy losses and reducing information losses.

2 | SIGNAL GENERATION AND SIGNAL CORRECTION

2.1 | Hypothetical Information Signal and Noise Signal

The $x(t)$ described in volts (V) units is shown inf Fig. 1 is a hypothetical sinusoidal information signal sampled at 80Hz. This signal has a phase angle of 0° and can be mathematically given in Eq. 9 where ω is the angular frequency

$$U(t) = x_a(t) = x(t) = 220V \sin(\omega t) \tag{1}$$

If the signals of a three-phase network are to be considered, the other two signal with phase differences can be written as in Eq. (2) and Eq. (3) given by

$$x_b(t) = 220V \sin(\omega t + 60) \tag{2}$$

and

$$x_c(t) = 220V \sin(\omega t + 120). \tag{3}$$

The noise forming on the single signal in the first equation of these three signals is reduced by using ANFIS. The information signal in Fig. 1 is clean and at a desired level for the system. However, the information sig-
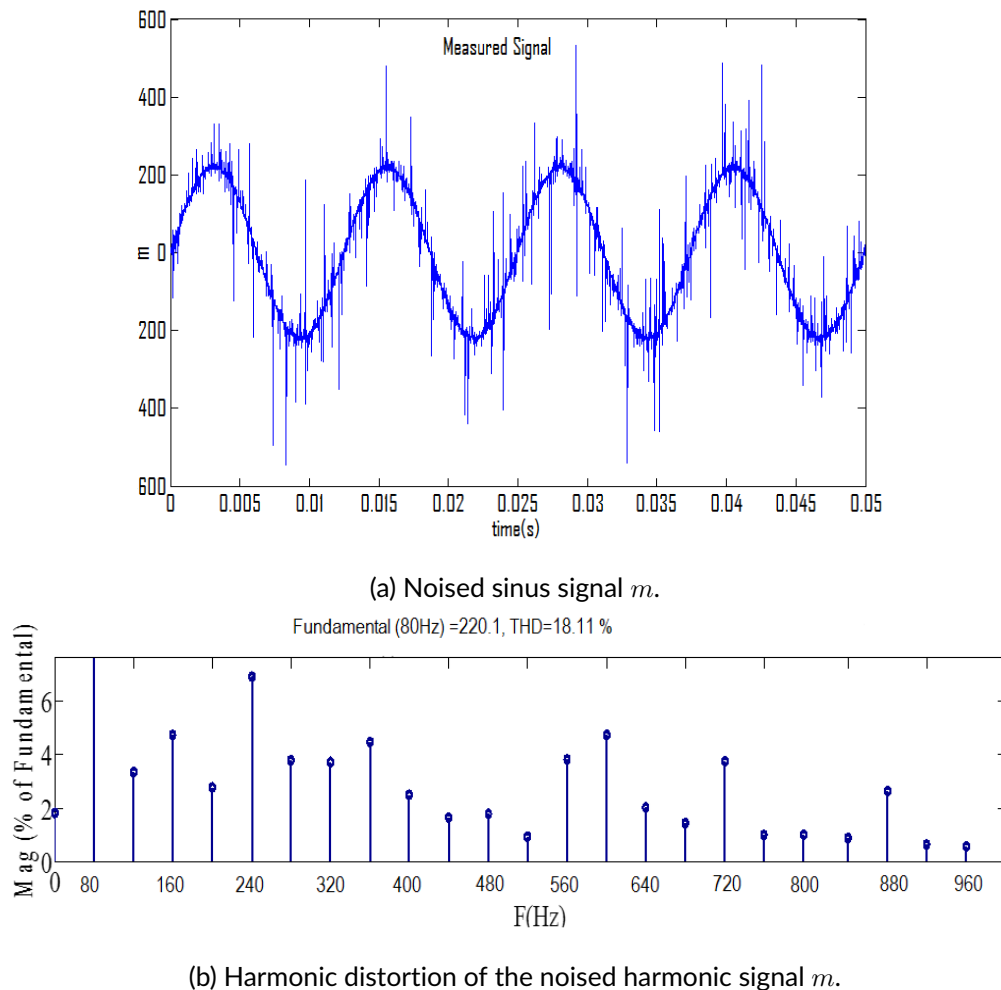

(a) Noised sinus signal m.

