Fourth International Conference on Natural Computation

Design of Power System Harmonic Measurement System Based on LabVIEW

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Abstract

Harmonic measurement plays an important part in power systems. In this paper, a brief introduction on sources and harms of harmonics is given. A harmonic measurement method based on interpolating windowed FFT is proposed and analyzed. According to the analytic results, a multifunctional virtual instrument system for harmonic measurement of voltage and current signals is designed and implemented in LabVIEW environment. Furthermore, the function of remote transfer of measured results is implemented using the AppletVIEW Toolkit in LabVIEW adopting a B/S framework. Measurement results show the feasibility and validity of the system.

1. Introduction

Rapid growth in the industrial and civil electrical power load and the applications of various electrical and electronic equipment have been witnessed during the last years. With the surge of the total number and capacity of the nonlinear components, the electrical harmonic pollution is becoming more and more serious a problem, and has been a great threat to the safety of electric power systems and the national economy as a whole. Treatment of harmonics in power systems is thus a major concern of power system administrators as well as engineers [1]. In this task, the measurement of harmonics in power networks, as the basic data provider for harmonic analysis and control, is one of the issues of fundamental importance.

Traditional methods of measuring power system harmonics employ power harmonic analyzers or software packages such as Matlab. However, these methods usually do not have powerful graphical programming capabilities and network functions for remote monitoring and control [2]. This paper presents a novel approach using a virtual instrument (VI) system with data transfer ability to perform power system harmonic measurement based on the interpolating windowed fast Fourier transform (FFT). The virtual instrument system is designed and implemented in LabVIEW environment. Harmonic parameters of three-phase voltage and current signals, such as the total harmonic distortion (THD) and the distortions of the 1^{st} to the 13^{th} harmonics can be measured. A B/S network scheme is adopted for data transfer, which is implemented using the AppletVIEW toolkit in LabVIEW. This data transfer option enables remote monitoring via the Internet Explorer. Experimental measurement results show accurate and stable measurement performance of the system.

The paper is organized as follows. Section Ⅱ describes the sources and effects of power system harmonics. Section Ⅲ presents the harmonic analysis method with interpolating windowed FFT. Section Ⅳ gives the design of our harmonic measurement system using LabVIEW. In Section Ⅴ, the method of remote data transfer is provided. Conclusions are given in Section Ⅵ.

2. Sources and Effects of Power System Harmonics

In ideal situation, the electric power in a network is supplied at a constant system frequency, known as the fundamental frequency, and at specified voltage magnitudes. In a realistic power system, however, the frequency and voltages are deviated from their designated values. The deviation of a wave form from its perfect sinusoid is generally expressed in terms of harmonics. Harmonics in a power system deteriorate the quality of electric energy and can result in communication interference, transformer overheating, or the malfunction of control devices, and so on [3, 4].

There are two general categories of harmonic sources: saturable devices and power electronic devices [5]. Saturable devices produce harmonics due mainly to iron saturation, as is the case for transformers, rotating machines, and fluorescent lightings (with magnetic ballasts). Power electronic

978-0-7695-3304-9/08 $25.00 © 2008 IEEE
DOI 10.1109/ICNC.2008.230

loads draw power only during portions of the applied voltage waveform. Thus, the current drawn by the load is no longer sinusoidal and appears chopped or flattened. The non-sinusoidal current can interact with system impedance to give rise to voltage distortion and, in some cases, resonance. These power electronic loads include switch-mode power supplies, fluorescent lightings (with electronic ballasts), voltage source converters and equipments with non-linear components. Today, harmonics induced by non-linear power electronic loads present inefficient operations of local and global power supply systems.

Harmonics have a number of effects on power system components and loads. Power system problems such as communication interference, heating, and solid-state device malfunctions can be the direct result of harmonics [2]. These problems are categorized and listed below.

a) communication interference;
b) excessive losses and heating in motors, capacitors, and transformers;
c) degraded meter accuracy;
d) blown capacitor fuses and failed capacitor;
e) solid-state device malfunctions.

3. Harmonic Analysis Method Using Interpolating Windowed FFT

The discrete Fourier Transform (DFT) is a popular method in the harmonic analysis of electric power system. The amplitude, frequency, and phase of each spectral component can be evaluated by the fast Fourier transform (FFT). When the sampling frequency is two times greater than the highest constituent frequency, and the sampling period is an integer multiple of the signal period, the harmonic components can be determined by the FFT with high accuracy, efficiency and simplicity.

