Approved as an American National Standard

ANSI Approval Date: May 18, 2021

NEMA Standards Publication ESM1-1 2021

Electrical Submeter—General Requirements

Published by

National Electrical Manufacturers Association
1300 North 17th Street, Suite 900
Rosslyn, Virginia 22209

www.nema.org

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Foreword

In the preparation of this Standard, input from users and other interested parties has been sought and evaluated. Inquiries, comments, and proposed or recommended revisions should be submitted to the concerned NEMA product subdivision by contacting the:

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1 General

1.1 Scope

This part, ESM1-1, specifies general requirements of the ESM1 Standard, which covers metrological requirements and associated testing for electrical energy submeters. The Standard applies to direct meters or metering systems comprising meters and associated sensors. These meters provide details of energy use for energy monitoring or revenue submetering.

The Standard does not apply to primary utility-owned meters.

The Standard applies to AC and DC kilowatt-hour meters, demand meters, load survey meters, and power quality meters, single and four-quadrant meters, etc.

The Standard applies to indoor and outdoor applications, portable, permanently installed, and embedded meters.

The Standard applies to AC meters rated at not more than 1000 V that measure active energy, apparent energy, reactive energy (capacitive, inductive and/or total) including received, delivered, and/or net and also those measuring current, voltage, active power, apparent power, reactive power (capacitive, inductive and/or total), power factor, phase angle, polarity, and frequency when measured in addition to energy.

The Standard also applies to DC meters rated not more than 1500 V that measure energy received, delivered, and/or net and also those that include additional measurement of power, current, and voltage.

The ESM1 Standard is broken into the following parts:

a. ESM1-1 General Requirements
b. ESM1-2 AC Active Energy Accuracy
c. ESM1-3 Revenue Submetering Requirements
d. ESM1-4 Additional Measurements Accuracy
e. ESM1-5 DC Energy Accuracy
f. ESM1-6 Power Quality Measurements and Accuracy
g. ESM1-7 Current Sensor Accuracy
h. ESM1-8 Demand Metering
i. ESM1-9 Field Testing

1.2 Definitions

1.2.1 Accuracy

The extent to which a given measurement agrees with the defined value. (from ANSI C12.1-2014)

1.2.2 Accuracy Class

The accuracy class is a nominal accuracy in percent from which particular test limits are determined. Some test limits may be higher or lower than the accuracy class. The accuracy class is written without the percent sign.

In the Standard, where a placeholder is used for accuracy class, it will take the form of C, C1, C2, etc. A variable like C1 does not mean class 1, but instead refers to a particular accuracy class, such as the accuracy class for active energy, as opposed to reactive energy.

See 2.12~~2.1~~ **Meter Accuracy Classes** below for more information.

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1.2.3 Accuracy Class, System

The accuracy class of a complete meter system, either a direct meter system or a sensor meter system. In a sensor meter system, the system accuracy class combines the class of the meter and the nominal accuracy class of any external sensors. See also **2.1.2~~2.1.2~~ Accuracy Class, Sensor Meter System**.

1.2.4 Accuracy Class, Meter Only

The accuracy class of a meter only system without some or all sensors attached or specified.

1.2.5 Accuracy Class, Sensor Only

The nominal accuracy class of a sensor intended for use in a complete system meter.

1.2.6 Control Power Connections

The control power connections are the meter connections used to power meters. Some meters may use the same connections for power and measurement; in this case, the shared connections are the control power connections and the line voltage measurement connections.

1.2.7 Line Voltage Measurement Connections

The line voltage measurement connections are the meter line voltage connections used for measurement. Some meters may use the same connections for power and measurement; in this case, the shared connections are the line voltage measurement connections and the control power connections.

Some meters use external voltage sensors, such as potential transformers. In this case, the line voltage measurement connections are on the external sensor primary.

1.2.8 Calibration

Comparison of the indication of the instrument under test, or registration of the meter under test (MUT), with an appropriate standard. (from ANSI C12.1-2014)

1.2.9 Circuit

A combination of multiple conductors that provide electrical power to a load. A circuit is measured by one or more meter elements.

1.2.10 Current, Rated

The nameplate current for a current sensor or direct meter. This will be the highest current used for the current sensor accuracy and meter Load Variation tests. This may be lower than the maximum allowable current. This is also referred to as Full-Scale Primary Current.

1.2.11 Current Sensor

A device able to measure and output analog or digital representations of one or more currents. Examples of current sensors are current transformers, low-voltage current transducers, and Rogowski coils.

1.2.12 Delivered

This is energy or power flowing from the grid or source. For reactive energy and power, an inductive load results in delivered reactive energy. Apparent power and energy are non-signed quantities, so this Standard does not define a distinction between delivered and received apparent power. See also 1.2.41~~**1.2.40**~~ **Received**.

1.2.13 Energy, Active

(from ANSI C12.1-2014) The integral of active power with respect to time. Typically measured in units of kilowatt-hours (kWh) or watt-hours.

$$E(T_{END}) = \int_{0}^{T_{END}} v(t) \cdot i(t) \cdot dt \qquad \textit{Eq. 1}$$

Where T_{END} is much greater than the period of the AC line frequency.

1.2.14 Energy, Apparent

The sum of the products of apparent power measurements and measurement time periods. Apparent energy is typically measured in units of kilovolt-ampere hours (kVAh).

$t(n)$: The measurement time period for measurement number n. The time period is generally many AC line cycles (e.g., 1 sec).

$V_{rms}(n)$: The RMS voltage measured for time period $t(n)$.

$I_{rms}(n)$: The RMS current measured for time period $t(n)$.

The apparent power is computed as follows:

$$apparent\ power(n) = V_{rms}(n) \cdot I_{rms}(n) \qquad \textit{Eq. 2}$$

The apparent energy over N apparent power measurements is:

$$apparent\ energy(N) = \sum_{n=0}^{N} V_{rms}(n) \cdot I_{rms}(n) \cdot t(n) \qquad \textit{Eq. 3}$$

> Note: The apparent power and energy measurements may change as $t(n)$ changes for voltage or current signals that are non-repetitive or repetitive with a period of repetition that is greater than or not evenly divisible into the RMS measurement time period. For example, if you have a load that cycles on for one second and off for one second and it is measured with RMS time periods of one second and two seconds, the results can vary by as much as 1.414 (the square root of 2.0).

1.2.15 Energy, Net Active:

Net meters (also called bidirectional or four-quadrant meters) calculate the net active energy by subtracting the received active energy from the delivered active energy or vice versa. The preferred sign convention is positive for delivered energy. See also 1.2.31~~1.2.30~~ **metering, net**.

1.2.16 Line Voltage

The voltage to be measured by the meter.

1.2.17 Line Voltage, Nominal Operating

The intended operating line voltages for a meter. These are common utility service voltages. This may be specified as a single voltage (e.g., 120 Vac), as a list of voltages (e.g., 120, 208, and 277), or as a range of voltages (e.g., 120 to 480).

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The nominal operating line voltage is not the same as the absolute maximum line voltages.

1.2.18 Linearity Factor, Sensor

The sensor linearity factor (LF) is a number (≥1) denoting the level of linearity of a sensor at low loads. A high-quality sensor (i.e. high linearity) will have a linearity factor equal to 1. See also 2.1.1~~2.1.1~~ **Linearity Factor, Sensor**.

1.2.19 Loading, Polyphase

Polyphase testing generally refers to testing with a three-phase service type, generally, with each voltage phase, 120 degrees rotated relative to the previous phase. More specifically, this refers to performing testing with a service type and loading that matches the service type for which the meter is being tested.

1.2.20 Loading, Series-Parallel

Testing with the current circuits effectively connected in series and the voltage circuits effectively in parallel. For sensor meters, the same current-carrying conductor is passed in series through all the current sensors.

1.2.21 Measurements, Accumulating

Accumulating measurements are those that accumulate over time, such as energy, reactive energy, and apparent energy. These are typically reported with a display, communication interface, or as pulses.

1.2.22 Measurements, Non-Accumulating

These are short-term measurements associated with values that do not accumulate, such as power, demand, voltage, current, and frequency. These may be measured or averaged over a time window.

1.2.23 Meter

A device or part of a device that measures and records electrical parameters.

1.2.24 Meter Design Type

A meter design type is a group of models that share the same basic design, measurement principle, measurement circuitry, and measurement firmware, but with the following allowable variations: rated AC power connection voltage, rated AC measurement voltage, rated current (for direct meters), user interface or display, communication interface, meter housing, and added accessories. One or more meter models may share the same design type.

