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The Effect of Measuring System Accuracy on Power Quality Measurements in Electrical Arc Furnaces

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Abstract* -- *With more stringent power quality requirements imposed by utilities on electrical furnace operators, the accurate measurement of electrical parameters becomes more important. The overall performance of a power quality measurement system is a function of the accuracy of all of its transducers. This paper, through the use of measured electrical arc furnace data, investigates the sensitivity of power quality calculations to the dynamics of instrument transformers and sampling devices. Improved accuracy in measurements with real-time digital compensating filters is demonstrated using the furnace data.

1. INTRODUCTION

The effect of field instrument transformers on signal measurement accuracy has been documented recently in [1], [2], [6], [7]. Linear distortion introduced by other components of the measurement systems having nonideal frequency responses are also sources of errors in multi-phase power quality measurements. This paper examines the sensitivity of power quality measures to the dynamics of measurement components through case studies using actual arc furnace data. The measures considered in this paper are: unbalance, power factor, active and reactive power, and harmonics.

Typically, electrical measurements are carried out using the existing arc furnace current and voltage transformers. The overall measuring system performance is determined by the accuracy of all the transducers and by the precision of the measuring system. The main components of a typical measuring system, shown in Figure 1, are:

- field instrument transformers (voltage and current transformers)
- measuring transducers used to interface the sampling device with the field transformers
- sampling device, and real-time analysis system.

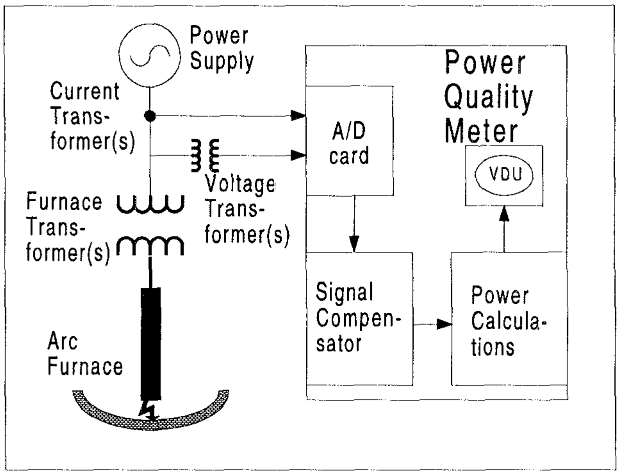

Figure 1: Power quality measurement system

Although all precautions are taken to ensure that the measurements made by the recording instruments are accurate, the field instrument transformers usually cannot be changed or adjusted. Moreover, even though instrument transformers typically have a flat magnitude response up to 10 kHz, their phase response may not be flat, nor linear, at frequencies above the fundamental frequency. Sampling cards may introduce a phase shift between signals on different channels which are usually assumed to be sampled at the same time. Most antialiasing filters also exhibit nonlinear phase responses.

Phase errors are usually not a concern when making RMS voltage and current measurements. However, power measurements may be significantly affected by

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phase errors. These errors are magnified when the power factor is much less than unity [8]. Consequently, the phase shift introduced by the instrument transformers and the sampling devices can have a significant effect on overall system measurement accuracy.

2. CORRECTION OF SIGNAL MEASUREMENTS

A. Accuracy of individual components

The accuracy requirement of the field transducers is established by the Electricity Metering Codes [3]. However, the present standards [3], [4] specify only the accuracy requirements for 60 Hz operation for a given burden and load. At frequencies higher than 60 Hz, the transformers will introduce ratio and phase-angle errors (see, e.g., [6], [10], [11]). When primary inputs differ from the nameplate values of the instrument transformers, the measuring errors may be significant [5], [6], [7].

Instrument current transformers (CT's) typically operate with the output current below 5 Amperes. Their accuracy can be less than 3% at frequencies up to 10 kHz for the nameplate current and load conditions [6]. Instrument voltage transformers (VT's) have nominal outputs that are typically 120 or 240 Volts. They can introduce errors greater than 4% for frequencies of up to 10 kHz with the nameplate voltage and load conditions [7]. Therefore, measurements of higher system harmonics and transients may be inaccurate.

