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PERFORMING ACCURATE POWER QUALITY MEASUREMENTS

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Abstract

The flicker and harmonics generated by electric arc furnaces present a problem that is well known to both the steel industry and electrical utilities. This paper presents a method to compensate for measurement errors introduced by current and voltage transformers and anti-aliasing filters in a power quality measurement system. Dynamic compensation may be performed in real time using digital filters. Measurement accuracy improvement was motivated by the development of a new real-time computer-based Power Quality Analyser (PQA). The PQA can be used for measuring electrical power quality parameters such as: voltage, current and power imbalances, flicker, harmonics, and active and reactive power fluctuations. Measurement results obtained from the PQA with and without the compensating digital filters are presented and compared, and it is shown that their use can improve power quality measurement accuracy significantly.

1. Introduction

Industrial consumers are required to limit the disturbances they cause on the utility grid, and may incur penalties, or be forced to install expensive compensators, to reduce the magnitude of these disturbances. Power contracts have been based on maintaining acceptable power factor, imbalance, flicker and harmonic levels. In particular, harmonics, imbalance and flicker are of concern to utilities when other consumers are nearby, and can be adversely affected.

Contractual agreements vary between utilities and industrial consumers, and can change with time as new standards are developed. Traditionally, short term power quality studies have been done to assess disturbance levels of existing or future operations and have required a wide range of metering equipment. As concern for power quality on utility grids is increasing, there has been a trend toward using power quality metering equipment to monitor contract compliance. As the consequences of non-compliance can be substantial, disputes will inevitably arise between the utility and the consumer, and the accuracy of the power quality measurements may be challenged. As measurement transformers, anti-aliasing filters, and sampling delays can introduce measurement errors that can significantly affect the accuracy of results, special care must be taken to provide accurate measurements, reliable enough to monitor contract compliance.

A compensating scheme [1], [3] was required as part of the development of a digital Power Quality Analyser (PQA) [2]. Compensation is performed using digital filters implemented in the PQA, to remove the effects of the measurement transformer and anti-aliasing filter dynamics. The dynamics of the plant measurement transformers may be incorporated into this error correction procedure if a set of frequency response measurements are available. The PQA was developed to be used as an all-in-one analysis tool for performing most metering functions done in traditional studies. It is well suited for monitoring the conditions of a power contract over extended periods. Future power contracts can be expected to set limits on flicker, harmonics, imbalance and voltage dips and a tool that can measure all of these disturbances simultaneously is attractive. Furthermore, the PQA is highly configurable, allowing it to meet site-specific requirements.

2. Power Quality Issues

Disturbances from operations may be compared to existing standards, however, these standards are subject to change. Acceptable levels of harmonics produced by consumers are generally guided by the IEC 1000-3-2 and 1000-3-6 standards [11]. However, standards are regularly being reviewed and revised. In the case of flicker, due to subjective nature of the problem, the point at which the disturbance is seen to be irritating to the human eye is subject to controversy, and there is no general scientific consensus. In the past, many standards existed, and they have changed frequently. Overall, it is important that analysis tools be flexible enough to be adapted and upgraded to suit individual requirements or to allow comparison with new standards.

Significant harmonics are generated by an AC electric arc furnace due to nonlinearity of the arcing process. This time-varying nonlinearity causes a distortion of the current and voltage waveforms. Harmonic currents injected back onto the plant bus, or back onto the utility transmission line, can lead to unexpected resonance conditions in other plant equipment or neighbouring users' systems. Harmonics or imbalance can lead to heating damages in electrical equipment and, hence, are of major concern.

Electric arc furnace operations are notorious for generating voltage disturbances. Rapid variations in arc impedance lead to a voltage fluctuation on the utility transmission line that causes flicker. Originally, complaints of flicker levels concerned a disagreeable effect on incandescent lighting most noticeable to the human eye in the 6-12 Hz range.

Utilities typically impose restrictions on flicker levels in power contracts. Ensuring that levels are not exceeded may restrict the operating capabilities of the furnace. As flicker levels depend on operating practices, continuous monitoring of flicker level is essential for furnace operation. Flicker control strategies can then be implemented.

