IMPROVING AND SIMPLIFYING HF DC CURRENT SENSORS

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ABSTRACT

This paper presents a simple and economic circuit for implementing a transformer isolated DC current sensor. The sensor uses a unipolar drive signal that may have an operating frequency of 500 kHz or higher, resulting in fast transient response and a small magnetic element.

INTRODUCTION

Transformer isolated DC current sensors are widely used in power conversion equipment. The transformer isolation feature is often very helpful, particularly when high current or high voltages are present. A great variety of such circuits exist and in general their performance can be very good. There are however a number of drawbacks to the present circuits. Many of them require transformers with large turns ratios (1000 to 5000:1) particularly if large currents are to be measured. Given the practical limitations on minimum wire size, the high turns ratio results in relatively large and expensive magnetic elements. The large number of turns also introduces a great deal of winding capacitance. The winding capacitance and inductance combine to severely limit the operating frequency and hence the obtainable bandwith or response time. Typical DC current sensors have drive signal frequencies of a few kHz and bandwidth of a few hundred hertz.

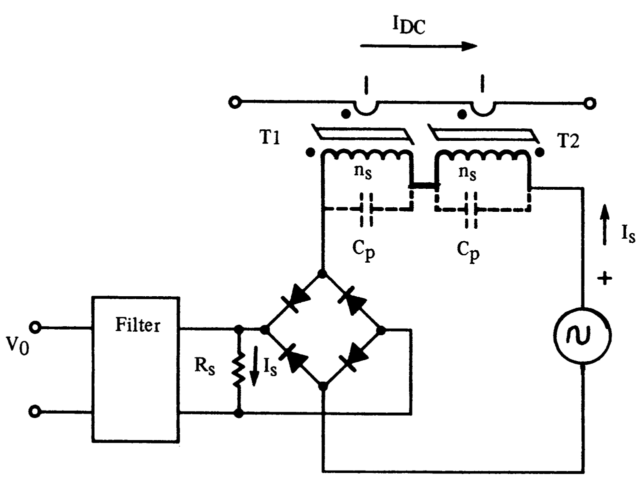

Figure 1, Typical transformer isolated current sensor.

REVIEW OF A CONVENTIONAL CURRENT SENSOR

Figure 1 shows a current sensor circuit which has been widely used for at least 60 years. The circuit was originally developed to measure both AC and DC on high voltage power lines.

The operating B-H loop is given in Figure 2 and a comparison of the flux excursion to the secondary voltages and currents is shown in Figure 3, for squarewave excitation.

Note that this sensor is bi-directional. If I_{DC} is reversed the roles of T_1 and T_2 invert.

Assuming for the moment that the diodes and windings are lossless, the power required to operate the sensor is simply:

$$P_s = \langle I_s \rangle V_o \qquad (1)$$

Where $\langle I_s \rangle$ is the average value for the secondary current (I_s) at full scale and Vo is the desired full scale output voltage.

