Measuring Accurately To 10 MHz With Fluxgate Balanced-Core Current Transducers

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For several decades, zero-flux current transducers have been used to extend the measuring range of power analyzers. Common devices usually have a bandwidth in the three-digit kilohertz range. However, when using wide-bandgap semiconductor modules, switching frequencies between 20 kHz and 100 kHz are widely used to generate sinusoidal current signals without heavy and expensive filter elements. At such switching frequencies, harmonics can be detected up to the megahertz range and provide active and reactive power components. As a result, to measure current accurately in such applications, bandwidths wider than those of conventional current sensors are required.

This article presents a zero-flux current transducer developed by Danisense (the DW500UB-2V) that can provide linear transmission behavior up to 10 MHz. To explain the challenges of designing such a transducer, we'll begin by reviewing the key calculation performed by power analyzers, discuss the requirements for power analyzer accuracy in efficiency measurements, and describe the sources of error in the current measurements needed to measure efficiency. Error due to phase displacement at higher frequencies is a particular challenge in measuring current accurately across a wide bandwidth, so we'll go into detail on this problem in particular.

After briefly reviewing the reasons for using zero-flux current transducers rather than conventional current transformers or Rogowski coils, the principles of operation of the zero-flux transducers will be explained and the different types of transducer designs will be described. To better understand the bandwidth limitations in these transducers, which contain active circuitry, we'll examine the circuit characteristics of passive current transducers that determine their bandwidth. With that as background, we'll explain how the new zero-flux current transducer overcomes these limitations to achieve flat measurement response out to 10 MHz.

Power Analysis

Power analyzers usually use the following basic formula for active power calculation.

$$P_{avg} = \frac{1}{T} \times \int_0^T v(t) \times i(t) \times dt$$

Thus, the digitized instantaneous values of the voltage v(t) and the current i(t) are multiplied together and the results are summed up over a defined time window. Basically, dc components, all harmonic and non-harmonic components up to the bandwidth limit or filter cut-off frequency of the power analyzer are all taken into account.

Power analyzers in the premium segment already operate up to an analog bandwidth of 10 MHz. But extending the measuring range with current sensors often results in a limitation of the bandwidth of the power analyzer. The filter settings are sometimes already set at 100 kHz so that higher frequency components can no longer be detected.

Efficiency Measurements

Especially for efficiency measurements the overall accuracy of the measurement chain must be very precise. Even small ratio errors can lead to major deviations when determining efficiencies and losses. This is because losses cannot be measured directly and can only be calculated as the difference between the input power and the output power. With the power values used in Fig. 1, an example calculation for current transducers with the ratio accuracy of 0.1% can now be performed as shown in the following equations.

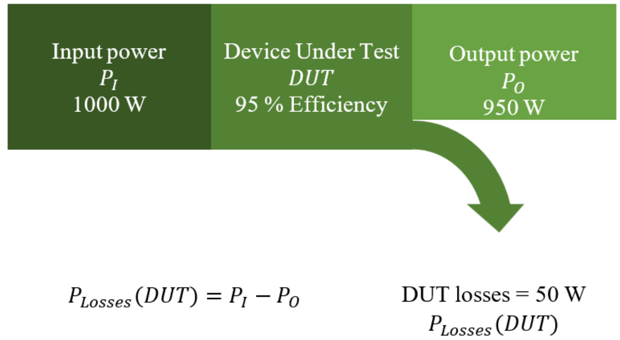

Fig. 1. DUT—determining the efficiency as the difference between input and output power.

In the worst-case scenario, the measured value of the input power is increased by 0.1% and at the same time the measured value of the output power is decreased by 0.1%. This results in the largest possible error for the calculation of the power loss.

$$P_I + 0.001 \times P_I = 1001\ W$$

$$P_O - 0.001 \times P_O = 949.05\ W$$

$$P_{Losses}(DUT) = 51.95\ W$$

Percentage error of the power loss:

$$\frac{(51.95 - 50)W}{50\ W} \times 100 = 3.9\ \%$$

If current transducers with an accuracy of 0.1% are used to measure the input and output power, the calculated power loss of the test device, such as a frequency converter, can deviate from the true value by 3.9% in the worst case. All the other necessary components like voltage dividers and the power analyzer itself are assumed to be ideal without any error.

Fig. 2 shows the effects of various ratio errors in current measurement on the percentage deviations in the loss calculation. The measurement errors of the power analyzer or the voltage sensors must also be considered in practice. The calculated value of 3.9% is marked on the green line for the accuracy of 0.1%. The percentage error in the loss calculation increases as the efficiency of the device under test increases.

