Electrical Energy Metering

Abstract: Some aspects of the selection and installation requirements for electrical energy metering are canvassed.

Situation

Electrical energy metering is extremely common, being installed in almost every household and business in Australia. Most of these meters are installed for the purpose of billing for energy consumed, but others provide more fine-grained information as sub-meters.

This “case study” is an attempt to provide an introduction to some of the key basics as well as to highlight some traps for the unwary. The metering covered here is for the measurement of energy associated with alternating current (AC) supplies only, meaning that metering of non-energy AC supply parameters and metering of direct current (DC) supplies are not covered here.

Also, this “case study” covers only low voltage application whereby voltage is measured directly. High-voltage metering applications require special voltage step-down devices and this is not covered here.

Some Basics

In an alternating current supply electrical power measured in watts (unit symbol: W) is the time-coincident product of voltage measured in volts, (symbol: V) and current measured in amperes (symbol: A).

Electrical energy is the integral of power over a time period. The fundamental unit for energy is the joule (symbol: J) which is the energy associated with 1 W of power of 1 W over the time period of 1 second. It is common to also refer to energy by the alternative term watt-hours. One joule is the same as one watt-second (symbol: Ws) and 3600 Ws (or 3600 J or 3.6 kJ) is the same as 1 Wh, and 1000 Wh is the same as one kilowatt-hour (symbol: kWh) which is the most commonly used term\(^1\).

Alternating current means current that alternates between positive value and a negative value. Each cycle starts at zero, then over time goes to maximum positive, then zero, then to maximum negative and back to zero. In Australia, there are 50 cycles per second, meaning the supply frequency is 50 hertz (symbol: Hz), meaning each cycle is completed in \(1/50^{th}\) of a second or 20 ms. Likewise, voltage follows an alternating cycle but the two waveforms may not coincide in time. The displacement of current relative to voltage is called the phase angle.

\(^1\) One commonly used equivalence to align energy measured in different units is that 1 kWh is identical to 3.6 MJ (3600 kJ).
This lack of coincidence means that there are two additional terms that need to be introduced:

- Reactive energy: measured in volt-ampere-hours (reactive) (unit symbol: VAhR), and
- Apparent energy: measured in volt-ampere-hours (unit symbol: VAh)

To distinguish the useful energy in Wh, it is sometimes referred to as real energy to distinguish it from reactive energy and apparent energy. See box out for basic equations.

### Basic Power and Energy Equations

In a 3-phase situation:

- \( I = \text{phase current (A)} \)
- \( V = \text{phase to phase voltage (V)} \)
- \( \phi = \text{phase angle between current and voltage (degrees)} \)

Real power in W, \( P_{\text{real}} = \sqrt{3} \times V \times I \times \cos \phi \)

Reactive power in VAr, \( P_{\text{reactive}} = \sqrt{3} \times V \times I \times \sin \phi \)

Apparent power in VA, \( P_{\text{apparent}} = \sqrt{3} \times V \times I \)

Note: the term power factor is commonly used to mean the cosine of the phase angle (\( \phi \))

In a single phase situation, \( V \) is the phase to neutral voltage and the \( \sqrt{3} \) term is dropped.

Real energy (Wh), reactive energy (VArh) and apparent energy (VAh) are the time integrated values associated with real power (W), reactive power (VAr) and apparent power (VA) respectively.

As noted in the main text, it is common for only real energy \( (E_{\text{real}}) \) and reactive energy \( (E_{\text{reactive}}) \) to be measured by a meter. Apparent energy \( (E_{\text{apparent}}) \) is readily derived using the following formula:

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E_{\text{apparent}} = \sqrt{(E_{\text{real}})^2 + (E_{\text{reactive}})^2}
\]

And power factor (PF) = \( (E_{\text{real}})/(E_{\text{apparent}}) \)

With the use of on-site generation of electricity from such sources as photo-voltaic, co-generation, wind turbine and the like, electrical energy may be passing through an electricity meter in different directions at different times. To accommodate this variation, the associated electricity meter must be bi-directional. The billing electricity meters in common use possess this capability and also provide four-quadrant metering capability\(^2\). Billing meters always use the outside world (the grid) as their reference. So:

- export electricity occurs when it is delivered from the grid (exported) to the customer meaning there is a net inflow to the customer’s site (value POSITIVE), and
- import electricity occurs when it is delivered to the grid (imported) from the customer meaning there is a net outflow from the customer’s site (value NEGATIVE).

