

# Performance Assessment of Current Sensing Coils Built into Resistance Welding Transformers

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## ABSTRACT

Advantages and disadvantages of using built-in current sensing coils to measure secondary welding current are discussed as described in ISO 10656:1996. Discrepant requirements for built-in coils are highlighted from ISO 10656. Factors that lead to measurement errors include temperature sensitivity, lack of uniform specification of mutual inductance values because of the use of transimpedance values, inability of coil manufacturers to produce the desired mutual inductance value, and sensitivity of the coils to external magnetic fields that result from the secondary loop geometry. The error sources were evaluated for five loose coils that are typically built into welding transformers, and for three coils which had been built into welding transformers. Some of the coils were found that did not comply with the requirements set forth in ISO Standard 10656.

## INTRODUCTION

ISO Standard 10656, <sup>(1)</sup> *Electric Resistance Welding – Integrated Transformers for Welding Guns*, specifies the use of integral current sensing coils built into single phase ac welding transformers. Two major advantages commonly cited for using integral current sensing coils are the reduced susceptibility to physical coil damage and the reduction in coil position sensitivity. Position sensitivity is commonly the leading cause of inaccurate current measurements. The “*advantages*” cited therein are acknowledged. However, many people and organizations falsely believe that significant advances have also been made in making *accurate* current measurements by using the built-in current sensing coils. This is not necessarily true.

Significant concern has been expressed by some users and manufacturers in the use of the ISO Standard 10656 (hereafter referred to as the “Standard”) to successfully provide acceptable current measurements as the result of embedding current sensing coils in welding transformers. Inconsistent results have been experienced in procuring coils from different manufacturers when applying the Standard. Concern has also been expressed regarding the wide temperature range to which the coils can be subjected in use. The Standard states in section 5.3 regarding the current detector, “*output: 150 mV/kA, +1.5% to –1.5% at a load of 1000  $\Omega$  under full wave, full voltage conditions up to 80 °C with a tolerance after mounting in the transformer of  $\pm 3\%$ .*”. The Standard further requires a coil resistance range of 20 to 25  $\Omega$  and that the coil be toroidal and not cylindrical.

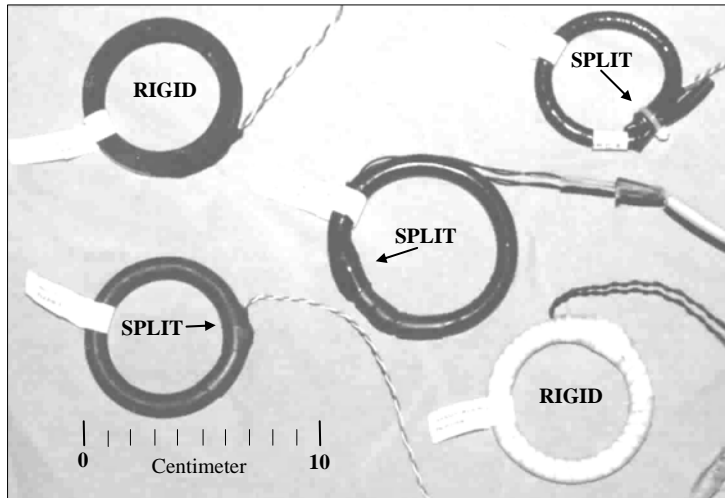
It is unclear from the wording if the 80 °C applies to the coil before installation or after installation in the welding transformer. It is assumed, although not specified in the Standard, that this resistance range is at near room temperature - commonly assumed to be 22 °C. The temperature coefficient of resistance for copper wire from which these coils are wound is typically 3900 ppm/°C <sup>(2)</sup>. Therefore, a 25 ohm coil at 22 °C will have a resistance of 30.7 Ω at 80 °C. If the temperature for the resistance range is not specified in the Standard, confusion could result between coil manufacturers, transformer manufacturers, transformer users and weld control manufacturers and users.

Although the Standard requires installation of the coils, some people do not even use the coils. Some use them for monitoring the actual secondary current but control the welding process by reading the primary current and some must use a separate secondary pick up coil to control the welding process due to the function of the weld control.

