November 13th, 2025

Current Sense Transformers for Precision Power Monitoring

Introduction

As energy efficiency becomes a defining requirement for modern electronic systems, the ability to measure current with high precision has never been more critical. Accurate current monitoring enables engineers to optimize power conversion, detect faults, and guarantee compliance with stringent safety standards.

Different application domains call for different sensing strategies. Broadly, current sensing can be divided into three categories:

- DC current measurement (e.g., battery monitoring in EVs or energy storage systems)
- Low-frequency measurement (50/60 Hz power distribution networks)
- High-frequency measurement (switch-mode power supplies operating above 40 kHz)

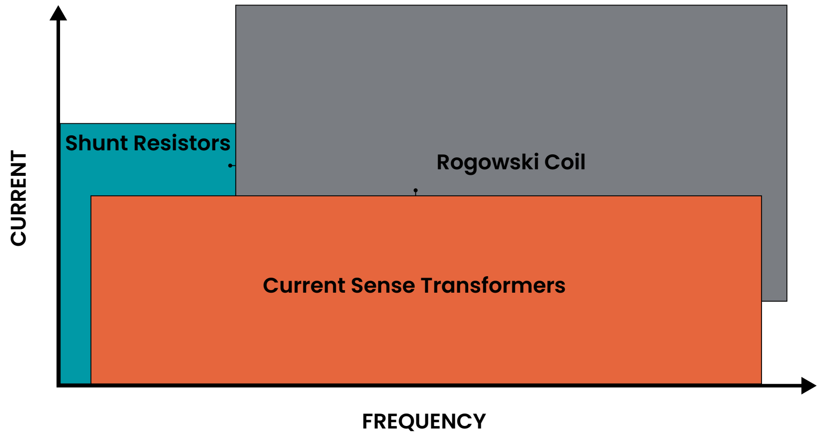


Fig. 1) Usage of Current Sense Transformers in Current-Frequency Domain

While several sensing technologies are available—including shunt resistors, Rogowski coils, and current sense transformers (CSTs)—the CST stands out when accuracy, galvanic isolation, and efficiency at high frequencies are essential. In this paper we briefly compare current sense technologies and introduce to main markets and applications, where current sense transformer technique is applicable. Afterwards a CST selection guidance with a real application case study is proposed.

November 13th, 2025

Technology Landscape: Comparing Sensing Methods

Selecting the right current sensing technology requires balancing trade-offs in accuracy, cost, power dissipation, isolation, and frequency response.

- Shunt Resistors offer simplicity and low cost, but they suffer from power losses and lack isolation.
- Hall-Effect Sensors provide accurate DC and AC sensing with isolation, but require external power and come at a higher cost.
- Rogowski Coils are unsaturable and cover very high bandwidths and current range, but require additional signal conditioning and are sensitive to EMI.
- Current Sense Transformers deliver high accuracy, low-loss, and isolated sensing—making them ideal for AC and high-frequency applications, though they are unsuitable for DC.

Table 1. Comparison of Current Sensing Methods

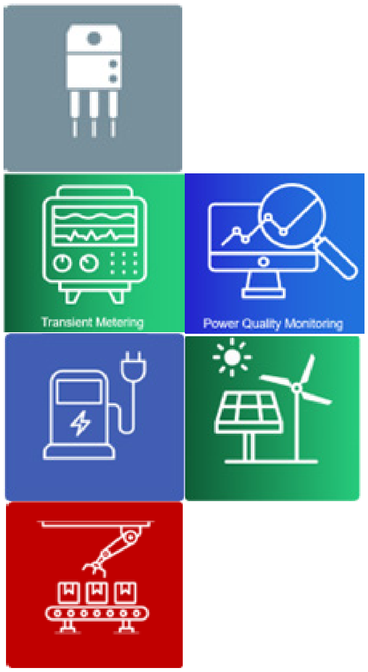
Technology	Advantages	Limitations	Typical Applications
Shunt Resistor	Low cost, simple, no phase error	High loss, no isolation	Low-power DC/DC, battery monitoring
Hall-Effect Sensor	High accuracy, galvanic isolation, DC & AC sensing	Expensive, requires power, temperature sensitive	Industrial drives, medical, precision systems
Current Sense Transformer (CST)	Accurate, low-loss, isolated, good EMI immunity	No DC response, core saturation at very low frequency	SMPS, AC line monitoring, solar/UPS
Rogowski Coil	Wide bandwidth, no core saturation, high current	Needs inegrator, poor low-frequency response	Transient analysis, arc fault detection, power quality

The decision often comes down to whether the application requires high efficiency and strong isolation at high frequency—an area where CSTs consistently outperform alternatives.

