

基于线调频小波变换的谐波快速可视化识别方法

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摘要: 线调频小波变换是傅里叶变换、短时傅里叶变换和小波变换的一般形式。在介绍高斯线调频小波变换算法的基础上,提出用线调频小波变换可视化地检测和识别出谐波的特性,即根据对电能质量谐波扰动信号的线调频小波变换矩阵的等高线图,可视化地区分出谐波是固定不变、线性时变或非线性时变,先识别谐波的大致类型,为选取合适的信号分析工具提供保证。仿真结果表明,线调频小波变换的等高线图可以很好地检测出电能质量信号扰动发生的时刻和持续时间。

关键词: 电能质量;谐波;线调频小波变换;可视化;扰动信号

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0 引言

随着各种复杂、精密、且对电能质量敏感的用电设备不断普及,人们对电能质量的要求越来越高,因此电能质量成为目前研究的热点^[1-18]。在电力系统发展的早期,电力负荷的组成比较简单,主要由同步电动机、异步电动机和各种照明设备等线性负荷组成,因此衡量电能质量的指标比较简单,主要有频率偏移和电压偏移 2 种。20 世纪 80 年代以来,随着电

力电子技术的发展,非线性电力电子器件和装置在现代工业中得到了广泛的应用,同时,为了解决电力系统自身发展存在的问题,直流输电和 FACTS、DFACTS 技术不断投入实际工程应用,调速电机以及无功功率补偿电容器也大量投入运营。这些设备的运行使得电网中电压和电流波形畸变越来越严重,谐波水平不断上升。另外,冲击性、波动性负荷,例如电弧炉、大型轧钢机、电力机车等,运行中不仅会产生电压波动、闪变、三相不平衡电能质量问题,而且还会产生大量的高次谐波。谐波是影响电能质量的关键因素之一。

电能质量扰动和短时谐波干扰持续时间短,发生时间具有很大的随机性,因此人们一直在研究新

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Comparison of UPFC performance between cross coupling and decoupling controls

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Abstract: Cross coupling and decoupling controls are two main UPFC(Unified Power Flow Controller) control schemes, which have same inner control loop and different outer control loop. Taking power flow as the control object, the cross coupling control is ascribing to the direct control scheme, which is simple and easy to be implemented. Taking line current as the control object, the cross decoupling control is ascribing to the indirect control scheme, which combines PI controller with current feedback loop and has the ability of fast power regulation. The cross coupling control is independent of the current feedback and uses PI controller alone to adjust the power flow, so it has better robustness. The cross decoupling control decouples completely using current feedback, which quickly restricts the concussion current under 3-phase unbalanced condition caused by single-phase grounding fault. The performance of cross coupling and decoupling controls are validated with simulations and experiments. Two methods are proposed to improve the robustness of cross decoupling control: the intelligent PI controller and the online identification of line parameters.

Key words: unified power flow controller; cross coupling; cross decoupling; capability comparison

的、有效的信号分析方法,提出了各种各样的分析工具和研究方法。例如模式识别方法^[1-3]、S 变换方法^[4-5]、模糊系统^[6-7]、小波变换与小波包方法^[8-10]、Hilbert-Huang 变换(HHT)^[11]、数学形态学方法^[12-13]、瞬时无功率理论^[14]和混合方法^[3-4,13,15-16]等。上述各类方法存在一个明显的不足,即在进行谐波分析和识别时,对谐波的类型、性质几乎不清楚,因而缺乏针对性,影响了分析和识别的效果。如对含有固定不变谐波的电能质量信号,用小波变换的效果较好,但对时变(线性、非线性)谐波分析,模式识别方法、模糊系统、小波变换、HHT 变换、数学形态学方法、规则集方法就不适应。需要寻找新的信号分析工具解决这个问题。

