Test&Measurement

YOKOGAWA

High Current Measurement Application Note

Introduction

Designing an instrumentation system for high current measurement requires careful consideration of the trade-offs associated with each type of sensing device.

The purpose of this application note is to help engineers understand the sensing choices available and the corresponding trade-offs with each technology.

Precision Making

What is electrical current?

Electricity is the movement of negatively charged electrons in a conductor from a region of high electron density to a region of low electron density. The difference in electric potential between these regions is known as voltage (measured in volts). This provides the electromotive force to move electrons.

The rate of charge flow carried by these electrons per second is what is known as electric current (measure in amperes), while the opposition to this current flow is known as a resistance (measured in Ohms).

Electric current is by convention said to flow from a region of high electric potential to a region of low electric potential, opposite to the direction of electron flow.

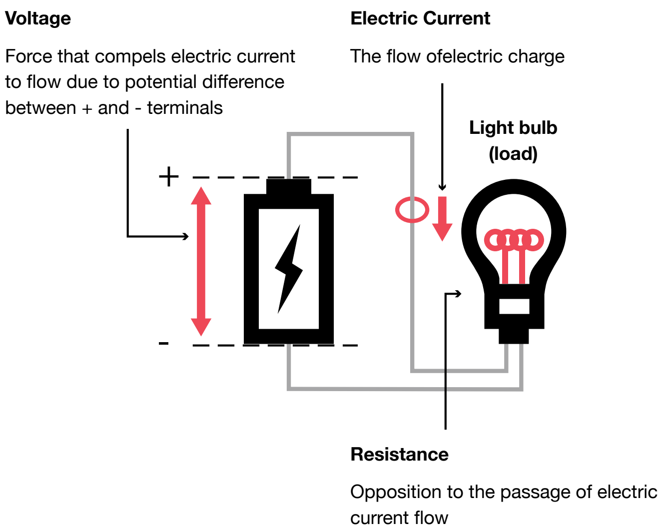


Figure 1. Basic components of electrical circuit.

Measuring current

As shown in Figure 1, current measurement is a series measurement of electron flow. There are two ways to make this measurement with a current sensor:

- **Direct measurement**
  Accomplished by passing the current directly through a sensing device itself (shunt-type measurement).
- **Indirect measurement**
  Accomplished by passing a current-carrying conductor through the aperture of a current-sensing device, such as a clamp or current transformer.

This application note focuses on indirect technologies as they apply to the measurement of electrical power. Listed devices target the measurement of inputs and outputs of electromechanical systems such as grid-tied inverters, variable-speed motor drives, motors, chargers, generators, appliances, and transformers. The required bandwidth of such systems is typically below 1MHz. For higher bandwidths, please refer to the high-bandwidth oscilloscope probes on the Yokogawa Test&Measurement website.

Key specifications

The use of a current clamp or current transformer greatly simplifies measuring high currents (>50A) where physical constraints (e.g., conductor sizes, insertion losses, safety) make a direct measurement through the precision internal shunt of a power analyzer, DMM, or external shunt into a data acquisition instrument impractical. This convenience comes with a cost, and system designers must educate themselves on these trade-offs in order to make the best practical engineering decision.

Key system design specifications

Key specifications for each device must be considered when selecting a current measurement device.

- Purposed of the measurement
- Budget constraint
- Physical constraint
- Accuracy
- Frequency response
- Phase shift
- Maximum current to be measured (Peak/rms)
- Minimum current to be measured (Peak/rms)
- Output signal (voltage/current)

Once all of the specifications are established, the sensor technology can be identified.

The most important specification to consider is the purpose of the measurement, as this often determines the rest of the specifications.

For example, if a high current measurement is needed for benchmarking power, energy consumption, or efficiency, then the accuracy specification will dictate the appropriate technology. Likewise, if a high current measurement is needed for understanding general current consumption, waveform shape, or event capture, then a different technology would likely be appropriate.

Performance vs. Technology									
	High Accuracy	Simple Installation	AC Current	DC Current	High Frequency	Low Phase Shift	Low Cost	Wide Measurement Range	Voltage Output*
Hall-Effect Clamp		X	X	X			X		X
Rogowski Coil		X	X		X		X		X
AC Transformer Clamp		X	X				X		X
AC Transformer	X		X		X	X			
Fluxgate Transformer	X		X	X	X	X		X	

**All other technologies are current output.*

Table 1. Performance versus technology of current transformers and clamps.

Choosing a sensor

Indirect current measurement relies upon sensing the magnetic field generated by a current-carrying conductor. Sensing this field is accomplished through a variety of technologies such as AC current transformers, Hall-effect sensors, Rogowski coils, and fluxgate sensors. Each one of these technologies has associated trade-offs that must be considered within the system design specifications.

General selection guidelines by technology and application include:

- **Closed Aperture vs. Clamp**
  A "donut-style" or "fully-closed aperture" current transformer design generally performs better than an "open clamp" or "split core" solution. This is due to the split core's lack of symmetry and necessary discontinuity of the magnetic core and associated windings. A split core makes the closed-loop zero flux design impossible to construct, especially if multiple cores and windings are needed for accuracy, like fluxgate sensing with closed-loop compensation.
- **AC Transformers**
  Purely AC current transformers are typically used in line power or constant frequency applications where the voltage waveform is of a static frequency and DC components or transient phenomena are not of concern. Many current transformer manufacturers target power line frequencies specifically (50/60Hz, 400Hz), therefore the performance specifications around those frequencies are generally acceptable (error ≤ 1%). These come in clamp or donut-style designs.
- **Rogowski Coils**
  Rogowski Coils are typically used when convenience is the deciding factor, obtaining a general wave shape for an AC or pulsed signal is desired, and accuracy is not of utmost importance. Rogowski coils are very sensitive to conductor position; this error alone can contribute up to 2% of total error excluding other sources (error >1%).
- **Hall-Effect AC/DC Clamp**
  Hall-effect current clamps are typically used when convenience is important, obtaining a general wave shape for any type of AC or DC signal is desired, and high accuracy is not a concern (error =>1%).
- **Fluxgate Closed-Loop**
  Fluxgate-based, closed-loop zero flux current transformer designs, such as fluxgate sensors, AC transformers, and zero flux compensation, benefit from the combination of sensing technologies. Capable of making measurements on very complex AC/DC waveforms, this design often provides the best linearity, accuracy, stability, and frequency response. These devices are typically used for benchmarking power measurements where switching waveforms are present (inverters) and errors must be minimal across a wide operating bandwidth (error ≤ 1%).

