BSR/ASHRAE Standard 41.11-2023R

Public Review Draft

Standard Methods for Power Measurement

First Public Review (August 2026)
(Complete Draft for Full Review)

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FOREWORD

Whether electrical power measurements are to be taken in a laboratory or in the field, selecting the appropriate instruments and components should be based on the required measurement accuracy. Once an instrument has been selected, the user might need to consult with the instrument manufacturer regarding installation specifics, operating range limits, calibration limits, and other similar performance specifics in order to obtain the expected measurement accuracy.

Working with electricity can be hazardous. Users of this standard are cautioned to obtain appropriate electrical safety training and equipment at the outset. For example, NFPA 70E (2024), Standard for Electrical Safety in the Workplace[A1]*, and OSHA 29 CFR 1910, Sub Part S*[A2] *describe all of the safety equipment required to perform energized equipment measurements, including arc-flash protection, approach boundaries, and other personal protective equipment.*

This update of the 2023 edition of Standard 41.11 includes updated methods for determining when steady-state operation has been achieved for data recording, as well as changes to make it easier for higher-tier standards to adopt this standard by reference. This standard meets ASHRAE's mandatory language requirements.

1. PURPOSE

This standard prescribes methods for power measurements.

2. SCOPE

This standard applies to power measurements under laboratory and field conditions when testing heating, ventilating, air-conditioning, and refrigerating systems and components.

3. DEFINITIONS

accuracy**:** the degree of conformity of an indicated value to the true value.

active power: see *power, active.*

apparent power: see *power, apparent.*

constant-speed drive (CSD): a device fitted between a rotating power source and the rotating load to achieve constant rotational speed regardless of the power source rotational speed. Compare to *variable-speed drives*.

crest factor: the ratio of peak value to RMS value of a waveform.

current shunt: a low-resistance device used to measure current in a circuit. Measure the voltage and apply Ohm's Law to calculate the current.

current transducer: a current transducer (sensor) is a device that detects electrical current (AC or DC) in a conductor and generates a signal proportional to it. The combinations of sensed current and the output signal are:

a. AC current input with:
    1. analog output that duplicates the wave shape of the sensed current.
    2. bipolar output that duplicates the wave shape of the sensed current.
    3. unipolar output that is proportional to the average or *RMS* value of the sensed current.

b. DC current input with:
    1. unipolar output that duplicates the wave shape of the sensed current.
    2. digital output that switches where the sensed current exceeds a certain threshold.

current transformer (CT): a transformer intended to have its primary winding connected in series with a circuit carrying the current to be measured or controlled; the current is measured across the secondary winding.

energy: capability to do work, J (ft-lb_f). Forms include chemical, electrical, mechanical, and thermal. Energy may be either stored or transient and can be transformed from one form into another. Compare to *power*.

error: the difference between the observed value of the measurement and the true value.

harmonics: currents or voltages with frequencies that are integer multiples of the fundamental power frequency.

linear: sinusoidal waveform, (for example, a constant-speed drive).

measurement system: the instruments, signal conditioning systems, if any, and data acquisition system, if any.

nonlinear: nonsinusoidal waveform, (for example, a variable-speed drive).

operating tolerance limit: the upper or lower value of an operating tolerance that is associated with a test point or a targeted set point.

phase transformer: see *real power factor.*

post-test uncertainty*:* an analysis to establish the uncertainty of a test result after conducting the test.

potential transformer (PT): an instrument transformer whose primary winding is connected in parallel for voltage measurement. Also known as *voltage transformer (VT).*

power: rate of doing work, or energy divided by time, W (hp). Compare to *energy*.

> ***power, active:*** the product of the voltage across a branch of an alternating-current circuit and the component of the electric current that is in phase with the voltage.
>
> ***power, apparent:*** the product of the RMS voltage and the RMS current delivered in an alternating-current circuit, no account being taken of the phase difference between voltage and current, measured in volt-amps (VA).
>
> ***power, non-electrical:*** types of non-electrical power include shaft power, power derived from the first law of thermodynamics, and fluid power.
>
> ***power, reactive:*** also called imaginary power or "wattless" power. Reactive loads such as inductors and capacitors dissipate zero power, but the fact that reactive loads drop voltage and draw current gives the deceptive impression that reactive loads actually dissipate power. This "phantom power" is called *reactive power*, measured in a unit called *volt-amps-reactive* (var).
>
> ***power, real:*** also known as *active power*, the product of the voltage across a branch of an alternating-current circuit and the component of the electric current that is in phase with the voltage, W (hp).

power factor: the ratio of the real power flowing to the load to the apparent power in the circuit, expressed as a dimensionless number between 0 and 1, or expressed as a percentage (for example, 50% pf).

power factor, displacement: the cosine of the angle between the voltage and the current zero crossings (θ) for linear AC loads (compare to *power factor*).

power factor, real: the ratio of the average (or active) power to the apparent power (RMS voltage times RMS current) of an alternating-current circuit. Also known as *phase factor*.

pretest uncertainty: an analysis to establish the expected uncertainty interval for a test result before conducting the test.

random error: the portion of the total error that varies randomly in repeated measurements of the *true value* throughout a test process.

reactive power: see *power, reactive.*

real power: see *power, real.*

root-mean-square (RMS): a statistical measure of the magnitude of a varying quantity. The RMS value of a set of values (or a continuous-time waveform) is the square root of the arithmetic average of the squares of the original values, or the square of the function that defines the continuous waveform.

steady-state criteria: the criteria that establish negligible change of power with time.

systematic error: the portion of the total error that remains constant in repeated measurements of the *true value* throughout a test process.

targeted set point: a specific set of test conditions where the required power is known and has an associated operating tolerance.

test point: a specific set of test operating conditions for recording data where the measured power is unknown and has an associated operating tolerance.

true value: the unknown, error-free value of a test result.

uncertainty: the limits of error within which the true value lies.

unit under test: the equipment under test, including all power-consuming control elements and accessories.

var: the units for reactive power (see *power, reactive*).

variable-speed drive (VSD): describes equipment used to control the speed of machinery. Also known as variable speed drives. Compare to *constant-speed drives*. Informative **Note:** An example would be to use a VSD to modulate assembly line speed to vary the drive speed for pumps or fans.).

voltage transformer (VT): see *potential transformer*.

volt-ampere (VA): the unit used for the *apparent power (see power, apparent)* in an electrical circuit, equal to the product of root-mean-square (RMS) voltage and RMS current.

4. CLASSIFICATIONS

4.1 Power Measurement Application. Power measurements that are within the scope of this standard are classified as one of the following two types in Sections 4.1.1 and 4.1.2.

4.1.1 Laboratory Applications. Power measurements under laboratory conditions are engineering development tests or tests to determine product performance.

Informative Note: Laboratory power measurements tend to use more accurate instruments than field measurements.

4.1.2 Field Applications. Power measurements under field conditions are tests to determine installed system power rates.

Informative Note: Field power measurements tend to use less accurate instruments than laboratory measurements.

4.2 Electrical Load Type. Electrical load configurations for electrical power measurement are classified as one of the following two types in Sections 4.2.1 and 4.2.2:

4.2 Electrical Load Type. Electrical load configurations for electrical power measurement are classified as one of the types in Sections 4.2.1 and 4.2.2.

4.2.1 Linear Loads. Linear loads do not contain power electronic switching devices interposed between the power source and the load to alter the voltage or current waveforms presented to the load. Linear alternating current (AC) drives use AC utility power or synchronous AC generators. Linear direct current (DC) power drives provide a constant DC voltage to the load.

Informative Notes:

1. Examples of linear AC drives include constant-speed drives (CSDs) and motor starters used in conjunction with induction motors that incorporate contactors or relays to connect the motor to the power source. These include across-the-line, star-delta, part-winding, auto-transformer, and primary-resistance starters.
2. Examples of linear DC drives include stepper motors and some fan motors.

4.2.2 Nonlinear Loads. Nonlinear loads contain power electronic switching devices interposed between the power source and the load. This alters the voltage and the current waveforms that are presented to the load impacting the crest factor.

Informative Notes:

1. Examples of nonlinear AC drives include
   a. Variable-speed AC induction motor drives
   b. Switched-reluctance motor drives
   c. Permanent-magnet motor drives
   d. Reduced-voltage starters
2. Examples of nonlinear DC drives include
   a. DC drives that operate from an AC source
   b. Brushless DC motor drives
   c. Variable-speed DC motor drives
3. Power measurements may be taken while the equipment is running or idle (for example, standby power consumption as in IEC 62301[A3] and EN 50564[A4]).

4.3 Electrical Power Analyzer Types. Electrical power analyzer types that are within the scope of this standard are the types listed in Tables 4-1 and 4-2.

4.4 Nonelectrical Power Measurements. Nonelectrical power measurements that are within the scope of this standard are:

a. Shaft input power to components including open-shaft compressors and shaft-driven fans
b. Power derived from the first law of thermodynamics
c. Pump input power

Table 4-1 Electrical Power Analyzer Types for Linear Load Measurements

Measured Parameter	Units	Type
Input and Output Voltage	Volts	Analog Voltmeter, Digital Voltmeter or Digital Power Instruments
Input and Output Current	Amperes	Analog Ammeter, Digital Ammeter or Digital Power Instruments
Input and Output Real Power	Watts	Analog Wattmeter, Digital Wattmeter or Digital Power Instruments
Input and Output Reactive Power	Vars	Use values from Input Real Power and Input Apparent Power or Digital Power Instruments
Input and Output Apparent Power	Volt-Amperes	Use values from Input Voltage and Current above or Digital Power Instruments
Input and Output Power Factor	Dimensionless	Use values from Input Real Power, Input Voltage and Current above or Digital Power Instruments
Frequency	Hertz	Oscilloscope or Digital Power Instruments

Table 4-2 Electrical Power Analyzer Types for Non-Linear Load Measurements

Measured Parameter	Units	Type
Input Voltage	Volts	Analog Voltmeter, Digital Voltmeter or Digital Power Instruments
Input Current	Amperes	Digital Power Instruments
Input Real Power	Watts	Digital Power Instruments
Input Reactive Power	Vars	Digital Power Instruments
Input Apparent Power	Volt-Amperes	Digital Power Instruments
Input Power Factor	Dimensionless	Digital Power Instruments
Input Crest Factor	Dimensionless	Digital Power Instruments
Output Voltage	Volts	Digital Power Instruments
Output Current	Amperes	Digital Power Instruments
Output Real Power	Watts	Digital Power Instruments
Output Reactive Power	Vars	Digital Power Instruments
Output Apparent Power	Volt-Amperes	Digital Power Instruments
Output Power Factor	Dimensionless	Digital Power Instruments
Frequency	Hertz	Oscilloscope or Digital Power Instruments

5. REQUIREMENTS

5.1 Test Plan. The test plan shall be one of the following options:

a. A document provided by the person or the organization that authorized the tests
b. A method of test standard
c. A rating standard
d. A regulation or code
e. Any combination of items (a) through (d)

The test plan shall specify:

a. The minimum value of the accuracy or the maximum value of measurement uncertainty of the power measurement system over the full range of operating conditions.
b. The values to be determined and recorded, selected from this list:
    - electrical power measurements,
    - pretest electrical power measurements uncertainty,
    - post-test electrical power measurements uncertainty,
    - shaft input or output power measurements,
    - pretest shaft input or output power measurements uncertainty,
    - post-test shaft input or output power measurements uncertainty,
    - power derived from the first law of thermodynamics,
    - pretest power derived from the first law of thermodynamics uncertainty,
    - post-test power derived from the first law of thermodynamics uncertainty,
    - fluid output power,
    - pretest fluid output power uncertainty,
    - post-test fluid output power uncertainty.
c. Any combination of test points and targeted set points to be performed together with operating tolerances.