November 13th, 2025

Application Domains

CSTs have become indispensable in areas where system efficiency and safety are paramount. Their combination of low power dissipation, strong isolation, and EMI robustness make them well-suited for:



Switch-Mode Power Supplies (SMPS): Precise current feedback for regulation and protection.

High-voltage Monitoring: Safe measurement of current in systems requiring reinforced isolation.

Solar Inverters and UPS Systems: Supporting reliable conversion and uninterrupted operation.

Industrial Automation: Providing accurate sensing in electrically noisy environments.

Operating Principles

The operation of a current sense transformer is grounded in the fundamentals of electromagnetic induction. When an AC current flows through the primary winding, it induces a proportional current in the secondary. This secondary current, when passed through a terminating resistor, produces a measureable voltage directly propoertional to the original current

$$I_{Prim} = N \cdot I_{Sense} \qquad (1)$$

Where *N* means a turn-ratio. Voltage sense is a direct measurement of a primary current I_{prim}.

$$V_{Sense} = R_T \cdot \frac{I_{Prim}}{N}$$

November 13th, 2025

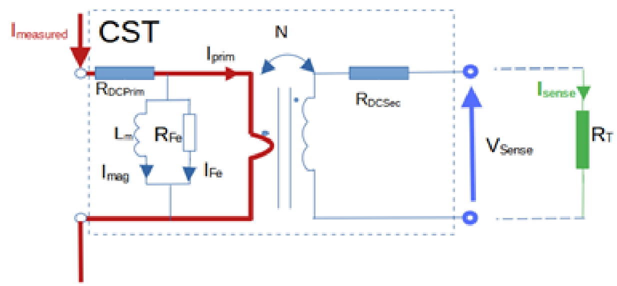
Flowing primary current slightly differs from measured current value, as the core of current sense transformers need to be magnetised by magnetising current I_{mag}. Of course, there exist also I_{Fe} and represents hysteresis losses, but for current sense transformers this value can be neglected, [3]. So, based on Fig 2a:

$$I_{Prim} = I_{measured} - I_{mag}$$

So our V_{sense} measured on terminals from current sense transformers under R_T loading conditions can be calculated as follow:

$$V_{Sense} = R_T \cdot \frac{I_{Prim}}{N} = R_T \cdot \frac{I_{measured} - I_{mag}}{N} \qquad (2)$$

a)



a)

Fig. 2a) Simplified Operating Principle of CST;
Fig 2b) Example photographs of CST products

Based on basic parameters, we can identify the I_{mag}, which represents here current losses:

$$I_{mag} = \frac{\left(\frac{V_{Sense}}{N}\right) \cdot duty_{cycle}}{L_m[mH] \cdot Freq[kHz]} \qquad (3)$$

To optimize CST parameters, YAGEO Group use magnetic Finite Element Method (FEM) Analysis. Magnetic field distribution analysis (*Fig.3*) can help to determine magnetic losses and phenomena related to phase shift between measured and sensed current values.

In an ideal transformer, the I_{prim} and I_{sense} relationship would be perfectly linear. In practice, however, factors such as magnetizing current, core permeability, hysteresis, and parasitic capacitances introduce measurement errors. These manifest as amplitude and phase inaccuracies. Fortunately thanks to FEM, careful selection of high-permeability materials and optimized resistor values is possible and minimizes these effects.