Sensor technologies

- **AC Current Transformers**
  AC current transformers rely upon Faraday's Law, which states that an electromotive force is generated in a coil when it is placed in a time-varying electromagnetic field. The operation of a current transformer is similar to that of a voltage transformer in that the secondary output current is proportional to the turn ratio. In some cases, the current transformer can be a direct (series) measurement or an indirect measurement (through a CT opening). Because a changing magnetic field is required, they cannot be used for DC measurements. Like voltage transformers, these sensing devices are passive and do not require excitation, consisting of wire wrapped around a magnetic core.

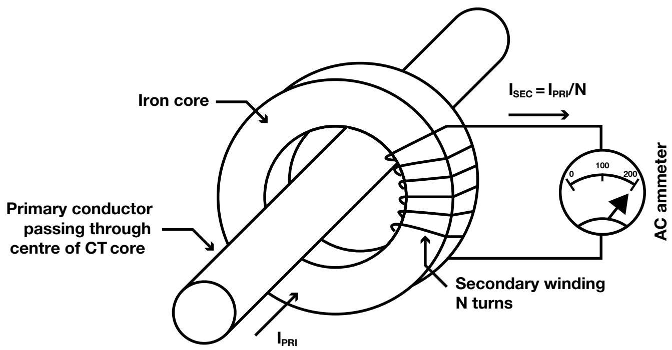


Figure 2. AC current transformer.

- **Hall-Effect Sensors**
  The Hall-effect utilizes a conductive sensing material carrying a current and placed perpendicular to a magnetic field. The magnetic field produces a Lorentz force, pushing the charge carriers to one side of the material. The resulting voltage difference across the material is proportional to the flow of the current generating the magnetic field. In a current sensor, the magnetic field is generated by the primary conductor that is set 90 degrees from a Hall sensor placed inside an airgap in the iron core. The gap in the core concentrates the magnetic field around the sensor. The resulting differential voltage across the sensing material is then amplified and conditioned to an appropriate output signal (voltage or current). The Hall-effect principal applies for both AC and DC signals. Hall-effect current clamps usually have mV/A or mA/A output signals and may have a range switch.

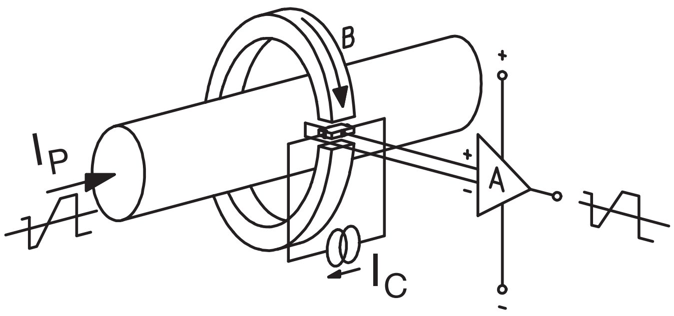


Figure 3. Hall-effect sensor.

- **Rogowski Coils**
  Rogowski Coils consist of a helical coil of wire with a center return lead wrapped around a straight primary conductor. The change in current (derivative) through the primary conductor induces a proportional voltage in the coil. This voltage is then integrated via signal conditioning electronics to produce a voltage that is proportional to the primary current. This is why Rogowski coils require a continuously changing (AC) or pulsed current in order to produce an output. The coils typically have an air core (no solid core) and therefore are flexible. Additionally, the coil wiring (center return lead) means the construction is often a flexible loop with an open end.

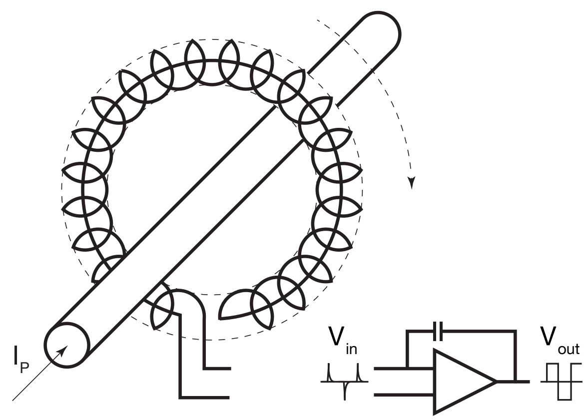


Figure 4. Rogowski coils.

- **Fluxgate Sensors**
  Fluxgate sensors are a saturable inductor constructed of a magnetic core and wound coil. The sensor is excited by a periodic square wave signal that sweeps the inductor across the B-H curve, in and out of saturation, resulting in a symmetric current waveform. When an external magnetic field is introduced (primary current through an aperture of the CT), the flux density is changed and the current waveform becomes asymmetric due to the change in time

to reach saturation. This asymmetry is measured via a change in duty cycle or via harmonic analysis, producing a linear output with respect to the primary current. Fluxgate sensors are capable of sensing both AC and DC currents and typically offer greater stability, resolution, and accuracy when compared to Hall sensors. Similar to a Hall clamp, a fluxgate sensor can be placed inside an airgap or constructed out of a second magnetic core placed inside of the current transformer itself.

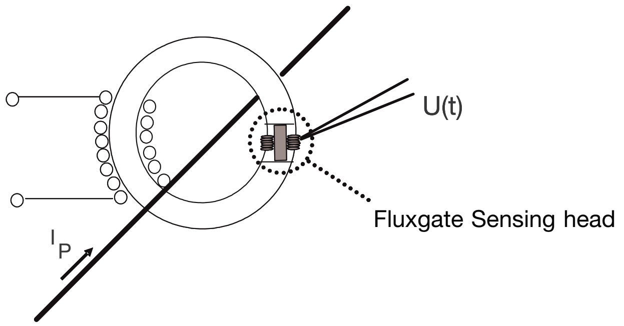


Figure 5. Fluxgate sensor.