1.2.25 Meter Model

A meter model means a particular meter design from a particular manufacturer.

If there are changes to any of the following aspects, the meter will be considered a different model: design type, rated current, rated volts, component values, interface or display, communication interface, meter housing, accessories, or metrology affecting firmware.

1.2.26 Meter Element

A hardware or software functional block, consisting of a single current input combined with a single associated voltage (such as Van or Vab) that computes power and energy quantities. Typically, two-meter elements are used to monitor delta services, and three-meter elements are required to monitor four-wire wye services.

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1.2.27 Meter, Direct

A direct meter is one that internally contains all sensing elements for the line voltage and current. For purposes of this Standard, a meter that accepts field connections to current or voltage sensors is not a direct meter. A manufacturer may market a meter model for use as both a direct meter and as a sensor meter.

1.2.28 Meter Housing

The housing over the metering components that makes the meter assembly a self-contained unit, exclusive of external sensors. This does not include additional enclosures that may be used in the field installation. Direct meters contain the current and voltage sensors within the meter housing.

1.2.29 Meter, Sensor

A sensor meter is one that uses external sensors such as current sensors, current transformers, potential transformers, etc.

1.2.30 Meter Under Test (MUT)

This refers to the meter or the meter system being tested. The testing may be type testing, field testing, or production testing.

1.2.31 Metering, Net

Net metering (also called bidirectional metering) distinguishes received and delivered active power and energy. This may be achieved with one or more of the following approaches:

a. Provide separate registers or outputs for received and delivered quantities.
b. Use different signs (positive and negative) to distinguish received from delivered.
c. Provide a net register or output that can accumulate up and down as the direction of the energy flow reverses.

The preferred approach is to provide separate measurements for delivered, received, and net. The delivered and received measurements should always be positive, while the net measurements should be positive for received energy.

1.2.32 Metering, Single-Quadrant

Single-quadrant meters do not have signed watts or VARs. They are intended for received energy metering only. Single-quadrant meters may be insensitive to the direction that the current sensor is placed on the wire.

1.2.33 Normal Operation

The term normal operation is used to describe a meter that functions correctly, but without specifying the accuracy. This includes but is not limited to 1) continues to make metering measurements, 2) continues to communicate, 3) user interface continues to operate, and 4) no errors in operation occur.

1.2.34 Power Factor

The term “power factor” most commonly refers to the apparent power factor but may refer to alternate definitions: displacement power factor, fundamental power factor, IEC power factor, IEEE power factor, or lead-lag power factor, and others.

For purposes of this Standard, any sign convention for power factor is acceptable, but the meter documentation must document which definition for power factor is used.

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If unsigned, the power factor ranges from 0.0 to 1.0. If signed, the power factor ranges from −1.0 to +1.0.

1.2.35 Power Factor, Apparent (PF)

The apparent power factor is also referred to as the true power factor, total power factor, or the power factor. The apparent power factor is the ratio of the active power P to the apparent power S:

$$PF = \frac{P}{S} \qquad \textit{Eq. 4}$$

1.2.36 Power Factor, Displacement (DPF)

The displacement power factor is also referred to as the fundamental power factor. The DPF is the ratio of the fundamental (first harmonic) of the active power (P_1) to the fundamental apparent power (S_1):

$$DPF = \frac{P_1}{S_1} \qquad \textit{Eq. 5}$$

The DPF may also be calculated as the cosine of the angle between the fundamental sinusoids of the voltage and current:

$$DPF = \cos(\theta) \qquad \textit{Eq. 6}$$

1.2.37 Power Factor, Fundamental

See **1.2.36 Power Factor, Displacement (DPF)**.

1.2.38 Power Factor, IEC

The IEC power factor is the ratio of the absolute value of the active power P to the apparent power S.

1.2.39 Power Factor, IEEE

See 1.2.35**1.2.35 Power Factor, Apparent (PF)** .

1.2.40 Pulse

A change of state of an electrical signal that conveys an event or information. Note: A sudden change of voltage or current produced, for example, by the closing or opening of a contact. (from ANSI C12.1-2014)

1.2.41 Received

This is energy or power flowing to the grid. For reactive energy and power, a capacitive load results in received reactive energy. See also 1.2.12~~1.2.12~~ **Delivered**.

1.2.42 Sensor

A component used to sense the line voltage or the load current.

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1.2.43 Sensor, Active

Current or voltage sensors with powered active circuitry, including amplifiers, active signal filtering, and active signal processing. See also 1.2.46**1.2.46 Sensor, Passive**.

1.2.44 Sensor Design Type

A sensor design type, for current or voltage sensors, is a group of models that share the same basic design, measurement principle, core material, and interface to the meter, but with the following allowable variations: turns ratio, burden resistor value, core dimension, and passive component values. One or more sensor models may share the same design type.

1.2.45 Sensor Model

A current or voltage sensor model means a particular sensor design from a particular manufacturer.

If there are changes to any of the following aspects, the sensor will be considered a different model: sensor design type, rated amps, rated volts, core size, core shape, turns ratio, wire gauge, winding geometry, schematic, component values, or metrology affecting firmware.

1.2.46 Sensor, Passive

Current or voltage sensors without powered active circuitry. Passive sensors may include passive components for filtering, phase compensation, temperature compensation, and other functions.

1.2.47 Service Type

The service type refers to the configuration of the voltages and phase angles between voltages being metered. Common service types include four-wire wye, three-wire delta, and two-wire single-phase. For this Standard, service type refers to what is being metered; this may not be the same as the utility service.

1.2.48 Submeter

A meter or meter system downstream of the master meter. Submeters provide details of energy and associated quantities for monitoring or revenue submetering.

1.2.49 System, Direct Meter

A meter system with internal voltage and current sensing, without the use of external current sensors or external voltage sensors.

1.2.50 System, Meter Only

A meter system with a meter that requires external sensors but tested without some or all of the sensors attached or for which the sensors models are not specified. This does not form a complete metering system but may be used to test a meter in isolation from the external sensors.

1.2.51 System, Sensor Meter

A meter system where the meter uses external current sensors, external voltage sensors, or both to measure the primary power conductor quantities.

1.2.52 Temperature, Nominal Ambient

The ambient temperature at which testing is performed.

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1.2.53 Temperature Range, Working

This is the manufacturer-specified temperature range over which the meter continues to function. The meter does not need to meet the ESM1 performance requirements over the working temperature range.

1.2.54 Temperature Range, Specified

This is the temperature range over which the meter accuracy is specified to meet the requirements of ESM1.

1.2.55 Test, In-Service

An in-service test is one where the correct operation and accuracy of the meter is monitored during the test.

1.2.56 Test, Survival

A survival test is one where the meter operation and accuracy are verified after the test is complete. This may also include requirements concerning allowable changes to readings (such as accumulated energy) after the completion of the test.

1.2.57 Total Harmonic Distortion (THD)

(from ANSI C12.1-2014) The ratio of the root-mean-square of the harmonic content (excluding the fundamental) to the root-mean-square value of the fundamental quantity, expressed as a percentage.

1.2.58 Voltage Sensor

A device able to measure and output representations of one or more AC line voltages. An example of a voltage sensor for electric metering is the potential transformer.

1.2.59 Watthour Meter

An electricity meter that measures, registers, and reports the active energy of the circuit to which it is connected.

