

## DC Current Measurement Using Magnetic Flux in an Electronic Null Balancing Arrangement

Miguel T. Escoto, Jr.\*

*ASTEC Power Electronics Laboratory  
Department of Electrical and Electronics Engineering  
University of the Philippines Diliman  
Quezon City 1101 PHILIPPINES*

### ABSTRACT

DC current measurement using magnetic flux balancing with an automatic controller is presented. A ferromagnetic, toroidal core is used both as a flux detector and magneto motive force summer element. A symmetrical, AC triangular current sent through an excitation coil builds up flux in the core. The DC current to be measured is sent through a another coil, which sets up a bias magneto motive force or mmf. The bias mmf causes the core to reach saturation earlier on one side of the flux build up than on the other side. As core saturation is reached, a voltage pulse transition is detected in a separate winding by a Schmitt trigger. Its duty cycle varies with the amount of flux imbalance affecting an automatic control feedback which strives for zero flux, by sending an opposing current, through a fourth coil, producing a canceling flux. An electronic null balancing circuit was wired to verify the technique.

Keywords: Coercion point, flux, magneto motive force, Opamp, proportional-integral, residual flux, remanence, saturation, Schmitt trigger

### 1. INTRODUCTION

Current measurement techniques have been devised in many configurations. There are both passive and active techniques. Passive measurement techniques do not need any other external power. In passive current measurements, the current is passed in series, through a small, precision calibrated resistance. Typically, these resistor shunts produce 50mV for 100 amperes or more and are placed directly on the terminals of a D'Arsonval meter. Typical accuracy of these meters are 3% to 5% and offer the simplest kind of current indication.

In other cases, the voltage is processed further with circuitry for galvanic isolation and amplification. Different current ranges are made possible by the addition of multiplier resistances on the meter.

Active techniques use more circuitry and require external power. In current mirror configurations, current is entered on one side of the mirror. By the use of a scaling resistor,

---

\*Correspondence to: ASTEC Power Electronics Laboratory, Department of Electrical and Electronics Engineering, University of the Philippines Diliman, Quezon City 1101 PHILIPPINES

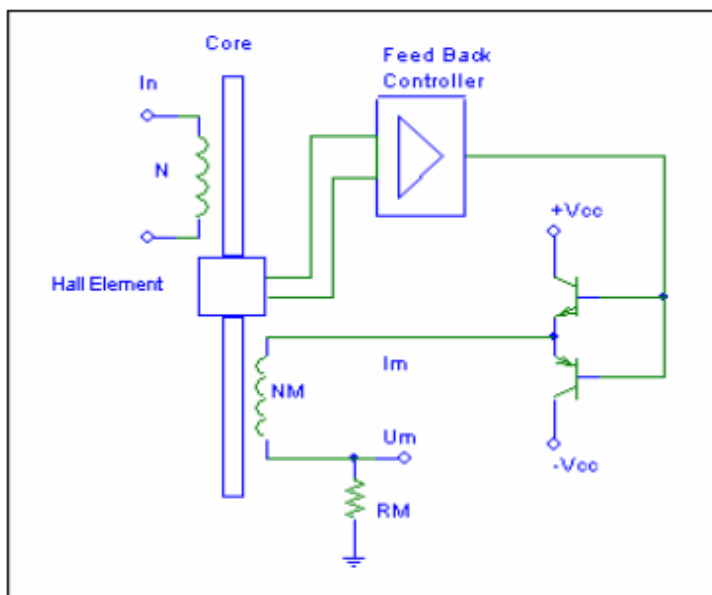


Figure 1. DC Current "Transformer" Simplified Block Diagram. The mmf from a current  $i_M$  flowing in an auxiliary winding opposes the mmf from  $I_n$  and the output signal from a Hall element in an air gap of the core, affects an automatic control system striving for zero flux in the core, such that  $Ni_N = N_M I_M$ . Under balance conditions, the voltage,  $U_m$  is a measure of  $I_n$ .

the output of the mirror is converted to a voltage referred to ground, thus a measure of the original input current is obtained. Sense FETs use this technique to minimize insertion power loss.