\(^2\) As an aside, a simple meter that measures Wh EXPORT only is a “partial” Quadrant 1 meter and a slightly less simple meter that measures Wh and VAhr EXPORT might be called a “full” Quadrant 1. These terms are not in common use.
The term four-quadrant metering refers to:

- Quadrant 1: export real energy (Wh) with export reactive energy (VArh)
- Quadrant 2: import real energy (Wh) with export reactive energy (VArh)
- Quadrant 3: import real energy (Wh) with import reactive energy (VArh), and
- Quadrant 4: export real energy (Wh) with import reactive energy (VArh)

All are referenced to the grid as noted previously. Although it might seem impossible, in any time measurement period there may be both EXPORT and IMPORT of electrical energy. This may occur if on-site generation is close to matching on-site requirements whereby for some of the time it is more and for some of the time it is less than used on site. At any instant, power can only be EXPORT or IMPORT in nature.

Finally a quick look at the types of electrical loads that might be metered. Three types are considered:

1. 3-phase unbalanced loads
2. 3-phase balanced loads
3. 1-phase loads

In commercial and industrial electricity metering situations, the first type is by far the most common. An example of this is a switchboard with a mix of 3-phase and single phase loads (outgoing circuits) and a meter on its incoming 3-phase supply. Because the three incoming phases will rarely have both the same current draw and the same current to voltage phase relationship, it is said that they are not “in balance” or “unbalanced” and a fourth conductor (called the neutral) is necessary to carry any residual current imbalance. The term 4-wire connected load is used for obvious reasons.

Balanced 3-phase loads are less common but if the load to be metered is a device such as a 3-phase motor, this load is inherently balanced and is therefore a 3-wire connected load with no neutral necessary. Because each phase is identical, a simplified metering installation is possible, namely that of only one phase with total power and total energy derived by multiplying by three (3).

Single phase (1-phase) loads are extremely predominant in residential situations but also common in commercial and industrial situations too such as in lighting and general power circuits. Outside of residential, metering of 1-phase loads is not common mainly because the greatest benefits are derived by metering larger loads which are, almost without exception, 3-phase.

**Selection Requirements**

The basic questions that need to be answered are:

- What sorts of loads are there, 3-phase unbalanced, 3-phase balanced or 1-phase?
- What is the maximum expected current draw?: if under 100A, direct-connect metering is possible but if over 100A, current transducer metering is required
- What parameters are needed?: 1-quadrant, 2-quadrant or 4-quadrant
- What measurement accuracy is required? The requirements for real energy and reactive energy accuracy may be different.
- What is the purpose? If for revenue or billing such as in an embedded network, then ‘pattern approved’ meters of suitable accuracy are required (see separate box out).

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3 3-phase unbalanced loads with only a 3-wire connection can occur but are not considered here.
What are the environmental conditions the meter is likely to encounter? Conditions include dry-bulb temperature, relative humidity, condensing or non-condensing, dust/dirt, sprays, EMI and the like.

Following on, secondary level questions are:

- To maintain accuracy of metering installation, the current transducer\(^4\) (CT) accuracy must be at least as good if not better than that of the meter itself. So, a Class 1 meter will require Class 1 or better accuracy CT's.
- What is the required current measurement range?
- How much space is available for meters and associated transducers? This might lead to meters external to electrical boards or within electrical boards (such as DIN rail mounted meters).
- What is the distance between current measurement transducer and meter\(^5\)? Note that under-sized cables will compromise measurement accuracy.
- What special features are to be provided? See separate box for some examples of features which may be available.

Supplementary questions relating to an overall system in which the meter may be found which may need to be answered are:

- What data connectivity is required? Such as to building management or other system, web-browser, and so on, and how will the data be transmitted (wired or wireless, own system or external data network). Or no connectivity, meaning manual read type.
- Is data storage required? Local, remote? What storage capacity (time period) is needed.
- Are there special data storage requirements? Such as end of month values.
- Does the installation location cause the need for special protection e.g. from weather, dust?
- Is the equipment accessible?
- Is there an internal battery for memory? Is the device bus-powered?
- If connected on a data bus, what special requirements are there for cabling for high speed data transfer, minimisation of interference, drop-outs and the like?
- What measurement units are required (Wh, kWh, MWh, VArh, kVArh, MVArh) and what discrimination (1 unit, 0.1 units, 0.01 units, 0.001 units etc.)? This will depend on the connected load being metered. For example, a 10 kW load with a 1 kWh energy discrimination will lead deliver a poor representation, particularly under low load conditions. Conversely, it would be overkill to have a discrimination of 1 Wh for a 1000 kW load.
- What local product knowledge and support is available?

