

The design, confirmation and use of a compact Current Coil set for clampmeter calibration.

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Abstract:

There are a growing number of current clamp meters and current clamp accessory devices appearing in the calibration workload capable of measuring currents up to 1000 Amps AC and DC. In the past users have attempted to make their own current coils to enable calibration sources with 10A outputs to provide stimuli adequate to calibrate these devices close to their full scale values, often without success. A compact current coil set was introduced as an accessory to a recent new 'universal' calibrator product to provide accurate sourcing of currents up to 1000A for clamp devices.

This paper discusses error sources and constraints on practical current coil design, describes measurements made to confirm performance of examples of the final design, and discusses how to avoid misleading results when using such current coils in practice.

Introduction:

It is not uncommon for the calibration of current clampmeters to be performed with the use of current coils - there are very few sources capable of directly outputting currents in the region of 500 - 1000A, the typical values required for calibration of these instruments. Many laboratories have 'home made' coils which they use with varying degrees of success. As will be illustrated later in this paper, there are many potential sources of error from the coil design, the clampmeter under test, and the source which users may not be fully aware of and can lead to unexpected results or unrealistic accuracy claims - errors in the region of 2% can easily be encountered. One of the design requirements for a recently design 'universal' calibrator was to provide capability to address both AC and DC clamp meters with a complementary solution of a calibrator and purpose designed current coil accessory.

Workload analysis revealed that the majority of clamp meters are used and calibrated at currents up to 1000A but only at power line frequencies, with a few applications involving measurements at higher frequencies, usually at lower current levels. This suggested a design target of providing 1000A at 65Hz extending to 200A at 440Hz from the coil/calibrator combination would satisfy workload requirements. Accuracy specification is 0.2% for the coil, applicable to both current transformer and Hall sensor clampmeter types.

Theoretical considerations and practical requirements present conflicting requirements - to avoid magnetic field fringing effects a large coil is needed which increases inductance but space limitations and source drive capability require a low inductance, compact solution. The solution chosen was to design a pair of physically small 10 and 50 turn coils in a single robust unit with integral magnetic shielding, allowing a very compact design to meet electrical and magnetic performance requirements.

Coil Design Influences:

AC current clampmeters have been part of the calibration workload for many years. They are effectively current transformers with the current carrying conductor to be measured forming the primary and a winding around a jaw and closing mechanism forming a secondary. The jaw is composed of a suitable magnetic core material which completes the magnetic circuit when closed. Introduction of semiconductor Hall Effect sensors a few years ago made it possible to employ similar techniques to construct current clampmeters which respond to both DC and AC currents. However, the older current transformer (CT) and newer Hall sensor clamp meters present different loads which the current coils and their source must be designed to cope with. Hall based devices are typically much higher inductance than the CT types and are more sensitive to magnetic field non-uniformity and interference within the clamp area, the result of design differences needed to accommodate the Hall sensor within the jaw magnetic circuit. CT devices can also have a sensitivity to magnetic field non-uniformity and interference within the clamp area if the jaw mechanism significantly increases the reluctance of the magnetic circuit, by effectively introducing an air gap.

Both types of clamp require an essentially uniform magnetic field in the region of the jaws (as would be created by an infinite straight conductor) to avoid misleading results with clamps incorporating low reluctance magnetic circuits which are more sensitive to field non-uniformity/interference and positioning within the jaw. The current coil must create a magnetic field equivalent to a single conductor from a number of turns carrying a lower current. Inevitably the conductors must form a loop which will cause the field to distort - the smaller the coil dimensions the larger the distortion (non-uniformity). Practical space limitations in a working cal lab environment limit the size of coils, and weight is also an important factor.

Another limitation with respect to AC applications is the impedance presented to the source of the combination of the current coil and the clampmeter. The voltage developed across the coil is the product of current and impedance - the dominant effect being inductance, producing a compliance voltage increasing with frequency. The calibrator which these coils accompany has the highest inductive load drive capability for any commercial product of its type: able to drive 20A at DC with compliance voltages up to 4V and up to 20A AC from 10Hz to 10kHz into a 700 μ H load with compliance voltages up to 2.5V RMS. Effect of coil winding resistance on compliance voltage and coil temperature rise are also considerations - particularly when a compact design is required which implies the use of winding material of low cross sectional area and consequently higher resistance.

