Using Current Transformer In Core Saturating Mode Enables DC Current Measurements

by Viktor Vogman, Power Conversion Consulting, Olympia, Wash.

Many power distribution networks have requirements for galvanic isolation between their power delivery paths and control circuits. Such isolation is required to conform to safety regulations and to prevent control circuitry malfunction due to noise coupling.

Current transformers (CTs) in which the primary and secondary windings are not electrically connected are considered among the most effective isolated current sensors and can measure up to thousands of amperes. Besides providing immunity to common-mode noise and low power dissipation, the CT-based sensor has another important benefit. Being a passive component, a CT does not require the usage of separate converters supplying isolated dc voltage to power up the sensor input circuitry.

Normally, CT-based current sensors are only intended for monitoring of ac or pulsing currents with zero minimum levels. However, utilizing the transformer's saturation mode and a special technique for detection of the dc component can expand CT-based sensor usage to enable dc current monitoring, for example, in dc output power supplies or dc PDN applications. This article studies an opportunity for adopting such a technique and presents design considerations for CT-based dc current monitoring.

How A DC Component Can Be Transmitted Via Isolating Transformer

Because any transformer needs an alternating current to create a changing magnetic flux in its core, only a varying component of a pulsing (peak-to-peak) current waveform can be captured by a conventional CT-type sensor. For ac current waveforms or pulsing waveforms with a minimum level of zero such sensors provide current readings with a given accuracy. However, ac current waveforms with dc offsets or pulsing currents with minimum levels other than zero, such as forward or push-pull converter inductor current in continuous-conduction mode, would be reflected onto the CT secondary without their dc components.[1]

The reason for this effect is that the dc current flowing in the CT primary winding does not generate a time-varying magnetic field in the core and therefore does not produce any electromotive force across the CT secondary winding. One of the ways to extract a signal that contains the dc current level data is using an external excitation evolving in time and forming a certain CT transient response that enables the dc level reconstruction.[2]

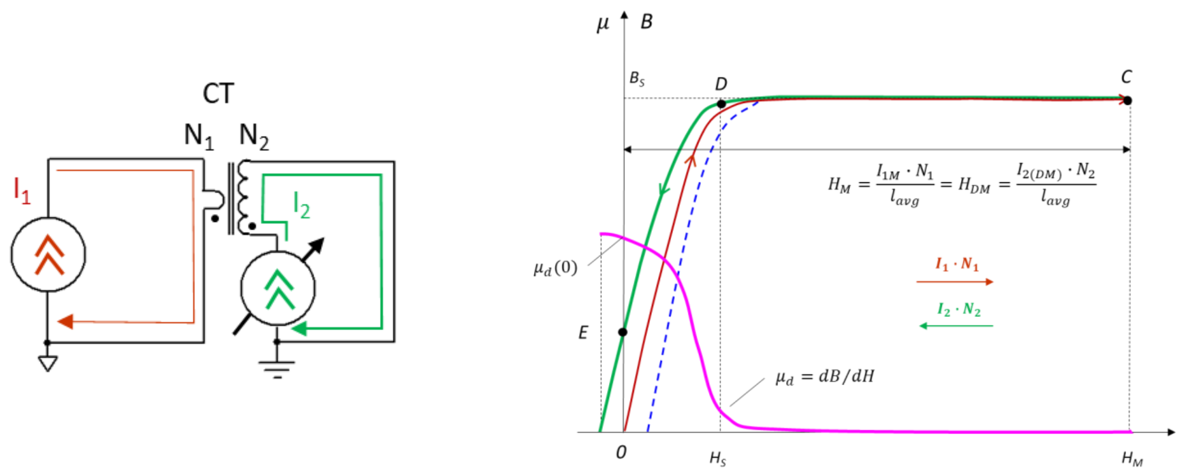
This study has two goals. One is to come up with a waveshape for an excitation signal that is able to drive CT core flux changes in a way that permits the extraction of the primary's dc current component. The other goal is to determine how the obtained secondary-side signal needs to be processed so that the dc current level in the primary winding can be reconstructed with high accuracy.

The Method

Transformer Core Operating Point

The proposed method is based on the ability of ferromagnetic materials, such as ferrites, to saturate at comparatively low magnetic fields. When a CT magnetic core made from such material gets magnetized and demagnetized, the core operating point follows the magnetizing B-H curve, representing the graph plotted between magnetic flux density (B) and magnetizing force (H).