3. Accuracy In Measurements

Measured voltage and current signals are corrupted by the effects of nonideal frequency responses of hardware measurement components. These components include the field current transformers (CT's) and voltage transformers (VT's), the instrument CT's and VT's, and the anti-aliasing filters. Furthermore, for three-phase systems, the analog-to-digital card cannot sample all channels at exactly the same time, which introduces delays between signal samples.

Typically, the frequency responses of the measurement components are not flat, and have phase leads or lags of several degrees at frequencies above 500 Hz. Such frequency responses will distort signals containing high-frequency harmonic components. Signal distortion may cause inaccuracies in power calculations such as active and reactive power, power factor, harmonics and imbalance.

A technique to compensate for the nonideal frequency responses of the measurement components was introduced in [1] and was detailed in [3]. The technique involves inverting the frequency-response data of the components with real-time digital filters in the measurement instrument. This technique has been tested successfully on the PQA to compensate for the dynamics of the measuring VT's, and the short time delay between each channel of the A/D board when sampling in burst mode. Furthermore, the effect of anti-aliasing filters can also be compensated for.

Compensating filters that approximately invert the frequency responses of the measurement components are calculated using frequency-domain interpolation techniques [3]. These techniques are used to interpolate the inverse of the complex frquency-response data with a proper, stable transfer function on the imaginary axis. This transfer function can be implemented as a digital filter in the PQA, so that approximate cancellation takes place and the resulting combined frequency response is close to unity magnitude and zero phase in the frequency band of interest. The interpolating transfer function is mapped into the z-domain via the bilinear transformation with the appropriate sampling period. The resulting discrete-time filter is implemented as a first-order, discrete-time state-space matrix equation in the PQA's software.

Example 1: Compensating a sinusoidal signal

Frequency-Response Measurements

A frequency-response measurement was performed from 60Hz (fundamental frequency) to 2100 Hz (35^{th} harmonic) on a 120V/3.5V VT used with the PQA. Eight points of the frequency response were selected: at the 60Hz fundamental frequency, and at its 3^{rd}, 5^{th}, 9^{th}, 15^{th}, 21^{st}, 27^{th}, and 33^{rd} harmonics. Measurements at these frequencies were used to design a compensating filter. Since the input of the VT was sampled on channel 0 and its output was sampled on channel 1, the accuracy of the measurements were affected by the 10 μs delay between channels 0 and 1 of the A/D card used for the frequency-response experiment. It was found that the frequency response of the VT has a flat magnitude over the frequency band of interest, but it has a positive phase of up to four degrees in that band. Anti-aliasing filters for the PQA were not available when this research was conducted.

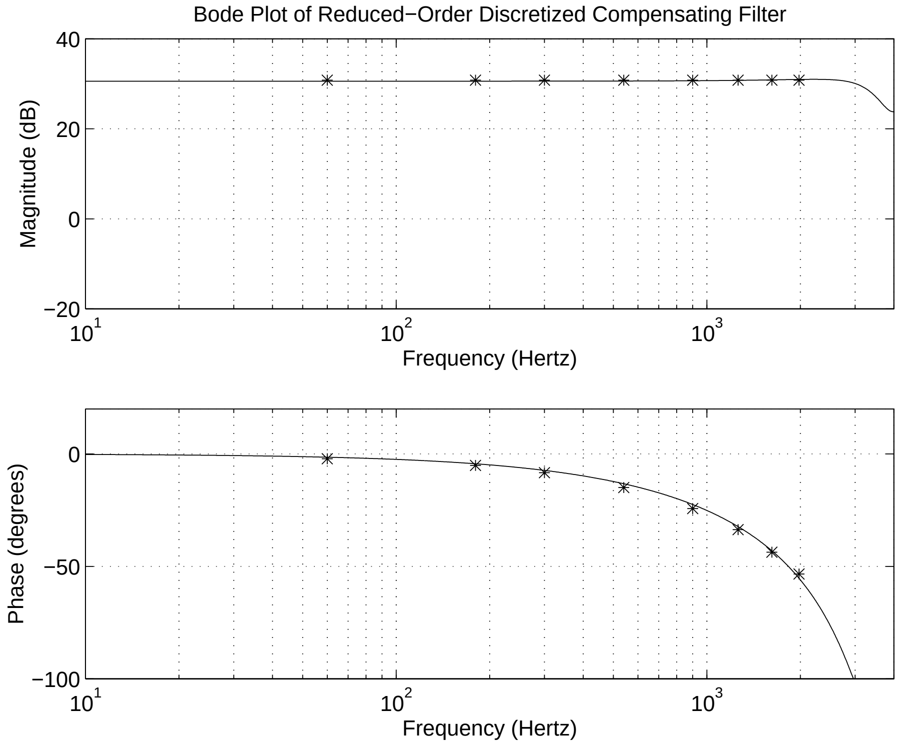

Figure 1: Bode plot of reduced 4th-order discrete-time compensating filter. The frequency-response points used in the filter design are indicated with asterisks.