The total impedance (Z) seen by the source driving the coils is given by:

$$|Z| = \{R_{\text{coil}}^2 + [2\pi f(L_{\text{coil}} + L_{\text{clamp}})]^2\}^{0.5}$$

where R_{coil} is the coil resistance, L_{coil} is the coil inductance, L_{clamp} is the clamp meter inductance seen at the coil terminals, and f is the frequency.

A smaller coil will reduce the inductance and hence the voltage drive capability required from the source. The clampmeter contributes and increases the inductance by modifying the magnetic circuit with the additional iron (usually) of its clamp/sensor mechanism. Unfortunately smaller coils suffer greater field distortions which lead to the results varying with the positioning of the clampmeter with respect to the coil, and some clamps with poor magnetic circuits will give incorrect results in any position.

Design Implementation:

The technique employed in the coils under consideration to overcome the field uniformity difficulties and produce a compact useable coil is magnetic shielding. The classic circular coil is modified to a square shape, providing the most convenient form with a uniform field on each side and allowing simpler magnetic shielding arrangements with the smallest loop area to accommodate the clamp. By applying magnetic shielding the field on the fourth side where the clamp jaw will be located is protected from interfering fields due to the other portions of the windings. Consequently the field on the fourth side closely resembles that from an ideal infinite conductor.

The coil design is depicted in Figure 1, showing the final product as supplied to customers. There are two electrically and magnetically separate coils providing ratios of x10 and x50, physically integrated into a single unit. A number of lower current (up to 200A) clampmeters have a small jaw area making it difficult to provide sufficient turns of adequate cross sectional area in the space available, for example fifty turns capable of carrying 20A - hence the provision of a ten turn coil able to accommodate smaller clamps. The 'measurement' area where clamps

under test are intended to be applied are clearly visible as the area where the coil thickness reduces to allow access by the clampmeter jaws. In addition to allowing the coils to be used with varying sizes of clamp jaws, this feature ensures the user always applies the clampmeter under test to the portion of the coil where the magnetic field is uniform.

Design Confirmation:

Confirmation of the coil design must address two issues: the ability of the design to produce a field equivalent to a single conductor carrying the current to be simulated, and the interaction between coil and clampmeter where clampmeter magnetic circuit shortcomings could influence results. The former is relatively simple, and is to some extent taken care of by the laws of physics. The second is more complex and involves an understanding of the effects described above.

The approach taken was to produce a practical realization of an ideal coil and compare results obtained with a suitable clamp type sensor capable of sufficient resolution to results obtained with the final coil design and the same sensor. To explore clampmeter positioning and stray field sensitivity it was necessary to make use of the 'worse' examples of clampmeter design - an interesting reversal of normal evaluation philosophy of using the very best equipment available!. Obviously, this testing required the sourcing of the coil input current, which also presents some challenges.

The 'ideal coil' was constructed as a 400mm diameter circular coil of 10 turns presenting an impedance of $110\mu\text{H}$ in series with $68\text{m}\Omega$, and another of 300mm diameter circular coil and 50 turns, presenting an impedance of 1.4mH in series with $160\text{m}\Omega$. Both are constructed from insulated flat strip copper windings. At these diameters, the field may be considered as sufficiently uniform and free from interference from the other 'side' of the coil and allow assessment of the effectiveness of the magnetic screening of the compact designs. However such a load is difficult to drive from available calibration sources - its impedance requires sources capable of driving compliance voltages somewhat higher than those that commercial calibration equipment are capable of. Sources were specially constructed and included the use of high current transformers energized from variacs (variable transformers) driven from a synthesized mains power supply. Since the major use of clampmeters is at power line frequencies this offered a convenient source for much of the testing, however work was also undertaken at other frequencies using specially engineered sources.

The 'ideal' coil and 'compact' coil under test were series connected and comparative measurements made with various clamp devices. Clamp probes intended for use as voltmeter accessories provided one means of measurement and allowed the use of higher resolution measurements. Where clampmeter devices of limited resolution were used the current was adjusted to operate the device at a one least significant digit boundary to provide maximum

discrimination. Measurements with magnetic field probes were also made to investigate field distortion and interference.