针对上述情况,提出了一种新的信号处理方法——线调频小波变换 CT(Chirplet Transform)^[17,19-21]预处理电能质量的谐波分析和识别问题。线调频小波变换可以分析具有固定不变带宽和非固定比例的非平稳信号,傅里叶(Fourier)变换、短时 Fourier 变换和小波变换是它的特殊情形,与小波变换相比,具有更为灵活的时频窗口^[19-20]。对含谐波电能质量信号的线调频小波变换矩阵生成等高线进行分析,可视化地检测和识别出谐波种类(固定谐波、线性时变谐波和非线性时变谐波)以及电能质量扰动(谐波)发生位置和持续时间,为进一步识别谐波提供了很好的前提条件。

1 高斯线调频小波变换算法

具有单位能量的高斯线调频小波包^[19-21]:

$$g(t) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{t-b}{\sigma}\right)^2\right] \times \exp[j(\omega t + qt^2)] \quad (1)$$

高斯线调频小波是一种非正交、冗余小波。其中, q 为线调频系数, ω 为调制圆频率($\omega = 2\pi f$, f 为频率), 而 $\sigma > 0$ 控制高斯波形的宽窄, 即尺度参数。图 1 为线调频小波变换的核函数及频谱图(图中, U 为电压幅值, n 为采样点数, f 为频率; 后同)。

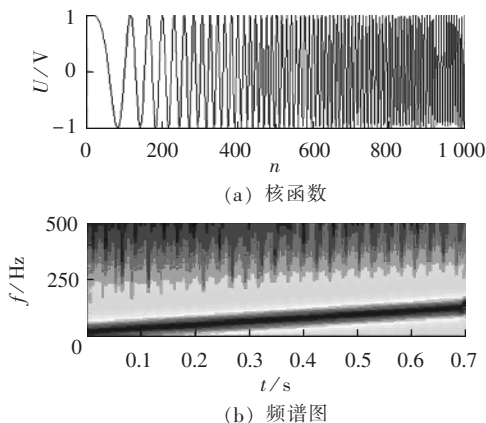


图 1 线调频小波变换核函数及其频谱图

Fig.1 The kernel function of Chirplet transform and its spectrum

定义线调频小波变换如下^[21]:

$$CT(T, b) = \int_{-\infty}^{+\infty} f(t) \frac{1}{\sqrt{2\pi}T} \exp\left[-\frac{1}{2}\left(\frac{b-t}{T}\right)^2\right] \times \exp[-j(\omega t + qt^2)] dt \quad (2)$$

$$\text{并定义 } CT(\infty, b) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-T/2}^{+T/2} f(t) dt.$$

记 $h(t) = f(t) \exp(-jq t^2)$, 时间序列 $h(pT)$ ($p = 0, 1, \dots, N-1$) 的离散 Fourier 变换为

$$H\left(\frac{n}{NT}\right) = \frac{1}{N} \sum_{p=0}^{N-1} h(pT) \exp\left(-\frac{j2\pi np}{N}\right) \quad (3)$$

其中 $n = 0, 1, \dots, N-1$ 。

逆离散 Fourier 变换为

$$h(pT) = \sum_{n=0}^{N-1} H\left(\frac{n}{NT}\right) \exp\left(\frac{j2\pi np}{N}\right) \quad (4)$$

离散时间序列 $h(pT)$ 的线调频小波变换为

$$CT\left(\frac{n}{NT}, iT\right) = \sum_{m=0}^{N-1} F\left(\frac{n-m}{NT}\right) \times \exp\left(-\frac{\pi^2 m^2}{2N^2}\right) \exp\left(\frac{-j2\pi ni}{N}\right) \quad (5)$$

且对于 $n = 0$, $CT(0, iT) = \frac{1}{N} \sum_{m=0}^{N-1} H\left(\frac{m}{NT}\right)$ 。其中, i, m 和 n 取 $0, 1, \dots, N-1$ 。

