Analog Circuit Fault Detection Using Relative Amplitude and Relative Phase Analysis

A new method for detection of parametric faults occurring in analog circuits based on relative amplitude and relative phase analysis of the Circuit Under Test (CUT) is proposed. The relative amplitude is the common power change of the signals and the relative phase presents the relative phase offset of the signals. In the proposed method, the value of each component of the CUT is varied within its tolerance limit using Monte Carlo simulation. The upper and lower bounds of relative amplitude and phase of the CUT sampling series are obtained. While testing, the relative amplitude and phase value of the analog circuit are obtained. If any one of the relative amplitude and phase values exceed the bounds then the CUT is declared faulty. The effectiveness of the proposed method is validated through HSpice/MATLAB simulations of two benchmark circuits and the practical circuit test of Tow-Thomas circuit.

Key words: Relative amplitude, Relative phase, Parametric fault, Analog circuit, Fault detection
There are two classes of wavelet transforms: continuous wavelet transforms (CWT) and discrete wavelet transforms (DWT). References [4–13] use DWT as preprocessors to extract useful information from the original signals, and employ the wavelet energy values of the measured signal as fault signatures. DWT provides a fast, local, sparse, multi-resolution analysis way to analysis signals. However, DWT also brings three main disadvantages: shift sensitivity [14], poor directionality [15], and lack of phase information. Because we are interested in extracting fault signatures from wavelet energy and wavelet phase, respectively, CWT is more suitable and we discuss only CWT in this paper. Meanwhile, complex cross-wavelet transform is used in this paper in order to extract phase information from the series. Complex cross-wavelet transform exposes the relative amplitude and the relative phase of the two time series in time-frequency space. Because the relative amplitude and the relative phase of the time series depend upon the circuit parameters, they can be used as fault signatures in fault detection of analog circuits.

In this paper, a fault detection method for analog circuit parametric faults is presented based on the complex cross-wavelet analysis of the measured signal waveform, that is the output voltage (VOUT). The remainder parts of this paper are organized as follows. Section 2 outlines the fundamental theory about complex cross-wavelet transform, then discusses the choice of the mother wavelet and the method used to extract useful information from the original series. Section 3 presents the detection method based on parametric faults is presented based on the complex cross-wavelet and to be localized in both time and frequency space. The proper choice of the mother wavelet plays a crucial role in the signal preprocessing. For the choice of the mother wavelet, several conditions must be satisfied. First, the mother wavelet is usually required to have a zero mean and to be localized in both time and frequency space. Second, in order to collect the relative amplitude and the relative phase information from the signal, the mother wavelet must be continuous and complex. In this paper, we focus on two different mother wavelets, namely the Morlet and Paul wavelets which are fully analyzed in paper [18].

The Morlet and Paul wavelets in the time domain are respectively shown below, where \( \omega_0 \) is the frequency and \( m \) is the order:

\[
\text{Morlet: } \varphi(t) = \pi^{-1/4}e^{i\omega_0 t}e^{-t^2/2} \\
\text{Paul: } \varphi(t) = \frac{2^m i^m m!}{\sqrt{\pi(2m)!}}(1-it)^{-(m+1)}
\]

In this paper, we will let \( \omega_0 \) equal to be six in the Morlet wavelet and \( m \) equal to be four in the Paul wavelet as suggested [18].

In CWT, Fourier frequency \( f \) and wavelet scale \( s \) are not direct reciprocals of each other. In order to estimate equivalent Fourier frequency, the equations are summarized as the follow:

\[
\text{Morlet: } \frac{1}{f} = \frac{4\pi s}{\omega_0 + \sqrt{2 + \omega_0^2}} \\
\text{Paul: } \frac{1}{f} = \frac{4\pi s}{2m + 1}
\]

Another thing to be noted is that the wavelet scale \( s \) need cover this equivalent Fourier frequency, which is helpful to extract the useful information from the original series.