(b) Harmonic distortion of the noised harmonic signal m.

FIG. 4

nal $x(t)$ must be measured with an interference signal $m_2(t)$ which can form from another noise source m_1 from an unknown nonlinear process. The noise source signal m_1 is shown in Fig. 2. The interference signals $m_2(t)$ appearing at the measured signal can assume to be formed from an unknown nonlinear mathematical expression as in Eq. (4)

$$m_2(k) = 220\frac{\sin[m_1(k)]m_1(k-1)}{1 + m_1(k-1)^2} \tag{4}$$

where k is an iterator. Fig. 3 shows the source with noise m_1 and interference m_2 together. Noise m_2 is related to m_1 because of the highly nonlinear process demonstrated previously; it is difficult to see if these signals are related in any way.

$$f1=p1x_i+q1y_i+r1 \qquad f2=p2x_i+q2y_i+r2 \qquad f=\frac{w1.f1+w2.f2}{w1+w2}$$
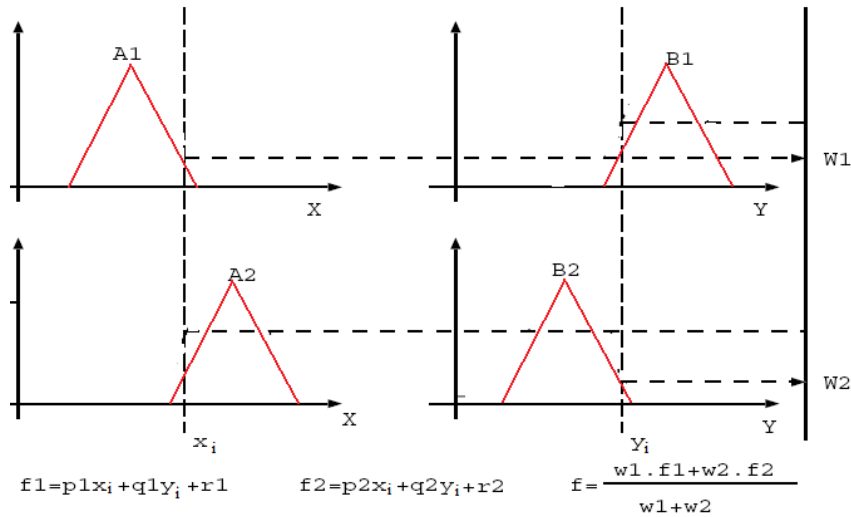
(a) Sugeno method of the fuzzy logic system with 2-input and 2-rule
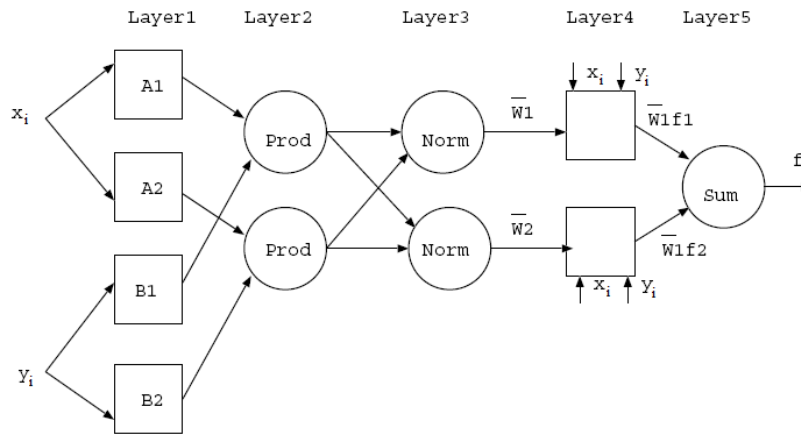
(b) Inference structure and the equivalent ANFIS architecture of this model