Measurements were made throughout the frequency range, including both the ten and fifty turn coils, and results showed that field uniformity was good. Nevertheless, some clamp designs have an inherent sensitivity which is present even with a single straight conductor and results will vary with positioning. Users must be aware of such effects, which are discussed in the following section.

Practical Use of Coils:

It is clear from the foregoing that there are a number of pitfalls for the unwary attempting to make use of current coils for calibration of clampmeter type instruments. Many result from the use of inappropriate coils, particularly when 'homemade' coils are involved and the users have not appreciated the consequences of the electrical and magnetic effects involved.

One of the most common problems arise from use of coils with sources not specifically designed to operate with them, the inductance of the coil/clampmeter combination may well cause the source to oscillate and give wildly unexpected results. More commonly, it is the compliance voltage developed across the coil/clampmeter combination that is the problem. Frequently the source will be unable to drive the load - the voltage developed across the coil/clampmeter impedance will exceed the limits of the source. This may cause the source's protection circuitry to detect an out of limits condition and produce an error or warning message, or simply to switch off the output, depending on the design and sophistication of the source.

Over compliance conditions (too much voltage across the load) can result in errors from a number of factors. The two most likely are distortion of the signal (typically clipping of an AC waveform) and the effect of load regulation. Load regulation is seen as a variation of output current with load, and is a consequence of a practical current source having a non-infinite output impedance. This load regulation (or compliance) error is typically included in equipment specification to a certain level of load, but if the specified loading conditions are exceeded, even though the source may continue to function, the accuracy will be degraded.

Modern sources are usually more sophisticated and incorporate overcompliance detectors which warn the user. Unfortunately some well known modern calibration sources do not incorporate such features and continue to supply output current but with severely degraded accuracy and no indication to the user that results may carry excessive inaccuracies.

Even with a calibrator/coil combination specifically design to address the workload encountered in the modern calibration laboratory, it is possible to encounter some unexpected results if users are not aware of the factors that influence successful calibrations. A few of the Hall type clampmeters that are available today have particularly high inductance that can cause the source's compliance voltage detectors to warn the user that the limit is being exceeded. If it is

not possible to supply sufficient current at the frequency desired, say 1000A at 65Hz, an alternative approach is to calibrate the clampmeter's zero to full range linearity at a lower frequency, such as 40Hz, and then to check for frequency flatness at a lower current level, for example 750A on the 1000A range. Performing checks at lower frequency is, in fact, a much better test, as linearity problems in clamp meters are generally more evident at low frequencies than at midband frequencies.

The effect of conductor positioning and sensitivity to interfering fields are factors which influence achievement of correct results for both usage and calibration of clampmeters. Some clamp devices have alignment markers on the jaws to assist users in positioning the current carrying conductor in the optimum position. When using current coils the users must pay regard to such features of individual clamp devices and to correct alignment with the coils. The correct position is to maintain the coil windings centrally within the jaws with the plane of the jaw perpendicular to the coil windings and the body of the clamp device in line with the body of the coil. Even though the design of the current coils described substantially reduce the dependency on positioning for the majority of clamp devices, it is important for optimum alignment to be used for highest accuracy and repeatability. Figure 2 depicts correct alignment.



Figure 1. Ten turn and fifty turn coil assembly.

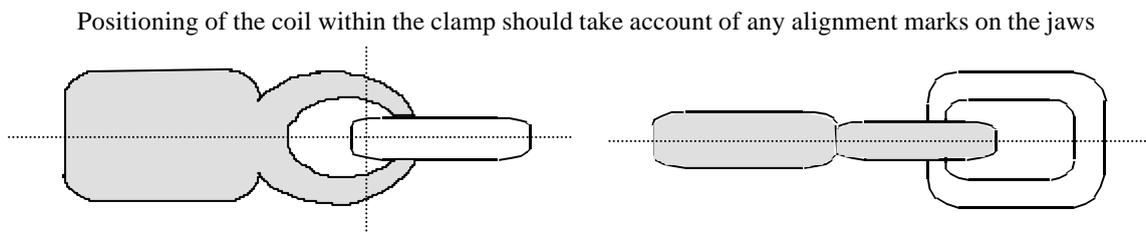


Figure 2. Correct coil and clampmeter alignment.