Still other active techniques use the idea of zero flux null balancing. Null balancing affords the greatest isolation and the least insertion loss in the circuit whose current is being measured. What is required, however, is that the null detector remain consistent as the balance condition is reached. The detector, likewise, has to be very sensitive near the null point. Signal bandwidth is limited by the closed loop bandwidth of the system. Signal range is limited by the compliance of the closed loop elements, but is easily scaled by the turns ratio of the coupled coils producing the flux.

A convenient way of measuring DC currents from a few amperes to several kilo-amperes is to use a DC current transformer based on a Hall element as in reference [1]. In Figure 1, the DC current "Transformer" contains a ferrite core which is magnetized by the current  $I_n$  to be measured. The magneto motive force or mmf, from a current  $I_m$  flows in an auxiliary winding with  $N_M$  turns. It opposes the magneto motive force, mmf from  $I_n$  and the output signal from a Hall element in an air gap of the core.

This affects an automatic control system, striving for zero flux in the core, such that  $N I_n = N_M I_m$ . The voltage  $U_m$  across an external resistor,  $R_M$ , is therefore a measure of the current  $I_n$ .

The turns ratio provides a means for ranging the current to be measured. For example, a transformer rated for 100 amperes needs 1 turn through the primary section. If it is used

for measuring a current less than 20 amperes, then the primary winding should have 5 turns to obtain the maximum accuracy. The turns ratio of a 100 A dc current transformer is, for example, 1:1000, i.e.  $I_m = 100\text{ma}$  for  $I_n = 100$  amperes. Hall effect DC transducers have a typical accuracy of  $\pm 1\%$  from 0 to 50KHz and the response time  $< 1$  microsecond.

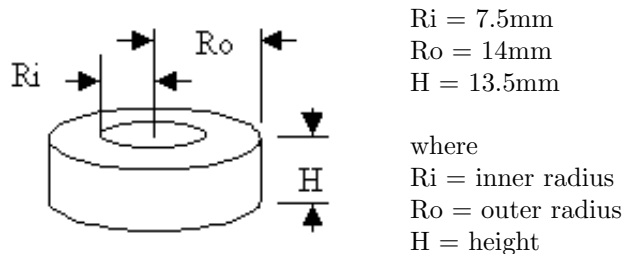
DC Current transformers are used in power electronics for measuring DC currents, AC currents with a DC current component, and also low frequency ac currents, such as phase currents of PWM variable speed motor drives. The measured quantity is used for instrumentation, as the current response in automatic control systems, and for tripping protective devices in case of overload or short-circuit.

## 2. MAGNETIC FLUX BALANCE METHOD

Current measurement can similarly be achieved by a magnetic flux balance technique. However, it makes use only of a toroidal ferrite core which acts as both the detector and magneto motive force or mmf summing component. No Hall device is employed. The core does not need an air gap.

### 2.1. Physical Core Measurements & B-H Characteristic

A toroidal core of ferrite material was measured for physical dimensions with a caliper. Table I shows the physical core data. The B-H magnetization curve is shown in Figure 2. This was obtained by driving an excitation coil with an AC triangular current source, recording the induced voltage in a separate pick up coil, and subsequently, numerically integrating the voltage taking core area,  $A_c$ , and mean path length,  $L_e$ , into consideration.



$$\begin{aligned} R_i &= 7.5\text{mm} \\ R_o &= 14\text{mm} \\ H &= 13.5\text{mm} \end{aligned}$$

where  
 $R_i$  = inner radius  
 $R_o$  = outer radius  
 $H$  = height

$$\begin{aligned} \text{Core Area, } A_c &= 0.8775 \text{ sq. cm.} \\ \text{Mean path length, } L_e &= 6.75442 \text{ cm.} \end{aligned}$$

Table I. Core Physical Data

### 2.2. Flux Balance Detection by Core Non-linearity

In Figure 3, when an exciting current passes through a coil,  $N_{exc}$ , wound around a core, magnetic flux builds up in the core. If the residual flux, or remanence in the core is opposite the magnetizing force, a coercion point is reached where the polarization of the residual flux goes to zero and reverses direction. If a detection coil,  $N_{det}$ , is wound on the core, such a

