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Application of Atomic Sparse Decomposition to Feature Extraction of the Fault Signal in Small Current Grounding System*

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ABSTRACT

Applying the atomic sparse decomposition in the distribution network with harmonics and small current grounding to decompose the transient zero sequence current that appears after the single phase to ground fault is occurred. Based on dictionary of Gabor atoms and matching pursuit algorithm, the method extracts the atomic components iteratively from the feature signals and translated them to damped sinusoidal components. Then we can obtain the parametrical and analytical representation of atomic components. The termination condition of decomposing iteration is determined by the threshold of the initial residual energy with the purpose of extract the features more effectively. Accordingly, the proposed method can extract the starting and ending moment of disturbances precisely as well as their magnitudes, frequencies and other features. The numerical examples demonstrate its effectiveness.

Keywords: Small Current Grounding System; Fault Line Selection; Atomic Sparse Decomposition; Matching Pursuit; Damped Sinusoids

1. Introduction

The small current grounding system include ungrounded neutral system, arc suppression coil compensated neutral system and high resistance-grounded neutral system. In our country, scientists and engineers have done a lot of researches on fault line selection in small current grounding system, a variety of line selection methods were put forward and some successes were achieved. But the problem of fault line detection hasn't been well settled because of that the fault current is small, the fault features are unobvious, the fault circumstances are complex and the mode of the system runs various. This will hinder the smooth development of power distribution automation system, damage the security and stability of the power system.

Fourier transforms and wavelet transforms are examples of time-frequency signal decomposition that have been used for many years. The Fourier basis provided a poor representation of functions well localized in time, and wavelet basis are not well adapted to represent functions whose Fourier transforms have a narrow high frequency support. In both cases, it is difficult to detect and identify the signal patterns from their expansion coefficients for the information is diluted across the whole basis. To extract information from complex signals, it is often necessary to adapt the time-frequency decomposition to the particular signal structures. [1]

Domestic and foreign scholars have proposed a variety of methods about fault line selection. Existing line selection method of stable state quantity [2-4] is difficult to meet the site operational requirements. There is still fault transient detection method [5-12]. The paper [5] proposes a distribution network fault line selection method about fusion of multiple sampling points' poll results based on S-transform through studying S-transform to extract the amplitude and frequency characteristic and phase-frequency characteristic of signal. This method needs to collect to the correct the feeder phase angle and frequency information. The paper [6,7] extract fault line travelling wave through using wavelet transform and structure criterion in order to determine fault line. Although wavelet transform has good enough time domain - frequency domain localization features to provide characteristics of the signal in different scales, it has ineffective application as it is vulnerable to the effects of noise. The paper [8] realizes the fusion line selection method through introducing the concept of fault measures and using Dempster-Shafer theory. The paper [11] captures feature band by comparing transient zero-sequence cur-

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rent amplitude and gets characteristic band signal through filtering. References[9,10] use wavelet packet to extract the transient signal, determined band which the transient capacitive current most concentrate by the principle of maximum energy and elected fault feeder. However, the feature band that can be used for line selection is influenced by the system parameters, failure modes and so on. Various feeders transient capacitive current concentration of energy bands are not the same, if the band is selected improperly, it is easy to make the fail selection of the fault line.

The paper [12] uses S-transform to process zero sequence current of each feeder, and determines the dominant frequency of the capacitive current by comparing transient energy of different frequency points, and selects the fault line according to the size of the energy. S-transform is the development of continuous wavelet transform and the short time Fourier transform, and has good time-frequency characteristic, but amount of information is so much after decomposition. As well as there is some line selection methods which combine steady state with transient state, but neural network algorithm exists local optimum problem, poor convergence, longer training time and limited reliability.

To compensate for these shortcomings, this paper provides an algorithm that can decomposes signal into a linear expansion of waveforms that belong to a redundant dictionary of functions, these waveforms are selected in order to best match the signal structures. For a particular signal, according to the characteristics of the signal, the algorithm can choose the best spread functions adaptively. By using less function more accurate represent the signal, it can decompose a signal into coherent components. The new feature extraction of the fault signal method in the neutral indirectly grounded system which is based on the atomic sparse decomposition.