FIG. 5

The measuring signal m is found by summing of the reference data signal x and the parasite m_2. However, m_2 is unknown. The only, the signal with noise m_1 and the measuring signal m are known. The measuring signal m is expressed mathematically as in Eq. (5) while Fig. 4-a shows that m is a noised sinusoidal signal. This signal is given by

$$m(t) = x(t) + m_2(t) \qquad (5)$$

Fig. 4-b shows the harmonic distortion of the signal on which the noise is affected. The clean reference source signal in Fig. 1 contains a lot of noise signal as it is shown in Fig. 4. The noise on this signal greatly distorts the sinusoidal structure of the reference signal. Therefore, the harmonic distortion of this signal is 18.11%. This signal is not ideal for use in power electronics applications and the generation of signals used to carry information in communications and is therefore not preferred. Using this signal adaptive neural fuzzy logic
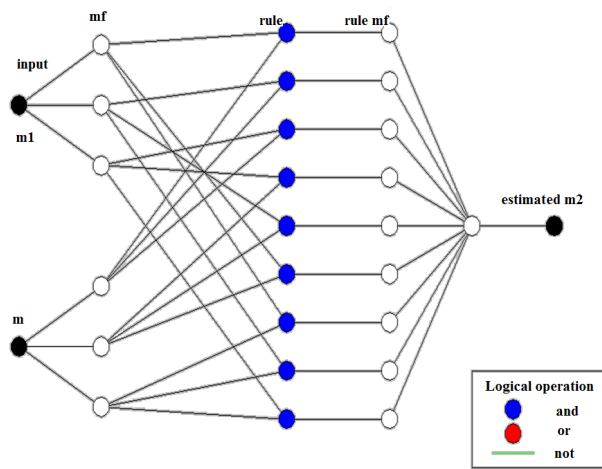
method, the noise value of this signal will be reduced.

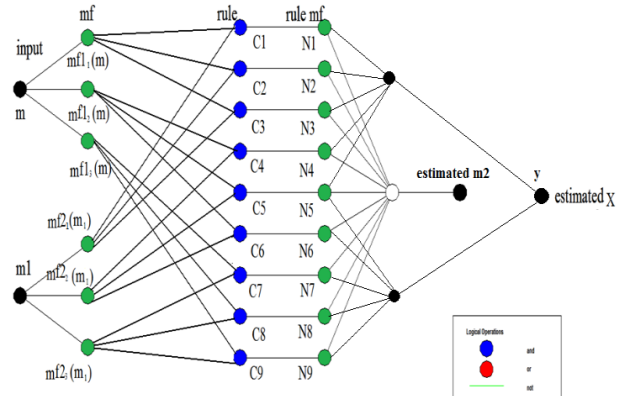FIG. 6   ANFIS created in toolbox of Matlab for estimation of m_2.

FIG. 7

ANFIS created in toolbox of Matlab for estimation of x. Input m, membership functions $mf1_1(m), mf1_2(m) and mf1_3(m)$, 2nd input m_1 and membership functions are $mf2_1(m_1), mf2_2(m_1) and mf2_3(m_1)$. The outputs of the membership functions are calculated as below.

ANFIS is referred in the literature by Adaptive Neural Fuzzy Inference System or Adaptive Network Based Fuzzy Logic Inference System. ANFIS is an adaptive network in which the topology of artificial neural networks can be used together with the principles of fuzzy logic. This method has the features of fuzzy logic and artificial neural network methods and eliminates some disadvantages when these two methods are used together according to used alone.
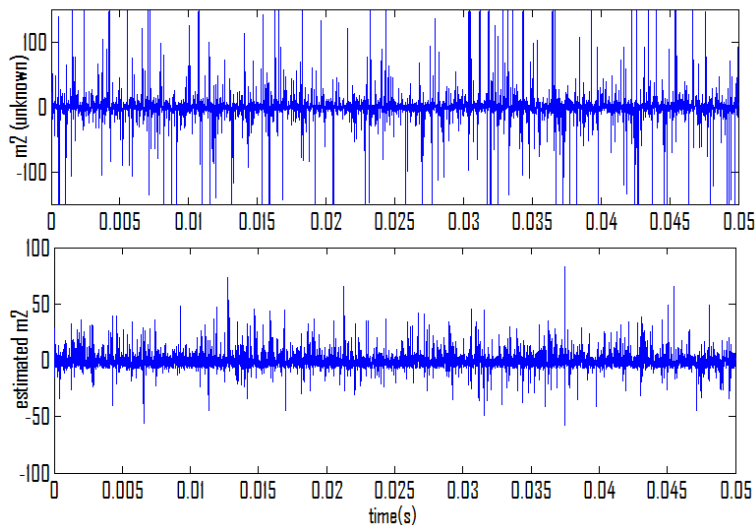

FIG. 8   Estimated m_2.

