The HP Model 428 Clamp-On DC Ammeter

Gord Rabjohn, November 2013.

Introduction

Measuring current the “usual” way is inconvenient. The typical multimeter has “Amp” ranges, but the circuit being tested must be broken to insert the ammeter. As a result, the measurement is often avoided, or other approximate measurements (such as measuring the voltage drop across a supposedly known resistance) are done instead. The Vector company made adaptors (such as the T-8-O-C) that can be placed between a tube and its socket that allows a special probe to divert the current flow to an ammeter, but these are rare. So, for many of us, current measurements are rarely done.

There is another way. Ampere’s law states that current flowing through a wire causes a predictable magnetic field to form around that wire that is proportional to the current. If this magnetic field from the wire can be measured (and other magnetic fields, such as Earth’s magnetic field, can be excluded), then it should be possible to measure current without interrupting or even touching the circuit.

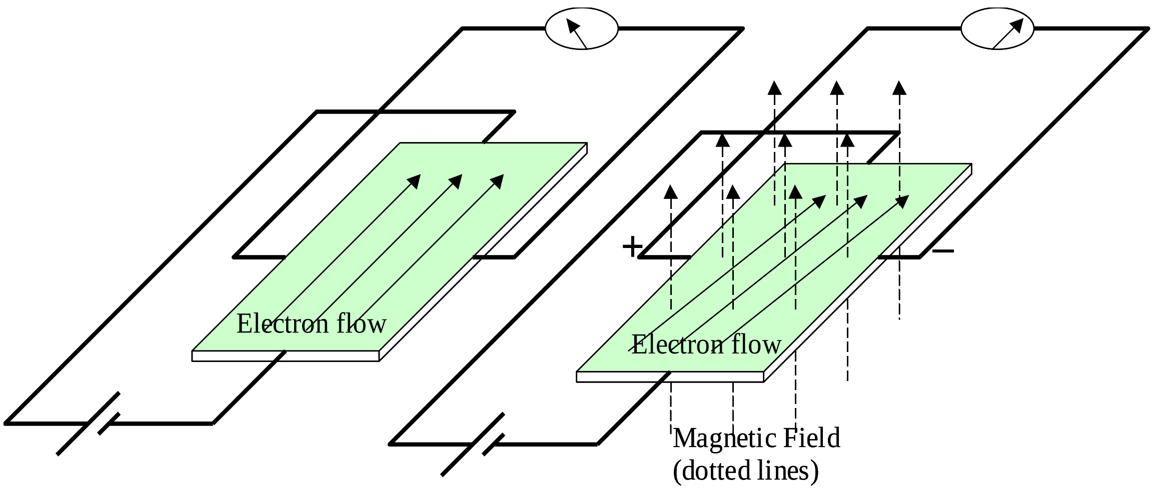
Measuring a Magnetic Field

Changing magnetic fields are quite easy to measure. Electricians have used clamp-on AC ammeters for years, the most popular brand being Amprobe.

These instruments are essentially transformers, with the primary being a single turn thru the aperture, and the secondary being multiple turns in the body of the instrument. The two are coupled with a magnetic path that can be opened to allow the electrician to insert the wire. However, they rely on Faraday’s law, the fact that a changing magnetic field induces a current into a wire. If the field is not changing (DC), these instruments do not work.