2. Time-Frequency Atom Dictionaries

Time-frequency signal decomposition such as Fourier transforms and wavelet transforms has been used for many years. It is often essential to adapt the time-frequency decomposition to the particular signal structures to extract information from complex signals. The algorithm provided in this paper can decomposes signal into a linear expansion of waveforms that belong to a redundant dictionary of functions, the selected waveforms are the best match of the signal structures. For a particular signal, the algorithm can choose the best spread functions adaptively on the basis of the characteristics of the signal. The functions more accurate to represent the signal are called atom, the possibly redundant dictionary of functions called atoms.

The matching pursuit algorithm is often used in the atomic decomposition process, it is a greedy adaptive decomposition to decompose signal into a linear expansion of waveforms that belong to atoms. The selected atoms have good time-frequency characteristic and can represent the inherent characteristics and critical information of the signal.

2.1. The Gabor Dictonary

Decomposing a signal over a redundant dictionary improves the compression efficiency, especially at low bit rate where most of the signal energy is captured by only few elements. We often use Gabor dictionary in atomic sparse decomposition. Define

$$g_\gamma(t)=\frac{1}{\sqrt{s}}g(\frac{t-\tau}{s})e^{j\xi t} \tag{1}$$

The real Gabor atoms:

$$g_\gamma(t)=\frac{K_\gamma}{\sqrt{s}}g(\frac{t-\tau}{s})\cos(\xi t+\phi) \tag{2}$$

$g(t)=2^{\frac{1}{4}}e^{-\pi t^2}$ is Gaussian window function, $\gamma=(s,\tau,\xi,\phi)$, γ is the index of $g_\gamma(t)$, s is Scaling parameters, τ is Displacement parameters, ξ is Frequency parameters, ϕ is Phase parameters. Such atomic space is boundless, and in practice, we can't search a boundless space, so the atomic database should be dispersed. $\gamma=(a^j, pa^j\Delta\tau, ka^{-j}\Delta\xi)$, while $a=2$, $\Delta\tau=1/2$, $\Delta\xi=\pi$, $0<j<\log_2 N$, $0<p<N2^{-j+1}$, $0<k<2^{j+1}$. Then we can get a Gabor dictionary

$$g_{rd}(n)=g_j(n-p2^j)\cos(nk\pi 2^{1-j}+\phi) \tag{3}$$

$$g_j(n)=\begin{cases}\delta(j) & j=0\\ K_{\gamma d}\,g(n2^{-j}) & j\in[1,L)\\ \frac{1}{\sqrt{N}} & j=L\end{cases} \tag{4}$$

$$n=0,1,...,N-1$$

2.2. Matching Pursuits Algorithm

In contrast to orthogonal transforms, over complete expansions of signals are not unique. The number of feasible decompositions is infinite, and finding the best solution under a given criteria is a NP-complete problem. In compression, one is interested in representing the signal to be coded with the smallest number of elements, which is in finding the solution with most of the energy on only a few coefficients. Matching Pursuit is one of the suboptimal approaches that greedily approximate the solution to this NP-complete problem [13].

Matching Pursuits algorithm, which is a greedy adaptive decomposition that has the potential of decomposing a signal into coherent components.

$$\begin{cases} f_x^0 = f \\ f_x^m = f_x^{m-1} - \left\langle f_x^{m-1}, g_\gamma^{(m)} \right\rangle g_\gamma^{(m)} \\ g_\gamma^{(m)} = \arg \max\limits_{g_\gamma^{(i)} \in D} \left| \left\langle f_x^{m-1}, g_\gamma^{(i)} \right\rangle \right| \end{cases} \quad (5)$$

f is the original signal. After m iterations, we decompose f into the concatenated sum

$$f = \sum_{n=0}^{m-1} \left\langle f_x^{(n-1)}, g_\gamma^{(n)} \right\rangle g_\gamma^{(n)} + f_x^{(m)} \quad (6)$$

If we stop the algorithm at this stage, the summation of (6) recovers an approximation of f, with an error equal to $f_x^{(m)}$.