1.3 Normative References

a. IEC 61000-4-2: Electrostatic Discharge Immunity Test
b. IEC 61000-4-3: Radiated, Radio-Frequency, Electromagnetic Field Immunity Test
c. IEC 61000-4-4: Electrical Fast Transient/Burst Immunity Test
d. IEC 61000-4-5: Surge Immunity Test
e. IEC 61000-4-6: Immunity to Conducted Disturbances
f. IEC 61000-4-8: Power Frequency Magnetic Field Immunity Test
g. IEC 61000-4-11: Voltage Dips, Short Interruptions and Voltage Variations Immunity Tests
h. IEC 61000-4-12: Ring Wave Immunity Test

1.4 Bibliography

a. ANSI C12.1-2014 American National Standard for Electric Meters—Code for Electricity Metering
b. IEC 62053-23 First edition 2003-01 Electricity metering equipment (a.c.)—Particular requirements—Part 23: Static meters for reactive energy (classes 2 and 3)
c. BS 8431:2010 Electrical static meters for secondary metering and sub-metering—Specification
d. IEEE Std 1459-2010 IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions
e. Power Flow Direction Definitions for Metering of Bidirectional Power—IEEE Transactions on Power Apparatus and Systems, Vol PAS-102, No. 9, September 1983
f. IEC 61326-1:2012—Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 1: General requirements

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g. IEC 60050-131:2002—International Electrotechnical Vocabulary—Part 131: Circuit theory
h. National Research Council Canada CLAS requirements document 3 3.6.
i. JCGM 100:2008—Evaluation of measurement data—Guide to the expression of uncertainty in measurement
j. JCGM 101:2008—Evaluation of measurement data—Supplement 1 to the “Guide to the expression of uncertainty in measurement”—Propagation of distributions using a Monte Carlo method
k. JCGM 102:2011—Evaluation of measurement data—Supplement 2 to the “Guide to the expression of uncertainty in measurement”—Extension to any number of output quantities
l. JCGM 104:2009—Evaluation of measurement data—An introduction to the “Guide to the expression of uncertainty in measurement” and related documents
m. JCGM 106:2012—Evaluation of measurement data—The role of measurement uncertainty in conformity assessment

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2 Performance Requirements and Test Procedures

2.1 Meter Accuracy Classes

This Standard allows the use of any accuracy classes for meters, but recommends the following accuracy classes:

0.1 0.2 0.5 1 2

For active energy, accuracy classes 0.1, 0.2, 0.5, and 1 are recommended in applications where submeter readings are used for the settlement of a commercial transaction between a provider and a consumer of energy. Accuracy class 2 is included as performance specification options for general energy management applications such as energy code compliance monitoring, building performance benchmarking, or energy efficiency awareness programs. Submeters that comply with accuracy class 2 may benefit the consumer by satisfying general energy management application requirements while reducing the total installed cost of the submetering system.

For reactive energy, accuracy classes 1, 2, or 3 are recommended in applications where submeter readings are used for the settlement of a commercial transaction between a provider and a consumer of energy.

Manufacturers may specify different accuracy classes for different measurements within the same meter.

Manufacturers may include measurement variables that are not tested to the ESM1 requirements.

2.1.1 Linearity Factor, Sensor

The sensor linearity factor (LF) is a number (≥1) denoting the level of linearity of a sensor at low loads. The linearity factor is the factor that the nominal accuracy class of a sensor shall be multiplied by for the sensor to determine compliance with the ESM1-2 accuracy limits.

Three levels of sensor linearity are defined:

- **High linearity (LF=1):** A sensor for which its nominal accuracy class meets the ESM1-2 accuracy limits.
- **Medium linearity (1<LF≤1.5):** A sensor for which its nominal accuracy class shall be multiplied by the specified LF in order to meet the ESM1-2 accuracy limits.
- **Low linearity (LF>1.5):** A sensor for which its nominal accuracy class shall be multiplied by the specified LF in order to meet the ESM1-2 accuracy limits. Sensors with a low linearity factor are typically used for monitoring purposes only.

2.1.2 Accuracy Class, Sensor Meter System

The accuracy class of a sensor meter system combines the class of the meter, the nominal accuracy class of the sensor and its linearity factor. It is calculated as follows:

$$C_{SMS} = \sqrt{C_M^2 + (LF * C_S)^2} \qquad \textit{Eq. 7}$$

Where:

C_{SMS}: The calculated accuracy class of the sensor meter system

C_M: The meter only accuracy class

LF: The linearity factor of the sensor

C_S: The sensor nominal accuracy class

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The calculated accuracy class of the system C_{SMS} may be rounded up to the next 0.1 multiple.

2.1.3 Accuracy Documentation

Product documentation must include a table, like the following example, indicating the class rating for each measurement. One or more of the “System Accuracy Class” and “Meter Only Accuracy Class” columns should be included as appropriate. Add or remove measurements as appropriate, but at least one measurement must be specified.

Measurement	System Accuracy Class	Meter Only Accuracy Class
Active Energy (kWh)	1	0.5
Reactive Energy (kVARh)	2	1

a. A direct meter system test or a sensor meter system test is required for a system accuracy class designation.
b. A meter only system test establishes the meter only accuracy class. Meter only systems are intended for use with sensors that meet the requirements IEEE C57.13, IEC 60044, or IEC 61869. No guidance is provided on the expected system accuracy.

2.2 Variables Measured

All submeters must provide one or more variables or outputs (hereafter referred to as “outputs”) for the active, reactive, or apparent energy that meet the ESM1 requirements. The energy outputs may report the total energy, the net energy, or both. Four-quadrant (co-generation) meters shall report delivered (to load or import) and received (to grid or export) energy outputs. The preferred sign convention is positive power and energy for delivered power and energy.

In addition to the required outputs, submeters may optionally provide the following measurement outputs. For each output covered by the ESM1 scope, the manufacturer must clearly document if the output meets the ESM1 performance requirements and, if so, the accuracy class. Manufacturers can include outputs that are not covered by the scope of ESM1.

a. Voltage (rms volts line-to-line). See **ESM1-4 ADDITIONAL MEASUREMENT ACCURACY**
b. Voltage (rms volts line-to-neutral). See **ESM1-4 ADDITIONAL MEASUREMENT ACCURACY**
c. Current (rms amperes). See **ESM1-4 ADDITIONAL MEASUREMENT ACCURACY**
d. Power (watts or kilowatts)—reported as a signed value for four-quadrant meters. See **ESM1-4 ADDITIONAL MEASUREMENT ACCURACY**
e. Demand (watts or kilowatts). See **ESM1-8 DEMAND METERING**
f. Reactive power (VAR), using any of the reactive power definitions, including nonactive power. Four-quadrant meters should provide signed (positive and negative) reactive power measurements. See **ESM1-4 ADDITIONAL MEASUREMENT ACCURACY**
g. Reactive energy (kVARh). Four-quadrant meters should provide separate accumulators for positive and negative reactive energy. See **ESM1-4 ADDITIONAL MEASUREMENT ACCURACY**
h. Apparent power (VA). See **ESM1-4 ADDITIONAL MEASUREMENT ACCURACY**
i. Apparent energy (kVAh). See **ESM1-4 ADDITIONAL MEASUREMENT ACCURACY**
j. Power factor. See **ESM1-4 ADDITIONAL MEASUREMENT ACCURACY**

For all variables, the manufacturer has the option of providing separate variables for each meter element, variables for the combination of all meter elements, or both.

When combining meter elements, the resulting variable may be the sum or the average of the values for each element. Combined volts and current are preferred as averages of the elements. Combined power (W, VAR, VA) and energy (kWh, kVARh, kVAh) are preferred as totals of the elements.

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2.3 Common Test Setup

Equipment Needed:

a. Voltage and current sources which can provide unity, 45º lagging, and 30º leading current.
    1. Voltage source to span the voltage input range of the meter, including frequency range.
    2. Current source to span 0.1% to 100% of the rated current of the meter or current sensors.
    3. Sinusoidal voltage and current sources, unless other waveforms are specifically required by the test.
b. EMC test equipment
c. Temperature chamber
d. Reference (REF) meter or reference source
    1. A reference meter may be integrated into the voltage/current source

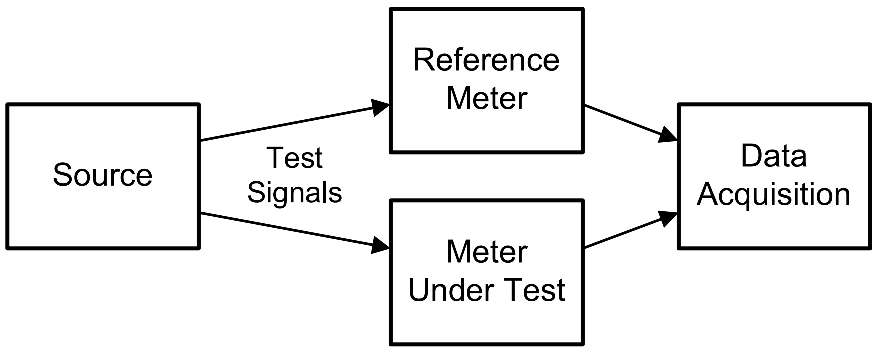

Figure 1 Test Setup Block Diagram with Reference Meter

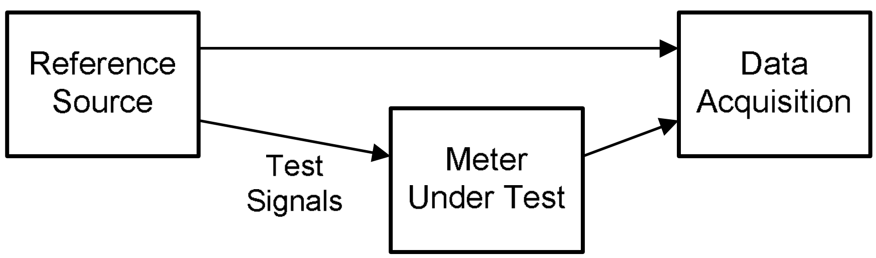

Figure 2 Test Setup Block Diagram with Reference Source

2.3.1 Performance of the Test Equipment

Any equipment used as a reference (meter, source, or other equipment) shall be traceable to NIST or equivalent national laboratories.

