

Burden Resistor Selection in Current Transformers for Low Power Applications

A. Conesa-Roca, R. Bargalló-Perpiñà¹, G. Velasco-Quesada, M. Román-Lumbreras

Electronic Department, EUETIB (CEIB), UPC, Barcelone, Spain

¹Electric Department, EUETIB (CEIB), UPC, Barcelone, Spain

Abstract—In order to sense AC current with electric isolation in high frequency switching power converters the most simple and low cost solution is to consider a current transformer with a burden resistor. But burden resistor selection is not a simple task because involves a lot of considerations that affect the output voltage and its signal-to-noise ratio and the bandwidth of the measure. In this paper, considering the basic equations of the transformer and applying the Laplace Transformation is obtained a simple model of the current transformer interesting to select burden resistor and even to design the current transformer in case of high frequency applications.

Index Terms—Current measurement, current transformer, burden resistor.

I. INTRODUCTION

CURRENT transformers (CT) are wide used components especially in power switched electronics converters [1]. These electronics systems need cheap solutions due to its extended use in the global world market, especially on rang of low power (less than 1 kW).

In order to sense AC current without DC component in a converter with electric isolating the most simple and low cost solutions is to consider a current transformer with a burden resistor. Other solutions considering current transformers are the use of current to voltage circuits based on operational amplifiers or especially dedicated integrated circuits. These solutions increase the complexity and cost of the electronic system, and can be considered when its use is justified by the application. However, considering the simplicity and low cost of the CT, there are contributions on bibliography in order to achieve AC+DC current measurement on the 1 kW range [2].

Burden resistor selection in current transformer circuit is not a simple task because involve a lot of considerations. Selection of burden resistor affects to the current measure in the signal-to-noise ratio and in the bandwidth [3] [4].

For a proper choice of this resistor it is necessary to model properly the current transformer and identify its intrinsic components. Then select the optimum burden resistor adequate to the application [5].

Often the current transformer manufacturers in its datasheet

present only a few of specifications [6]. Unfortunately most of these specifications are mechanical specifications and manufacturers only include as electrical specifications the narrow bandwidth of the measure and a value of burden resistor. Some datasheets only include mechanical specifications.

In this paper, a simple model of the component is obtained by considering the equations of the current transformer. Whith this model is analyzed the influence of the burden resistor and how to select a proper choice of this component to improve the signal-to-noise ratio of the measure with respect to the bandwidth of the measure. Furthermore a design pattern is obtained from the model in case of high frequency current transformers.

II. CURRENT TRANSFORMER MODEL

A. Review Stage

In Figure 1 the well know circuital model of the transformer is presented. In current transformer case the primary turn number is only one turn or a few of these. Then, it is usually to consider the intrinsic cooper resistance of the primary bound zero ($R_p=0 \Omega$). The most important components of the model, not considering the core specifications and characteristics, are going to be addressed to the secondary bound.

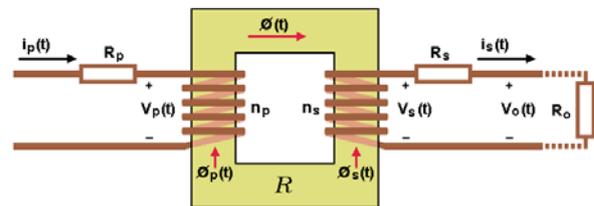


Fig. 1. Components of the current transformer.

The following equations (1) and (2) are obtained from the model, using Faraday's law and Ampere's law.

$$\phi(t) \cdot \mathcal{R} = n_p \cdot i_p(t) - n_s \cdot i_s(t) \quad (1)$$

$$v_s(t) = n_s \cdot \frac{d\phi(t)}{dt} \tag{2}$$

On the secondary circuit, applying KLV is obtained

$$v_s(t) = (R_s + R_o) \cdot i_s(t) \tag{3}$$

Introducing (3) and (1) in (2) is obtained

$$(R_s + R_o) \cdot i_s(t) + \frac{n_s^2}{\mathfrak{R}} \cdot \frac{di_s(t)}{dt} = \frac{n_s \cdot n_p}{\mathfrak{R}} \cdot \frac{di_p(t)}{dt} \tag{4}$$

Applying Laplace transformation in (4) is obtained

$$I_s \cdot \left(\frac{n_s^2}{\mathfrak{R}} \cdot s + R_s + R_o \right) = \frac{n_s \cdot n_p}{\mathfrak{R}} \cdot s \cdot I_p$$

