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ANFIS Approach for Noise Reduction of Lightning Current Online Monitoring System

***Abstract**. A novel de-noising algorithm, based on adaptive neural-fuzzy inference system (ANFIS) is proposed for noise reduction of the lightning current online monitoring system. The paper presents the theory and the implement procedure of the fuzzy neural system. Comparisons among the traditional strategies, such as curve fitting (CF), wavelet transform (WT) methods and the proposed ANFIS strategy are carried out. The simulation results demonstrate the superiority of the proposed method. Moreover, the employed approach has been tested on the practical measured current of lightning current online monitoring system. The testing results validate the proposed approach.*

***Streszczenie.** Zaproponowano n owy algorytm odszumiania bazujący na adaptacyjnym neuro-fuzzy systemie interferencji ANFIS. System zastosowano przy moniotorowaniuj prądu wyładowań. System porównano z innymi dotychczas stosowanymi – dopasowanie krzywej czy transformata falkowa. (**ANFIS – nowa metoda redukcji szumów w systemach monitorowania prądu wyładowań**)*

Keywords: lightning current online monitoring system; denoise; ANFIS; curve fitting (CF); wavelet transform (WT)
Słowa kluczowe: prąd wyładowań, odszumianie, ANFIS

Introduction

With the development of smart grid, self-monitoring and self-healing capability plays an important role in driving security and stability of large scale power networks [1], [2]. Since the increasing flashover tripped accidents of transmission lines and towers caused by lightning strokes, the online monitoring system for lightning current has been designed to diagnose the failure point and improve the self-healing ability of the transmission lines [3]-[5]. Fig.1 shows the structure schematic diagram of lightning current online monitoring system.

The platform is composed of the current sensor, signal processing unit, FPGA chip control unit, power supply, GPS and 3G wireless module. Rogowski coil as the current sensor turns the lightning current into voltage signal when lightning strike happens. Through the A/D processing unit, the signal can be sampled into the internal memory and then sent to the remote supervising center by 3G module. The lightning parameters such as the number of flashes, the location of the stroke, the polarity, peak value and decreasing rate of lightning current can be monitored by processing the character of flashover current. While the effect of noise and distortion on current waveform cannot be ignored during collecting and processing the lightning current signal. Generally, one lightning flash contains several return strokes, and the lightning current is composed of the initial current and the return stroke current impulses. Besides the oscillation and complication of lightning current waveform itself, the recorded data are corrupted by different kinds of noise, and needs to be filtered for identification of the lightning current waveform parameters.

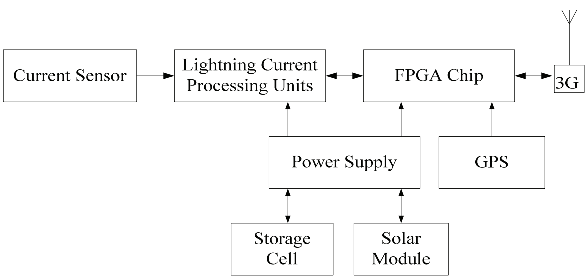


Fig.1 Structure schematic of lightning current monitoring system

The source of lightning current noise is very complicated and can be divided into two separate but related parts [6]-[8]. The first is from the external source such as white Gaussian noise, power fluctuation noise and electromagnetic interference noise. The second part is from the internal circuits such as thermal noise, schottky noise and pulse noise. To eliminate these different kinds of noise, many methods have been proposed. One common design methodology based on the noise modelling strategy needs to measure the noise source or make the noise signals under some assumptions, then models and approaches is carried out to subtract the simulated noise from the measured data. While for this method, the veracity and effectiveness of the noise assumption may greatly affect the signal processing results. A new approach for fluctuate and overshoot waveform is to adopt the techniques used in the optimization domain for denoising the lightning current directly, and the noise removal signal made it possible to calculate the current waveform parameters automatically [9]-[11].

