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Research of Dielectric Loss Measurement with Sparse Representation

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Abstract: Harmonics analysis based on wavelet transformation is used in the measurement of dielectric loss angle of power system in order to get the fundamental wave from the observed voltage and current. However, due to low signal-to-noise ratio (SNR) and frequency fluctuation, its accuracy drops greatly in many applications. After analysis of its disadvantages, a novel method using sparse representation is proposed here. Simulation results show that it has better accuracy than the wavelet transformation,

Keywords: Wavelet transform, Dielectric loss measurement, Sparse representation, Transformation, Signal-to-Noise.

1. INTRODUCTION

The tangent value of dielectric loss angle ($\tan\delta = I_R/I_C$) plays an important role in reflecting the insulating ability of the high voltage electrical equipment. The ability of measurement in real-time becomes important in high-voltage insulation test. Because of the frequency fluctuation in the power network (For example, within the scope of 50±0.2Hz), it is difficult to meet the requirement of cycle sampling. Consequently there are "stockade effect" and "frequency spectrum divulges", which bring large error in the phase δ.

Additionally, it is difficult to measure the value of tanδ when the equipment has high voltage, tiny current and small angle. In the recent years, many methods have been proposed to solve this problem. Theoretically, in order to get high-precision measurement, the high-order harmonics, Direct Current (DC) component and noise must be suppressed, but the fundamental wave must be retained. There are three software measurement methods, including wave fitting, filtering and harmonic analysis. The method of wave fitting and filtering have heavy computation burden. Harmonic analysis [1, 2] (Fourier transform, wavelet transform, etc.) is very efficient, without the influence from high-ordered harmonic wave and zero drift. As a representative medium method, it avoids the effect of DC component and harmonic interference. However, "stockade effect" and "frequency spectrum divulges" severely impact the accuracy of its measurement.

In order to resolve the measurement error of non-synchronous sampling, the windowed harmonic analysis is used. But when there is noise, especially low SNR, the fundamental wave will be covered by noise. Wavelet transfer [3] has better performance than windowed harmonic analysis, which is time-frequency analysis and avoids the influence of periodical factor and other uncertain factors. The disadvantage of this method is low accuracy.

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The contributions of this work are: (1) analysis of low accuracy of methods based on wavelet transform; (2) first introduction of sparse representation and successful application. This paper is organized as follows: In section 1, the difficulties of measurement and introduction of recent methods; In section 2, method based on wavelet transform is presented and its advantages and disadvantages are discussed; In section 3 based on the analysis in section 2, the sparse representation is introduced and detailed measurement steps are presented; In section 4, the simulation is carried out and simulation results are explained compared with the method based on wavelet transform. At last, conclusions are drawn.

2. DIELECTRIC LOSS MEASUREMENT OF WAVELET TRANSFORM

Wavelet transform is a time-frequency analysis tool. It generates a variable time-frequency window by flex and shift of wavelet function. It has good performance in the analysis of the transient and non-stationary signal. It extracts composition characteristic by offsetting the frequency spectrum of transient signal.

Assuming signal s = x+n (s is to be analyzed with noise n), its wavelet transform is y = Ws, θ =Wx, z = Wn, while wavelet curtail acts as filter H. The output of filter is the optimal estimate of wavelet coefficients $\hat{\theta}$. Through the inverse wavelet transform, system outputs the estimate of single x. The diagram of signal x recovery is shown in Fig.1 [4].

Many methods based on wavelet transform have been proposed for the dielectric loss measurement [4-8]. The key steps are summarized as follows.

Generally, besides the fundamental wave (50 Hz), the observable current and voltage in the power system contain the DC, the high-ordered odd harmonic waves and noise. They are expressed as follows:

$$A(t) = A_0 + \sum_{k=1}^{2n-1} A_k \sin(k\omega t + \varphi_k) \qquad (1)$$

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Where, ω is the fundamental frequency (around 50Hz in the power system), A_k and φ_k (k=0,1,3,5,7,…) are the amplitude of each component and the initial phase of each harmonic wave respectively.

According to the NY Quist sampling theorem, when we select the number of sampling points as 128 (*i.e.*, the sampling frequency is 6.4kHz), the cut-off frequency is 3.2kHz. So, we can decompose the signal s with 7 layers wavelet in Table **1** [7, 8].

According to the principle of wavelet transform, the observed signal can be reconstructed with scaling coefficient 'c7' and wavelet coefficients 'd7'~'d1'. In the measurement of dielectric loss, the fundamental wave (50Hz) needs to be reconstructed. Therefore, the coefficient 'd7' corresponding to the detailed information of 25~50Hz should be remained. Other wavelet coefficients ('d1'~'d6') and 'c7' should be set to be zeros. Then, we can extract the fundamental wave.