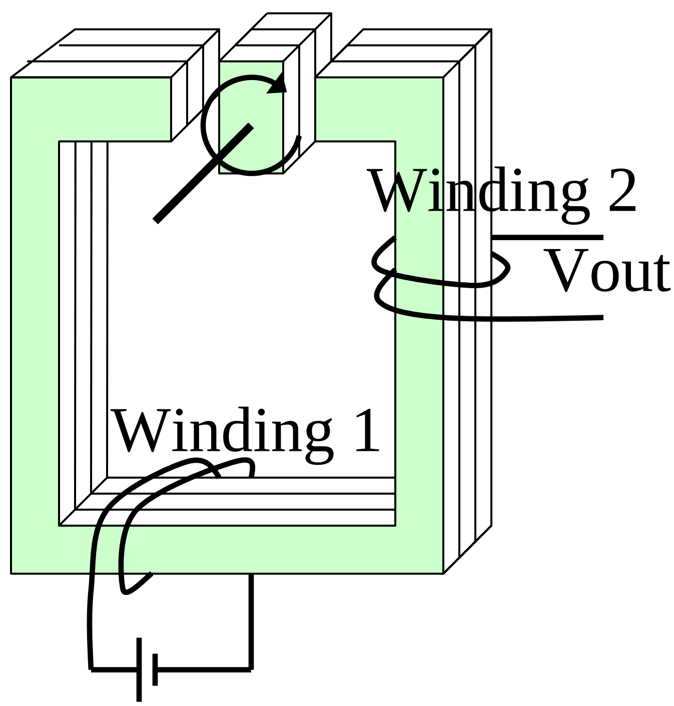
Static magnetic fields are much more difficult to measure. A compass can do it, but it is not very sensitive. If you look up magnetometers on the web, you will find a variety of obscure and weird ways to measure magnetic field strength and direction.

One way to measure a magnetic field is with a Hall effect device. The Hall effect is the tendency for moving electrons to deflect under the influence of a magnetic field, due to Lorentz force. Electrons (and holes in semiconductors) traveling in a conductor tend to follow a straight line (aside from collisions with the atoms forming the solid). However, if they move within a magnetic field, their trajectory tends to look more like an arc. The result is that a small voltage will appear across (from side to side) a conductor carrying current thru a perpendicular magnetic field. This is referred to as the Hall effect. In the left side of the figure below is electron flow in the absence of a magnetic field. On the right, the magnetic field (dotted lines) causes the electron flow to deflect, resulting in a small voltage from side to side.



In metals and semiconductors, the effect is quite subtle, but there are materials in which the effect is quite pronounced. There are Hall effect integrated circuits that include sensitive amplifiers and trigger circuits. These are used in electromechanical apparatuses such as DVD players to replace magnetic reed switches. More exotic materials (like "unobtanium") are employed in Hall effect devices have been used in Tektronix clamp-on DC current probes.

Flux Gate Magnetometer



If we cannot measure a static (DC) magnetic field, is there any way to turn a DC field into an AC field so it can be picked up with a coil? It turns out there is, and this apparatus is called a flux gate magnetometer.

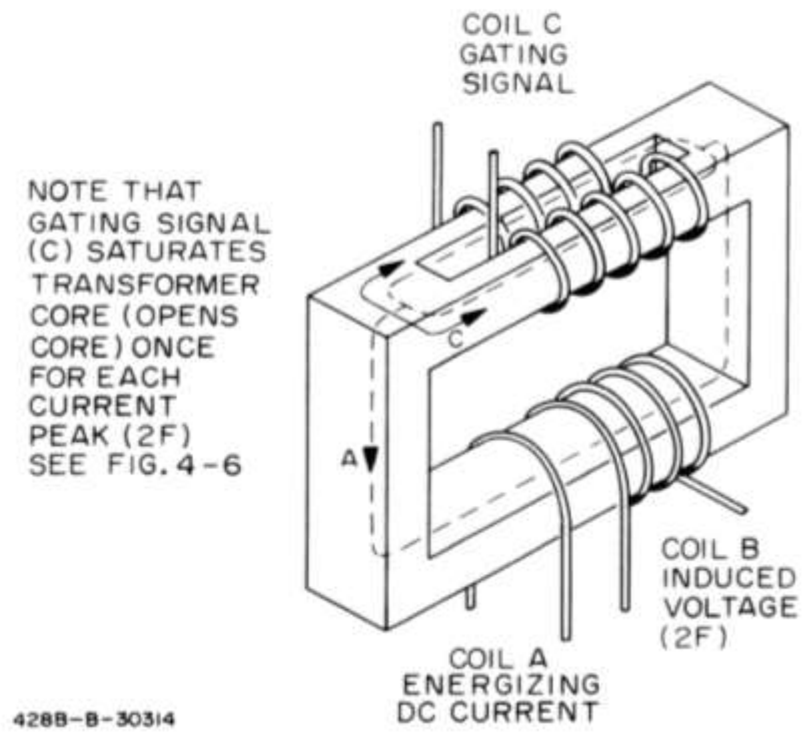
Picture an iron core, as in a transformer, but with a gap in one side. In that gap is rectangular vane of iron, attached to a motor so it spins. When "horizontal", this vane completes the magnetic circuit. When "vertical", there is still a gap in the magnetic circuit. So, the rotating iron vane causes the gap to open and close rapidly.

