A NEXT GENERATION AIRCRAFT POWER MONITORING SYSTEM

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Historically, aircraft power monitoring has required the use of multiple signal conditioning functions to measure various parameters including voltage, current, frequency and phase. This information was then post processed to determine the characteristics of the 3-phase power quality on the aircraft. Recent developments in embedded DSP processors within signal-conditioning systems provide the instrumentation engineer with expanded capabilities for real-time on-board power quality monitoring. Advantages include reduced space and bandwidth requirements and minimal wiring intrusion. For each phase, output data may include peak positive and negative voltages and currents, peak-to-peak, average and RMS voltages and currents, phase power (real and apparent), phase power factor, phase period (frequency), phase shift measurement from phase 1 (the reference phase) to phase 2, and from phase 1 to phase 3. In addition, a Fast Fourier Transform (FFT) is performed on each phase voltage to provide Total Harmonic Distortion measurements.

This paper describes the methods employed in the implementation of these functions on a single signal-conditioning card in order to provide detailed information about the power quality of a three-phase aircraft power source.

Key Words

Power Monitor, Fast Fourier Transform, Total Harmonic Distortion, Three-Phase Power

INTRODUCTION

Modern aircraft frequently require prodigious amounts of electrical power to run electrical, environmental, navigation and control systems as well as a host of other equipment. The source of all this electrical power is often a 120 Volt, three-phase AC generator or in some cases, several such units of varying sizes. With so much reliance on generated electrical power, any system responsible for monitoring the overall health of the aircraft must devote significant resources to monitoring electrical power quality. Historically, 3-phase AC aircraft power quality monitoring was done by collecting raw data components including:

- Voltages (3)
- Current (3)
- Generator Frequency (1)

These raw data components were later post-processed by ground stations to determine the overall power quality on the aircraft. While this method provided basic information about the health of the aircraft power and the load requirements on the generator(s), it did not directly provide additional key information about the system that is crucial to understanding the test vehicle's generator and loads. For example:

- True power of each phase which must take into account the power factor
- Power factor also provides valuable information about the nature of the load. Is the load inductive (voltage leads current) or capacitive (current leads voltage)?
- The phase difference between each of the three generator phases.
- Transient and Peak voltages and currents as well as the RMS voltages and currents of each phase.
- How pure is the 400Hz waveform? Does it approach the purity of a sine wave or is there substantial harmonic content? We need to get a measure of the total harmonic distortion.

While most of this valuable information could be gained through post-processing, it was not available in real time and the amount of raw data required made significant demands on the available telemetry bandwidth.

DESIGN APPROACH

The PMC-106A DSP based Power Monitoring card was developed to offer a new design approach to power quality monitoring. Specifically the PMC-106A is engineered for:

- Providing the user with maximum measurement flexibly and a wide selection of processed data parameters
- Continuous data processing so no transient events of interest are missed
- Minimizing the amount and complexity of the input wiring
- Providing the user with information rather than raw data alone
- Providing a built-in test signal generator
- Meeting a wide variety of applications including:
    - Multiple single phase supplies
    - Multiple phase supply
    - Wide range of input voltages, current levels, and signal frequencies

PMC-106A CARD HARDWARE ARCHETECTURE

As depicted in **Figure 1**, the PMC-106A has three (3) sets of paired voltage and current input channels, one set for each phase of a 3-phase system. Voltage input channels feature 1:20.1 differential input attenuators to allow input voltages up to ±205 volts (145V_{RMS} sine wave). Current channels require the use of external 400 Hz current transmitters with output voltages up to ±10.24 volts. Space is provided on the PC board for precision current-to-voltage conversion resistors for current transmitters with proportional current outputs. **Figure 2** depicts a typical example of how a 3-phase power generator might be instrumented, showing both the external 400 Hz current transmitters and the connections to the PMC-106A card.

Both current and voltage channels provide software selection of AC or DC input coupling and software configurable gains from 1 to 10, in 4100 steps. Each channel includes a pre-sample low pass filter with a fifth order (5-pole) Butterworth characteristic and –3dB frequency set at 8.0 KHz. The output of the pre-sample filter is applied to an ADC, which digitizes the analog data at 14-bit resolution. The filter output is also applied to a comparator circuit that serves as a zero-crossing detector, providing greater period (frequency) and phase resolution than would be available from the ADC data alone.

