Exceeding 60-Year Life Expectancy from an Electronic Energy Meter

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1.0 Introduction

For many years, traditional electromechanical meters have been the instrument used by utility companies to measure residential and commercial power consumption. As the deregulation of the generation and distribution of power progresses, the price for electricity becomes increasingly competitive. Consumers are also demanding better customer service, higher power quality, higher energy measurement accuracy and more timely data. Utility companies are being forced to find solutions that will enable more sophisticated energy measurement methods, giving greater information on the population's power consumption. The Automated Meter Reading system (AMR) is one of the ways in which utilities are striving to achieve these goals and an electronic energy metering is considered the lowest cost solution to AMR.

Until recently, one of the major technological barriers faced by electronic meter manufacturers was the difficulty in producing accurate, yet low cost energy meters. Fortunately, within the last few years, semiconductor manufacturers have applied low cost CMOS processes and circuit technology to energy measurement ICs enabling manufacture of cost effective electronic energy meters with high accuracy. However, the reliability and accuracy of an electronic energy meter as an overall system have been questioned. We will discuss the results of a recent reliability study on an energy measurement IC, which helps to demonstrate the reliability of an electronic energy meter to be comparable to an electromechanical meter.

2.0 A look inside an electronic energy meter

The life expectancy of a meter depends on the life expectancy of each of its components as well as on the overall system architecture. It is impossible to estimate the life expectancy of an energy meter as a whole system unless the component materials and the manufacturing processes are known. Figure 1 depicts the five basic components of an electronic energy meter; input sensors, power supply, energy measurement module, display (counter) and passive components. It also shows how they interconnect. The AMR module shown in the figure can be included for additional functionalities.

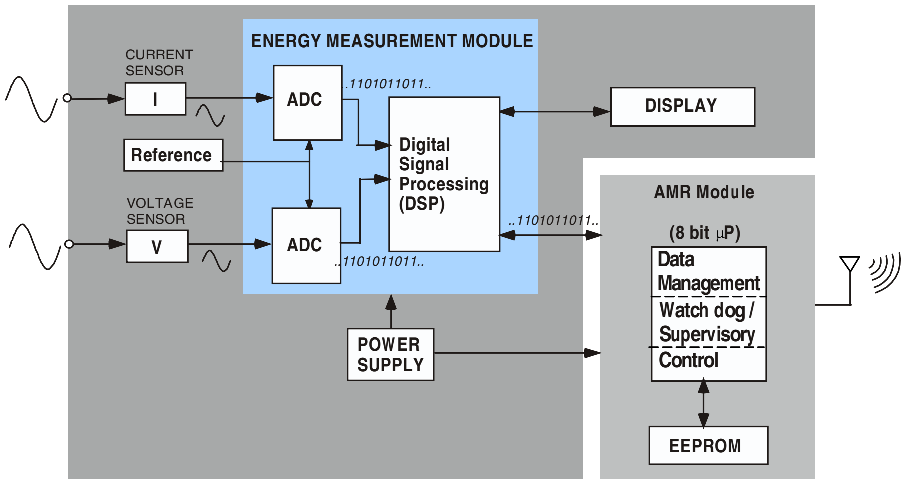


Figure 1: Functional block diagram of an electronic energy meter

There are many issues associated with choosing the necessary components to build an energy meter. Before any load consumption calculations can be made, an energy meter must be able to transform the load current and line voltage to a usable form. Current sensors such as shunts or current transformers (CTs) can be used to transform current to a voltage proportional to current at the interface with the energy meter. Several considerations when choosing a suitable current sensor are power consumption, thermal management (which includes heat dissipation), quality and performance over a wide current dynamic range. The meter must also include a voltage sensor such as a potential transformer (PT) or a resistive divider. The resistive divider also attenuates the line voltage to an acceptable input voltage for the energy measurement IC. When considering these sensors, the tradeoff for minimizing power dissipation and isolating the meter from the line voltage (electrical isolation) using the PT or CT is that they are more expensive solutions. Despite slightly higher power dissipation and no electrical isolation, a resistor-based sensor is an attractive choice in a cost-sensitive 2-wire application.