If the iron is not magnetized and there is no current flowing in the coils, nothing remarkable happens. However, if there is a DC magnetic field caused by the battery and winding 1, the magnetic flux in the iron core expands and contracts as the gap is opened and closed. An AC voltage will appear at winding 2, and this voltage will be proportional to the DC current in winding 1.

Clearly, this apparatus converts a DC current into an AC voltage that can be measured by conventional means, however it is a mechanical contraption that would be large, noisy, and awkward. A non-mechanical means to change the magnetic path rapidly would be preferred.

The magnetic permeability (ability to carry and constrict magnetic flux) of metals depends on the intensity of the magnetic flux. At high flux density, permeability tends to drop significantly; this is called saturation. (This is why the inductance of a choke depends on the DC current flowing through it) If we impose a large AC magnetic field to an iron alloy (that has been selected so it has a low saturation point), then the permeability will change at the frequency of the imposed AC signal, and it will behave like the spinning iron vane. This is the basis of the flux gate magnetometer.

If we are very clever, we can arrange 2 coils so they intermittently saturate the magnetic core, but are phased such that the alternating magnetic field cancels out over most of the core. An illustration taken from the HP 428 users manual shows how this can be done. A large AC signal on Coil C (call this the excitation frequency) drives the top part of the core in and out of saturation. Yet, their magnetic flux cancels on the rest of the core. So, this upper section behaves like the spinning vane. As long as there is no magnetic field elsewhere, there is no voltage coming out of coil B. If a DC current flows thru coil A, a voltage, with a frequency of twice the excitation frequency, appears on coil B. In principal, this apparatus can be used to measure DC current flowing thru the “Energizing current” wire.



The HP 428

The HP 428 uses the flux gate magnetometer to measure DC current with a clamp-on probe. The clamp-on probe has 4 magnetic signals present:

a) The "Gating" signal, 20kHz, applied TO the probe.
b) The sensed signal coming FROM the probe, which is 40kHz, with a magnitude proportional to the DC magnetic field in the core.
c) The current being measured.
d) The DC feedback signal TO the probe, described below.

Ideally, the gating signal (a) acts only to swing the permeability of the core, and is balanced so it does not appear directly elsewhere. A feedback loop (part of the instrument) forces DC thru the flux gate (signal d) until there is no induced AC voltage in the sense coil (b), thereby exactly canceling the DC current being measured (c). So, when balanced, there is no DC magnetic field present (feedback causes (d) to cancel (c)). The meter reads the value of this feedback current (d). Note that since the feedback current is fed through multiple turns in the core, it is smaller in magnitude (but is a scaled replica) of the current being measured (c). This means that the non-linear magnetic nature of the core permeability does not introduce errors in the current measurement.

The most important part of the ammeter is the probe. The earth's magnetic field is approximately the same strength as the field generated by 1 amp of current, so this field must be avoided if small currents are to be accurately measured. This means the probe must contain a good magnetic path surrounding the wire, and it must be possible to open this magnetic path to insert and remove the wire. It must close completely to avoid picking up external fields. The probe for the 428 is shown below. (Two probes are shown in the picture: One is open, the other is closed on a wire) All versions of the meter include a probe demagnetizer on the back, but I find that I rarely need to use it.