The power system voltage and current can be expressed as

$$x(t) = \sum_{i=0}^{\infty} A_i \cos(2\pi f_i t + \varphi_i) \quad (1)$$

Where f_i , A_i , φ_i are the frequency, amplitude, and phase of the *i*-th harmonic component, respectively.

Considering a signal *x(t)* sampled with a sampling period *Ts*, we have the following sequence *x(n)*.

$$x(n) = x(nT_s) = \sum_{i=0}^{\infty} A_i \cos(n\omega_i + \varphi_i) \quad (2)$$

where $\omega_i = 2\pi f_i T_s$

The DFT, or the discrete spectrum of the signal, is thus as follows:

$$X(e^{j\omega}) = \sum_{i=0}^{\infty}[\frac{A_i}{2}e^{j\varphi_i}\delta(\omega-\omega_i) + \frac{A_i}{2}e^{-j\varphi_i}\delta(\omega-\omega_i)] \quad (3)$$

A weighting window function *w(n)* is then applied on *x(n)* to truncate the infinite sequence, and the following result is obtained:

$$x_w(n) = x(n)w(n), n = 0,1,\cdots, N-1 \quad (4)$$

Following the product theorem of the Fourier transform, the spectrum of $x_w(n)$ is given by

$$X_W(e^{j\omega}) = X(e^{j\omega}) * W(e^{j\omega})$$
$$= \sum_{i=0}^{\infty}[\frac{A_i}{2}e^{j\varphi_i}W(\omega-\omega_i) + \frac{A_i}{2}e^{-j\varphi_i}W(\omega+\omega_i)] \quad (5)$$

Where $W(\omega)$ is the spectrum of the window function $w(n)$.

Considering the spectrum $X_w(e^{j\omega})$ sampled with a sampling interval $\Delta\omega = 2\pi / N$, the discrete spectrum $X_w(k)$ is

$$X_w(k) = X_w(e^{j\omega})\big|_{\omega=k\Delta\omega}$$
$$= \sum_{i=0}^{\infty}\frac{A_i}{2}e^{j\varphi_i}[W(k\Delta\omega-\omega_i) + W(k\Delta\omega+\omega_i)],$$
$$k = 0, 1, 2,\cdots N\text{-}1 \quad (6)$$

Assuming the sampling rate is sufficiently higher than the Nyquist rate, and the truncation length of the signal is equal to an integer multiple of the signal period, the amplitude and phase of the *k*-th harmonic obtained from $X_w(k)$ are given as:

$$X_w(k) = \frac{A_0}{2}e^{j\varphi_i} \quad (7)$$

Because of the picket fence effect and energy leakage of DFT, however, the results are not precise and cannot fulfill the requirements of harmonic analysis. To improve the precision of the DFT algorithm, the windowed interpolating algorithm was proposed. The interpolation can eliminate the errors caused by picket fence effects [6], and the errors produced by energy leakage can be reduced through signal windowing [7]. Various window functions have been proposed [8], among which the Hanning window is a popular one because of its relatively low side lobe amplitudes, fast attenuation, significantly less energy leakage compared with rectangular windows, and the easiness to access. The Hanning window is defined as

$$w(n) = 0.5 - 0.5\cos\left(\frac{2\pi n}{N}\right), \quad n = 0,1,\cdots,N-1 \quad (8)$$

and its Fourier transform is

$$W(e^{j\omega}) = 0.5U(\omega) + 0.25[U(\omega - \frac{2\pi}{N}) + U(\omega + \frac{2\pi}{N})] \quad (9)$$

Where

$$U(\omega) = e^{j\omega/2}\sin(\frac{\omega N}{2}) / \sin(\frac{\omega}{2}) \quad (10)$$

After windowing, the spectrum of the sampled sequence $X_w(e^{j\omega})$ is:

$$\left|X(e^{j\omega})\right|_{\omega=k_m\frac{2\pi}{N}} \approx \frac{A_m \sin(\pi\delta_m)}{2\delta_m(1-\delta_m^2)\pi} \quad (11)$$

$$\left|X(e^{j\omega})\right|_{\omega=(k_m+1)\frac{2\pi}{N}} \approx \frac{A_m \sin(\pi\delta_m)}{2\delta_m(1-\delta_m)(2-\delta_m)\pi} \quad (12)$$

