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Research on Evaluation Method of Transient Overvoltage Hazard Based on S-Transform

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Abstract. In field operation, the transformer with good insulation design and insulation condition may failure caused by transient over-voltage. The accumulation of transient overvoltage reduces the reliability of transformer internal insulation without signs. Therefore, it is necessary to assess the over-voltage hazards on the transformer. In order to evaluate the transient damage of transformers in operation, the transient overvoltage evaluation method based on S transform is proposed in this paper. Firstly, a method based on traditional Fourier transform is introduced. Secondly, the defects of traditional Fourier transform are analyzed. Finally, a transient overvoltage evaluation based on S transform is proposed to overcome the shortcomings of traditional Fourier transform method.

1. Introduction

Transformers are the most important equipment in the power station, whose damage could lead to serious consequences [1-4]. At present, there are many accidents occurred in the substation equipment, which contains a large number of unidentified insulation accident. In the analyzing, accumulation of transient overvoltage to transformer in substation leads to equipment insulation degradation, and then lead to sudden accidents [5,6]. At present, there are three methods of evaluating the insulation damage of transformers: Time Domain Waveform Conversion (TDWC), Time Domain Hazard Factor (TDSF), Frequency Domain Hazard Factor (FDSF, Frequency Domain Severity Factor) [7].

FDSF was proposed in 1988, but the FDSF method has not been widely used due to the lack of monitoring means and storage technology. This method is based on the traditional Fourier transform, but the traditional Fourier transform can not give the influence of transient overvoltage on insulation in different frequency bands due to the limitation of traditional Fourier transform in time-frequency analysis.

To solve above problems, this paper presents an evaluation method based on S-transform, which is used to evaluate the insulation damage of transformers.

2. Frequency Domain severity Factor(FDSF) based on Fourier Transform

In an attempt to systematically classify the severity of voltage transients on power transformers, Malewski et al. suggested that the analysis be performed in the frequency domain. The method was proposed in 1988, when the digital recording technique was still in its youth, and a limited number of transients could therefore be analyzed using this method.

The method uses a Fourier transform to compare the transient over-voltage and standard-voltage with spectrum. Compared with the signal analysis in the time domain, the waveform information at different frequencies can be highlighted in the frequency domain. The transient over-voltage whose amplitude is lower than the envelope of standard-voltage will not affect the insulation of the transformer. Otherwise, the transient over-voltages above the envelope will cause damage to the transformer insulation.

In figure 1, five standard test waveforms in frequency domain was given (lighting, operating and chopped lightning,).

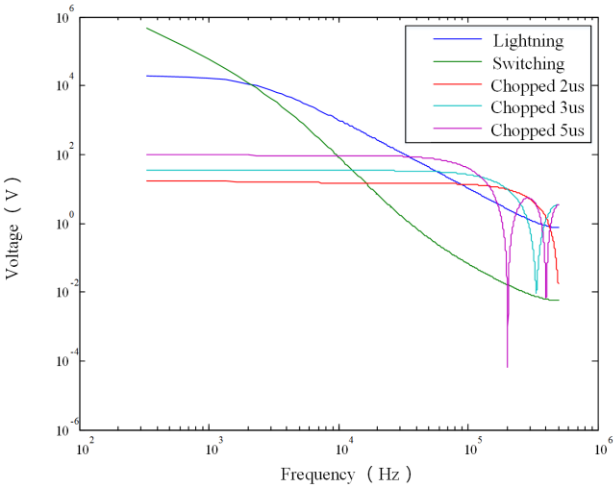


Fig. 1 Standard-voltage in frequency domain

Then a transient over-voltage was simulated with double exponential function, and the waveform was shown in figure 2.