An additional and important reason for the use of the coil on the secondary side of the transformer is related to typical differences in transformer design between U.S. and European manufacturers. With the high excitation currents typical of the European-made transformers built to ISO 10656 specifications, it is not feasible to use the primary current multiplied by the turns ratio to accurately predict the secondary current. For one European unit recently tested, for example, the primary excitation current was greater than 200 amperes for a 50 kVA, 50% duty-cycle transformer. U.S. manufactured transformers typically would not exceed a primary current of 30 amperes maximum for any size transformer. For the latter, the associated errors are smaller when using turns-ratio to predict secondary current from a primary current measurement.

Experience has shown the temperature range of typical water-cooled welding transformers to be +15 °C to +80 °C. Because of this range of temperature for welding transformers, the *current sensing coils*, which are built into the welding transformer, can be subjected to a similarly wide range of temperature. Even small temperature coefficients of mutual inductance can lead to significant errors in measuring weld currents over this type of temperature range. Similar coils used with resistance welding current meters have shown a temperature dependence of as high as 0.16 %/°C as verified by previous testing <sup>(3)</sup>. If this same temperature sensitivity were present for the built-in coils, current measurement errors of 9.6% or greater could be expected due to temperature effects alone for a temperature rise of 60 °C relative to a reference temperature of 20 °C .

The Rogowski coil has been in existence for approximately 100 years <sup>(4)</sup>. In concept, the Rogowski coil is a relatively simple device that provides a voltage output proportional to the time-rate-of-change of input current. Its main benefit is its amplitude linearity over a wider range of currents. It is assumed in many cases that the linearity is its main benefit. Unlike other sensors where amplitude linearity is a major error source, the Rogowski coil has other unique errors in its practical reduction to practice. These errors include position sensitivity, proximity of ferromagnetic materials, temperature sensitivity, and sensitivity to external magnetic fields. Many of these effects have been documented in the literature <sup>(3,5,6)</sup>. The ease of construction, amplitude linearity, simplicity of the coils, wide variety of physical sizes and shapes, and relatively low cost are the main features which assure the coil's continued use for welding applications. The types of coils tested and that are typically built into welding transformers are shown in Figure 1. The typical coil has dimensions of 7 cm O.D., 5 cm I.D., and a height of 1 cm.



**Figure 1. Coils used for non-built-in coil testing.**

*Mutual inductance* is the is factor that relates the coil output voltage to the current flowing through the coil window or opening. This relationship is given by:

$$V_{coil}(t) = -M \frac{di}{dt}, \quad [1]$$

where  $V_{coil}(t)$  is the coil output voltage,  
 $M$  is the mutual inductance of the coil, and  
 $di/dt$  is the time-rate-of-change of the current.

This classic relationship has been extended into the resistance welding community for a sinusoidal current and to yield a sensitivity parameter. This sensitivity value is often expressed in units of *millivolts per kiloampere*, abbreviated as mV/kA. This sensitivity is the result solving [1] for a sinusoidal current and is given by:

$$V_{coil} \sin(\omega t) = -\omega MI \cos(\omega t), \quad [2]$$

where  $\omega$  is  $2\pi f$ ,  
 $f$  is the frequency, and  
 $I$  is the amplitude of the current.

The coil sensitivity value,  $S$ , is determined from equation [2] by rearranging and solving for the output voltage ratio as a function of current as follows:

$$\frac{V_{coil} \sin(\omega t)}{I \cos(\omega t) 2\pi f} = S = -M. \quad [3]$$

It should be noted that there is a frequency dependence when solving for mutual inductance,  $M$ , using this method. This method is inadequate for the purpose of specifying mutual inductance or a coil's sensitivity because of the confusion created if frequency,  $f$ , is not specified. The Standard does not require the sensitivity to be specified with an associated frequency although it is assumed to be 50 Hz. This confusion is especially bad if a coil is manufactured in a country having a different power system frequency (50 Hz, for example) than where the coil will be inspected or used (60 Hz, for example). It is also worth noting that the above relationship is only valid for a current of a single frequency. This condition is only met for specialized current sources not readily available except in a few specialized testing facilities. Even slightly distorted *near-sinusoidal waveforms* will result in significant errors in the sensitivity or coil mutual inductance value. Calibration and test systems that derive current directly from power mains will usually result in additional errors that are very difficult to assess. Calibration errors generally result from this situation.