2.3. Building a Dictionary for Power System Signals

In a very simplistic way, power systems can be considered to be built from transmission lines, sources, and loads. Besides, we should add to this model the discontinuities due to circuit switching caused by operative maneuvers and by the protection system. The employed model is given by [14-16].

$$f(t) = \sum_{q=0}^{Q-1} A_q \cos(2\pi f_q t + \phi_q) e^{-\rho_q (t - t_{sq})} \times [(t - t_{sq}) - u(t - t_{eq})] \quad (7)$$

where each component is a damped sinusoid represented by a six-tuple ($A_q, f_q, \rho_q, \phi_q, t_{sq}, t_{eq}$), where A_q is its amplitude, f_q is the frequency, ρ_q is the damping factor, ϕ_q is the phase, and t_{eq} are the component starting and ending times. Note that the model in (7) by no means compactly represents "all" possible phenomena in power systems signals.

3. Example Analysis

3.1. Harmonics

The original analog signal model:

$$u(t) = \cos(100\pi t) + p(t)0.4\cos(700\pi t + \pi/6) + q(t)0.2\cos(1300\pi t + \pi/3)$$

$$p(t) = \begin{cases} 1 & 0.04s \le t \le 0.25s \\ 0 & otherwise \end{cases} \quad (8)$$

$$q(t) = \begin{cases} 1 & 0.1s \le t \le 0.5s \\ 0 & otherwise \end{cases}$$

The total time is 0.5 s, Adding seven times harmonic at 0.04 - 0.25 s; 13th harmonic at 0.1 - 0.5 s, sampling at 4 KHz.

Figure 1(a) shows the Waveforms of decomposed atoms, and the **Table 1** shows the atom parameters of each iteration. From the **Figure 1(a)** we can see that the atomic decomposition has iterated only three times to separate the fundamental component and harmonic component effectively, and the feature extraction of the Correlative Component is obtained. **Figure 1(b)** shows that the decomposed signal is closed to the original signal, and the error of this method reached 10-3, continuing decomposition can make the approximate degree higher. Besides, the data in **Table 1** shows that the frequency, phase angle, and the starting and termination time got from the atomic decomposition are basically identical to the original signal.

3.2. Earth Fault Line Selection

1) Put up a model of 10 kV distribution network with PSCAD. As **Figure 2** shows, there are four lines named m, n, w, p. The single-phase- to-ground fault happened at 0.5 s. Collecting and analyzing the zero sequence current in the four lines.

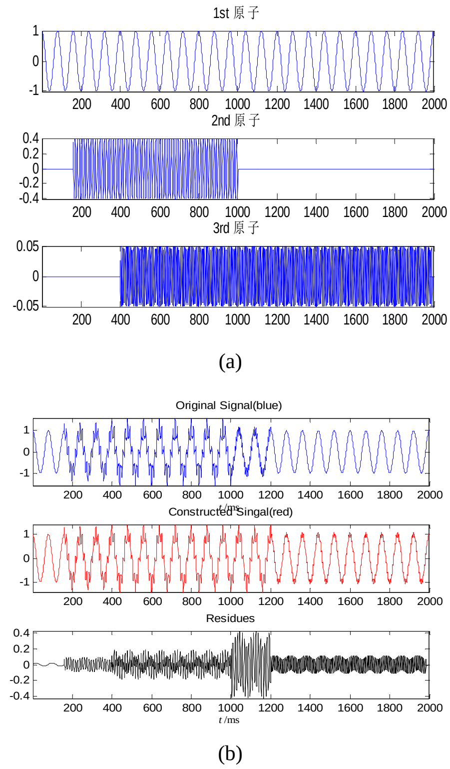


Figure 1. (a) Waveforms of decomposed atoms; (b) the reconstruction for harmonics.

Table 1. Decomposed atom parameters of signal.