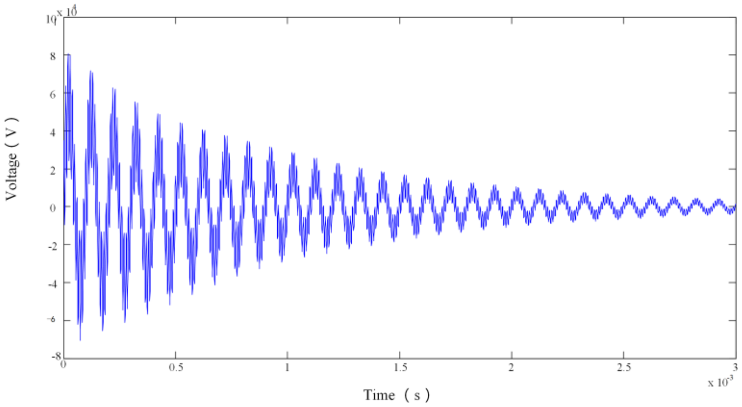


Fig. 2 Transient over-voltage in time domain

Thirdly, the transient over-voltage in frequency domain also could be acquired with F-transform. And in figure 3, the envelope of standard-voltage was compared with the simulation wave.

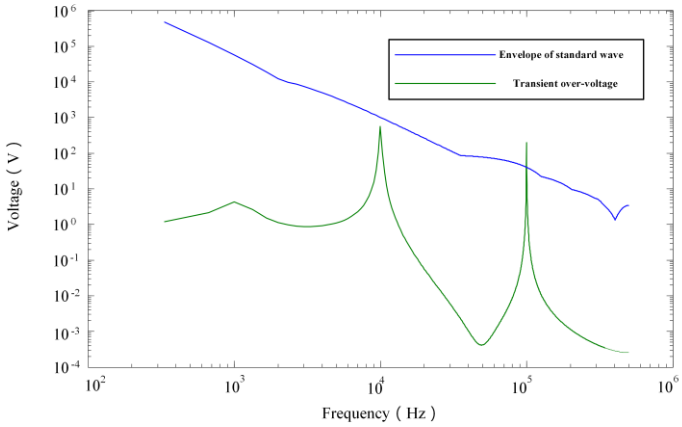


Fig.3 The waveform of transient over-voltage and envelope of standard-voltage in frequency domain

The curve in blue was the envelope of five standard-voltage after F-transform. The curve in green was the transient over-voltage in frequency. In figure 3, it was obviously that the amplitude of transient over-voltage is much higher than envelope of standard-voltage in the frequency around 0.1MHz.

In order to calculate the damage of transient over-voltage to insulation, the calculation method of frequency domain severity factor (FDSF)is defined.

$$FDSF\left(j\omega\right)=\frac{\left|X\left(j\omega\right)_{Transient}\right|^{2}}{\left|Xe\left(j\omega\right)\right|^{2}}. \quad (1)$$

According to the above formula the different FDSF value in different frequency was shown in figure 4. In figure 4 the signal around 0.1MHz was harmful to transform insulation.

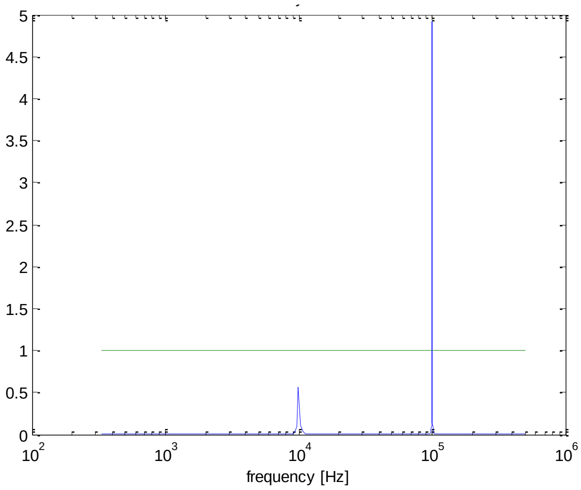


Fig.4 The different FDSF value in different frequency

3. The FDSF based on S Transform

3.1 Study on S transform. The Fourier transform can only get the characteristics of the signal in the frequency domain, but can not get the time points, duration and attenuation process of each frequency component. Transient over-voltage as a non-stationary signal, the Fourier transform can not get the information in the time domain. Therefore, in order to overcome this shortcoming, to improve the existing F-based FDSF method, the S-transform technique was studied.