The 428A (right) was introduced late in 1958. It has 11 tubes, and 6 ranges from 3mA full-scale to 1A full-scale. Around 1961, HP introduced the 428B, (left) which was a similar instrument (it uses the same probe), but with a wider current range (down to 1mA full scale, up to 10A full scale), and a larger meter. The 428B has an external output that can be fed to an oscilloscope or an AC meter for AC current measurements. Later versions feature a printed circuit board assembly rather than point-to-point wiring, and only 8 tubes.

I have had a 428B for several years and his is one of my favorite instruments. I purchased it on Ebay, and as received it was dead. I had to wind a transformer (which had been removed from the instrument!) and replace a few parts, but since then it has been stable, accurate and reliable. I just purchased a 428A at the recent OVRC auction but this one needs some work. Like a VTVM, these instruments have a zero adjust on the front panel. Other than that, it operates like a conventional ammeter. Most of my equipment is now solid-state, so this is the only piece of tube instrumentation that I frequently use, and I marvel at how well it works.

Many were made. It last appeared in the HP 1986 catalogue, a product lifetime of 28 years. So, if you look in the right places, it is fairly common. Certainly the 428B version is preferable to the 428A. I prefer the circuit-board versions of the 428B, as I find the circuitry easier to follow. The circuitry in the instrument itself is straightforward. In fact, I consider the inside of the circuit-board 428B *beautiful*. It is neat, spacious, and efficient. This is HP equipment at its best, and the service manuals, available on-line, are excellent. If you are seeking to purchase one, (and if you see one, I recommend you grab it!) it is of utmost importance to get one with an intact probe. The probe uses special materials, and has precision mechanical machining, so cannot be replaced. The same probe is used for the 428A and 428B.

HP elected not to replace this instrument when it was made obsolete in 1986. I suspect that the Tektronix P6042, which was released in 1967, captured most of this market. The Tek current probe (and subsequent generations, like the AM503B) is superior because it boasts 50MHz bandwidth (as opposed to the 428's 400Hz bandwidth), is solid state, and has a more compact probe. The Tek instrument uses a hall-effect sensor at low frequency and an inductor for high frequency. If you can pick one of these up they are also great instruments, but are much more expensive and rare, and the probes are reportedly much more fragile.

Uses of the HP428

I use this meter to find defective decoupling capacitors in radios. I remove all tubes except the rectifier, and run the radio at low line voltage (to avoid excessive voltage on the filter capacitors). I probe currents through the circuit, starting just past the bleeder resistor, looking for current thru capacitors. (Note that I do not generally do wholesale capacitor replacement in vintage radios. I replace only those requiring replacement. That way, future generations of radio enthusiasts will see something closer to an authentic radio. Besides, most of the radios I fix are rarely used) Then, with the tubes in place, I can check current on a stage-by-stage basis. I can easily measure the DC balance of a push-pull amplifier. I often leave the current probe on the B+ while I work on the radio so I can watch for telltale changes in current that would indicate failing capacitors. Doing these tests without a clamp-on meter can be difficult and awkward.

Unlike a conventional ammeter, the 428 is not damaged by a down-stream short-circuit. The worst that can happen is the probe may need to be demagnetized. If you have ever measured voltage while your multimeter is set to "amps", you will appreciate having a 428 around for routine use.

At introduction, HP bragged that the lack of extra voltage drop in low impedance solid-state circuits was a key feature of the 428, and this is true. The meter can read 1mA full-scale in a short length of #16 wire, a 3-inch length of which is about 0.001 ohms. That's a voltage drop of about 1 microvolt; compare this to a DMM, which typically has a voltage drop 5 orders of magnitude higher.

As a party trick, take 2 wires made with different metals (say, copper and steel), and form a series connected loop thru the 428 current probe. If you heat one of the junctions with your body heat, the thermoelectric effect (the way a thermocouple works) will produce a half-scale reading. You can't do that with your DMM!

So, I recommend the HP 428B to anyone who does restoration of radios made with point-to-point wiring. They are convenient, reliable, and very easy to use.

References

HP428A manual
HP428B manual
HP Journal vol. 9, No 10,11, Summer 1958

Wikipedia article on the Hall Effect