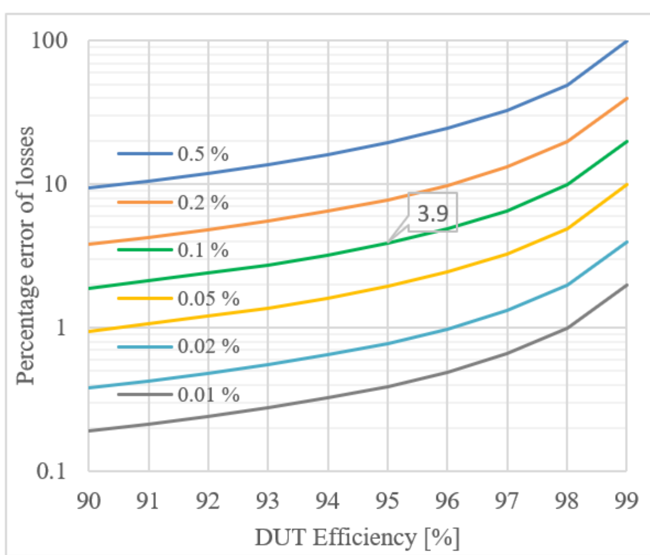

Fig. 2. Accuracy of the loss measurement as a function of efficiency and current measurement error for the worst-case scenario.

To keep the error as low as possible, even for high-efficiency frequency converters or motors, current transducers with an amplitude error in the ppm range are needed.

Influence Of The Phase Displacement

The phase error of the current transducers that are used also results in an additional error in the power measurement. The basis here is the generally known power triangle and the power factor defined via the power triangle.

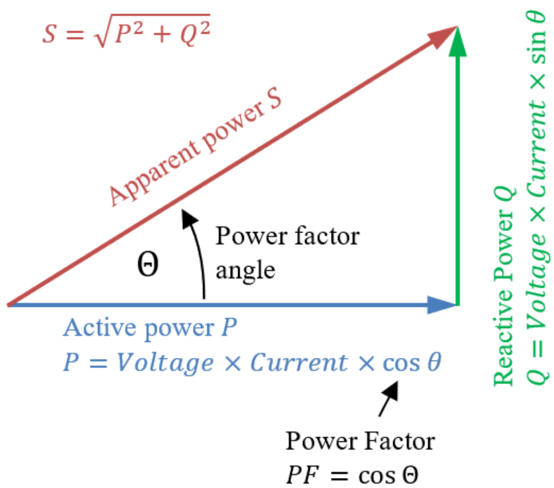

Fig. 3. Power triangle.

Power factor is described as leading if the current signal is advanced in phase with respect to voltage, or lagging when the current signal is behind the voltage signal. A lagging power factor signifies that the load is inductive, as the load will consume reactive power.

A phase error of the current transducer changes the phase angle Θ between the current and voltage signal. The effect on the percentage error in the active power measurement depends strongly on the power factor of the system, since the trigonometric functions are non-linear.

If the DUT (device under test) consumes active and reactive power, an increase of the phase shift angle by the current transducer or the measuring system causes an increase of the reactive power with a simultaneous decrease of the active power. This relationship is shown in the following Fig. 4.

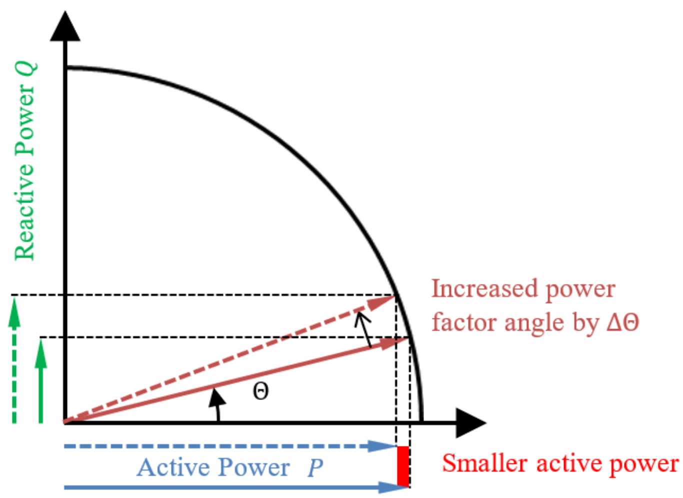

Fig. 4. Graphics of an enlarged power factor angle.

To calculate the impact on the active power, the percentage reduction of the power factor can be calculated as follows.

Percentage reduction in active power

$$= \frac{\cos(\Theta + \Delta\Theta) - \cos(\Theta)}{\cos(\Theta)} \times 100$$

The influence of the phase displacement on the active power becomes significantly larger with an increasing reactive power component, as Fig. 5 shows. The calculation is based on sinusoidal waveforms. For current and voltage signals generated by PWM (pulse width modulation), the influences can be even greater. In any case it can be said that the entire measuring system and thus also the current transducers used should have the smallest possible phase displacement.