S transform as a time-frequency analysis technique, can observe the signal energy distribution simultaneously from the time domain and frequency domain. 1996 Stockwell proposed the S-transform, the essence of S-transform is the development of continuous wavelet transform and short-time Fourier transform. S-transform is a reversible local time-frequency analysis method. The S-transform of signal $x\left(t\right)$ is $S\left(\tau, f\right)$. The definition is as following:

$$S(\tau, f)=\int_{-\infty}^{\infty}x(t)w(\tau-t, f)\exp(-2\pi ift)dt. \quad (2)$$

$$w(\tau-t, f)=\frac{|f|}{\sqrt{2\pi}}\exp\left[\frac{-f^{2}(\tau-t)^{2}}{2}\right]. \quad (3)$$

$w\left(\tau-t, f\right)$ is Gaussian Window， τ can control the Gaussian Window position in time axis.

From (2) and (3), it can be seen that the height and width of the Gaussian window in the S-transform change with the change of the frequency, which is also different from the short-time Fourier transform. The original signal $x\left(t\right)$ can be obtained by inverse S-transform with $S\left(\tau, f\right)$.

$$x(t)=\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\infty}S(\tau, f)\ d\tau\right]\exp(j2\pi ft)df. \quad (4)$$

S transform can be regarded as a phase correction of continuous wavelet transform, and its derivation process is based on continuous wavelet transform. The continuous wavelet transform of $x\left(t\right)$ can been definite as follow:

$$w(\tau,d)=\int_{-\infty}^{\infty}x(t)w(\tau-t,d)dt. \quad (5)$$

d -stretching parameter， τ -time shift parameter； $w(t-\tau,d)$ -shifted transform of parent wavelet. Select the transform kernel to multiply a complex vector with Gaussian window.

$$w(\tau, f)=\frac{|f|}{\sqrt{2\pi}}\exp\left[\frac{-f^2t^2}{2}\right]\exp(-j2\pi ft). \tag{6}$$

d is the reciprocal of frequency f. Then formula (6) is multiplied by phase correction factor, and the formula (2) can be converted into the formula (7).

$$S(\tau, f)=e^{i2\pi f\tau}w(\tau,d). \tag{7}$$

After inverse transformation $S(\tau, f)$ can be expressed as:

$$S(\tau, f)=\int_{-\infty}^{\infty}X(\nu+f)\exp(-\frac{2\pi^2\nu^2}{f^2})dt\exp(j2\pi\nu t)d\nu. \tag{8}$$

A discrete representation of the S transform can be obtained by formula (8).

$$S[m,n]=\sum_{k=0}^{N-1}X[n+k]e^{-2\pi^2k^2/n^2}\bullet e^{j2\pi km/N}\ (n\neq 0). \tag{9}$$

$$S[m,n]=\frac{1}{N}\sum_{k=0}^{N-1}x[k]\ (n=0). \tag{10}$$

$$X[n]=\frac{1}{N}\sum_{k=0}^{N-1}x[k]e^{-j2\pi km/N}. \tag{11}$$

So the discrete signal points $x[i], i=0,1,\cdots,N-1$ are calculate with S-transform. And the transformation result is presented by a two-dimensional matrix. The column vector of the matrix corresponds to the sampling time point. The row vector corresponds to the frequency value, and the matrix elements correspond to the amplitude.

2.2 Comparison between S-Transform and F-Transform. Figure 5 is the non-standard lightning waveforms for attenuation oscillations.