Analogue antialiasing filters must be used when high noise levels are present, such as in a plant environment. These low-pass filters attenuate the noise corrupting the signals and limit aliasing problems that may introduce low-frequency distortion in the sampled digital signals. The cutoff frequency of antialiasing filters is chosen to be lower than the Nyquist frequency, which is equal to half of the sampling frequency. Typically, the phase response of these filters starts to be significant at lower frequencies than cutoff, thereby distorting signals that have some energy at those frequencies.

The analogue-to-digital cards used in computer-based electrical measurement systems typically exhibit a short sampling delay of about 10 μs between each channel, when sampling in burst mode. Ideally, all channels would be sampled at the same time. The short time delay between signals is equivalent to a linear phase that becomes significant at even at low harmonic frequencies, see [2] for further details.

Real-time digital filters have been proposed to compensate for the overall frequency response of the measurement system [1], [2]. These filters are designed based on dynamic models and measured frequency-response data of the instrument transformers, antialiasing filters, and sampling devices used. The correction filters are implemented as dicrete-time state-space matrices in the measurement system's computer.

B. Frequency Responses of Measurement System Components

The frequency response of a 120V/3.5V instrument voltage transformer used with a real-time power quality analyser was measured at harmonic frequencies of 60 Hz, up to 2100 Hz (35th harmonic). Figure 2 show a Bode plot of this frequency response which exhibits a phase lead effect.

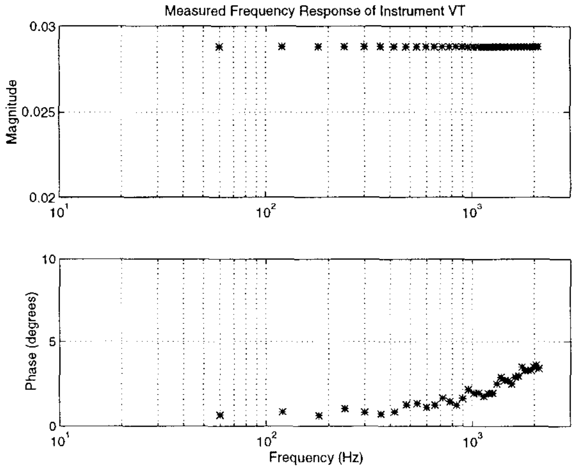

Figure 2: Measured frequency response of an instrument voltage transformer

A model of a field voltage transformer taken from [7] was used to generate the frequency response shown in Figure 3.

In order to generate the frequency-domain data needed to design compensating filters, a frequency response combining the effect of the field and instrument VT's, and of the sampling card must be computed. This is done by multiplying the complex numbers of each individual component's frequency response at the corresponding frequencies. Then, the resulting combined frequency response is the one to be "inverted" or canceled out by the compensating filters.

Let us consider the case where three-phase voltage signals sensed by field and instrument VT's are measured on channels 0,1, and 2 of a sampling card, as in Section 3.A below. A Bode plot of the inverse combined frequency response for channel 2, combining the responses of field and instrument VT's, and the sampling card delay between channels 0 and 2, is shown in Figure 4. The small circles denote the combined (inverted) measured data, whereas the solid lines are the frequency response of the fourth-order compensating filter. Notice how the filter's magnitude and phase curves interpolate the data points. This digital compensating filter, and two others similarly designed for channels 0 and 1, were used to compare power quality measurements with and without compensating filters in the next section.