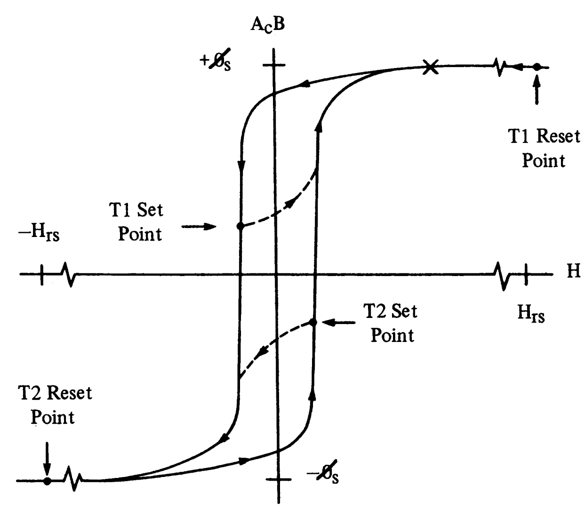

Figure 2, DC current sensor B-H loop

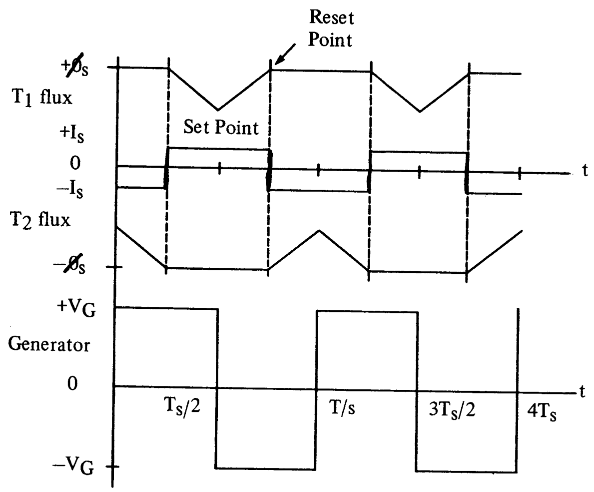

Figure 3, Core flux excursion for square-wave drive.

I_s can be found from the primary current (I_{DC}) and the turns ratio N_s:

$$I_s = \frac{I_{DC}}{N_s} \tag{2}$$

For sinewave excitation:

$$\langle I_s \rangle = \frac{.63\ I_{DC}}{N_s} \tag{3}$$

And for squarewave excitation:

$$\langle I_s \rangle = \frac{I_{DC}}{N_s} \tag{4}$$

Very frequently in instrumentation applications it is desirable that the current sensor consume as little power as possible. This is particularly important if the instrumentation is battery powered.

It would appear from equations (1) and (2) that I_s and P_s could be made arbitrarily small by simply making N_s large. The limits on this possibility can be shown by a simple example:

Suppose that:

$$I_{DC} = 100\text{A} \tag{5}$$

$$\langle I_s \rangle = 10\text{mA} \tag{6}$$

Then from equations (3) and (4)

$$N_s = 6{,}300{:}1 \text{ for sinewave excitation} \tag{7}$$

$$N_s = 10{,}000{:}1 \text{ for squarewave excitation} \tag{8}$$

Unfortunately, such a large number of turns is not usually practical unless a relatively large core is used, which runs the cost up. Another problem that arises from the large number of turns is the parasitic capacitance (C_D, Figure 1) of the windings. This capacitance limits the maximum generator frequency which leads to small bandwidths (or slow response times) and perhaps an increase in the core size. The filter component size will also increase.

With the advent of high frequency switching regulators, particularly those operating above 100 kHz, current sensors with response times of μs rather than ms are needed. If large turns ratios are required, the conventional sensors cannot respond quickly enough. Even if fast response is not needed the large size of the sensor transformer may not be in keeping with the reduced size of the power converter.

A HIGH FREQUENCY CURRENT SENSOR

Many of the problems of the conventional sensors at high frequencies can be overcome by using the circuit shown in Figure 4. The circuit shown is uni-directional. It can however be made bi-directional if desired.

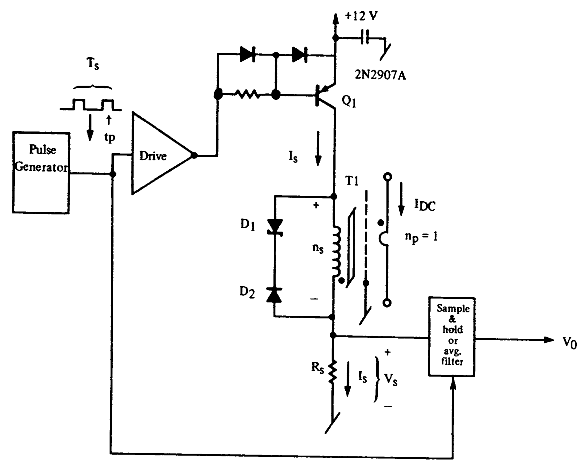

Figure 4, High frequency current sensor circuit.

The circuit functions as follows:

1. The pulse generator provides a train of narrow pulses at the operating frequency with a "high" duty cycle of 1 to 10%. For example, at 200 kHz the pulse width is .1 to .5 μs.

2. When the pulse is "low" Q_1 is off, the core of T_1 is held in hard saturation by I_{DC} as indicated by point A in Figure 5. The secondary current (I_s) is zero.