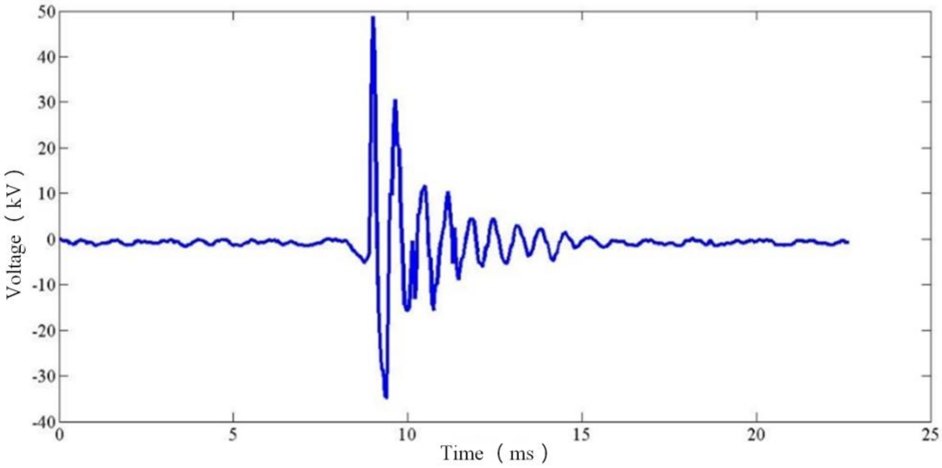


Fig. 5 Transient over-voltage

Firstly, the transient over-voltage signal in frequency domain can obtained from F-transform. the distribution of signal in frequency was shown in Figure 6.

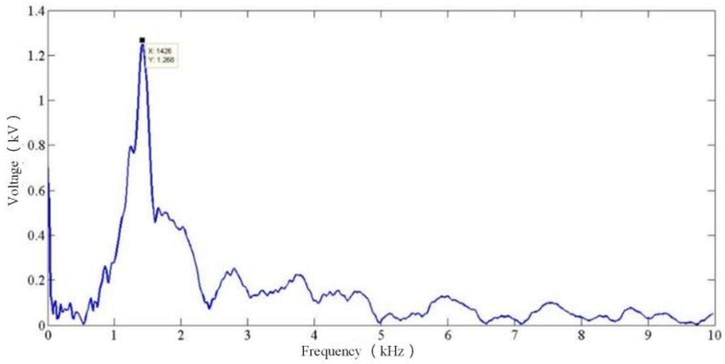


Fig. 6 Spectrum of transient over-voltage

From Figure 6, it can be seen that the oscillation frequency of the oscillation waveform is in the range of 1 kHz to 2 kHz. At the same time, it can be seen that the F-transform could effectively distinguish the distribution of the frequency components, but it could not get the time information.Then analyze the original signal with S-transform. And the energy distribution could see in figure 7.