It allows optimizing the values of the rule base and membership function to model fuzzy logic of known systems with input and output values. In ANFIS, it is provided to optimize the rule base and membership function values for modeling the systems with certain input and output values using fuzzy logic. The optimization process is done using the learning methods of the Artificial Neural Network. In this way, fuzzy systems, which normally do not have the ability to learn, are provided with the ability to learn the data sets to model.

ANFIS uses the back-propagation method or the combination of the back-propagation method and the least squares estimation method as the learning method [20]. ANFIS architecture consists of 5 layers. Each layer has neurons as many as the number of fuzzy logic rules. In this architecture, each layer performs a different function [21]. In Fig. 5 (a), the Sugeno method of the fuzzy logic system with 2-input and 2-rule is modeled [19]; Inference structure and the equivalent ANFIS architecture of this model are given in Fig. 5-b where p and q are the coefficients of the input terms constituting the function, r is the constant term of the function and w is the weight determined by the method.

(a) Estimated signal.

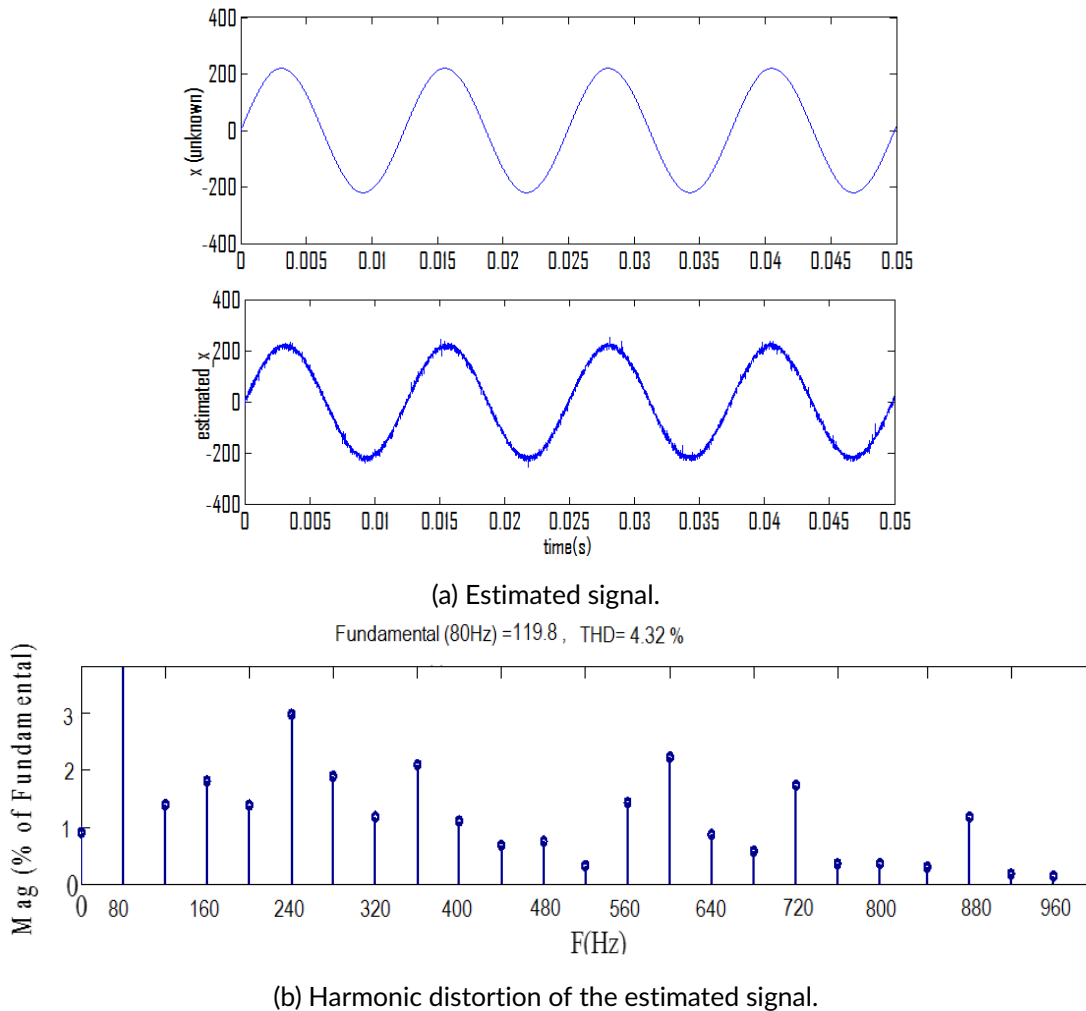(b) Harmonic distortion of the estimated signal.

