Today's vision of a smart grid consists of an efficient, reliable, self-healing electricity distribution grid. To be successful, this grid must accommodate distributed resources while still generating energy needed by equipment such as massive fleets of electric vehicles. Because so much depends on this grid, it must function efficiently at all times. The typical, even normal, system faults and failures found with many complex systems simply can't be tolerated. Thus, the smart grid must automatically detect system faults and quickly isolate them for fast repair. Data-acquisition systems play an important role in keeping the electricity flowing.

Utilities worldwide are deploying smart grid devices that provide accurate, time-aligned information about loads which change constantly. To accurately collect electric-power data, voltage and current measurements must be simultaneously gathered for all power lines because utilities must understand the timing among phases and ensure maximum efficiency and uptime. The most demanding application is measurement of 3-phase power, which requires multiple, time-aligned analog inputs for voltage and current measurements.

**3-Phase electric-power measurements**

A 3-phase electric power system carries three phases of AC (alternating current) at the same frequency. Each phase is separated from the other by 120°. **Figure 1** shows the waveform of the 3-phase voltage.

![3-phase power waveform](image)

Figure 1. A 3-phase power waveform. The three phases are alternating currents (AC) with
the same frequency. Each phase is separated from the other by 120°.

Figure 2 shows the three single phases configured in 4-wire wye or star connection. A 3-wire wye connection is exactly the same as a 4-wire connection, but without the neutral line. The neutral line (black in Figure 2) that connects to the center of the wye configuration system is used with an unbalanced load. If the loads are well balanced, meaning that the currents taken from each phase are equal, the phase currents cancel one another and the neutral line carries no current. Consequently, a 3-wire connection is commonly used for a balanced load. The advantage of losing the fourth wire is the cost of the copper wire.

![Diagram of 4-wire wye configuration](image)

Figure 2. In 4-wire wye configuration, the neutral line (black) is used when the load is not balanced.

Power is the product of voltage and current across a load. A wattmeter consists of a current meter and voltage meter, used together to measure power. For a 3-phase, three-wire system, at least two wattmeters are required to measure the total power consumption, as shown in Figure 3. Total power is the sum of the wattage on the two wattmeters.
Figure 3. A 3-wire wye system load. Total power is the sum of the wattage on the two wattmeters.

A short digression for the circuit analysis of Figure 3 is worthwhile here.

Let the center of the 3-phase load be the 0V reference. Then:

\[
\text{Power} = (V_a \cdot I_a) + (V_b \cdot I_b) + (V_c \cdot I_c)
\]

\[
V_a = V_c + V_1
\]

\[
V_b = V_c + V_2
\]

\[
I_c = -(I_a + I_b)
\]

\[
I_a = A_1
\]

\[
I_b = A_2
\]

Therefore:

\[
\text{Power} = [(V_c + V_1) \cdot A_1] + [(V_c + V_2) \cdot A_2] - [V_c \cdot (A_1 + A_2)]
\]

\[
\text{Power} = V_1 \cdot A_1 + V_2 \cdot A_2
\]

Unfortunately, power on each phase can't be calculated with only two wattmeters. Three wattmeters, one on each phase, are required to measure the power on each phase, as shown in Figure 4. In this case, a neutral line is used as the ground reference. For the 4-wire, 3-phase system with imbalanced load, there is current on the neutral line. Although the current through the neutral line can be calculated by summing the current in all three phases, adding another current meter to measure the current on the neutral line is a simpler approach. In addition, this method provides better data in the event of current faults.
As illustrated in Figure 4, there are three voltage meters and four current meters. Each meter requires a current transformer or voltage transformer (to scale down the voltage or current) and an ADC (analog-to-digital-converter) to convert the analog voltage/current information into digital data. The central control unit will process this data and respond accordingly. Unlike DC power sources, the AC voltage and current on each phase changes over time, regardless of the load. Therefore, a data-conversion system must simultaneously sample the inputs to correctly calculate the instantaneous power.