Atom	Amplitude (V)	Frequency (Hz)	Phase Angle (rad)	Start Time (s)	Terminal Time(s)
1ed atom	0.999	50.0000	0	0	0.5
2rd atom	0.388	350.0000	0.524	0.04	0.25
3rd atom	0.200	650.000	1.075	0.1	0.5

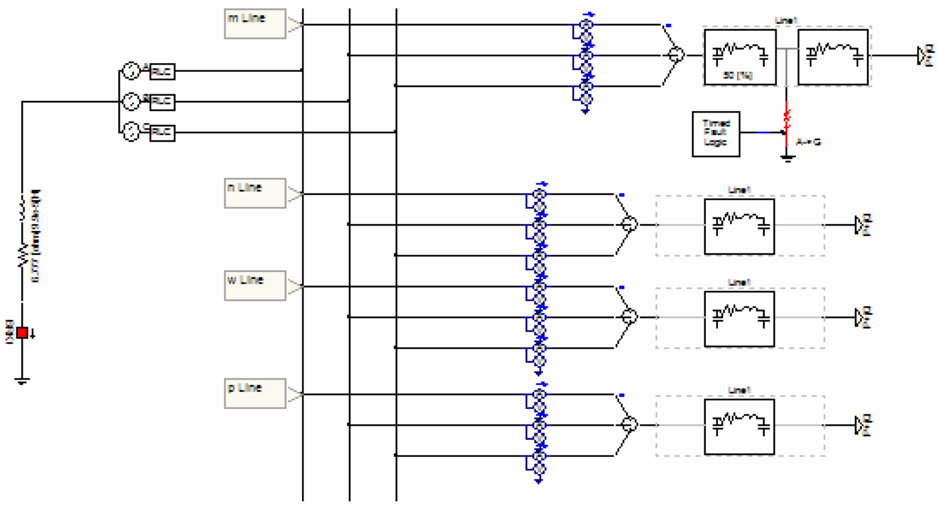
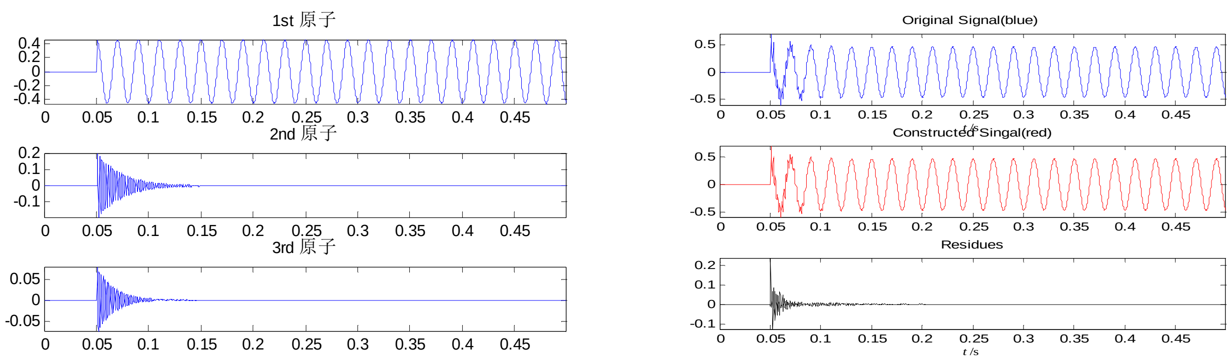


Figure 2. The model of 10 kV distribution network.



(a) (b)

Figure 3. (a) Waveforms of decomposed atoms; (b) the reconstruction for zero sequence transient current of m line.

Table 2. Decomposed atom parameters of signal.

Line	Atom	Amplitude (V)	Frequency (Hz)	Phase Angle(rad)
m line	2ed atom	0.2048	488.08	-5.6284
	3rd atom	0.0812	547.03	26.8752
n line	2ed atom	0.1320	487.87	179.0498
	3rd atom	0.0603	549.71	-209.0478

2) It is clearly observed from **Figure 3(a)** that the atomic decomposition can separate the fundamental component and harmonic component effectively with only three iterations. **Figure 3(b)** shows that the decomposed signal is similar to the original signal. From **Table 2** we can see that the phase angles of the second atom is opposite to the third atom. Through which we can identify Single-Phase-to-Ground Fault line.

4. Summary

By the above analysis of the actual case, we apply a compression algorithm for signals measured during power system disturbances that obtains good effect while preserving important features for signal analysis. The damped sinusoidal dictionary by no means compactly represents "all" possible phenomena in power systems signals. Adaptive, analyticity and the sparse of Atomic decomposition make the algorithm has obvious advantages in power system fault line selection. Therefore, the method is feasible and practical, and can be applied broadly in power system.

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