2.2 Choices of Complex Mother Wavelet

The proper choice of the mother wavelet plays a crucial role in the signal preprocessing. For the choice of the mother wavelet, several conditions must be satisfied. First, the mother wavelet is usually required to have a zero mean and to be localized in both time and frequency space. Second, in order to collect the relative amplitude and the relative phase information from the signal, the mother wavelet must be continuous and complex. In this paper, we focus on two different mother wavelets, namely the Morlet and Paul wavelets which are fully analyzed in paper [18].

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\]

Another thing to be noted is that the wavelet scale \( s \) need cover this equivalent Fourier frequency, which is helpful to extract the useful information from the original series.

2.3 Information Extraction Method

In this paper, we present a method to extract sensitive relative amplitude and phase information. In analog circuit fault diagnosis, the circuit outputs are often band-limited
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3.2 Fault Detection Stage

The fault detection procedure is implemented in two stages namely pre-testing (fault dictionary construction) stage and fault detection stage.

3.1 Pre-testing Stage

The bound limits of relative amplitude and the relative phase associated with each component are obtained using Monte Carlo simulation [19]. In the fault-free circuit, the component parameters are set to a Gaussian distribution with a variation of 1 sigma. The components are allowed to vary up to 1 sigma. Monte-Carlo simulation. Step3: Apply complex cross-wavelet transform to \( X_n \) and \( X_M(i) \) series.

\[
W_n^{N-N}(s) = W_n^{N}(s)^* \quad (9) \\
W_n^{M(i)-N}(s) = W_n^{M(i)}(s)^* W_n^{N}(s)^* \quad (10)
\]

Step4: Use the information extraction method discussed to achieve the sensitive information.

\[
AMP_{ref} = SEF(|W_n^{N-N}(s)|) \quad (11)
\]

Step5: Normalized variables are shown as below.

\[
AMP_{REF}(i) = \frac{1}{M} \sum_{i=1}^{M} (AMP_{mon}(i) - AMP_{ref})^2 \quad (15)
\]

\[
ARG_{REF}(i) = \frac{1}{M} \sum_{i=1}^{M} (ARG_{mon}(i) - ARG_{ref})^2 \quad (16)
\]

The normal circuit relative amplitude response range:

\[
[min(AMP_{REF})..max(AMP_{REF})] \quad (18)
\]

The normal circuit relative phase response range:

\[
[min(ARG_{REF})..max(ARG_{REF})] \quad (19)
\]
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4 SIMULATION AND EXPERIMENT RESULTS

The proposed method is validated through the practical Tow-Thomas circuit and two benchmark circuits: the low-pass filter circuit and leapfrog circuit. The test algorithms in Section 3 have been implemented in MATLAB and have been utilized for testing various analog circuits.

4.1 Low-pass Filter Simulation Results

![Fig. 1. Low-pass filter circuit benchmark](image)

Low-pass filter circuit is shown in Fig. 1. A low-frequency sinusoidal input of 1kHz with an amplitude of 3V is applied to input VIN. The tolerance limits for the normal circuit are obtained from a set of 2 000 Monte-Carlo simulations. For the fault-free circuit, the VOUT is sampled at a 100KSPS sampling rate and stored 2048 samples per waveform. The upper and lower bounds of the relative amplitude and the relative phase are obtained and shown in Table 1, where AMP(Morlet) indicates the relative amplitude value using the Morlet wavelet and ARG(Morlet) presents the relative phase value using the Morlet wavelet. Then some parametric faults are independently injected into the circuit and the relative amplitude and the relative phase values are obtained and shown in Table 2 for every fault. MorletOBS indicates an out of bound signature using the Morlet mother wavelet. C1-6Sigma fault means a '-6 sigma variation of the value of C1.

