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## Which current sensor for power measurement?

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Which is the best current sensor for your power measuring application? Solid-core current sensing technology provides good performance at low cost. But split-core sensors are making strong progress particularly for applications such as retrofitting power meters into existing equipment. Some of the newer split-core current transformers are lighter, opening the way to sensors that are cost-effective and more accurate. Here's an analysis of traditional current sensing technologies and some innovative ones to help you design-in the best system for your power measuring task.

### Overview

Whether it's power supply management, electricity usage control or monitoring the general state of a system's "electric grid" large or small, gauging energy conservation and doing it cost-effectively looms heavily in more applications.

Most designers equate power measurements with power supply management. It's tied in with power generation and distribution, but also industry professionals monitoring their power quality and power factor to control rate tariffs imposed by their utilities, especially when operating low-power-factor loads.

Energy sub-metering is also gaining importance among facility and plant managers as it allows tracking and allocating energy costs. It also allows managers to perform advanced analysis of electricity consumption for best system efficiency. Intelligent sizing of power supplies depends on knowing the peak consumption and planning for sufficient safety margin to minimize system failures. Energy sub-metering is also required to understand and manage commercial and industrial layouts and identify efficiency issues caused by defective appliances and inefficient facilities usage (e.g., inappropriate lighting, heating, or air conditioning).

Another related major area, condition monitoring, requires systems to anticipate and react to failures that impinge upon vital services. Here again, electrical power measurement is much more efficient than transducer based systems using temperature, pressure, or vibration sensors. What's the best current-sensor solution for your task? Here's how to go about finding it.

### Selection criteria

Whatever the application, pay careful attention to the following parameters in designing your power monitoring system:

1. Accuracy: Class 1 power meters require current sensors with much better than 1 percent accuracy. The sensor is generally expensive and utilizes costly manufacturing processes. An alternative to using expensive sensor elements is to calibrate the power meter for each single element. Taking into account the specific

characteristics of each sensor allows you to use it in its most precise operating mode and to mitigate the variations from one sensor to another.

2. Drift: A sensor's drift defines its ability to sustain a given reading over time independent from the initial system calibration. Some variations in sensor characteristics may be caused by changes in ambient humidity and temperature as well as component aging. Clearly the designer's task is to select a sensor with low-drift consistent with the most cost-effective solution

3. Linearity: We can define linearity as the sensor's ability to retain its characteristics over its full operating range. A high linearity of the analog sensing part is essential to provide accurate measurement over a wide range of primary currents, and especially at low current levels. Several technologies offer good performance over only a limited measuring range, thus limiting their application to rather high or low currents.

4. Phase shift: The accuracy of the true active power or energy calculation is related not only to the accuracy and linearity of the AC current and voltage sensor in terms of amplitude, but also the phase shift that may occur between the measurement of these correlated values. The phase shift should of course be as low as possible.

5. Integration: The sensor's current transformers are essentially self powered, and do not require wiring other than a 2-wire output connection to the main power monitor unit. Many of them provide calibrated standard outputs, allowing easy integration in the power monitoring system. The typical 1- and 5-amp or 333 mV outputs are compatible with most standard power meters on the market.

High-accuracy power meters require specific calibration with sensors that are no longer interchangeable. As a consequence, these systems often deliver low-current outputs that are safer than traditional 1- and 5-amp signals. Sensors with current outputs are almost insensitive to interference and are preferable to voltage outputs when long cables are required to connect the sensors to the power meter.

6. Price: The cost of the sensors come into play especially when three accurate current sensors are required for 3-phase power measurement. When considering overall price, also consider installation and maintenance costs. Although more expensive, reliable and easy to install and replace, split-core sensors bring greater cost reduction to the system as a whole.

## **The transformers**

### *Solid-core current transformers*

Power measurement systems generally implement contactless current sensors rather than shunts, because the latter cause power losses as well as installation and safety issues. Traditional solid-core current sensors are based on the principle of a transformer, i.e. primary and secondary windings magnetically linked by a core. The measured current induces a magnetic field in the core which generates a current in the secondary windings proportionate to the primary current divided by the number of turns of the secondary windings. These basic current transformers are designed to measure sinusoidal alternating currents in the typical 50/60 Hz range. This well known technology is very affordable due to the use of common materials and processes.