Let

$$\beta_m = \left|X(e^{j\omega})\right|_{\omega=(k_m+1)\frac{2\pi}{N}} \Big/ \left|X(e^{j\omega})\right|_{\omega=k_m\frac{2\pi}{N}} \quad (13)$$

and we have

$$\delta_m = \frac{2\beta_m - 1}{1+\beta_m} \quad (14)$$

From Equations (11) and (12), the amplitude and phase of the harmonic are as follows.

$$A_m = \left|X(e^{j\omega})\right|_{\omega=k_m\frac{2\pi}{N}} \frac{2\pi\delta_m(1-\delta_m)}{\sin(\pi\delta_m)} \quad (15)$$

$$\varphi_m = angle[\left|X(e^{j\omega})\right|_{\omega=k_m\frac{2\pi}{N}}] - \delta_m\pi(N-1)/N \quad (16)$$

4. Design of Harmonic Measurement System using LabVIEW

The proposed method was implemented and integrated into our new virtual instrument developed in LabVIEW. The overall block diagram of the virtual harmonic measurement system is shown in Figure 1. The system consists of conditioning circuit, data acquisition component, processing computer, etc. Voltage and current signals of the power network are converted to 0~100V voltage and 0~5A current through voltage and current transformers, and are then forwarded to the conditioning circuit, where pre-processing on the signals are performed, and the signals are transformed into -5~5V voltage input signals. The input signals are fed into the data acquisition card for conversion into digital signals, which are afterwards analyzed, computed, and output by the computer. Measurement results can be displayed, printed as reports, stored, or transferred to remote station.

As the central component of the system, the systems software was completely implemented using the LabVIEW graphical programming language. The software can be divided into four main modules,

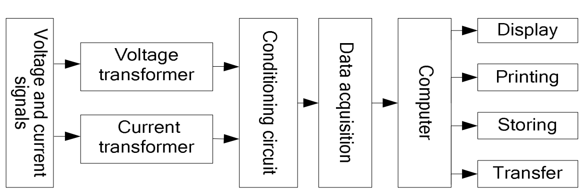


Figure 1 **Block diagram of the virtual power system harmonic measurement system**

being the data acquisition card driving program, data acquisition program, harmonic measuring program, and harmonic analyzing program. The data acquisition card driving program and data acquisition program execute continuous data acquisition of the voltage and current signals to be measured, and the harmonic measuring program and analyzing programs carry out filtering of the acquired signals and the computation of the harmonic parameters of the three-phase voltage and current signals. There are also some other auxiliary modules, such as the storing module, which uses the LV Report Generation Toolkit for Microsoft Office toolbox to store the measured results in MS Word documents, and the remote transfer module adopting the distributing tool AppletVIEW in LabVIEW to transfer measurement results to remote stations in B/S mode. The block diagram for the software system is shown in Figure 2.

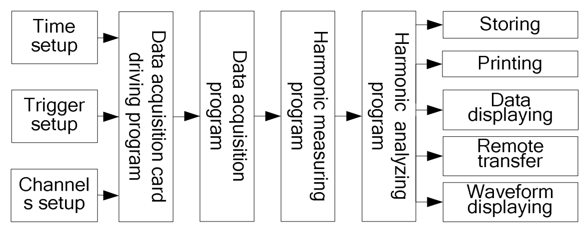


Figure 2 **Block diagram of the system software**

The harmonic analyzing module is coded using a set of functions provided by LabVIEW. Measurement of THD, total distortions of even harmonics and odd harmonics, and the distortions of the 1^{st} to the 13^{th} harmonics of three-phase voltage and current signals are realized using the given interpolating windowed FFT algorithm. Before the data analysis, signals are pre-processed to reduce spectrum energy leakage by the Hanning window function (Hanning Window.vi) provided in LabVIEW's Functions panel. The auto power spectrum function (Auto Power Spectrum.vi) is called to compute the auto power spectrum of the acquired temporal signals, followed by the call to the harmonic analyzing function (Harmonic Analyzer.vi) to obtain the frequencies and phases, THD, and each individual distortion of the harmonics. The THD and the *n*-th voltage harmonic distortion are given by Equations (17) and (18), respectively