November 13th, 2025

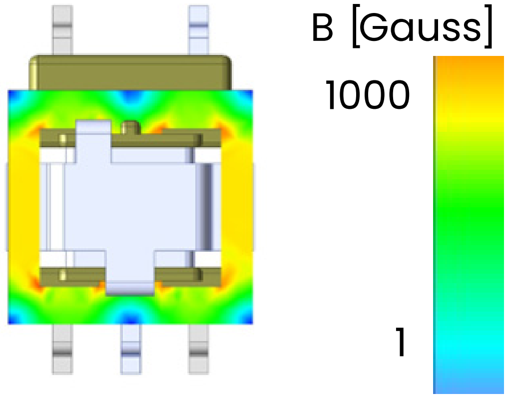


Fig. 3) Example magnetic field distribution within CST (shape core version)

A CST is ready to use and applicable to an analog and or digital measurement system. As mentioned before, the V_{Sense} – as a voltage drop on external to CST - terminating resistor R_T is mostly used as comparator input voltage (Fig. 4).

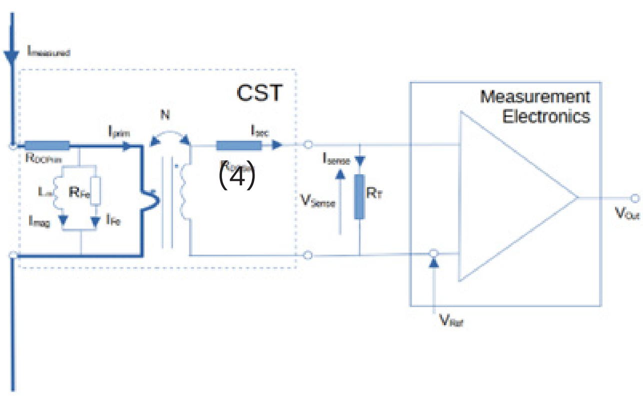


Fig. 4) Functional electric schematic of CST in measurement circuit burden resistor R_T

Comparator's tasks is to compare measured V_{sense} value to assigned reference voltage V_{ref}, where V_{ref} value typically defines maximum voltage drop we can measure on R_T – under Isense is flowing

$$V_{ref} = Max(V_{sense}) = R_T \cdot I_{sense} \qquad (4)$$

As result – we get final referenced output voltage V_{out}, which can be directly used for discrete or analog regulation systems or for monitoring purpose.

November 13th, 2025

Current Sense Transformer Selection Guidelines

Successful implementation of CSTs requires careful attention to design parameters:

- RMS Current Rating: Prevents overheating under maximum load.
- Volt-Second Product alternatively magnetic flux density: Ensures the magnetic core avoids saturation.
- Terminating Resistor (R_T): Balances output voltage levels against measurement accuracy.
- Isolation Voltage: Must meet safety regulations such as basic, functional, or reinforced insulation.
- Mechanical Constraints: Package dimensions, creepage, and clearance distances must fit within system design requirements.

STEP 1. Choice of product series based on application safety requirements.

At first step, it is to define the current requirement, insulation requirement and size constraint. All those considerations are reflected in manufacturer datasheets, which provide detailed specifications for mechanical dimension, insulation ratings, clearance distances, and safety certifications.

YAGEO Group offers the largest product portfolio in the market. CST products are suitable for applications with voltage rating up to 1.5kV, and fulfill safety conditions defined by creepage and clearance requirements as well as reinforced insulation barrier.