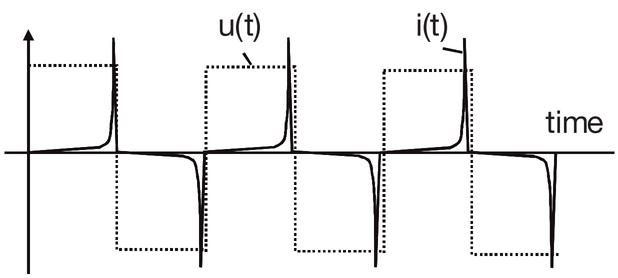


Figure 6. Fluxgate sensor without primary current.

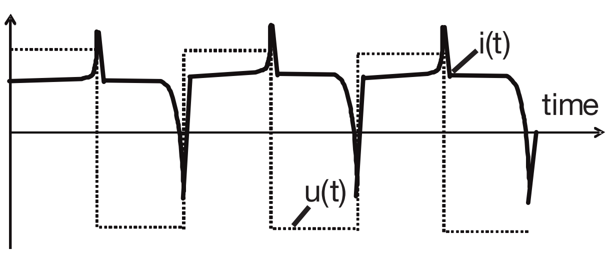


Figure 7. Fluxgate sensor with primary current.

Errors

All of these technologies can have measurement errors attributed to factors such as linearity, offset, temperature, or noise.

- Errors in AC current transformers are can be a function of manufacturing quality or residual flux.
- Hall-effect sensors are vulnerable to errors arising from the necessity of sensing and amplifying very small voltages and the properties of the Hall sensing material (offset, temperature drift, noise).
- Rogowski coils are prone to positioning, droop/offset, and phase delay errors.
- Linearity error is a concern for any type of sensor, and is a function of the technology, construction, and temperature characteristics.
- Fluxgate sensors provide more robust measurement due to a time-based measurement (duty or spectral analysis), low magnetic offsets due to the cyclic excitation, and a low temperature drift.

Zero flux technique

To compensate for linearity errors, operate the sensing technology in a “zero flux” condition, where the magnetic field being measured by the sensor is essentially zero. This is accomplished through a compensation winding inside of the current transformer that generates an equal-yet-opposing magnetic field to that of the primary field. This winding is driven in a closed-loop circuit formed by the sensor (fluxgate or Hall) and associated amplification circuitry as shown in Figure 8. This allows the sensor to essentially operate around a zero sensing condition (a single point), minimizing any gain errors. Offset errors can further be eliminated by applying a zero offset or a “nulling function” in the sensing instrument that the current transformer is connected to, such as a data acquisition, oscilloscope, or power analyzer.

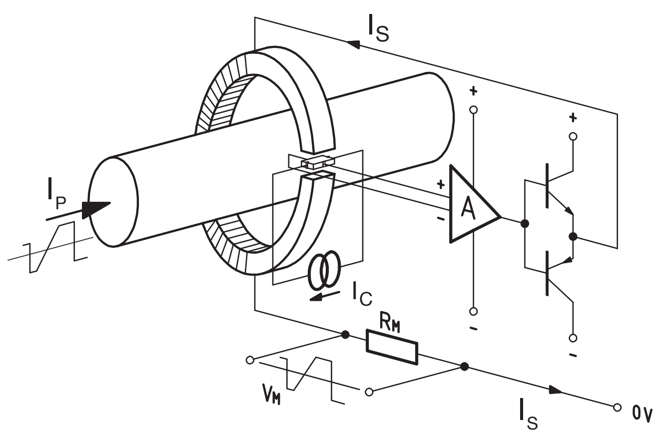


Figure 8. Closed-loop Hall-effect zero flux CT.

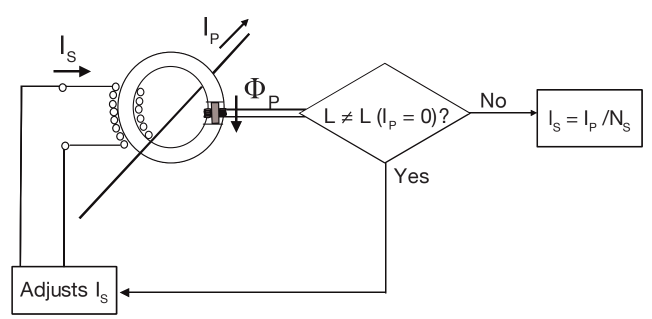


Figure 9. Closed-loop fluxgate zero flux CT.

Frequency response

Current sensing technology and associated electronics have limited bandwidth. However, an advantage of the closed-loop zero flux configuration is that at higher frequencies, the compensation winding acts as an AC current transformer. This significantly extends the bandwidth and reduces the response time of the transducer. Essentially, the zero flux (closed-loop) current transformer design incorporates multiple current sensing techniques (e.g., AC current transformer, Hall-effect, fluxgate). As a result, zero flux designs are capable of measuring AC, DC, and complex waveforms of any shape.

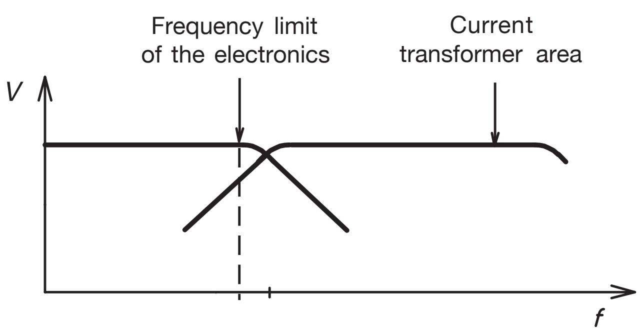


Figure 10. Frequency response of closed loop design.

