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Real World Measurement Errors in Smart Meters

Qile Zhang

School of Electrical, Electronic and Mechanical Engineering, University of Bristol, Bristol, UK
mc24996@bristol.ac.uk

Abstract. The increasing use of nonlinear electrical loads and power electronic devices has created new challenges for accurate energy measurement in modern distribution networks. Although smart meters are normally tested under controlled laboratory conditions, their accuracy is still affected by real world disturbances such as harmonic distortion, electromagnetic interference, sensor nonlinearity, and limitations in measurement circuits. This paper reviews the main sources of measurement errors in smart meters and analyses how these errors affect the measurement process. This paper places particular focus on nonlinear loads, harmonics, electromagnetic interference, and errors introduced by sensors, analogue front-end circuits, and analogue-to-digital converters. This paper also discusses a representative case study of a static energy meter affected by conducted electromagnetic interference. The case demonstrates that high frequency components generated by nonlinear household appliances can cause significant energy measurement errors. The use of an analogue low pass filter was shown to reduce the reported error from 1632% to below 2.5%. Then this paper reviews existing mitigation methods, including filtering, Hardware EMI Suppression, compensation, and signal processing. Finally, the limitations of current research and possible future directions are discussed. The review indicates that reliable smart meter operation requires a measurement system designed to account for realistic electrical environment conditions.

Keywords: Smart electricity meter, electrical energy metering, measurement error, nonlinear load, electromagnetic interference

1. Introduction

The development of smart grids has increased the importance of accurate electrical energy measurement. Over the past ten years, the power network has continued to develop, and the smart grid has been implemented at all levels. Therefore, the accuracy of smart-meter measurements can directly influence both consumers and electricity suppliers. In addition, measurement data collected by smart meters also can be used by other power systems. This means that unreliable measurement data may affect subsequent analysis and control.

However, practical distribution networks rarely operate under perfectly sinusoidal conditions. With the increasing use of electronic equipment, a large number of nonlinear loads are introduced into residential and industrial networks. Devices such as microwave ovens, desktop computers, battery chargers, and air conditioners may result in distorted current waveforms. Studies of

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residential distribution systems have demonstrated that harmonic distortion is present under realistic operating conditions [1]. The interaction between different nonlinear loads can further change the waveform and influence electrical energy measurement [2].

Harmonic distortion is not the only problem. Modern electronic appliances can also generate high-frequency current components. These components may enter the measurement system as conducted electromagnetic interference (EMI), and they become more pronounced as the measurement bandwidth expands. Therefore, the bandwidth used in the electricity meter measurement is particularly important. Although this can improve waveform information, it may also increase susceptibility to electromagnetic disturbances [3].

A recent experimental study provides a clear example of this problem. Hartman et al. used a Rogowski-coil current transducer to investigate a static energy meter and found that conducted EMI generated by nonlinear household appliances could cause very large measurement errors [4]. This result shows that a disturbance containing only a relatively small amount of useful energy can still produce an obviously large measurement error when it interacts with the frequency response of the measurement system.

Measurement errors can also be caused by the components inside the smart meter. Current and voltage sensors may have gain errors, phase errors, nonlinearities, and frequency dependent characteristics. Voltage transformer nonlinearities, for example, can affect the measurement of distorted waveforms and require compensation techniques to maintain measurement accuracy [5]. After the sensor stage, analogue front-end circuitsand analogue to digital converters can cause additional offset, gain, quantisation, and sampling errors.

Therefore, various techniques have been developed to improve smart-meter accuracy. Advanced power calculation methods can improve measurement under nonsinusoidal conditions [6]. Calibration and online error-estimation techniques can compensate for measurement-chain imperfections [7]. And filtering can prevent unwanted high-frequency disturbances from entering the measurement system.

Although many studies have investigated individual error sources, the effects of real world disturbances on the complete smart meter measurement chain remain an important topic. Therefore, this paper reviews the major sources of measurement errors in smart meters and analyses their effects on measurement accuracy.

