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A novel linear ridgelet network approach for analog fault diagnosis using wavelet-based fractal analysis and kernel PCA as preprocessors

Yingqun Xiao *, Lianggui Feng

Department of Mathematics and Systems Science, College of Science, National University of Defense Technology, Changsha 410073, China

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ABSTRACT

We have developed a novel fault diagnosis approach of analog circuits based on linear ridgelet network using wavelet-based fractal analysis, kernel principal components analysis (kernel PCA) as preprocessors. The proposed approach can detect and identify faulty components in the analog circuits by analyzing their time responses. First, using wavelet-based fractal analysis to preprocess the time responses obtains the essential and reduced candidate features of the corresponding response signals. Then, the second preprocessing by kernel PCA further reduces the dimensionality of candidate features so as to obtain the optimal features as inputs to linear ridgelet networks. Meanwhile, we also adopt the kernel PCA to select the proper numbers of hidden ridgelet neurons of the linear ridgelet networks. The simulation results show that the resulting diagnostic system using these techniques can not only simplify the architectures (including input nodes and hidden neurons) and minimize the training and processing time of these networks considerably, but also diagnose single and multiple faults effectively in classifying faulty components of example circuits to improve the accuracy and efficiency of fault diagnosis with a highly correct classification rate.

0. Introduction

In recent years, fault diagnosis of analog circuits has been extensively studied, and a large amount of diagnostic techniques have been developed and used widely at the system, board and chip levels [1–15]. However, the analog systems become the most unreliable and least testable systems because of poor fault models, component tolerances and nonlinear effects. As a consequence, this makes application of neural networks to this area very appealing since no model or comprehensive examination of these effects is required. In [3], the samples of impulse responses of the linear analog circuits are directly fed to the neural network as inputs without any preprocessing. As a result, for even a relatively small circuit, a large number of inputs and a large architecture for the neural network are required for this approach. Consequently, in [4,5], the authors have taken the simulation program with integrated circuit emphasis (SPICE) model of a faulty circuit and excited it with a narrow pulse to expose its natural frequencies. Then, the response is preprocessed by wavelet transform and principal component analysis (PCA) so as to obtain the optimal features for training neural network. To some extent, this approach reduces the inputs of neural network and improves its performance. In [6], the authors have constructed a wavelet network for analog fault diagnosis. Although the wavelet network can further improve diagnostic performance, it leads to the problem of large network structure due to the constructive problem of tensor wavelet neurons. In addition, Ref. [7] proposes a novel method for analog fault diagnosis based on neural network and genetic algorithms. However, this method needs to simultaneously sample the data of several accessible

* Corresponding author. Address: Department of Mathematics and Systems Science, National University of Defense Technology, Changsha Hunan Province 410073, China. Tel.: +86 13973127652.
E-mail address: yqxiao_hn@yahoo.cn (Y. Xiao).

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nodes, which makes data acquisition very difficult because in most applications only output terminal is directly accessed. In [8], the authors perform feature extraction in frequency domain using kurtosis and entropy as a preprocessor, which leads to two fixed features as inputs to neural network. This reduces the number of inputs to neural network and improves the performance of diagnostic system. However, the choice of number of hidden neurons for the networks is based on experience and intuition. In [10–13], Czaja et al. have presented some novel diagnostic techniques to perform effective fault diagnosis on mixed-signal circuits and analog parts of embedding systems with tolerances. The authors, in [14], adopted support vector machines classifier to diagnose the faults of analog circuits. In addition, in [15], the improved kernel PCA was employed as preprocessor for performing effective feature extraction on analog fault data sets so as to achieve a high fault diagnostic accuracy.

In particular, in [9], we first proposed the linear ridgelet neural network (linear ridgelet network) and the associated steepest gradient descent based training algorithm for fault diagnosis. As shown in [9], the proposed network can diagnose the analog faults effectively. However, because PCA as a preprocessor can only capture linear structure on a data set and the number of hidden ridgelet neurons is determined by trial and error, the resultant linear ridgelet network has a large structure consisting of too many input nodes and hidden neurons. This implies that the proposed network needs a large amount of computational costs in the phase of operations and suffers from over-fitting problem, which results in poor diagnostic performance.

