Use of a Single High Speed Analog-to-Digital Converter for Precision Measurements of Three Phase Electrical Power

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Abstract: A Three Phase Digital Sampling Wattmeter (DSWM) is described that uses a Keithley DAQ board KPCI-3116 with a single 16-bit Analog-to-Digital Converter, a computer, and the software developed in LabVIEW. Measurements of power with full power factor range can be made on both sinusoidal and non-sinusoidal voltages and currents with the fundamental frequency from 15 to 420 Hz.

Keywords: sampling wattmeter, non-sinusoidal, harmonics, Fast Fourier Transform

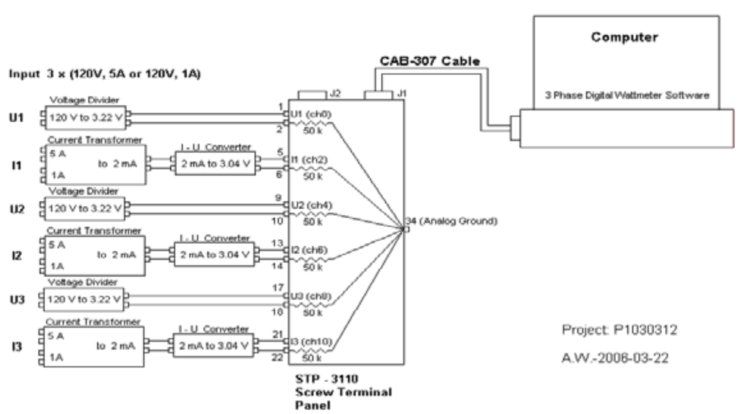
1. INTRODUCTION

Measurements International Ltd. has manufactured a Transformer Loss Measurement System "Acculoss™" for more than 10 years. The AccuLoss™ system was based on using three (3) single phase wattmeters which featured uncertainties of less than 50 ppm in magnitude and phase, its principle of operation is based on the Time Division Multiplier (TDM) technology developed by the National Research Council of Canada (NRC).

However, this kind of wattmeter is fairly expensive and the system must use 3 units for 3 phase power to be able to measure losses in 3-phase transformers. There was a justified need to replace the three (3) TDM wattmeters with only one unit that would be cheaper and able to measure losses in all the 3 phases of a transformer under test (TUT) simultaneously and with an uncertainty not worse than the Model 2010A. The new wattmeter being developed is basically a virtual instrument consisting of a computer with a PCI DAQ board available on the market. By running the software in LabVIEW and by continuously processing the samples from 6 input channels of the DAQ board, the total losses can be calculated and every second. To perform the most advanced and complicated calculations of the processing, like for example, extracting the fundamental frequency from a series of samples or applying the Fast Fourier Transform to the samples to extract the magnitudes and the phases of the signal harmonics, the software takes advantage of the power of NI LabVIEW that are already available as a part of the LabVIEW development environment.

2. DESCRIPTION

The Three Phase Wattmeter is being developed is a stand-alone unit as shown in Figure 1. The voltage and current input circuits from the 2010A, a precision voltage divider and two-stage-compensated current transformer, are used to scale down the voltage and current inputs to usable levels, their functionality, reliability and accuracy have already been proven. The main processing consists of a high speed microprocessor with touch screen and USB drive. PCI slots are available for the DAQ and IEEE488 interface cards.



functionality, reliability and accuracy have already been proven. The main processing consists of a high speed microprocessor with touch screen and USB drive. PCI slots are available for the DAQ and IEEE488 interface cards. Windows XP operating system is used. The unit can be controlled over the GPIB. It has 3 sets of voltage and current input terminals with voltage ranges 120 and 240 V and 10 current ranges from 5 mA to 5 A. To switch between ranges latching relays are used that are controlled by the software over another PCI board. In the voltage input channels there are resistive voltage dividers to step down input voltages to about 3 Vrms for each range and in the current input channels two-stage-compensated current transformers are used with current-to-voltage converters with output voltages also equal to about 3 Vrms per current range. A block diagram is shown in Figure1