With the finite layers of wavelet decomposition, we can only obtain a small range of frequency (see 'd7' which corresponds to the signal of 25~50Hz in Table **1** [7, 8]), but not the specific frequency. When the frequency in the power system is fluctuating, the reconstruction result of the fundamental wave is not very accurate. However, we can obtain the fundamental frequency accurately with sparse representation.

3. DIELECTRIC LOSS MEASUREMENT OF SPARSE REPRESENTATION

3.1 Sparse Representation

During the signal analysis, the signal is expressed by some sets of orthogonal basis. Considering the complexity of the signal and the limitation of the orthogonal decomposition, we propose a novel method for the measurement of dielectric loss with sparse representation. Sparse Representation (abbreviated as SR, also named as sparse

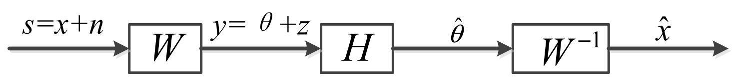

Fig. (1). Filtering diagram of wavelet transform.

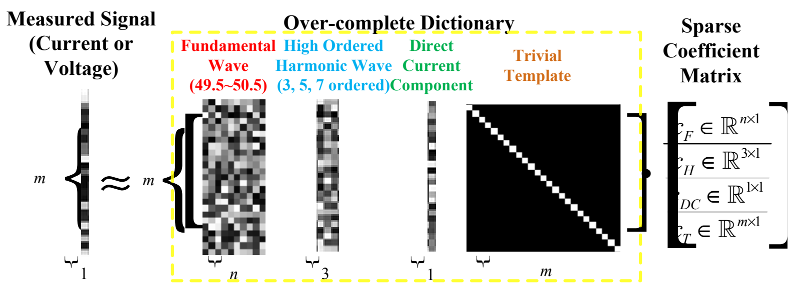

Fig. (2). Sparse representation based dielectric loss measurement.

Table 1. The decomposing procedure of wavelet transform for signal with 6.4kHz sampling frequency.

Scaling Coefficient (Approximate Component)	Signal Component/Hz	Wavelet Coefficient (Detail Component)	Signal Component/Hz
c1	0~1.6k	d1	1.6k-3.2k
c2	0~800	d2	800-1.6k
c3	0~400	d3	400-800
c4	0~200	d4	200-400
c5	0~100	d5	100-200
c6	0~50	d6	50-100
c7	0~25	d7	25-50

sensing or compressive sensing), is an attractive signal reconstruction method proposed by Candes [9, 10]. The main purpose of SR is to reconstruct a signal $s \in \mathbb{R}^{m\times 1}$ by an over-completed dictionary $D \in \circ^{m\times n}$ with sparse coefficient vector $c \in \mathbb{R}^{n\times 1}$. The formulation of SR can be written as the following l_0-norm constrained optimization problem:

$$\min_c \left\|s - Dc\right\|_F^2 + \alpha\left\|c\right\|_1 \quad (2)$$

Obviously, in the dielectric loss measurement, once we have an over-completed dictionary with some odd-ordered harmonic waves (1, 3, 5, 7 ordered), sparse representation can be used for decomposing the measured current and voltage signals. This performance of sparse representation is much better than wavelet as the specific frequency of fundamental wave can be obtained.

3.2. Dielectric Loss Measurement of Sparse Representation

Since the fundamental wave, the high-ordered harmonic waves and the direct current component must be included in the over-completed dictionary *D*. Here, we take 3, 5, 7 ordered harmonic waves into account (blue part in Fig. **2**). The value of 9 and higher ordered ones is very small in the power system. In order to reduce the influence of frequency fluctuation on measurements accuracy, we use a number of columns of fundamental waves (the preset values of fundamental frequency are 49.5, 49.6, … , 50.5Hz) instead of only one column of 50Hz fundamental wave (red part in Fig. **2**). For the sake of noise reduction, we add a column of DC component (green part in Fig. **2**) and an additional unit matrix (brown part in Fig. **2**) in *D*. In Fig. (**4**), *m* is the product of the number of the sampling points in each cycle and the number of cycles; *n*=11 is the number of fundamental frequency.

With the over-completed dictionary *D*, we can solve the l_1-optimization problem with different numerical algorithms, such as BP, MP, OMP etc.. At the same time the sparse coefficients can be obtained. Here, we are only concerned about the coefficients c_F corresponding to the fundamental wave, while ignoring the other coefficients c_H, c_{DC} and c_T corresponding to high-ordered harmonic waves, DC component and trivial template respectively. The fundamental component in the observed voltage or current can be reconstructed by the sparse fundamental wave coefficient c_F and the fundamental component in *D* (red part in Fig. **2**).

Fig. (**3**) shows some reconstruction results using our method. We find that, with sparse representation, we can filter out the high-ordered harmonic waves and reserve the fundamental wave with much lower sampling frequency than with wavelet transform [7, 8].