Filtering Experiment

The output voltage of the VT was measured on channel 7 of the PQA, for which a compensating digital filter had been implemented. The input signal to the VT was directly measured on channel 0, without any filter. Note that an additional 60μs advance between channels 1 and 7 on the A/D card was accounted for in the combined frequency response used for the design of the filter.

After adjusting the measured frequency-response data of the VT for the phase lead of the burst mode, we used the adjusted data to design a compensating filter using the procedure described in [3]. Figure 1 shows the frequency response of the digital filter interpolating the inverse of the frequency-response data. Figure 2 compares a filtered to an unfiltered sampled 880 Hz sinusoid. It can be seen how the compensating filter corrects the phase lead of the sampled output of the VT.

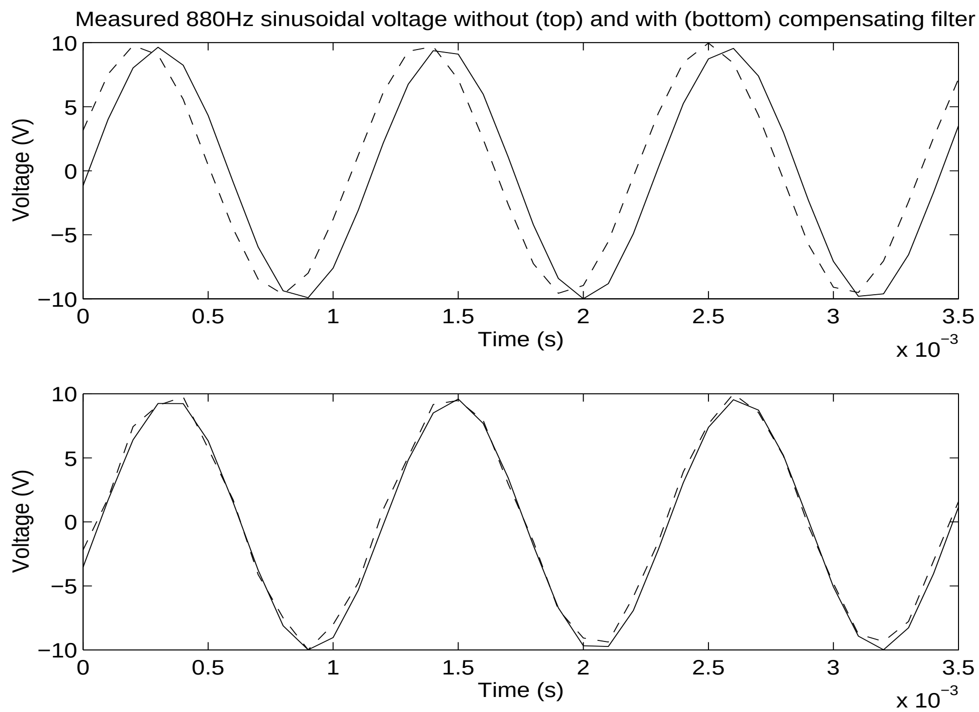

Figure 2: Measured 880Hz sinusoidal input and output of VT without and with filtering (solid: input of VT, dashed: output of VT)

Example 2: Effect of inaccurate measurements on power calculations

We now consider the effect of inaccurate measurements on three-phase imbalance calculations. Real three-phase current signals from a steel furnace were played back from a digital tape and treated as if they were uncorrupted signals from the field. By splitting the signals from the tape recorder, the three-phase currents were sampled simultaneously on channels 0, 1, 2, and 3, 4, 5, respectively. The compensating filters were active on the first three channels only. The same imbalance calculations performed on the compensated and uncompensated current systems resulted in differences in positive, negative, and zero sequence component values.

Differences of up to 1% in the percent imbalance (calculated as the ratio of negative sequence component to positive sequence component) and 6% in the zero sequence components can be seen in Figure 3. Such differences in the calculated results are significant and justify the use of compensating filters for accuracy improvement.