Test Uncertainty Ratio (TUR): The ratio of the tolerance limits of the device being measured to the uncertainty of the measurement system shall be a minimum of 4 except for the Starting Load test. TUR values lower than 4 may be used if an error analysis is performed.

It is permissible to add the reference uncertainty and the MUT uncertainty as an additional allowance in the meter accuracy requirements up to a maximum value of 0.05% or one-quarter of the meter accuracy class, whichever is greater. Details of the uncertainty are provided in Annex B.

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2.3.2 Test Condition Tolerances

Table 1
Test Condition Tolerances

Condition	Tolerance
Voltage	±1.0%
Current	±1.0%
Phase angle	±2.0°
Frequency	±0.2%
Voltage and current waveform distortion (THD)	±2.0%
Ambient temperature	23°C ±3°C

Note: the test condition tolerances and test uncertainty ratio do not apply for the Starting Load test. The test condition tolerance for the applied current in the Staring Load test is ±10% of specified starting load test amperes.

2.4 Common Accuracy Test Procedure

Unless otherwise specified, all accuracy tests will follow the same basic procedure.

a. Ensure correct environmental conditions.
b. Connect test equipment (if not already connected).
c. Configure the test equipment output conditions such as line voltage, test current, displacement power factor, etc., and apply to the device or devices under test.
d. Wait for the pre-test interval to allow the test equipment outputs and readings to stabilize and to allow the meter readings to stabilize.
e. Run the test for the necessary test duration (see Annex BAnnex B **MEASUREMENT UNCERTAINTY** for guidance). Record relevant measurement variables at the start of the test, at the end of the test, and during the test if necessary.
f. After the test duration is complete, record, and process the results as necessary.
g. If this test is one in a sequence of tests, optionally return to step 3 to perform the next test in the sequence.
h. If the sequence is complete or testing is concluded, turn off the test signals.

2.4.1 Outputs

Data acquired from the reference meter and the MUT (meter under test) can be acquired by pulse output, counters, numerical displays, or digital communicated numerical values using any physical medium and any protocol. Other means of data presentation by the meter are permissible, provided these means are documented in the test report. Any convenient means to record the data are permissible.

For meters of the same design type available with different or with multiple output interfaces, such as different communications interfaces, pulse outputs, displays, etc., there are two options for testing the different interfaces.

a. Option 1: If technically feasible, all output interfaces specified by the manufacturer should be monitored together during the test sequence to establish output equivalence.
b. Option 2: Perform all testing with the preferred output interface, and then for each additional output interface, repeat the Lagging PF, Load 100% test from ESM1-2 to establish output equivalence.

At the manufacturer's discretion, not all output interfaces need to be tested. In this case, the manufacturer must document which output interfaces have been accuracy tested.

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During external influences testing, only one output interface needs to be monitored for accuracy (on tests that require such monitoring), while all tested output interfaces must be verified at the conclusion to ensure they continue to function correctly.

2.4.2 Meter System Type Testing

This Standard may be used to test three different meter types and system configurations (see definitions above):

a. **Direct Meter System:** tests the system accuracy of a direct meter.
b. **Sensor Meter System:** tests the system accuracy of a sensor meter with external sensors attached
c. **Meter Only System:** tests the meter only accuracy of a sensor meter without external sensors attached

The accuracy limits and tests are the same for all three of the configurations above.

For the meter-only configuration, it may be necessary to simulate the sensor outputs or use reference external sensors. For example, to test a meter that uses millivolt output current transducers, a normal current signal could be converted into a millivolt signal with the use of a precision shunt resistor. These methods are considered secondary injection.

2.4.2.1 Multiple Service Type Meters

If the meter can be configured for more than one service type (such as single-phase, split-phase, four-wire wye, three-wire delta, and four-wire delta), unless otherwise specified by the test, the service type which uses the most elements shall be used for the full suite of tests.

2.4.3 Number of Meters to Test

Only one meter of each design type needs to be tested. Tested meters must be production equivalent samples. Some ESM1 parts, such as ESM1-2, may have testing requirements for additional meter models of the same meter design type with variations such as different rated current or voltage.

a. Meters of the same design type but rated for different control power voltages require a repeat of the Load 10% test from ESM1-2 to establish equivalence.
b. No retesting is required for different meter housings except tests from section 2.6~~2.6~~ **Electromagnetic Compatibility (EMC) Tests** where the changes may affect the performance. Examples changes are from metallic to polymer, EMC coatings, or polymers with EMC shielding.
c. No retesting is required for added accessories.
d. See section 2.4.1~~2.4.1~~ **Outputs** above for testing of output interfaces.
e. Meters of the same design type but rated for different electrical service (e.g., wye, delta, etc.) require a subset of tests to be repeated. See ESM1-2 for details.
f. The same meter model being tested as a meter only system or a sensor meter system requires a subset of tests to be repeated. See ESM1-2 for details.
g. Direct meters of the same design type with different rated currents require a subset of tests to be repeated. See ESM1-2 for details.
h. Sensor meter systems with different current sensor models require a subset of tests to be repeated. See ESM1-2 for details.
i. Meters of the same design type but rated for different AC measurement voltages require a subset of tests to be repeated. See ESM1-2 for details.
j. Direct meters of the same design type with different rated voltages require a subset of tests to be repeated. See ESM1-2 for details.
k. Sensor meter system with different voltage sensor models require a subset of tests to be repeated. See ESM1-2 for details.

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2.4.4 Test Grouping and Sequence

Each tested meter shall be tested against all the accuracy tests in any desired order.

Each EMC and temperature test may be run in parallel on different test samples, in series on the same sample, or a combination of series and parallel, in any order.

If a meter is being tested against multiple parts of ESM1 (e.g., ESM1-2 AC Active Energy Accuracy, ESM1-4 Additional Measurement Accuracy, and ESM1-8 Demand Metering), then identical tests should not be repeated for each part. Furthermore, reasonable efforts shall be made to combine tests from different parts or to run them concurrently.

During the testing of a meter model, the MUTs may not be modified except as allowed by **2.4.5**~~**2.4.5**~~ **Failed Tests**.

2.4.5 Failed Tests

If retesting updated meter samples due to any failed test, then all the accuracy tests must be repeated. An engineering determination may be used to decide which EMC tests need to be repeated and if the temperature test needs to be repeated.

2.4.6 Meter Changes Affecting Metrology

Meters should be retested after changes have been made, which could affect metrology. An engineering determination may be used to decide which tests need to be repeated.

2.5 Temperature Variation

The manufacturer must specify the temperature range over which the meter meets the accuracy requirements of this Standard, called the **specified temperature range**. This range may be smaller than the **operating temperature range**. The meter shall be tested at the lowest and highest temperatures of the specified temperature range. The particular tests to be performed are specified by other ESM1 parts, such as ESM1-2.

This Standard defines the following specified temperature ranges:

a. **Minimum:** 0°C to 40°C
b. **Standard:** −20°C to 50°C
c. **Extended:** manufacturer specified, one or more limits must exceed the standard temperature range.

Prior to performing tests, while energized, the meter under test shall be held at the tested temperature for a time duration long enough for the temperature of the meter to stabilize, but not less than one hour.

2.5.1 Allowable Error from Temperature Variation

Unless otherwise documented, the ESM1 Standard handles temperature variation by allowing an error based on the difference in temperature from the test temperature to the nominal ambient temperature. This allowable error is relative to the reference measurement for a given test made at the nominal ambient temperature. If the same meter is being used for ESM1-2 accuracy tests and the temperature variation tests, then the accuracy-test measurements should be used as the reference measurements.