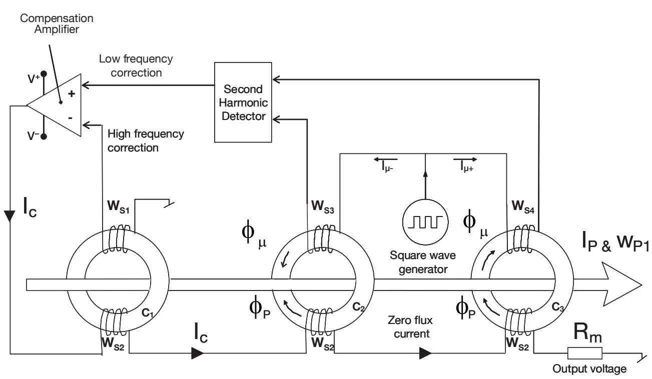


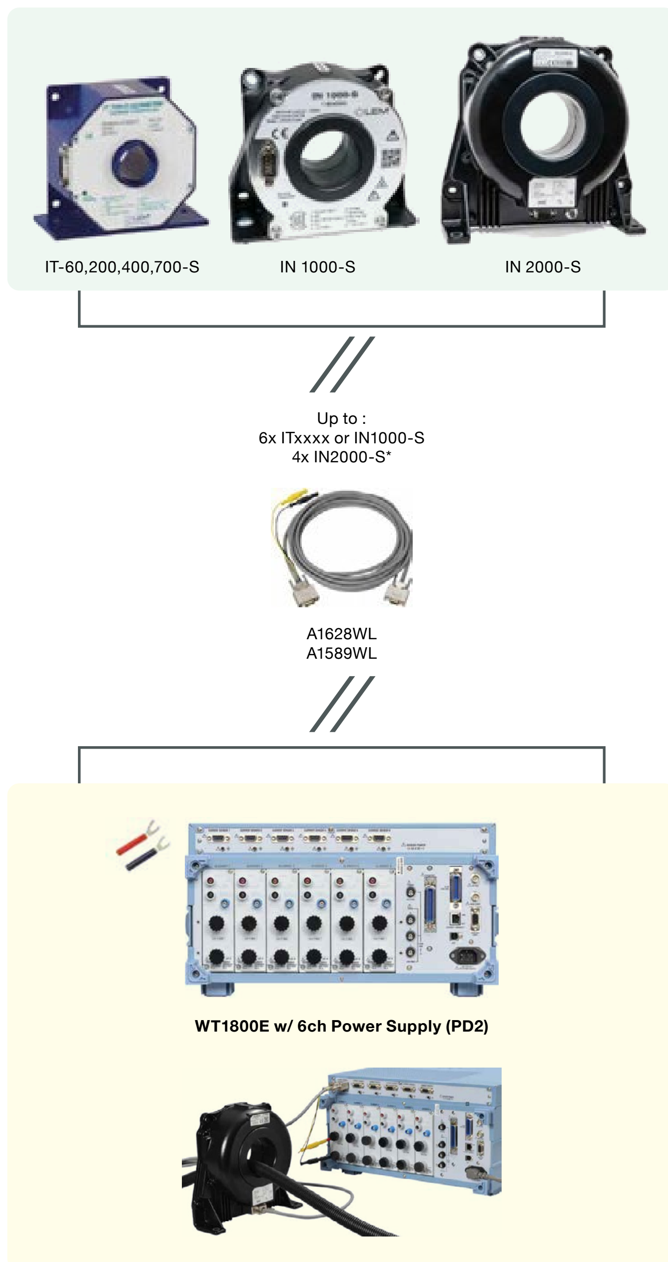
Figure 11. Multi-core closed-loop fluxgate design.

Output

Yet another advantage of the closed-loop design is that the output signal is current-based. This provides a more robust signal in high noise environments. It is also the preferred signal for power analyzers, which can directly measure current with high accuracy.

When dealing with any current transformer, the output is considered a constant current source. This means as current flows through the primary conductor, the secondary must never be left as an open circuit. An open circuit essentially produces infinite resistance, by Ohm's law V = I*R, and results in a very high voltage that damages the current transformer and presents a significant safety hazard. Design systems with caution so that the current transformer does not disconnect when performing a measurement.

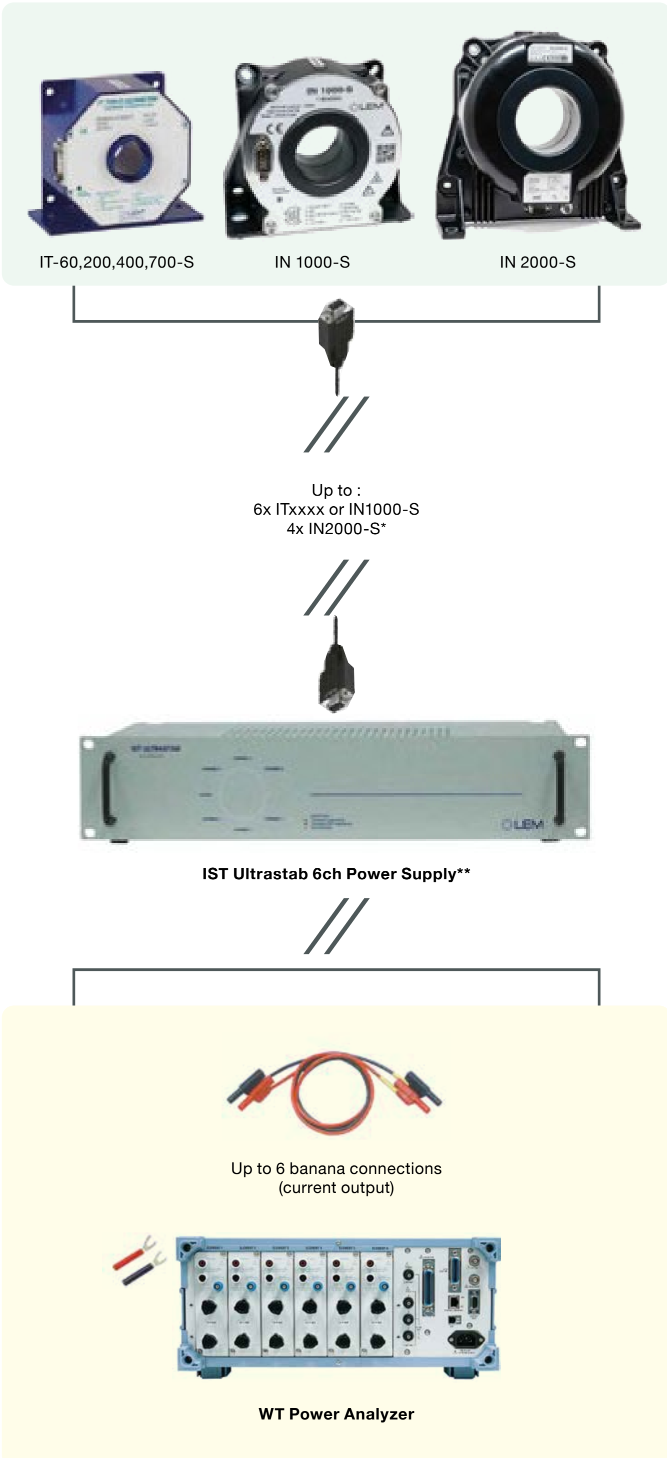
High current power measurement configuration examples