由上可知, 线调频小波变换的计算利用了卷积运算和快速 Fourier 变换 FFT, 计算速度快。变换的结果是 $n \times m$ 矩阵, 每一列代表以该时间点为起点、长度为 NT 的信号的短时(或加窗)FFT 频谱。

2 谐波特性分析与识别

下面运用所提方法分别对谐波失真信号、线性时变谐波失真信号、非线性时变谐波失真信号的谐波类型、成分进行分析和识别。

2.1 频率分段时变谐波信号

设时变谐波模拟信号为

$$s(t) = \begin{cases} \sin(2\pi \times 50t) & 0 \leq t \leq 0.10 \text{ s} \\ 2 \sin(2\pi \times 50t) + 1.6 \sin(2\pi \times 150t) + \\ 1.2 \sin(2\pi \times 350t) & 0.10 \text{ s} < t \leq 0.20 \text{ s} \\ \sin(2\pi \times 50t) + 0.8 \sin(2\pi \times 150t) + \\ 0.6 \sin(2\pi \times 350t) & 0.20 \text{ s} < t \leq 0.30 \text{ s} \end{cases}$$

图 2 为其波形和其线调频等高线图, 等高线纵坐标实则为与频率有关的采样点数, 与横坐标一样用 n 表示。

从图 2 可以看出 3 点:

- 模拟时变谐波信号含有 2 个干扰谐波;
- 3 次谐波和 7 次谐波发生 2 次的时刻和持续时间与实际情况相符;
- 模拟时变谐波信号中 3 次谐波在 $0.1 \sim 0.2 \text{ s}$ 的扰动幅值为 1.6, 大于其在 $0.2 \sim 0.3 \text{ s}$ 的扰动幅值 0.8, 7 次谐波在 $0.1 \sim 0.2 \text{ s}$ 的扰动幅值为 1.2, 大于其在 $0.2 \sim 0.3 \text{ s}$ 的扰动幅值 0.6, 这些特性可从等高线图 2(b) 中清楚地看出。

2.2 线性时变谐波信号

设线性时变谐波信号模拟表达式为

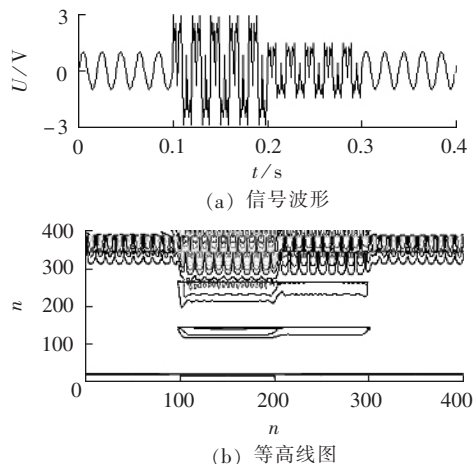


图2 分段固定时变谐波信号及其线调频小波变换矩阵等高线图

Fig.2 A time-varying ladder harmonic signal and its Chirplet transform matrix contour figure

$$s(t) = \begin{cases} \sin(2\pi \times 50t) & 0 \leq t \leq 0.06 \text{ s} \\ \sin[2\pi \times (50 + 0.5t)t] & 0.06 \text{ s} < t \leq 0.14 \text{ s} \\ \sin(2\pi \times 50t) & 0.14 \text{ s} < t \leq 0.2 \text{ s} \end{cases}$$

该信号在 0.06~0.14 s 的信号分量为线性调频信号,瞬时频率 $f=50+0.5t$ 依时间线性变化。图 3 为其波形和等高线图,可明显识别出频率线性变化情况。谐波扰动发生的时间和终止时刻与实际相符。