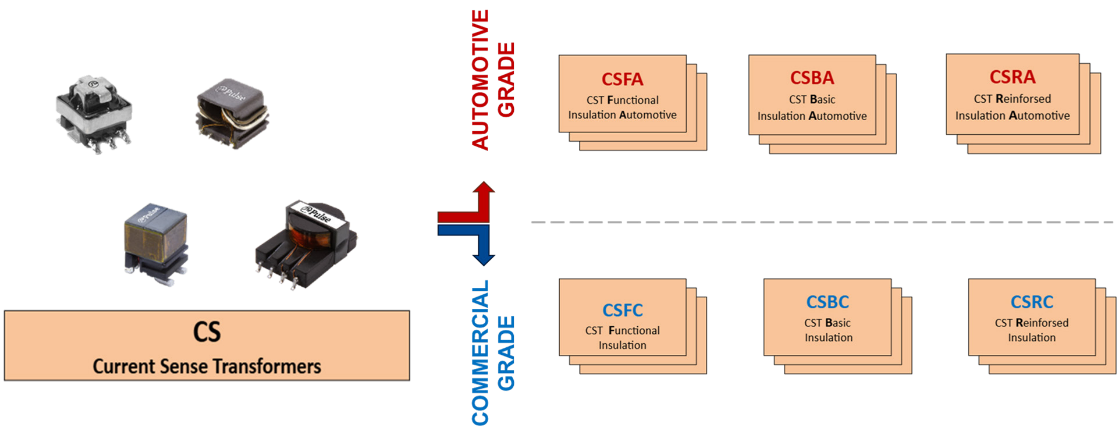


Fig. 5) Catalog Product Portfolio range of CST

The YAGEO Group catalog portfolio covers mechanically optimized constructions for applications up to 50A with market largest range of turn-ratio. Within catalog portfolio (Fig. 5), some products are suitable for measuring of current frequency up to 2MHz. Full customized design is possible for much wider range of currents.

November 13th, 2025

STEP 2: Choice guidance of suitable part number.

The CST part number selection process starts by defining of application and assumed to use comparator and available reference voltage V_{ref} as well as operating frequency or frequency range.

In general, a simplified mathematical analysis of the current sense circuit can be used to get a first pass at selecting the required turns ratio and reference voltage V_{ref}.

To start this step we need to define follow parameters:

a. Measured maximum value of a current peak (primary current)
b. Duty cycle of measured signal
c. Maximum value of V_{sense} we want to measure. This value will base on reference voltage V_{ref} - defined by preselected comparator or measurement method (Fig. 3)

Calculation starts with selection of of CST's Turn-Ratio based on calculated under given conditions working point (Flux density *B*): current frequency (*Freq*), $Duty_{Cycle}$ and available comparator's voltage reference V_{ref}.

$$B[Gauss] = \frac{1}{Ae} \cdot \frac{V_{ref} \cdot Duty_{cycle}}{N \cdot Freq_{kHz}} \qquad (5)$$

The equation (4) includes A_e – core cross-section coefficient. This formula is specified in every Pulse Electronics datasheet for product range specifically. It is recommended to plot *B(Freq)* CST characteristics as shown on Fig. 6, to understand change of the working point of CST in wider range of frequency.

To stay in linear part of magnetic B/H characteristic from a core, in most cases, the working Point B (Magnetic Flux Density) should be limited by minimum ***B>=250[Gauss]*** and not exceed ***B=2200[Gauss]***. The maximum B value is also specified in the datasheet. This working area (green marked on *Fig. 6*). determines possible solution domain for choice of the part number.

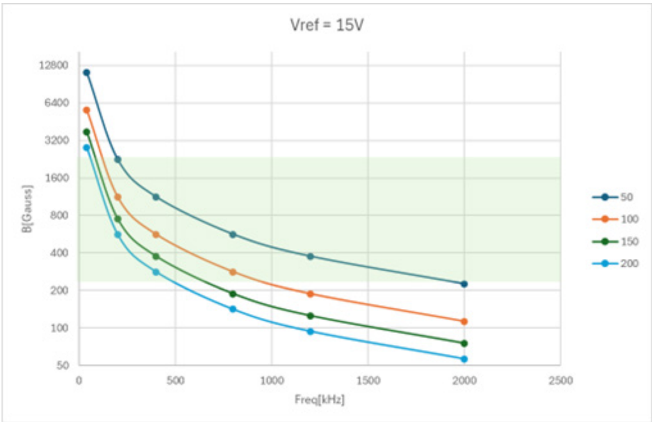


Fig. 6) Example of Flux Density vs. Frequency characteristics for CST calculated based on Eq.4. for constant V_{ref} condition (Eq.3.)