Then, the secondary current versus primary current is

$$\frac{I_s}{I_p} = \frac{\frac{n_s \cdot n_p}{\mathfrak{R}} \cdot s}{\frac{n_s^2}{\mathfrak{R}} \cdot s + R_s + R_o} \tag{5}$$

Arranging (5) is obtained

$$\frac{I_s}{I_p} = \frac{n_p}{n_s} \cdot \frac{\frac{s}{\omega_o}}{\frac{s}{\omega_o} + 1} \tag{6}$$

being

$$\omega_o = \frac{R_s + R_o}{\frac{n_s^2}{\mathfrak{R}}} = \frac{R_s + R_o}{L_s} \tag{7}$$

The asymptotic representation of relation (6) versus frequency is depicted in Figure 2. The representation corresponds with the canonical response of first order high-pass filter, being ω_o the cut-off angular frequency (in rads/s).

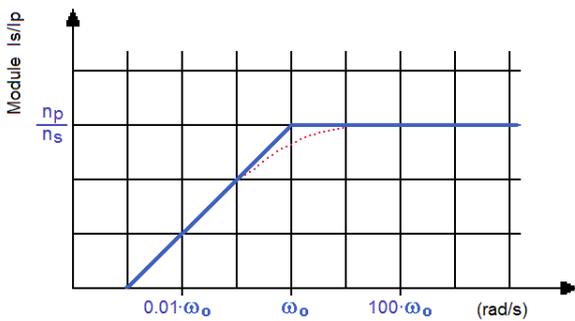


Fig. 2. Asymptotic representation of the relation between secondary and primary current versus frequency.

The frequency range of interest is above ω_o when it holds the well know relation of the current transformer

$$\frac{I_s}{I_p} = \frac{n_p}{n_s}$$

It is important to remark that ω_o establishes the minimum

frequency component of the current to sense or measure, and this frequency value is function of the burden resistor R_o as confirm (7).

The maximum frequency component of the current to sense will be conditioned by the core characteristics and the intrinsic capacitance resulting in the secondary bound. The bandwidth of the measure become establish between the cut-off frequency f_o (in Hz)

$$f_o = \frac{\omega_o}{2\pi}$$

and the frequency limitations introduced by the core and capacitance of the secondary bound.

From equation (7) the cut-off angular frequency ω_o depends on the burden resistor R_o and the inductance L_s and resistance R_s of the secondary bound. The value of L_s and R_s are easy to find in laboratory with a simple LC meter.

The output voltage on the burden resistor R_o in Laplace form is

$$V_o = R_o \cdot I_s$$

Introducing equation (6) it is easy to obtain the output voltage versus primary current:

$$\frac{V_o}{I_p} = R_o \cdot \frac{n_p}{n_s} \cdot \frac{\frac{s}{\omega_o}}{\frac{s}{\omega_o} + 1} \tag{8}$$

The asymptotic representation of relation (8) versus frequency is depicted in Figure 3 for several cut-off angular frequencies. The canonical response is similar to the Figure 2.

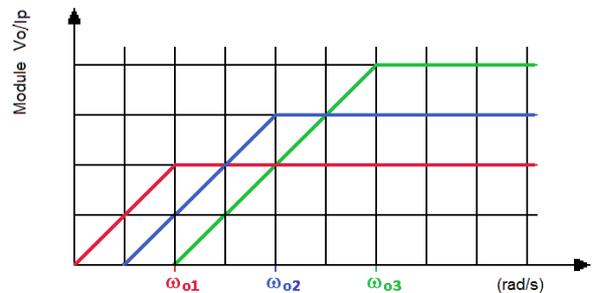


Fig. 3. Asymptotic representation of the relation between output voltage and primary current versus frequency.

As the burden resistor value R_o increases the output voltage value increases, but the bandwidth of the measure decreases. This presents a trade-off solution of design. A high level of output voltage will perform a better signal-to-noise ratio of the measure. The typical kind of applications considered are power switched converters, who are inherent noise electronic circuits due to the high level of electromagnetic emissions. From this point of view, it will be of interest to increase the R_o value. Nevertheless, the circuit of measure must guarantee the desired bandwidth, and now will be of interest to decrease the R_o value.