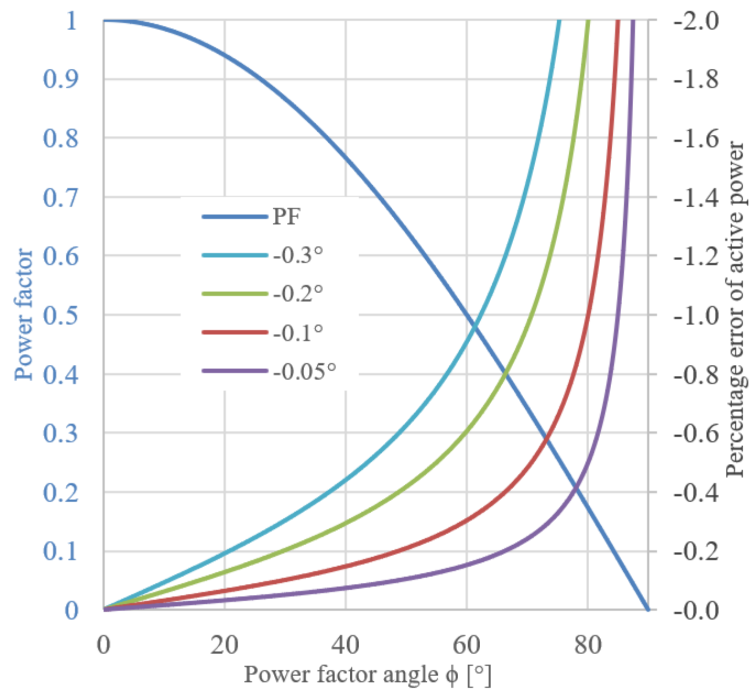

Fig. 5. Phase displacement of current transducer and its influence on the active power measurement depending on the power factor angle Θ of the system.

The Phase Displacement At Higher Frequencies

At high frequencies it is very challenging to realize a small phase error. For example, a time delay of 12.5 ns in the current transducer results in a phase displacement of just of -225µ° at 50 Hz. However, at 10 MHz the same time delay will generate a phase displacement of -45°.

An additional problem is that the power factor of many DUTs drops significantly with frequency, making it more important to measure with very small phase displacements. Especially if inductive motors are tested. At higher frequencies, the reactance of the motor increases. This reduces the power factor. The higher oscillating current components are usually significantly damped by the higher impedance values.

Power Factor At Higher Frequencies

As an example, the data of a 2.2-kW three-phase motor is used to determine the power factor up to 1 MHz. The table lists the impedance characteristics of the motor at 50 Hz. From the current and voltage measurements taken in Fig. 6, the impedance and power factor of the motor can be calculated as shown in Fig. 7.

Table. Impedance characteristics of a three-phase, 2.2-kW, 50-Hz, 400-V, 5.7-A motor spinning at 925 RPM.

Stator resistance, R_s	2.20 Ω
Stator reactance, X_s	3.05 Ω
Rotor resistance referred to stator side, R_r'	3.50 Ω
Rotor reactance referred to stator side, X_r'	4.50 Ω
Magnetizing reactance, X_m	70.10 Ω

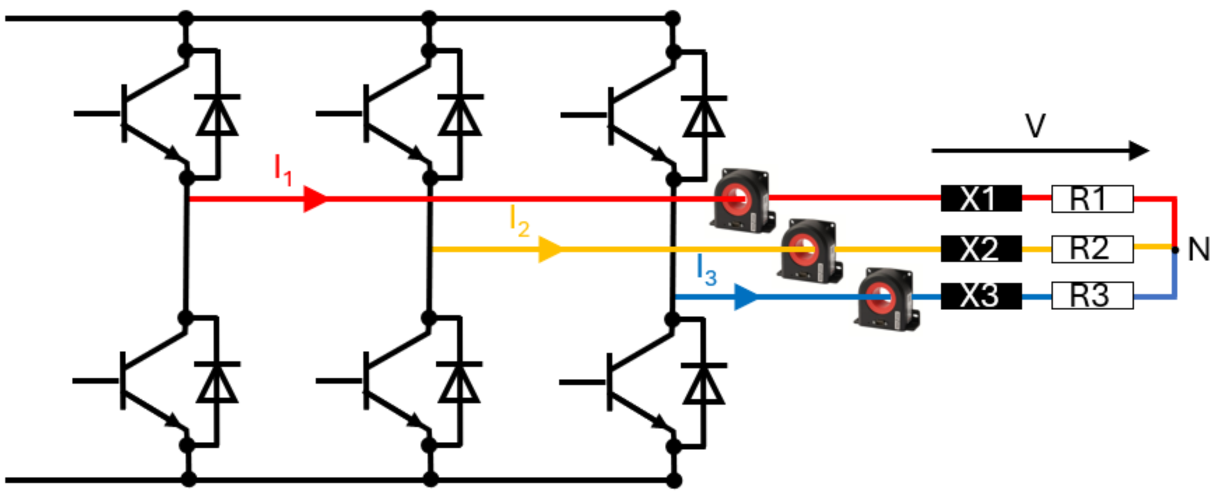

Fig. 6. Using current sensors to measure motor phase currents for determination of power factor.