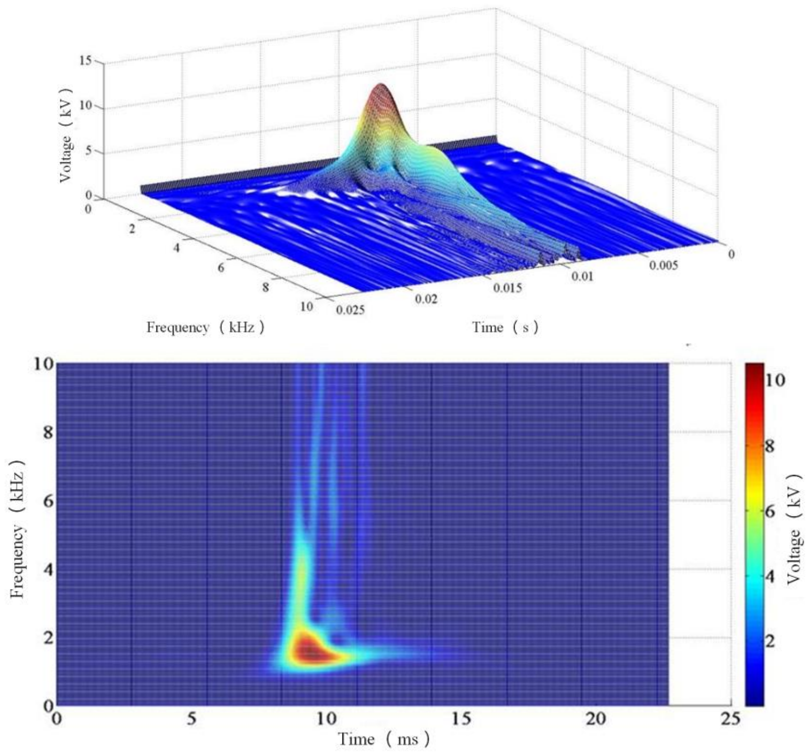


Fig. 7 The energy distribution in time and frequency domain

It can be seen from Figure 6 that the component in the frequency range of 1kHz ~ 2kHz is slow and the voltage amplitude is high. Which is same with the F-transform. At the same time, it can be seen from Figure 6, the main frequency component decay time is about 2.5ms, this result is close to the original signal. It is shown that the S-transform technique is superior to the F-transform. And the FDSF is considered to improve by S-transform technique.

2.3 Research on Improved FDSF Method. Compare the transient over-voltage calculated with invasion wave to the standard lightning waveforms. According to the simulation results of the transformer winding voltage, the maximum voltage between disks of intrusion wave is 0.6 times of the inlet voltage, and the average value is 0.3 times of the inlet voltage. Strictly considering, compare the maximum voltage difference between disks of intrusion wave(180kV multiplied by 0.6) with the average value of the voltage difference between disks of the standard lightning waves(1050kV multiplied by 0.3), The time domain waveform is shown in Figure 8.

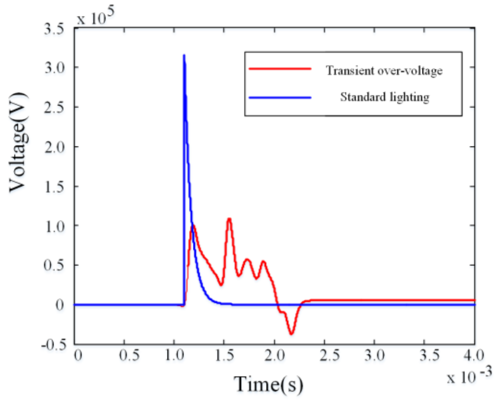


Fig. 8 Transient over-voltage and standard lighting in time domain

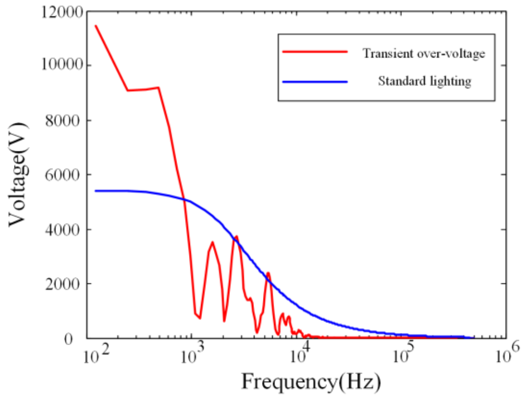


Fig. 9 Transient over-voltage and standard lighting in frequency domain

Make the above two waveforms Fourier transform and the results are shown in Figure 9. Through the Fourier transform, it can be found that there is a case where the intrusion wave exceeds the standard lightning wave in the range of 1 kHz to 10 kHz, but it is not obvious.

Similarly, make the above two waveforms S-transform. Figure 10 shows the time-frequency diagram of the intrusion wave after S-transform. Figure 11 shows the time-frequency diagram of the standard lightning wave after S-transform.

