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Research of Dielectric Loss Measurement with Sparse Representation

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Abstract: For the sake of the measurement of dielectric loss angle in power system, wavelet transformation based harmonics analysis method has been proposed to filter the real fundamental wave from the original observed voltage and current signals by many researchers. But the precise of these approaches is dissatisfactory for practical applications, especially in the circumstances of low signal-to-noise ratio and frequency fluctuation. The shortcomings of these wavelet transform based approaches are discussed in this paper, and a novel algorithm based on sparse representation is proposed. Experimental results describe the advantages of our method.

Keywords: Wavelet transform; Dielectric loss measurement; Sparse representation

1. INTRODUCTION

The tangent value of dielectric loss angle (tanδ=I_R/I_C) plays an important role in reflecting the insulating ability of the high voltage electrical equipment, and the on-line measurement for the electric capacity equipment mainly depend on its dielectric loss tanδ, which becomes the critical issue in the high voltage insulation and test research. Because of the frequency fluctuate in power network (in the scope of 50±0.2Hz), the entire cyclical sampling condition is difficult to satisfy, and “stockade effect” and “frequency spectrum divulges” are arouse, which cause large errors when measuring the phase δ during the course of real measure.

The measurement of tanδ is a problem under high voltage, tiny current and small angle. In recent power system, there are many different digital measurement methods. In these high-precision measurement methods, the high ordered harmonics, direct current (DC) component and noise component must be suppressed, while the fundamental wave must be remained. Wave fitting, filtering and harmonic analysising are three categroies of methods in software measurement of tanδ. The first two ones cost expensive in computation, and the last one calculates tanδ with harmonic analysis[1-2] (Fourier transform, wavelet transform, etc.) is high efficiency, which are not affected by high-ordered harmonic wave and zero-drift. Harmonic analysis is a representative medium measurement without DC component and harmonic interference. But the stockade effect and frequency spectrum divulges caused by frequency fluctuate in power system influences the phase measurement seriousely with harmonic analysis.

In order to resolve the measure error in non-synchronous sampling, the windowed harmonic analysis is used. But when noise exists (especial SNR is lower), the real fundamental wave is covered by noise, windowed harmonic analysis is not suitable, and wavelet transform is one of the effective time-freqency analysis method0, which overcomes the influence casued by periodicity factor and some other uncertainly factors. But we find that, the measurement results are not very precise with wavelet.

The main contribution of this work is: (1) the reason for the inaccuracy of wavelet based methods is analysised; (2) sparse representation is introduced into the measurement of dielectric loss for the first time, and the experimental results show the superior performance. The rest of this paper is organized as follows: In section 2, wavelet based method for dielectric loss measurement is introduced, and the reason for the measurement inaccuracy is discussed; In section3, sparse representation is introduced into the task of dielectric loss measurement; Experimental results with our method and wavelet based method are reported in section 4; The conclusion and future work are summarized in Section 5.

2. WAVELET TRANSFORM BASED DIELECTRIC LOSS MEASUREMENT

Wavelet transform is a new time-frequency analysis tool. It produces a variable time-frequency window by flex and shift of wavelet function, so it has unique advantages in transient and non-stationary signal analysis aspect, especially set off transient signal of the frequency spectrum to extract the characteristics of components.

Assume $s = x+n$ (s is the signal for analysis, n is noise), their wavelet transform were expressed as $y = Ws$, $\theta = Wx$, $z = Wn$, the course of wavelet curtail look as the course of filter H action. The output of filter is the best estimate to wavelet coefficients $\hat{\theta}$ of the original signal x, the estimate $\hat{x}$ of the original signal is obtained through the inverse wavelet transform to estimate $\hat{\theta}$. The course of signal recovery is shown in Fig.(**1**) 0.

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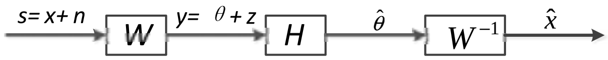


Fig.(1). Filtering diagram of wavelet transform

There are many methods have been proposed for dielectric loss measurement based on wavelet transform00[6-8]. The main procedure can be summary as follow.