\(^4\) The term “current transducer” is intended to cover a range of types. The most common is the current transformer which typically has an output range of 0 to 5A (secondary current), with 5A produced for the maximum rated primary current under measurement. For example, a CT with a rated current load of 800A (primary) will produce 5A (secondary) when 800A primary current is being measured. This would be designated as a 800/5 CT. The secondary output is linear with primary current so at 50% primary current, 2.5A will be developed. Other common current transducers have a millivolt or milliamp output (typically 4-20 mA over the measuring range).

\(^5\) This is an issue with 0-5A output transducers. The term “burden” (measured in VA) is a CT parameter from which the cross-sectional area of the electrical cable connecting the CT to the meter can be determined. A meter with a high burden value will allow a smaller cable size than one with a low burden value. If the cable length from meter to CT and back to meter is short, this will allow a smaller cable size whereas if it is long it will require a larger cable size.
- Does the supplier offer a programming/commissioning/troubleshooting service?
- Would pulse input capability be useful such as to collect data from other meters nearby with basic pulse outputs? This could include nearby water meters (cold/hot) and gas meters. What value should each pulse have, to losing load pattern data accuracy.

## Pattern Approved Meters

A “pattern approved” meter is one that has been tested by an approved testing authority against documented test procedures. The standard test procedures in use here are from the National Measurement Institute

- “NMI M 6-1 Part 1: Metrological and technical requirements”
- “NMI M 6-2 Part 2: Test Report Format”

Approved meters are listed on the NMI web-site:


For revenue, class 0.2 or 0.5 meters are common which generally refers to their accuracy in percentage error over a specified measurement range. Non-revenue meters are often class 1 or sometimes Class 2. It might be expected that a more accurate meter is more expensive than a less accurate one, but this is not always so, mainly because the high volume of revenue grade meters produced for the electricity retail market.
Meter Features

Examples of features which may be provided are:

- On-board programming of CT ratio
- Real-time clock with calendar
- On-board memory: how much? Will depend on how many channels, sample time period and data extraction frequency
- A range of time periods over which data is binned (such as 1, 2, 3, 5, 10, 15, 30, 60 minutes\(^6\))
- Data binning according to tariff such as peak, off-peak and shoulder
- Low level interface (LLI), such as pulsed energy outputs (real energy and/or reactive energy)
- Pulse inputs, such as from water and gas meters to collect and store their data
- Wired high-level interface (HLI) such as Modbus over RS485 (usually multi-drop) or over ethernet (Modbus/IP for example)
- Wireless HLI such as ZigBee™
- Multi-parameters such as P-P volts and amps, P-N volts and amps, N amps, power factor, apparent power/energy, current harmonics
- Waveform capture (voltage and/or current)
- Threshold excursion data such as start time and duration of sags and swells
- High power alarms
- Load shed/restore

A Few Loose Ends

The following is a grab bag of miscellaneous bits and pieces

- **CT Polarity**
  If a CT is reverse-connected, it will have a dramatic impact on measured power and energy. In a 3-phase balanced load, one reversed CT in a set of 3 will cause measured power/energy to be one-third of the correct power/energy.

- **Polarity-independent CT’s**
  Some manufacturers offer polarity independent CT’s as a way of overcoming the all too common polarity misconnections. While this seems like a good idea it will be useful only for 1 or 2 quadrant metering. For 4-quadrant metering it is absolutely imperative that correct polarity is adhered to (see box).

- **Phase Rotation**
  In any 3-phase electrical system there is a known phase rotation, whether it be designated as L1-L2-L3 or red-white-blue or in some other way. This designation indicates the connection order of CT’s onto the meter. For simplicity, if we assume the phase rotation of the electrical system is L1-L2-L3 then a CT measuring on phase L1 must be connected (in correct polarity) to the L1 terminals at the meter. The same applies to L2 and to L3. Failure to do this will lead to gross measurement inaccuracies.