* WT1800 - Total current consumption for IN 2000-s cannot exceed 6Arms (+2Arms secondary)

* PX8000 - Total current consumption for IN 2000-s cannot exceed 4Arms (+2Arms secondary)

Figure 12. Power analyzer with built-in power supply.



* Total current consumption for IN 2000-s cannot exceed 6Arms (+2Arms secondary)

* Yokogawa M114** kits include IT or IN CT's and IST power supply (banana/ fork terminals not included)

Figure 13. Power analyzer with external power supply kit.

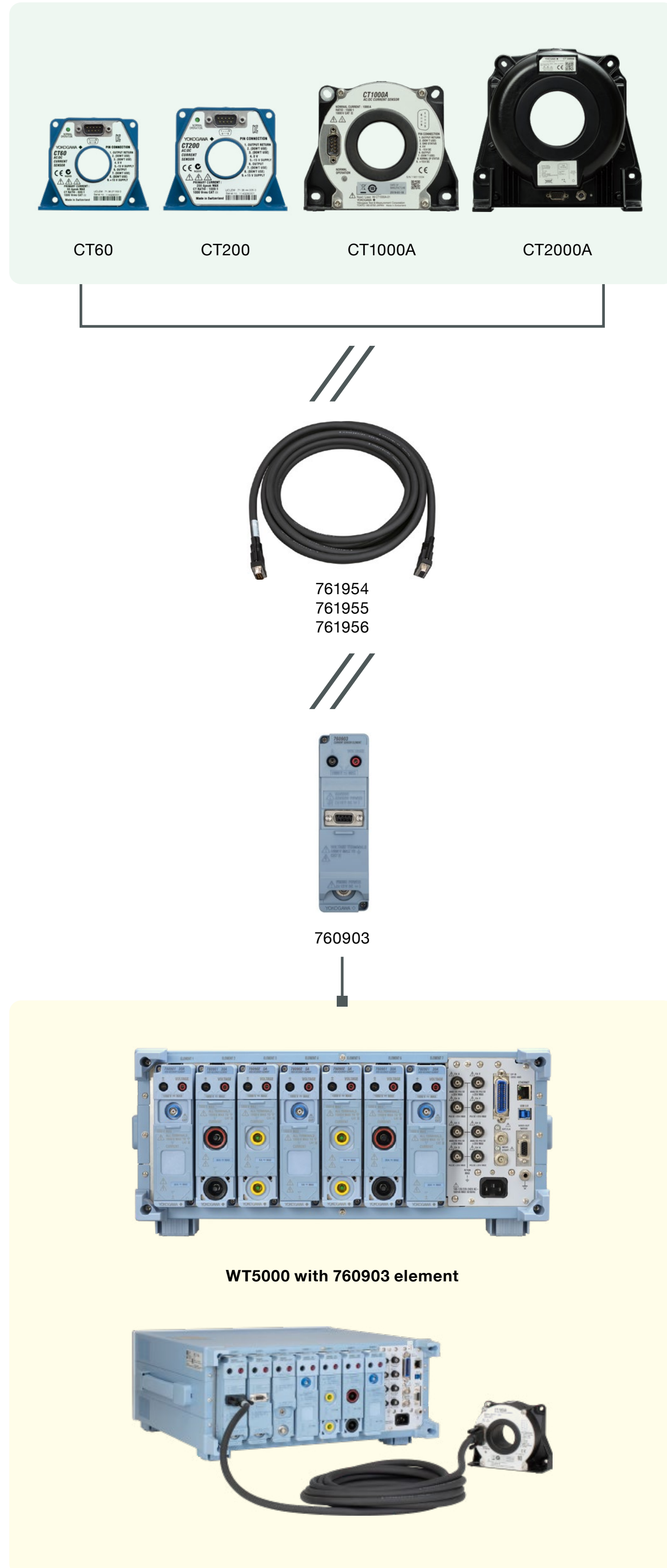


Figure 14. Power analyzer with built-in power supply integrated in the element.

Integration considerations

After selecting the appropriate current sensing product, the integration of the device must be carefully engineered, thoroughly evaluating all output types, accuracy, measurement range, and interconnections.

Example use cases

Case One

A manufacturer of UPS systems is engineering an instrumentation system to monitor and make measurements on six phases of AC voltage, current, power, and one DC phase (480Vrms, 75Arms). Power and harmonic monitoring is important. However, capturing distorted wave shapes during changeover events is critical. The instrumentation system is data acquisition-based and requires the ability to easily move to different installations.

Data acquisition systems generally consist of voltage signals and are typically not highly accurate when making power measurements, so it makes little sense to select a highly accurate current device. In this case, the engineer has selected a Hall-effect-based clamp-style sensor, which is valid for any type of wave shape (AC/DC).

Engineering Considerations

- The output voltages from Hall-effect clamps are often in mV/A, where the maximum output voltage is less than 1V. The data acquisition system should have a comparable full-scale input range. For example, utilizing a 10V input range would result in poor resolution measurement. Take into consideration the proper scaling for the instrument when using clamps that have multiple range switches (400A/40A), as changing range on the clamp requires a range change on the instrument.
- Hall-effect clamps require power, usually supplied by a small 9V or AA batteries, USB power, or a wall-style AC-to-DC plug.
- Many Hall-effect clamps have a BNC-style interconnection. The data acquisition system should have the same or an adapter, if banana jacks are used.
- Hall-effect is prone to offset drift. Because of this, the nulling (zero offset) function of the probe itself and/or the data acquisition should be used before making critical measurements.