Compared with wavelet transform, sparse representation is an enormous challenge for NY Quist sampling theorem. With well-definited over-completing dictionary (like the dictionary *D* above), the fundamental wave can be extracted from the observed signal, even when the sampling frequency is equal to or lower than 800Hz.

4. SIMULATION

4.1 Simulation Settings

In order to test the performance of our algorithm, the dielectric loss angle is recovered respectively by windowed harmonic analysis, wavelet transform d sparse representation.

Sine wave is set as fundamental wave. It is assumed that there are 30% of DC component, 30% of 3th-ordered, 20% of 5th-ordered and 20% of 7th-ordered harmonic. The dielectric loss angle of equipment is 0.02rad. Sampling frequency f_s=6.4kHz. The number of sampling points is 128. The number of sampling cycles is 2. Thus, we have *m*=256 in Fig. **4**.

Let the expression of voltage be as follows:

$$\begin{aligned} u(t) = 3e^{(-3t+\varphi_{u0})} + 10\sin(wt+\varphi_{u1}) + 3\sin(3wt+\varphi_{u3}) \\ + 2\sin(5wt+\varphi_{u5}) + 2\sin(7wt+\varphi_{u7}) + n_u(t) \end{aligned} \quad (3)$$

Where, $n_u(t)$ is the noise, $\varphi_k\ (k=0,1,3,5,7)$ is the initial phase of each component. The expression of current is similar to Eq. 3.

4.2 Simulation Results

Using our method, we can extract the fundamental wave from the observed voltage and current signals. Fig. **4(a)** shows the comparison between sparse representation and wavelet. As shown in Fig. (**4**), the absolute errors and relative errors of two algorithms are increased with the increased noise, but the relative errors of our method are always much lower than the method with wavelet transform. The maximum value of error is no more than 8%. As shown in Fig. **4(b)**, the frequency fluctuation of power system impacts these two algorithms. Compared with the wavelet transform, our method excellently repels the influence caused by frequency fluctuation. Whether the frequency of the power system is 50Hz or far away from 50Hz (such as 49.5Hz and 50.5Hz), the relative errors for measurement of dielectric loss are under 3% for the most part.