Each ESM1 part, such as ESM1-2, will specify the specific tests, if any, to be performed for temperature variation testing.

For example, suppose the load variation test at 10% of rated current allows an error of C, where C is the meter accuracy class. If the test temperature is −20°C and the nominal is 23°C, then the temperature difference is 43°C. Based on the equation (*Eq. 8*~~*Eq. 8*~~) below, the allowable error would be $\pm 2.58 \cdot C$, relative to the reference measurement. For an accuracy class of 0.5, the allowable error would be $\pm 1.29\%$.

a. E : The allowable error relative to the reference measurement due to the temperature variation
b. T_N : The nominal ambient temperature: 23°C
c. T_T : The temperature at which the test is being performed
d. $\Delta T = T_N - T_T$: The difference in temperature between the nominal ambient temperature and the test temperature
e. C : The accuracy class of the meter as a percentage. E.g. C = 0.5 means C = ±0.5%
f. K : Allowable error temperature coefficient as a percentage in units of percentage per degree Celsius (%/°C)
   1. Unity power factor: K = 0.06% / °C
   2. Any lagging or leading power factor: K = 0.10% / °C

The formula for the allowable error as a function of the temperature difference follows:

$$E = \Delta T \cdot K \cdot C \qquad \text{Eq. 8}$$

Examples: Temperature change between 23˚C and −20˚C

Class 0.5, unity power factor: $E = 43 \cdot 0.06\% \cdot 0.5 = 1.29\%$

Class 0.5, lagging power factor: $E = 43 \cdot 0.10\% \cdot 0.5 = 2.15\%$

2.6 Electromagnetic Compatibility (EMC) Tests

This set of EMC external influence tests are generally applicable to all ESM1 parts unless otherwise noted. This section describes common external influence testing conditions and procedures. Specific ESM parts may add additional requirements, such as a change in measurements after the test, accuracy, etc.

During the EMC tests, the meter shall be energized with the highest nominal line voltage applied to all line voltage measurement connections, and if there are separate control power connections, then the highest nominal supply voltage applied to the control power connections. No current signal is applied unless otherwise specified by the test. Sensor meters shall have external sensors connected. All accessories, conditioning circuitry, etc. required for normal operation shall be connected and operational. Accuracy testing during the EMC tests is not required unless otherwise specified.

During or after the EMC tests, perform any EMC accuracy tests specified in other applicable ESM1 parts, such as ESM1-2. If the meter has multiple output interfaces (see section 2.4.1~~2.4.1~~ **Outputs**), then verify that all interfaces function correctly at the conclusion of testing. At the request of the manufacturer, accuracy tests may be performed after each EMC test, even if testing is only required at the end of a sequence of tests.

See Annex A~~Annex A~~ **Test Alternates** for alternate tests from other standards that may be used in place of some of these EMC tests. If alternate tests are used, then the accuracy check from the alternate standard may be used in place of the ESM1-1 final accuracy check.

2.6.1 Performance Criteria

The following performance criteria are used to evaluate the result of EMC tests. Performance Criterion A is more stringent than Performance Criterion B, so any test that requires Performance Criterion B is satisfied if the meter meets the Performance Criterion A requirements. Unless otherwise specified by a particular test, the MUT accuracy is not monitored during testing but will be verified after the conclusion of the EMC tests, as described in 2.6~~2.6~~.

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2.6.1.1 Performance Criterion A

The equipment shall continue to operate as intended **during and after** the test. No degradation of performance or loss of function is allowed.

2.6.1.2 Performance Criterion B

The equipment shall continue to operate as intended **after** the test. During the test, degradation of performance is allowed. After the test, no change of operating state is allowed.

2.6.2 Electrostatic Discharge Immunity Test

Tests shall be conducted in accordance with IEC 61000-4-2.

The test levels shall be 6kV for contact discharge, 8kV for air discharge.

Number of discharges for contact and air discharge: 10 positive polarity, 10 negative polarity

Discharges shall be applied only to points of the meter that are accessible with the cover and terminal compartment cover, where applicable, in place. Discharges shall not be applied to any point that is accessible only for maintenance purposes, including, but not limited to, the meter terminals or the conductors connected to the terminals. Air discharge shall be used for ports with recessed pins.

The control power and line voltage measurement connections are not tested.

The MUT shall meet Performance Criterion B of **2.6.1**~~2.6.1~~.

2.6.3 Radiated, Radio-Frequency (RF), Electromagnetic Field Immunity Test

Tests shall be conducted in accordance with IEC 61000-4-3.

All-access panels, doors, etc. should be closed and in the in-use condition.

The field strength shall be 10 V/m over following frequency ranges:

a. 80 MHz to 1.0 GHz
b. 1.4 GHz to 6.0 GHz

The MUT shall meet Performance Criterion B of **2.6.1**~~2.6.1~~.

Testing at a higher field strength is permitted at the manufacturer’s discretion.

2.6.4 Electrical Fast Transient (EFT)/Burst Immunity Test

Tests shall be conducted in accordance with IEC 61000-4-4.

Use the following levels for different product connections:

a. Control power connections, line voltage measurement connections, and current sensor primary: 4 kV (5/50 ns, 5 kHz)
b. All I/O signal and control lines that may be longer than 3 meters: 2 kV (5/50 ns, 5 kHz). This includes all communications cables such as Ethernet and RS-485, external current sensor cables, and all I/O signal and control lines that the manufacturer does not specifically limit to less than 3 meters.

The MUT shall meet Performance Criterion B of **2.6.1**~~2.6.1~~.

2.6.5 Surge Immunity Test

Tests shall be conducted in accordance with IEC 61000-4-5.

For meters up to 300V (line-to-line or line-to-neutral): 4 kV peak line-to-ground, 2 kV peak line-to-line

For meters up to 600V (line-to-line or line-to-neutral): 6 kV peak line-to-ground, 3 kV peak line-to-line

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For meters up to 1000V (line-to-line or line-to-neutral): 8 kV peak line-to-ground, 4 kV peak line-to-line

Surge testing is required for control power connections and line voltage measurement connections, and the current sensor primary for sensor meters.

The MUT shall meet Performance Criterion B of 2.6.1~~2.6.1~~.

2.6.6 Ring Wave Immunity Test

Tests shall be conducted in accordance with IEC 61000-4-12.

The test levels shall be 4 kV line-to-ground and 2 kV line-to-line.

The ring wave signal shall be applied to control power connections, line voltage measurement connections, and current sensor primaries.

The MUT shall meet Performance Criterion B of 2.6.1~~2.6.1~~.

2.6.7 Immunity to Conducted RF Test

Tests shall be conducted in accordance with IEC 61000-4-6.

The test level shall be 10 V from 150 kHz to 80 MHz.

The RF test signal shall be applied to the line voltage measurement connections, current sensor connections, control power connections, protective earth, and functional earth.

The MUT shall meet Performance Criterion B of 2.6.1~~2.6.1~~.

2.6.8 Voltage Dips and Interruptions Immunity Tests

Tests shall be conducted in accordance with IEC 61000-4-11.

The tests may be performed at 50 or 60 Hz. The test shall be performed at the lowest nominal rated voltage of the MUT. The dips and interruptions shall be applied to the AC or DC power connections.

(adapted from IEC 61326-1:2012, Table 2 for industrial electromagnetic environment):

Voltage dips:

The voltage dips shall be applied with not less than 3.0 s between dips and in any order. The MUT shall meet Performance Criterion A of 2.6.1~~2.6.1~~.

a. 0% of nominal voltage for 20 ms
b. 40% of nominal voltage for 200 ms
c. 70% of nominal voltage for 500 ms

Short Interruptions:

The interruptions shall be applied 10 successive times with an interval of 200 ms to 1000 ms between each interruption. The MUT shall meet Performance Criterion B of 2.6.1~~2.6.1~~.

a. 0% of nominal voltage for 100 ms

2.6.9 Power Frequency Magnetic Field Immunity Test

Tests shall be conducted in accordance with IEC 61000-4-8.

The test level shall be 30 A/m at 50 Hz or 60 Hz. The test frequency of the magnetic field must match and be phase-locked to the frequency of the voltage and current signals measured by the meter. The magnetic field shall be applied to the meter. External sensors shall not be located in the magnetic field.