Solid-core current transformers offer a cost-effective and accurate solution for designing power meters dedicated to new equipment and buildings. They are not suitable, however, for the numerous applications involving power monitoring of existing machines and facilities, where it would be necessary to shut down power and disconnect cables before retrofitting the solid-core sensors in all the places where they might be used. Installing power-metering systems is generally not possible, prohibitively expensive and even dangerous if it requires a service interruption, even for a short while (e.g. stopping a production line, a

telecom or datacenter power supply, or nuclear plant equipment).

#### *Split-core current transformers*

Contactless self-powered split core current transformers simply snap over a conductor, without the need to screw or weld on complex brackets. Thus installation and maintenance is straightforward. They can be installed in electrical control panels, thus avoiding complex wiring, to remotely monitor devices that sometimes operate in inaccessible or harsh environments. Split-core transformers can be retrofitted into a live installation without disturbing it, which often make them the best choice for engineers designing power meters.



**Figure 1: Split-core current transformer**

But these advantages have a price. The split-core current transformer is more expensive and less accurate than the solid-core transformer. Thus the specific application is important.

Split-core current transformers are generally based on the same principle as solid-core transformers. In split-core, however, the magnetic core comprises two parts and thus can be separated. The part's inaccuracy mainly comes from the imperfect contacts between the two parts; and because the secondary windings are not uniformly distributed around the magnetic core (around one of the two parts only). The price and performance of these transformers generally are a function of these physical and mechanical characteristics. Very flat contact surfaces are required as well as sufficient pressure between the two parts of the core. The part's case generally features flexible sections or materials and/or hinges to provide sufficient compression as well as a reliable opening mechanism.

#### *FeSi split-core current transformers*

FeSi has been widely used in split-core current transformers, mainly due to its affordable price. The performance offered by this material is generally poor, however. It has poor linearity (especially at low currents) and a large phase shift. This restricts its use to low-cost current transformers for measuring rather high currents, where power monitoring doesn't require high accuracy. Often, system engineers need only a rough estimation of the power consumption rather than an analysis of exact consumption. In this application, the system user can draw operating time profiles. In these cases the large phase shift is not a big issue. A typical application is branch current monitoring in panel boards allowing a system to detect when some circuits may come to overload and generate an alarm or balance loads.

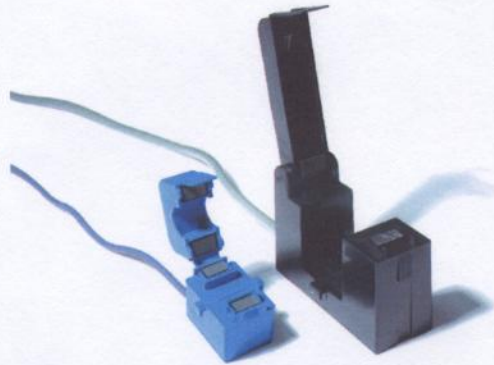
Another disadvantage of FeSi current transformers is that they are large and heavy. They're thus not very appropriate for environments with limited space.

#### *FeNi split-core current transformers*

FeNi has been a better material for split-core current transformers for a long time. It offers good

performance but at high price. And it's a good alternative to FeSi when accuracy and phase shift are important, or when the transformers need to measure small currents.

Apart from the price, FeNi current transformers have some limitations. As with FeSi current transformers, they take up considerable space within industrial facilities and panel boards. They also suffer from poor linearity and drift, mainly due to the air gaps induced by the split-core architecture.



**Figure 2: 800-amp ferromagnetic split-core (right); 100-amp ferrite split-core (left)**

#### *Ferrite split-core current transformers*

Ferrite materials are poor performers when it comes to saturation level and magnetic permeability. That drawback gets in the way when it comes to applications at 50/60 Hz. Recent developments, however, bring these materials into play for a wide range of power monitoring applications. Newer types have significantly improved permeability and can be implemented in 50/60 Hz current transformers as a substitute for FeSi or FeNi cores, despite their low magnetic saturation level.