$$THD_U = \frac{U}{U_1} \times 100\% \quad (17)$$

$$THD_{Un} = \frac{U_n}{U_1} \times 100\% \quad (18)$$

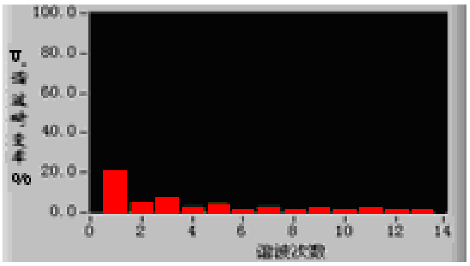
Where

$$U = \sqrt{\sum_{n=2}^{\infty} U_n^2} \quad (19)$$

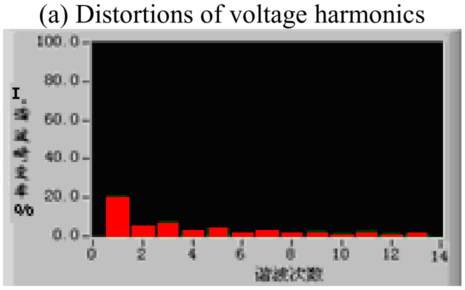
Un is the effective voltage of the n-th harmonic, and U_1 is the effective voltage of the fundamental harmonic.

Distortions of current harmonics can be computed in the same way.

Measurement results for harmonics from the fundamental harmonic to the 13th harmonic are displayed on the VI panel of the system. Harmonic distortions of voltage and current signals are shown in Figure 3.



(a) Distortions of voltage harmonics



(b) Distortions of current harmonics

Figure 3 **LabVIEW VI panel for harmonic measurement results**

5. Remote Data Transfer

For convenient remote monitoring and control, a remote data transfer module adopting B/S framework is implemented using AppletVIEW, the network distributing tool in LabVIEW. The client program is developed also through AppletVIEW. The combination of AppletVIEW and Java & TCP/IP enables users to interact with remote LabVIEW programs via network browsers such as Internet Explorer free from plug-ins, security setting up, and extra download and license. The virtual instrument system, standard Web server, and Web browser are thus incorporated to form a single system.

The Java applet used by AppletVIEW is compatible to Java 1.1 standard, and can be run in any browser supporting the standard. The Applet Builder in AppletVIEW package generating the instrument interfaces can embed the Java applets created by LabVIEW VI panels into Web pages, resulting in virtual instruments in B/S mode.

Besides, Applet Builder requires Java 1.4 JRE runtime environment, which means that a Java 1.4 Runtime should be installed at the server end. By incorporating the proxy functions of AppletVIEW in LabVIEW platform at the server end, multi-user situations can be handled more elegantly.

Our system is implemented using LabVIEW 7.1 and AppletVIEW 4.1. The remote measurement and control system program, Temp.vi, is coded in LabVIEW. Run Temp.vi, start AppletVIEW Server, and then start Applet Builder, Temp.viml and corresponding HTML code are created in Applet Builder. Save the HTML code in an html file, and refine the page through FrontPage or other Web page design software.

When temperature.vi is opened and AppletVIEW is started at the server end, remote clients can easily actualize remote measurement and control through a browser. The interface appearing at the client end is as shown in Figure 4.

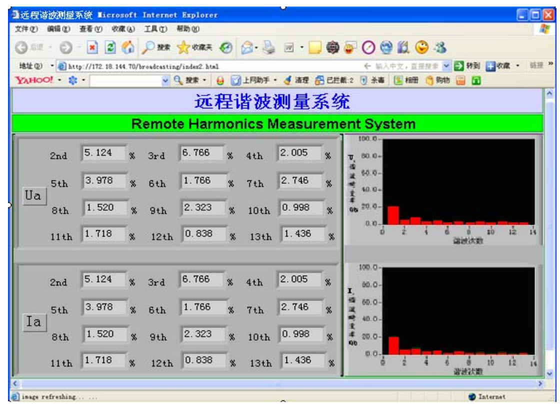


Figure 4 **Client interface of the remote harmonic measurement system based on AppletVIEW**

6. Conclusions

Harmonic detection and measurement is becoming more and more intelligent, networked, multifunctional, and practical. The virtual harmonic measurement system designed in this paper is of the following advantages: the simplicity of the system hardware, user-friendly interfaces, easy-to-use options, continuous or timed measurement of the amplitudes, phases, THD, and distortions of the fundamental harmonic and other harmonics of voltage and current signals in power systems. In addition to the functions of traditional harmonic measurement system, further software implementation enables the remote transfer, wave form display, numeric display and storing of the measurement results of voltage and current signals. The application results show the feasibility and veracity of the system. By sufficiently exploiting the capabilities of the latest computer technologies and measurement/control technologies, virtual instruments realize and enrich the functions of traditional instruments. Power system harmonic measurement based on virtual instruments is now an obvious development direction.

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