Generally, besides the fundamental wave (50Hz), the observed current and the voltage signals in power system contain the direct current component, the high ordered odd harmonic components and noises. The mathmatical model of which can be formulated as follow:

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

where, ω is the fundamental frequency (around 50Hz in a real 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 signal, respectively.

According to the Nyquist 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 original signal with 7 layers wavelet transform as shown in Tab.(**1**) 0.

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 wave we need to reconstruct is the fundamental wave (50Hz), therefore, the coefficient ‘d7’ which corresponding to the detail information of 25~50Hz signal component should be remained, and the other wavelet coefficients (‘d1’~’d6’) and ‘c7’ should be set to be zeros. Then, we can extract the fundamental wave from the original wave with inverse wavelet transform with ‘d7’ , ‘d6’~’d1’ (all zeros coefficient vectors), and ‘c7’ (all zeros coefficient vectors).

With the finite layers of wavelet composing, we can only obtain a domain of frequency (see ‘d7’ which corresponding to the signal of 25~50Hz in Tab.1[7-8]), but not the exact frequency. When the frequency fluctuating in a real power system, the reconstruction result of the fundamental wave with wavelet transform is not very accuracy, however, we can obtain the fundamental frequency accurately with sparse representation based dielectric loss measurement.

Tab.(1). The decompose 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

3. SPARSE REPRESENTATION BASED DIELECTRIC LOSS MEASUREMENT

3.1 Sparse Representation

In this section, we introduce sparse representation for dielectric loss measurement, which has not so far proposed by anyone else. In the traditional algorithms of signal analysis, the signal is expanded with some sets of orthogonal basis. Because of the complexity of the signal and the limitation of the orthogonal decomposition, we propose a novel method for the measurement of dielectric loss based on sparse representation. Sparse representation (abbreviated as SR, also named as sparse 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 $s \in \mathbb{R}^{m\times 1}$ with an over-completed dictionary $D \in \mathbb{R}^{m\times n}$ 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:

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

It is obviously for us to see that, in the domain of dielectric loss measurement, once we have an over-completed dictionary with some odd ordered harmonic components (1, 3, 5, 7 ordered), sparse representation can be used for decomposing the measured current and voltage signals with fundamental component and other high ordered odd harmonic components. This progress with sparse representation is much better than that with wavelet, because the exact frequency of fundamental wave can be obtained.

3.2 Sparse Representation based Dielectric Loss Measurement

As discussed above, the fundamental wave, the high ordered harmonic waves, the direct current component must be included in the over-completed dictionary *D*. Here, we take 3, 5, 7 ordered harmonic waves into account, and the higher ordered ones than these are very tiny in a real power system (blue part in Fig.2); In order to reduce the influence of frequency fluctuate for accuracy measurements, we use a number of columns of fundamental waves (the preset values of fundamental frequency are 49.5, 49.6, …, 50.5) instead of only one column of 50Hz fundamental wave (red part in Fig.2); For the sake of denoising, 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., and the sparse coefficients can be obtained. Here, we are only concerned with 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 wave, DC component and trivial template, respectively. The fundamental component in the measured voltage or current signal can be reconstructed with the sparse fundamental wave coefficient c_F and the fundamental component in *D* (red part in Fig.(**2**)).

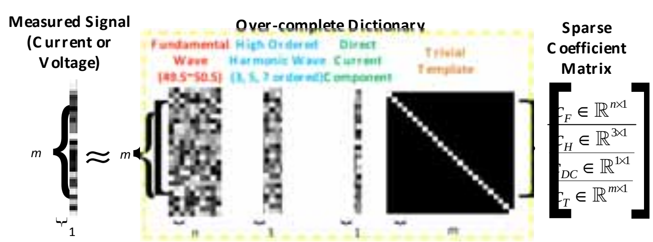


Fig.(2). Sparse Representation based Dielectric Loss Measurement

Fig.(**3**) shows some reconstruction results with 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 that with the categories of wavelet based methods[7-8]. Exactly, compared with wavelet transform, sparse representation is an enormous challenges for Nyquist sampling theorem. With well-definited over-completing dictionary (like the dictionary *D* definited above), the fundamental wave can be extracted from the observed signal, no matter how we reduce the sampling frequency, even equal to or more lower than 800Hz.