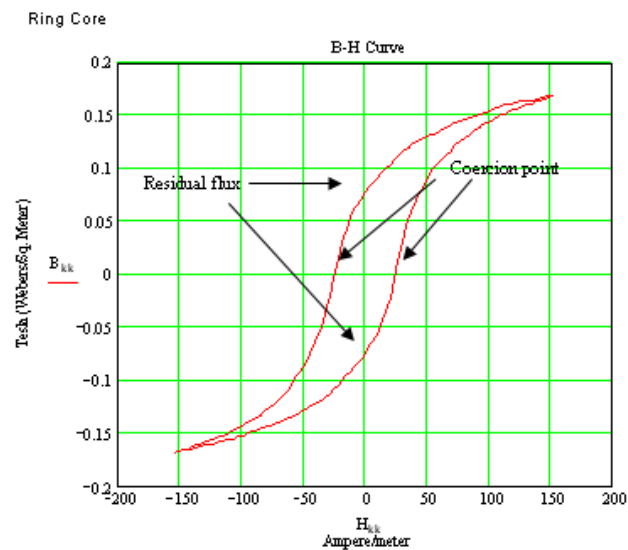


Figure 2. B-H Curve of the Ferrite Core. Core reaches a level of 0.17 Tesla at 150 Amperes per meter. Coercion point occurs around 25 Ampere per meter. Residual flux or remanence is about 0.07 Tesla.

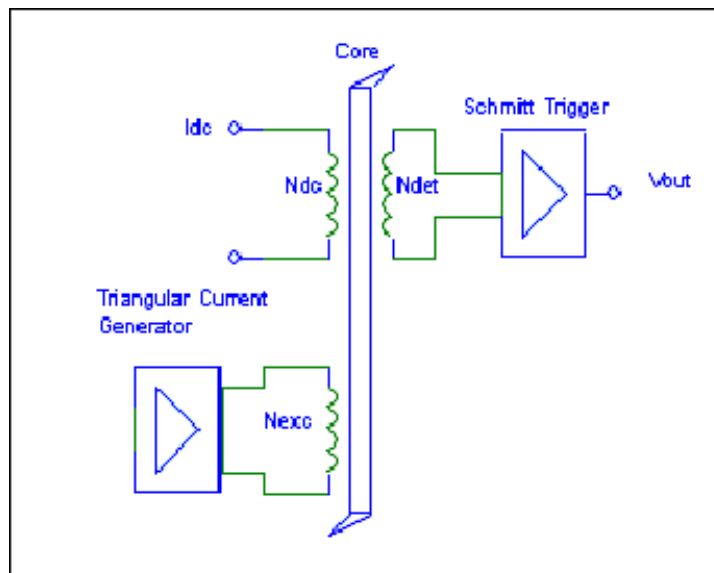
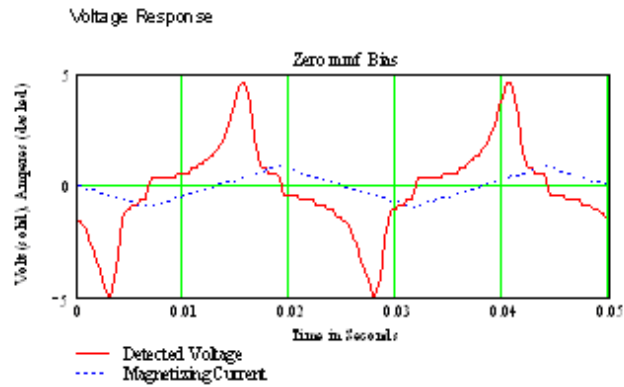
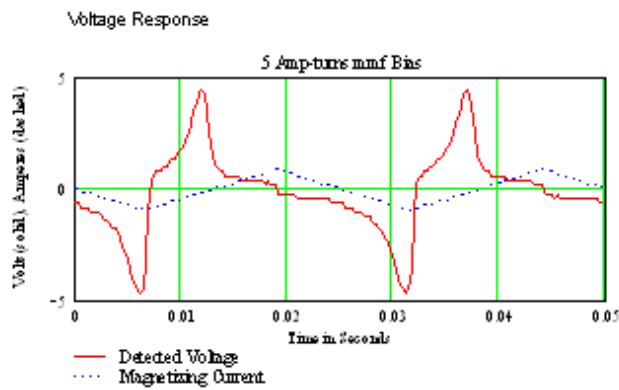


Figure 3. Magnetic Flux Balance Detection. Uses a non-linear core driven to saturation by a triangular exciting current. Duty ratio at  $V_{out}$  is a function of core imbalance.