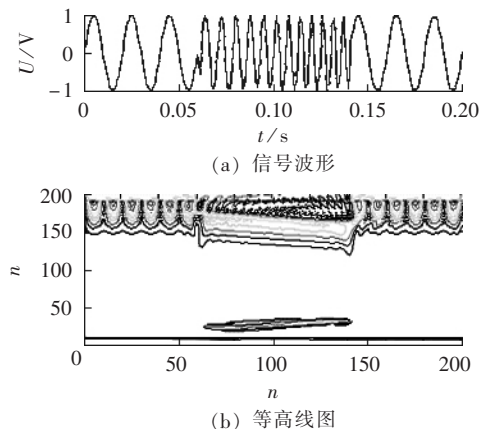


图3 频率线性时变的谐波信号及其线调频小波变换矩阵等高线图

Fig.3 A frequency linear time-varying harmonic signal and its Chirplet transform matrix contour figure

2.3 非线性时变谐波信号

设非线性时变谐波信号为

$$s(t) = \begin{cases} \sin(2\pi \times 50t) & 0 \leq t \leq 0.06 \text{ s} \\ \sin[2\pi \times (50 + 0.5t + 0.1t^2)t] & 0.06 \text{ s} < t \leq 0.14 \text{ s} \\ \sin(2\pi \times 50t) & 0.14 \text{ s} < t \leq 0.2 \text{ s} \end{cases}$$

该信号的瞬时频率 $f=50+0.5t+0.1t^2$ 。图 4 为其波形及线调频小波变换矩阵等高线,从图中可识别出非线性时变谐波的变化情况。

从以上分析可知,根据含谐波干扰电能质量信号的线调频小波变换等高线图可先识别谐波的大致类型。这为选择合适分析工具,进一步分析和识别

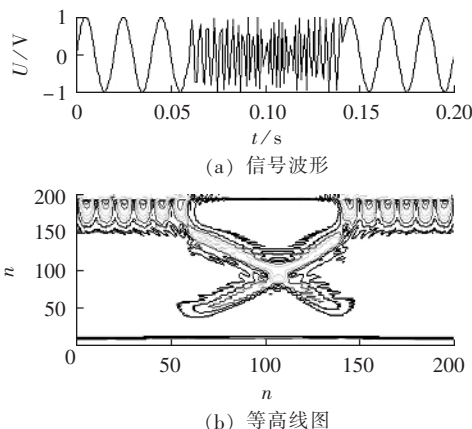


图4 频率非线性时变的谐波信号及其线调频小波变换矩阵等高线图

Fig.4 A frequency nonlinear time-varying harmonic signal and its Chirplet transform matrix contour figure

电能质量谐波扰动提供很好的帮助。对谐波固定的电能质量信号用小波变换、HHT 等方法解决较好,对线性时变和非线性时变的谐波分析,用小波变换的方法得到有意义的结论。对线性时变谐波可采用诸如小波脊线方法^[18],而对非线性时变的谐波分析,要考虑用其他数学工具做进一步分析。

3 结论

电能质量的好坏直接影响社会生产、生活的各个方面,提供和维护高品质的电力能源是全社会共同追求的目标。用傅里叶变换、短时傅里叶变换和小波变换的一般形式——线调频小波变换可视化地检测和识别出谐波的特性,即根据对电能质量谐波扰动信号的线调频小波变换矩阵的等高线图,清楚地区分出谐波分量是固定不变、线性时变和非线性时变,为选取合适的信号分析工具提供了便利,避免了盲目性。

仿真实验表明,线调频小波变换等高线图可较好地检测出电能质量信号扰动发生的时刻和持续时间。

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Rapid and visual harmonic identification based on Chirplet transform

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Abstract: Chirplet transform is the general form of Fourier transform, short-time Fourier transform and Wavelet transform. The algorithm of Chirplet transform is introduced and used to detect and identify harmonics. Harmonics can be visually classified to non-variable, linear time-varying and non-linear time-varying according to Chirplet transform matrix contour figures of power quality harmonic signals, based on which an appropriate signal analysis tool is thus selected. Simulation results show that, the Chirplet transform matrix contour figures can effectively detect the beginning time and duration of power quality signal disturbance.

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Key words: power quality; harmonic; Chirplet transform; visualization; disturbance signal