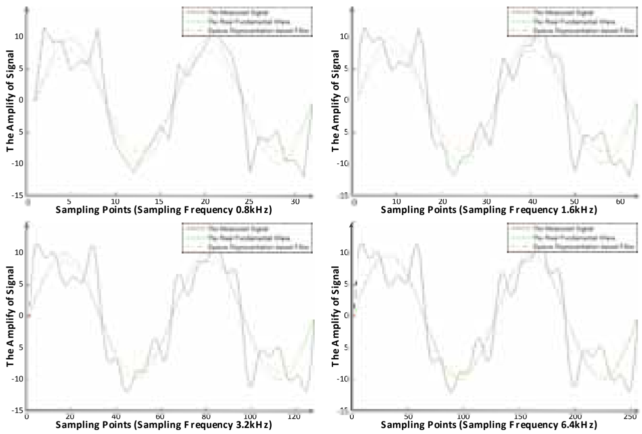


Fig.(3). Reconstruction results of our method

4. EXPERIMENTS

4.1 Experiment Settings

In order to test the performance of our algorithm, the dielectric loss angle is computed and compared respectively with windowed harmonic analysis, wavelet and sparse representation.

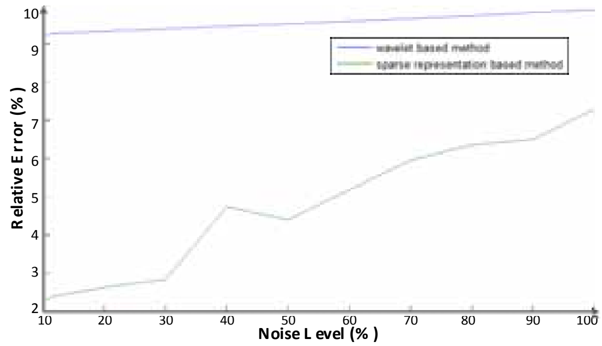
The fundamental-wave component of voltage and current of sine wave analog measured is as basis in simulation experiment, and assume to include 30% of DC component, 30% of 3th-ordered, 20% of 5th-ordered and 20% of 7th-ordered harmonic; the dielectric loss angle of equipment is from 0.02rad, f_s=6.4kHz, the number of sampling points is 128 and the number of sampling cycles is 2. Thus, we have m=256 in Fig.(**4**). Let the expression of voltage to be

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

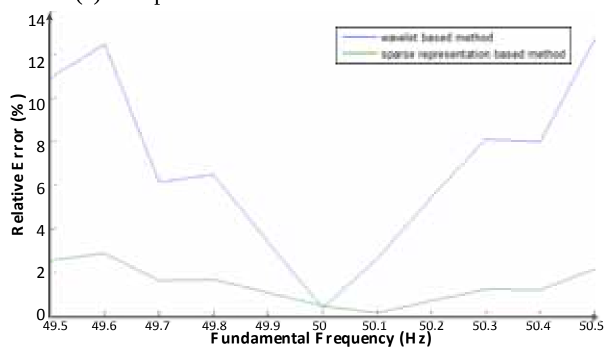
where, $n_u(t)$ is the noise components of voltage, $\varphi_k\ (k=0,1,3,5,7)$ is the initial phase of each component, and the expression of current is similar to Eq.(3).

4.2 Experimental Results

Use our sparse representation based method, we can extract the fundamental wave from the observed voltage and current signals. Fig.(**4**a) shows some comparison results between sparse representation and wavelet based methods. As shown in Fig.4, the absolute errors and relative errors of these two algorithms are increased with the noise components increased, but the relative errors of our method are always much lower than that of wavelet based harmonic analysis. The greatest 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 based method, our method suppresses the influence caused by frequency fluctuation excellently. No matter 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%, and under 1% for the most times.



(a) Comparison of relative error with noise level



(b) Comparison of relative error with frequency fluctuation

Fig.(4). The relative errors contrast of changing noise weight and fundamental frequency

5. CONCLUSION

In this paper, we introduce a novel sparse representation based measurement method for dielectric loss, which is proposed for the first time. Compared with wavelet transform based method, our method is much more accurate and very stability for the frequency fluctuation.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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