Table 1. Bounds of relative amplitude and phase of low-pass filter

| Fault Type   | Bound of Fault Signature | Min     | Max     |
|--------------|--------------------------|---------|---------|
| AMP(Morlet)  | -3.413713                | 8.058208|
| ARG(Morlet)  | -1.476805                | 1.77993 |
| AMP(PAUL)    | -1.201012                | 2.834847|
| ARG (PAUL)   | -1.476908                | 1.76682 |

Table 2. Test results of the proposed fault detection method applied to low-pass filter circuit

| Fault Type   | AMP(Morlet) | ARG(Morlet) | MorletOBS |
|--------------|-------------|-------------|-----------|
| C1-6Sigma    | 8.244857    | -3.413713   | AMP/ARG   |
| R2-6Sigma    | -0.751803   | 0.924036    | AMP       |
| R2+6Sigma    | 15.116115   | -3.728297   | AMP       |
| R3-6Sigma    | 96.080808   | -0.512812   | AMP       |
| R3+6Sigma    | -4.535191   | 0.851484    | AMP       |
| Fault Type   | AMP(Paul)   | ARG(Paul)   | PaulOBS   |
| C1-6Sigma    | 2.900095    | 1.669873    | AMP/ARG   |
| R2-6Sigma    | -1.671385   | 0.923032    | AMP       |
| R2+6Sigma    | 5.317709    | -0.372441   | AMP       |
| R3-6Sigma    | 33.801105   | -0.512178   | AMP       |
| R3+6Sigma    | -1.595194   | 0.850570    | AMP       |

For C1-6sigma fault, the corresponding relative amplitude and phase values are obtained in Table 2. While compared with the lower and upper bounds it can be found that the AMP and ARG parts are exceeding the bound and hence this fault is detected. The R2-6Sigma, R2+6Sigma, R3-6Sigma, R3+6Sigma faults are more sensitive to the relative amplitude analysis than the relative phase analysis.

4.2 Leapfrog Circuit Simulation Results

The leapfrog circuit shown in Fig. 2 passes signal from DC to 1.4kHz for desired system operation. The input VIN is a 1kHz sinusoidal wave with an 3V amplitude. VOUT is sampled with 100KSPS sampling rate and stored 2048 samples per waveform. The Monte-Carlo simulation is performed for 2000 times. Similarly parametric faults occurring in a Leapfrog circuit have been detected by applying the proposed method. The bound limits of its relative amplitude and phase and the results are shown in Table 3 and 4.

The upper and lower bounds of the leapfrog circuit are different with different complex mother wavelets. The
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Table 3. Bounds of relative amplitude and phase of leapfrog circuit

| Bound of Fault Signature | Min      | Max      |
|--------------------------|----------|----------|
| AMP(Morlet)              | -13.498259 | 12.343993 |
| ARG(Morlet)              | -8.895469  | 9.295972  |
| AMP(PAUL)                | -4.740685  | 4.336003  |
| ARG (PAUL)               | -8.885899  | 9.293368  |

ranges of the relative amplitude of the fault-free circuit change significantly. For the Morlet mother wavelet, the AMP(Morlet) absolute range is about 22.794231, while the AMP(PAUL) is about 9.076688. We can infer that the Morlet mother wavelet in the proposed method has a better resolution in relative amplitude analysis. On the contrary, the ranges of the relative phase of the fault-free circuit are almost the same. It can be contributed to the nature of the relative phase analysis.

For C1-6sigma fault, the relative amplitude value crosses the upper boundary value of 12.343993, and the parametric fault in C1 has been detected using relative amplitude analysis. For C3+6sigma fault, the relative phase value crosses the lower boundary value of -8.895469. Thereby the parametric fault in C3 has been detected using relative phase analysis. Using either Morlet or Paul mother wavelet, the C1-6Sigma and C3+6Sigma faults can be detected. The main effect of choices of mother wavelets is the resolution in distinguishing faults using either the relative amplitude analysis or the relative phase analysis.