FIG. 9

In the fuzzy logic approach, the result part of a rule is a linguistic expression taken with expert opinion. However, this linguistic information can be expressed as the linear sum of the entries by the Sugeno inference method as follows

$$\textbf{if} \quad x_i = A_1 \wedge y_i = B \quad \textbf{then} \quad f_1 = p_1 x_i + q_1 y_i + r_1 \qquad \text{Rule 1} \qquad (6)$$

and

$$\textbf{if} \quad x_i = A_1 \wedge y_i = B \quad \textbf{then} \quad f_2 = p_2 x_i + q_2 y_i + r_2 \qquad \text{Rule 2} \qquad (7)$$

where x_i and y_i are input values, f_1 and f_2 scalar functions, q_1 and q_2 are coefficients, and r_1 and r_2 are constants. The final output is the average of the weights of each rule as in Eq. (8)

$$f = \frac{w_1 f_1 + w_2 f_2}{w_1 + w_2}. \tag{8}$$

Noise reduction of a sinusoidal signal including noise is performed in accordance with the described rules. So, the determination of the nonlinear relationship between m_1 and m_2 are found by the function ANFIS. Even when m_2 is not known directly, m can be considered as a contaminated version of m_2 for practice.
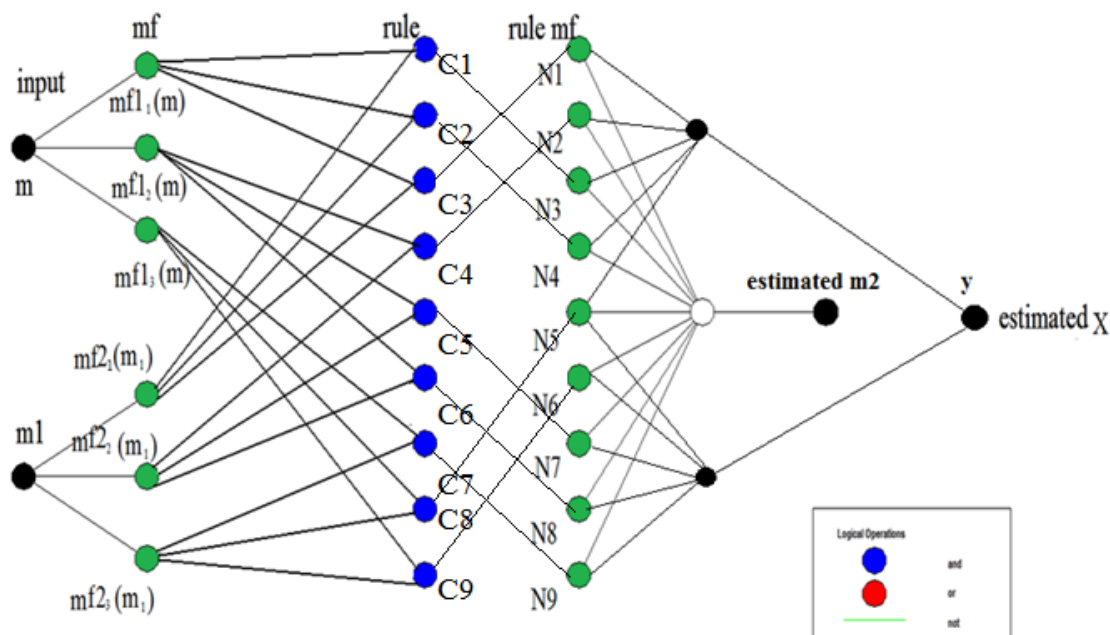

FIG. 10   ANFIS with arrangements on relationships and normals.