All these analysis are considering the reluctance of the core

a constant value. In other words, the flux density in the core is below saturation value.

Another important consideration is the response of the core flux with respect to the primary current. Applying Laplace transformation to equation (1) and introducing equation (6) is obtained

$$\frac{\phi}{I_p} = \frac{n_p}{\mathfrak{R}} \cdot \frac{1}{\frac{s}{\omega_o} + 1} \quad (9)$$

The asymptotic representation of relation (9) versus frequency is depicted in Figure 4. The representation corresponds with the canonical response of first order low-pass filter.

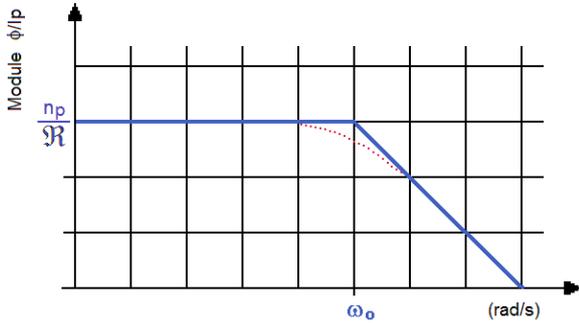


Fig. 4. Asymptotic representation of the relation between core flux and primary current versus frequency.

The worst case for the flux core is when secondary current is zero as can be deduced from equation (1). From equation (9) is possible to conclude the simple design consideration of the core that must satisfy for low frequencies cases ($s \ll \omega_o$)

$$\frac{\phi_{Sat}}{A_{core}} > \frac{\phi_{max}}{A_{core}} = \frac{n_p}{\mathfrak{R}} \cdot \frac{I_{p,max}}{A_{core}} \quad (10)$$

being $I_{p,max}$ the peak primary current and A_{core} the section of the ferromagnetic core of transformer. The reluctance of the core can be obtained from the secondary inductance L_s and turn ratio of the transformer n ($n = n_p/n_s$).

Arranging equation (10) is obtained

$$B_{Sat} > \frac{n_p}{\mathfrak{R}} \cdot \frac{I_{p,max}}{A_{core}}$$

and finally, the core must hold (11) for a peak maximum primary current and number of primary turns (usually one).

$$l_e > \frac{\mu_{core}}{B_{Sat}} \cdot n_p I_{p,max} \quad (11)$$

III. EXPERIMENTAL VERIFICATION OF THE MODEL

In order to verify the model several current transformers have been tested. The experimental set-up consists in a primary current of 0.2 A peak to peak of the desired frequency.

The first component is the PREMO CF-200. Its component

values are: secondary resistance $R_s = 4.5 \Omega$, secondary inductance $L_s = 94.5 \text{ mH}$ and turn ratio $n = 1/200$ (n_p/n_s). These values are obtained from the manufacturer datasheet, and verified in laboratory by low-cost instruments. The manufacturer not recommends any value of burden resistor for this part number.

Figure 5 shows the Matlab plot obtained from the model considering the following burden resistors: 10 Ω (red line), 27 Ω (blue line), 100 Ω (green line) and 1 k Ω (black line). Figure includes as dot points the experimental results obtained at the selected frequencies of 50 Hz, 100 Hz and 200 Hz for each burden resistor.

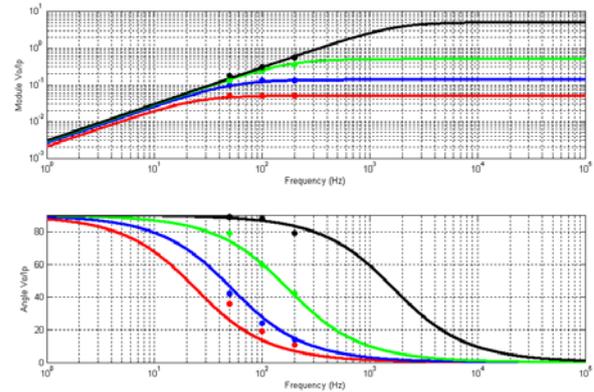


Fig. 5. Plot representation for PREMO CF-200 current transformer and experimental verification.

The error between the plot based on equation (8) and the experimental values are small. The results corroborate the accuracy of the model.