The performance criteria for this test appear in other ESM1 parts. Use the ESM1 parts that are appropriate for the product, such as ESM1-2.

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ANNEX A Test Alternates

(Normative)

ESM1 allows the requirements for some tests to be met by equivalent or comparable tests from other standards. This annex lists those alternate tests.

A.1 Electrostatic Discharge Immunity Test

In place of 2.6.2~~2.6.2~~ **Electrostatic Discharge Immunity Test**, meters may instead be tested in accordance with the following alternate test:

a. ANSI C12.1, Test No. 28: Effect of electrostatic discharge (ESD)

A.2 Radiated, Radio-Frequency (RF), Electromagnetic Field Immunity Test

In place of 2.6.3~~2.6.3~~ **Radiated, Radio-Frequency (RF), Electromagnetic Field Immunity Test**, meters may instead be tested in accordance with the following alternate test:

a. ANSI C12.1, Test No. 26: Effect of Radio Frequency Interference

A.3 Electrical Fast Transient (EFT)/Burst Immunity Test

In place of 2.6.4~~2.6.4~~ **Electrical Fast Transient (EFT)/Burst Immunity Test**, meters may instead be tested in accordance with the following alternate test:

a. ANSI C12.1, Test No. 25: Effect of electrical fast transient/burst test

A.4 Surge Immunity Test

In place of 2.6.5~~2.6.5~~ **Surge Immunity Test**, meters may instead be tested in accordance with the following alternate test:

a. ANSI C12.1, Test No. 17: Effect of high voltage line surges. This test covers both ring waves and combination surges.

A.5 Ring Wave Immunity Test

In place of 2.6.6~~2.6.6~~ **Ring Wave Immunity Test**, meters may instead be tested in accordance with the following alternate test:

a. ANSI C12.1, Test No. 17: Effect of high voltage line surges. This test covers both ring waves and combination surges.

A.6 Power Frequency Magnetic Field Immunity Test

In place of 2.6.9~~2.6.9~~ **Power Frequency Magnetic Field Immunity Test**, meters may instead be tested in accordance with the following alternate test:

a. ANSI C12.1, Test No. 18: Effect of external magnetic field

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ANNEX B Measurement Uncertainty

(Informative)

This informational annex provides guidance on determining the measurement uncertainty of power and energy measurements.

In laboratory work, there are always two deviations associated with a reading, the accuracy, and the precision. Precision is the closeness of agreement between measured quantity values obtained by repeated measurements of the same parameter under specified conditions. It is related to the resolution of the digital increment that can be measured and reported. The precision is a primary source of uncertainty in a reading. This section specifically addresses the precision and uncertainty of measuring metering values. It also addresses the minimum readable values of the MUT and the influence these have on verifying a specific accuracy.

This information is provided to assist the manufacturer and the test professionals in determining the details of the test procedures, such as test durations. It can also be used to address potential aberrations that may arise from test protocols. Ideally, this guidance would be used in defining the test protocols upfront and eliminating the potential aberrations in the first place. It can also be used as guidance in meter design, but that is not the intent of including this annex.

This information can assist in determining if a measurement can be made and the duration of a test to verify an accuracy given the precision of the measurements. An example of “if a measurement can be made” is the starting load energy. If the minimum measurable power is not less than the starting load power, then the starting energy will never accumulate regardless of the test duration. An example of the test duration is the 1% load test. Because energy is a continuously increasing value, the precision in the time at which readings are taken is reflected in the energy value. As the test duration increases, the precision becomes a smaller percentage of the accumulated value. Thus, the time calculation provides guidance on how long the test should be run so that the lack of precision is not mistaken for inaccuracy.

B.1 Measurement Uncertainty

“Measurement uncertainty is the doubt about the true value of the measurand [the property intended to be measured] that remains after making a measurement. Measurement uncertainty is described fully and quantitatively by a probability distribution on the set of values of the measurand. At a minimum, it may be described summarily and approximately by a quantitative indication of the dispersion (or scatter) of such distribution.

Measurement uncertainty implies that multiple [measured] values of the measurand may be consistent with the knowledge available about its true value, derived from observations made during measurement and possibly also from pre-existing knowledge: the more dispersed those multiple values, the greater the measurement uncertainty. For scalar measurands, measurement uncertainty may be summarized by the standard deviation (standard uncertainty) of the corresponding probability distribution, or by similar indications of dispersion (for example, the median absolute deviation from the median).” (from NIST Technical Note 1900, October 2015).

When measuring energy, each of the measured parameters involved in the energy calculation is subject to measurement uncertainty. This typically includes voltage, current and time.

With respect to time, there is general time uncertainty as well as an uncertainty between the time interval used by the MUT (meter under test) and the time interval used by the REF (reference).

In the ideal case, the time measurements are not subject to any minimum increment, rounding, or truncation, thus providing the certainty that the MUT (meter under test) and REF (reference) can measure an identical time interval. In this ideal case, the measurements of the MUT and REF could be directly compared with no time uncertainty.

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In practice, the time measurements (from both the MUT and REF) are subject to an uncertainty due to clock accuracy and drift, limited time resolution (i.e. increment, rounding, or truncation), and lack of time synchronization between the MUT and REF, causing an additional uncertainty in the measurements.

B.2 Minimum Measurable Quantity (MMQ)

To evaluate this uncertainty more easily, the minimum measurable quantity (MMQ) is introduced. The MMQ is the minimum magnitude of a metering quantity that a meter can measure and report repeatedly. The MMQ should be sufficiently small to reduce the uncertainty of the MUT so that the required accuracy can be measured at the test load.

The MMQ may not be a single value for all loads, it may have multiple values because of metering range changes, changes to the exponent of a floating-point number, or changes to the position of the decimal place on a display.

The MMQ denotes the quantization amount of a certain parameter and is related to, but is not, the resolution of a displayed or communicated value. For example, the display might have a resolution of 0.1, but the displayed value might increment by 0.2. The MMQ is the minimum increment the MUT can measure and report. The MMQ is used in determining the uncertainty of a measurement. The internal meter measurement resolution may be more precise than the MMQ to ensure performance compliance. It is recommended that the manufacturer provide the MMQs to assist test labs in determining the test durations. The meter internal measurement limits do not need to be disclosed.

The evaluations in this section are performed using the worst-case use of the MMQ. That is, the reading of the MUT is evaluated as being off by the MMQ. This represents the situation where the input load is just below the transition, where the digital result would increase to the next increment.

The MMQ is not the lowest limit of a quantity the meter can measure, sometimes referred to as a creep limit or noise floor. The MMQ of a metering quantity is the minimum increment of the meter when the input is above the creep limit. If a creep limit is used, it should be sufficiently small so that it does not interfere with the minimum value, including tolerance; the meter is intended to measure.

B.3 Use of the MMQ

B.3.1 Uncertainty due to Power MMQ

The power measurement uncertainty is affected by several components which are derived from the MUT design. This section describes the power uncertainty calculation due to the minimum measurable power (MMP). The MMP is the MMQ of the power or the minimum power (watts) that the meter can measure and report repeatedly at a specified load. Using the MMP, the uncertainty in the power measurement is:

$$P_u = \frac{MMP}{TL} \qquad \textit{Eq. 9}$$

Where

TL = test load in watts.

MMP is the minimum measured power in watts.

The test load is the actual test power from a precision source or as measured by a precision reference.

An example is a 200 A meter with a 120 V single-phase element that has an MMP of 1 W. Tested at 0.1%, the starting current, the test load is:

$$TL = 200\ A \cdot 120\ V \cdot 0.001 = 24\ W$$

At this test load the power uncertainty is:

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$$P_u = \frac{MMP}{TL} = \frac{1}{24} = 0.042\ or\ 4.2\%$$

B.3.2 Energy Uncertainty

Energy is a function of power and time. The minimum measurable energy (MME) contributes to the uncertainty.

The time uncertainty must also be included. There are two sources of time errors, a constant error generated by multiple time errors that all contribute to the measurement time error (MTE). The MTE is the maximum possible time difference between the MUT and the REF in the time elapsed from the beginning of the test until the readings are taken. See section **B.7.4~~B.7.4~~ Sources of MTE**, for additional details. Time also has a clock drift error that is an increasing error contribution as the duration of the test increases. Including these four contributors, the energy uncertainty, Eu, is:

$$E_u = \frac{(TL \cdot time) - [(TL - MMP) \cdot (time - MTE - CD \cdot time) - MME]}{TL \cdot time} \qquad \textit{Eq. 10}$$

Where

a. time is the duration of the test in hours.
b. MME is the minimum measurable energy in watt-hours (Whr).
c. MTE is the Measurement Time Error in hours (hr).
d. CD is the clock drift.