Let's assume that in our case a dc current I_{1M} flowing through the primary CT winding (Fig. 1a) creates a magnetizing force that makes the operating point follow the initial magnetizing process (brown line in Fig. 1b) and shifts it far into the saturation area of the magnetizing curve (point C in Fig. 1b). The drift direction of the operating point is shown with brown arrows in Fig. 1b.



(a) *(b)*

Fig. 1. Demagnetization of the CT core, saturated by primary dc current I_1, can be provided through its secondary winding with a smaller current I_2 (a). In this process, the operating point of the CT core follows the upper branch (green curve) of the hysteresis (b). The magenta curve represents the core permeability. The dashed blue curve shows the first quadrant portion of the magnetizing trajectory for a case when the demagnetizing force applied on the secondary side exceeds the primary magnetizing force.

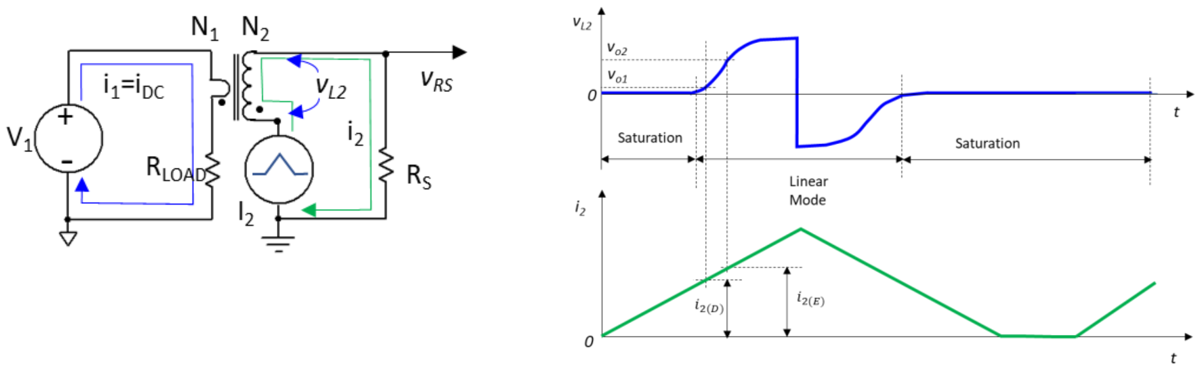
If the magnetizing force gets reduced to a level below the one corresponding to the saturation magnetic field intensity H_S, the operating point following the upper branch of the hysteresis (green line in Fig. 1b) enters the linear region of the magnetization curve (point D in Fig. 1b) and eventually, when the magnetizing force reaches zero, appears at the residual flux density point E.

Core demagnetizing can be provided not just by reducing the magnetizing current I_1 in the primary winding, but also by injecting a current I_2 creating magnetic flux in the opposite direction of the original magnetic flux, i.e. flowing into the dot end of the other winding placed on the same core (Fig. 1a). If the demagnetizing force is applied via the secondary CT winding, as shown in Fig. 1a, the current required for demagnetizing of the CT core $I_{2(DM)}$ and bringing the operating point to position E depends on the turns ratio and at $N_2 >> N_1$ can be much lower than the dc current in the primary winding:

$$I_{2(DM)} = I_{1M} \cdot N_1 / N_2$$

where N_1 and N_2 are numbers of turns in the primary and secondary windings (usually in CTs $N_1 = 1$). However, dc currents flowing through the primary and secondary transformer windings do not generate any meaningful signals across them, except for negligible dc voltage drops. For producing indicative signal levels across the CT winding the flux needs to vary at a sufficient rate.

Let's consider the circuit with a more practical value (see Fig. 2) in which dc voltage source V_1 supplies power to the load R_{LOAD}, and the dc current source on the secondary side is replaced with a source forming a cyclic sawtooth current signal. Similar to the circuit in Fig. 1, in this network a voltage source V_1 creates a dc current flow through the primary CT winding and load resistor R_{LOAD}, but in the diagram shown in Fig. 2a the current source injects a linearly varying demagnetizing current into the CT secondary winding.