The second component is the PREMO CWL-0601 A2. The only component obtained from the datasheet of manufacturer is the turn ratio $n = 1/2500$ (n_p/n_s). The secondary resistance $R_s = 137 \Omega$ and secondary inductance $L_s = 70 \text{ H}$ has been obtained in laboratory by low-cost instruments. The manufacturer presents on the datasheet the value of 12.5 Ω as burden resistor not indicating if this value is recommended value, minimum or maximum value.

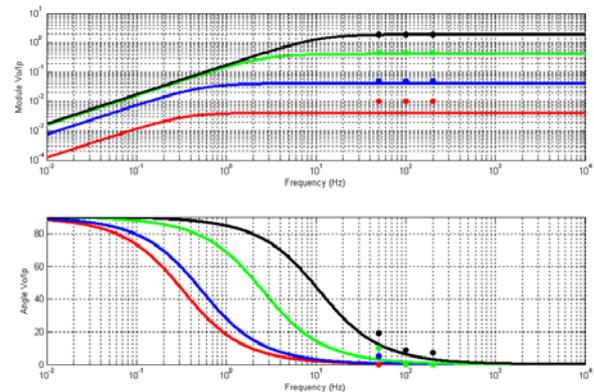


Fig. 6. Plot representation for PREMO CWL-0601 A2 current transformer and experimental verification.

Figure 6 shows the Matlab plot obtained from the model considering the following burden resistors: 10 Ω (red line), 100 Ω (blue line), 1 k Ω (green line) and 4.7 k Ω (black line). Figure includes as dot points the experimental results obtained at the selected frequencies of 50 Hz, 100 Hz and 200 Hz for each burden resistor.

The error between the plot obtained based on equation (8) and the experimental values are small. Note that some important values of the component have been obtained with low-cost instrumental, and, despite this, the error remains small.

From figure 6 also it can be deduced that the burden resistor 'recommended' by the manufacturer is not the ideal value. For example, with a 100 Ω resistor, the current measure in volts at the output will be ten times higher. This modification improves the SNR of the measure and not penalize with significant delay on measurement.

The third component is an unknown solenoid based on laminated iron core. In laboratory are determined the values: $R_s=1100 \Omega$, $L_s=7 \text{ H}$ and $n=1/1000$.

Figure 7 shows the Matlab plot obtained from the model considering the following burden resistors: 10 Ω (red line), 100 Ω (blue line), 1 k Ω (green line) and 4.7 k Ω (black line). Figure includes as dot points the experimental results obtained at the selected frequencies of 50 Hz, 100 Hz and 200 Hz for each burden resistor.

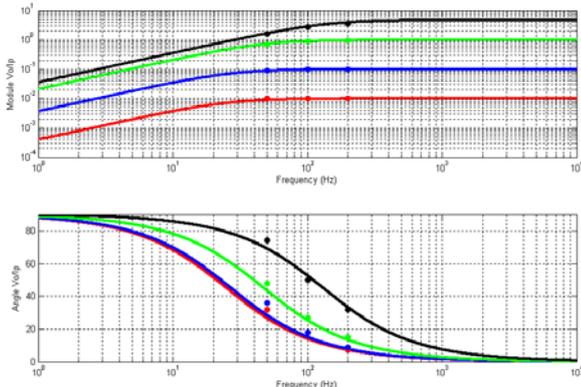


Fig. 7. Plot representation for the current transformer based on iron solenoid and experimental verification.

Again the experimental values agree with the model of equation (8).

The last component considered is a homemade in lab current transformer based on a high frequency ferrite toroid of Ferroxcube TN16/9.6/6.3 with 3E25 material. Its components measured by low-cost instrumentation are: $R_s=0.3 \Omega$, $L_s=3.5 \text{ mH}$ and $n=1/29$.

Figure 8 shows the Matlab plot obtained from the model considering the following burden resistors: 10 Ω (red line), 100 Ω (blue line), 1 k Ω (green line) and 4.7 k Ω (black line). Figure includes as dot points the experimental results obtained at the selected frequencies of 50 kHz, 100 kHz and 200 kHz for each burden resistor.

As expected the results between model (equation 8) and

experimental values are close.

From the analysis is possible to optimize the output value of the output voltage selecting the proper burden resistor. The designer only must know the minimum frequency of the desired current measure, the peak value of the primary current and to characterize the current transformer. Also the designer can establish from plot information the gain and phase delay of the measure.

