TIME-FREQUENCY ANALYSIS OF NON-STATIONARY SIGNALS IN POWER SYSTEMS

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INTRODUCTION

Representation of signals in time and frequency domain has been of interest in signal processing areas for many years, especially taking in the limelight time-varying non-stationary signals. The standard method for study time-varying signals is short-time Fourier transform (STFT) that is based on the assumption that for short-time basis signal can be considered as stationary. The spectrogram utilizes a short-time window whose length is chosen so that at least 2 times the length of the window signal is stationary. Then, the Fourier transform of this windowed signal is calculated to obtain the energy distribution along the frequency direction at the time corresponding to the center of the window. The crucial drawback of this method is that the length of the window is related to the frequency resolution. Increasing the window length leads to improving frequency resolution but it means that the nonstationarities occurring during this interval will be smeared in time and frequency. This inherent relationship between time and frequency resolution becomes more important when one is dealing with signals whose frequency content is changing rapidly, Baraniuk (1), Choi and Williams (2).

A time-frequency characterization of signals that would overcome above drawback became a major goal for signal processing areas. Starting with classical works of Gabor, Ville and Page, there has been an alternative development for study of time-varying spectra. The concept of the Wigner distribution was introduced in the context of quantum mechanics, although reintroduced by Ville for signal analysis. In eighties Claasen and Mecklenbräuker, Janse and Kaizer, Boashash, Rihaczek, Mecklenbrauker, Janse and Kaizer developed ideas uniquely situated to the time-frequency situation and demonstrated useful methods for implementation. Their works beard fruit derivations of few time-frequency distributions, Claasen and Mecklenbräuker (3,4), Cohen (5), Hahn (6).

Cohen employed characteristic function and operator theory to derive a general class of joint time-frequency representation. It can be shown that many bilinear representations can be written in one general form that is traditionally named Cohen's class, (5).

What is the motivation for devising a joint time-frequency distribution? Having such distribution it can be found what fraction of energy is in a certain frequency and time range, it can be calculated the distribution of frequency at particular time, the global and local moments of the distribution such as the mean frequency and its local spread. The fundamental goal is to devise a joint function of time and frequency, which represents the energy or intensity per unit time and per unit frequency. Such joint distribution $P(t,\omega)$ means intensity at time $t$ and frequency $\omega$ or $P(t,\omega)\Delta t\Delta \omega$ means fractional energy in time-frequency cell $\Delta t\Delta \omega$ at $t,\omega$. For deterministic signals where no probabilistic consideration enter, the distribution can be treated as intensities or densities which shows how the energy is distributed in the time-frequency cells.

The summing up of the energy distribution for all frequencies at particular time would give the instantaneous energy, and the summing up over all times at particular frequency would give the energy density spectrum (5):

$$\int P(t,\omega)\Delta \omega = |s(t)|^2$$ (1)

$$\int P(t,\omega)\Delta t = |S(\omega)|^2$$ (2)

Observing the recent approaches to the time-frequency representations we can separate two main groups in point of the estimation manner as non-parametric and parametric methods. Further, due to different structure of definition equation the non-parametric methods can be parted into groups, which carry out the linear or non-linear operation on the signal. At least if there is a need to scale the time or frequency argument we treat the representations as a scalogram or spectrogram respectively, (6), Quian and Chen (9), Zielinski (10).

Nowadays an issue of energy quality is strongly outlined in point of power utilities, electric energy consumers or manufactures of electric and electronics engineering.

The estimation of parameters of transient components is very important for design of protection and control instruments. Transients resulting from the switching capacitor banks in electrical distribution systems affect power quality. The analysis of fault mode behaviour can be utilised for development of monitoring and diagnostic systems. In this paper we present some results of simulation investigations of a converter-fed induction motor drive. Pulse-width modulation (PWM) converters supplying asynchronous motor were simulated. Detection of irregular frequencies may be useful for diagnosis of some drive faults, Leonowicz and Lobos (7), Lobos et al (8). The transient waveforms have been investigated using two members of Cohen class: Wigner-Ville Distribution (WVD) and Choi-Williams Distribution (CWD).
TABLE 1. Some transformation and their kernels (1,2,5,6,9)

<table>
<thead>
<tr>
<th>Name</th>
<th>Kernel $\Phi(\theta, \tau)$</th>
<th>Distribution $P(t, \omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wigner (WD)</td>
<td>$I$</td>
<td>$\int \frac{S(t + \frac{\tau}{2}) S^*(t - \frac{\tau}{2}) e^{j\omega \tau} d\tau}{\sqrt{2\pi}}$</td>
</tr>
<tr>
<td>Wigner-Ville (WVD)</td>
<td>$I$</td>
<td>$\int \frac{S(t + \frac{\tau}{2}) S^*(t - \frac{\tau}{2}) e^{j\omega \tau} d\tau}{\sqrt{2\pi}}$, where $S(t)$ is analytic signal, obtained as a Hilbert transform on signal $s(t)$</td>
</tr>
<tr>
<td>Choi and Williams (CWD)</td>
<td>$e^{-\frac{\tau^2}{\sigma^2}}$</td>
<td>$\frac{1}{\sqrt{4\pi}} \int s(u + \frac{\tau}{2}) \hat{s}(u + \tau) e^{-j\omega \tau} d\tau$</td>
</tr>
<tr>
<td>Spectrogram with window $h(t)$ (STFT)</td>
<td>$\int h(t) \hat{h}(t - \tau) e^{j\omega \tau} d\tau$</td>
<td>$\frac{1}{\sqrt{2\pi}} \int s(t) \hat{h}(t - \tau) e^{j\omega \tau} d\tau$</td>
</tr>
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</table>

COHEN CLASS OF TRANSFORMATION

Investigations

Utilizing symmetric ambiguity function of the signal $s(t)$ Cohen defined a general class of bilinear time-frequency transformation by (1,5):

$$P(\omega, \tau) = \frac{1}{2\pi} \int A(\theta, \tau) \Phi(\theta, \tau) e^{j\omega \theta} d\theta d\tau$$ (3)

where the symmetric ambiguity function of signal $s(t)$ can be defined as:

$$A(\theta, \tau) = \int s(t + \frac{\tau}{2}) \hat{s}(t - \frac{\tau}{2}) e^{j\theta \tau} d\tau$$ (4)

and it is named auto ambiguity function (9).