(a) (b)

Fig. 2. Demagnetizing CT core with linearly varying current (a) and voltage and current timing diagrams (b). Injecting a linearly ramping current into the secondary CT winding enables detection of the demagnetizing current levels corresponding to points D and E on the magnetizing curve in Fig. 1b.

If a linearly ramping current i_2 of sufficient magnitude ($I_{2DM} > I_1N_1/N_2$) gets cyclically injected into the CT secondary winding (Fig. 2) the core magnetic field intensity will also vary periodically passing the H_S level (point D in Fig. 1b) and reaching zero (point E in Fig. 1b). The voltage across the winding can be expressed as follows:

$$v_{L2} = \frac{d\Phi}{dt} = \frac{d\Phi}{di}\frac{di}{dt} = L_2(i)\frac{di}{dt}$$

where Φ is magnetic flux, and L(i) is the secondary winding inductance. Substituting into the above equation expressions for Φ:

$$\Phi(t) = B(t)N_2A$$

where A is cross-sectional area, and for current as a function of magnetic field intensity:

$$i(t) = \frac{H(t)l_{avg}}{N_2}$$

where l_{avg} is the average magnetic line length.

Now we can write the following equation for the voltage across the secondary winding:

$$v_{L2} = \frac{N_2^2A}{l_{avg}}\frac{dB}{dH}\frac{di}{dt} = \frac{N_2^2A}{l_{avg}}\mu_d(H)\frac{di}{dt} \qquad (1)$$

where μ_d is the core dynamic permeability determined by the magnetizing curve slope: $\mu_d = dB/dH$.

The $\mu_d(H)$ curve is shown in Fig. 1b with the magenta line. As the magnetic field intensity drops, material relative permeability defined by the curve slope or by a derivative dB/dH increases which results in the inductance of the winding increasing. This phenomenon can be used to generate the required transient response, i.e. an indicative signal for current sampling when the operating point moving towards the y-axis exits the saturation region.

For specific core materials and a given current slew rate, the magnetizing curve can be modeled, for example, with a polynomial function which will produce an analytical equation for $\mu_d(H)$ and for the voltage across the secondary winding. With constant slew rate (linear ramp) the instantaneous voltage across the secondary winding will follow the $\mu_d(H)$ curve, under the assumption that the x-axis direction for demagnetizing current i_2 is reversed. The instantaneous voltage waveform is shown in the top diagram in Fig. 2b.

As it can be seen from the diagrams in Fig. 2b, the secondary current sequentially passes two levels corresponding to the operating point positions D and E (Fig. 1b). If any of these secondary current levels can be detected (sampled) the dc current flowing in the primary winding can be determined with good accuracy. Thus, the problem of detecting the primary dc current level reduces to measuring the secondary demagnetizing current bringing the core operating point to the position D or E.

Detecting The DC Current Level

Let's quantify the secondary current levels corresponding to operating point positions D and E on the magnetizing curve and examine if and how these levels can be detected. Dc current level I_1 creates a magnetic field intensity in the CT core H_M which can be expressed as follows:

$$H_M = \frac{I_1 \cdot N_1}{l_{avg}}$$

That is, initially the core operating point is positioned in the saturation region (point C in Fig. 1b) As the demagnetizing current (i_2) ramps up, the operating point (as in the static case) will be following the upper portion of the B-H curve sequentially passing positions D and E (Fig. 1b). For the point D position, we can write the following expression for the magnetic field intensity:

$$H_S = H_M - \frac{i_{2(D)} \cdot N_2}{l_{avg}} = \frac{I_1 \cdot N_1}{l_{avg}} - \frac{i_{2(D)} \cdot N_2}{l_{avg}} \qquad (2)$$

where $i_{2(D)}$ is demagnetizing current level at point D.

Equations (1) and (2) represent two ways of detecting the dc current level I_1. In the first case, the secondary current at point D $i_{2(D)}$ needs to be detected. This can be done by comparing the voltage across L_2 with some small offset voltage V_{o1}. This offset voltage can be determined by expression (1) with substitution of value $\mu_d(H)$ with the residual permeability $\mu_d(H_S)$ at the saturation field intensity. That is, for point D:

$$V_{o1} = v_{L2}(H = H_S) = \frac{N_2^2 A}{l_{avg}} \mu_d(H_S) \frac{di}{dt} \qquad (3)$$

In the second method, when the core operating point crosses the y-axis the magnetizing and demagnetizing forces are equal:

$$I_1 \cdot N_1 = i_{2(E)} \cdot N_2$$

and an equation for the voltage across the secondary winding reaching the second threshold V_{o2} can be derived from expression (1). That is, for point E,

$$V_{o2} = v_{L2}(H = 0) = \frac{N_2^2 A}{l_{avg}} \mu_d(0) \frac{di}{dt} \qquad (4)$$

where $\mu_d(0)$ is the permeability of the core material in point E (Fig. 1b).