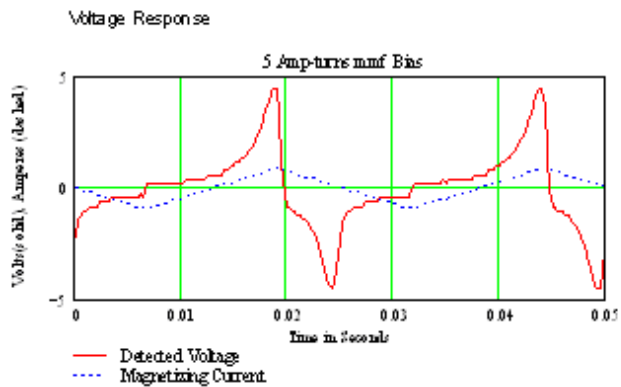
huge change of flux accompanied by a change in current will induce a spike voltage in it. As the current reaches its peak value, core saturation begins; the induced voltage decreases. As the current returns towards zero, induced voltage reverses. When the magnetizing current hits



(a) Balanced Case

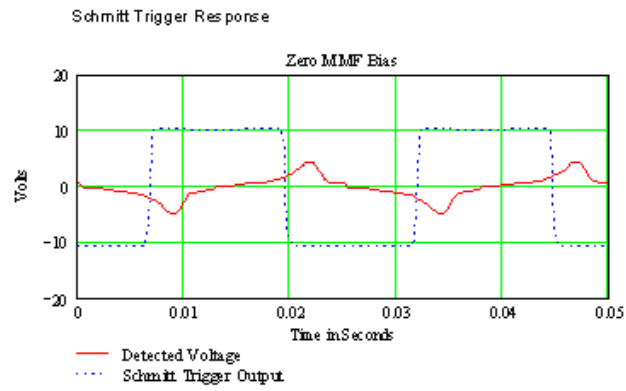


(b) Unbalanced Case, Positive Bias

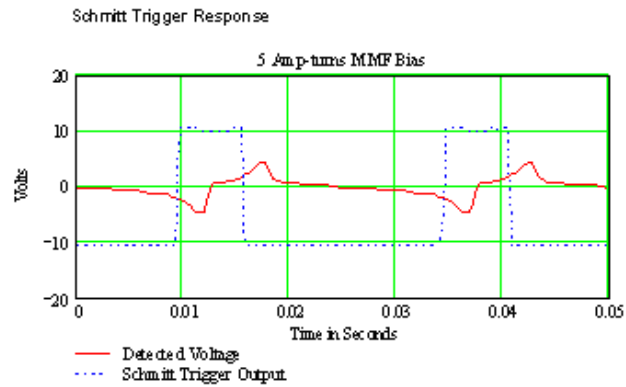


(c) Unbalanced Case, Negative Bias

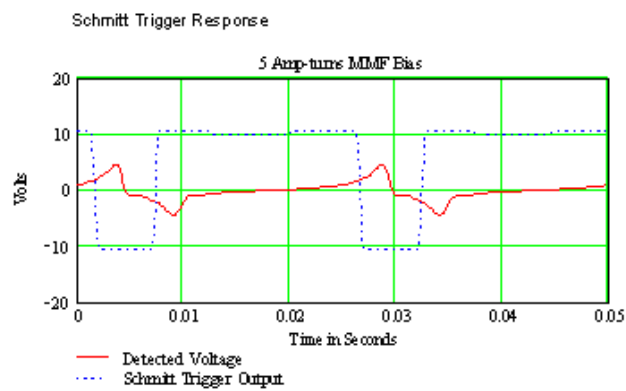
Figure 4. Magnetization vs. Induced Voltage: Triangular current of  $\pm 1$  amp peak applies mmf in core. (a) No bias mmf produces a symmetrical (balanced) induced voltage (b) Positive and (c) Negative bias mmf produces an asymmetrical induced voltage (unbalanced).