November 13th, 2025

From Fig 6, we see that higher frequencies require to use parts with lower number of turns as well as higher values of V_{ref} used on comparator side. Lower frequencies force to use parts with higher turn-ratio and may require lower values of reference voltage. Selection of working point is critical to get good voltage quality signal. To low positioned working point (below recommended value) may have a consequence on received Vsense signal. It can be than very low, so signal quality expected may not fulfill our expectations. We can also observe that N impacts to the sensitivity. The higher the turn ratio, the lower the working point. This cause lower Vsens and in the result lower sensitivity.

For selected part number, based on previous calculation results, we can determine a value of terminating resistor.

$$R_T = \frac{V_{Sense} \cdot N}{I_{Prim}} \qquad (6)$$

<u>STEP 3: Analysis of CST measurement error. Signal delay & Sensibility.</u>

Within Step 3 of selection guide, we analyze error and sensibility to check, how chosen CST can fit requirements of our application. The most important is to define amplitude and phase shift error. Amplitude error is mostly caused by CST losses, where magnetizing current plays a significant role.

The Current amplitude error can be defined by:

$$I_{Error}[\%] = \left(1 - \left| \frac{I_{measured} - I_{mag}}{I_{measured}} \right| \right) \cdot 100\% \qquad (7)$$

Amplitude error is linear – so not critical one's if determined. From most of CST, the error doesn't exceed 2%. This error can be easily compensated by measurement system.

The current phase shift error is important to determine as phase-shift between measured and sensed current and it can be defined:

$$\alpha[Deg] = atan\left(\frac{R_T + R_{DCsec}}{2 \cdot \pi \cdot Freq_{kHz} \cdot L[mH]} \right) \qquad (8a)$$

Mostly, when to $R_T >> R_{DCSec}$, thus R_{DCSec} can be neglected, and equation (8a) can be simplified to:

$$\alpha[Deg] = atan\left(\frac{R_T}{2 \cdot \pi \cdot Freq_{kHz} \cdot L[mH]} \right) \qquad (8b)$$

This allows as to calculate maximum current phase measurement error:

$$Error_{\alpha}[\%] = (1 - \cos\alpha) \cdot 100\% \qquad (8c)$$

November 13th, 2025

This error has nonlinear character (Eq.8a-c) and is difficult to compensate. So, it is very important to keep this error value of chosen CST solution as low as possible. Under normal circumstances, the phase error is lower than 0,1% for Pulse Electronics products. In case of higher values – a different value of terminating resistor is to consider.

Finally, the sensitivity of current sense transformer and its error can be calculated as:

$$sensitivity[V/A] = \left(\frac{V_{sense}[V]}{I_{measured}[A]}\right) \quad (9a)$$

$$I_{Error}[\%] = \left(1 - \left|\frac{I_{measured} - I_{mag}}{I_{measured}}\right|\right) \cdot 100\% \quad (9b)$$

Case Study: High-Accuracy CST Performance

To illustrate a process of CST choice let's consider specification defined by automotive application (i.e. BMS). Project consist of measurement system with reference voltage V_{ref} of 15V to be used for current measurement. Estimated measured current (Peak-Value) is 29A under 200kHz with a duty cycle of 0,8 conditions. Mechanically, part cannot be bigger than 13mm x 11mm and must be lower than 8mm.

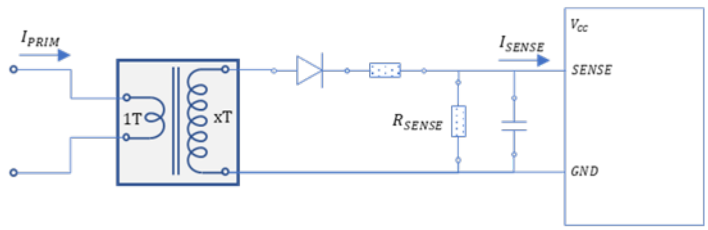


Fig. 7) Case study schematics

STEP 1: Choice of product series based on application safety requirements

An automotive application requires a CST with functional insulations. Mechanically, part maximum volume is limited by 13mm x 11mm x 8mm. Based on Fig. 5, we select CSFA product series and use http://www.yageogroup.com product selector for searching of suitable product range.