5.2 Values to be Determined and Reported

The values to be determined and reported if specified in the test plan in Section 5.1 shall use the units of measure listed in Table 5-1 unless otherwise specified in the test plan.

Table 5-1 Measurement Values and Units of Measure

Quantity	Units of Measure	
	SI	I-P
Power	W	hp
Uncertainty in the power measurement	W	hp
Displacement Power Factor for linear AC electrical power load	dimensionless	dimensionless

measurements		
Real Power Factor for non-linear AC electrical power load measurements	dimensionless	dimensionless

5.3 Test Requirements

5.3.1 Accuracy or Measurement Uncertainty. A selected power measurement system accuracy or measurement uncertainty shall meet or exceed the required power measurement system accuracy or measurement uncertainty specified in the test plan in Section 5.1 over the full range of operating conditions**.**

5.3.2 Pretest Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected uncertainty for each power test point prior to the conduct of that test in accordance with the pretest uncertainty analysis procedures in ASME PTC 19.1[1].

5.3.3 Post-Test Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected power measurement uncertainty for each power or power difference test point in accordance with the post-test uncertainty analysis procedures in ASME PTC 19.1[1]. Alternatively, if specified in the test plan, the worst-case uncertainty for all test points shall be estimated and reported for each test point.

5.3.4 Steady-State Test Criteria. Power test data shall be recorded at steady-state conditions unless otherwise specified in the test plan in Section 5.1.

5.3.4.1 Steady-State Test Criteria for Power Measurements Under Laboratory Test Conditions. If the test plan requires power test data points to be recorded at steady-state test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, then determine that steady-state test conditions have been achieved using one of the following methods:

a. Apply the steady-state criteria in Section 5.3.4.3 if the test plan provides test points for power measurement.
b. Apply the steady-state criteria in Section 5.3.4.4 if the test plan provides targeted set points for power measurement.

5.3.4.2 Steady-State Test Criteria for Power Measurements Under Field Test Conditions. If the test plan requires power test data points to be recorded at steady-state test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, the methods in Section 5.3.4.1 are optional.

Informative Note: The steady-state methods in Section 5.3.4.1 are likely to be impractical under field test conditions. Section 5.3.5 provides instructions for making measurements that are not at steady state conditions.

5.3.4.3 Steady-State Power Criteria for Test Points
Sample not less than 30 power measurements, N, at equal time intervals, δt, over a test duration,

Δt, where Δt is in time units. Equation 5-1 states the relationship of the test duration to the number of power samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t \tag{5-1}$$

Informative Note: Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed power fluctuations during operation near the steady-state conditions.

Record each sampled power measurement, P_i, and the corresponding time, t_i. Apply the least-squares line method to determine the slope, *b,* of the power data trend line using Equation 5-2.

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i P_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} P_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} t_i^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]} \right\} \tag{5-2}$$

Informative Note: It should be noted that the units for the slope in Equation 5-2 are power, W (hp), divided by the units that the user has selected for time.

The mean of the sampled powers, $\bar{P}$, is defined by Equation 5-3.

$$\bar{P} = \frac{1}{N}\left[\sum_{i=1}^{N}(P_i)\right], \text{ W (hp)} \tag{5-3}$$

The difference between the maximum and minimum sampled values shall be less than or equal to the specified operating tolerance limit as defined in Equation 5-4 where P_L is the operating tolerance limit.

$$P_{max} - P_{min} \leq P_L, \text{ W (hp)} \tag{5-4}$$

The restriction on the slope of the trend line b is defined in Equation 5-5 where Δt is the sample time interval.

$$|b \times \Delta t| \leq 0.5 \times P_L, \text{ W (hp)} \tag{5-5}$$

$\bar{P}$, as determined by Equation 5-3, represents the steady-state mean power where Equations 5-4 and 5-5 are both satisfied.

Informative Note: For further reading about methods of determining steady-state conditions, refer to Informative Appendix A – Bibliography items A8 and A9.

5.3.4.4 Steady-State Power Criteria for Targeted Set Points

Sample not less than 30 power measurements, N, at equal time intervals, δt, over a test duration, Δt, where Δt is in time units. Equation 5-6 states the relationship of the test duration to the number of samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t \tag{5-6}$$

Informative Note: Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed power fluctuations during operation near the steady-state conditions.

Record each sampled power measurement, P_i, and the corresponding time, t_i. Apply the least-squares line method to determine the slope, *b,* of the power data trend line using Equation 5-7.

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i P_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} P_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} t_i^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]} \right\} \tag{5-7}$$

Informative Note: It should be noted that the units for the slope in Equation 5-7 are power, W (hp), divided by the units that the user has selected for time.)

The mean of the sampled powers, $\bar{P}$, is defined by Equation 5-8.

$$\bar{P} = \frac{1}{N}\left[\sum_{i=1}^{N} (P_i)\right] \text{W (hp)} \tag{5-8}$$

The difference between the maximum and minimum sampled values shall be less than or equal to the specified operating tolerance limit as defined in Equation 5-9 where P_L is the operating tolerance limit.

$$P_{max} - P_{min} \le P_L \text{, W (hp)} \tag{5-9}$$

The restriction on the slope of the trend line *b* is defined in Equation 5-10 where Δt is the sample time interval.

$$|b \times \Delta t| \le 0.5 \times P_L \text{, W (hp)} \tag{5-10}$$

The difference between the test condition and mean of the sampled values shall be less than or equal to half of the specified operating tolerance limit as defined in Equation 5-11 where P_{SP} is the set point pressure and P_L is the operating tolerance limit.

$$|P_{SP} - \bar{P}| \le 0.5 \times P_L \text{, W (hp)} \tag{5-11}$$

$\bar{P}$, as determined by Equation 5-8, represents the steady-state mean power where Equations 5-9, 5-10, and 5-11 are all satisfied.

Informative Note: For further reading about methods of determining steady-state conditions, refer to Informative Appendix A – Bibliography items A8 and A9.

5.3.5 Unsteady Power Measurements. If required by the test plan in Section 5.1, power test data shall be recorded:

a. at operating conditions that are not steady state,
b. at the time intervals specified in the test plan,
c. within the test condition limits specified in the test plan,
d. using instrument response times specified in the test plan.

5.3.6 Current Transformer Restriction. An open circuit across the secondary winding of a current transformer is not permitted.

5.3.7 Potential Transformer Restriction. A short circuit across the secondary winding of a potential transformer is not permitted.

6. INSTRUMENTS

6.1 Instrument Requirements for All Measurements

6.1.1 Instruments and data acquisition systems shall be selected to meet the measurement system accuracy specified in the test plan.

6.1.2 Measurements from the instruments shall be traceable to primary or secondary standards calibrated by the National Institute of Standards and Technology (NIST) or to the Bureau International des Poids et Mesures (BIPM) if a National Metrology Institute (NMI) other than NIST is used. In either case, the indicated corrections shall be applied to meet the uncertainty stated in subsequent sections. Instruments shall be recalibrated on regular intervals that do not exceed the intervals prescribed by the instrument manufacturer, and calibration records shall be maintained. Instruments shall be installed in accordance with the instrument manufacturer's requirements or the manufacturer's accuracy does not apply.

6.1.3 Instruments shall be applied and used in accordance with the following standards and codes:

a. Electrical: IEEE 120[2] if electrical measurements are required in the test plan in Section 5.
b. Shaft power: ASME PTC-19.7[3] if shaft power measurements are required in the test plan in Section 5.1

6.2 Laboratory Electrical Measurements, Linear Loads

Electrical power measurement system accuracy for linear loads in laboratory applications shall be within ±1.0% of reading unless otherwise specified in the test plan.

Informative Note: See Informative Appendix B, Section B3 for electrical power measurement locations. For example, voltages, currents, and frequencies are measured for each AC phase at the equipment terminals for linear loads to prevent the power losses associated with power leads from reducing power measurement system accuracy.

6.3 Laboratory Electrical Measurements, Non-Linear Loads

Electrical power measurement system accuracy for non-linear loads in laboratory applications shall be within ±1.0% of reading unless otherwise specified in the test plan.

Informative Note: See Informative Appendix B, Section B3 for electrical power measurement locations. For example, voltages, currents, and frequencies are measured for each AC phase at the equipment terminals for linear loads to prevent the power losses associated with power leads from reducing power measurement system accuracy.

6.4 Field Electrical Measurements, Linear Loads

Electrical power measurement system accuracy for linear loads in field applications shall be within ±3.0% of reading unless otherwise specified in the test plan.

Informative Note: See Informative Appendix B, Section B3 for electrical power measurement locations. For example, voltages, currents, and frequencies are measured for each AC phase at the equipment terminals for linear loads to prevent the power losses associated with power leads from reducing power measurement system accuracy.

6.5 Field Electrical Measurements, Non-Linear Loads

Electrical power measurement system accuracy for non-linear loads in field applications shall be within ±3.0% of reading unless otherwise specified in the test plan.

Informative Note: See Informative Appendix B, Section B3 for electrical power measurement locations. For example, voltages, currents, and frequencies are measured for each AC phase at the equipment terminals for linear loads to prevent the power losses associated with power leads from reducing power measurement system accuracy.

6.6 Non-Electrical Power Measurements

6.6.1 Shaft Power Measurements. Shaft power measurement system accuracy in laboratory or field applications shall be within ±1.0% of reading unless otherwise specified in the test plan. Shaft power shall be measured using instrumentation in accordance with ASME PTC 19.7.[2]

6.6.2 Measurements of Power Derived from the First Law of Thermodynamics. Measurement system accuracy in power derived from the first law of thermodynamics in laboratory or field applications shall be within ±1.0% of reading unless otherwise specified in the test plan.