In recent years, fuzzy-neural network combines with nonlinear adaptive method have received considerable interest as a mean of signal processing in power system [12]-[14]. Especially the ANFIS algorithm possesses the merits of Sugeno type fuzzy inference system and neural networks. With this technique, it is possible to construct an input-output mapping based on both human knowledge and stipulated input-output data pairs and is able to approach any linear or nonlinear functions. Comparing with other traditional denoising method, i.e. CF [15], WT [16], ANFIS presents more powerful filtering ability, and makes the resulting network more robust with respect to global approximation problems [17], [18].

This paper is devoted to develop a novel noise cancelling strategy which contributes to the study of noise interference in lightning current monitoring system. Firstly, based on ANFIS algorithm the structure of lightning current fuzzy model is designed. Comparing with CF and WT techniques, simulation results demonstrate the superiority and efficiency of the proposed method. This novel noise reduction approach is general and easy to be extended to other power system devices. The practical measured data from lightning current monitoring system are employed to validate the methodology analysis.

Simulating model of lightning current

A. Lightning current modelization

Double exponential function of lightning current waveform was first introduced by Bruce and Golde, and gets revised constantly. Since the first derivative of double exponential function is not continuous when t=0, hence the function can be expressed as

(1) $$i(t) = \begin{cases} 0 & 0 \le t \le t_0 \\ I_0 \cdot (e^{-t/\tau_1} - e^{-t/\tau_2}) & t_0 \le t \end{cases}$$

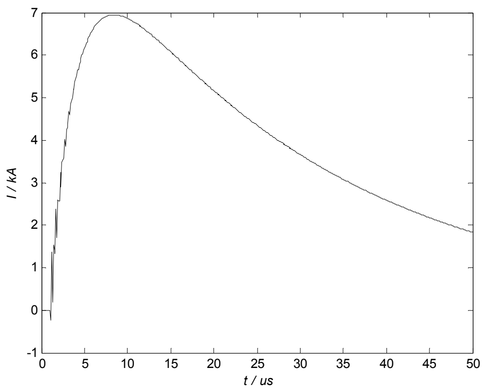
where I_0=10kA is the current peak, τ_1 and τ_2 are the time constants determining the current rise and decay times, respectively. IEC standard gives $1/\tau_1$=34650, $1/\tau_2$=343310 with *8/20 μs* lightning waveform, thus the original signal for simulation is

(2) $$I(t) = \begin{cases} 0 & 0 \le t \le t_0 \\ 10[e^{(-34650(t-t_0))} - e^{(-343310(t-t_0))}] & t_0 \le t \le 50\mu s \end{cases}$$

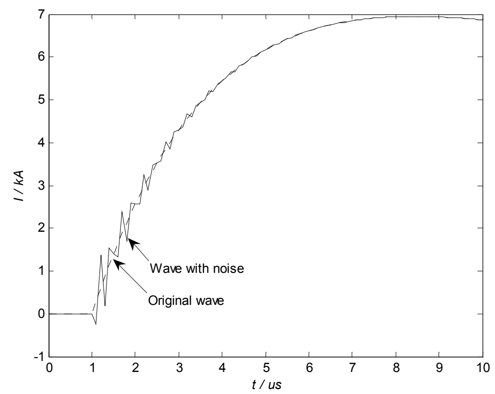
Suppose the noise source $n(t)$ at wave front and peak with oscillation frequency f=6 *MHz*,

(3) $$n(t) = \begin{cases} 0 & 0 \le t \le t_0 \\ I_n \sin(2\pi 6 \cdot 10^6 (t - t_0)) \cdot e^{-10^6 (t-t_0)} & t_0 \le t \le 50\mu s \end{cases}$$

where t_0=1μs, I_n=1A is the peak value of noise. The simulation of lightning current corrupted by noise is shown in Fig. 2.



(a)



(b)

Fig.2 Simulation of lightning current with noise. (a) The whole waveform; (b) Enlargement of the wave front.

B. Design of lightning current filter

In order to eliminate the noise interference of measured output, filter has been widely used for signal process. The proposed nonlinear filter based on ANFIS can construct the architecture of the measured data $m(t)$ which is contaminated by the noise $n(t)$ and after training, the output $md(t)$ of ANFIS estimation is obtained with increasing approximation of the real lightning current. Fig. 3 is the schematic of the proposed filter based on ANFIS for lightning current.