(a) Balanced Case



(b) Unbalanced Case, Positive Bias



(c) Unbalanced Case, Negative Bias

Figure 5. Induced Voltage vs. Schmitt Trigger output: The detected voltage is processed by an inverting Schmitt Trigger whose thresholds are about  $\pm 2$  Volts. (a) With no bias mmf, duty ratio is 50% (balanced case) (b) With a positive bias mmf, duty ratio is 24% (c) Negative bias mmf, duty ratio is 76%.

zero, residual flux remains. When the current builds up in the opposite direction, a similar process occurs.

*The induced voltage has half wave symmetry.* This is shown by the time responses in Figure 4a. Note that the peak voltage does not occur at the zero crossing of current on either side of the positive and negative current excursions due to the coercion points.

Direct current is introduced via a third coil,  $N_{dc}$ . It will produce a static bias mmf that causes mmf offset on the B-H curve. Normally, direct current will not induce any voltage in a set of coupled coils but with an alternating current present in the excitation winding, the core experiences a rate of change of flux that induces a voltage in the detection winding. *Without any bias mmf, the induced voltage has half wave symmetry. It loses symmetry with a bias mmf.* Figure 4 shows the time dependent responses of the core for three different cases: a) with zero mmf, b) with an mmf caused by the direct current in one direction c) with an mmf in the opposite direction. Similar voltage curves are reported as in reference [2].

An inverting type Schmitt trigger picks up the detected voltage and produces a pulse width that varies in accordance with the asymmetry of the detected voltage. Figure 5 shows the three Schmitt trigger outputs: (a) with zero mmf and aio, DR, of 50%, the balanced case, (b) and (c) with an mmf caused by the direct current in one direction and in the opposite direction, with DR=24% and DR= 76%, respectively.

### 2.3. Automatic Feedback Balance Controller

The magnetic flux balance current measuring block diagram is shown in Figure 6. A toroidal core of ferri-magnetic material is used as flux sensor. The magneto motive forces are introduced via 3 coils:  $N_{dc}$ ,  $N_m$ , and  $N_{exec}$ . The  $N_{det}$  coil is used to sense the induced voltage transition pulse as coercion is reached. Operational amplifiers provide automatic feedback to achieve null at the balance condition. A symmetrical AC triangular current excites the core through a coil of  $N_{exc}$  turns. As the current ramps up, flux builds up in the core. The DC current to be measured is sent through a coil of  $N_{dc}$  turns, which sets up a static bias mmf in the core. The bias mmf causes the core to reach saturation earlier on one side of the flux build up than on the other side. As core saturation is reached, a voltage pulse transition is detected in a separate winding of  $N_{det}$  turns. The pulse is sent to a Schmitt trigger, that produces an output duty cycle whose value represents an amount of flux imbalance and polarity. The duty ratio is converted to an average voltage by a low pass filter. This is fed back to  $G(s)$ , which is selected to be a proportional-integral controller to produce a balancing current on the core through a coil  $N_m$  turns that strive to zero out the flux, i.e.,  $I_{dc} N_{dc} = I_m N_m$ . The current  $I_m$  is passed through  $R_m$  to produce a voltage  $U_m$ , *whose average value is proportional to the current  $I_{dc}$  under null (balanced) conditions.*

## 3. SYSTEM SETUP

Electronic circuits in Figure 7 were built using standard operational amplifiers. Class AB configurations with buffered darlington emitter followers are used as voltage to current converters as in reference [3]. With an  $R_m$  equal to 2.5 ohms, the transconductance gain is at 0.4 Amps/volt. The Schmitt trigger requires an operational amplifier with a high slew rate. A 12 Volt/microsecond slew rate was used. The upper and lower trip points are  $\pm 2$  volts