     Thus, x is determined as noise in this type of nonlinear fitting. For ANFIS, three mf consisting of triangles is used for both input values that are m and m_1. ANFIS in Fig. 6 is created in toolbox of Matlab for estimation of m_2. ANFIS in Fig. 7 is created in toolbox of Matlab for estimation of x. Input m, membership functions $mf1_1(m), mf1_2(m)$ and $mf1_3(m)$, 2nd input m_1 and membership functions are $mf2_1(m_1), mf2_2(m_1)$ and $mf2_3(m_1)$. The outputs of the membership functions are calculated as follows

if $m = mf1_1(m)$ $\wedge$ $m_1 = mf2_1(m_1)$ **then** $y1 = f1(z, m, m_1)$

if $m = mf1_1(m)$ $\wedge$ $m_1 = mf2_2(m_1)$ **then** $y1 = f2(z, m, m_1)$

if $m = mf1_1(m)$ $\wedge$ $m_1 = mf2_3(m_1)$ **then** $y1 = f3(z, m, m_1)$

if $m = mf1_2(m)$ $\wedge$ $m_1 = mf2_1(m_1)$ **then** $y1 = f4(z, m, m_1)$

if $m = mf1_2(m)$ $\wedge$ $m_1 = mf2_2(m_1)$ **then** $y1 = f5(z, m, m_1)$

if $m = mf1_2(m)$ $\wedge$ $m_1 = mf2_3(m_1)$ **then** $y1 = f6(z, m, m_1)$

if $m = mf1_3(m)$ $\wedge$ $m_1 = mf2_1(m_1)$ **then** $y1 = f7(z, m, m_1)$

if $m = mf1_3(m)$ $\wedge$ $m_1 = mf2_2(m_1)$ **then** $y1 = f8(z, m, m_1)$

if $m = mf1_3(m)$ $\wedge$ $m_1 = mf2_3(m_1)$ **then** $y1 = f9(z, m, m_1)$

In the second stage, the relationships between the membership function outputs are formed and the output

values of these relations are calculated. Relations between membership functions are achieved by matching each membership function at m in input 1 and each membership function at m_1 in input 2. Since there are three membership functions for the first input and three membership functions for the second input, a total of 9 correlations will be obtained as follows

Correlation 1: $\quad C_1(m, m_1) = mf1_1(m)mf2_1(m_1)$

Correlation 2: $\quad C_2(m, m_1) = mf1_1(m)mf2_2(m_1)$

Correlation 3: $\quad C_3(m, m_1) = mf1_1(m)mf2_3(m_1)$

Correlation 4: $\quad C_4(m, m_1) = mf1_2(m)mf2_1(m_1)$

Correlation 5: $\quad C_5(m, m_1) = mf1_2(m)mf2_2(m_1)$

Correlation 6: $\quad C_6(m, m_1) = mf1_2(m)mf2_3(m_1)$

Correlation 7: $\quad C_7(m, m_1) = mf1_3(m)mf2_1(m_1)$

Correlation 8: $\quad C_8(m, m_1) = mf1_3(m)mf2_2(m_1)$

Correlation 9: $\quad C_9(m, m_1) = mf1_3(m)mf2_3(m_1)$

In the third stage, the relations between membership functions are subjected to a process called normalization. The normalized value of the relationship is obtained by dividing the relationship output value by the sum of the output values of all relationships. The sum of all relationships C_T is calculated as follows

$$
\begin{aligned}
C_T = {}& mf1_1(m)mf2_1(m_2) + mf1_1(m)mf2_2(m_2) + mf1_3(m)mf2_3(m_2) \\
& + mf1_1(m)mf2_3(m_2) + mf1_2(m)mf2_1(m_2) + mf1_2(m)mf2_2(m_2) \\
& + mf1_2(m)mf2_3(m_2) + mf1_3(m)mf2_1(m_2) + mf1_3(m)mf2_2(m_2) + mf1_3(m)mf2_3(m_2).
\end{aligned}
\tag{9}
$$

The normal values of the relationships are calculated as follows

$$
\textbf{jth-Normal}: \qquad N_j \coloneqq C_j(m, m_1)/C_T \qquad \forall \quad j \in [1, 9] \subset \mathbb{N}
\tag{10}
$$