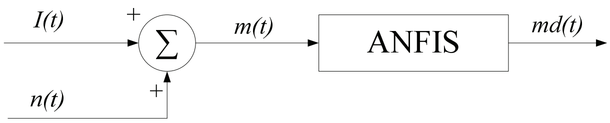


Fig.3 The arrangement of lightning current filter

Lightning current denoising by ANFIS

A. ANFIS Architecture

ANFIS is a neural-fuzzy system that combines the learning capabilities of neural networks with the functionality of fuzzy inference system. ANFIS uses a hybrid learning algorithm to identify parameters of Sugeno-type fuzzy inference system. It applies a combination of the least-squres algorithm and the back-propagation gradient descent method for training FIS membership function parameters to emulate a given training data set. Based on the ANFIS alogrithm, a four layers Fuzzy-Neuaral Networks (FFN) is constructed, as shown in Fig. 4. Square nodes express the existence of tuneable variables and circle nodes means the layer without tuneable variables. The input variable of the architecture is the measure signal m of lightning current and is divided into 5 fuzzy subspaces. The node functions in the same layer are of the same function family as described below:

Layer 1: Layer 1 is input and fuzzification layer, every node i in this layer is a square node with the gauss node function

(4) $$u_i = e^{-\frac{(m-c_i)^2}{\sigma_i^2}} \qquad i=1,\ldots,5$$

where $\{c_i, \sigma_i\}$ is the parameter set. As the values of these parameters change, the gauss-shaped functions vary accordingly.

Layer 2: Layer 2 is the rule layer to calculate the firing strength of each rule, every circle node stands for one rule, for SISO system, there are

(5) $$\alpha_i = u_i \qquad i=1,\ldots,5$$

Layer 3: Layer 3 is de-fuzzification layer, each node i in this layer is a square node with a node function

(6) $$f = \sum_{i=1}^{5} \alpha_i f_i = \sum_{i=1}^{5} \alpha_i (p_{1i} m + p_{2i})$$

where, α_i is the output of layer 2; and p_{1i}, p_{2i} are referred as consequent parameters.

Layer 4: Layer 4 is the output layer designed to calculate the overall output as the summation of all incoming signals

(7) $$md = f / \alpha = \frac{\sum_{i=1}^{5} [(\alpha_i m) p_{1i} + \alpha_i p_{2i}]}{\sum_{i=1}^{5} \alpha_i} = A\theta$$

where θ is the unestimated variable set of $\{p_{1i}, p_{2i}\}$.

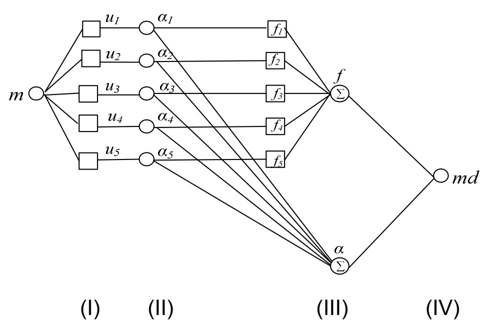
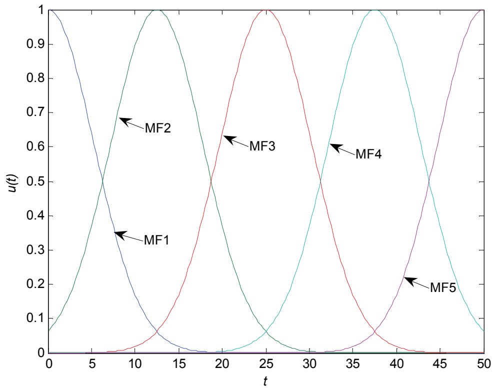
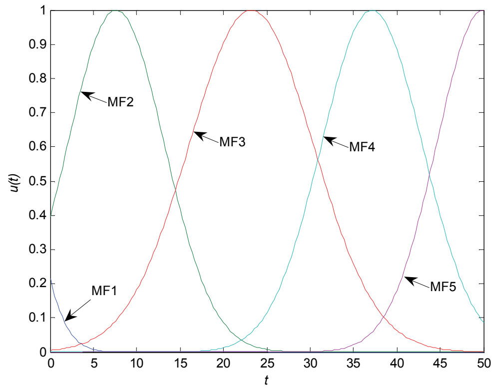