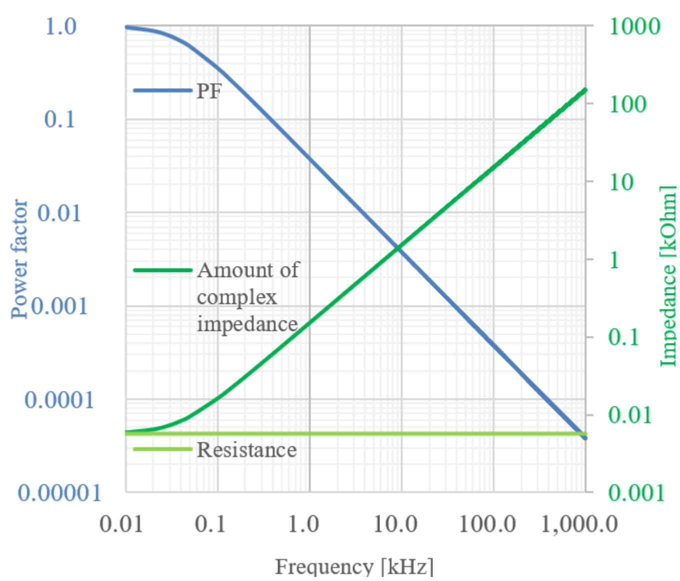

Fig. 7. Power factor and total impedance as a function of frequency.

Current Measurement

In many cases, zero-flux current transducers are used for these types of measurement because the ratio error is in the ppm range. Even if conventional current transformers or Rogowski coils had a similar accuracy, these technologies would not be able to detect a dc component of the DUT.

In general, a dc component can occur in the input and output current signal.[1, 2] These parasitic signal components have an influence on the measured active power. Many national directives already specify maximum values for those dc components that must be complied with for any certification procedures.[3] They can harm inductive devices like power transformers on the grid.[1]

Zero-Flux Current Transducers Principle

The technological basis of the zero-flux current transducers is a conventional current transformer. The primary current induces a magnetic flux in the iron core, which generates a current in the secondary winding (W_2) according to the transformer principle in Fig. 8. The resistance of this winding and the connected burden impedance lead to a voltage drop across the core and thus determine the magnetic flux density in the iron core.

If a compensation current (i_c) is set against the measuring current so that the two flux levels cancel each other out to zero, i_c can be used as the measured value. To ensure zero-flux in the iron core, an additional sensor winding W_s is added to the core. The current transformer then operates continuously in the area around the zero point of the magnetization characteristic.

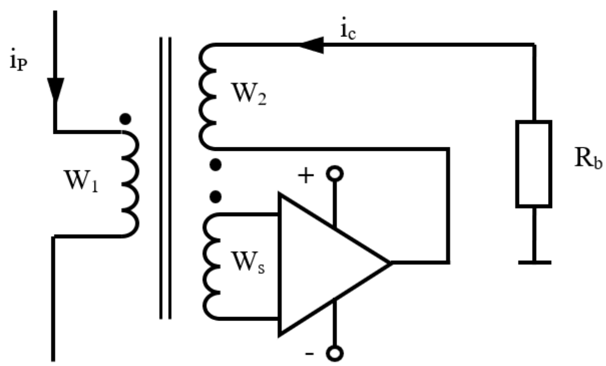

Fig. 8. Circuit principle of a zero-flux transducer. In this diagram, i_p = primary current; i_c = compensation current, measured value; W_1 = primary winding; W_2 = secondary winding; W_s = sensor winding with integrated amplifier and R_b = burden resistor.

With this principle, only ac components can be measured, as the transformer principle is required for the secondary winding. If a third winding is additionally applied to the core and supplied with an ac voltage source, the iron core can be driven alternately into the saturation range with a correspondingly large voltage amplitude. With a dc primary current, the additional magnetic flux will then drive the saturation areas of the iron core further into the positive or negative range, depending on the polarity of the primary current. The summation of the current which is generated by the ac voltage source and the primary current can then be analyzed in the sensing winding.

In the case of an inductor (ideal coil), the current follows the voltage by 90°. As a result, the current peaks are located at the zero crossings of the voltage excitation signal in Fig. 9.

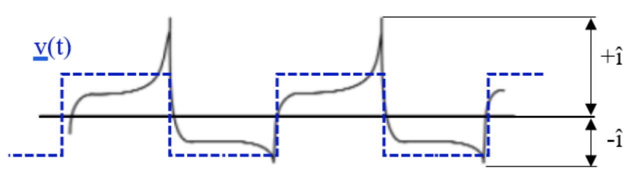

Fig. 9. A positive primary dc current shifts the current signal in the positive direction.

Zero-Flux Balanced-Core Design

A negative effect of the excitation voltage signal is that the primary current can be influenced by the generated alternating current through the excitation winding. For this reason, a second iron core is added to which the excitation winding is applied in the opposite direction to the first iron core (see Fig. 10). This neutralizes the magnetic fields generated by the excitation current. The primary current remains almost unaffected.

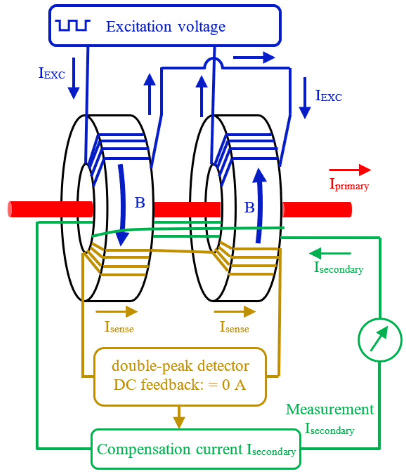

Fig. 10. Fluxgate element of the balanced-core design.