Feature extraction is a key problem in pattern recognition, which is important and strongly affects successive classifier design. The effective features show significant differences from one class to another so that the classifier can be designed more easily with better performance. At the same time, because ridgelet [16–19] is a novel version of wavelet functions with additional orientation information so as to deal with higher dimensional data and approximate the functions with line-like and hyperplane-like singularities, it is extensively used for multivariable function approximation [16–20], complex pattern recognition [21] and image processing [22], especially various adaptive ridgelet neural networks constructions [23,24].

In this paper, based on the aforementioned reviews and the disadvantages of proposed network in [9], we adopt the wavelet-based fractal analysis and kernel PCA for feature extraction and reduction and reasonable design of linear ridgelet network for feature recognition in order to reduce the network structure and achieve better fault diagnostic performance.

Specifically speaking, we first acquire the time responses of circuits under test (CUTs) in time domain using SPICE simulation; then the responses are preprocessed by wavelet-based fractal analysis combining wavelet transform with fractal analysis to get the fractal dimensions (FDs) of wavelet coefficients; finally the related FDs are further preprocessed by kernel PCA to obtain the optimal features (the smallest size of FDs) used for training and testing the proposed networks. In addition, we adopt kernel PCA method for selecting the proper numbers of hidden ridgelet neurons of the networks.

The material in this paper is arranged in the following order. In Section 1, we describe the fundamentals of wavelet-based fractal analysis that is one of preprocessing techniques used in this paper. Section 2 reviews the kernel PCA approach for performing feature extraction and reduction. Section 3 focuses on the formulation of linear ridgelet network and the alternative design of corresponding architecture using kernel PCA. Section 4 presents the example circuits and applications of wavelet fractal analysis and kernel PCA for extracting the effective features, and gives the corresponding simulation results. Finally, we draw our conclusion in Section 5.

1. Wavelet-based fractal analysis

1.1. Wavelet transform

Wavelet transform as an effective technique of signal analysis has been widely applied in a broad range of signal analysis and image processing fields [25]. Wavelet transform is to decompose a signal into the details and approximations so that we can acquire more essential features of the signal. So, wavelet transform is accomplished using the translated and scaled versions of a mother wavelet $\psi(x)$ defined by

$$\psi_{s,g}(x) = \frac{1}{\sqrt{s}}\psi\left(\frac{x-g}{s}\right) \tag{1}$$

where s and g denote the parameters of scaling and translating of the mother wavelet, respectively.

Given a signal $f(x)$ and mother wavelet function $\psi(x)$, the wavelet transform of $f(x)$ is:

$$c(s,g) = \langle f(x), \psi_{s,g}(x)\rangle = \frac{1}{\sqrt{s}}\int_{-\infty}^{+\infty} f(x)\psi\left(\frac{x-g}{s}\right)dx \tag{2}$$

where $c(s,g)$ denote the wavelet coefficients of signal $f(x)$. The wavelet coefficients that are approximations and details can reflect a variety of intrinsic properties of a signal and characterize the original signal effectively.

As we know in [25], the important properties of wavelets evaluating the appropriateness of practical applications of them are support and regularity. Since support is a measure of the duration of a wavelet in time domain and regularity is related to its ability to correlate to smooth functions, wavelets with different properties are suitable for certain applications. For example, wavelets belonging to Biorthogonal family are suitable to image processing and the Mexican Hat wavelet with good regularity has been widely applied to rotation-invariant pattern recognition [4]. Thus the proper choice of the mother wavelet for preprocessing the analog circuit's output is crucial for optimal extraction of the fault features. In [4], it can be seen that Haar function has a compact support and a regularity of zero because of its discontinuous nature so that it is very well suited to extract features from signals characterized by short durations and swift variations. When an input pulse is applied to a circuit, it is the localized behavior of the output signal at its onset that carries the distinct