Each of these cases is illustrated in Fig. 2b. The corresponding demagnetizing current levels can be detected by comparing V_{L2} with corresponding thresholds V_{o1} and V_{o2} determined by equations (3) and (4). That is, the demagnetizing current levels $i_{2(D)}$ and $i_{2(E)}$ must be sampled at the moment of crossing the corresponding thresholds, defined by equations (3) and (4), respectively.

Because magnetizing and demagnetizing forces at point E are equal, detecting the $v_{L2}(H = 0)$ level provides a straightforward dc current value reading. Deriving dc current value by detecting the $v_{L2}(H = H_S)$ level requires adding an offset to compensate the saturating magnetizing force, which will be determined below.

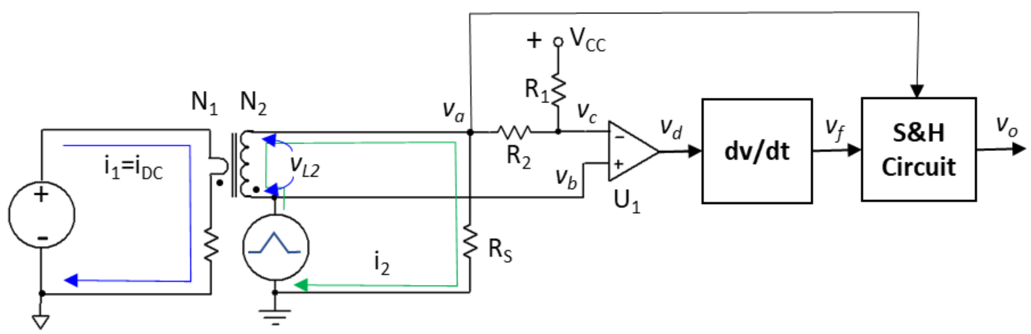
These two detection approaches will produce very close results when $H_S \ll H_M$. However, in the general case each of these detection methods has different areas of applicability. While detecting demagnetizing current at point E is applicable to typical nonlinear cases, detecting demagnetizing current at point D provides a more accurate result in a special linear case, when the B-H curve represents a piecewise linear function for which: $\mu_d(H_S) = \mu_d(0)$ and $V_{o1} = V_{o2}$.

Implementation

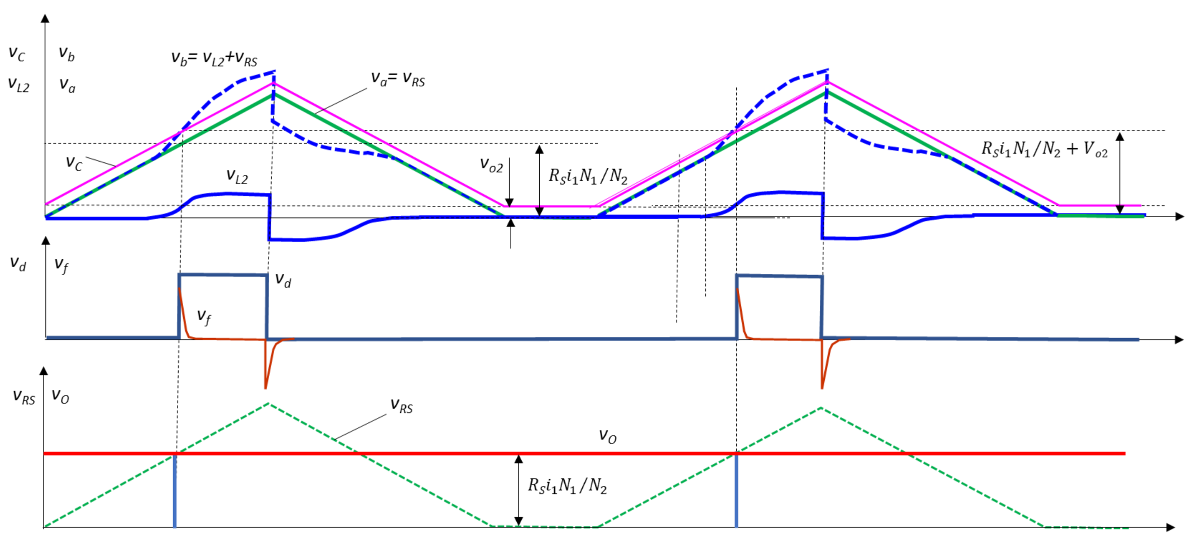
An example of a circuit implementing the described dc current sensing method is shown in Fig. 3a. The block diagram illustrates the process of forming an output proportional to the current flowing in the primary CT winding. This circuit realizes the detection of the core operating point crossing the y-axis ($i_{2(E)}$ level detection—