The balanced-core design must have identical hysteresis characteristics to obtain the required accuracy. Special care must be paid to even small mechanical forces to avoid magnetostriction during the winding process, which can easily change the B-H characteristic.

Other Designs Of Zero-Flux Current Transducers

Due to the high technical production requirements of the balanced-core design, other variants have become established on the market (Fig. 11).

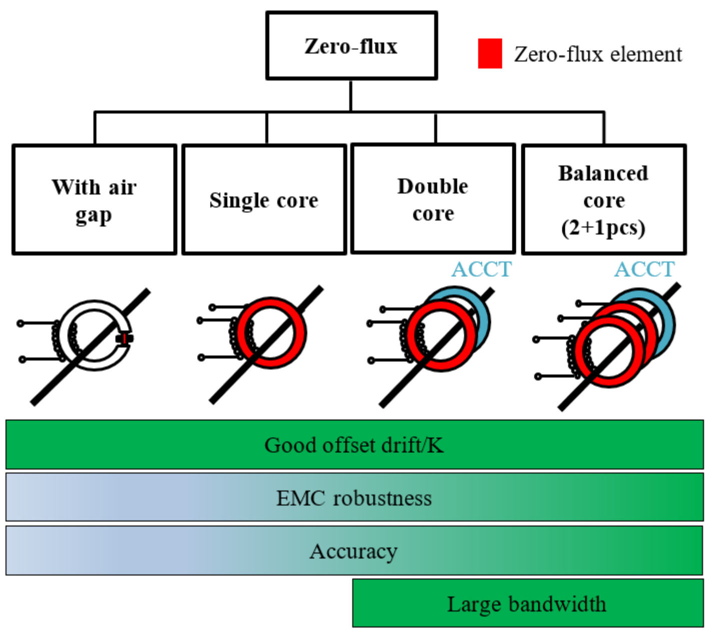

Fig. 11. Different zero-flux designs.

The bandwidth of the zero-flux detector is limited by the electronic circuits. To obtain wide bandwidth out of a zero-flux current transducer a third core in passive mode is mandatory for transferring the ac signal (Fig. 12).

In most cases the ac signal in the third core can be compensated in the single-digit kilohertz range. Above several kilohertz, the power amplifier for the secondary compensation current no longer has active control over its output current, but simply forms a short circuit. The third core now operates as a normal inductive current transformer. So to understand what factors limit the bandwidth of the zero-flux balanced-core design, we must examine the characteristics of the current transformer further.

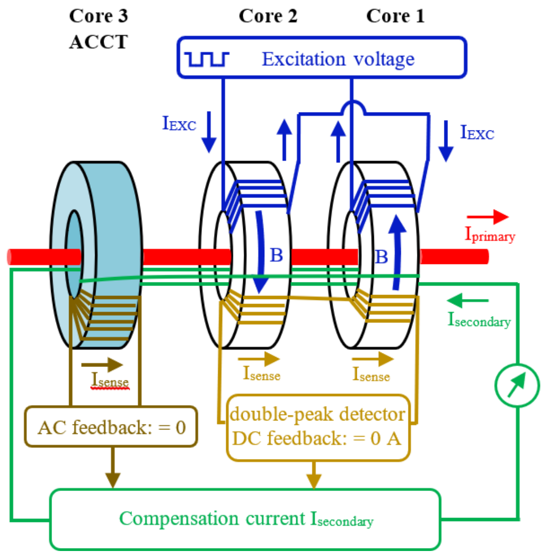

Fig. 12. Zero-flux balanced-core design.

Passive Current Transformers

Passive inductive current transformers have a copper wire winding and a magnetizable core as their main component. Also, Rogowski coils consist of a coil body wound with copper wire. This construction results in a winding inductance and unwanted capacitances that are always formed between the individual windings and between the individual winding layers which degrades the frequency response.

CTs And Their Frequency Response

Measurements have shown that only the capacitances within the secondary winding are relevant. The capacitances to the unearthed core play a negligible role. The internal capacitance of the primary coil or the capacitance of the primary winding against the secondary winding can also be neglected in most cases. Fig. 13 shows a single-layer-wound iron core and the corresponding capacitances.