Split-core current transformers implementing the new types of ferrite can perform accurate measurement of AC signals in an extended frequency range that includes the 50/60 Hz application domain. They take advantage of the intrinsic ferrite qualities, providing high accuracy and excellent linearity even at very low current levels. They also feature particularly low phase-shift between input and output currents, which is essential to accurate measurement of true active power or energy. Their hard and dense core minimizes air gaps and they are virtually insensitive to aging and temperature changes in contrast to other materials like FeSi or FeNi. They're also available at low cost.

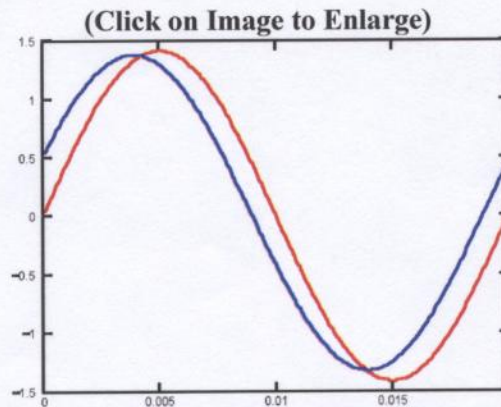
With high currents, larger ferrite cores should be used for measurement. The large cores aren't generally available, however, due to some fabrication limitations. In these applications, both FeNi transformers and Rogowski coils are more appropriate.

#### **Comparing FeSi, FeNi and ferrites**

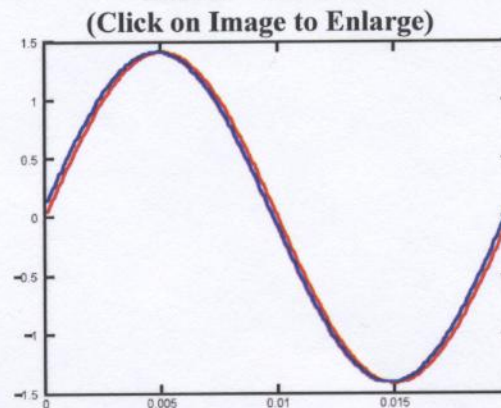
High-permeability ferrites do not provide the best results in solid-core current transformers. Here, split-core current transformers serve best. The hardness of the solid material (consider ferrite as a ceramic) allows very fine machining, providing air gaps down to a few microns that are stable over many years. Laminated materials such as FeSi or FeNi do not allow air gaps smaller than 20 or 30 microns, and these are more sensitive to aging and temperature changes. Given the small air gaps and better linearity of the ferrite at low

magnetic excitation (i.e., for low current), the ferrite offers a better performance than FeNi-80% and a lower cost.

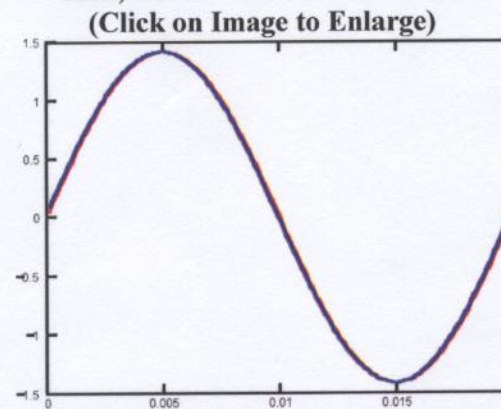
Figures 3a-c compare the phase shift behaviour of FeSi, FeNi, and high-permeability ferrite in a 5-amp current transformer.



**Figure 3a: FeSi, 20% rated current,  $f = 50$  Hz, air gap = 25 microns (one leg); 20% phase shift, 5% transfer ratio error**



**Figure 3b: FeNi-80%, 20% of rated current,  $f = 50$  Hz, air gap = 25 microns (one leg), 3.8% phase shift, 0.15% transfer ratio error**



**Figure 3c: Ferrite, 20% of rated current,  $f = 50$  Hz, air gap = 5 microns (one leg); 1.9% phase shift, 0.004% transfer ratio error**

The phase shift for the ferrite is half that of the FeNi core. The reduced air gap of the ferrite core also allows

a better accuracy of transfer ratio (primary turns to secondary turns).