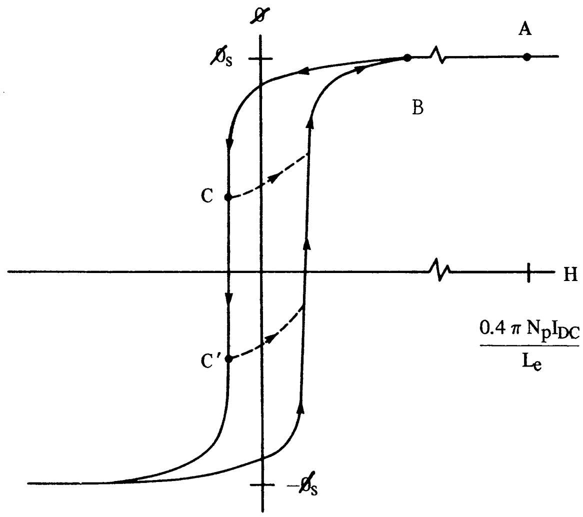

Figure 5, Operating B-H loop.

3. When the pulse switches to "high", Q_1 turns on, applying a positive potential across N_s as shown in Figure 4. This polarity of voltage pulls T_1 out of saturation and as shown in Figure 5, the flux follows the path A-B-C or C´. The proportion of available $\Delta ø$ is a design variable which will be discussed shortly.

4. During the transition from A to C or C´, T_1 acts as a current transformer where $I_S = I_{DC}/Ns$.

5. The current pulse (I_S) produces a voltage (V_S) across R which is sampled synchronously by the sample and hold circuit or if preferred may be simply averaged by an RC filter.

6. $$V_s = \frac{I_{DC} R}{Ns} \qquad (9)$$

7. When the pulse again goes "low" Q_1 turns off reducing I_S to zero. The core flux is at point C or C´.

8. At this point the core is reset by $I_{DC} N_p$ from point C or C´ back to point A. The reset voltage is limited by the clamp diode (D_1). The circuit is now ready for another cycle.

For sampling pulses of .1 µs a sampling rate of 1 MHz is practical. This means that current transients as fast as 10 µs can be reconstructed with reasonable fidelity and a sudden current overload could be detected in 1 to 2 µs.

The power consumption (P_S) for the circuit will be:

$$P_s = \frac{I^2_{DC} R t p}{N_s{}^2 T_s} \qquad (10)$$

Where tp is the on pulse width and T_S is the sampling period.

A typical example would be:

I_{DC} = 20A

N_s = 100T

tp = .25 µs

T_s = 5 µs

V_S = 5 V

R = 25Ω

P_S = 50 mW

Obviously the true total power would have to include the power for the integrated circuits. Fortunately a large variety of low power consumption ICs are available.

Note that N_S is small and in general can be kept small enough to allow operation at very high frequencies.

An experimental circuit operating at 200 kHz was built and the I_{DC} to V_S transfer function is shown in Figure 6.

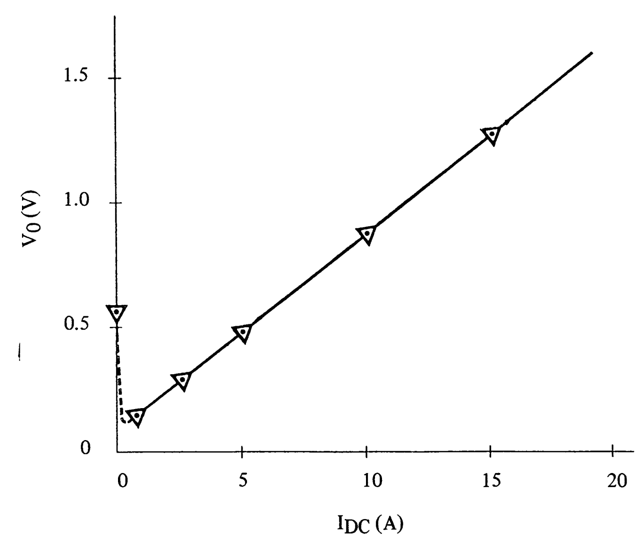

Figure 6, Typical current sensor response.

Down to about .05 Imax the linearity is quite good. Below .05 Imax the magnetizing current of N_S begins to cause an error. The test circuit used only a simple RC filter rather than the sample and hold. The sample and hold would improve both the accuracy and the linearity.

With R-C averaging the transient response is slowed markedly and the circuit has an accuracy of ± 3 to 4%, adequate for many applications. if an accuracy of $\pm 1\%$ or better is needed then the sample and hold circuit will be needed.

PRACTICAL CONSIDERATIONS

Any circuit has its limitations and idiosyncrasies, this one is certainly no exception.