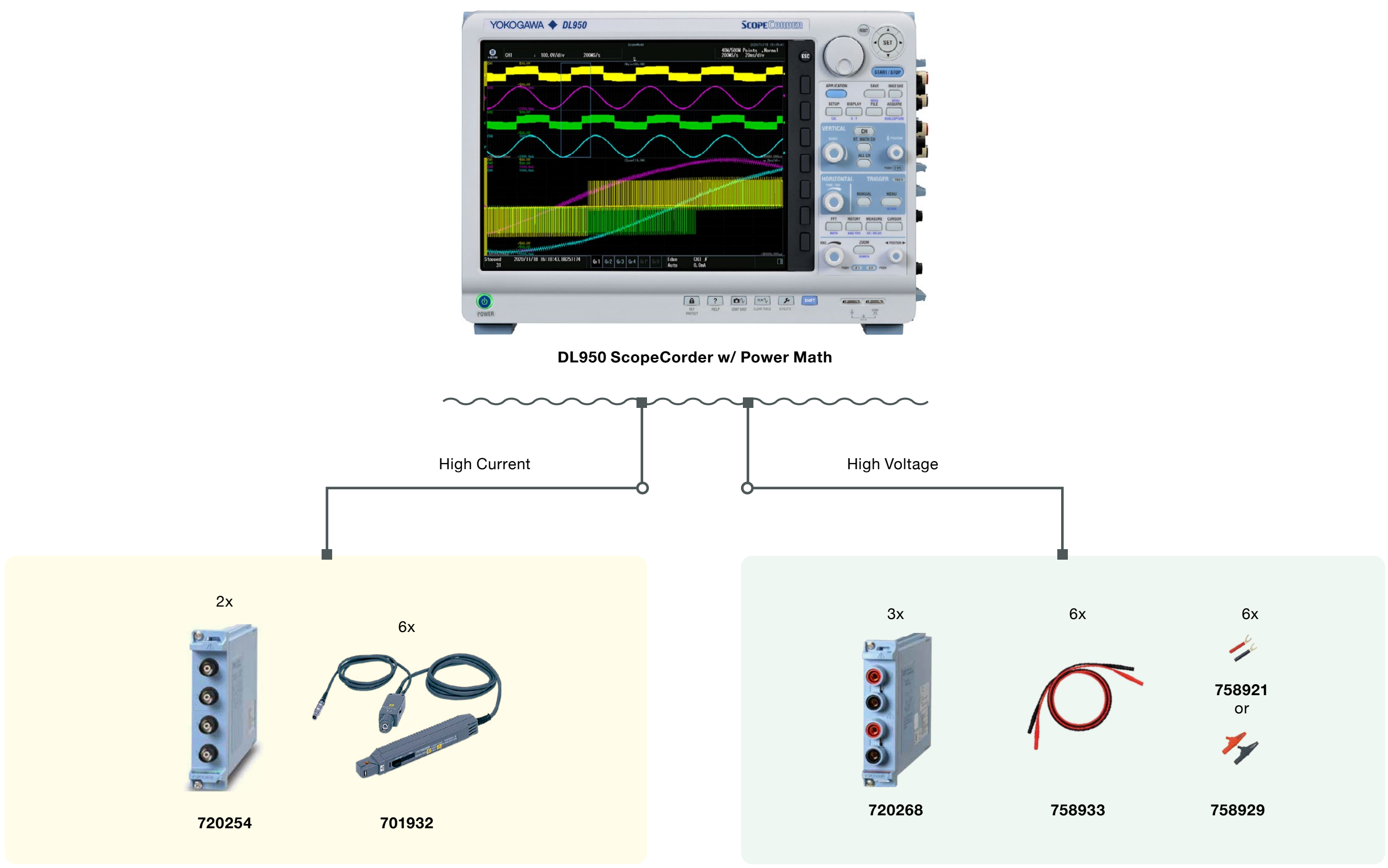


Figure 15. Example configuration of a six-phase high-power monitoring system.

Yokogawa Test&Measurement DL950 ScopeCorder with Real-Time Power		
QTY	**Part Number**	**Description**
1	DL950-D-HE/M1/HD1/G2/G5	DL950 ScopeCorder chassis with power math
3	720268 1MS/s 16bit 2ch analog input module	High voltage module, isolation to 1000Vrms, three modules for six phases of voltage
2	720254 1MS/s 16bit 4ch analog input module	Four-channel module 16bit resolution to handle six phases of current clamps
6	701932 current probe 100 AC/DC	Hall-effect current clamps, BNC connection
6	758933 measurement lead set	Connects to 720286 for voltage measurement, 1000V
6	758929 large alligator clip leads	Connects to 758933 for voltage measurement, 1000V (alligator clip)
6	758921 fork terminal adapter	Connects to 785933, for voltage measurement, 1000V (screw terminal)

Table 2. Configuration chart for Case One using DL950.

Case Two

A manufacturer of inverter-based motor drives is engineering an instrumentation system for benchmarking power measurements on three phases of PWM-based AC voltage, current, power, and one DC input phase (800Vrms, 1100Arms). Waveforms are of interest. However, capturing the most accurate power measurements is most critical, as the efficiencies of new inverter designs are over 90%. The instrumentation system is power analyzer-based and must provide highly accurate power, energy, and harmonic measurements.

In this instance, the engineer has selected a fluxgate-based zero flux current transformer. The fluxgate is valid for any type of wave shape (AC/DC) and provides the highest accuracy solution for PWM application requiring high bandwidths. Power analyzers are highly accurate devices, and the most precise current measurement is required to keep errors to a minimum. A low-accuracy clamp or fixed-frequency current measurement device would not be a good selection.