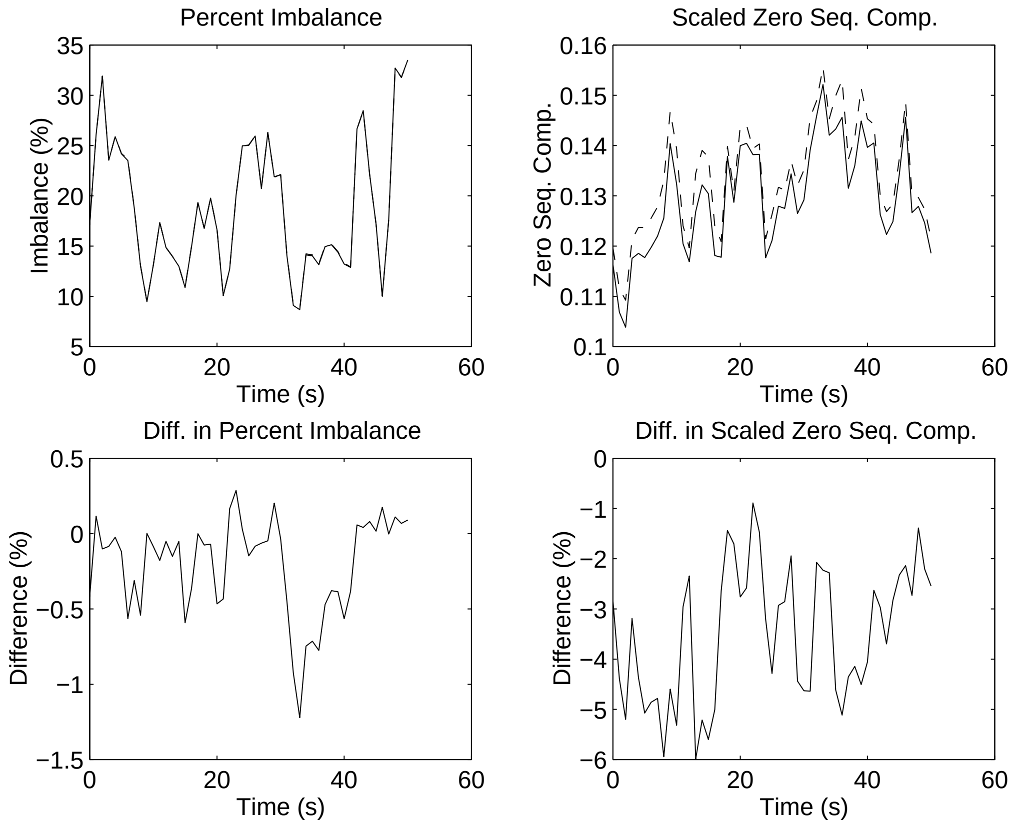

Figure 3: Percent imbalance and zero sequence component for compensated and uncompensated current signals (solid: without filters, dashed: with filters). The dashed curve in the percent imbalance plot lies on top of the solid curve. The differences in percent imbalance and zero sequence component are shown as percentages of the dashed curves.

4. PQA Features

The PQA consists of an Intel-based processing unit connected to its own instrument current transformers and voltage transformers, via a 16-bit analog-to-digital card. Software modules have been developed to perform real-time calculations in a multitasking environment. The multitasking environment combines power quality measurements that, up to now, required many meters. In addition, the user may configure calculation output averaging intervals to match individual requirements or specific contract clauses — a feature that most other meters do not provide. Use of an Intel-based processing unit rather than custom hardware provides flexibility and an economical way to monitor all power quality needs.

The PQA was designed in a modular fashion, allowing calculations to be easily added or removed to suit individual requirements. New standards and custom calculations can be implemented easily with such a modular approach. The power quality calculations that have been developed for the PQA, to date, have been grouped together into three separate modules; the basic electrical module (BEM), the advanced electrical module (AEM), and the arc furnace module (AFM).