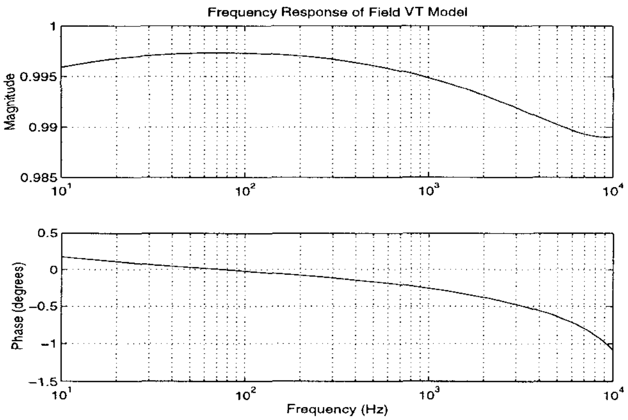

Figure 3: Frequency response of a field voltage transformer model

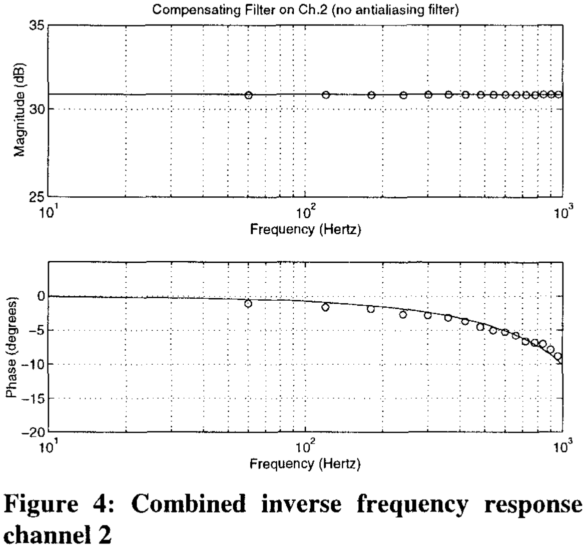

Figure 4: Combined inverse frequency response for channel 2

3. ACCURACY IN POWER QUALITY MEASUREMENTS

A. Unbalance Measurements

We now consider the effect of uncompensated measurements on three-phase unbalance calculations. Recorded three-phase signals from a steelmaking electrical arc furnace were played back from an arbitrary waveform signal generator *within* the Power Quality Analyser, a real-time computer-based meter developed at Hatch [9]. The signals were treated as if they were distorted by field and instrument VT's, and embedded the effect of sampling delays (Figure 5).

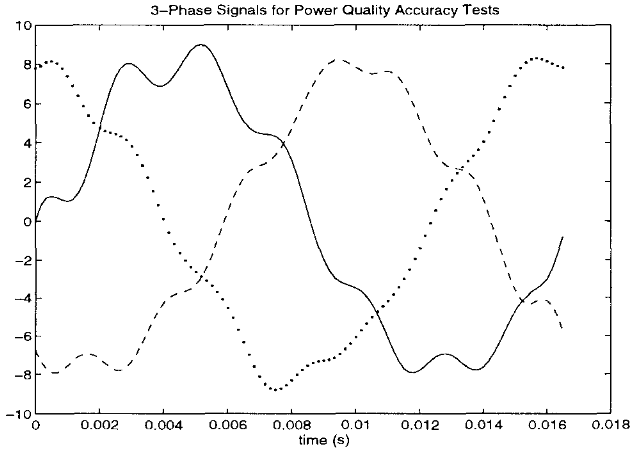

Figure 5: One period of three-phase voltage signals used for unbalance measurements

The three-phase signals were processed simultaneously on channels 0, 1, and 2 of the Power Quality Analyser. The compensating filters were active for the first experiment only. The second experiment consisted of repeating the first, but without the compensating filters. The same unbalance calculations performed on the compensated and uncompensated voltages resulted in differences in positive, negative, and zero sequence component values, see Table 1.

Table 1: Unbalance calculation results

unbalance parameter	without filters	with filters	difference (%)
pos. seq.	193.6307	193.5505	0.0414
neg. seq.	25.3534	25.5983	-0.9567
zero seq.	26.7959	27.0302	-0.8668
% unbalance	13.1261	13.2586	-0.9994

Differences of up to 1% in the percent unbalance (calculated as the ratio of negative sequence component to positive sequence component) can be seen in Table 1. Such differences in the calculated results can be significant for certain applications, e.g., utility contract monitoring, and justify the use of compensating filters for accuracy improvement.