When designing a power supply, a designer can choose between a potential transformer (PT) and a capacitor-based power supply. In a capacitor-based design, a rectifier and capacitor divider network are used to attenuate the line voltage (e.g. 220V) to an acceptable input level for a DC voltage regulator.

In the heart of an electronic energy meter is an energy measurement IC, a fixed function DSP that calculates watts and accumulates watt-hours. The energy measurement IC must interface with the chosen sensors, accurately calculate power and interface with an external display. In a more sophisticated application such as AMR, it must also interface with a microprocessor for data management and other required housekeeping tasks.

The external display of an energy meter can either be mechanical or electronic in nature. A stepper motor counter is an example of a mechanical counter, while a digital counter and liquidcrystal-display (LCD) are examples of electronic counters. An advantage of using an LCD-display is that such a meter can display more than one type of information at a time. For example, the display could include power information in watts, kWh, apparent power (VA), power factor (PF) and/or meter temperature. The drawbacks are that LCDs are significantly more expensive than stepper motor counters and require non-volatile memory to store data in the event of a power shutdown.

Passive components such as resistors, capacitors, light emitting diodes (LEDs), and jumpers that are used in the attenuation, power supply and calibration network have associated accuracy, tolerance and life expectancy. For example, an electrolytic capacitor used in the power supply network may leak out before any other components in the energy meter fail. This paper focuses on the critical component responsible for power calculation, similar to the moving parts of an electromechanical energy meter.

3.0 Accuracy Issues with Electromechanical Meters

The induction principles of operation for an electromechanical energy meter are similar to that of an electric motor or other electromechanical devices. Therefore, we should acknowledge the inherent susceptibility of electromechanical devices to errors due to environmental variations and regular operation. We also note how the accuracy of electronic energy meters is not affected by many of these errors.

3.1 Errors due to Environmental Conditions

An electromechanical energy meter contains many moving parts that are prone to wear over time and varying operating temperature and conditions. The mechanical gears wear with exposure to dirt, dust and humidity, affecting the accuracy of the meter. Mechanical gear lubricants may also dry up over time and cause the gear teeth to break and lose their specified gear ratios. Furthermore, vibration and shock can lead to miscalibration of the meter and cause the spinning disk to jitter or possibly stop completely. Clearly, these errors do not affect the accuracy of an electronic energy meter because there are no mechanical moving parts.

3.2 Errors due to Meter Design and Operation

An electromechanical meter measures power by multiplying the magnetic flux of current and voltage. The mechanisms of its energy measurement such as iron cores, potential coils, current coils and braking magnets cause the meter to react to changes more slowly than do electronic energy meters. For example, low and high loading errors can often cause over-register or under-register because of an iron core's lack of linearity and inertia in the spinning disk. Low loading error is due to meter creep when all the loads are disconnected. High loading error at full load is caused by the reduced ability of the compensation mechanism (typically a magnetic shunt) to offset the increased intensity of the braking magnets as the load increases. A meter that is not compensated properly and a spinning disk tilted at an angle can experience severe under-register. Furthermore, at power-up and power-down or when an electromechanical meter jumps from a high reading to a low one, its scale factor, linearity, drift and instability can change permanently [10].

4.0 Motivation for Long Life Expectancy

The main motivation for long life expectancy in an energy meter is to reduce system cost and maintenance. It is known that electromechanical energy meters wear out with time and require periodic calibration to maintain their accuracy. Periodic calibration translates to labor, which means more cost.

Electronic energy meters are more stable because the power calculation is done digitally and the absence of many mechanical and magnetic components reduces the number and magnitude of errors due to environment, use and age. In addition to accuracy and stability, electronic energy meters offer greater design flexibility and the ability to upgrade. Because the output of the electronic energy meter is digital, it can potentially interface with communications modules to allow greater design flexibility. Enabling communications between an electronic meter and a base station allows remote meter reading thus reducing the overhead utility costs. In addition, load profiling, prepayment and multi-tariff billing would be made possible. Utility companies would have more control over their ability to provide more efficient power over the grid. As more information such as power factor could be calculated, power generation companies would be able to maintain cleaner power distributed over the grid and reduce the cost associated with building additional power generator equipment. Utility companies would also be able to detect power outages more quickly.