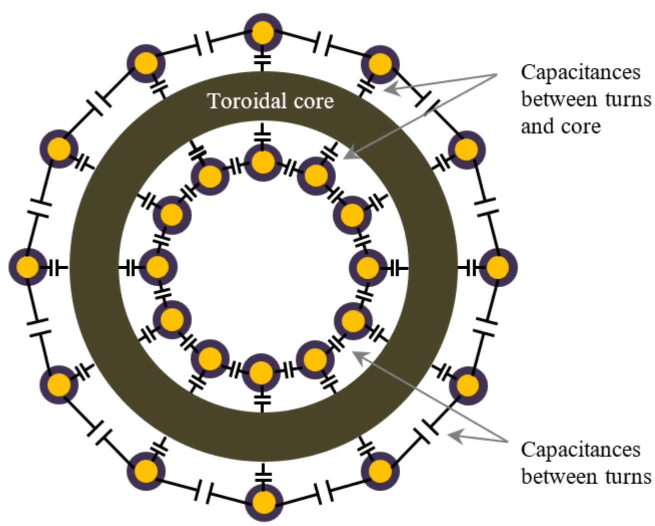

Fig. 13. Schematic diagram of a secondary winding.

Accordingly, each copper wire winding represents a potential oscillating circuit. With Thomson's oscillation equation it is possible to calculate the resonant frequency.

$$f_r = \frac{1}{2 \times \pi \times \sqrt{LC}}$$

Due to losses in the secondary winding resistances are added to the parallel resonant circuit (Fig. 14).

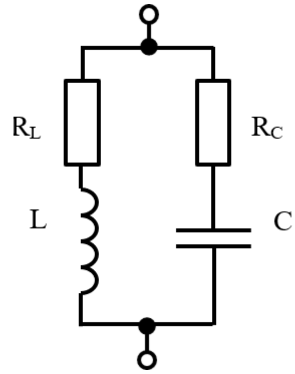

Fig. 14. Equivalent circuit diagram of a parallel resonant circuit with losses.

If you operate this circuit far below the self-resonance frequency this static model is sufficient, and the aim is to reduce the inter-turn stray capacitance. The Thomson's oscillation equation is extended with a correction factor which takes the ohmic losses into account.

$$f_r = \frac{1}{2 \times \pi \times \sqrt{LC}} \times \sqrt{\left[\frac{L/_C - R_L^2}{L/_C - R_C^2}\right]}$$

A low coil quality, which is described by the ratio of the reactance to the effective resistance of a coil, results in resonance points with a large amplification of the primary current.

In Fig. 15a a frequency response of a passive current sensor with a primary rated current of 1000 A and a secondary output of 333 mV is shown up to 150 kHz.

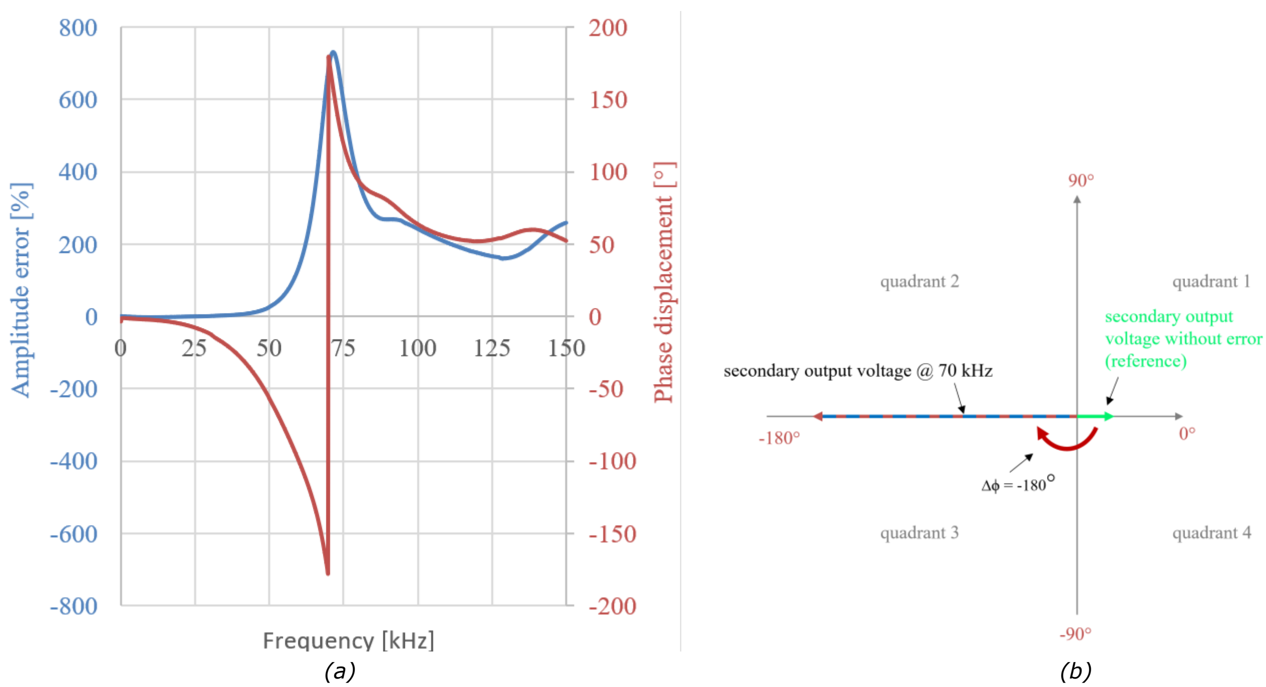

Fig. 15. Frequency response of a 1-kA current sensor with voltage output.