In step 4, the output functions $\{Fi\}_{i=1,2\ldots,9}$ of the system are calculated as in Eq. (11). Z are the coefficients of the terms in the series and $i \in [1, 9] \subset \mathbb{N}$. Those functions are given by

$$
F_i(m; m_1; Z_0, 1, 2) = Z_{i0} + mZ_{i1} + m_1 Z_{i2}
\tag{11}
$$

In the stage-5, the normalization outputs and the system output functions are multiplied and the multiplication results are summed and the system output value y is obtained as in Eq. (12). C_T is calculated as in Equation 20 this is

$$
C_T = \sum_{i=1}^{9} C_i
$$

and the value of y is computed as follows

$$
y(m, m_1) = \frac{1}{C_T} \sum_{i=1}^{9} C_i F_i = \sum_{i=1}^{9} N_i F_i
\tag{12}
$$

The information of ANFIS is presented in Table 1. ANFIS training is completed with epoch 10 (see Table 2). After ANFIS training completed; estimated m_2 is as in Fig. 8 while estimated x is in Fig. 9. The distortion values of the corrected signal as a result of the first ANFIS study applied to the noise affected the harmonic signal

are shown in Fig. 9-b.

At the end of the first ANFIS study, the distortion value of the distorted signal is reduced from 18.11% to 4.32%. This value is ideal for power electronics applications and energy quality improvement applications and other signal processing and generation applications. By making new arrangements on relationships and Ns, a new estimate can be created for further correction of the signal as in Figure 10.

TABLE 1   ANFIS Information.

Number of nodes	35
Number of linear parameters	27
Number of nonlinear parameters	18
Total number of parameters	45
Number of training data pairs	5001
Number of checking data pairs	0
Number of fuzzy rules	9

TABLE 2   ANFIS training.

Epoch	Step size
1	155.305
2	155.305
3	155.305
4	155.305
5	155.305
Step size increases to 0.011000 after epoch 5	
6	155.305
7	155.305
8	155.304
9	155.304
Step size increases to 0.012100 after epoch 9.	
10	155.304

The normal values of the relationships at the Fig. 10 are calculated as follows

Normal 1: $N_1 = mf1_1(m)mf2_3(m_1)/C_T = C_3/C_T$

Normal 2: $N_2 = mf2_1(m)mf2_1(m_1)/C_T = C_4/C_T$

Normal 3: $N_3 = mf1_1(m)mf2_1(m_1)/C_T = C_1/C_T$

Normal 4: $N_4 = mf1_1(m)mf2_2(m_1)/C_T = C_2/C_T$

Normal 5: $N_5 = mf1_3(m)mf2_2(m_1)/C_T = C_8/C_T$

Normal 6: $N_6 = mf1_3(m)mf2_3(m_1)/C_T = C_9/C_T$

Normal 7: $N_7 = mf1_2(m)mf2_2(m_1)/C_T = C_5/C_T$

Normal 8: $N_8 = mf1_2(m)mf2_3(m_1)/C_T = C_6/C_T$

Normal 9: $N_9 = mf1_3(m)mf2_1(m_1)/C_T = C_7/C_T$

and y is evaluated by using Eq. (12). The signal obtained after further modifications to the ANFIS is shown in Fig. 11-a. The distortion values of the corrected signal as a result of the second ANFIS study applied to the noise affected harmonic signal are shown in Fig. 11-b.

At the end of the second ANFIS study, the distortion value of the distorted signal is reduced from 18.11% to 1.21%. This value is much more ideal for power electronics applications and energy quality improvement applications and other signal processing and generation applications.

The estimation of m_2 is successfully made by the network of 5-layer adaptive neural fuzzy logic in Fig. 6. The estimated signal x is obtained from signal m with noise pollution as in Fig. 9. The distorted sinus signal is shown in Fig. 9, which is very close to the hypothetical clear signal after it corrected. In the second experiment, the signal is further corrected after C and N are arranged for new coupling. Then, the noised signal approaches the reference signal according to the first experiment. Therefore, ANFIS performs good work on the electrical signal. These results show that it can be used both in the correction of the distortions to occur in the loads fed by the sinus voltage source, or in the correction of the signals to be used in modulation techniques for control or information transfer purposes. Therefore, extra equipment will not be necessary for the correction of the