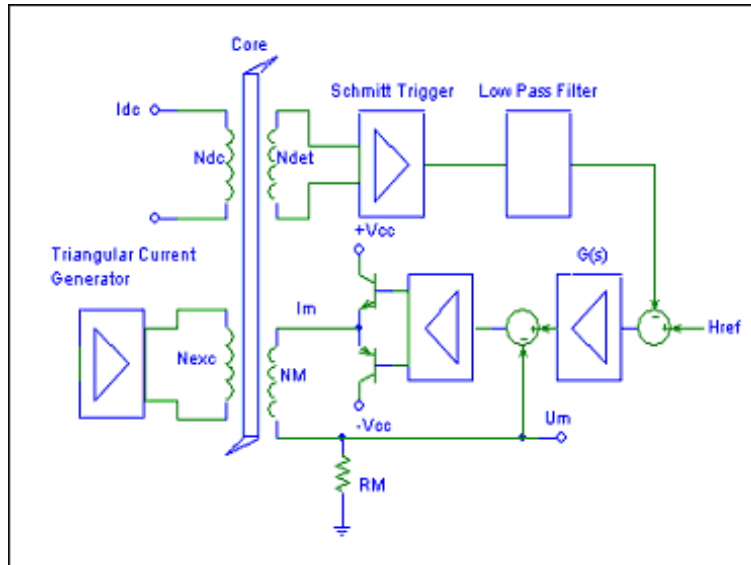


Figure 6. Magnetic Flux Balance Current Measuring Expanded Block Diagram. It uses the non-linear ferrite core characteristic to detect flux imbalance. An automatic feedback controller strives for zero flux in the core, such that  $I_{dc}N_{dc} = I_m N_m$ . The current  $I_m$  flows into  $R_m$ , causing a proportional voltage,  $U_m$ , to be a measure of the DC current,  $I_{dc}$ .

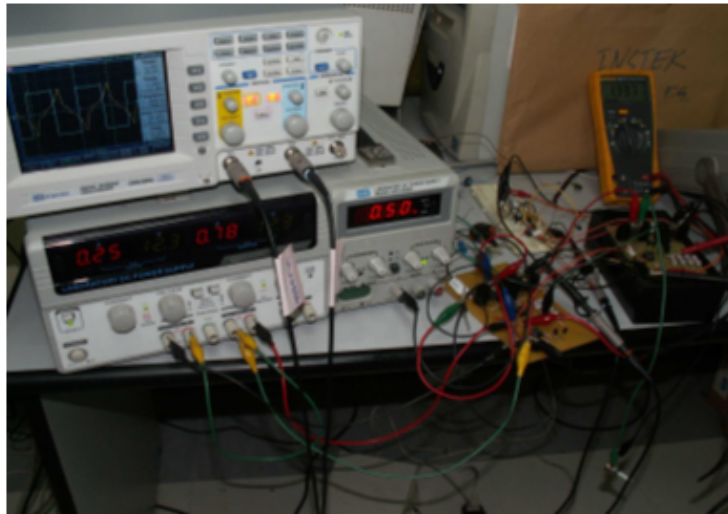


Figure 7. Photo of Test Set up. Oscilloscope display traces the Schmitt trigger output and the induced voltage in the detection coil. DC test current is 0.5 A.



respectively. Operational amplifier saturation levels are made symmetrical by a double level clipper using the zener breakdown mode of bipolar junction transistors. Reference [4] shows a similar double level trigger circuit for measurements.

An active low pass filter, with unity gain and a cutoff frequency of 1.6Hz, processes the Schmitt trigger output for average voltage. This is compared with set point, Href, which is set to zero. The proportional plus integral (PI) controller takes the error signal and adjusts IM until the 50% duty cycle is attained by the Schmitt trigger. This corresponds to an average voltage of zero under balanced conditions.

A cascaded current loop insures that the balancing current follows the command current of the PI controller at null conditions. The PI controller has a gain of 16, with the corner set at 10Hz. Closed loop bandwidth is about 30 Hz.

Core windings are as follows: Ndc=10 turns, Ndet=30 turns, Nexc=10 turns, Nm=10 turns. #22 AWG copper wire was used for all 10 turn coils; #26AWG wire was used for the 30 turn coil. Core data and B-H characteristics are shown in Table I and Figure 2 respectively. A soft magnetization type material of ferrite is used for the core as this is easily de-magnetized and re-magnetized.

The excitation coil is current fed with a 1kHz triangular signal whose peak current is 1 ampere. A standard +/-12 Vdc, 3Ampere laboratory supply was used to power all blocks. A separate adjustable supply with a series resistance was used to provide the test direct current.

Um is measured with a Fluke 77III multi-meter. An Instek Scope (Model GDS-820C) and Function Generator (Model GFG-8020H) were used.