November 13th, 2025

Compare	Part Number	Stock	Series	Type	Style	Technology	Temp. Max.	Temp. Min.
☐	PMS9494.200NLT	2,146	CSFA	Current	SMD	AC Current	125°C	-40°C
☐	PMS9494.150NLT	2,233	CSFA	Current	SMD	AC Current	125°C	-40°C
☐	PMS9494.100NLT	2,116	CSFA	Current	SMD	AC Current	125°C	-40°C
☐	PMS9494.050NLT	2,134	CSFA	Current	SMD	AC Current	125°C	-40°C

Fig. 8) Screenshot of YAGEO Group Product Selection Tool

STEP 2: Choice of suitable part number.

The next step is to open datasheet to check detailed parameters of available product range. In this case, four turns rations are available.

SMT Current Sense Transformer

PMS9494.XXXNLT EE8 SMD Platform

Pulse a YAGEO company

- **Current Rating:** up to 30A
- **Footprint:** 13mm x 10.5mm x 7.2mm Max
- **Frequency Range:** 20kHz to 1MHz
- **Insulation:** Functional
- **Hipot Isolation:** 1200Vrms, 6 sec
- **Voltage Rating:** Up to 375Vpk

Electrical Specifications @ 25°C — Operating Temperature -40°C to +125°C						
Part Number	Turns Ratio ±1.50	Current² Rating (A)	Secondary Inductance (mH Min)	DCR Primary (8-7)(mΩ Max)	DCR Secondary (1-3)(Ω Max)	Hipot (V_{rms})
PMS9494.050NLT	50	30	0.55	0.35	0.66	1200
PMS9494.100NLT	100	30	2.2	0.35	3.3	1200
PMS9494.150NLT	150	30	5.0	0.35	8.2	1200
PMS9494.200NLT	200	30	9.0	0.35	14	1200

NOTES:

1. The temperature of component (ambient temperature plus temper-ature rise) must be within the specified operating temperature range.
2. The maximum current rating is based upon temperature rise of the component and represents the DC current which will cause a typical temperature rise of 40°C .
3. To calculate value of terminating resistor (Rt) use the following formula: Rt (W) = V_{REF} * N / (Ipeak_primary)
4. The peak flux density of the device must remain below 2200 Gauss. To calculate the peak flux density for uni-polar current use following formula: Bpk = 18.8* V_{REF} * (Duty_Cycle_Max) * 10^5 / (N * Freq_kHz) * for bi-polar current applications divide Bpk (as calculated above) by 2.
5. Rated voltage is based on a positive partial discharge test (discharge < 10pC) during the design phase (not production tested) for a 375V repetitive peak voltage (Urp). The test condition was with an extinction voltage, U2 = 1.1* Urp, after an inception voltage, U1 = 1.25*U2.

Fig. 9) Example of datasheet (Series CSFA- product range PMS9494)

To better understand, we calculate working point based (flux density *B*) according to Eq.5 based on our automotive application conditions: *Freq.* = 200kHz, V_{ref}=15V, $Duty_{Cycle}$=0.8. This equation is also specified in datasheet (Fig. 9, Notes, Pkt 4). Calculations can be systemized as in Table 2:

November 13th, 2025

Table 2. Calculations based on PMS9494.XXXNLT datasheet

N	$Duty_{Cycle}$	V_{ref}[V]	Freq[kHz]	I_{pk}[A]	B[Gauss]	R_{sense}[Ohm]
50	0,8	15	200	29	2256	25,86207
100	0,8	15	200	29	1128	57,72414
150	0,8	15	200	29	752	77,58621
200	0,8	15	200	29	564	103,483

First product version with N=50 slightly can not be applied, as it exceeds the suggested by producer limit of B=2200Gauss. However all 3 other variants of product could be applicable, for flexibility, the best choice will be part with Turn-Ratio of 1:100 offered by part: PMS9494.100NLT, because the B value is middle of the recommended flux density. This gives flexibility for wider switching frequency range or overcurrent.