Input signals and calculation results may be accessed or viewed while calculations are being performed. Data access is achieved by reading output data files to a local machine, or by connecting to a remote machine through a TCP/IP network connection. With the use of TCP/IP, worldwide access to the output of any PQA can be obtained via the Internet. More private and secure access can be established on an internal network. As the PQA was developed to be useful for monitoring remote sites with only modem or low bandwidth WAN/Internet connections, care was taken to keep network traffic to a minimum. Data is compressed, and transferred data is cached locally. Thresholds and event detection may be used to have data transfer focused on events.

Calculations can be pre-configured to write to disk, either continuously, or upon the detection of pre-selected events, thereby conserving disk space. In the latter case, the meter may be left unattended for weeks or months, and later provide a record of events that have occurred during that time.

The output from the PQA calculations can be averaged over overlapping, or non-overlapping demand intervals (sliding or fixed demand intervals respectively). Both the demand interval and overlap interval (See
Figure 4) may be set to any number of electrical cycles. The size of the demand and overlap intervals can be as small as 1 cycle, or as large as required; hours or even days. In the example in Figure 4, the demand and overlap intervals are set to 3 and 1 cycle respectively. For each demand interval, the user can choose to have any of the average, minimum, maximum, median or standard deviation calculated. Calculations can be configured to output for every demand interval, or only for demand intervals in which the average value of the output is outside of a user-selected range.

The averaging and statistical evaluation described above provides unusual flexibility in data trending. As an alternative to storing large data trends, a facility to store the statistical cumulative probability function is provided. The cumulative probability function can be computed on a daily and/or weekly basis, and have only a few percentiles retained, in order to compare the disturbance levels for the day or week to standard compatibility levels.

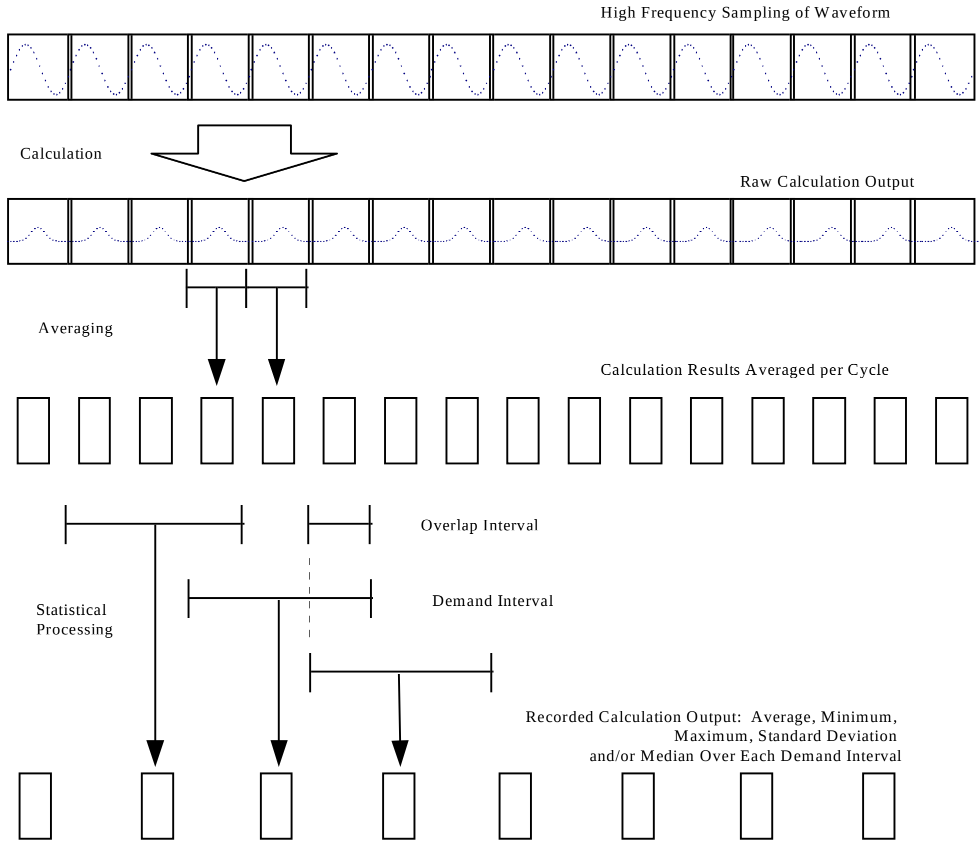

Figure 4: Output averaging of calculation data. PQA calculations provide raw output at the same rate as waveform sampling. Averaging of the data is done to reduce the output data to one sample per cycle. Using a user-specified demand and overlap interval, further statistical processing is done on each demand interval to produce the recorded calculation output