2. Error sources

2.1. Nonlinear load

Nonlinear loads are one of the main sources of waveform distortion in modern electrical networks. Different from conventional resistive loads, when a nonlinear electronic device receives a sinusoidal voltage, it does not necessarily draw a sinusoidal current.

Switching power supplies are a good example. Their input current is normally concentrated around particular parts of the voltage cycle, resulting in a distorted waveform. LED lighting, computers, televisions, variable-speed drives, and battery chargers can produce similar effects.

The current waveform of a nonlinear load can be expressed as a combination of the fundamental component and harmonic components, as shown in equation (1):

$$i(t) = I_1 sin(\omega t + \phi_1) + \sum_{h=2}^{\infty} I_h sin(h\omega t + \phi_h) \quad (1)$$

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Here, I_1 represents the fundamental current, while I_h represents the amplitude of the h-th harmonic.

The presence of several nonlinear loads can make the situation more complicated. Different appliances may operate simultaneously and produce different harmonic components. Their currents can interact through the distribution network, resulting in a combined waveform that differs significantly from the waveform produced by any individual device [2].

Thus, a smart meter operating in a real household cannot be considered to be measuring one simple load. Instead, it measures the combined electrical behaviour of many devices.

2.2. Harmonics

Harmonics are frequency components whose frequencies are integer multiples of the fundamental frequency. For example, in a 50-Hz system the second harmonic occurs at 100 Hz, the third at 150 Hz, and so on.

A common parameter used to describe current distortion is total harmonic distortion (THD). For the current waveform this quantity is usually written as the total harmonic distortion of current (THDI), defined in equation (2):

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \tag{2}$$

A high value of THD_I means that a considerable proportion of the current consists of harmonic components. Harmonics can affect energy measurement in several ways. For the current,they change the shape of the measured current waveform. For the voltage,harmonic currents can interact with the impedance of the distribution network and cause voltage distortion. In addition, the measurement system will respond differently to different frequency components.

Research into residential distribution systems has shown that harmonic distortion exists under realistic household operating conditions [1]. So smart meters cannot simply be tested usingsimplified sinusoidal voltage and current signals. Such tests may not fully represent the conditions experienced after installation.

This problem will be more significant when nonlinear loads operate simultaneously. Experimental research has shown that harmonic interactions between loads can influence power quality and electrical energy measurement [2]. Consequently, when considering smart meter accuracy analysis, harmonic distortion should be an important part.

2.3. Electromagnetic interference

Electromagnetic interference (EMI) represents another important source of real-world measurement error. Modern nonlinear appliances can generate rapidly changing current waveforms. A steep current pulse contains not only the fundamental component but also higher-frequency components. These components may propagate through the electrical network and enter the smart-meter measurement circuit.

The problem is particularly important for current sensors with wide bandwidth. A sensor designed to reproduce a wide range of frequencies may also respond to unwanted high frequency disturbances. Hartman et al. analysed the relationship between measurement bandwidth and electromagnetic compatibility in energy measurement systems [3]. Their research pointed out thata

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wider measurement bandwidth does not necessarily lead to better energy measurement because high frequency components may increase the system's susceptibility to interference.

This issue was demonstrated experimentally in a static energy meter [4]. The study showed that conducted EMI generated by nonlinear household appliances could cause extremely large errors in the measured energy. Therefore, electromagnetic interference should be considered as part of the measurement accuracy problem.

2.4. Measurement error

Errors can also be generated inside the smart meter itself.

The first stage is usually the voltage and current sensing system. Sensors may cause gain errors, offset errors, phase errors, nonlinearities, and frequency-dependent responses. These effects become more pronounced whenthe input waveform contains harmonics. Voltage transformer nonlinearity provides an example. D'Avanzo et al. investigated compensation methods for voltage-transformer nonlinearities and demonstrated the importance of considering sensor behaviour when measuring distorted waveforms [5].