The resonant point is located around 70 kHz. The amplitude error is at approximately +700%. Looking at the sensor's response in the complex plane in Fig. 15b, up to the resonance point, the pointer runs from the fourth quadrant to the third, which means from 0° to -180°, then it crosses -180° around 70 kHz and enters in the second quadrant. For illustration reasons, the phase angle in the second quadrant is counted positively. The amplitude error and the phase displacement at frequencies above 75 kHz show floating behavior. Obviously, Thomson's oscillation equation can no longer be applied here.

Optimized Zero-Flux Current Transducers

By optimizing the number of turns and decreasing the parasitic capacitances in the third core of a zero-flux transducer with a rated primary current of 500 A the first resonance could be shifted above 10 MHz. An internal shunt converts the current signal into a voltage signal. The frequency response is shown in Fig. 16.

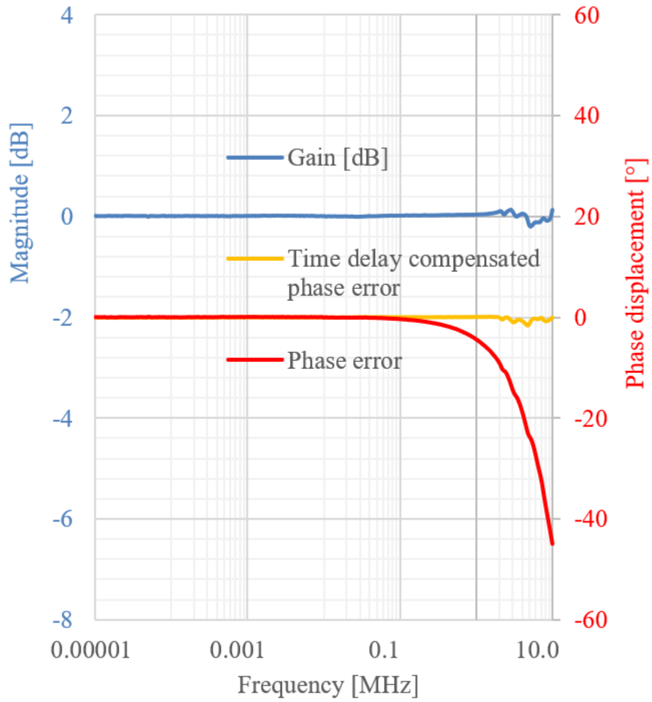

Fig. 16. Frequency response of the optimized zero-flux current transducer. Reducing parasitic capacitances in the third core of a zero-flux current transducer shifted the resonant point from somewhere in the tens of kilohertz range to beyond 10 MHz.

There are no larger ratio errors up to 10 MHz and the phase displacement consists of a fixed time delay which is mainly caused by a 2-m coaxial cable. This time delay is mentioned in the Danisense test protocol for the sensor.

Some power analyzers have the option for compensating time delays that are generated by the measuring sensors. With this compensation method, high accuracy current measurements up to 10 MHz are possible. Just as an example, ZES Zimmer's LMG671 power analyzer[4] allows for entry of the time delay in a corresponding input template (Fig. 17).