N_S will have a finite magnetizing inductance (Lm) and parasitic capacitance (C_S) as shown in Figure 7A. The effect of C_S is to generate a spike on the leading edge of the current pulse as shown in 7B. C_S may be minimized by minimizing N_S and by winding the turns on in a single pass with a gap between the ends. The effect of the spike can also be minimized by delaying the sampling towards the middle of the pulse.

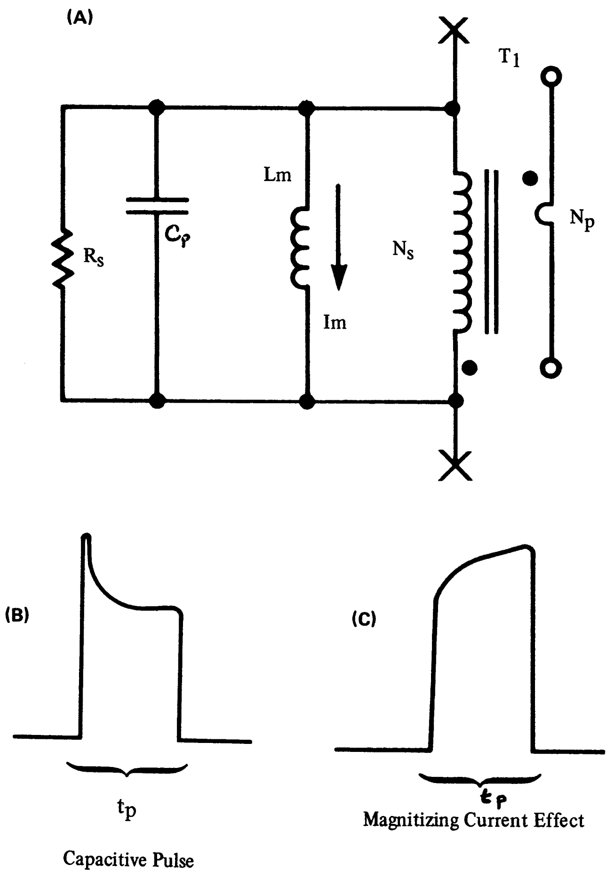

Figure 7, Parasitic components and pulse effects.

The magnetizing current (Im) adds to the desired current pulse causing an error in V_S. Im may be minimized by use of a core material with a high pulse permeability such as mag-Inc 1/8 mil permalloy 80 or a pulse ferrite material such as TDK H5B2 or mag-Inc J material. N_S should be made as large as possible, consistent with an acceptable value for C_S. A bit of cut and try usually converges quickly on an acceptable compromise. However, as shown in Figure 6 at some low current Im will begin to dominate and create error. A minimum diameter core will also be helpful in reducing Im.

In pulse applications, the full catalogue value for $\Delta \phi$ will often not be attainable. For this reason and well known temperature effects, it is best to restrict the flux excursion (points C or C´) to 50% or less of the theoretically available $\Delta\phi$. This will seldom cause the core size to increase unacceptably.

The core material chosen should have reasonably low losses at the operating frequency. The core losses will add a shunt resistance (R_S) which can add an error current to the desired pulse current. This can be particularly noticeable at very low or very high temperatures where the core losses increase. This is another reason to restrict the flux excursion.

If a simple RC filter is used on the output, variations in T_S, tp and the rise and fall times of the pulse will become noticeable because all of these parameters effect the average value of V_S. In very high frequency applications these parameters may not be easily controlled and the accuracy of the sensor will be degraded. The use of a sample and hold largely eliminates these problems.

The sample and hold is however, noise sensitive. For this reason a primary/secondary shield is indicated on T_1 and it will be necessary to have a careful layout and good bypassing.

The asymetrical pulse generator can be synthesized in many ways. In this example a dual monostable I_C was connected as an asymetrical oscillator.

Conclusions

From the example discussed, it is clear that high frequency transformer coupled, DC current sensors can be built with very simple magnetics and associated circuits.

Acknowledgement

It has come to the author's attention that a bidirectional circuit with very similar characteristics has been presented by Houldsworth [1]. The basic idea has no doubt been reinvented many times.

Bibliography

[1] J. Houldsworth "Purpose Designed Ferrite Toroids for Isolated Current Measurement in Power Electronics Equipment," Signetics, Inc., Applications Note.