Compounding the questionable adequacy of the Standard is the lack of meaningful specifications for the coils. The use of sensitivity (*transimpedance*) of "150 mV/kA" is meaningful only if the single frequency is also specified. A frequency is not specified in the Standard. A "sensitivity" of 150 mV/kA at a frequency of 50 Hz will be 180 mV/kA at 60 Hz. Using equation [3] above to determine the mutual inductance which results in the above sensitivities, yield a mutual inductance value of 0.4774  $\mu\text{H}$  – a value that is independent of frequency or waveform and is traceable to national measurement laboratories through out the world.

There is a significant difference between 50 Hz and 60 Hz values of *transimpedance*. This directly effects import and export markets. Further, coil sensitivity that is based on sinusoidal current is inconsistent with the use of coils in transformers producing dc-inverter welding currents. In this situation equations [2] and [3] have no meaning since the currents are not sinusoidal. If mutual inductance is specified for a coil the relationship of output voltage to current for any waveform is known through applying equation [1] regardless of current wave shape

*Coil position sensitivity*, as used herein, is the change in coil output voltage caused by any changes in the three-dimensional magnetic field shape or distribution that couples to the coil. Factors known to effect the coil output are the relative position of the current carrying conductor in the window or opening of the coil, the proximity of ferromagnetic materials, the shape and size of conductors carrying the current, and current path geometry relative to the location of the coil. Sometimes the coil position sensitivity errors will go completely unnoticed by users although the errors are present. This can occur if, for example, the coil is tested by a manufacturer in one current path geometry and then installed in the welding transformer having a different current path geometry. It is erroneously assumed to still have the same mutual inductance. Only coils having zero positional sensitivity and zero sensitivity to external magnetic fields will have the same mutual inductance. This is not achievable in the most finite sense.

Because of position sensitivity, corrections have to made for the amount of shift in mutual inductance for each type of coil and transformer installation. Inconsistent test methods used by coil manufacturers, such as using distorted waveforms, can also lead to significant differences in coil mutual inductance values. This condition presently necessitates that every transformer/coil combination must be calibrated at the time of installation.

Coil position sensitivity may not be completely eliminated simply by placing the coil inside the transformer. Certainly, it is no longer free to be moved to other positions once installed in a transformer. Differences in coil mutual inductance result because of magnetic field changes external to the coil window such as those caused by current loop connections, bus geometry, and transformer winding configurations. Testing of the coils before installation in transformers may not indicate their performance once installed. Additionally, the coil sensitivity may be greatly influenced by the nearby presence of ferromagnetic materials or the effects of magnetic fields from nearby buses external to the coil or transformer winding configurations. In practical installations, the iron core of the transformer seriously warps the magnetic field. Additionally, leakage flux from the transformer also interacts with the coil. In addition, the return current conductor and pad are in very close proximity to the outside edge of the coil. The latter represents a very serious external field condition for the coil.

The Standard calls for a coil load-resistance of 1,000 ohms to be connected across the coil. It is common practice for weld current monitors and controllers to have an input impedance of as low as 1,000 ohms. Most resistance welding current meters have input resistances in the range of 1 k $\Omega$  to 20 k $\Omega$ . Weld controls have similar input resistances as a result of using coils similar to those for meters. However, modern instrumentation electronics now routinely have input resistances of 1 M $\Omega$  or higher. The following testing considers the possibility of the input resistances to which the coils will be attached by testing at 1 k $\Omega$  and 1 M $\Omega$ .

## **COIL TESTING**

The subject investigation verified, through independent and unbiased testing, some of the significant error sources for non-built-in and built-in coils. Before testing each coil and transformer with a built-in coil was identified by assigning a unique tracking and identification number to it – an HCT number. Throughout the remainder of this paper, the coils and transformers are only identified using this HCT number. All testing was conducted using measurement standards directly and indirectly traceable to NIST (National Institute of Standards and Technology)<sup>(7,8)</sup>. The mutual inductance of the coils under test were determined in ratio against a precision, Machined Rogowski coil. The uncertainty of the reference standard used to determine mutual inductance of the coils under test was  $\pm 0.09\%$  of reading.

### **Non-Built-In Coil Testing**

Five coils were tested which were not mounted in a welding transformer (see figure 1). Two of these coils were of a solid core design, i.e., non-opening. Three of the coils were semi-flexible and of a split-core design. The five coils were from three different manufacturers. The five coils were mounted in a coaxial current configuration for testing.

