

# THE FUNDAMENTALS OF CURRENT SENSE TRANSFORMER DESIGN

Patrick A. Cattermole, Senior Applications Engineer  
MMG  
10 Vansco Road, Toronto Ontario Canada

## Abstract

The following paper will first review the basic principles of operation of a Current Sense Transformer and then follow a simplified design procedure. The design procedure will take into account the effects of temperature and frequency and how they relate to the choice of a magnetic core.

## Introduction

Current sense transformers (CTs) are used in a variety of applications ranging from power management to precise current measurement in the automotive telecommunications, computer, industrial, consumer and medical industries. A current sense transformer is essentially a standard transformer whose primary is placed in series with a conductor carrying AC current. The secondary is usually terminated in a resistance and the voltage on the secondary is more or less proportional to the current in the primary. Some CTs are designed to produce a voltage output which accurately tracks the AC component of the current in the primary; a linear design. Others may be designed to merely produce a change in output for a significant change in input current so that a logic device or fault circuit may be triggered. This type would not be linear.

## Basic Principles of Operation

The equivalent circuit of a typical current transformer is shown in figure 1.

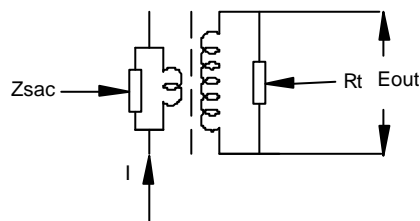


Figure 1

This standard design uses an accurate and specific resistive termination on the secondary. By transformer action, the loading effect of this resistance is transferred to the primary and appears as a shunt resistance across the primary. The parallel combination of this shunt resistance and the impedance of the primary winding form the impedance through which the current flows.

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Typically, the transformer is designed so that the impedance of the primary winding is much greater than the shunt resistance reflected into the primary side and thus the primary impedance is mostly resistive. This shunt resistance acts as a current viewing resistor for AC current and it is this AC voltage drop that gets transferred to the secondary. It is this AC shunt resistance that the circuit sees and it is relatively easy to keep its value very low so as to have minimal effect on the circuit.

Because of the isolation feature of the current sense transformer, it can be placed at any desired location in a circuit, including above ground, to monitor current there.

### Design Procedure

Typical starting points, or inputs, to the design process are the following:

- Primary turns ( $N_p$ )
- Sensitivity ( $S$ )
- Desired series AC impedance ( $Z_{sac}$ )
- Maximum current rating ( $I_{max}$ )
- Minimum frequency response ( $f_{min}$ )

Desired design results or outputs would include:

- Secondary turns ( $N_s$ )
- Secondary termination resistance ( $R_t$ )
- Minimum inductance factor ( $A_{Lmin}$ )

The suggested design steps using the inputs listed above are as follows:

1. The desired series AC impedance ( $Z_{sac}$ ) introduced into the circuit by the current transformer can be expressed in volts per ampere instead of ohms. Using this figure as the volts per ampere on the primary side of the transformer and using the desired sensitivity ( $S$ ) in volts per ampere at the secondary, the turns ratio ( $n$ ) is calculated.

$$n = \frac{S}{Z_{sac}}$$

2. Calculate secondary turns ( $N_s$ ) using the primary turns ( $N_p$ ) and the turns ratio.

$$N_s = n \cdot N_p$$

3. Calculate the secondary termination resistance ( $R_t$ ) using the turns ratio and the series AC impedance at the primary.

$$R_t = Z_{sac} \cdot n^2$$

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4. The minimum primary inductance required ( $L_p$ ) is a function of how accurate and linear the volts per ampere versus current transfer function of the transformer needs to be. A good rule of thumb for an accurate and linear transformer is to design for minimum primary inductance whose inductive reactance is 100 times the primary  $Z_{sac}$  at the minimum low frequency ( $f_{min}$ ) design point.

$$L_p \text{ min} = X_L (2p \cdot f_{min})$$

5. Calculate the required inductance factor to obtain the required primary inductance ( $L_p$ ) with the specified number of primary turns ( $N_p$ ).

$$A_L = \frac{L_p \text{ min}}{N_p^2}$$

### Design Example

Following is an example of a design using the above approach:

#### INPUT

Primary turns ( $N_p$ ) = 1

Sensitivity ( $S$ ) = 0.5 V/A

Series AC impedance ( $Z_{sac}$ ) = 0.005  $\Omega$

Maximum current rating ( $I_{max}$ ) = 5 A

Minimum frequency response ( $f_{min}$ ) = 20 kHz

#### OUTPUT

Secondary turns ( $N_s$ ) = 100

Secondary termination resistance ( $R_t$ ) = 50  $\Omega$

Minimum inductance factor ( $A_{Lmin}$ ) = 3981 nH/n<sup>2</sup>

### Choosing a Core

Quite often, a soft ferrite toroidal core is used for a current sense transformer. A core of surprisingly small cross section will be sufficient for current transformers handling multiple amperes at typical switch mode power frequencies. A toroidal core is well suited for a transformer with a single turn primary since it is desired to keep the primary to secondary coupling as good as possible. The toroidal core works well here because the secondary turns are completely surrounding the single primary conductor passing through the hole. Other shapes are also used, particularly at lower frequencies, where the required cross section is larger and higher numbers of both primary and secondary turns are used.