Engineering Considerations

- Because this is a “donut style” design, the primary cable must be able to pass through the center aperture (check diameter). In some cases, a bus bar or smaller cable with smaller diameter insulation is necessary.
- This is a powered device and requires a power supply with the appropriate voltage and current capacities, along with a location for mounting (rack).
- Combining the fluxgate AC current transformer technologies in a closed-loop method, there is always a constant current output on the secondary when the primary has current flow. The current transformer cannot be disconnected when a measurement is being performed. Appropriate labels or design considerations should be made for safety and to avoid damage to the device.
- The closed-loop sensor provides a current-based output that is less susceptible to noise. This is the preferred signal type for a high-performance power analyzer (such as the Yokogawa WT series), that employs a unique shunt design that compensates for thermal drift and ensures the most precise measurement.
- Size the full-scale output of the secondary current appropriately in relation to the power analyzer. For example, a 2000:1 ratio for a 280Arms transformer results in a 140mA full-scale output. The power analyzer should have comparable low current measurement ranges.
- A power analyzer with a 40A input and a 500mA minimum full-scale range is too large. A better choice is a power analyzer with a 5A range and a 5mA minimum full-scale range.
- While closed-loop sensor designs are less prone to offset drift, the nulling (zero offset) function of the power analyzer can be used to further reduce offset error.

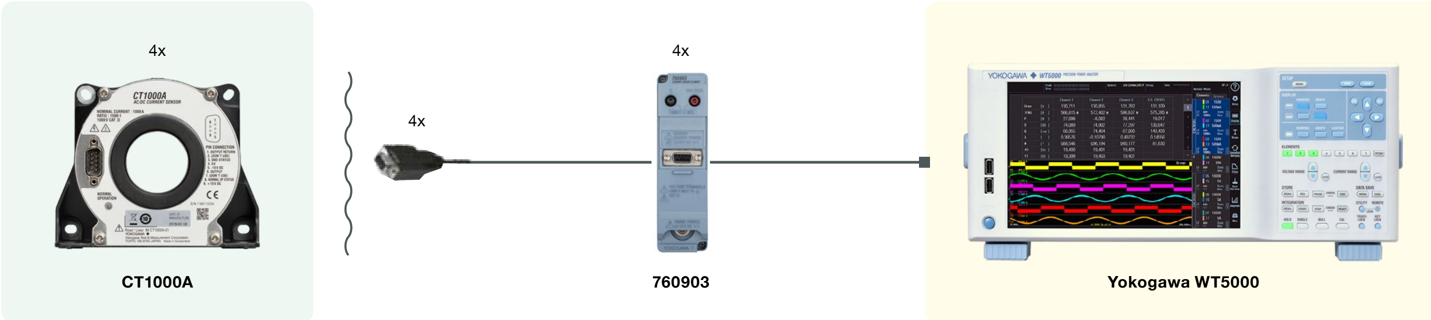


Figure 16. WT5000 example configuration.

Yokogawa Test&Measurement WT5000 Power Analysis System		
QTY	**Part Number**	**Description**
1	WT5000/MTR1/US-HE-D	High performance power analyzer chassis, motor option
4	760903 Current sensor element	4x current sensor element input elements for WT5000 (voltage and current connectors included)
4	CT1000A Current transformer	4x 1000Arms high accuracy current transformers, fluxgate, zero flux design
4	761954	3m cable for current sensor

Table 3. Configuration chart for Case Two using WT5000.

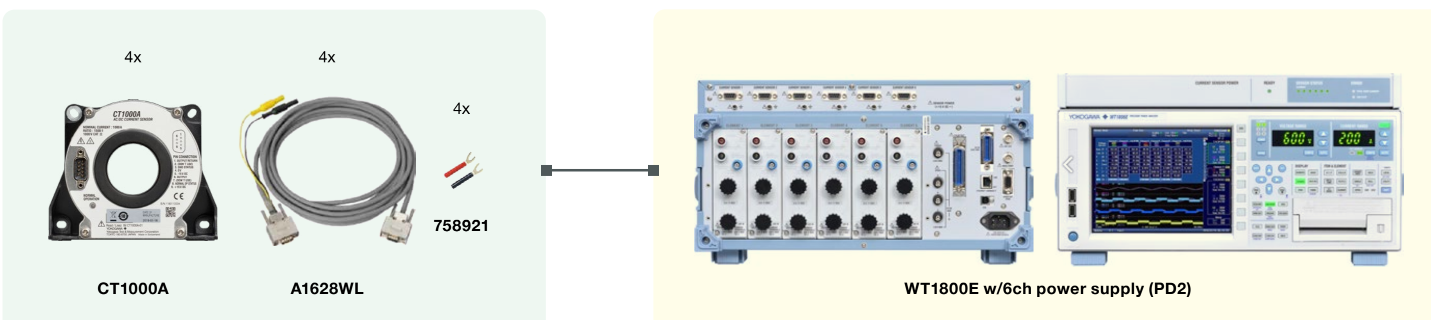


Figure 17. WT1800E example configuration.

Yokogawa Test&Measurement WT1800E Power Analysis System		
QTY	**Part Number**	**Description**
1	WT1804E-5A4-50A0-HE-D/G6/PD2/MTR	Mid-range power analyzer, 4x 5A elements, integrated current transformer power, motor eval
4	90.N6.60.000.0 LEM IN-1000 Current transducer	1000Arms high accuracy AC/DC current transformers, fluxgate, zero-flux design 0.6A output
4	A1628WL Direct current input cable	Cable powering IN-1000s, and providing signal to WT1800E (plug into fork terminal)
4	758921 Fork terminal adapter	Connect to A1628WL and WT1800E binding post for current

Table 4. Configuration chart for Case Two using WT1800E.

Cable Length Considerations

When it is necessary to lengthen the cables of the IT, IN, or CT series current transformers, the voltage drop in power supply lines and total burden resistance seen by the transformer needs to be considered.

- The voltage drop across the power supply cables must be <%5 of the +15V lines.
- The total resistance seen by the secondary of the current transformer must be less than the transformers RM (burden resistance) specification. This is curve of primary current vs. resistance, with multiple operating temperatures. It is important to consider the resistance of the entire signal length from transformer to power analyzer, as well as the internal resistance of the power analyzer.