The analogue front end introduces another group of errors. The analysis of harmonics and the elimination of harmonics will be typically carried out in this section [8]. In this part, the amplifiers can have offsetand gain errors, while analogue filters can change both amplitude and phase. Component tolerances and temperature variation can also change circuit characteristics.

After analogue conditioning, the signals are converted into digital values using an analogue-to-digital converter (ADC). The ADC causes offset, gain, and linearity errors. The way in which power quantities are then computed in the digital domain also matters, because different calculation methodologies can give different energy results for the same distorted waveforms [9]. Sampling frequency also limits the range of frequency components that can be represented accurately.

These errors demonstrate that there are also many sources of error within the smart meter.

3. Analysis

3.1. Error propagation

The smart meter measurement process can be simplified as shown in Figure 1.

Therefore, errors introduced at an early stage can affect all subsequent stages. For example, the digital system calculates instantaneous power using the measured voltage and current, as given in equation (3):

$$p(t) = v(t)i(t) \tag{3}$$

Here, p(t) denotes the instantaneous power in watts, while v(t) and i(t) denote the instantaneous voltage in volts and the instantaneous current in amperes. Then, the energy is obtained by integrating the calculated power, as shown in equation (4):

$$E = \int p(t)dt \tag{4}$$

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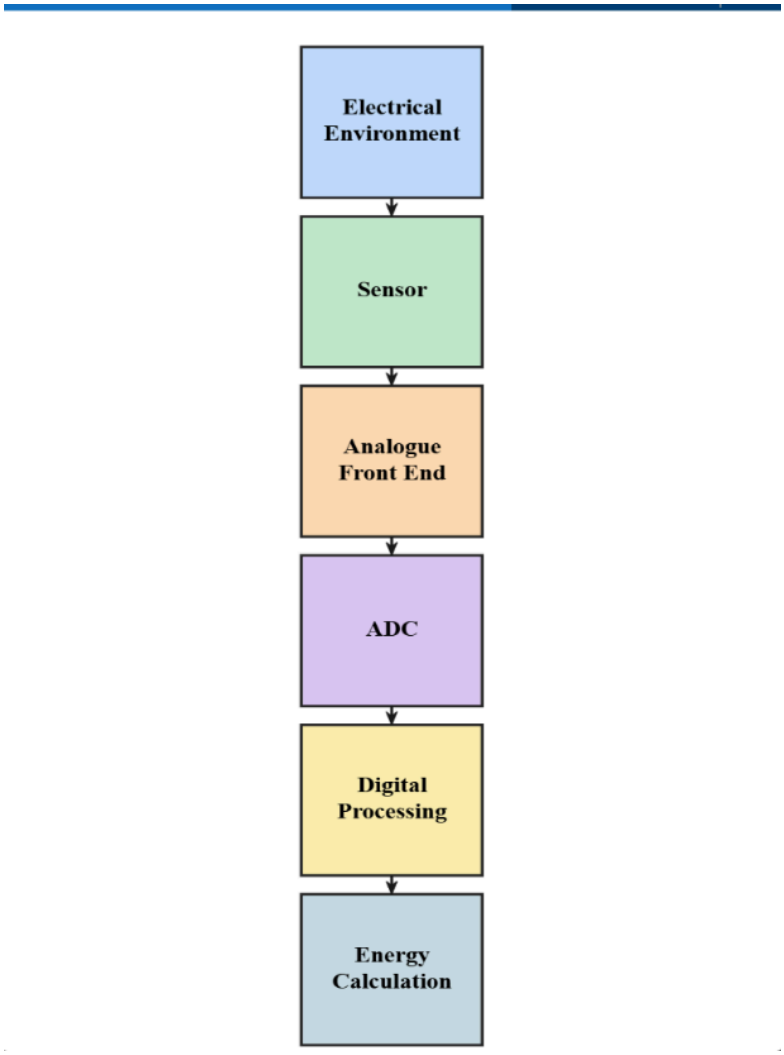


Figure 1. Smart meter measurement flow chart (picture: original)

Here, E denotes the electrical energy in watt-hours, p(t) the instantaneous power in watts, and dt the infinitesimal time interval in seconds over which the power is integrated. So, if the measured current has unwanted high frequency components, these components can influence the calculated instantaneous power. On the basis of the phase and frequency characteristics of the measurement chain, the resulting error can appear as either overestimation or underestimation of energy.