As next, based on peak current value specified in application, terminating resistor can be calculated and noted in Table 2. From formula (Eq. 6)

$$R_T = \frac{V_{ref} \cdot N}{I_{pk}} \qquad R_T = \frac{(15V \cdot 100)}{29A} = 51,72[Ohm]$$

we determine the value of 50[Ohm] – nearest to calculated result in the Table 2. for chosen part number. Value of DCR from Secondary winding is less than 10% of calculated RT, so we assume has no significant influence on phase shift.

Previous calculated values of B and RT allows us to calculate the amplitude error of the magnetizing current:

$$I_{mag} = \frac{\left(\frac{V_{sense}}{N} . duty_{cycle}\right)}{L_m[mH] \cdot Freq_{kHz}}$$

$$I_{mag} = \frac{\left(\left(\frac{14,5}{100}\right) \cdot 0,8\right)}{2,2 \cdot 200} = 0,28mA$$

This part of current is will not be measured in the system.

$$I_{Error}[\%] = \left(1 - \left|\frac{I_{measured} - I_{mag}}{I_{measured}}\right|\right) \cdot 100\% \qquad I_{Error}[\%] = \left(1 - \left|\frac{29 - 0,0028}{29}\right|\right)$$

100%=0,00154%

November 13th, 2025

Based on simplified Eq. 8b phasor shift between measured current and resulted current value can be calculated:

$$\alpha[Deg]=atan(\frac{R_T}{2\cdot\pi\cdot Freq_{kHz}\cdot L[mH]})$$

$$\alpha[Deg]=atan\left(\frac{50[Ohm]}{2\cdot\pi\cdot 200[kHz]\cdot 2{,}2[mH]}\right)=atan\left(\frac{50[Ohm]}{2763[Ohm]}\right)=atan(0{,}0181)=1{,}037^{o}$$

This value indicates a very low signal shift. Based on this value, measurement error can be estimated

$$Error_{\alpha}[\%]=(1-cos_{\alpha})\cdot 100\% = (1-0{,}99984)\cdot 100\% = 0{,}0164\%$$

In this configuration, the measurement error is only 0.0164% and demonstrates exceptional accuracy achievable with well-designed CSTs.

Sensitivity of selected part number under application requirements will be:

$$sensitivity[V/A]=\frac{V_{sens}[V]}{I_{prim}[A]}=\frac{I_{sens}[A]\cdot R_T[\Omega]}{I_{prim}[A]}=\frac{14.5[V]}{29[A]}=0.5[V/A]$$

$$Error_{sensitivity}[\%]=\frac{V_{sense}-V_{Ref}}{V_{Ref}}\cdot 100\%=\frac{(14.5-15)}{15}\cdot 100\% = 0{,}033\cdot 100\% = 3{,}3\%$$

Choice of terminating resistance influence sensitivity and sensitivity error.

Conclusion

YAGEO Group offers a wide range of current sensing solutions covering full frequency range. Into this group belongs Current Sense transformer solutions branded by YAGEO Group, that can be applied into projects from most of market segments.

Current sense transformers uniquely combine accuracy, galvanic isolation, and low-loss operation, positioning them as the sensing technology of choice for high-frequency AC current measurement. With careful selection and design, CSTs empower engineers to meet stringent safety standards while delivering long-term reliability and efficiency in demanding applications such as SMPS, solar inverters, and industrial automation systems. Current Sensor measurement errors are very low, however its design-in requires a proper adjustment into measurement system.

As the drive toward energy efficiency accelerates, CSTs will continue to play a vital role in enabling next-generation power systems. It is worth to mention, that CST method characterize lowest measurement error (compare to shunts and Rogowski Coil) because low temperature rise (to be neglected influence of eddy currents) and no influence of external EM field or EMI signals (fully shielded). From same reason can be shown, that energy dissipation is much lower than using shunts.

Key Takeaway: Current Sense Transformers enable high-precision, isolated, and efficient current measurement, making them an essential technology for the future of power electronics.

References

[1] Current Sense Overview
[2] Current Sense Magnetics: How Does It Work?
[3] Colonel WM T. McLyman, Transformer and Inductor Design Handbook, CRC Press, 2017