Fig.4 Fuzzy-neural network structure



(a)



(b)

Fig.5 Membership function (a) Before training; (b) After training

B. Learning Algorithm

Here, we use BP algorithm training the antecedent parameters c_i, σ_i and consequent parameter θ. The error measure function is assumed as

(8) $$E=\frac{1}{2}(A\theta-Md)^2$$

where $A\theta$ is the actual output and Md is the target output.

For n pairs of input-output data set and fixed the antecedent parameters, the initial consequent parameter can be determined by weighted least squares method with minimum error. Then fixing the consequent parameter θ obtained by the last step and back propagating the error from output to input side, the varying parameters can be updated by gradient search algorithm to change the shape of membership function and consequent parameter. The training procedure of ANFIS architecture is repeated until the maximum training times or error precision is satisfied.

C. Denoising and comparison

The simulated lightning current with noise signal gets filtered by the proposed approach. The number of training data pairs is 501, the maximum training time is 100 and training step is 0.2. Considering modeling precision and computation efficiency, the number of gauss MF is 5 and the training end condition is to reach the Max. training time. The distributions of initial and final gauss MF are shown in Fig. 5. Comparing Fig. 5(a) and (b), the shape and location of MF1, MF2 and MF3 have changed greatly, while MF4 and MF5 are almost no change. The result is constant with the simulated noise signal that is only corrupted the wave front and peak. Fig. 6 shows the RMSE (root mean squared error) curve of ANFIS. With quick propagation, the RMSE between output data and training data set gets smaller and ends at E_{mse}=0.0758.

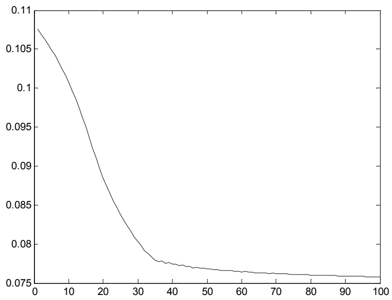
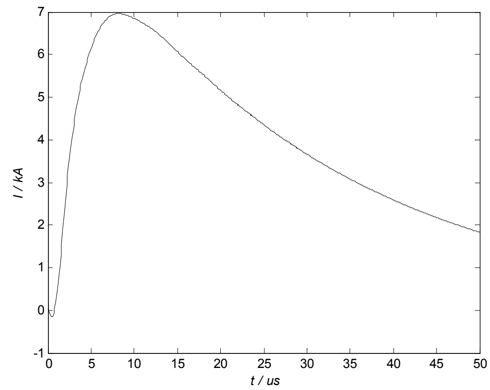
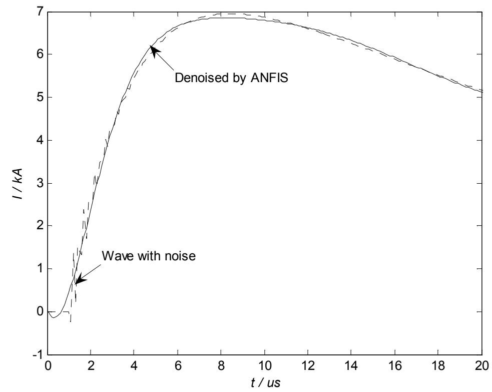


Fig.6 Training error

The simulating result of lightning current de-noised by ANFIS is given in Fig. 7. For the entire waveform as shown in Fig. 7(a), the de-noised curve gets much smoother comparing with the initial waveform. In Fig. 7(b) with the amplification of wave head, the oscillation at wave front and peak has been effectively eliminated and the real waveform has been finely recovered.