According to the test results, it is easily seen that the signatures produced by the proposed method have the ability of preventing aliasing and high robustness. The relative amplitude and relative phase of each fault correspond to one and only one fault in the circuit under test. Plotting the relative amplitude values as x-axis and the relative phase values as y-axis, some typical parametric faults of the leapfrog circuit are demonstrated in Fig. 3. The Morlet mother wavelet is used for the following leapfrog circuit fault detection. The yellow square represents the fault-free area and any fault lying inside the square cannot be detected. C3-1Sigma-C3-40Sigma fault means that the value of C3 decreases from 1 sigma to 40 sigma, and the step of the decrease is 0.5 sigma.

C3-5Sigma-C3-40Sigma fault can be detected using the relative phase analysis, and it shows that the sampling series of the fault circuit have a positive time delay compared with the fault-free circuit. On the contrary, there is a negative time delay between the fault circuit and fault-free circuit, when C4 value increases from 1 sigma to 40 sigma. These typical faults are sensitive to the relative phase anal-

Table 4. Test results of the proposed fault detection method applied to low-pass filter circuit

| Fault Type      | AMP(Morlet) | ARG(Morlet) | MorletOBS |
|-----------------|-------------|-------------|-----------|
| C1-6sigma       | 13.958415   | 9.011746    | AMP       |
| C3-6sigma       | 15.073037   | 11.909609   | AMP/ARG   |
| C3+6sigma       | -13.169358  | -16.475253  | ARG       |
| C4+6sigma       | -8.451804   | -13.481419  | ARG       |
| R2-6sigma       | -17.605256  | -8.142736   | AMP       |
| R6-6sigma       | 8.148630    | 14.872265   | ARG       |
| R8+6sigma       | -14.687502  | -11.018723  | AMP/ARG   |
| R11+6sigma      | -14.032108  | -13.088741  | AMP/ARG   |
| Fault Type      | AMP(Paul)   | ARG(Paul)   | PaulOBS   |
| C1-6sigma       | 4.900607    | 9.008554    | AMP       |
| C3-6sigma       | 5.290877    | 11.907371   | AMP/ARG   |
| C3+6sigma       | -4.617859   | -16.460244  | ARG       |
| C4+6sigma       | -2.964703   | -13.469648  | ARG       |
| R2-6sigma       | -6.180655   | -8.134594   | AMP       |
| R6-6sigma       | 2.856833    | 14.872338   | ARG       |
| R8+6sigma       | -5.150037   | -11.006162  | AMP/ARG   |
| R11+6sigma      | -4.923924   | -13.075026  | AMP/ARG   |

Fig. 2. Leapfrog circuit benchmark

Fig. 3. Leapfrog circuit typical parametric fault
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ysis. R6-3Sigma-R6-40Sigma faults are sensitive to the relative phase analysis. Similarly, With R2 value changing from 5 Sigma to 25 Sigma, the relative amplitude value changes from -13.5 to -40. These faults show the fact that the energy of the fault circuit sampling series change significantly.

4.3 Experiments on Tow-Thomas Filter Circuit

The structure and parameters of Tow-Thomas filter circuit is illustrated in Fig. 4(B) with \( R_1 = R_2 = R_3 = R_4 = 16k\Omega \), \( R_5 = R_6 = 10k\Omega \) and \( C_1 = C_2 = 1nF \). The actual circuit is shown in Fig. 4(C), and the amplifier in the circuit is TLO84 produced by TI. The actual test system is shown in Fig. 4(A). It consists of a National Instruments USB-6251 multifunction data acquisition (DAQ), which is used to generate the input sinusoidal signal and acquire the output signal. Eight fault cases are randomly chosen, and the experimental results using Morlet mother wavelet are listed in Table 5. Especially, the relative amplitude and the phase value obtained by using the proposed method also show strong robustness for actual circuit. For example, shown in Table 5, the experimental AMP/ARG is \([-0.561991, 7.696691]\), whereas AMP/ARG is \([1.494697, 8.755999]\) for Fault No.1. They are different and all of them are beyond the nominal range of the fault-free circuit, so Fault No.1 and Fault No.5 can easily be separated. The same conclusion can be drawn for any other cases as well. Furthermore, the out aliasing. For example, for Fault No.5, the experimental AMP/ARG is \([-0.561991, 7.696691]\), whereas AMP/ARG is \([1.494697, 8.755999]\) for Fault No.1. They are different and all of them are beyond the nominal range of the fault-free circuit, so Fault No.1 and Fault No.5 can easily be separated. The same conclusion can be drawn for any other cases as well. Furthermore, the