As seen in the equivalent circuit in Figure 1, the primary is in shunt across the primary side series AC impedance ( $Z_{sac}$ ). If the primary is only one turn, the inductance factor of the core needs to be relatively large to provide sufficient inductive reactance at the low frequency end of the passband. A toroidal shape is also efficient for this reason because the magnetic path length of a small toroid can be made small relative to the cross sectional area which will yield a high inductance factor per unit volume.

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A high permeability material is also desirable in achieving a high inductance factor. However, one also has to take into account the required operating temperature range of the transformer. The permeability of high permeability grade materials can drop significantly with decreasing temperature.

The required cross sectional area of the core is approached in essentially the same way as with any transformer. It is a function of the core material, the series AC impedance ( $Z_{sac}$ ) on the primary side, the maximum AC<sub>rms</sub> current the primary will see, and the number of primary turns. It will first be necessary to calculate the maximum voltage ( $E_p \text{ max}$ ) that will appear across the primary.

$$E_p \text{ max} = I_p \text{ max} \cdot Z_{sac}$$

For a sinusoidal AC current with no DC component, the formula relating primary voltage ( $E_p$ ), turns ( $N_p$ ), frequency ( $f$ ), and cross sectional area ( $A_e$ ) is:

$$E_p = 4.44 \cdot f \cdot N_p \cdot B_{peak} \cdot A_e \cdot 10^{-10}$$

Solving for  $A_e$ , we have:

$$A_e = \frac{E_p}{4.44 \cdot f \cdot N_p \cdot B_{peak} \cdot 10^{-10}}$$

As with any transformer, determining a suitable  $B_{peak}$  is a function of core material and the maximum operating temperature of the transformer, as well as core losses. It is suggested to keep the maximum peak flux density at no more than 50% of the saturation flux density of the material at a particular temperature.

### Designing for A DC Component

As with any transformer, if the current in the circuit into which the current sense transformer will be inserted has a DC component, it must be taken into account in the transformer design. The DC component of the current in the primary will produce a DC component of flux density in the core material. An equation for calculating the approximate value of the DC component of flux density is as follows:

$$B_{dc \text{ peak}} = \mu_e \cdot H_{dc \text{ peak}}$$

Where:

$$H_{dc} = \frac{4\mu \cdot N_p \cdot I_{dc \text{ peak}}}{l_e}$$

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The units are  $B$  in gauss,  $I$  in amperes,  $l_e$  (the magnetic path length of the core) in mm, and  $H$  in oersteds. This is only an approximation because the permeability of the core material will decrease as DC current increases.

The  $\mu_e$  in the  $B_{dc}$  formula above is the effective permeability of the magnetic circuit of the transformer. Of course, if an ungapped toroid core is used, the effective permeability is the permeability of the material. On the plus side, usually the primary of a current sense transformer has a small number of turns. Since  $H_{dc}$  is proportional to turns, this is desirable. A gapped ferrite core or powdered metal core may be required for situations with high DC components.

### Frequency Response

As has already been discussed, the low frequency rolloff of the transformer is a function of the primary inductance. A high inductance factor core is desired because of the low number of primary turns. As the inductive reactance of the primary decreases with decreasing frequency, it will effectively shunt an excessive amount of current away from the series AC current sense impedance as frequency decreases.

As for the high frequency rolloff of a current sense transformer, there are both positives and negatives to this type of design. On the positive side, coupling between primary and secondary is usually good, so leakage inductance is relatively low. On the negative side, the turns ratio of these transformers tends to be high which causes a relatively large shunt capacitance to appear across the primary. It is the distributed capacitance of the secondary winding reflected into the primary. The reflected capacitance varies with the square of the turns ratio.

$$C_p = C_s \cdot n^2$$

The larger the value of  $C_p$ , the lower the high frequency rolloff of the transformer. It begins to shunt current away from the  $Z_{sac}$  element as frequency goes up and reactance goes down.

### Transient or Pulse Response

The current sense transformer will respond adequately to pulse or transient type currents. Leakage inductance and shunt capacitance tend to deteriorate transient response. The leakage inductance of a toroidal unit using a high permeability core is relatively small. The shunt capacitance at the primary is not large except for very high turns ratios.

With a unipolar rectangular pulse of current applied through the primary, a unipolar rectangular voltage pulse is developed across  $Z_{sac}$  and a calculation of the resulting flux density change ( $?B$ ) in the core material can be calculated on the basis of voltage.

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$$\Delta B = \frac{E_p \cdot \Delta T \cdot 10^4}{N_p \cdot A_e}$$

Where  $B$  is in gauss,  $E_p$  is in volts,  $T$  is in  $\mu\text{s}$ , and  $A_e$  is in  $\text{mm}^2$ .

Energy is stored in the magnetic field of the transformer when the pulse is applied. If there is an off time between pulses, that magnetic field collapses and the energy is returned to the circuit. However, in the case of most current sense transformers, the very low shunt resistance makes the discharge path highly over-damped and there is no significant voltage spike during energy discharge.

### Conclusions

With the ever expanding electronics universe, there will continue to be a push for the precise measuring of electric current for safety and control issues as well as a need for better device efficiency through power management solutions. Current sense transformers are essential components in these solutions. The design engineer needs to remain aware that there are many different types of CTs available using several different types of core materials from ferrite to iron powder to amorphous alloy. A simple design produce like the one demonstrated in this paper can aide in the design process and increase the speed at which new solutions are brought to the marketplace.