6.6.3 Measurements of Fluid Output Power from a Pump. Measurement system accuracy in fluid output power from a pump in laboratory or field applications shall be within ±1.0% of reading otherwise specified in the test plan.

7. TEST METHODS

The test methods that are within the scope of this standard are the methods that are described in Sections 7.1 through 7.4.

7.1 Electrical Power Measurement Test Methods

Informative Note: Each test method in this section shows direct and indirect (PT/CT) connections, where used, for generic electrical power analyzers. A combination of direct and indirect connections may be applied if the restrictions in Sections 5.3.6 and 5.3.7 are met.

7.1.1 Single-Phase Single-Element or DC Method

Single-phase single-element or DC power measurements using direct connections are illustrated in Figure 7-1 and using indirect connections are illustrated in Figure 7-2. When measuring single-phase or DC power, the current measurement device is placed between the source and the load while the voltage is measured between the input and output.

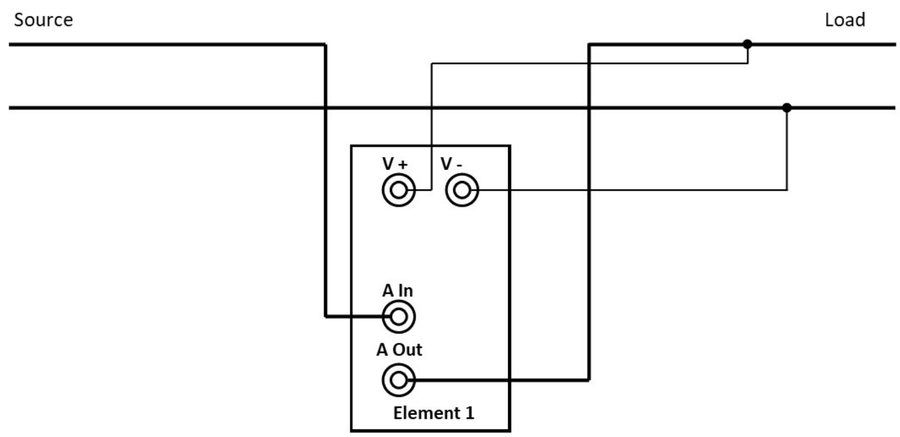

Figure 7-1 Electrical Power Analyzer Direct Connections for Single-Phase Single-Element or DC Circuits

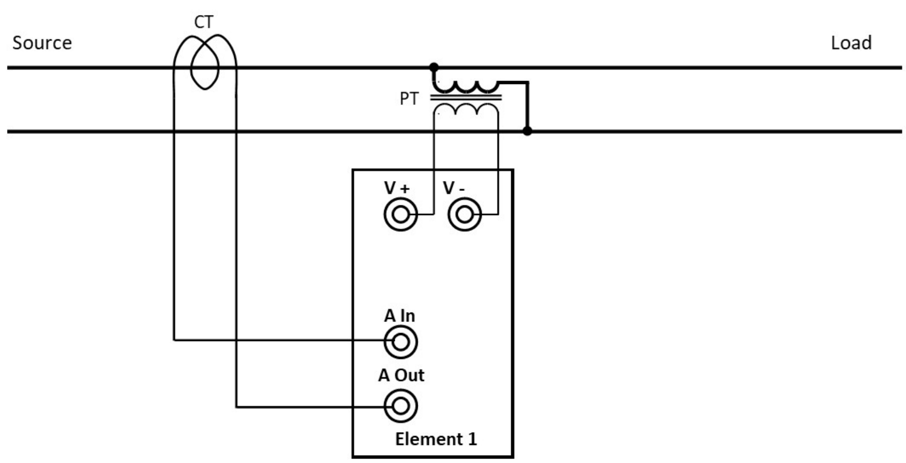

Figure 7-2 Electrical Power Analyzer Indirect (PT/CT) Connections for Single-Phase Single-Element or DC Circuits

7.1.2 Single-Phase Two-Element Method

Single-phase two-element power measurements using direct connections are illustrated in Figure 7-3 and using indirect connections are illustrated in Figure 7-4. Single-phase two-element power measurement is used with single-phase circuits that contain a current-carrying neutral. The current measurement devices are on the line portions of the circuit while the voltage reference readings are taken from each line to the neutral conductor.

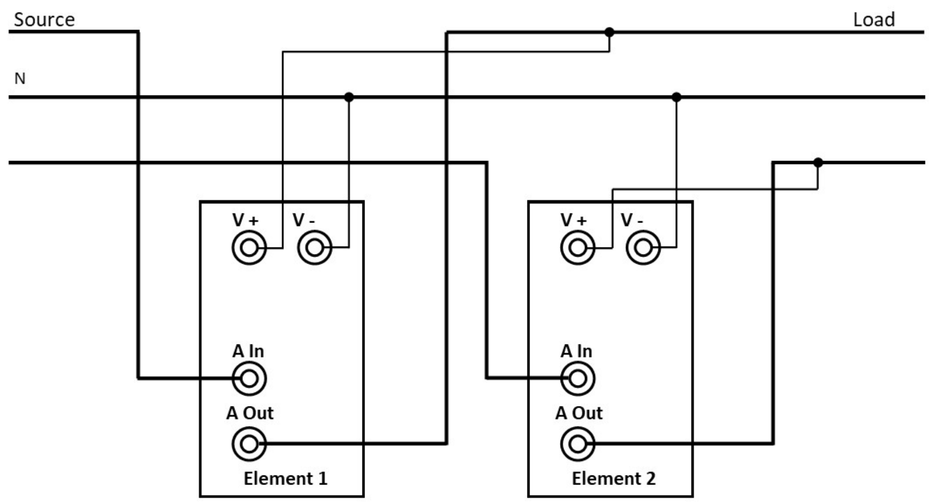

Figure 7-3 Electrical Power Analyzer Direct Connections for Single-Phase Two-Element Circuits

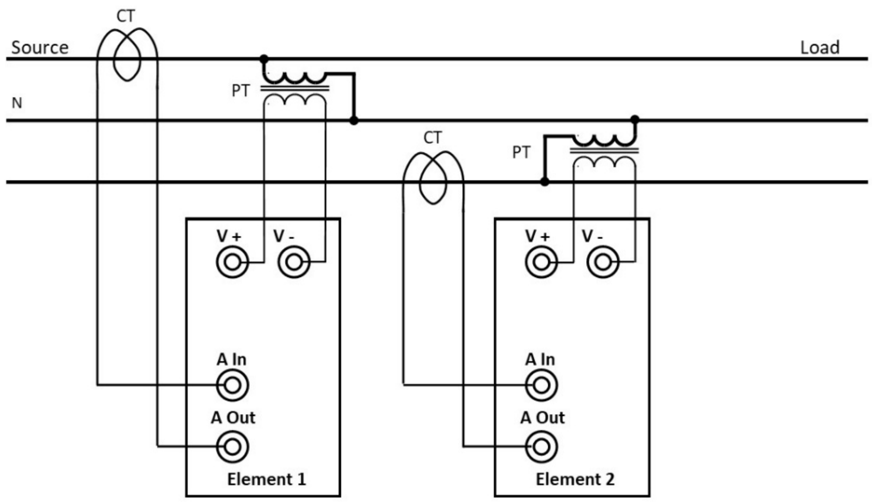

Figure 7-4 Electrical Power Analyzer Indirect (PT/CT) Connections for Single-Phase Two-Element Circuits

7.1.3 Three-Phase Two-Element Method

Three-phase two-element power measurements using direct connections are illustrated in Figure 7-5 and using indirect connections are illustrated in Figure 7-6. When measuring power in a three-phase, two-element circuit, two phases have current measuring devices during voltage measurement between each current measuring-phase and the remaining phase without a current measuring device.

Informative Note: This method is used where three-phase power has a balanced load.

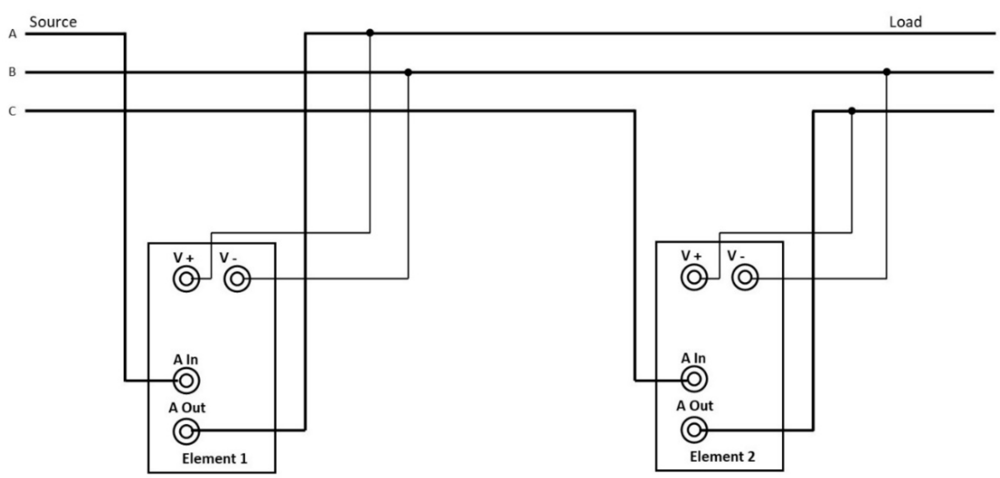

Figure 7-5 Electrical Power Analyzer Direct Connections for Three-Phase Two-Element Circuits

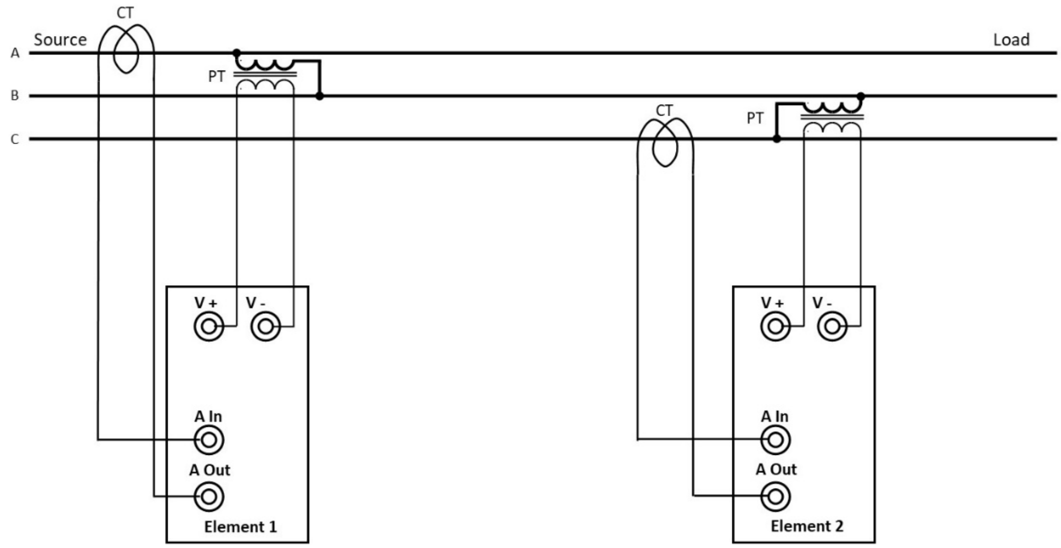

Figure 7-6 Electrical Power Analyzer Indirect (PT/CT) Connections for Three-Phase Two-Element Circuits

7.1.4 Three-Phase Three-Element Method

Three-phase three-element measurements using direct connections are illustrated in Figure 7-7 and using indirect connections are illustrated in Figure 7-8. In a three-phase three-element system, each power phase has a current measuring device, and voltage is measured between each phase.