Figure 1
Block diagram of 3 phase wattmeter

3. SOFTWARE PROCEDURE

The procedure used by the software has already been known and described in several papers [1]. However, it was not applied to a stand-alone unit, but first used in laboratory conditions in a measuring system that consisted of a computer controlling two digital multimeters HP3458A over the GPIB, using them as digitizers and measuring active power in only one phase. The software of such a system was developed in a text based programming language like C or Pascal, and sophisticated subroutines were used to extract the fundamental frequency from a series of samples and to calculate the harmonic magnitudes and phases.

The software of the Three Phase Digital Sampling Wattmeter uses full power of LabVIEW programming language with its ready-to-use subroutines (Sub VIs) that perform complicated calculations on the samples.
The voltage and current signals at the inputs of the wattmeter can be described as Fourier functions of time by the following expressions:

$$v(t)=Vo+\sum_{h=1}^{M} Vch*\sqrt{2}*\cos(2*h*\pi*f*t)+Vsh*\sqrt{2}*\sin(2*h*\pi*f*t) \qquad (1)$$

$$i(t)=Io+\sum_{h=1}^{M} Ich*\sqrt{2}*\cos(2*h*\pi*f*t)+Ish*\sqrt{2}*\sin(2*h*\pi*f*t) \qquad (2)$$

where Vo, Vch, Vsh and Io, Ich, Ish, are, respectively, the dc component and the rms value of the cosine and sine *h*th harmonic components of both the voltage and the current, and f is the frequency of the fundamental [1].

When all these components are known the active power can be calculated as:

$$P=Vo*Io+\sum_{h=1}^{M}[Vch*Ich+Vsh*Ish] \qquad (3)$$

The procedure used by the software to extract the fundamental frequency as well as the components Vo, Vch, Vsh, Io, Ich, Ish from series of samples taken at three pairs of input channels consists of the following steps:

a) Sample continuously all the signals of the 6 input channels of the wattmeter with a high sampling frequency (100 kHz) using the DAQ board with a single 16 bit Analog-to-Digital (ADC) converter working in the multiplexing mode. Under such conditions the signal of each channel is effectively sampled with the frequency equal to one sixth of the ADC sampling frequency (in this case 16.67 kHz). Use a constant buffer size for each channel (7000 samples, 14000 if the fundamental frequency is greater than 200 Hz).

b) Determine the fundamental frequency of the signals with the help of the ready-to-use LabVIEW subroutine (Sub VI) “Extract Single Tone Information.vi.”

c) Using the obtained value of the fundamental frequency, take for further processing only such number of samples (starting from the beginning of each buffer) that corresponds to an (exact) integer number of periods. “The important thing is to take N equal-spaced samples during exactly M periods and making sure that M and N have no common factors. Active power of a stationary periodic signal requires that the measurement is made over an (exact) integer number of periods.” [2]. Before further processing multiply also the values of the samples by the calibration factors obtained during the calibration of the meter and stored permanently in a file.

d) For each series of samples calculate the components Vo, Vch, Vsh , Io, Ich, Ish with the help of a ready-to-use LabVIEW sub VI “Real FFT.vi”

e) Using the formulas (1) and (2) with the obtained components perform calculations to “shift” five of the six channel signals back in time from 1 to 5 sampling periods, accordingly, to compensate for the multiplexing mode of the Analog-to-Digital Converter. Obtain new series of samples for 5 channels that correspond to the same time as the samples from the first channel.

e) Calculate new components Vo, Vch, Vsh, Io, Ich, Ish and the active power of each phase using formula (3). Show the results on the display, go to the beginning of the loop - step a)

The Three Phase Digital Sampling Wattmeter not only is able to measure the active power but other quantities as well: the amplitude and phase angle of individual harmonics of non-sinusoidal voltages and currents, reactive power, apparent power, rms and dc voltage and current, phase angle and power factor.