Um, Volts (Negative Current)	Idc	Um,Volts (Positive Current)
0.004	0.00	.003
-0.116	0.05	0.119
-0.23	0.10	0.253
-0.371	0.15	0.388
-0.482	0.20	0.510
-0.606	0.25	0.641
-0.726	0.30	0.777
-0.862	0.35	0.908
-0.981	0.40	1.035
-1.112	0.45	1.177
-1.232	0.50	1.299
-1.368	0.55	1.438
-1.498	0.60	1.574

Table II. Direct Current Measurement Raw Test Data

#### 4. DISCUSSION OF TEST RESULTS

Preliminary tests were conducted for static and transient responses. Direct current was provided by a separate power supply. Tests were conducted at a room temperature of 24 degrees Celsius.

##### *4.1. Static Tests*

Table II shows the direct current test data for both directions of  $I_{dc}$ . Regression results are shown in Figures 8 and 9. The slope is 2.625 Ohms for Figure 8 and 2.501 Ohms for Figure 9. Zero offset has been observed to be within  $\pm 0.004$  volts. Accuracy is within  $\pm 3\%$ .

##### *4.2. Step Response*

A step input of 0.5 ampere is set for  $I_{dc}$ . The response is shown in Figure 10. The time constant is about 1 millisecond if one assumes an approximate, first order response.

##### *4.3. Limitations*

Under dynamic tests, the loop must be fast enough to maintain balance, otherwise, if the core saturates, all induced voltages disappear resulting in loss of the Schmitt trigger signal. Loss of signal causes  $U_m$  to take on the value of the supply rail voltage. The system has to be reset by turning off the power.

The circuit also introduces a small ripple into the DC current loop as a result of the turns ratio coupling with the exciting current. This is minimized by reducing the number of turns on  $N_{dc}$ .

#### 5. CONCLUSION AND RECOMMENDATION

The half wave symmetry of the detected voltage, as a balance detection point, suffices for current measurement as found in this technique. The core must have this non-linear property. The actual magnetic field strength, mmf level, can be computed by multiplying the balancing current  $I_m$  by  $N_m$ . The level of bias flux in the core can be determined from B-H curve of the material, if required. The technique may also find possible applications in the measurement of static, external magnetic fields.

Preliminary tests have shown a viable, isolated, direct current measuring scheme. Tests should be performed for long term drift, temperature stability, accuracy, and off balance due to sudden, large, changes in current. Tests also could be conducted to determine the consistency and accuracy of the proposed method when using a different batch of cores belonging to the same series or cores of a different type of material. Empirical equations could be formulated to help size and select the magnetic and physical parameters of the core and the windings.

#### ACKNOWLEDGEMENT

I thank Prof. Moises dela Cruz for initial discussions on isolated, direct current measurements using supermalloy cores in a push-pull configuration. I wish to thank also my colleagues Prof.