The MTE is a measure of how well the MUT and REF are synchronized, the precision of the durations, the clock accuracy, and the measurement update rate. Two contributors, for example, are the update rate of the MUT and the latency of reading the MUT and reference meter. See section **B.7.4~~B.7.4~~ Sources of MTE**, for additional details. The MTE is dependent on the MUT, the REF, and the test methodology.

So, for the 0.1% load test example for a 10-minute test duration using a meter where:

a. TL = 24 W
b. MMP is 1 W
c. MME is 0.2 Whr
d. MTE is 3 sec
e. CD is 50 ppm (0.00005)

Energy uncertainty is:

$$E_u = \frac{(24 \cdot 0.167) - [(24 - 1) \cdot (0.167 - 0.00083 - 0.00005 \cdot 0.167) - 0.2]}{24 \cdot 0.167} = 0.097\ or\ 9.7\%$$

If the test duration is doubled to 20 minutes, the E_u is 6.9%. This shows that, in general, the energy uncertainty decreases with increasing time.

B.3.3 Test Durations

In Eq. 10~~Eq. 10~~ above, it is shown that the desired level of uncertainty (D_u) can be reduced by increasing the testing time. Even with a very long test duration, the uncertainty cannot be reduced below P_u.

Eq. 11~~Eq. 11~~ can be used to calculate the duration of a test to achieve a desired level of energy uncertainty (D_u).

$$time = \frac{TL \cdot MTE - MMP \cdot MTE + MME}{TL \cdot D_u - TL \cdot CD - MMP + MMP \cdot CD} \qquad \textit{Eq. 11}$$

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Using the same meter as the previous example where:

MMP = 1.0 watts, MME = 0.2 watt-hours, MTE = 3 seconds, CD = 50 ppm

And the test is performed at 1% load. The test load is:

$$TL = 200\ A \cdot 120\ V \cdot 0.01 = 240\ W$$

Next, the P_u (power uncertainty) is calculated, establishing the lowest uncertainty that can be achieved:

$$P_u = \frac{MMP}{TL} = \frac{1}{240} = 0.0042\ or\ 0.42\%$$

For a desired uncertainty, D_u, of 1% the test duration is:

$$time = \frac{240 \cdot 0.00083 - 1 \cdot 0.00083 + 0.2}{240 \cdot 0.01 - 240 \cdot 0.00005 - 1 + 1 \cdot 0.00005} = 0.29\ hr\ or\ 17\ min$$

The same equation can be used to establish the minimum time to achieve a desired level of uncertainty for other test loads. Generally, the time to achieve the same level of uncertainty decreases as the test load increases. Time decreases as the desired uncertainty increases.

B.4 MUT Uncertainty

The MMQs of an MUT are parameters specified by the manufacturer and result from the basic design of the MUT. It is recommended the manufacturer select the desired accuracy class for an MUT in such a way that the MMQ's result in an uncertainty ratio during a test of 4 or greater. This ensures that the MUT energy uncertainty has a minor influence on the testing result.

The following example illustrates the use of the MMQs to estimate the total measurement uncertainty.

a. Meter Ratings: 200 A, 120 V single- phase = 24,000 W.
b. Test load 1% of rating = 240 W
c. Desired accuracy class: 0.2
d. Target MUT accuracy at 1% load = 2*C = 0.4

The uncertainty characteristics of the meter provided by the manufacturer are:

a. MMP = 0.12 W
b. MME = 0.002 Whr
c. CD = 50 ppm (0.00005)

First, the MMP is checked at the limit of an infinite test time to verify the uncertainty ratio can be 4 or greater. Using Eq. 10~~Eq. 10~~ the E_u at the test limit is:

$$\lim_{t\to\infty} E_u = CD + \frac{MMP}{TL} - \frac{MMP \cdot CD}{TL} \qquad \textit{Eq. 12}$$

$$\lim_{t\to\infty} E_u = 0.00005 + \frac{0.12}{240} - \frac{0.12 \cdot 0.00005}{240} = 0.000550$$

It is recommended that the uncertainty ratio be 4 or greater. In this case, the uncertainty ratio at the limit is:

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$$uncertainty\,ratio = \lim_{t\to\infty} \frac{Target\ MUT\ accuracy}{E_u} \qquad \text{Eq. 13}$$

$$uncertainty\,ratio = \frac{0.004}{0.00055} = 7.27$$

The MMP and the clock drift are sufficient so that the desired accuracy and recommended uncertainty ratio can be achieved for this meter design.

Because the initial check verifies that the MMP is correct to achieve the desired accuracy, the energy uncertainty for a selected test duration is verified next. For a test of finite duration, the MTE is needed. For this example, the testing is automated, and the energy is read by digital communications. The update rates are of the MUT and REF are known and are:

a. MUT update rate = 0.2 s
b. REF update rate = 0.1 s

The reading latency, in this case, will be the communication latency. It is tested and is found to be 0.6 seconds with sufficient network constraints and margin to ensure 0.5 sec or less.

The MTE; therefore, is:

MTE = 0.2 s +0.6 s = 0.8 s

The test duration is chosen as 20 minutes. Using Eq. 14~~Eq. 14~~ the energy uncertainty is:

$$E_u = \frac{(TL \cdot time) - [(TL - MMP) \cdot (time - MMT - CD \cdot time) - MME]}{TL \cdot time} \qquad \text{Eq. 14}$$

$$E_u = \frac{(240 \cdot 0.33) - [(240 - 0.12) \cdot (0.33 - 0.00022 - 0.00005 \cdot 0.33) - 0.002]}{240 \cdot 0.33} = 0.001241$$

For the 20-minute test duration, the uncertainty ratio is 0.004/0.00124 = 3.22. This is less than the desired uncertainty ratio of 4 but the test could still be performed with these parameters recognizing there is an increased risk that the MUT may fail because of the uncertainty. Alternately, Eq. 11~~Eq. 11~~ can be used to calculate the test duration to achieve the uncertainty ratio of 4. The solved duration is 31 minutes.

The energy uncertainty calculation can also be used to illustrate the impact of the test methods on the test outcome. The above example uses automated data acquisition and has a low MTE of less than 1 second. If the data was read and recorded manually, the latency could be expected to be 5 seconds. With a 2-second update of the displays, the MTE, in this case, is 2 s + 5 s = 7 s. With the 7 second MTE, the energy uncertainty for a 31-minute test duration is 0.0049, with an uncertainty ratio of 0.81. The low uncertainty ratio indicates the test method is more likely to cause a non-conforming result than any inaccuracy of the meter itself. Of course, the uncertainty can be overcome by increasing the test duration; but the test would take nearly 5 hours to complete. Additionally, other methods such as pulse synchronization and switching the current and voltage can be used to reduce the MTE.

B.5 Reference or Precision Source Uncertainty

There is also uncertainty in the reference or the precision source. To avoid a significant interference of the REF uncertainty in the test results, section **2.3.12~~2.3.1~~ Performance of the Test Equipment** recommends that a minimum TUR of 4 be used. A TUR of 4 is not recommended for the Starting Load

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test. For example, if the meter desired accuracy is 0.2%, then the uncertainty of the reference should be less than:

$$R_u = \frac{0.002}{4} = 0.05\%$$

Typically, it is expected to use a REF with a lower uncertainty than the MUT.

TURs of less than 4 may be used if testing techniques and analysis methods show the results to be statistically significant at the desired class.

B.6 Total Uncertainty

The total uncertainty of the measurement system is a combination of the MUT uncertainty and reference uncertainty. In that respect, the total uncertainty ratio is defined. This is the ratio of the tolerance limits of the device being measured (i.e., the required accuracy) to the uncertainty of the measurement system (i.e., the combined uncertainty of both the MUT and reference). The total uncertainty ratio should be a minimum of 4 except for the Starting Load test.

It is permissible to add the reference uncertainty and the MUT uncertainty as an additional allowance in the meter accuracy requirements up to a maximum value of one-quarter of the meter accuracy class.