Example:

- IN 2000-s current transformer
- WT1800E with 5A element
- Maximum operating current 3000Apk

The specifications for the 5A module state the internal resistance is 100 mΩhm. The IN 2000-S specifications show the maximum burden resistance at 3000Apk is approximately 1 Ω @ 25C, with a transformation ratio of 2000:1 (NS), and an overhead current consumption of about 200mA (IC).

- Size power supply cables to maintain <0.75V drop when operating at 3000Apk primary current or 1Apk of secondary current ~1.2Apk total supply current.
- At 2000Apk primary current (1Apk secondary) the total resistance of the signal cables from the current transformer to the power analyzer must be <0.89 Ω @ 25 (1Ω-0.11Ω).

Recommendations on wire types and shielding for the power supply cables are detailed in the IST power supply user manual. For long runs, twist the signal wires from the power supply to the power analyzer to reduce the influence of noise, though bear in mind this increases the total length of the wires.

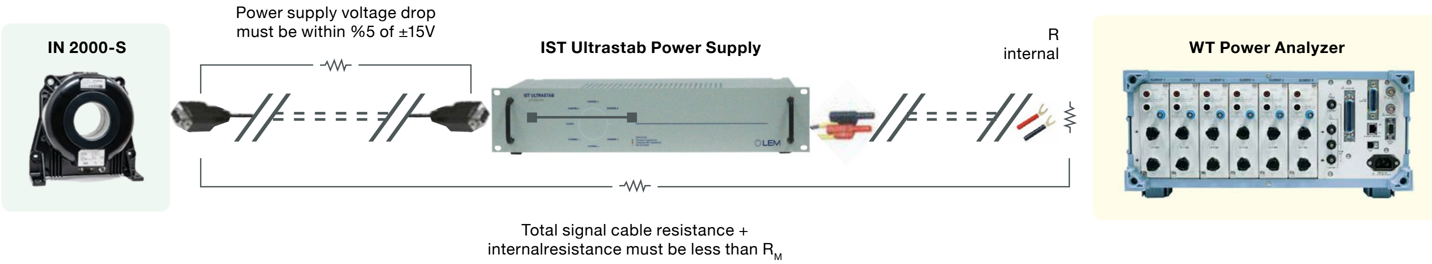


Figure 18. Lengthening IN/IT transformer cables.

Input	Voltage
Impedence	2MΩhm approximately 10pF
	Current
	Approximately 100 mΩhm + approximately 0,07 µH

# of Secondary turns	N_S			**2000**		
Positive Current Consumption	$+I_C$	mA	**180**	**200**	**225**	Add IS for total current consumption
Negative Current Consumption	$-I_C$	mA	**80**	**89**	**100**	Add IS for total current consumption

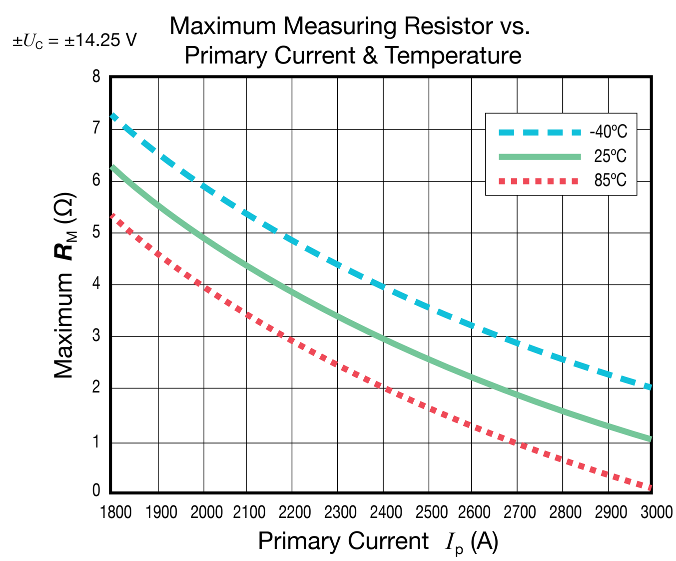


Figure 19. WT5000 and IN 2000-S specifications.

Combining uncertainty for power measurements

Power analyzer uncertainty is a percentage of reading plus a percentage of range error. Current transformers are a percentage of reading plus offset. The following shows methods for estimating the total uncertainty in a power analyzer and current transformer system.

Example (sum of errors/worst case)

Power analyzer	WT1800E
CT	CT1000A
Input conditions	200V, 100A, PF = 1, effective power: 20kW
Range settings	300V/500A (150 kW effective range, internal current range 0.5A)
Current transformer rating	200A 1000:1 ratio (0.2A)
Power analyzer uncertainty	0.05% of reading + 0.05% of range
Current transformer uncertainty	0.04% of reading + 30 μA
Distribution (based on uniform rectangular distribution)	$\sqrt{3}$
Sensitivity coefficient	$C_i = 200$
Confidence level (95%), k=1	1.65

Total Uncertainty of Power Analyzer (U_i(WT)) =

$$\frac{(\text{Power Reading x Error of Power Reading (\%)} + \text{Power Reading x Error of Power Range (\%)})}{\text{Distribution}}$$

Total Uncertainty of Power Analyzer =

$$\frac{20\text{kW x } 0.05\% + 20\text{ kW x } 0.05}{1.77305081}$$

Total Uncertainty of Power Analyzer = 43.307W

Total Uncertainty of Current Transformer (U_i (CT)) =

$$\frac{0.04\%\text{ of Reading} + 30\mu\text{A}}{\text{Distribution}} \text{ x Sensitivity Coefficient}$$

Total Uncertainty of Current Transformer =

$$\frac{0.04003}{1.73205081} \text{ x } 200$$

Total Uncertainty of Current Transformer = 4.622W

Total Uncertainty = $\sqrt{(U_i\text{ (WT)}+U_i\text{ (CT)})}$ x Confidence Level (95%)

Total Uncertainty = $\sqrt{(43.307+4.622)}$ x 1.65

Total Uncertainty = 71.8624W

Total Power (P) = Power Reading ± Total Uncertainty

P = 20kW ± 0.72kW