Table 5. Test results of the proposed method applied to Tow-Thomas circuit using Morlet mother wavelet

| Fault No. | Faulty AMP(Morlet) | ARG(Morlet) |
|-----------|-------------------|-------------|
| 1         | C1 variation (1nF->0.82nF) | 1.494697    | 8.755999 |
| 2         | C1 variation (1nF->1.2nF) | -1.636697   | -10.153168 |
| 3         | R6 variation (10k->9.1k) | 1.138892    | -7.348737 |
| 4         | R6 variation (10k->11k) | 4.440179    | 6.949636 |
| 5         | R2 variation (16k->14.7k) | -0.561991   | 7.696691 |
| 6         | R2 variation (16k->18k) | 3.479317    | -7.357379 |
| 7         | Fault 1 + Fault 4 + Fault 5 | -1.263060   | 18.214645 |
| 8         | Fault 2 + Fault 3 + Fault 6 | -4.099782   | -18.526999 |
| 0         | Fault free | Min(AMP)–Max(AMP)= [-7.000810–6.861794]; Min(ARG)–Max(ARG)= [-6.472527–6.657202]; |

Table 6. Test results of the proposed method applied to Tow-Thomas circuit using Paul mother wavelet

| Fault No. | Faulty AMP(Paul) | ARG(Paul) |
|-----------|------------------|-----------|
| 1         | C1 variation (1nF->0.82nF) | 0.523009   | 8.736694 |
| 2         | C1 variation (1nF->1.2nF) | -0.563765  | -10.132291 |
| 3         | R6 variation (10k->9.1k) | 0.397835   | -7.353568 |
| 4         | R6 variation (10k->11k) | 1.560994   | 6.964533 |
| 5         | R2 variation (16k->14.7k) | -0.207224  | 7.670346 |
| 6         | R2 variation (16k->18k) | 1.233490   | -7.343457 |
| 7         | Fault 1 + Fault 4 + Fault 5 | -0.450518  | 18.204644 |
| 8         | Fault 2 + Fault 3 + Fault 6 | -1.448169  | -18.512438 |
| 0         | Fault free | Min(AMP)–Max(AMP)= [-2.457858–2.430449]; Min(ARG)–Max(ARG)= [-6.485154–6.654602]; |
multiple parametric faults can also be detected by using the proposed method. For example, AMP/ARG is \([-1.263060, 18.214645]\) for Fault No.7 and experimental AMP/ARG is \([-4.099782, -18.526999]\) for Fault No.8. They are quite different, so two multiple parametric faults can be detected respectively.

The experimental results of the proposed method are listed in Table 6 when the mother wavelet is Paul mother wavelet. The experimental results show that the proposed method shares the high efficiency of diagnosis for the same fault by either the Morlet or the PAUL mother wavelet. Because the relative phase values of the same fault are almost identical using the two mother wavelet, we can infer that the choice of different mother wavelets does little affect on the relative phase analysis of the proposed method. On the contrary, the relative amplitude analysis using the Morlet mother wavelet has a higher fault resolution than using the PAUL mother wavelet.

5 CONCLUSION

In this paper, the complex cross-wavelet transform of the measured output voltage VOUT for analog circuit test has been studied, and we propose a new parametric faults detection method, which extracts fault signatures not only from the wavelet energy values of the measured signal, but also the wavelet phase values. The relative amplitude and the relative phase analysis proposed in this paper can detect parametric faults occurring in analog circuits efficiently. Tests results confirm that fault detection of analog circuits is fairly easy with the combination of the relative amplitude and relative phase analysis. Two benchmark circuits and Tow-Thomas filter circuit have been investigated to validate the proposed method.

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