One solution is to use seven individual ADCs, one for each voltage meter or current meter; the central control unit would interface with all the ADCs in parallel. But, this approach requires many control lines between the controller and the ADCs. A large controller package size might also be needed to support the numerous I/O pins. Instead, you can use a multichannel simultaneous-sampling ADC.

**Ensuring accurate 3-phase monitoring**

To accurately calculate instantaneous power consumption, a 3-phase power monitoring system must simultaneously sample all of the analog inputs. Also, the ADC system needs sufficient resolution, low distortion, and a fast sampling rate.

**Figures 5, 6, and 7** show an AC signal's FFT (fast-Fourier Transform) and DC histogram. These plots give important information about the performance of the data-acquisition system. FFT analysis of a block of the sampled data of a low-distortion, sinusoidal-wave input signal is often used to determine the system's dynamic specifications. A low-distortion signal source, one with higher resolution than the system being tested, is absolutely required. Some of the important dynamic specifications are:

- **SNR (Signal-to-noise ratio)**
- **THD (Total harmonic distortion)**
- **SINAD (Signal-to-noise and distortion ratio)**
- **SFDR (Spurious-free dynamic range)**

SNR is the ratio of the RMS (root-mean square) value of the input signal to the RMS quantization
error produced by the ADC. From the FFT diagram in Figure 5, the SNR is about 80 dB. This means that the RMS value of the input signal is 10,000 times greater than the RMS quantization error—calculated by using the formula $X_{dB} = 20\log(\text{ratio})$.

Clearly, the higher the ratio, the lower the ADC’s quantization error. Similarly, THD is the ratio of the input signal to the total harmonic distortion. SINAD is the ratio of the input signal to the quantization error plus harmonic distortions, and SFDR is the ratio of the input signal to the largest distortion component.

**Figure 5.** AC FFT for channel 7 (AIN7) using on-board power; a -10V to +10V, 10 kHz sine wave input signal sampled at 250 ksample/s and passed through Blackman-Harris window at room temperature. Data generated with the MAXREFDES30# subsystem reference design.
Figure 6. AC FFT for channel 7 (AIN7) using on-board power. A ±2.5V, 10kHz sine wave input signal sampled as 250ksamples/s passed through a Blackman-Harris window at room temperature. Data generated with the MAXREFDES30# subsystem reference design.

A histogram of a sampled DC signal is often used to determine the noise of the data-acquisition system. Because of noise, an ADC will produce codes around the main bin. The spread of the codes reveals the noise information of the A/D conversion system. The Figure 7 histogram shows the calculated standard deviation of 0.711 (which is equivalent to the effective resolution of 16.5-bits), and 97.7% of the codes fall within the first three center bins. In this case, the lower the standard deviation, the lower the system noise.
Figure 7. DC histogram for channel 7 (AIN7) using on-board power. A 0 V DC input signal sampled at 250 ksamples/s shows 65536 samples with a code spread of 21 LSBs. 97.7% of the codes fall within the three center LSBs. That produces a standard deviation of 0.711 at room temperature.

System example

An example of a system that meets all of these critical requirements is Maxim Integrated’s Petaluma (MAXREFDES30#) reference design. This subsystem reference design (Figure 8) is a highly accurate, low-power, AFE (analog-input front-end) targeted for distributed automation applications. Figure 9 shows the block diagram. The 16-bit accuracy and 8-channel operation let you collect smart-grid analog data from all phases simultaneously. The 250 ksample/s sample rate per channel accepts ±10V input signals and ensures accurate capture of fault events so utilities can take immediate action within a single cycle.
Today’s smart grid is an intelligent system that can monitor the distribution network, deliver power efficiently, and accommodate distributed alternative resources. Data acquisition plays a key role in
providing the information needed. The smart grid must accurately monitor the power on a 3-phase power distribution network, all phases simultaneously and in real time.

Thanks to Ted Salazar and Dave Andeen for their helpful review and critique of this article.