Informative Note: This method can be used with three-phase delta and with three-phase wye systems with or without a balanced load.

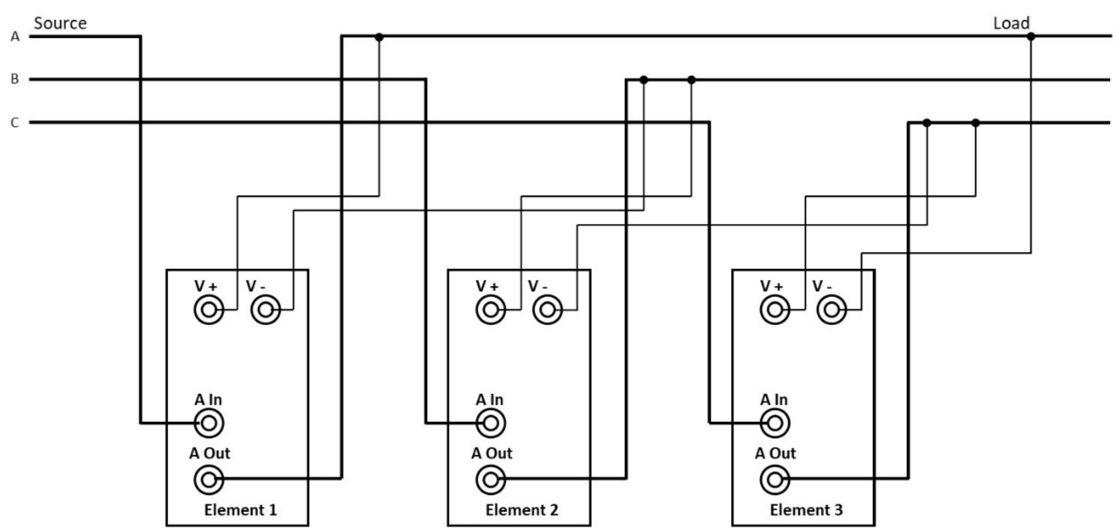

Figure 7-7 Electrical Power Analyzer Direct Connections for Three-Phase Three-Element Circuits

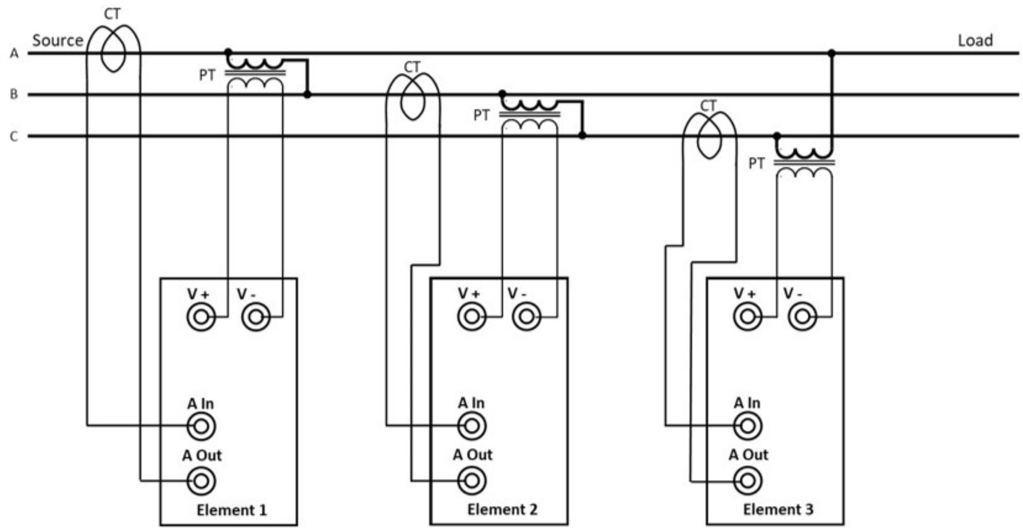

Figure 7-8 Electrical Power Analyzer Indirect (PT/CT) Connections for Three-Phase Three-Element Circuits

7.1.5 Three-Phase Three-Element Four-Wire Method

Three-phase three-element four-wire power measurements using direct connections are illustrated in Figure 7-9 and using indirect connections are illustrated in Figure 7-10. In a three-phase three-element four-wire system, current measuring devices are placed on each phase while the voltage measurements are made between the phase and the neutral line. ***(Informative Note:*** This method is used in three-phase three-element four-wire power systems that have a current-carrying neutral, typically a wye.)

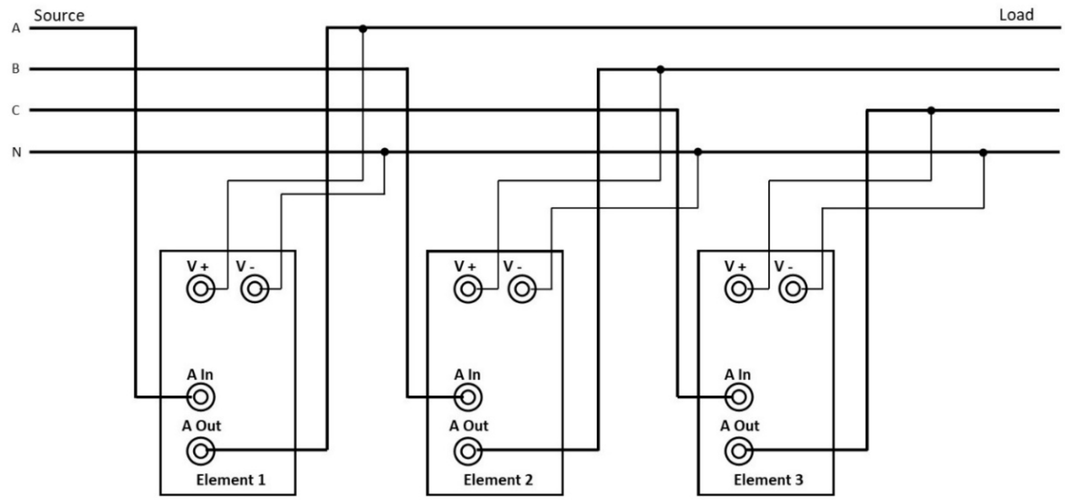

Figure 7-9 Electrical Power Analyzer Direct Connections for Three-Phase Three-Element Four-Wire Circuits

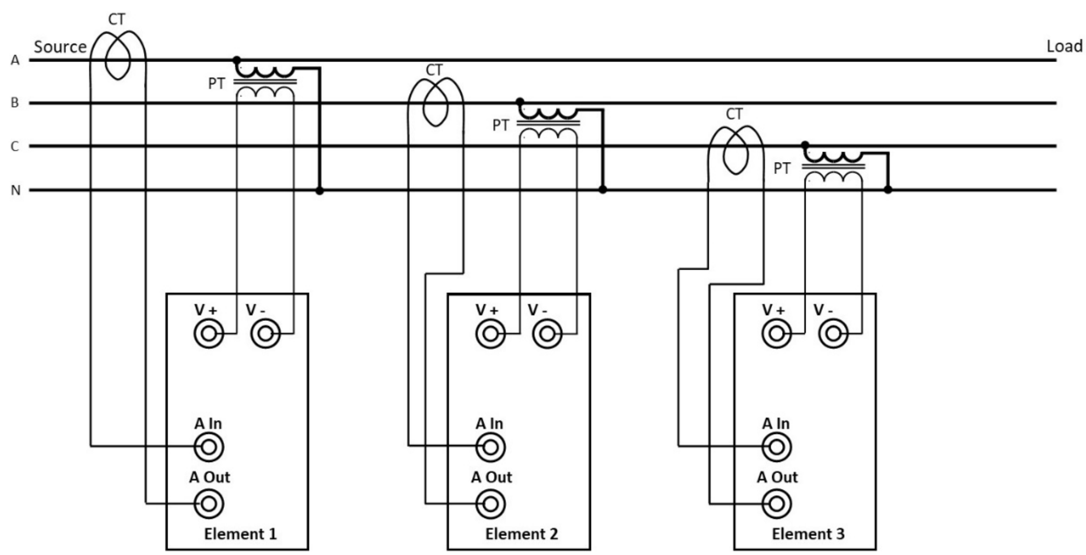

Figure 7-10 Electrical Power Analyzer Indirect (PT/CT) Connections for Three-Phase Three-Element Four-Wire Circuits

Informative Notes to Sections 7.1.1 through 7.1.5:

1. The direct and indirect electrical measurement methods for measuring voltage and current that are described in Sections 7.1.1 through 7.1.5 can be combined to measure the power of variable-speed drives on the input or output side as required by the test plan.
2. See Informative Appendix C for uncertainty examples.

7.2 Shaft Power Measurement Test Methods

The measurement of shaft power of rotating machines, in the absence of transients, utilizing a dynamometer or a torque meter, shall be determined using Equation 7-1 for SI units or Equation 7-2 for I-P units.

For SI units:

$$P = \omega T \tag{7-1}$$

where:

P = power, W
ω = shaft angular velocity, rad/s
T = torque, N-m

For I-P units:

$$P = \frac{2\pi NT}{33000} \tag{7-2}$$

where:

P = power, hp
N = shaft speed, rev/min
T = torque, ft-lb_f

7.3 Measurements of Power Derived from the First Law of Thermodynamics

This section provides an example of deriving power by applying the first law of thermodynamics.

7.3.1 Deriving the Power Required to Heat Moist Air to a Selected Temperature. Determine the required input heater power to increase the temperature of the air to a prescribed outlet temperature by heating the moist air to steady state with no change in the moisture content of the air.