see Fig. 2b. In this arrangement, the offset voltage V_{o2} is generated across resistor R2 (R_2 and $R_1 >> R_S$). Comparator U1 compares this offset and a voltage across the secondary winding v_{L2}. This circuit provides the most accurate current detection because it uses a higher threshold (Eqn. 4) and the comparator self-offset and thermal drift have less impact on the detection accuracy.

When v_{L2} crosses the V_{o2} level, the comparator generates a voltage pulse. The formed pulse signal passes through a differential circuit, which controls the timing input of the sample-and-hold circuit. When this input is activated, a sample of the current ramp represented by the signal across R_S is taken which generates an output proportional to its analog input voltage V_a each time when ramping up current $i_2 = i_{2(E)}$ (Fig. 2b) and the comparator output switches from low level to high.



(a)



(b)

Fig. 3. A circuit implementing the described dc current sensing method (a) and timing diagrams illustrating its operation (b).

Fig. 3b is a set of diagrams that shows the signal waveforms at particular points in the functional block diagram in Fig. 3a. The top diagram shows the voltage across the secondary winding v_{L2} and voltage waveforms V_c and V_b at the comparator inputs relative to ground. The middle diagram shows the comparator and differentiator circuit signals, and the bottom diagram illustrates the process of sampling the ramp voltage $V_{RS} = V_a$ at the moments when magnetizing and demagnetizing forces become equal, and the detection of a ramp voltage level corresponding to the current in the primary CT winding. This output level matches the CT sensor output in conventional applications in which linear CT monitors pulsing current:

$$v_a = \frac{N_1}{N_2} \cdot I_1 R_S$$

For $i_{2(D)}$ (Fig. 2b) current detection, the circuit in Fig. 3a needs some minor modifications. The offset voltage needs to be reduced to the level V_{o1} defined by equation (3). Resistor R1 needs to be split into two—R_{1a} and R_{1b}—to create a dc bias compensating for the current corresponding to the H_S level:

$$V_{S.comp} = V_{R1b} = \frac{H_s l_{avg} R_S}{N_2} - V_{o1}$$

and the sample-and-hold circuit analog input must be moved to the split-resistor common point.

The core dimensions must be small enough to guarantee its transition into the saturation region with the lowest current level that needs to be detected. In the range below this boundary the CT will be operating in the linear mode and all the current levels will be reflected as zeros. To cover the full monitored current range the secondary current magnitude I_{2M} must be greater than the maximum dc current I_{1MAX} referred to the secondary side:

$$I_{2M} > I_{1MAX}\, N_1/N_2$$

Other circuit building blocks can be implemented in standard ways by using discrete or integrated components.

Future Work

Future work could be focused on the control optimization e.g. selecting a ramp rate and a duty cycle of the injected sawtooth current signal providing minimum power consumption. It could also be focused on developing an IC that includes all the building blocks processing the signals.

References

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About The Author

Viktor Vogman currently works at Power Conversion Consulting as an analog design engineer, specializing in the design of various power test tools for ac and dc power delivery applications. Prior to this, he spent over 20 years at Intel, focused on hardware engineering and power delivery architectures. Viktor obtained an MS degree in Radio Communication, Television and Multimedia Technology and a PhD in Power Electronics from the Saint Petersburg University of Telecommunications, Russia. Vogman holds over 50 U.S. and foreign patents and has authored over 20 articles on various aspects of power delivery and analog design.

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