(a)



(b)

Fig.7 Waveform denoised by ANFIS (a) Whole wave; (b) Enlargement of the wave front

To identify the effectiveness of ANFIS strategy, a comparison among CF, WT and ANFIS methods is taken. The approach based on CF adopts the general least square fitting algorithm and WT drives a four layer scheme by sym8 wavelet and quantizes the wavelet coefficient threshold with heuristic soft threshold method, the denoising results are shown in Fig. 8 and Fig. 9. Comparing with ANFIS, the denoised waveform obtained by CF reduced the curve gradient and increased the wavefront time and peak value. In Fig. 7 and Fig. 9, the simulation results of ANFIS and WT are quite close with little greater derivation by WT at the wave head.

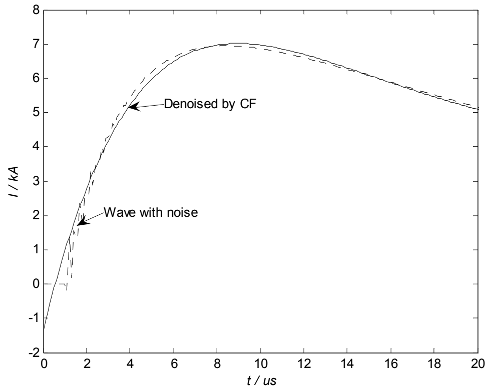
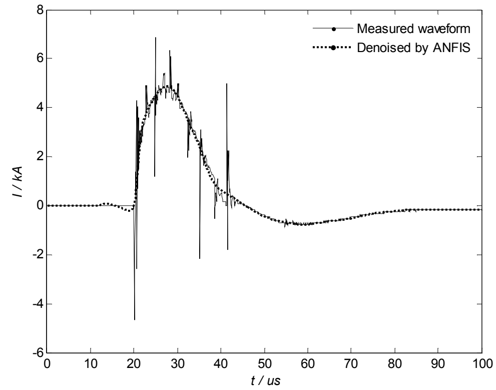


Fig.8 Waveform denoised by CF



(a)

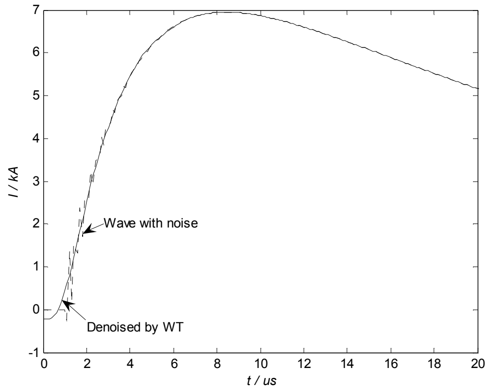
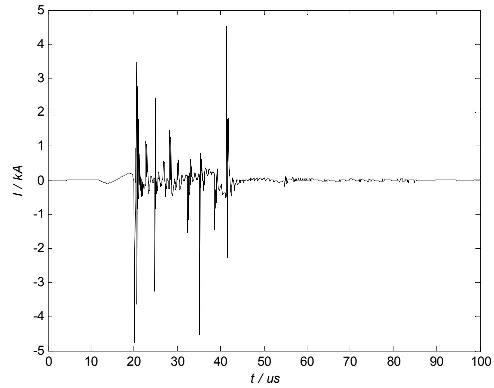


Fig.9 Waveform denoised by WT



(b)

Fig. 11 Results of noise reduction for measured wave with ANFIS (a) Comparison of measured wave and denoised wave; (b) Reduction part of noise signal

Test results

The lightning current online monitoring system is experimented by impulse current generator, and the practical measured waveform is shown as Fig. 10. The sampling time is 100 *us*, sampling frequency is 10 *MHz* and total 1000 sample points.

Fig. 11 presents the filtering results of practical current waveform based on ANFIS strategy. From Fig. 11(a), it can be seen that the denoised waveform is smooth, both wave front and wave tail time are accordance with the measured waveform and the peak value almost has no derivation demonstrating the strong nonlinear approach ability and the effectiveness of the proposed methodology. Fig. 11(b) gives the noise waveform of measured current signal, it can be seen that the noise is a high frequency oscillation with big amplitude at steep slope on time domain corresponding to the measured signal.