The initial tests were conducted to establish the nominal mutual inductance value for each coil. This was then converted to a sensitivity value by using equation [3] above. It should be noted that the current waveform was very low in harmonic distortion produced by a precision laboratory current source. The coils were tested at frequencies of 50 Hz and 60 Hz using a sinusoidal current of 240 A<sub>rms</sub>. Further, the frequency was precisely known. The temperature of the coils under test and the reference coil during this testing was 22 °C. The results of the tests are presented in

Table 1. Note that there is approximately a 2.2% difference in mutual inductance or sensitivity values depending on whether a given coil is loaded by 1 k $\Omega$  or 1 M $\Omega$ .

**TABLE 1. Test results for 5 coils in a coaxial test loop.**

Coil HCT Number	Construction	Manufacturer	Coils loaded by 1 M $\Omega$		Coils loaded by 1 k $\Omega$	
			Mutual Inductance, $\mu$ H	%Error relative to Standard of 150 mV/kA at 50 Hz or 180 mV/kA at 60 Hz	Mutual Inductance, $\mu$ H	%Error relative to Standard of 150 mV/kA at 50 Hz or 180 mV/kA at 60 Hz
1626	Solid	A	0.454	-4.9	0.445	-6.9
1627	Split	B	0.491	2.9	0.480	+0.6
1628	Split	A	0.433	-9.2	0.425	-11.1
1629	Split	C	0.490	+2.6	0.479	+0.4
1630	Solid	C	0.490	+2.5	0.479	+0.3

The coils were then measured at 4 progressively increasing temperatures from 21 °C to 43 °C to determine their temperature coefficients. A reference precision Machined Rogowski coil was used to monitor the coils under test. The reference coil remained outside of the thermal environment during the tests. Ratio methods were utilized to determine the mutual inductance values of the coils under test. At each test temperature, the mutual inductance of the coils was determined with a load of approximately 1 M $\Omega$  and 1 k $\Omega$ . The 1-M $\Omega$  load represents a load typical of test instrumentation and the 1-k $\Omega$  load is that specified by the Standard. The results of the temperature sensitivity testing are shown in Table 2. In Table 2, the temperature coefficients are based on measurement data for a 22 °C rise and extrapolated for temperatures of 50 °C and 80 °C. Note that there is about a 2 to 1 ratio between the highest to lowest temperature coefficients if the coils are loaded by 1 k $\Omega$ . There is a 7 to 1 ratio in temperature coefficients if the coils are loaded by a high impedance of 1 M $\Omega$ .

The coils were then subjected to position sensitivity testing in a typical test loop used for this purpose.<sup>(3)</sup> The test loop has dimensions of 9 inches by 9 inches and is constructed using 1-inch diameter conductors. This test was performed to compare the results of these smaller coils to the belt-type coils usually associated with most current meters and weld controllers. This data also allows a comparison of position sensitivity in the test loop to those test geometries chosen later for testing of the coils built into welding transformers.

**TABLE 2. Non-built-in coil temperature test results for 5 coils in a coaxial test loop.**

Coil HCT Number	Construction	Manufacturer	Coils loaded by 1 MΩ			Coils loaded by 1 kΩ		
			Temperature coefficient %/°C	%Error at 50 °C	%Error at 80 °C	Temperature coefficient %/°C	%Error at 50 °C	%Error at 80 °C
1626	Solid	A	-0.035	-1.0	-2.1	-0.043	-1.3	-2.6
1627	Split	B	-0.005	-0.2	-0.3	-0.021	-0.6	-1.2
1628	Split	A	-0.016	-0.5	-0.9	-0.024	-0.7	-1.5
1629	Split	C	-0.025	-0.7	-1.5	-0.033	-1.0	-2.0
1630	Solid	C	-0.030	-0.9	-1.8	-0.038	-1.1	-2.3

Each coil was placed at the following positions in the 9-inch by 9-inch test loop:

- 1) centered front to back and radially,
- 2) centered radially and 2 inches from rear of loop,
- 3) centered radially and 1/2 inch from rear of loop,
- 4) hung off axis and 1/2 inch from rear of loop,
- 5) hung off axis and 1/2 inch from rear of loop and twisted 20°.

At each of these five positions, the coil was rotated in 45° increments through 360°. Each coil was tested in a total of 45 positions. The maximum and minimum mutual inductance values were determined and normalized to the grand mean value of mutual inductance for all positions. The results are presented in Table 3.