In SI units, Equations 7-3 and 7-4 express the First Law of Thermodynamics at steady state to this case.

$$\dot{m}(h_2 - h_1) = Q_{in} \tag{7-3}$$

$$\dot{m}c_p(T_2 - T_1) = Q_{in} \tag{7-4}$$

where

$$c_p = c_{pa} + Wc_{pv} \tag{7-5}$$

The efficiency of the heater is the rate of heat input to the air stream divided by the heater input power as expressed in Equation 7-6.

$$\eta = \frac{Q_{in}}{P} \tag{7-6}$$

The equation for determining the required input power to the heater in Equation 7-7 is obtained by combining Equations 7-3, 7-4, and 7-6.

$$P = \frac{\dot{m}(c_{pa}+WC_{pv})(T_2-T_1)}{\eta} \tag{7-7}$$

where:

$\dot{m}$ = the mass flow rate of moist air, kg/s
h_2 = the specific enthalpy of the moist airstream leaving the heater, kJ/kg
h_1 = the specific enthalpy of the moist airstream entering the heater, kJ/kg
Q_{in} = rate of heat transferred to the moist airstream, kW
c_p= specific heat of moist air, kJ/(kg-°C)
c_{pa} = specific heat of dry air, kJ/(kg-°C)
c_{pv} = specific heat of moist air, (kJ/(kg-°C)
W = humidity ratio of moist air, (kg water vapor)/(kg dry air)
η = efficiency of the heater, dimensionless
P = Power input to the heater, kW

In I-P units, Equations 7-8 and 7-9 express the First Law of Thermodynamics at steady state to this case.

$$\dot{m}(h_2 - h_1) = Q_{in} \tag{7-8}$$

$$\dot{m}c_p(T_2 - T_1) = Q_{in} \tag{7-9}$$

where

$$c_p = c_{pa} + Wc_{pv} \tag{7-10}$$

The efficiency of the heater is the rate of heat input to the air stream divided by the heater input power as expressed in Equation 7-11.

$$\eta = 0.2931\left(\frac{Q_{in}}{P}\right) \tag{7-11}$$

The equation for determining the required input power to the heater in Equation 7-12 is obtained by combining Equations 7-8, 7-9, and 7-11.

$$P = 0.2931\left[\frac{\dot{m}(c_{pa}+WC_{pv})(T_2-T_1)}{\eta}\right] \tag{7-12}$$

where:

$\dot{m}$ = the mass flow rate of moist air, lb_m/h
h_2 = the specific enthalpy of the moist airstream leaving the heater, Btu/lb_m
h_1 = the specific enthalpy of the moist airstream entering the heater, Btu/lb_m
Q_{in} = rate of heat transferred to the moist airstream, Btu/h
c_p= specific heat of moist air, Btu/(lb_m-°F)
c_{pa} = specific heat of dry air, Btu/(lb_m-°F)

c_{pv} = specific heat of moist air, Btu/(lb_m-°F)
W = humidity ratio of moist air, (lb_m water vapor)/(lb_m dry air)
η = efficiency of the heater, dimensionless
P = Power input to the heater, W

7.4 Measurements of Fluid Power Output from a Pump

The measurement of fluid input power to a pump, in the absence of transients, shall be determined using Equation 7-13 for SI units or Equation 7-14 for I-P units.

For SI units:

$$P = Q(\Delta P) \tag{7-13}$$

where:

P = fluid input power to a pump, W, W
Q = volumetric flow rate, m^3/s
ΔP = pressure differential across the pump, Pa

For I-P units:

$$P = \frac{Q(\Delta P)}{1714} \tag{7-14}$$

where:

P = fluid input power to a pump, W, hp
Q = volumetric flow rate, gpm
ΔP = pressure differential across the pump, psid

8. UNCERTAINTY CALCULATIONS

8.1 Post-Test Uncertainty Analysis. A post-test analysis of the measurement system uncertainty, performed in accordance with ASME PTC 19.1[1], shall accompany each power measurement if specified in the test plan in Section 5.1. Installation effects on the accuracy of the instrument shall be included in the uncertainty analysis for each installation that does not conform to the instrument manufacturer's installation requirements.

Informative Note: Informative Appendix C provides an example of uncertainty calculations for a laboratory test of an electrical power measurement with a non-linear load.

8.2 Method to Express Uncertainty. All assumptions, parameter, and calculations used in estimating uncertainty shall be clearly documented prior to expressing any uncertainty values. Uncertainty shall be expressed as shown in Equation 8-1:

$$v = \bar{X}_m \pm U_{\bar{X}}\ (P\%) \tag{8-1}$$

where

v = the variable that is a measurement or a calculated result
$\bar{X}m$ = the best estimate of the true value
$U_{\bar{X}}$ = the uncertainty estimate for the variable
P = the confidence level, %

9. TEST REPORT

If the test plan in Section 5.1 defines the test report requirements, the test report requirements in the test plan supersede the test requirements in Section 9. Otherwise, Section 9 specifies the test report requirements.

9.1 Electrical Power Measurements Described in Section 7.1 if Specified in the Test Plan in Section 5.1

9.1.1 Test Identification

a. Date, place, and time.
b. Operator identification.

9.1.2 Unit Under Test Description

a. Model number and serial number.

9.1.3 Instrument Description

a. Power meter description, model number, serial number, operating range, calibrated accuracy.
b. Current transducer description, model number, serial number, operating range, if used in the measurement system.
c. Voltage transformer description, model number, serial number, operating range, if used in the measurement system.
d. Instrument accuracy based upon specification or calibration.
e. Documentational evidence of instrument calibrations

9.1.4 Measurement System Description

a. Description of instrument installation specifics.
b. Measurement system accuracy based on specifications or calibration.
c. Documentational evidence of measurement system calibrations.

9.1.5 Test Conditions

a. Test conditions in accordance with the test plan in Section 5.1
b. Ambient temperature, ºC (ºF).
c. Barometric pressure Pa, (psia) if pressure instruments are measuring gauge pressure.

9.1.6 Test Results. Test results, if specified in the test plan in Section 5.1, are:

a. Electrical power, W (hp).
b. Electrical power pretest uncertainty, W (hp).

c. Electrical power post-test uncertainty, W (hp).

9.2 Shaft Power Measurements Described in Section 7.2 if Specified in the Test Plan in Section 5.1

9.2.1 Test Identification

a. Date, place, and time.
b. Operator identification.

9.2.2 Unit Under Test Description

a. Model number and serial number.

9.2.3 Instrument Description

a. Shaft speed sensor and shaft torque description, model number, serial number, data acquisition system description, operating range.
b. Operating range.
c. Instrument accuracy based on specifications or calibration.
d. Documentational evidence of instrument calibrations.

9.2.4 Measurement System Description

a. Description of instrument installation specifics.
b. Measurement system accuracy based on specifications or calibration.
c. Documentational evidence of measurement system calibrations.

9.2.5 Test Conditions

a. Test conditions in accordance with the test plan in Section 5.1
b. Ambient temperature, ºC (ºF).
c. Barometric pressure Pa, (psia) if pressure instruments are measuring gauge pressure.

9.2.6 Test Results. Test results, if specified in the test plan in Section 5.1, are:

a. Shaft speed, rev/s (rpm).
b. Shaft torque, N-m (ft-lb_f).
c. Shaft power, W (hp).
d. Shaft power pretest uncertainty, W (hp).
e. Shaft power post-test uncertainty, W (hp).

9.3 Fluid Input Power Measurement to a Pump Described in Section 7.4 if Specified in the Test Plan in Section 5.1

9.3.1 Test Identification

a. Date, place, and time.
b. Operator identification.

9.3.2 Unit Under Test Description

a. Model number and serial number.

9.3.3 Instrument Description

a. Volumetric flow rate sensor description and differential pressure sensor, model number, serial number.
b. Operating range.
c. Instrument accuracy based on specifications or calibration.
d. Documentational evidence of instrument calibrations.

9.3.4 Measurement System Description

a. Description of instrument installation specifics.
b. Data acquisition system description,
c. Measurement system accuracy based on specifications or calibration.
d. Documentational evidence of measurement system calibrations.

9.3.5 Test Conditions

a. Test conditions in accordance with the test plan in Section 5.1
b. Ambient temperature, ºC (ºF).
c. Barometric pressure Pa, (psia) if pressure instruments are measuring gauge pressure.

9.3.6 Test Results. Test results, if specified in the test plan in Section 5.1, are:

a. Volumetric flow rate, m^3/s (gpm).
b. Differential pressure across the pump, kPa (psid).
c. Pump power, W (hp).
d. Pump power pretest uncertainty, W (hp).
e. Pump power post-test uncertainty, W (hp).

10. REFERENCES

1. ASME. 2018. ASME PTC 19.1, *Test Uncertainty*. New York: American Society of Mechanical Engineers.
2. IEEE. 2023. IEEE 120-2023, *IEEE Master Test Guide for Electrical Measurements in Power Circuits*. Piscataway, NJ: Institute of Electrical and Electronics Engineers. (See Note 1.)
3. ASME. 1988. ASME/ANSI Power Test Code PTC 19.7-1980 (R1988), *Part 7—Measurement of Shaft Power*. New York: American Society of Mechanical Engineers. (See Note 2.)

Informative Notes:
1. Reference 2 is only required when electrical power measurements are included in the test plan.
2. Reference 3 is only required where shaft power measurements are included in the test plan.

(This appendix is not part of this standard. It is merely informative and does not contain requirements necessary for conformance to the standard. It has not been processed according to the ANSI requirements for a standard and may contain material that has not been subject to public review or a consensus process. Unresolved objectors on informative material are not offered the right to appeal at ASHRAE or ANSI.)

INFORMATIVE APPENDIX A
INFORMATIVE REFERENCES AND BIBLIOGRAPHY

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A2. OSHA. 29 CFR 1910, Sub Part S, Electrical. Occupational Safety and Health Standards, Washington D.C.
A3. IEC. 2011. IEC 62301, *Household Electrical Appliances—Measurement of Standby Power*. Geneva, Switzerland: International Electrotechnical Commission.
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A5. ISA. 1988. ANSI/ISA S82.02, *Safety Standard for Electrical and Electronic Test, Measuring, Controlling, and Related Equipment—Electrical and Electronic Test and Measuring Equipment*. Research Triangle Park, NC: International Society of Automation.
A6. ISA. 1988. ANSI/ISA S82.03, *Safety Standard for Electrical and Electronic Test, Measuring, Controlling, and Related Equipment Electrical and Electronic Process Measurement and Control Equipment*. Research Triangle Park, NC: International Society of Automation.
A7. ISA. 1999. ANSI/ISA S82.01, *Safety Standard for Electrical and Electronic Test, Measuring, Controlling, and Related Equipment—General Requirements*. Research Triangle Park, NC: International Society of Automation.
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A9. Miller, S.J. 2006. *The Method of Least Squares*. Providence, RI: Brown University

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INFORMATIVE APPENDIX B
POWER MEASUREMENT BASICS

B1 POWER COMPARED TO ENERGY

Power is the time rate of doing work, expressed in Watts (horsepower). In contrast, *energy* is the capability to do work, expressed in joules (ft-lb_f). Energy, which may be either stored or transient, has several forms and can be transformed from one form into another. Forms of energy include chemical, electrical, mechanical, and thermal.