The Cohen’s transformation could be interpreted as two-dimensional Fourier transformation of the product $A(\theta, \tau) \Phi(\theta, \tau)$ in respect to the shift variables ($\theta, \tau$), frequency and time respectively. Function $\Phi(\theta, \tau)$ is called the kernel and it is strictly connected with desirable distribution. By choosing different kernels, different distributions are obtained which properties are completely determined by its kernel function.

The ambiguity function $A(\theta, \tau)$ is a bilinear function of the signal therefore it indicates intensity in regions where zero-values are expected. These undesirable components, sometimes called artefacts or cross-terms, are usually attributed to the bilinear nature of the distribution and reduce auto-components resolution, obscure the true signal features and make interpretation of the distribution difficult. The significance of Cohen’s work is to reduce the problem of the design of time-dependent spectrum to the selection of the kernel function $\Phi(\theta, \tau)$, with respect to preservation of all useful properties of the distribution, but also to reduction of cross-term interferences. It inspired to search for a kernel function $\Phi(\theta, \tau)$ such that the product $A(\theta, \tau) \Phi(\theta, \tau)$ is enhanced in the vicinity of origin and suppressed everywhere else. To obtain mentioned goal Choi and Williams introduced the exponential kernel, where $\sigma(\sigma > 0)$ is a scaling factor and controls the decay speed of suppressing the cross-terms. The smaller the $\sigma$ is the more the cross-terms are suppressed. On the other hand, such smoothing brings some influence on auto-terms. Table 1 shows some examples of connections between few distributions and their kernels.

Switching on the capacitor banks

Transients resulting from the switching on the capacitor banks in simulated electrical distribution were investigated. The first capacitor bank (900kVar) installed 0.2km from the station (110/15kV, 25MVA) was switched on at time 0.03s and the second one (1200kVar) installed 1.2km from the station was switched on at time 0.09s. Current signal measured at the beginning of the feeder was illustrated in Fig. 1. When the Wigner-Ville Distribution was applied the basic component 50Hz and transient components 475Hz and 270Hz, appearing after switching operations, were detected (Fig. 2). Interactions between mentioned auto-terms brought undesirable cross-term components (160, 265, 375Hz). In unfavorable cases cross-term components can even cover the auto-terms as was happened with auto-term 270Hz and cross-term 265Hz. When Choi-Williams Distribution with factor $\sigma = 0.05$ was applied suppression effect of the cross-terms can be observed (Fig. 3). On the other hand, such smoothing brings some influence on auto-terms. For comparison cross-section of time-frequency plane for $t=0.04s$ was shown in Figures 4 and 5.

Fig. 1. Current waveform at the beginning of the feeder during subsequent switching of two capacitor banks
Fault operation of the inverter drive

This paper shows also investigation results for a 3kVA-PWM-converter with a carrier frequency of 1kHz supplying a 2-pole, 1kW asynchronous motor (supply voltage 220V, nominal power 1.1kW, slip 6%, cos=0.81). Characteristic RC-damping components at the rectifier bridge and at the converter valves were considered. To design the intermediate circuit, the L, C values of a typical 3kVA converter were chosen. Fault operation of the inverter drive was considered as short-circuit between two phases with fault resistance 100Ω, which occurs at the time 0.1s (Fig. 6).

The results obtained when using WVD are following. Before and after the fault, the basic component (60Hz) and the carrier component (1000Hz) can be seen. Additionally, a cross-term interference component (590Hz) appears. Due to 5kHz sampling frequency, only components up to 1250Hz can be considered. Evident fluctuating cross-term at 960Hz can be interpreted as interference between higher additional contribution about 1880Hz and basic component. After the fault two modulation components (880Hz and 1120Hz) appeared which brought another cross-term components (1060Hz, 940Hz, 530Hz, 470Hz) (Figs 7,9). Suppression of undesirable cross-term components can be observed when Choi-Williams Distribution with $\sigma=0.05$ was applied (Figs 8,10). Unfortunately such kernel decreases time resolution hence the beginning of the auto-terms after the fault are smeared.

CONCLUSIONS

The article considers the ideas of applying Cohen's approach to joint time-frequency analysis of non-stationary signals in power systems. Such analysis offers possibility to track the frequency and amplitude changes of non-stationary signals.
The effect of analysis strongly depends on kernel function. Designed kernel should preserve time-frequency resolution and suppress undesirable cross-terms, which occurred because of bilinear nature of algorithm.

As was shown transients resulting from switching the capacitor banks or fault operation of the frequency converters generate a wide spectrum of harmonics and irregular components, which affect power quality. Discussed approach can be used to identify transient events in power systems, which even consists the interharmonics. Matching the kernel function with different class of signals gives the idea for real-time improvement of time-frequency analysis.

References


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