### Rogowski coils

A Rogowski coil is used to make an open-ended and flexible sensor that easily wraps around the conductor to be measured. It consists of a helical coil of wire with the lead from one end returning through the center of the coil to the other end, so that both terminals are at the same end of the coil. The length is selected according to the relevant current measuring range to provide optimal transfer characteristics.

This technology provides very precise detection of the rate of change (derivative) of the primary current that induces a proportionate voltage at the terminals of the coil. An electronic integrator circuit is required to convert that voltage signal into an output signal that is proportional to the primary current. In other words, the Rogowski coil enables the fabrication of very accurate and linear current sensors, at the price of additional electronics and calibration.

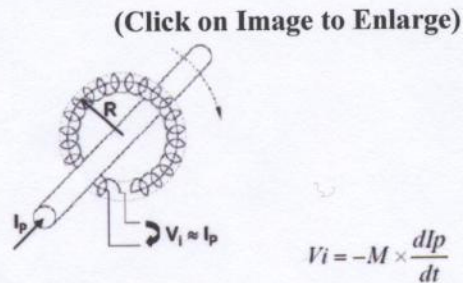


Figure 4: Rogowski coil principle

A Rogowski coil has lower inductance than current transformers, and consequently a better frequency response because it uses a non-magnetic core material. It is also highly linear, even with high primary currents, because it has no iron core that may saturate. This kind of sensor is thus particularly well adapted to power measurement systems that can be subjected to high or fast-changing currents. For measuring high currents, it has the additional advantages of small size and easy installation, while traditional current transformers are big and heavy.

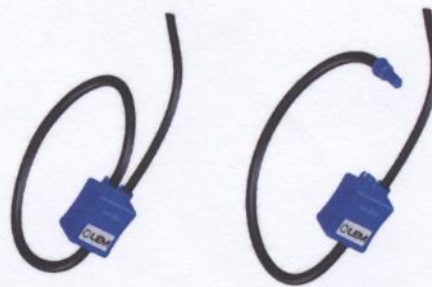


Figure 5: Rogowski coil product

The performance of such current sensors highly depends on the manufacturing quality of the Rogowski coil, since equally spaced windings are required to provide high immunity to electromagnetic interference. Another critical characteristic is the closing point that induces a discontinuity in the coil, creating some sensitivity to external conductors as well as to the position of the measured conductor within the loop. The locking or clamping system should ensure a very precise and reproducible position of the coil extremities, as well as a high symmetry. Some new technologies have recently appeared in this area, with special mechanical and electrical characteristics that allows much better accuracy and immunity to the primary

cable positioning. While the error due to the primary cable position is typically not better than  $\pm 3$  percent in the 50/60 Hz frequency domain, it has been reduced to less than  $\pm 0.5$  percent on some of the latest Rogowski coil sensors.

### **Summary**

Many new installations benefit from solid-core transformers, and split-core technology is not designed to compete with these. However, existing machines and building equipment have no way to add solid-core devices without a costly shut-down of the system. New materials and technologies equip advanced split-core current transformers for immediate retrofitting of high-performance and cost-effective condition monitoring, power metering and facility supervision systems. Thus the fast growing energy efficiency market and the large deployment of power measurement systems point towards the need for high performance but cost effective split-core current transformers.

Conventional split-core current transformers present a few shortcomings. These transformers either implement expensive materials (e.g., FeNi), or provide usually poor performance, especially in terms of linearity and phase-shift (e.g., FeSi). New types of ferrite with dramatically improved magnetic permeability achieves both high performance and affordable price. The Rogowski coil technology has also made good progress, allowing small, light and flexible sensors for high currents. However, they require some signal adaptation and calibration to take advantage of the best of its characteristics. The major improvements that have been made in the designs and manufacturing processes have allowed them to reduce both the cost and the sensitivity to the coil positioning around the primary cable. Thus they've overcome one of their main problems.

### **About the authors**

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