B2 ELECTRICAL VOLTAGE AND CURRENT MEASUREMENT BASICS

Refer to IEEE-120[1], Section 2, for additional information on this topic.

B2.1 Instrumentation. Voltage and current instrumentation may be based on analog or digital technology. Digital instrumentation is the more modern of the two technologies and often has wider bandwidth, greater accuracy, and the capability to accurately measure waveforms associated with both linear and nonlinear loads. ANSI/ISA Standards S82.01 A5, S82.02 A6, and S82.03 A7 outline safety requirements for electrical and electronic test, measuring, controlling, and related equipment.

B2.2 Adequate Bandwidth. Bandwidth is defined at a gain of -3 dB, corresponding to a spectral density that is greater than half of the maximum. Therefore, with an adequate bandwidth, the gain at the frequency of what is being measured will be 0 dB. Depending on the frequency response characteristics of the measurement instrumentation, adequate bandwidth may require up to 10 times higher frequency rating than what is being measured. For example, if one is only concerned in measuring a 60 Hz waveform without harmonics, then a sensor with a bandwidth of 600 Hz is sufficient. Harmonics need to be considered when selecting adequate bandwidth, especially for non-linear waveforms.

B2.3 Range Extenders. The ranges of instrumentation may be extended through the use, for example, of resistive shunts, current transformers, Hall-effect transducers, potential transformers, or resistive dividers. The accuracy, bandwidth, and impedance of the selected range extender shall be carefully scrutinized and its uncertainty shall be included in uncertainty calculations. Where utilizing range extenders, be very careful to understand the equipment scaling, limitations, and safety concerns. For example, an open circuit across the secondary winding of a current transformer shall be avoided and a short circuit on the secondary winding of a potential transformer cannot be tolerated.

B2.4 Harmonic-Related Losses. *Harmonics* is the name given to the condition where currents or voltages have frequencies that are integer multiples of the fundamental power frequency. In a normal alternating current power system, the voltage varies sinusoidally at a specific or fundamental frequency, usually 50 or 60 Hz. Where a linear electrical load is connected to the system, it draws a sinusoidal current at the same frequency as the voltage (though usually not in phase with the voltage). Where a non-linear load, such as a rectifier, is connected to the system, it draws a current that is not necessarily sinusoidal. The current waveform of a non-linear load can become quite complex, depending on the type of load and its interaction with other components of the system. Regardless of the current waveform complexity, all periodic waves can be generated with sine waves of various frequencies using Fourier series analysis. Fourier series analysis combines a series of sinusoidal waveforms that are integer multiples of the fundamental frequency. These multiples of the fundamental frequency are called harmonics. The harmonic currents generated by non-linear electronic loads can cause audible noise in electrical power panels and transformers due to mechanically resonating laminations and can increase power system losses due to frequency and higher root-mean-square (RMS) currents. These harmonic-related losses reduce system efficiency, cause apparatus overheating, and increase power and air conditioning cost.

B3 ELECTRICAL POWER AND POWER FACTOR MEASUREMENT BASICS

Refer to IEEE-120[1], Section 3.1, for additional information on this topic.

B3.1 Power. Power is the time average of the product of the instantaneous magnitude of voltage and current for both linear and non-linear loads. The power associated with linear alternating current (AC) loads may be obtained if the RMS values of voltage and current are known, and the power factor of the load is known.

B3.2 Power Factor. *Power Factor* is defined as the ratio of the *true power* in watts to the *apparent power* in volt-amperes. This is true for both linear and non-linear loads. *Power Factor* is a figure of merit, indicating how much of the apparent power is being actively used by the load. In the case of linear single-phase loads, the power factor may also be determined by taking the cosine of the angle between the voltage and the current zero crossings (θ). Cosine θ is also defined as *Displacement Power Factor*, a term specifically applied to linear AC loads. Refer to Section 3.3 of IEEE-120[1] for additional information on this topic.

Figures B-1 through B-3 are examples of variable-speed drive input waveforms with different power factor corrections to illustrate the benefits of active power factor correction. The upper waveform in each of these figures represents input voltage, and the lower waveform represents input current.

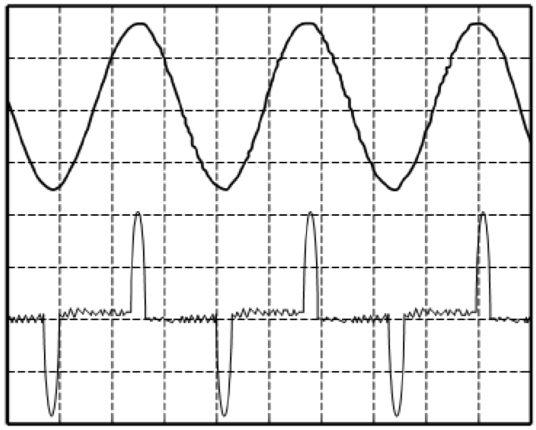

Figure B-1 No Power Factor Correction

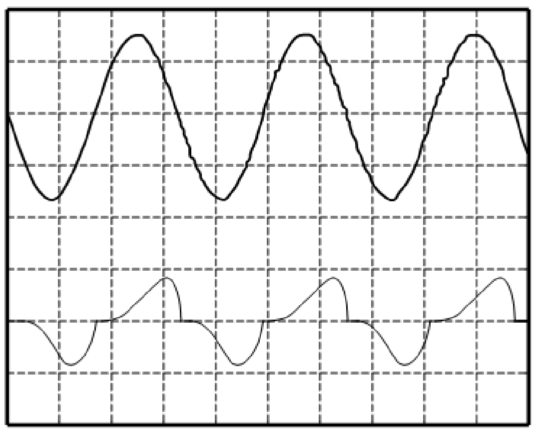

Figure B-2 Passive Power Factor Correction

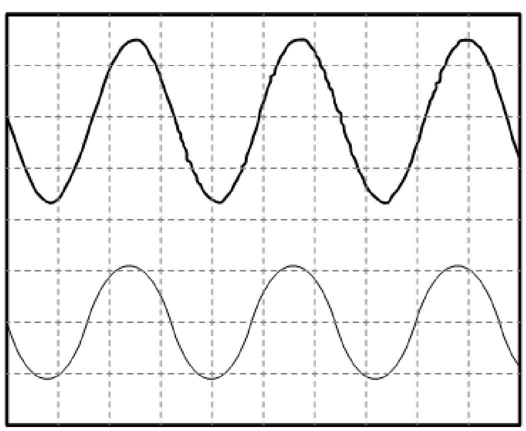

Figure B-3 Active Power Factor Correction

B3.3 Considerations for Non-Linear Units Under Test. Non-linear units under test (UUTs) may require appropriate isolation and precautions to ensure that accurate power measurements are obtained. Non-linear UUTs may require the use of instrumentation that is capable of accurately measuring signals containing high frequency and/or high crest factors. For example, voltages and currents measured at the input to the power converter of variable speed compressors may contain significant levels of high frequency energy. In these cases, the instrumentation used shall have adequate bandwidth and/or crest factor specifications to ensure the electrical power input measurements are within the required accuracy.

B3.4 Connections and Loading Effects. The impedance of the voltage and current measuring elements and their loading effects may introduce errors in either the voltage or current reading, and thus the power reading. The connections required to measure the power are a function of the number of conductors connected to the load and the polarity marking on the instrument being used. Where measuring the power on a multi-phase AC system, the power measurement instrument shall include the ability to accurately measure the total power assuming the power is not balanced between the phases.

B4 Non-Electrical Power Measurements

B4.1 Shaft Power Measurement. Shaft power is the product of the instantaneous shaft torque and the instantaneous shaft speed as prescribed in Section 7.2. Alternatives for measuring equipment include a non-contact speed sensor combined with an in-line torque sensor, an in-line combination torque-and-speed sensor, and other methods that are capable of meeting the prescribed power measurement accuracy in Section 6.6.1.

B4.2 Power Derived from the First Law of Thermodynamics. Power derived from the first law of thermodynamics, as defined in the test plan, is determined from combinations of temperature measurements, pressure measurements, flow rate measurements, and fluid properties—for example, measuring the thermal power loss from a liquid-cooled variable-speed drive at a given operating condition by measuring the (a) coolant flow rate, (b) coolant inlet temperature, and (c) coolant outlet temperature, and then using the coolant property data to calculate the coolant heat gain. ASHRAE has several method of test standards focused on determining the overall efficiency of systems or components where the efficiency is defined as the ratio of the thermal capacity to the power input.

B4.3 Fluid Power Output from a Pump. Fluid power output from a pump is the product of the volumetric flow at the pump outlet and the pressure differential across the pump as defined in the test plan.

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INFORMATIVE APENDIX C
AN UNCERTAINTY ANALYSIS EXAMPLE FOR THE INPUT AND OUTPUT POWER OF A VARIABLE FREQUENCY DRIVE

A test plan requires a variable frequency drive (VFD) to be used to power a 460 V/3 phase/60 Hz 260 kW (350 hp) refrigerant compressor from 30 to 261 nominal kW (40 to 350 hp). Incoming power to the drive is from a three phase-three wire system. Power is to be measured in the input and output side of the inverter to help evaluate VFD performance at an accuracy of at least ± 0.5% at a 95% confidence level. Determine the expected measurement uncertainty of the selected power measurement equipment while measuring over the expected operating range and at the minimum and maximum test conditions.

Because the VFD is a non-linear device, digital power instrumentation will be required to accurately measure power to the low level of uncertainty requested. The power level also dictates that current transformers will need to be used that have a good high frequency response. Since this is a low voltage application, potential transformers will not be needed as the digital power meter that will be used is capable of 600V RMS.

According to the step-by-step procedure outlined in Section 9 of ANSI/ASME PTC 19.1-2018[1], do the following.