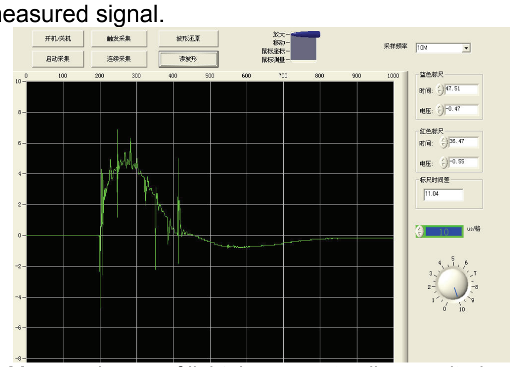


Fig.10 Measured wave of lightning current online monitoring system

Fig. 12 shows the denoised results of practical waveform by different method, e. g. CF, WT and ANFIS. Comparing the three curves, the effect of CF is worst to solve the measured current mixing with complicated noise signal. Although the curve obtained by CF is quite smooth, the wave front time increased obviously and wave front, wave tail exist great oscillation. After denoising with WT, the high frequency oscillations are also not completely eliminated, because of the weak general fitness of wavelet function and threshold chosen. The proposed ANFIS method presents adaptive and satisfactory performance on retaining the steepness of the real signal and reducing the oscillation.

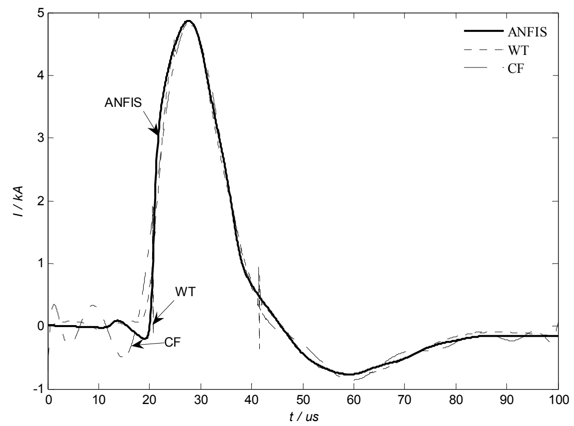


Fig. 12 Denoised results with different methods

Table 1 Denoised waveform parameters with the three methods

	I_m / kA	ε_{Im} / %	t_m / us	ε_{tm} / %	t_f / us	ε_{tf} / %	t_t / us	ε_{tt} / %
R_0	4.87	0	27.6	0	7.6	0	15	0
R_{ANFIS}	4.869	0.02	27.7	0.36	7.7	1.3	15.06	0.4
R_{WT}	4.85	0.4	27.9	1.1	7.9	3.9	14.82	1.2
R_{CF}	4.815	1.13	27.8	0.72	8.8	15.8	16.1	7.3

Then, by the denoised curve produced above, the waveform parameters based on three methods are computed and listed in Table I. With ANFIS method, the peak value is close to the original signal and the errors of peak time, wavefront time and wave tail time are smallest as 0.36%, 1.3% and 0.4% respectively. The errors of WT are also not significant with reducing peak value 0.4%, delaying wavefront time 3.9% and advancing the wave tail time 1.2%, therefore the disposed curve gets narrow by WT. The changes of parameter values from CF are obviously large, especially the wavefront and wave tail time. From these results, it can be illustrated that the proposed design method of filter based on ANFIS can effectively reduce the noise inference and performs nice adaptability.

Conclusion

In this paper a systematic method based on ANFIS algorithm is presented for filter design of lightning current online monitoring system. The effectiveness of the method is verified by the simulated model of lightning current and comparison among Curve Fitting, Wavelet Transforming and ANFIS is carried out. Finally, the approach is employed to the practical test data from the lightning current monitoring system. By analyzing the results of simulated and measured signal, we can conclude:

(1) The ANFIS based strategy is capable of modeling and optimizing the lightning current corrupted by noise, and provides good computing efficiency and effective de-noising characteristics.

(2) Comparing with CF and WT algorithm, ANFIS can realize global approximation, highly match the original waveform with smallest errors and indicates fine generality.

(3) The proposed method is convenient for remote customs to eliminate the noise interference from the measured data directly and then extract the parameters of the waveform. The generality and flexibility of the method make it easy to be extended to accommodate other signal processing system.

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