A digital phase locked loop (DPLL) is used to provide the ADC sample rate. The output of each voltage channel zero-crossing detector is used to provide a sampling signal of 128 x the input frequency. In a 400Hz generator system, the ADC sample rate will be 51.2 Ksps. This arrangement is depicted in **Figure 3**. Phase locked sampling conveys multiple benefits. When the generator frequency varies from nominal, the ADC sample rate varies with it, allowing the number of samples per line cycle to always remain at the integer value of 128. This allows measurements such as average and RMS values to be based on a specific number of full power cycles (8 in this case), even as the generator frequency varies. Measurement ripple caused by measurement over a partial power line cycle is prevented. Furthermore, the accuracy of Total Harmonic Distortion (THD) measurements based on the discrete Fourier transform is enhanced since the harmonic content levels (based on the ADC sample rate) will always be exact multiples of the power frequency.

Output data from the channel zero-crossing detector are analyzed by the DSP with a resolution of 1µs, providing much higher resolution for period (frequency) and phase measurements than could be obtained from the channel ADC, sampling at its nominal rate of 51.2KHz.

The on-board DSP continuously analyzes data in 8-cycle blocks (except for THD which is analyzed in 2-cycle blocks). Simultaneously, the next 8 cycles of data are being collected. All selected parameters are read from a current value table that is updated every 40ms (25 times per second) except for raw data, which is updated at an 8KHz rate. Thus, any potential for missing a significant data event is avoided, provided that all parameters of interest are sampled every 40ms or faster. Every peak positive, peak negative and peak-to-peak excursion within the analog bandwidth of the channel will be captured.