C1. REVIEW TEST OBJECTIVES AND TEST DURATION

The experimental goal is to determine an estimate of average power and its uncertainty at the input and output of the VFD. The measuring system will require an 8.7:1 turndown to be able to measure the expected speed variation. The acceptable accuracy is defined in the test plan above to be ±0.5% at a 95% confidence level. Uncertainty will be estimated between the minimum and maximum power levels, and the worst-case accuracy will be reported as the overall uncertainty per Section 5.3.3 of this standard.

The important variable is power. This measurement will require an estimate of uncertainty over the entire frequency spectrum of the wattmeter as well as the current transformers that will scale the actual current to a level that is acceptable to the digital power meter. Two separate sets of digital power instrumentation will be used so that the input and output power may be measured simultaneously.

C2. LIST ALL INDEPENDENT MEASUREMENT PARAMETERS AND THEIR NOMINAL LEVELS

Table C-1 shows the expected variations in the operating power and current at 10% and 100% load.

Table C-1 Estimated Test Condition Operating Range

Nominal Motor kW	Estimated Nominal Power hp	Maximum Power Error for 0.5% Accuracy kW	Estimated Current Amps
30	40.2	0.2	50
261	350	1.3	420

Additionally, because the full power spectrum distribution must be known to estimate uncertainty, previously acquired power spectrum data from a similar drive and compressor will be used as an initial estimate of uncertainty for the power meter and current transformers. Once the actual data is acquired, the final calculations will need to be recalculated with the actual test power spectrum data to determine system uncertainty. The power distribution on the output of the VFD is shown later in Figures C-1 and C-2. The previous data also showed that the motor had a 0.95 power factor.

C3. LIST ALL CALIBRATIONS AND INSTRUMENT SETUPS THAT WILL AFFECT EACH PARAMETER

Two different digital watt meters are evaluated for this test plan for the same unit under test (UUT). Digital watt meter (DWM) A is a less accurate meter but may be acceptable and has an accuracy spec as shown in Table C-2. DWM B has higher accuracy than DWM A, and its accuracy is shown in Table C-3. The third column in the last two tables will be defined in the next step.

Table C-2 DWM A Accuracy Specification and UUT Power Spectrum Estimates

Frequency Range	**Frequency Band Accuracy of DWM A**	**Power Spectrum Weighting**
0.5 Hz < f < 45 Hz	±(0.3% of reading + 0.2% of range)	0.010%
45 Hz ≤ f ≤ 66 Hz	±(0.1% of reading + 0.1% of range)	0.000%
66 Hz < f ≤ 1 kHz	±(0.2% of reading + 0.2% of range)	98.000%
1 kHz < f ≤ 10 kHz	±(0.1% of reading + 0.3% of range)	0.640%
10 kHz < f ≤ 100 kHz	±(0.5% of reading + 0.5% of range)	1.350%
	Sum of all Power Spectrum Weights =	**100.000%**

Table C-3 DWM B Accuracy Specification and UUT Power Spectrum Estimates

Frequency Range	**Frequency Band Accuracy of DWM B**	**Power Spectrum Weighting**
0.0 Hz ≤ f < 0.1 Hz	±(0.05% of reading + 0.1% of range)	0.01796%
0.1 Hz ≤ f < 30 Hz	±(0.2% of reading + 0.3% of range)	0.00192%
30 Hz ≤ f < 45 Hz	±(0.05% of reading + 0.05% of range)	0.04005%
45 Hz ≤ f ≤ 66 Hz	±(0.02% of reading + 0.04% of range)	0.00427%
66 Hz < f ≤ 1 kHz	±(0.05% of reading + 0.05% of range)	98.35196%
1 kHz < f ≤ 10 kHz	±(0.15% of reading + 0.1% of range)	0.57216%
10 kHz < f ≤ 50 kHz	±(0.3% of reading + 0.2% of range)	0.99384%
50 kHz < f ≤ 100 kHz	±(0.014 x f % of reading + 0.3% of range)	0.01784%

100 kHz < f ≤ 500 kHz	±(0.012 x f % of reading + 1% of range)	0.00000%
500 kHz < f ≤ 1 MHz	±((0.048 x f -19)% of reading + 0.2% of range)	0.00000%
	Sum of all Power Spectrum Weights =	**100.0000%**

High accuracy ± 0.05% wide band current transformers were available and selected to reduce the actual current to a level that is acceptable for the digital power meter. The combined uncertainty will be a root-sum-squared of the watt meter uncertainty and the 0.05% the current transformer uncertainty.

C4. DEFINE THE FUNCTIONAL RELATIONSHIP BETWEEN INDEPENDENT PARAMETERS AND THE TEST RESULT

Estimating the power uncertainty requires that the error of the meter is applied to each band of the power spectrum. From the unit under test data shown in Step 3, the percentage of each content window is shown in column 3 of Table C-2 for DWM A and column 3 of Table C-3 for DWM B. The current transformers that will be used have a worst-case uncertainty of 0.05% across the entire power spectrum, so that value will be used for frequency bands. As can be seen in Tables C-2 and C-3, most of the spectrum content is concentrated in the 66 to 1 kHz, which is typical for the output of a VFD. The power spectrum weighting and the associated error bands for DWM A and DWM B are shown in Figure C-1 and Figure C-2, respectively.

Figure C-1 Power Weighting of DWM A

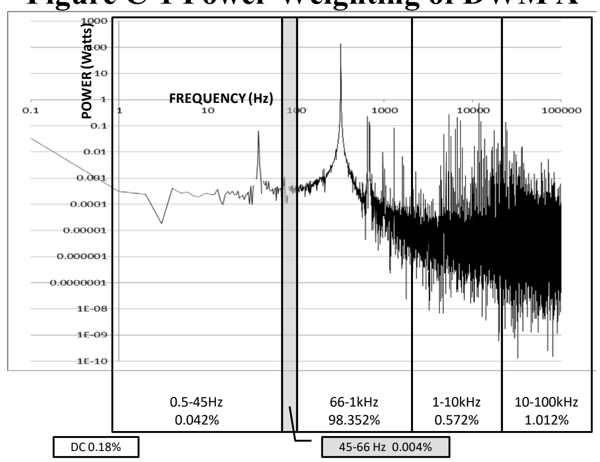
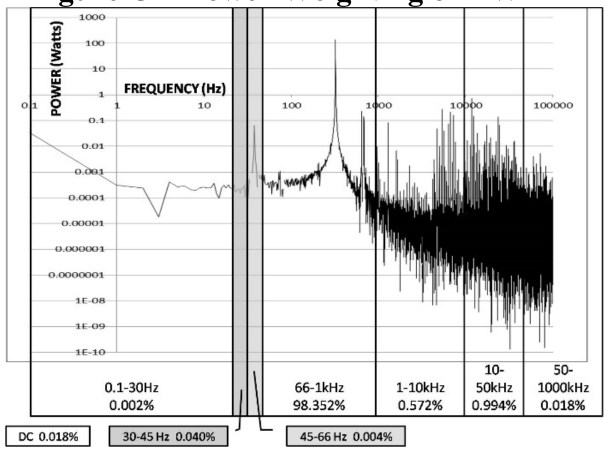


Figure C-2 Power Weighting of DWM B



A spreadsheet was set up to take the accuracy of each frequency band from the manufacturer's specification and then calculate the uncertainty based on the % of scale and reading for the specific measurement. The current range selection on the DWM was adjusted to use the maximum amount of the input range of the DWM without over-ranging it. A typical data point of DWM A and DWM B are shown in Tables C-1 and C-2, respectively.

Table C-4 DWM A Typical Data Point Spreadsheet Example

Voltage:	**Reading**	460	**INPUT PARAMETERS**	
	Range	600		
Current:	**Reading**	0.008192726		
	Range	0.5		
		1P-2W	**3P-3W**	**3P 4W**
Watt:	**Reading**	24	6.5275	72
	Fixed Meter Range	300	600	900
Frequency:	**kHz**	100	**Power Factor**	0.95

Calculated Meter Output Errors

Frequency	**Voltage Error Volts**	**Current Error Amps**	**Watt Error Watts/Element**	**Watt Error 3P 3W**
DC	2.120	0.0010	0.6720	N/A
0.5< f < 45 Hz	1.660	0.0010	0.6878	1.2239
45 < f < 66 Hz	1.060	0.0005	0.3398	0.6108
66 < f < 1 kHz	1.660	0.0010	0.6638	1.2173
1 kHz < f < 10 kHz	34.000	0.0021	2.5317	2.2438
10 kHz < f < 100 kHz	21.860	0.0028	3.5798	3.5657

Table C-5 DWM B Typical Data Point Spreadsheet Example

Voltage:	**Reading**	460	**INPUT PARAMETERS**	
	Range	600		
Current:	**Reading**	0.00819273		
	Range	0.01		
		1P-2W	**3P-3W**	**3P-4W**
Watt:	**Reading**	4.86	6.5275	14.6
	Range	6	12	18
Frequency:	**kHz**	1000	**Power Factor**	0.95

Calculated Meter Output Errors

Frequency	**Voltage Error Volts**	**Current Error Amps**	**Watt Error Watts/Element**	**Watt Error 3P-3W**
DC	0.53	9.0964E-06	0.0084	N/A
0.1< f < 30 Hz	1.66	2.8193E-05	0.0282	0.0497
30 < f < 45 Hz	0.438	7.4578E-06	0.0059	0.0099
45 < f < 66 Hz	0.226	3.8193E-06	0.0039	0.0067
66 Hz < f < 1 kHz	0.438	7.4578E-06	0.0059	0.0099
1 kHz < f < 10 kHz	0.76	1.3193E-05	0.0138	0.0224
10 kHz < f < 50 kHz	1.98	3.4578E-05	0.0271	0.0442
50 kHz < f < 100 kHz	56.4	0.00100313	0.6989	0.9505
100 kHz < f < 500 kHz	44.4	0.00078735	0.6437	0.9039
500 kHz < f < 1 MHz	75	0.00132891	1.5299	2.1336

Using the data from the above steps, uncertainty is estimated for each power band over the expected test conditions for DWM A that is shown in Table C-6 and for DWM B in Table C-7. The combined Root Sum Squared (RSS) error percentage in the last line of Tables C-3 and C-4 does not always decrease as the power level increases as the current measurement range on the DWM is switched at the various power levels to maximize the current measurement range which will minimize the meter's current range error. A 4kW point was added to see how fast the error increases in case a lower test point is requested in the future.