5.0 Semiconductor Reliability

For many years the electromechanical energy meter has provided a cost effective and “reliable” energy measurement solution. With this kind of proven reliability, any new meter technology will have to have a comparable or better operating life. For a solid-state metering solution, the reliability of semiconductor devices and the parameters that affect it are important considerations.

Semiconductor reliability is typically depicted with the *Bathtub Curve* shown in Figure 2. This curve shows the failure rate of products with respect to time and is made up of three individual curves related to infant mortality, useful life and wear-out.

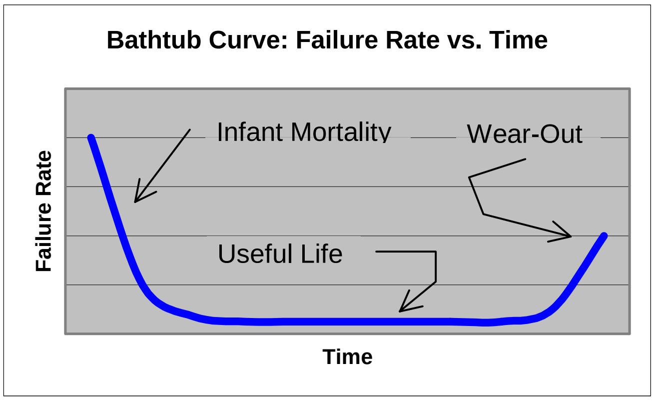


Figure 2. Bathtub Curve

Each region is characterized separately with potential failures classified as quality failures, random failures, and wear-out failures, respectively. The early life failures can be manufacturing related, such as process-induced defects, and would be characterized by a decreasing failure rate over time. Random failures occur for a variety of reasons and usually account for only a very small number of failures. They are characterized by a constant failure rate. The wear-out failures, on the other hand, are inherent process limitations and are generally well characterized before process release. These failures would be due to such mechanisms as oxide wear-out, electromigration, and hot carrier effects, all of which limit the life of the product. The wear-out region is characterized by an increasing failure rate over time. The ideal shape to the curve is to have a very long useful life period and a low amount of quality defects.

5.1 Semiconductor Failure Mechanisms

For purposes of discussion, semiconductor failures will be categorized as either intrinsic failures or extrinsic failures. Intrinsic failures are those failures that are related to the component's design, wafer fabrication, package assembly, etc., and caused during operation within the specified use conditions. Examples would include time dependent dielectric breakdown, electromigration, hot carrier effects and ionic contamination.

Extrinsic failures are failures typically related to use outside the specified use conditions (e.g. electrical overstress, overload conditions, misapplication, etc.). These types of failures are usually attributed to the component end-user, but, as will be discussed later, the semiconductor manufacturer can ensure that the components can handle many of the external overstresses [1].

5.2 Building In Reliability

The reliability of any semiconductor component depends on the design, wafer fabrication, assembly and product test. By using reliability-guided design and manufacturing rules for each of these stages, component reliability can be "built-in".

For intrinsic-related failures, reliability can be built-in through the use of statistical process controls throughout the wafer fabrication and package assembly processes to effectively eliminate process-induced defects such as foreign particles and contamination. Engineering of the fabrication process and device-level structures can enhance the reliability of CMOS transistors to minimize the effects of gate oxide wear-out and hot carriers. The use of circuit design rules and layout checkers can ensure circuit elements and interconnects will not prematurely wear-out such as in the case of electromigration. Lastly, assembly-related design rules ensure the integrity and reliability of the finished package.

Extrinsic failure related reliability can be increased by building-in robustness through design and layout of the circuit, as well as utilizing advanced materials that protect the integrated circuit die from physical abuse and damage. The use of proven protection circuitry can increase the component robustness to electrostatic discharge events and other electrical overstress transients. Proper layout of the circuit can decrease susceptibility to latch-up and other transient related failure mechanisms [8].

5.3 Reliability Stress Testing

An integrated circuit can potentially undergo a number of stresses during its lifetime. Reliability stress tests have been designed to evaluate the effects of these stresses over time. The function of reliability stress testing is to evaluate how the product will perform when used in the machines, systems, and environment for which it is manufactured.