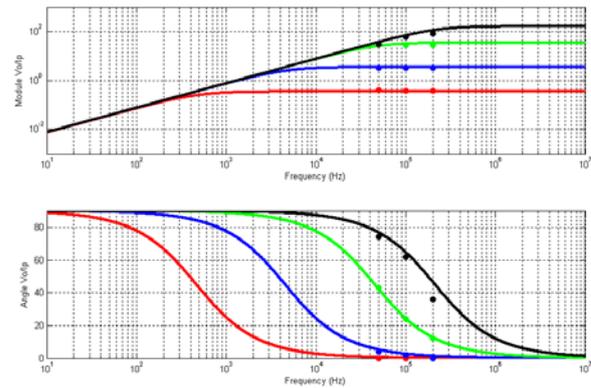


Fig. 8. Plot representation for the current transformer based on high frequency ferrite toroid and experimental verification.

A. Design considerations

Consider design case of low power and low cost switching power converters. The design of homemade in laboratory current transformer in high frequency range (from 20 kHz to 200 kHz) is usual for switching converters designers.

In this case, the cut-off angular frequency ω_o of the current transformer to design is large enough to consider a small value of secondary inductance L_s . Then the resistance of the secondary circuit ($R_s + R_o$) is mainly influenced by burden resistor R_o because resistance R_s of secondary bound is negligible due to is typically small number of turns and dimensions. Arranging properly equation (7) is obtained

$$\omega_o = R_o \frac{\Re}{n_s} \quad (12)$$

In the same way with equation (8) in the adequate frequency range is obtained:

$$\left| \frac{V_o}{I_p} \right| = R_o \cdot \frac{n_p}{n_s} \quad (13)$$

The two start values to develop the current transformer design are the peak primary current and the minimum frequency of measure. Around this frequency value will be establish the cut-off frequency ω_o depending of the accepted delay on the measure. Also the frequency range of measure will be important on the selection of the core material. The peak primary current value I_p influences the choice and dimensions of the toroidal core (equation 11). Also the current value must be considered to select a suitable V_o/I_p gain or module depending of the signal value and signal-to-noise ratio

desired.

Then the proper steps to design the current transformer are:

- 1) Selection of a proper core that satisfies equation (11).
- 2) Obtain the reluctance of the core.
- 3) With equations (12) and (13) to calculate the burden resistor R_o and the secondary turns n_s . When primary turns n_p is 1, this is the simplest case and mainly implemented in design, but n_p can be else others values.

From the proposed analysis of the current transformer is easy to analyze and calculate a component of high-frequency and low-cost.

IV. CONCLUSION

In a design context focused to simplicity, low cost and electric isolating, solutions considering current measure with a current transformer and a simple burden resistor can be a good choice. Applying Laplace Transformation to the classical equations of the transformer it is easy to obtain a simple model of the current transformer based on easy to obtain circuital components. The analysis is based on the plot of the model versus frequency. This model has been verified with commercial current transformers. This model helps the designer to select a proper burden resistor on the design and even to design the current transformer in case of high frequency applications.

REFERENCES

- [1] Philip T. Krein, *Elements of Power Electronics*, New York: Oxford University Press, 1998, pag. 562-565.
- [2] Michael Hartmann, Juergen Biela, Hans Ertl, and Johann W. Kolar, "Wideband Current Transducer for Measuring AC Signals With Limited DC Offset", *IEEE Transactions On Power Electronics*, vol. 24, no. 7, July 2009.
- [3] Stig Munk-Nielsen, Flemming Buus Bendixen, Hans Christiansen, "Characterization of 50/60 Hz current transformers from 20 Hz to 10 kHz", *IEEE SPEEDAM 2006, International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, Taormina, Sicily, Italy, 23-26 May, 2006.
- [4] G. Fernqvist, P. Dreesen, G. Hudson, J. Pickering, "Characteristics of Burden Resistors for High-Precision DC Current Transducers", *IEEE Proceedings of Particle Accelerator Conference 2007 (PAC07)*, Albuquerque, New Mexico, USA, 25-29 June 2007.
- [5] Predrag Pejovic and Dragan Stankovic, "Transient Analysis of Compensated Hall-effect Current Transducers", *IEEE Proceedings 21st International Conference on Microelectronics (MIEL'97)*, vol.2, Nis, Yugoslavia, 14-17 September, 1997.
- [6] Premo (2013). Datasheet of the AC-current transformers. [Online]. Available: <https://www.grupopremo.com/es>