Figure 1: PMC-106A Voltage/Current Input Block Diagram

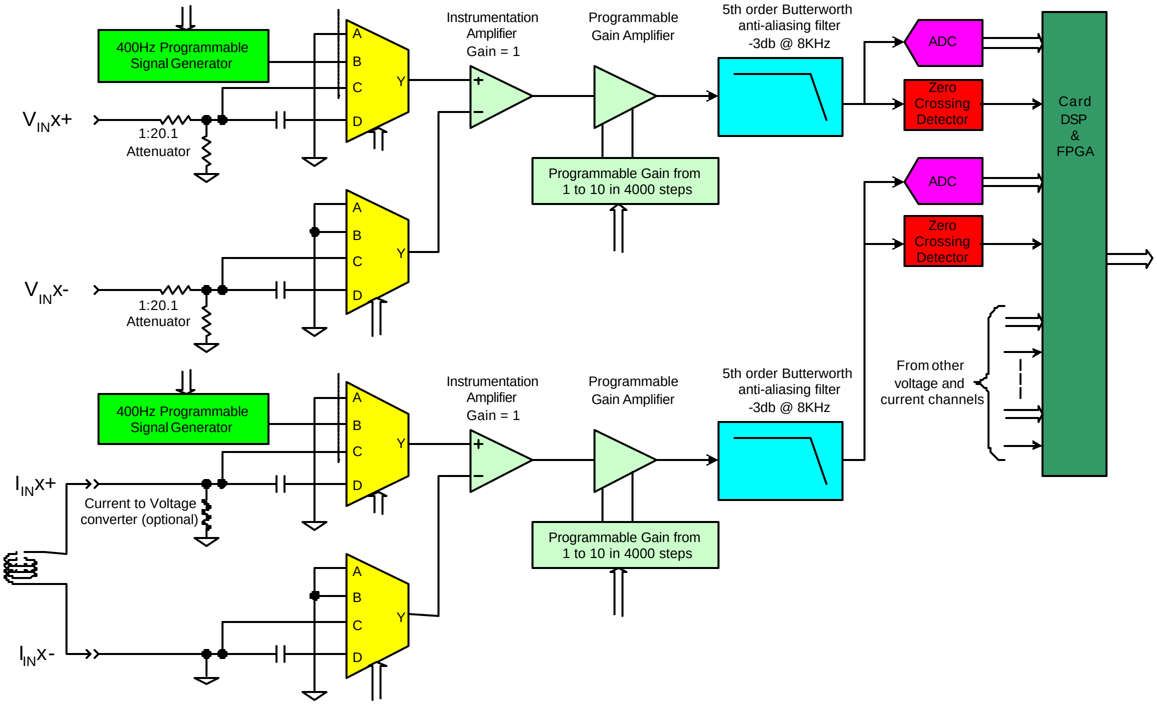


Figure 2: Example of a 3-phase power generator to be instrumented

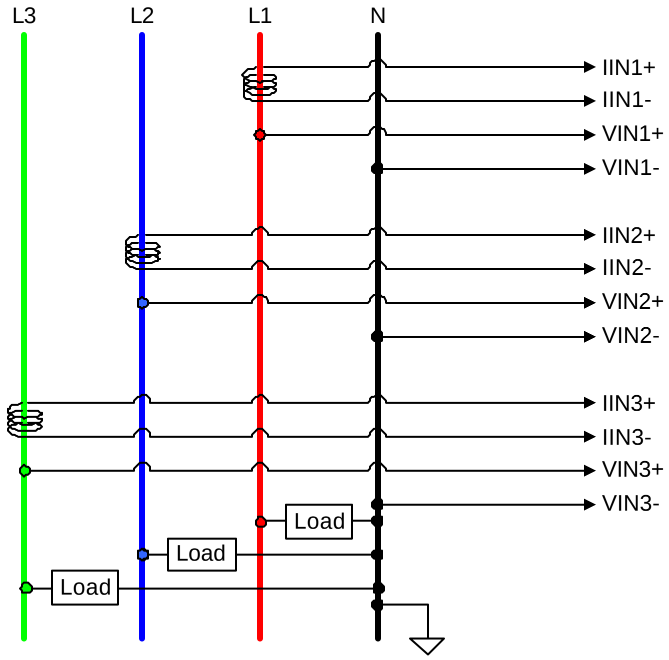
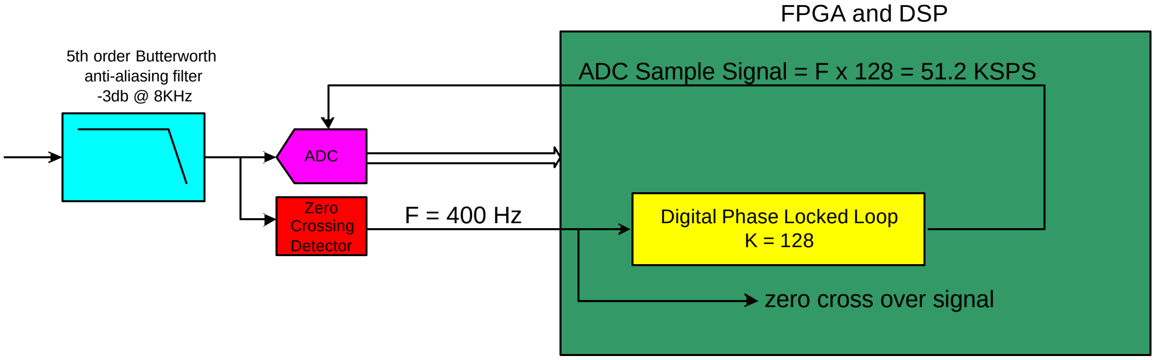


Figure 3: PMC-106A ADC Sampling Signal



MONITERED DATA AVAILABLE FOR ANALYSIS

The PMC-106A setup software allows any or all of the following parameters to be included in the PCM data stream. All selected parameters are read from a current value table that is updated every 40ms (25 times per second) unless otherwise stated.

Raw Channel Data (RAW):

The low-pass filtered, but otherwise raw, current or voltage channel output data. Raw channel data also includes the parasitic offset correction if that feature is selected in the PMC-106A setup software. The data update rate is 128 x the channel voltage frequency. At 400Hz, the data update rate = 51.2 KHz (19.53µs). RAW may be software configured as a 14-bit signed binary value or a 14-bit unsigned binary value. With the channel gain set to 1, the full scale input range for voltage channels is -205.81V to +205.81V and the full scale input range for current channels is -10.24V to +10.24V.

Peak Positive Amplitude (PPOS):

The peak positive voltage or current measured during the recording interval. PPOS is a 13-bit unsigned binary value.

Peak Negative Amplitude (PNEG):

The peak negative voltage or current measured during the recording interval, negated to provide a positive number. PNEG is a 13-bit unsigned binary value.

Peak To Peak Amplitude (PPA):

$$PPA = PPOS + PNEG$$

PPA is a 14-bit unsigned binary value.

Average Amplitude (AVG):

The average of the absolute values of voltage or current measured during the recording interval, calculated as shown below. AVG is an unsigned binary value scaled to 16-bits.

$$AVG = \frac{8}{N} \sum_{i=1}^{N} |di|$$

Where N = the number of samples collected during the sample period and di is the i^th^ data sample collected during the sample period. The constant 8, is a scaling factor used to provide a full scale 16-bit output for this parameter when the sampled data is at full scale.

RMS Amplitude (RMS):

The root mean square of the values of voltage or current measured during the recording interval, calculated as shown below. RMS is an unsigned binary value scaled to 16-bits.

$$rms = 8 * \sqrt{\frac{1}{N} \sum_{i=1}^{N} di^2}$$

Where N = the number of samples collected during the sample period and di is the i^{th} data sample collected during the sample period. The constant 8, is a scaling factor to provide a full scale 16-bit output for this parameter when the sampled data is full scale.