Because of the different types of failures that can occur, many different reliability stress tests can be applied to a product. Generally, they are separated into electrical-, thermal- and moisture-related tests that have been developed and refined over time. Various models exist to extrapolate the accelerated test conditions to useful lifetime predictions.

In product stress testing, the main emphasis is on the useful life section of the bathtub curve. The test methodology used to predict the useful life period is usually an electrically biased life test, sometimes referred to as High Temperature Operational Lifetest (HTOL). This industry-standard stress test is conducted by loading ICs onto special boards that apply DC bias and AC signals to the IC while they are in a high-temperature oven. HTOL is typically designed to maintain an IC junction temperature of 125^{o}C to 150^{o}C for a period of time ranging from hundreds to thousands of hours. Full electrical testing of the ICs is conducted at set time intervals to determine the failure rate of the ICs.

In order to relate the high stress temperature to a more normal equipment operating temperature, the Arrhenius relationship is used. The Arrhenius equation determines the amount of acceleration achieved by stress of the samples at evaluated temperature, activating any latent failure mechanisms. A key factor in the equation is the value of activation energy used to simulate the acceleration. The activation energy is considered to be an energy barrier that separates reactants from products in a chemical or physical process and the value is specific to the failure mechanism [1]. For purposes of standardization, a value of 0.7 eV is often used as an activation energy for life test reliability predictions within the semiconductor industry.

The temperature acceleration factor, T_{acc} derived from the Arrhenius equation is defined as

$$T_{acc} = exp[(E_a/k)*(1/T_a - 1/T)]$$

where E_a is the activation energy (eV), k is Boltzmann's constant (8.62E-5 eV/K), T is the accelerated life test temperature (Kelvin) and T_a is the operating use temperature (Kelvin).

Figure 3 depicts the acceleration factor (T_{acc}) when correlated from an accelerated life test temperature of 150°C to various operating use temperatures. Figure 3 also depicts calculated lifetimes from data obtained in which 73 Analog Devices' AD7755 ICs were subjected to an accelerated life test at 150°C for 3000 hours. Therefore, a life test performed at 150°C would provide an acceleration factor of 179x and a calculated lifetime of 60 years when correlated to an operating temperature of 60°C. Figure 4 shows parameter distributions and shifts from the same experiment, which yielded zero failures and no device degradation over the duration of the life test. The dots represent outliers.

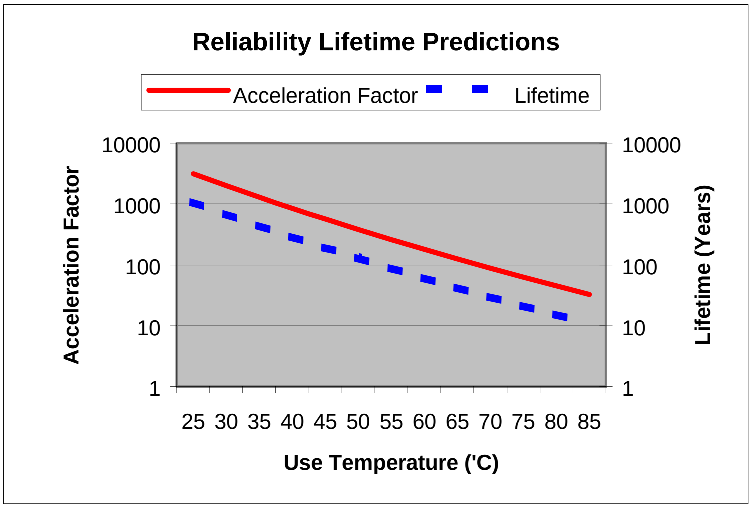
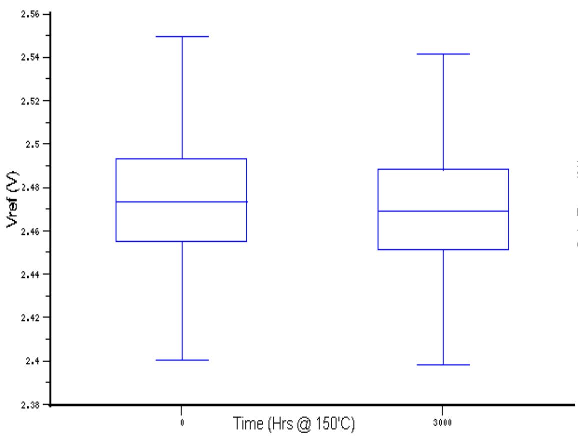
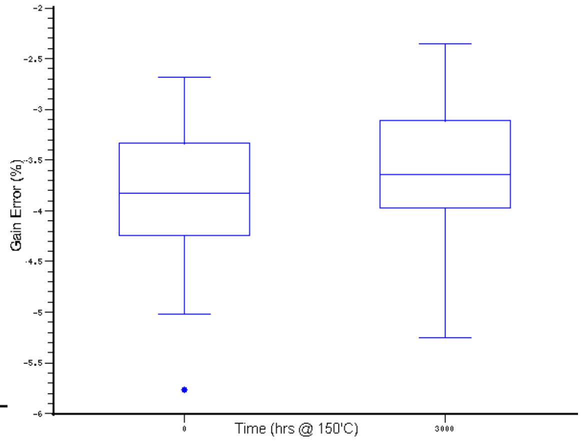