B. Power and Power Factor Measurements

Power factor measurements were conducted on voltage and current waveforms originally recorded from an electrical arc furnace, and played back with an arbitrary waveform generator for the experiments. For example, the voltage and current waveforms shown in Figure 6 were used to compute the results of Table 2 below (0.47 power factor).

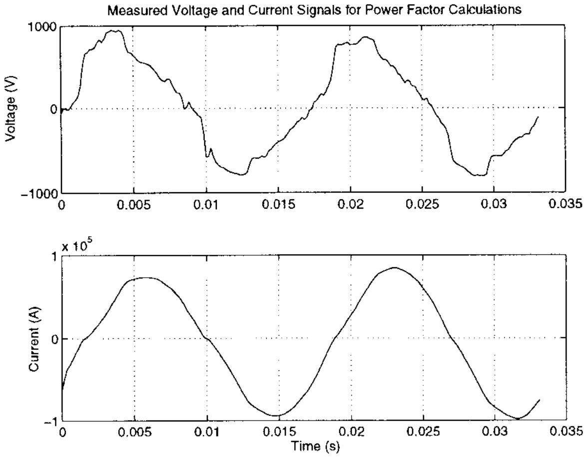

Figure 6: Voltage and current waveforms used for power and power factor measurements

Three experiments were conducted, with and without the compensating filters, for power factors of 0.47, 0.75, and 0.83. The results are tabulated in Tables 2, 3 and 4, which also include active and reactive powers. The percent difference in the last column of Tables 2, 3 and 4 was calculated with the assumptions that the filtered values are the "correct" values. Note that the apparent power, computed as $\sqrt{(P^2+Q^2)}$, where P and Q are the active and reactive powers respectively, remained essentially constant for each experiment, with and without the compensating filters. This follows from the observation that apparent power is mostly a function of signal magnitudes, not phase difference.

Table 2: Calculation results for 0.47 power factor

power calculation	without filters	with filters	diff. (%)
power factor	0.47468	0.46555	1.9611
active power (MW)	11.9858	11.7535	1.9764
react. power (MVAR)	21.9551	22.0741	-0.5391
app. power (MVA)	25.0137	25.0082	0.0220

Table 3: Calculation results for 0.75 power factor

power calculation	without filters	with filters	diff. (%)
power factor	0.75819	0.75196	0.8285
active power (MW)	25.1472	24.9377	0.8401
react. power (MVAR)	20.8277	21.0769	-1.1823
app. power (MVA)	32.6523	32.6516	0.0021

Table 4: Calculation results for 0.83 power factor

power calculation	without filters	with filters	diff. (%)
power factor	0.84045	0.83499	0.6539
active power (MW)	16.9889	16.8757	0.6708
react. power (MVAR)	10.7982	10.9729	-1.5921
app. power (MVAR)	20.1302	20.1294	0.0040

C. Harmonic Measurements

Harmonic measurements are also affected by the frequency response of the measurement system in a direct way. The magnitudes of harmonic components are amplified (or attenuated) by the gain of the combined frequency response of the measurement system at the corresponding harmonic frequencies. Total Harmonic Distortion calculations are then corrupted by these harmonic magnitudes perturbed from unity.

Measured phases of harmonic components are also affected in a similar way. For example, referring back to Figure 4, the phase measurement of the 8th harmonic on channel 2 would have an error of 5 degrees. Harmonic power flow monitoring based on phase measurements may then give misleading information.

4. CONCLUSION

We have shown, through case studies, that power quality measurements may be sensitive to the effects of nonideal frequency responses of the components of a measurement system. This sensitivity was illustrated with unbalance, power, and power factor calculations performed on actual arc furnace voltage and current measurements, with and without real-time digital compensating filters. It was shown that, despite the fact that high-performance VT's were used, errors as large as 2% can result in power quality measurements when correction filters are not implemented.

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