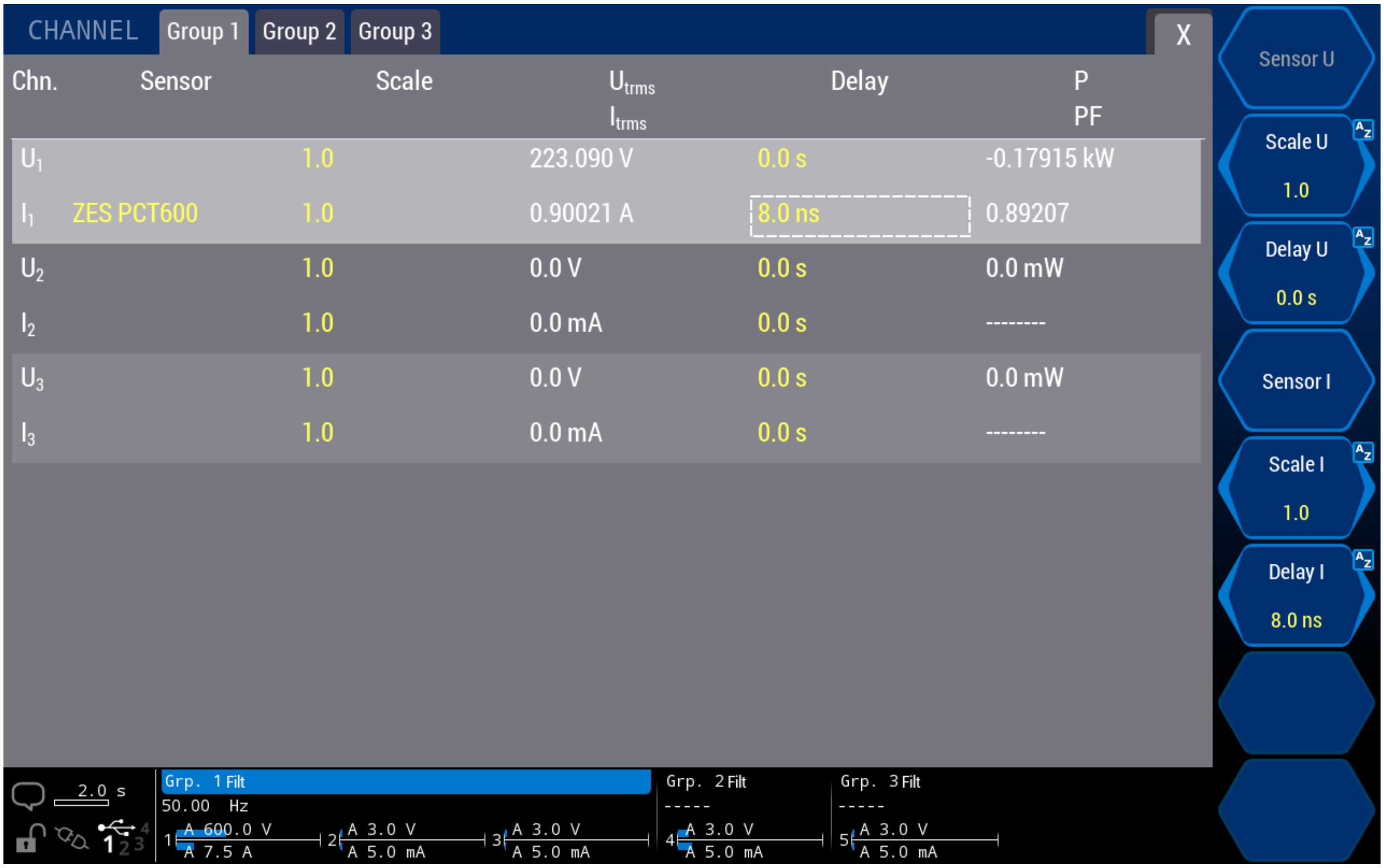

Fig. 17. The ZES Zimmer LMG671 power analyzer allows time delay compensation as part of the measurement configuration.

Fig. 18 shows the typical bandwidths of selected zero-flux balanced-core current transducers from Danisense including the DW500UB-2V which is featured in this discussion.

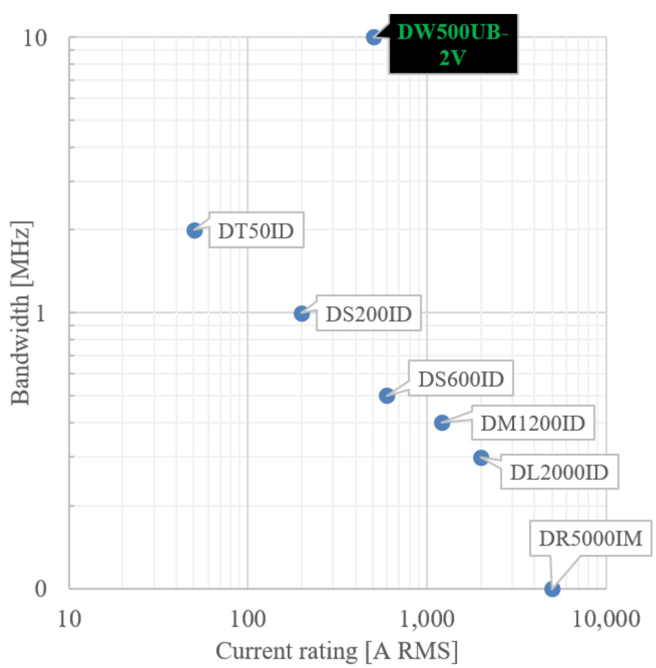

Fig. 18. Danisense's current transducers with rated primary current and bandwidth.

In general, the bandwidth decreases for devices with a higher primary current. This is due to the usually larger number of turns on the third core, which is responsible for the transmission of higher-frequency signal components. The optimized 10-MHz design for the DW500UB-2V is a significant improvement compared to the existing portfolio.[5]

Conclusion

Due to their high accuracy, zero-flux current transducers have become an integral part of the measuring range extension of power analyzers—especially when high switching frequencies are expected. An example of this is when using wide-bandgap power semiconductors based on SiC and GaN.

The frequency response of the current transducers used should also be taken into account. Bandwidths of up to 10 MHz can be realized with the right design. In order to raise awareness of the active power components present in higher-frequency harmonics, we propose that the new term "deformed active power" or "harmonic active power" be introduced in the field of electrical engineering.

In the latest IEC 61869-1:2023, accuracy classes of instrument transformers have recently been published with regard to their frequency response. However, the defined classes are only intended for power quality measurements and are not suitable for active power measurements. The lack of basic rules in international standardization repeatedly leads to uncertainties in the determination of active power above the defined fundamental frequency.

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4. LMG671 1 to 7 Channel Power Analyzer product page.

5. DW500UB-2V product page.

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