5. CONCLUSION

In this paper, we introduced the sparse representation in the measurement of dielectric loss. According to the simulation results, our method has better performance on accuracy than the method with wavelet transform. Our method is also robust against the frequency fluctuation.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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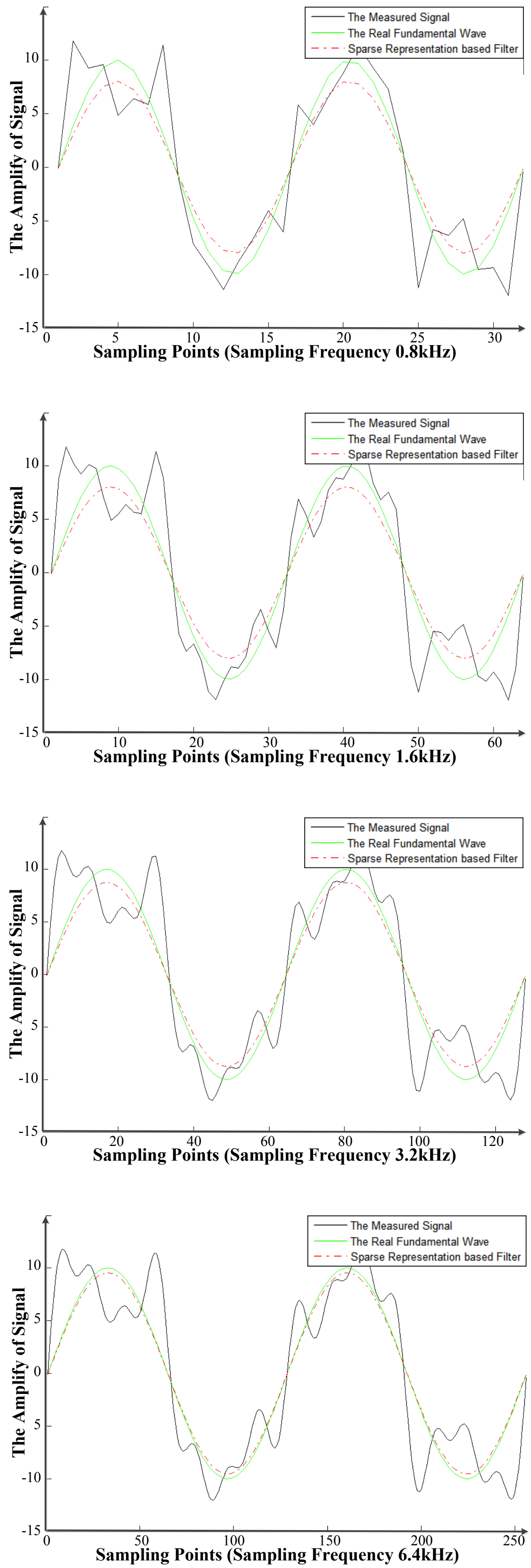
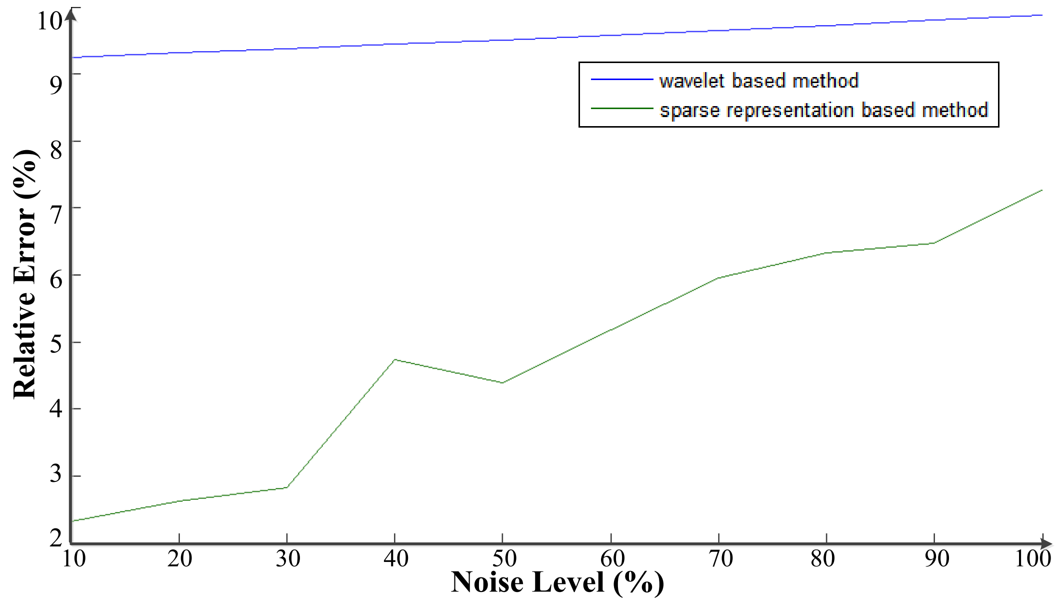
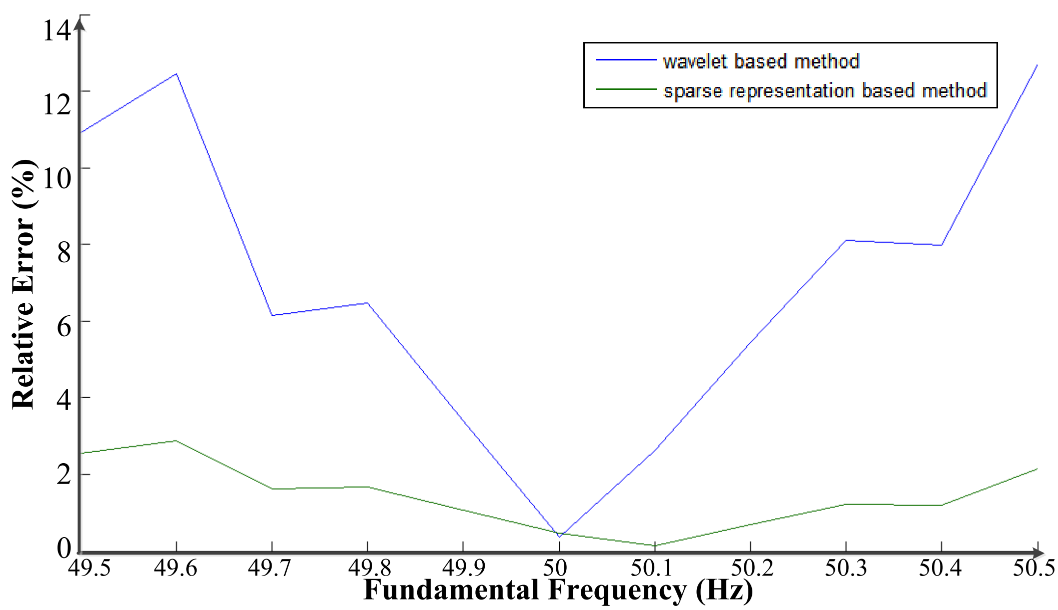


Fig. (3). Reconstruction results of our method.



(**a**) Comparison of relative error at different noise level



(**b)** Comparison of relative error at different frequency fluctuation

Fig. (4). The relative errors with different noise weight and fundamental frequency.

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