For example, consider a nonlinear household appliance. If the current sensor has a wide frequency response, these components will be detected by the sensor. The analogue front-end then amplifies the signal, and the ADC may convert it into digital samples. Therefore, in the process of error analysis, not only the disturbance of the original signal should be taken into account, but also the results after the signal propagates through the measurement chain.

3.2. Case study

A particularly useful example is the experimental investigation of conducted EMI in a static energy meter reported by Hartman et al. [4].

The study considered a static energy meter using a Rogowski-coil current transducer. Nonlinear household appliances were used to generate steep current pulses. These pulses contained high

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frequency components which could couple into the current measurement system. The important observation was that the energy meter did not simply ignore the high frequency disturbance. Instead, the disturbance interacted with the frequency response of the current sensor and measurement circuit, producing a significant error in the measured energy.

Then the researchers introduced a simple first-order analogue low-pass filter between the current transducer and the amplifier. This filter aims to preserve the fundamental 50 Hz component while attenuating high frequency interference. The result was significant. The reported error was reduced from 1632% to below 2.5% [4].

This research provides important support for the subsequent analysis. First, the existence of high frequency components in a current waveform does not mean that these components must always be measured. If they contribute little useful information to the required energy calculation but strongly affect the measurement system, filtering them can improve accuracy.

Second, a simple hardware solution can sometimes be more effective than a complicated digital algorithm. The analogue filter prevents unwanted interference from entering later stages of the measurement chain.

Third, the result demonstrates the importance of designing a smart meter for its actual measurement objective. For example, a power quality analyser may require a wide bandwidth; the smart electricity meters used for billing may requiregreater resistance to high frequency interference.

Therefore, this case explains that real world smart meter accuracy depends not only on the accuracy of individual components but also on how the complete measurement system responds to realistic electrical disturbances.

4. Mitigation methods

4.1. Filtering

Filtering is one of the most direct methods for reducing unwanted measurement components.

A low pass filter can be placed before the ADC or amplifier. Its purpose is to filter unwanted high frequency components while maintaining the frequency range required for energy measurement.

The previous analyzed cases have also confirmed this approach. The use of a first order analogue low pass filter reduced the measurement error from 1632% to below 2.5% [4]. Another filtering method is digital filtering. After the analogue signal has been sampled, digital filters can remove selected frequency components. The advantage is that digital filters can be modified through software and can provide more flexible frequency responses.

However, digital filtering cannot completely replace analogue filtering. If a high frequency disturbance is super large, it may overload the analogue circuit or ADC before digital processing takes place. Therefore, analogue and digital filtering can be used together.

4.2. Hardware EMI suppression

Another way to enhance the reliability of smart meter's measurement is by using hardware to suppress electromagnetic interference. Using ferrite beads is a common practice; ferrite beads can be placed on power supply lines or sensitive circuit connections to suppress high frequency interference. The principle is their frequency dependent impedance, so they allow low-frequency signals to pass with little attenuation while reducing unwanted high-frequency noise. Bačmaga et al. investigated the high frequency impedance characteristics of surface-mount ferrite beads and showed significant EMI suppression through modeling [10].

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Other hardware methods, such as electromagnetic shielding and shortening the distancebetween the power supply and the chip, can also reduce interference entering the measurement.

4.3. Compensation

Another method is to use known or predictable errors to improve measurement accuracy, which is called compensation. For example, if the frequency response of a current or voltage sensor is known, a digital compensation algorithm can be designed to correct the amplitude and phase errors caused by the sensor. The study by D'Avanzo et al. demonstrated compensation techniques for voltage-transformer nonlinearities [5]. Such method can improve measurement performance without requiring the physical sensor to be completely redesigned.