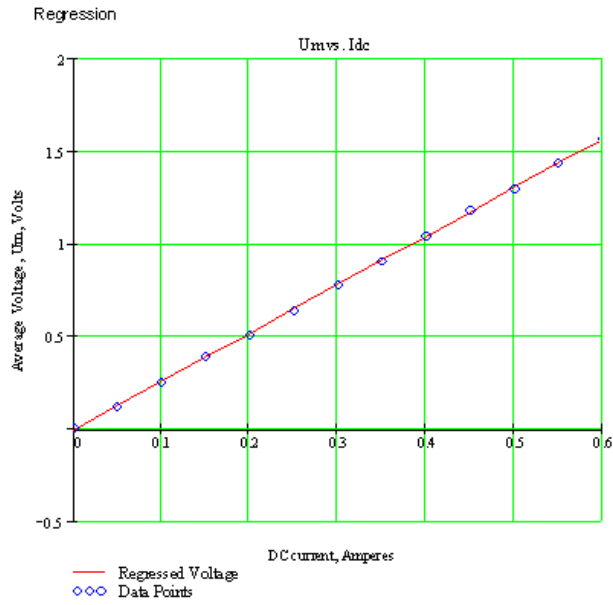


Figure 8. Regression for Positive Direction of Direct Current

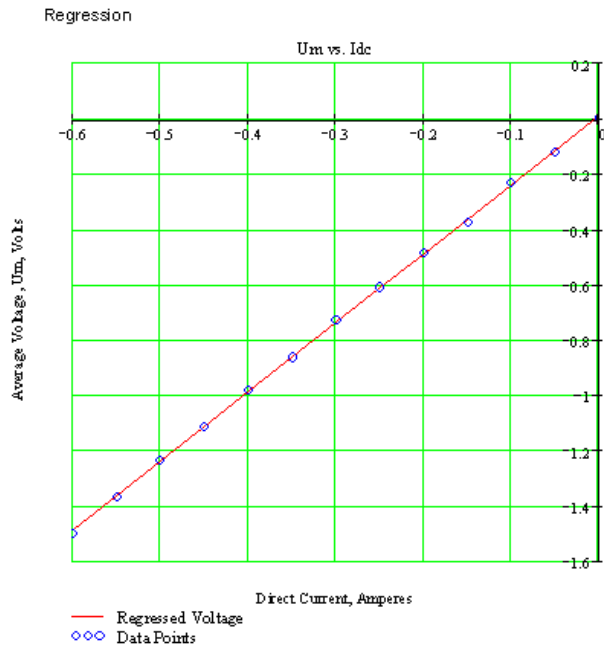


Figure 9. Regression for Negative Direction of Direct Current

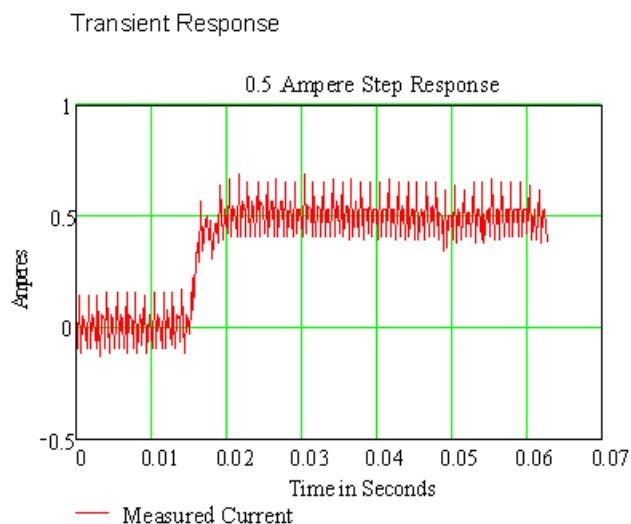


Figure 10. Magnetic Flux Balance Current Measuring 0- 0.5 ampere Step Response

Michael Pedrasa and Prof. Carl Odulio for their comments on core characteristics and circuit tests, and Rolando Guerrero for fabricating the printed circuit boards.

#### NOMENCLATURE

Symbol	Description	Units
mmf	Magneto motive force	Amp-turns/m
Rm	Measuring resistance	Ohms
Href	Magnetizing force	Amp/m
Um	Measured voltage	Volt
Im, Idc	Balancing current, direct current	Ampere
Ndc, Nm	Turns of wire	Turns
T	Magnetic flux	Webers/square meter
H	Magnetizing force	Amp/m

#### REFERENCES

1. Kjeld Thorborg, *Power Electronics*, Prentice Hall International, UK , ch 10, pp. 334-335 (1988)
2. Olivier Dezuari, Eric Belloy, Scott E. Gilbert, and Martin A. M. Gijts, "New Hybrid Technology for Planar Fluxgate Sensor Fabrication", *IEEE Transactions on Magnetics*, Vol. 35. No. 4 , July 1999, pp 2111-2117, (1999)
3. Albert Malvino, *Electronic Principles 6th ed*, Glencoe/McGraw-Hill, ch 12, pp. 398-399, (1999)
4. M. Filanovsky and V.A. Piskarev, "RL-Multivibrator and Retrieving the Coil Magnetization Curve", *IEEE Transactions on Circuits and Systems*, Vol. 38, No. 6, June 1991, pp. 650-653 (1991)
5. An Introduction to the MI sensor Electronic Compass IC Transistor Gijutsu magazine , Dec. 2003 issue [Online] Available: [http://www.aichi-mi.com/5.3.transistor\\_gijutu\\_E/transistor\\_gijutu\\_E.htm](http://www.aichi-mi.com/5.3.transistor_gijutu_E/transistor_gijutu_E.htm) (2003)