Basic Electrical Module (BEM)

The Basic Electrical Module provides standard power calculations. With flexible user-defined output capabilities, the BEM is useful for evaluating a wide range of electrical problems on-line. Problems evaluated may include:

1. Fault-induced voltage dips
2. Short-term RMS variations
3. Long-term RMS variations
4. Phase imbalance
5. Asymmetrical operation
6. Low power factor

Advanced Electrical Module (AEM)

The Advanced Electrical Module provides detailed waveform calculations. Calculations include harmonics, flicker, and voltage dip classification.

Harmonics: The harmonic calculation provides real-time monitoring of the complete frequency spectrum as well as the individual harmonic components. The input signal to this calculation may be a voltage or a current. Since many harmonic calculations may be executed simultaneously, both current and voltage spectra for all three phases may be calculated at the same time.

The harmonic calculation is performed on a window of data whose size is user-defined. The calculation can be performed on each consecutive window of data or, alternatively, a user-defined number of fundamental frequency cycles can be skipped between analysed windows.

To prevent spectral leakage, the input data may be windowed before the harmonic calculation is performed. Standard window functions implemented include Kaiser-Bessel, Hamming, Hanning and Exponential. A comprehensive discussion of data windowing can be found in [4].

With each analysed window of data, the following parameters are calculated:

1. Total Harmonic Distortion (THD) using the fundamental component,
2. Total Demand Distortion (TDD) using a user-specified nominal value,
3. Telephone Interference Factor (TIF),
4. Crest Factor,
5. Form Factor,
6. Peak Volts/Amps of the fundamental component.

The harmonic calculation outputing facility is very flexible, allowing storage of discrete harmonic components and/or the magnitude of the continuous frequency spectrum. Both outputs may be configured to limit the data storage to that outside user-defined thresholds. A single level may be set for the continuous spectrum, and individual levels may be set for each of the harmonic components.

Flicker: The flicker calculation requires a single voltage signal as an input and provides real-time monitoring of the voltage fluctuations.

The algorithm for the flicker calculations provides a short-term (P_{st}) and long-term (P_{lt}) flicker severity level evaluation using the 50 Hz, 230V weighting curve [5] or the 60 Hz, 120V weighting curve [6]. The P_{st} is a statistical evaluation of flicker over a 10-minute window and the P_{lt} is a combination of the P_{st} values over a 2-hour window.

The flicker calculation also provides an output of percent voltage fluctuation versus time, and the output can be weighted. The different weighting curves that are included are:

1. General Electric borderline of irritation curve [7].
2. General Electric borderline of visibility curve [7].
3. Commonwealth Edison (CE) curve [7].
4. Japanese ΔV10 curve [8].

User-defined weighting curves can be accommodated with minor software upgrades.

Voltage Dip: Voltage dips are characterized by profiling the fault-induced voltage variations on a Computer Business Equipment Manufacturers Association (CBEMA [9][10]) curve. Voltage excursions are saved by duration and magnitude, and/or by means of a detailed output which gives the shape of the voltage excursion. Custom voltage dip classification curves can be implemented if required.

Arc Furnace Module (AFM)

Since poor electrode regulation can lead to arc instability and loss of arc, effective electrode regulation is a necessary element in enhancing power quality. Power, Voltage and Current (PVI) diagrams (derived from plant specific parameters) display true characteristics of the theoretical circle diagrams. A regulator setpoint would appear as a fixed dot on the PVI diagram. During operation, the true operating point would fluctuate about this dot, with the distance from the setpoint being a measure of controller error.

More advanced performance measures may be implemented, such as: normalized autocorrelations computed automatically on a step change in setpoint, real-time FFT calculations to display the frequency content of the arc or of disturbances occurring in the bath, etc. These performance measures provide a baseline for furnace control improvements.

5. Conclusion

As contracts between utilities and loads trend toward continous monitoring of various power quality measures, accuracy of simultaneous real-time power quality measurements and calculations is becoming increasingly important. Accurate power quality measurements require the use of digital compensating filters to attenuate the distortion caused by hardware measurement components. Such compensating filters were implemented in the PQA with a significant improvement in accuracy, as was shown with recorded arc furnace current data.

6. References

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