Compensation can also be used for other types of error, such as temperature. If the relationship between temperature and sensor gain is known, the measurement system can adjust the measured value according to the measured temperature.

4.4. Signal processing

The most flexible method for improving measurement accuracy is signal processing. Modern smart meters can use digital algorithms to calculate active power, reactive power, apparent power, and harmonic components. Field-programmable gate array (FPGA)-based systems have been investigatedfor energy measurement under sinusoidal and nonsinusoidal conditions [6].

Such systems can separate different frequency components and apply appropriate calculation methods. This is particularly useful when the electrical environment contains nonlinear loads.

Online error estimation provides another application of signal processing. Kong et al. proposed an online method for estimating smart-meter measurement errors using an Extended Kalman Filter and a limited memory recursive least squares method [7].

The advantage of online estimation is that the measurement system can potentially identify changing errors during operation. Thus, it can promptly correct the errors. However, advanced signal processing methods require additional computational resources. Therefore, it needs to find balance between cost, accuracy and complexity.

5. Limitation and future perspectives

5.1. Limitations

Although existing research has demonstrated several important error analyses, there are still limitations.

First, laboratory experiments cannot perfectly reproduce the complexity of real residential electrical networks. Real households may contain many nonlinear appliances operating at the same time. Their operating states change continuously, producing a time-varying electromagnetic environment.

Second, different studies use different measurement systems and test conditions, with differences in sensors, measurement bandwidth, loads, network impedance, and error definitions. These differences make direct comparison difficult.

Finally, some studies focus on one error source in isolation. In practice, harmonic distortion, EMI, sensor nonlinearity, temperature variation, and ADC errors can occur simultaneously. Their combined effects may differ from the effect of each individual error.

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5.2. Future perspectives

Future research should focus more strongly on realistic operating environments.

One important direction is the development of more realistic laboratory test systems. These systems should include multiple nonlinear household loads, distributed generation, realistic network impedance, and controlled EMI sources. It can help to conduct tests that are more in line with reality.

Another direction is adaptive measurement. Instead of using a fixed measurement bandwidth, a smart meter could change its bandwidth according to the application. For ordinary energy measurement, a lower bandwidth could provide stronger EMI resistance. When detailed power-quality information is required, the system could temporarily use a wider bandwidth.

The combination of analogue and digital techniques is also promising. Analogue filtering can prevent strong high frequency disturbances from entering the measurement chain, while digital processing can correct residual sensor and circuit errors.

As smart meters become increasingly connected, online calibration and error estimation may also become more important. Instead of depending entirely on factory calibration, future systems could continuously monitor their own measurement performance and identify abnormal behaviour.

6. Conclusion

With increasingly complex electrical environments, nonlinear loads and power electronic equipment are widely used. These have introducedharmonic distortion and high frequency disturbances into distribution networks. These conditions can affect the accuracy of smart meter measurements, particularly when conducted electromagnetic interference interacts with sensors and analogue front-end circuits.

The analysis presented in this paper shows that measurement errors can originate from several stages of the measurement chain. Nonlinear loads produce distorted current waveforms, harmonics modify the electrical environment, and electromagnetic interference can enter the measurement system. After that, sensor characteristics,analogue circuits, ADCs, and digital algorithms can then further influence the final result. The static energy meter case used in this paper provides a clear demonstrationof the practical significance of these effects.

There are several methods for suppressing these disturbances, including filtering, Hardware EMI Suppression, compensation, and signal processing. Each method has advantages and limitations. Filtering is simple and can guard against high frequency interference; hardware EMI suppression can achieve the same result in a different way,compensation can correct sensor characteristics, and digital signal processing can provide flexible measurement and error estimation functions.

Overall, accurate smart meter measurement needs to consider the complete measurement system and its real operating environment. In the future, research should focus on realistic field testing, adaptive measurement, integrated analogue-digital error mitigation, and online calibration. These developments can improve the reliability of smart meters as electrical networks become increasingly complex.

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