Phase Real Power (PWR):

The sum of products of the instantaneous voltage and current values measured during the recording interval, calculated as shown below. PWR is an unsigned binary value scaled to 16-bits from 0 to $|V_{Max}| * |I_{Max}|$.

$$PWR = \frac{1}{N * 2^{10}} \sum_{i=1}^{N} Vi * Ii$$

Where N = the number of samples collected during the sample period Vi is the i^{th} voltage sample and Ii is the i^{th} current sample collected during the sample period. The constant 2^{10}, is a scaling factor to provide a full scale 16-bit output for this parameter when both Vi and Ii are at their full scale values.

Phase Apparent Power (APR):

The product of the phase *rms* voltage and current values measured during the recording interval, calculated as shown below. APR is an unsigned binary value scaled to 16-bits from 0 to $|V_{Max}| * |I_{Max}|$.

$$APR = \frac{V_{RMS} * I_{RMS}}{2^{16}}$$

Where V_{rms} is the phase rms voltage and I_{rms} is the phase rms current measured over the sample period. The constant 2^{16}, is a scaling factor to provide a full scale 16-bit output for this parameter when both V_{RMS} and I_{RMS} are at their full scale values.

Phase Power Factor (PFAC):

The ratio of the phase real power and apparent power measured during the recording interval, calculated as shown below. PFAC is an unsigned binary value scaled to 15-bits from 0 (purely reactive) to 1 (purely resistive) with an additional inductive/capacitive indicator bit.

$$PFAC = LC \text{ [bit 15]} + \frac{PWR}{APR} * 32768 \text{ [bits 14 - 0]}$$

Where *LC* is 0 for inductive (V leads I) and 1 for capacitive (I leads V), PWR is the phase real power and *APR* is the phase apparent power measured over the sample period.

Period (PER):

The average period of the channel 1 voltage waveform (reference channel) measured over the sample period. This measurement is based on negative to positive zero crossings. PER is a 12-bit unsigned binary value in which each count represents 1.0 µs. The measurement range is thus from 0 to 4095 µs with a 400.00 Hz frequency providing a PER reading of 2500 or 94C hex (12bpw).

Phase (PHS):

The average time difference between positive going zero crossings of the selected phase voltage and the phase 1 voltage (reference channel) divided by the period, calculated as shown below. PHS is a signed binary value scaled to 16-bits from $-\pi$ radians to $+\pi$ radians (-180° to +180°). One count therefore equals $\pi/32768$ or 0.0000959 radians (180/32768 or 0.005493°).

$$PHS = \frac{\Delta TIM_S}{PER} * 32768$$

Where $DTIM_S$ is the average time difference in µsec between positive going zero crossings of the selected phase voltage and the phase 1 voltage (may be either positive or negative) and PER is the average period of the channel 1 voltage waveform as measured over the sample period.

Average 3-Phase Power (PAV3):

The sum of the real power for all three phases divided by 3 measured over the recording interval, calculated as shown below. PAV3 is an unsigned binary value scaled to 16-bits from 0 to $|V_{Max}| * |I_{Max}|$.

$$PAV3 = \frac{1}{3}\sum_{i-1}^{3} PWR_i$$

Where PWR_i is real power in phase i measured over the sample period.

Total Harmonic Distortion (THD):

Calculated for each voltage phase in sequence with a data update rate for each phase of 6.67 Hz (15ms). THD is defined as the square root of the sum of the squares of harmonic component voltages for harmonics 2 through 20 divided by the total rms voltage measured over the recording interval. THD is calculated as shown below. THD is an unsigned binary value scaled to 16-bits from 0 to 1.

$$THD = \frac{\sqrt{\sum_{i=2}^{20} VHrms_i^{\,2}}}{VTrms} * 65536$$

Where $VTrms$ is the total rms phase voltage and $VHrms_i$ is the rms voltage of the i^{th} harmonic only, measured over the sample period. Note that the rms voltage of the fundamental frequency (i=1) is NOT present in the numerator term.

CONCLUSIONS

The PMC-106A power monitor card is engineered to provide the user with an integrated capability for performing real-time monitoring of a 120 volt, 400Hz, 3-phase AC generator and its load. Alternatively, it may be used to monitor up to three (3) single-phase AC generators. Input to the card consists of six signals (3 voltages and 3 currents). The user may then select from up to 54 output parameters regarding the health of the power generation system and its load.

The card analyzes a previously collected block of data while simultaneously collecting the next data block (there is no potential for missing data if parameters of interest are sampled every 40ms or faster). Every peak positive, peak negative and peak-to-peak excursion within the analog bandwidth of the channel is captured. Engineering data calculations including FFT for providing total harmonic distortion measurements as well as extensive power and load calculations are provided on a single circuit card with minimal use of valuable data bandwidth.

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