4. TEST RESULTS

The total uncertainty of the Three Phase Digital Sampling Wattmeter consists of the following components.

-Processing routine
-A/D converter
-Voltage dividers
-Current transducers (current transformers and current-to-voltage converters)

The uncertainty of the processing routine

The measuring method could easily be tested by delivering 6 series of samples to the software every second that are not obtained from the Analog-to-Digital Converter but generated mathematically using the formulas (1) and (2) with the components Vo, Vch, Vsh , Io, Ich, Ish freely chosen and the active power exactly known (3), any chosen fundamental frequency f from 15 to 420 Hz, and also applying the multiplexing delay to the samples from 5 channels in reference to the first channel.
This method simulates an ideal Analog-to-Digital Converter with no sampling time-jitter, perfectly constant sampling frequency and the magnitude error equal to zero; the error of the active power indicated by the wattmeter is then due to the processing method only. Some magnitude noise and jitter noise could be also added to the samples by using the LabVIEW random number generator in order to check their influence on the final results. The power shown by the wattmeter (the output power of the routine) must be equal to the input power that is known. For this kind of "sampling" the starting point for each series has to be chosen randomly because the beginning of sampling can start at any point of the periodical wave of the first channel as the samples are taken asynchronously (without phase-locking to one of the voltages).

The uncertainty of the Analog-to-Digital converter

A DAQ board with 2 analog outputs driven by accurate 16-bit Digital-to-Analog Converters (DACs) can be used to test the Analog-to-Digital Converter of the Three Phase Digital Sampling Wattmeter. The analog outputs can be programmed to constantly generate 2 periodical waves with the frequency and contents of harmonics determined by the programmer. If the components of the waves are Vo, Vch, Vsh and Io, Ich, Ish and the frequency are chosen by the programmer, the active power of the u(t) and i(t) is, assuming no hardware errors, also accurately known. Any pair of U, I input channels of the wattmeter Analog-to-Digital Converter, or all the pairs simultaneously, can be supplied from the analog outputs of the DAQ board. The error of the wattmeter depends then on the combined error of the analog outputs, Analog-to-Digital Converter and the processing routine.
The uncertainty of the voltage dividers and current transformers

The prototype of the Three Phase Digital Sampling Wattmeter has been tested at different power factors using the Power Calibration System 2100A manufactured by Measurements International Ltd. that can deliver power at any power factor from zero lag to zero lead through unity with the systematic uncertainty estimated to be not more than 20 parts per million. The differences between the active power set by the system and indicated by the wattmeter are shown in Table 1.

Table 1. Comparison between the MI Power Calibration System and the gigh speed A/D technique.

Power Calibration System 2100A				Three Phase Digital Sampling Wattmeter					
				greatest error of 3 phases [ppm]					
U [V]	I [A]	Power Factor	f [Hz]	U	I	S	P	Q	Power Factor
120	1	1	50	17	16	3	4	19	2
120	1	0.5	50	15	18	37	27	26	9
120	1	0	50	23	5	22	6	20	6
120	1	1	60	32	5	33	32	12	1
120	1	0.5	60	2	19	24	28	9	17
120	1	0	60	2	3	6	17	7	17

Table 1
MIL 3 Phase wattmeter principle vs MIL power Calibration System

5. CONCLUSION

The method of using a Single High Speed Analog-to-Digital Converter for Precision Measurements of Three Phase Electrical Power has given satisfactory results at its preliminary stage. The Three Phase Digital Sampling Wattmeter that has been built needs still to be tested in much more demanding practical conditions while being used in measuring losses of the three phase transformers. The number of samples taken in each period determines the number of harmonics that can be measured, and the number of harmonics is equal to the half of the number of samples. Anti-alias low-pass filters are needed to avoid those harmonics whose frequencies are higher than fs/2. The quality of those filters is an important factor although in the laboratory conditions it is better not to use anti-aliasing filters because they have some influence on the parameters of the "good" harmonics as well.

6. REFERENCES

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