There is a significant difference in position sensitivity based on the range values between all coils tested. There is a factor of 4.8 between the coil with the maximum range (HCT 1628) of position sensitivity and the coil with the minimum range of position sensitivity (HCT1630). The impact of this is that there can be a significant difference in manufacturers coil values and the coil value when built into a welding transformer. The amount of difference in these two conditions will depend on the test geometry utilized by a coil manufacturer and the location in the transformer where the coils will be built-in and the current path for the secondary welding loop. The results of the position testing for the split-core coils may change significantly depending on the method and relative locations of the ends of the coils and if they are overlapped or *butted* together. It is worth noting that the split core coil HCT1626 had equal or worse position sensitivity than the solid-core coils.

**TABLE 3. Non-built-in coil position sensitivity results for 5 coils in a 9-inch by 9-inch current test loop (errors are relative to sensitivity stated in the Standard).**

Coil HCT Number	Construction	Manufacturer	% minimum value	% maximum value	% range (max – min)
1626	Solid	A	-4.7	+1.8	6.5
1627	Split	B	-4.1	+2.5	6.6
1628	Split	A	-5.9	+1.7	7.6
1629	Split	C	-2.2	+1.2	3.4
1630	Solid	C	-1.2	+0.4	1.6

The requirement of the Standard is to have a tolerance of  $\pm 3\%$  for a temperature up to 80 °C. For the uninstalled (loose) coils, and based on the temperature sensitivity, position sensitivity, and the mutual inductance values determined in the coaxial cage and in the 9-inch by 9-inch test loop it is doubtful if any of the coils would satisfy the  $\pm 3\%$  uncertainty requirement. A better indication of coil performance will be determined by testing coils built into transformers as described in the next section.

### **Built-In Coil Test Results**

Three welding transformers were tested with built-in coils. All tests for the built-in coils utilized a sinusoidal test current of 560 A at a frequency of 50 and 60 Hz. The current was simultaneously measured using a precision Machined Rogowski coil. Initially, each coil's mutual inductance was determined as installed in the transformer. Then the transformers were heated using circulated water to determine the coil temperature coefficients. Finally, the change from nominal mutual inductance values were determined using 4 different current paths. The current paths were created using 2-inch by 1/8-inch strap formed into different shapes to simulate shunts and guns used on welding transformers. Finally, 4/0 cable was connected to the transformer secondary terminals and the cable was moved in many positions to determine the maximum and minimum outputs from the coils. Only one coil that was built into the transformers was of the same model and manufacturer as the non-built-in coils discussed above.

**TABLE 4. Measured values of mutual inductance for 3 built-in coils.**

Coil HCT Number	Construction	Coil Manufacturer	Transformer Manufacturer	Coils loaded by 1 M $\Omega$		Coils loaded by 1 k $\Omega$	
				Mutual Inductance, $\mu$ H	%Error relative to Standard of 150 mV/kA at 50 Hz or 180 mV/kA at 60 Hz	Mutual Inductance, $\mu$ H	%Error relative to Standard of 150 mV/kA at 50 Hz or 180 mV/kA at 60 Hz
1631	Solid	A	D	0.442	-7.5	0.433	-9.3
1632	Unknown	G	E	0.487	+2.1	0.474	-0.7
1633	Unknown	H	F	0.486	+1.9	0.475	-0.4

Values in Table 4 were determined with a current path similar to that created using bus configuration 1 as shown in Figure 2. Coil HCT 1631 and HCT 1626 are the same model of coil. There is a significant difference in errors, 2.6% loaded by 1 M $\Omega$  and 2.4% when loaded by 1 k $\Omega$  between these coils, as shown in Table 1 and Table 4. This may be attributable to differences in position sensitivity or inconsistency in the coil manufacturing process.