Table C-6 DWM A Estimated Error at Various Power Levels

kW	**4**	**30**	**75**	**150**	**225**	**261**	**Power**
hp	**5.4**	**40.2**	**100.5**	**201.1**	**301.6**	**349.9**	**Weighting**
% of Rdg	**18.351%**	**2.074%**	**1.171%**	**0.720%**	**0.571%**	**0.785%**	**100.00%**
F (Hz)							
22	18.75%	2.20%	1.28%	0.83%	0.67%	0.89%	0.04%
60	9.36%	1.08%	0.63%	0.40%	0.32%	0.43%	0.00%
500	18.65%	2.10%	1.18%	0.73%	0.57%	0.79%	98.35%
10,000	28.34%	3.53%	2.15%	1.46%	1.23%	1.56%	0.57%
100,000	54.63%	13.26%	10.96%	9.81%	9.43%	9.98%	1.01%
Combined RSS Error of DWM with 0.05% Current							

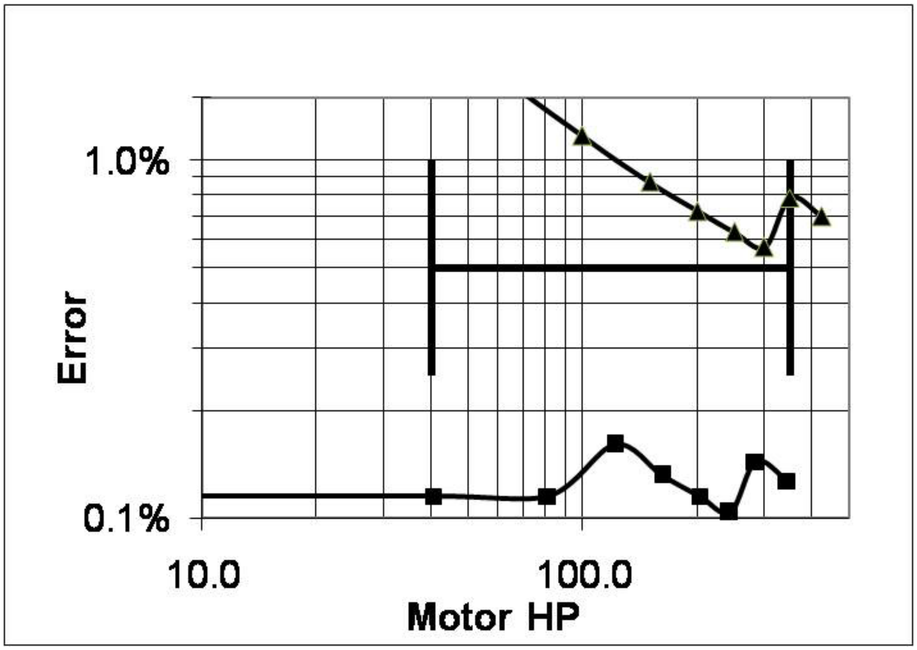
Transformers							
	18.351%	**2.074%**	**1.172%**	**0.722%**	**0.573%**	**0.786%**	

Table C-7 DWM B Estimated Error at Various Power Levels

kW	**4**	**30**	**90**	**150**	**225**	**261**	**Power**
hp	**5.4**	**40.2**	**120.6**	**201.1**	**301.6**	**349.9**	**Weighting**
% of Rdg	**0.149%**	**0.149%**	**0.210%**	**0.149%**	**0.188%**	**0.166%**	**100.00%**
F (Hz)							
15	0.76%	0.76%	1.13%	0.76%	1.00%	0.86%	0.002%
37	0.15%	0.15%	0.21%	0.15%	0.19%	0.17%	0.040%
60	0.10%	0.10%	0.15%	0.10%	0.13%	0.12%	0.004%
500	0.15%	0.15%	0.21%	0.15%	0.19%	0.17%	98.352%
10,000	0.34%	0.34%	0.47%	0.34%	0.42%	0.38%	0.572%
50,000	0.68%	0.68%	0.92%	0.68%	0.84%	0.74%	0.994%
100,000	1.96%	1.96%	2.33%	1.96%	2.20%	2.06%	0.018%
500,000	7.85%	7.85%	9.07%	7.85%	8.64%	8.17%	0.000%
1,000,000	32.69%	32.69%	35.14%	32.69%	34.26%	33.34%	0.000%
Combined RSS Error of DWM with 0.05% Current Transformers							
	0.158%	**0.158%**	**0.216%**	**0.158%**	**0.195%**	**0.173%**	

To better visualize the error relationship with the two meters being evaluated, the data shown in Tables C-3 and C-7 are plotted along with additional points in Figure C-3. The upper curve with triangle data points is for DWM A, and the lower curve with squares marking data points is DWM B. The horizontal axis limits at 40 hp and 350 hp are shown, and the maximum error of 0.5% is shown on the vertical axis.

Figure C-3 DWM A and B Error Comparison



Looking at Figure C-3, it is clear that the less accurate power meter, DWM A, will not meet the required accuracy, and DWM B will meet the 0.5% accuracy requirement. The worst-case estimated error occurs at 120 hp and has a value of 0.216% and would be the value reported if individual uncertainty values are not calculated at each test point. Based on this, two DWM B and 0.05% current transformers will be selected to meet the test plan requirements.

Two DWM B meters and two sets of 0.05% accuracy current transformers will be installed per manufacturer's guidelines while observing electrical safety considerations and guidance per IEEE 120-1989.

A data reduction spreadsheet was created to calculate the actual uncertainty error based on the nine accuracy ranges as a function of frequency for DWM B, and these calculations were verified prior to entering actual test data.

Data was taken with two DWM B measurement systems, including power spectrum distribution data. The results were tabulated and shown in Table C-8 for the input power to the VFD and in Table C-9 for the VFD output power for each error uncertainty band that is present in DWM B. The final line of Tables C-8 and C-9 shows the total estimated error of the test data that includes the RSS of % of reading error of the wattmeter and the 0.05% current transformers. It is noted that the input power is predominately in the 45 to 66 Hz band as expected, and the output power is concentrated in the 66 to 1,000 Hz band, which is typical for most VFD.

Table C-8 Estimated Input Power Errors at Various Test Points

Digital Wattmeter Estimated Error Only									
kW	**30.3**	**60.5**	**90.8**	**121.0**	**151.3**	**181.5**	**211.8**	**256.9**	**Component**
hp	40.6	81.1	121.7	162.2	202.8	243.3	283.9	344.3	**Power**
Current	**49**	**98**	**147**	**197**	**246**	**295**	**344**	**417**	**Weighting**
Err % of Rdg	**0.10%**	**0.10%**	**0.15%**	**0.12%**	**0.10%**	**0.09%**	**0.13%**	**0.12%**	**100%**
F (Hz)									
15	0.76%	0.76%	1.13%	0.90%	0.76%	0.67%	1.00%	0.86%	0.001%
37	0.15%	0.15%	0.21%	0.17%	0.15%	0.14%	0.19%	0.17%	0.000%
60	0.10%	0.10%	0.15%	0.12%	0.10%	0.09%	0.13%	0.12%	99.856%
500	0.15%	0.15%	0.21%	0.17%	0.15%	0.14%	0.19%	0.17%	0.142%
10,000	0.34%	0.34%	0.47%	0.39%	0.34%	0.31%	0.42%	0.38%	0.001%
50,000	0.68%	0.68%	0.92%	0.77%	0.68%	0.62%	0.84%	0.74%	0.000%
100,000	1.96%	1.96%	2.33%	2.10%	1.96%	1.87%	2.20%	2.06%	0.000%
500,000	7.85%	7.85%	9.07%	8.31%	7.85%	7.54%	8.64%	8.17%	0.000%
1,000,000	32.69%	32.69%	35.14%	33.61%	32.69%	32.07%	34.26%	33.34%	0.000%
Combined RSS Error of DWM with 0.05% Current Transformers									
	0.11%	**0.11%**	**0.16%**	**0.13%**	**0.11%**	**0.10%**	**0.14%**	**0.13%**	

Table C-9 Estimated Output Power Errors at Various Test Points

Digital Wattmeter Estimated Error Only									
kW	**30.3**	**60.5**	**90.8**	**121.0**	**151.3**	**181.5**	**211.8**	**256.9**	**Component**
hp	**40.6**	**81.1**	**121.7**	**162.2**	**202.8**	**243.3**	**283.9**	**344.3**	**Power**
Current	**49**	**98**	**147**	**197**	**246**	**295**	**344**	**417**	**Weighting**
Error % of Reading	**0.15**	**0.15%**	**0.21%**	**0.17%**	**0.15%**	**0.13%**	**0.19%**	**0.17%**	**100.%**
f (Hz)									0.018%
15	0.76%	0.76%	1.13%	0.90%	0.76%	0.67%	1.00%	0.86%	0.002%
37	0.15%	0.15%	0.21%	0.17%	0.15%	0.14%	0.19%	0.17%	0.040%
60	0.10%	0.10%	0.15%	0.12%	0.10%	0.09%	0.13%	0.12%	0.004%
500	0.15%	0.15%	0.21%	0.17%	0.15%	0.14%	0.19%	0.17%	98.352%
10,000	0.34%	0.34%	0.47%	0.39%	0.34%	0.31%	0.42%	0.38%	0.572%
50,000	0.68%	0.68%	0.92%	0.77%	0.68%	0.62%	0.84%	0.74%	0.994%
100,000	1.96%	1.96%	2.33%	2.10%	1.96%	1.87%	2.20%	2.06%	0.018%
500,000	7.85%	7.85%	9.07%	8.31%	7.85%	7.54%	8.64%	8.17%	0.000%
1,000,000	32.69%	32.69%	35.14%	33.61%	32.69%	32.07%	34.26%	33.34%	0.000%
Combined RSS Error of DWM with 0.05% Current Transformers									
	0.16%	**0.16%**	**0.22%**	**0.18%**	**0.16%**	**0.14%**	**0.19%**	**0.17%**	

Reviewing the data and results in Tables C-8 and C-9, all the data appears to be as expected with no apparent outliers and there were no known field effects during the testing.

The final experimental results for the eight test points shown in Tables C-8 and C-9 are on the last line of each table and need to be noted that they are at a 95% confidence level. The initial test plan called for the error uncertainty to be determined at the maximum and minimum test conditions. Noting that the largest error occurs at the 90 kW (121 hp) power level due to current range changes to the digital wattmeter, Table C-10 was made to show the variation of all the test points.

Table C-10 Estimated Power Errors at Various Test Points for VFD Input and Output Power

kW	30.3	60.5	90.8	121.0	151.3	181.5	211.8	256.9
hp	40.6	81.1	121.7	162.2	202.8	243.3	283.9	344.3
Current	49	98	147	197	246	295	344	417
VFD Input Power Estimated Error at 95% Confidence Level								
	0.11%	0.11%	0.16%	0.13%	0.11%	0.10%	0.14%	0.13%
VFD Output Power Estimated Error at 95% Confidence Level								
	0.16%	0.16%	0.22%	0.18%	0.16%	0.14%	0.19%	0.17%