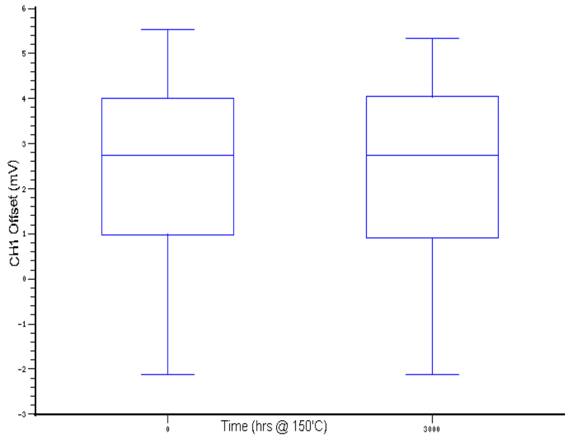
Figure 3. Acceleration factor and lifetime predictions in relation to temperature used.



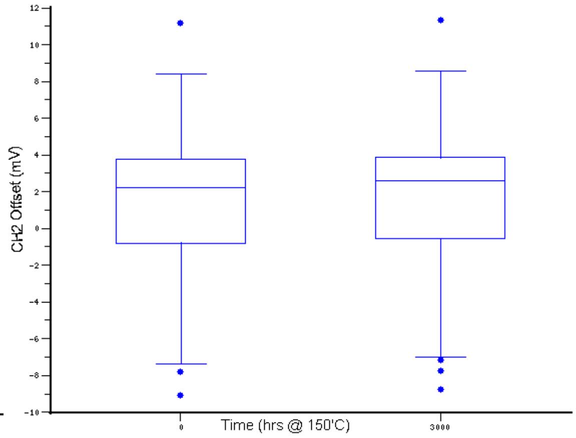
a. Reference Voltage



b. Gain Error



c. Current Channel Offset (16X)



d. Voltage Channel Offset

Figure 4. Parameter ranges and means at t=0 and after 3000 hour life test at 150^{o}C.

6.0 Conclusions

The High Temperature Operational Lifetest (HTOL) results that show that an energy measurement IC can achieve a 60-year life expectancy at an operating temperature of 60 degrees Celcius brings us another step closer to accepting electronic energy meters as the energy meter of the future. A very important fact to keep in mind when designing an energy meter is to carefully select each component to ensure a long life expectancy and accuracy of the entire system. Although it may be argued that it is very costly to replace all the existing electromechanical meters in the world with electronic energy meters for all the benefits that they bring, it is even more costly to tolerate the inaccuracies of electromechanical meters and be bound to their limited functionalities. After all, what is the use of longevity without accuracy? The perception of reliability of any measurement instrumentation should not only be limited to long life expectancy but should also include consistent performance [6].

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