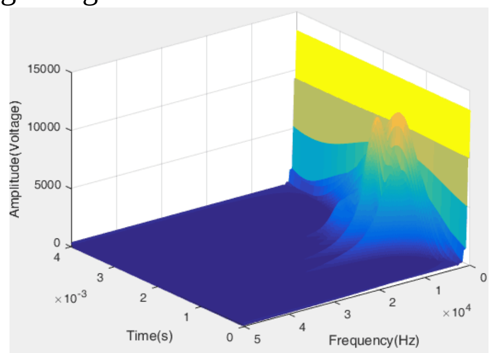


Fig. 10 Transient over-voltage after S-transform

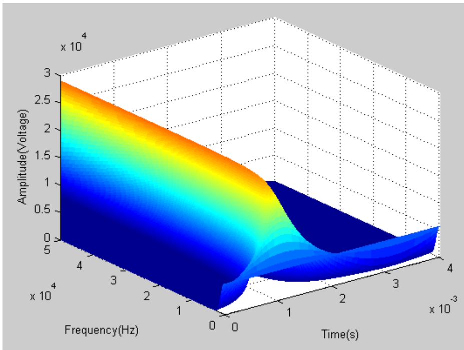
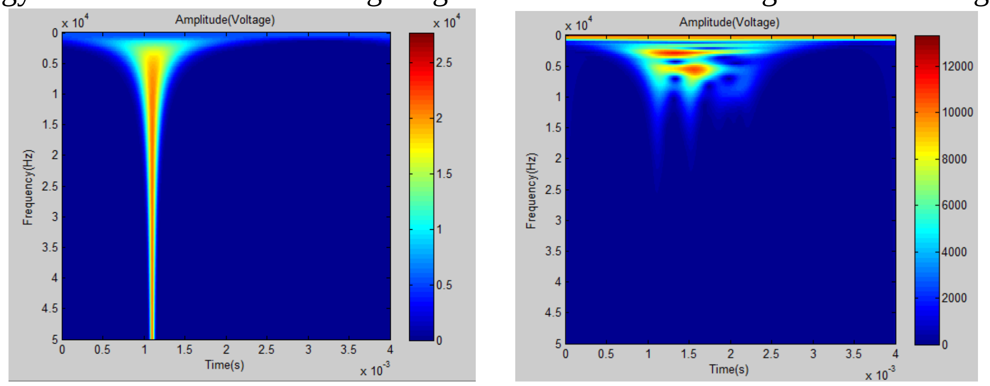


Fig. 11 Standard lighting after S-transform

The energy distribution of standard lighting and transient over-voltage is shown in figure 12。



(a) Standard lighting (b) Transient over-voltage

Fig. 12 The energy distribution of standard lighting and transient over-voltage

As can be seen from Figure 12, the amplitude of the frequency component used by the intrusion waves amplitude at 1.1 milliseconds is less than that of the standard lightning wave. However, from 1.1 milliseconds to about 2.5 milliseconds, it can be clearly seen that the amplitude of the intrusion wave is significantly beyond the standard lightning amplitude in the range of 1kHz to 10kHz.

In order to more clearly see the hazards of intrusion waves, make the two plants in figure 4-16 subtract, the value less than the standard lightning is expressed as 0, as shown in Figure 13.

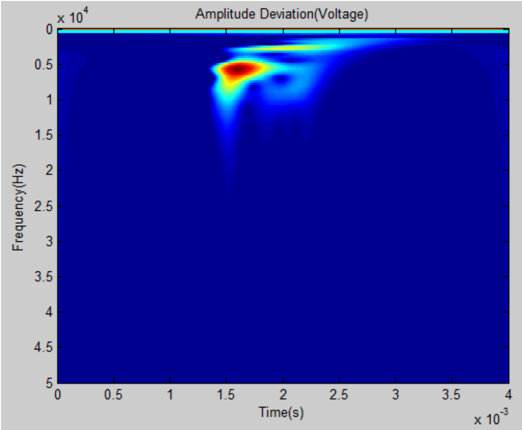


Fig. 13 The hazard of transient over-voltage in time and frequency domain

As can be seen from Figure 13, the amplitude of the intrusion wave in the range of 1kHz to 10kHz will significantly exceed the standard lightning wave, and the duration is about 1 millisecond, which will undoubtedly affect the transformer insulation.

The above results show that compared with the F-based FDSF method, the improved method can show the duration during which the intrusion wave beyond the standard line at different frequencies. Therefore, the improved method can assess the hazards of intrusion waves considering the frequency domain and time domain.

Summary

In this paper, a method to evaluate the insulation damage of power transformer based on the S-transform technique is proposed. The method can analyze the influence of transient overvoltage on the transformer insulation based on the over-voltage transient monitoring waveform. It can be effectively used in condition evaluation, fault prevention and life estimation of power transformer in operation.

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