\(^6\) If data from a non-revenue meter is to be compared to data from a revenue meter, it makes sense to adopt a time interval on the non-revenue meter that can readily be matched to that adopted by the revenue meter.
**Pulse Output Value**
If a meter has an energy output pulse, accurate measurement requires knowing the energy value represented by each pulse coming from the meter. For some meters this is automatic, such as a meter that produces a pulse of 1Wh if direct-connected and 1 Wh times the CT ratio if CT-connected. For this type of meter, if the CT ratio is 100:1, the pulse value will be 100 Wh. Other meters allow programming of the energy pulse value and the CT ratio as a pair. See box out for example on why getting this wrong can lead to gross inaccuracies.

**Protection**
Installation must comply with regulations. If a CT is carrying current but is open-circuited (not connected to the meter) a very high voltage may exist between the two wires. As a safety measure, a “test block” may be installed to allow CT’s to be shorted prior to connection to or disconnection from the meter. Once all CT’s are connected to the meter, the shorting arrangements will need to be removed to allow correct measurement. Another safety measure is the in-line installation of fuses in the voltage cables upstream of the test block. Note that the current return legs of CT’s may be bridged to ground/earth.

Note:
While it may not be mandatory to include such safety provisions for non-revenue metering installations, if they are not fitted, CT’s may only be in an open-circuit condition when the load they are intended to measure has been isolated and there is nil current passing in the primary conductor.
CT Polarity Convention

The most common convention is as follows:

- The side of the CT marked P1 must face towards the SUPPLY SIDE and the side of the CT marked P2 must face towards the LOAD side
- The cables exiting the CT are marked S1 and S2 must connect to the correct terminals on the meter as indicated by the meter manufacturer’s literature

See below for an example:

This shows CT connections at meter which are clearly identified. Another common connection scheme in use is:

- L1: CT S1 at [1], V at [2] and CT S2 at [3]
- L2: CT S1 at [4], V at [5] and CT S2 at [6]
- L3: CT S1 at [7], V at [8] and CT S2 at [9]

Where [1] signifies terminal number “1”. Every meter manufacturer produces a correct connection schematic diagram which must be strictly adhered to,
**Example: CT ratio and Energy Pulse Value**

Assume a meter for CT connection is supplied from the manufacturer with default settings of CT ratio of 1 and energy pulse value of 1 kWh or 1000 Wh.

The connected load current to be measured is 900 A and 1000 A CT’s have been installed to allow a small overload margin. With 750A measured at 400V P-P\(^7\) and a power factor of 0.8 (meaning \(\cos\phi = 0.8\)), the instantaneous power draw is 416 kW. For simplicity, a steady load is assumed.

*Calculation:* \(\left(\sqrt{3} \times 400 \times 750 \times 0.8\right) \text{ in } W \text{ then } \div 1000 \text{ to convert to } kW\).

If the meter CT ratio is retained in the as-supplied condition, it will work under the impression that the secondary current it “sees” is also the primary current. This is because the CT ratio is still 1. The actual primary current of 750 A is 75% of CT full load current, likewise the CT output or secondary current will be 75% of full output (5 A) or 3.75 A. Within the meter this current is translated to 2.08 kW of “measured” power which means that over a 1 hour period, 2.08 kWh of energy will be consumed and 2.08 pulses will be produced or one every 28.8 minutes. If the CT ratio had been correctly programmed into the meter, the measured energy would have been 416 kWh over 1 hour and 416 pulses would have been produced or one every 8.7 seconds. In this case, the incorrect CT ratio has led to measured energy of only 0.5% of actual energy (99.5% error!) as well as the poor discrimination of load.

In this example, a further improvement may be achieved by reducing the pulse value to 0.1 kWh (100 Wh), which would produce 4160 pulses per hour or one pulse every 0.87 seconds. Looking at this another way, the pulse frequency is 1.16 per second or 1.16 Hz. To avoid missed pulses, a frequency of not greater than 5 Hz is commonly recommended.

**Integration**

Unless the user has special knowledge and capability, the most reliable approach is to source from a single supplier, all the components that are known to operate together to create an integrated package. This simplifies the provision of support, troubleshooting, programming and warranty issues.

It is also important that if the device is to be connected to a third party system such as a building automation system or similar, the third party provider has the necessary skills, knowledge and experience to create an integrated system.

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\(^7\) Equivalent to 230 V P-N which is the standard in Australia (until recently it was 240 V).