For example, the desired accuracy for the meter under test is 0.5% (class 0.5). The reference uncertainty is 0.05%, and the MUT uncertainty is 0.089%. The additional allowance would be 0.05% + 0.089% = 0.139% but is limited to the maximum allowance of 0.125%, which is one-quarter of the meter accuracy class.

B.7 MMQ Derivations

B.7.1 Power Uncertainty Derivation

The minimum measurable power (MMP) is looked at first. This is the minimum power (watts) that the meter can measure and report repeatedly.

First, the equation for an error is used as the basis:

$$\frac{Actual - MUT\ Reading}{Actual} \qquad \textit{Eq. 15}$$

Where

a. Actual is the true quantity input and is the test load applied to the MUT by a precision source or measured by a precision reference in watts.
b. MUT Reading is the reading registered by the MUT in watts.

The “Actual” is the test load, denoted as TL, for a specific load being tested.

In any digital device, the reading can be off by the minimum amount the digital system can measure, the MMP. The MUT reading is expressed as:

$$MUT\ Reading = TL - MMP \qquad \textit{Eq. 16}$$

So, the uncertainty in the power, Pu is:

$$Pu = \frac{TL - (TL - MMP)}{TL} \qquad \textit{Eq. 17}$$

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Pu reduces to:

$$P_u = \frac{MMP}{TL} \qquad \textit{Eq. 18}$$

B.7.2 Energy Uncertainty Derivation

Starting with the same equation for error, including the digital increment uncertainty and introducing the minimum measurable energy (MME), in watt-hours, the energy uncertainty is:

$$E_{u1} = \frac{TV - [TV - MME]}{TV} \qquad \textit{Eq. 19}$$

Where:

a. TV = test value in Whr
b. E_{u1} is the partial energy uncertainty without the influence of time uncertainty

The test value is the actual input to the MUT from a precision source or measured by a precision reference.

The energy is the integral of the power over time:

$$E(T_{END}) = \int_0^{T_{END}} p(t) \cdot dt \qquad \textit{Eq. 20}$$

Where T_{END} >> the period of the AC line frequency.

Therefore, the test value is

$$TV = TL \cdot time \qquad \textit{Eq. 21}$$

Because the energy is the integral of the power over time, the energy uncertainty is also dependent on the power uncertainty:

$$E_{u1} = \frac{(TL \cdot time) - [(TL - MMP) \cdot time - MME]}{TL \cdot time} \qquad \textit{Eq. 22}$$

Thus, the energy uncertainty with both power and energy contributions reduces to:

$$E_{u1} = \frac{(MMP \cdot time) + MME}{TL \cdot time} \qquad \textit{Eq. 23}$$

Energy is a function of time. There is uncertainty in the time as well that contributes to the total energy uncertainty, Eu. The time error also includes the clock drift that increases linearly with the test duration. Sources of MTE are discussed in more detail in the section B.7.4~~B.7.4~~ **Sources of MTE**. MTE is not a characteristic of the meter alone: it also includes the testing methods.

This time uncertainty will be denoted as the measurement time error (MTE), and the clock drift will be denoted as CD. Using the MMP, MME, MTE, and CD contributions, the energy uncertainty is:

$$E_u = \frac{(TL \cdot time) - [(TL - MMP) \cdot (time - MMT - CD \cdot time) - MME]}{TL \cdot time} \qquad \textit{Eq. 24}$$

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Rearranging Eq. 24Eq. 24 and evaluating at the limit of time approaching infinity yields:

$$\lim_{t \to \infty} E_u = CD + \frac{MMP}{TL} - \frac{MMP \cdot CD}{TL} \qquad \textit{Eq. 25}$$

As the test duration approaches infinity, the energy uncertainty approaches a combination of the clock drift and the power uncertainty (MMP/TL). If the clock drift is small compared to the power uncertainty, then the energy uncertainty is approximately:

$$E_u \lim_{t \to \infty} \approx \frac{MMP}{TL} \approx P_u \qquad \textit{Eq. 26}$$

This shows that the best achievable energy uncertainty is the power uncertainty regardless of how long the test is run.

B.7.3 Compute Duration as a Function of Desired Uncertainty

The energy uncertainty equation can also be used to calculate the duration of a test for a desired level of energy uncertainty. Solving the energy uncertainty equation for time and replacing the calculated energy uncertainty, E_u, with the desired uncertainty, D_u, yields:

$$time = \frac{TL \cdot MTE - MMP \cdot MTE + MME}{TL \cdot D_u - TL \cdot CD - MMP + MMP \cdot CD} \qquad \textit{Eq. 27}$$

This equation can be used to determine the time needed to achieve the desired level of energy uncertainty.

Alternatively, using the power uncertainty, Pu, the test duration can be expressed as:

$$time = \frac{TL \cdot MTE - MMP \cdot MTE + MME}{TL * [D_u - P_u * (1 - CD) - CD]} \qquad \textit{Eq. 28}$$

With D_u as the desired uncertainty, the test duration can be solved. Note that the desired uncertainty D_u cannot be less than the power uncertainty P_u. Otherwise, it results in an invalid solution (i.e., negative duration time).

B.7.4 Sources of MTE

The MTE (measurement time error) is the time error generated during a test, due to the time-associated differences between the MUT and REF. It is the time influence on the value that is the read vs. what the actual value would be if read at the exact instant of time. It is the maximum possible time difference between the MUT and REF intervals (without the clock drift error) accumulated from the beginning of the test until the readings are taken. Sources of this error are:

a. Update rate of the MUT and the REF
b. The latency or delay in reading the value of the MUT and REF

The clock drift also contributes to the time error. The clock drift (CD) between the MUT and REF is part of the energy uncertainty equation. Since the clock drift time error is calculated by multiplying CD by time, it

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is not considered part of the MTE. In modern devices using crystal clocks (MUTs or reference), the clocks typically have a drift of 20 ppm or less.

To illustrate the MTE, consider the following example:

The update rate of the meter is once every 2 seconds, and the update rate of the REF is once every 1 second. Therefore, the maximum difference would be the larger of the two, which is 2 seconds.

The reading latency is 5 seconds. This is the difference in the time when the MUT and REF are read. This assumes the values are read and recorded from displays by a person. Obviously, if the values were read automatically through digital communications, this would typically be 0.5 seconds or less.

For this example, the MTE is 2 s + 5 s = 7 s.

A second example is for values being read automatically. The update rate of the registers that are known to be 0.2 seconds for the MUT and 0.1 seconds for the REF. The reading latency is found to be 0.5 seconds.

The total MTE is: 0.2 s + 0.5 s = 0.7 s.

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ANNEX C Errors combination

(Informative)

This informational annex provides guidance on the optimal combination of measurement errors in a meter system. Traditionally, in a sensor meter system, the system accuracy class is calculated by adding the meter class to the sensor nominal class. Although this calculation method is very simple, it has several disadvantages:

- The calculated system class is typically higher (i.e., reduced accuracy) than it could be. This is more dominant when high quality sensors are used.
- When medium-low quality sensors (i.e., sensors with significantly high errors at low loads) are connected to a meter, the calculated system class does not ensure compliance with the ESM1-2 accuracy limits,

The system class calculation method presented below in this section, provides better results since it overcomes the disadvantages of the traditional method while maintaining a low calculation complexity.

Combined Meter and Sensor Errors

When the exact meter and sensor gain errors are known, then the total error is calculated by a simple addition. The same would apply for phase angle errors.

However, when both the meter and sensor errors are random variables, normally distributed such that two or three standard deviations from the mean fall within the specified error limits, then the error limits should be combined.

Under this condition, it is reasonable to combine gain errors or phase errors using the root-sum squared (RSS) approach. This results in smaller combined errors and with a higher statistical relevance.

To be clear, when combining errors this way, if the meter had the largest specified error and the sensor also had the largest specified error and both errors were in the same direction, then the combined error could exceed the value reported with the RSS approach.

The combined gain error using RSS (root sum squared):

$$\epsilon = \sqrt{{\epsilon_M}^2 + {\epsilon_S}^2} \qquad \textit{Eq. 29}$$

Where:

ϵ_M: The **meter** gain error

ϵ_S: The **sensor** gain error

The combined phase angle error using RSS (root sum squared):

$$\delta = \sqrt{{\delta_M}^2 + {\delta_S}^2} \qquad \textit{Eq. 30}$$

Where:

δ_M: The **meter** phase angle error

δ_S: The **sensor** phase angle error

The errors could also be summed, but as described above, RSS is statistically correct and the conventional way of combining errors.

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