signals. Extra energy losses in energy transmission will be avoided. By modifying the noise of the signals used in modulation, an effective switching control is made. Additionally , the loss of information will be prevented by eliminating the noise in the modulation signals in data transportation of communication.
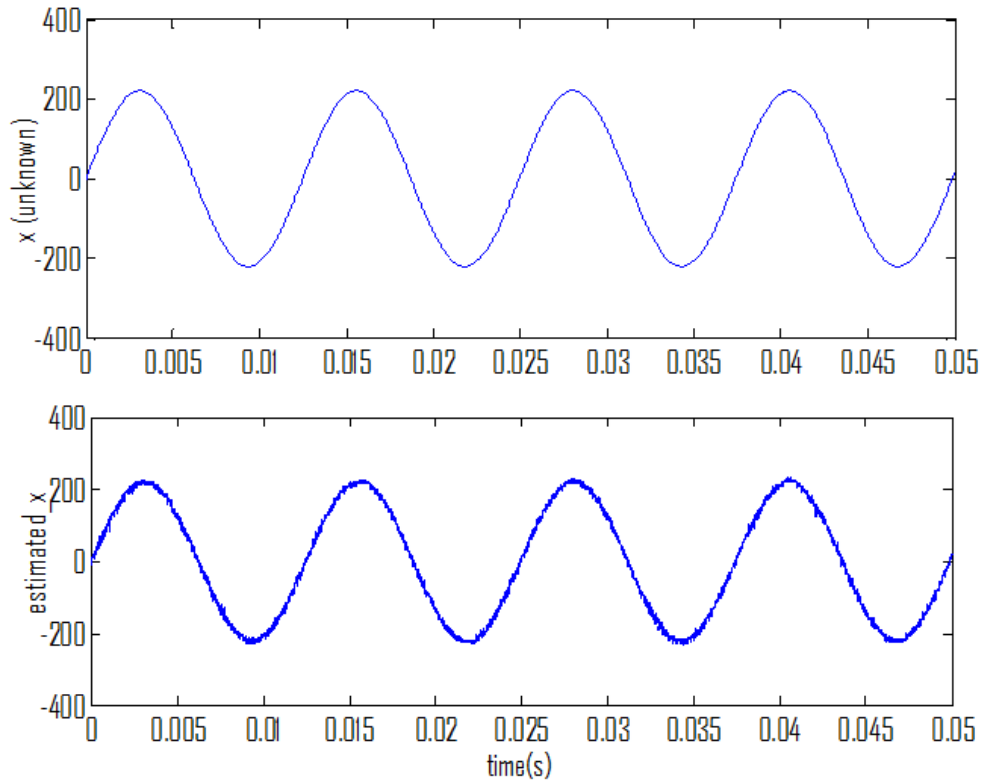
(a) Estimated x after arrangements on relationships and Ns at the ANFIS.
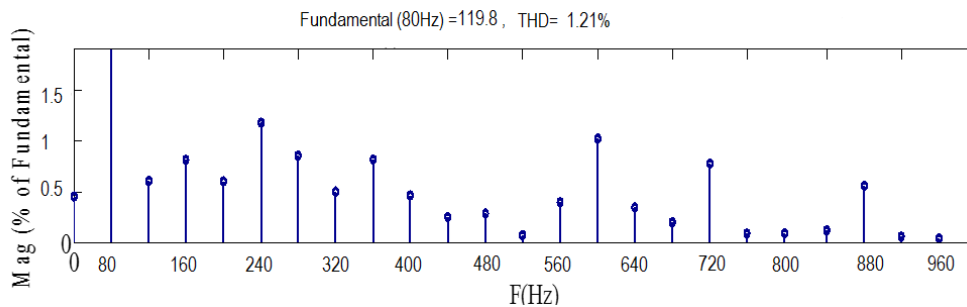
(b) Harmonic distortion of estimated x after arrangements.

FIG. 11

3 | CONCLUSIONS

The correction of the distorted electrical signal with an adaptive fuzzy logic (ANFIS) due to noise forming in electrical signals was discussed. Therefore, after considering the structure of the clear reference signal equation, a noise that occurred in the sinus structure was included in the clear reference signal structure. The measured information signal with an interference signal that was formed from a separate noise source with a nonlinear process that was a certain unknown. After an interference signal was generated, the measured signal

was given with the original information signal, and the interference summing. In the correction stage of the signals, the adaptive fuzzy logic system in the Matlab toolbox, the source noise signal, and the measured signal values were entered. Then, the experiment is performed via a 3-triangular membership function. According to our results the distorted signal after the correction operations was very close to the reference signal. Therefore, ANFIS was affected on a noised electrical signal.

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