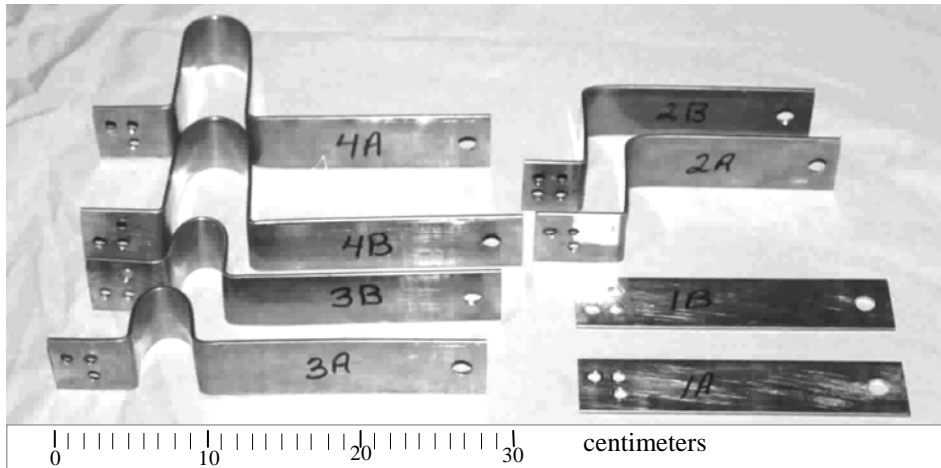
The temperature sensitivity of the coils was tested by circulating heated water through the secondary cooling ports of the transformers. The temperature of the circulating water ranged from approximately 22 °C to 69 °C. The temperature coefficients for each of the three built-in coils are shown in Table 5.

**TABLE 5. Built-in coil temperature test results for 3 coils.**

Coil HCT Number	Construction	Coil Manufacturer	Transformer Manufacturer	Coils loaded by 1 M $\Omega$			Coils loaded by 1 k $\Omega$		
				Temperature coefficient %/°C	%Error at 50 °C	%Error at 80 °C	Temperature coefficient %/°C	%Error at 50 °C	%Error at 80 °C
1631	Solid	A	D	-0.007	-0.3	-0.7	-0.012	-0.6	-1.2
1632	unknown	?	E	-0.014	-0.7	-1.4	-0.022	-1.1	-2.2
1633	unknown	?	F	-0.025	-1.2	-2.5	-0.032	-1.6	-3.2

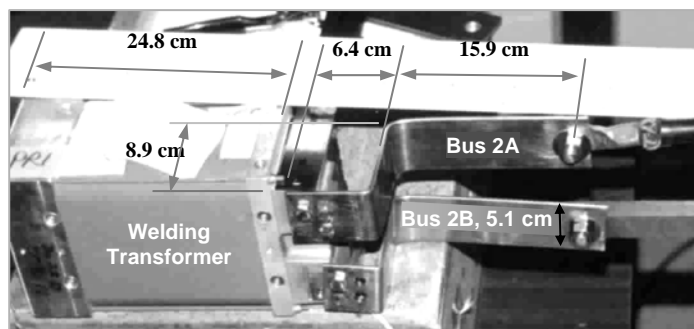
There is a significant difference in the temperature coefficient between the non-built-in coil HCT 1625 and the built-in coil HCT 1631. This difference is unexpected if indeed the coils are the same model and construction. It would be expected that they would have nearly the same temperature coefficient. However, there may be an impact on the loose coil temperature coefficient by confining the normal material expansion that occurs in a non-built-in coil.

The final test conducted on the three transformers was an external field sensitivity test. This consisted of changing the secondary loop or current path rather than moving the coil. This test can be considered an examination of the coil's susceptibility to external magnetic fields. Identical conductors were fabricated using 2-inch wide by 1/8-inch thick strap. The four sets of conductors are shown in Figure 2. These were chosen to simulate current paths for "typical" gun welding systems. Ideally, the coil should not show any change of output in the presence of an external magnetic field. It should be noted that there are additional errors not accounted for in this testing that will effect the mutual inductance of the built-in coils. These errors include rotational and lateral position sensitivities of the coils, variation in consistency of the coils mutual inductance values during manufacturing of the coils and physical termination of the split-core coil ends.



**Figure 2. Four sets of bus bars used to simulate secondary loop paths on welding transformers.**

One set of conductors is shown in Figure 3 as installed on the transformer secondary.



**Figure 3. One set of bus bars connected to a welding transformer.**

A 4/0 cable was also attached to the transformer secondary terminals. The cable was moved around the transformer to search for the maximum and minimum coil output while monitoring for any changes in the current. The relative percentage error between the measured mutual

inductance of each coil and the 0.4774  $\mu\text{H}$  from the sensitivity value as specified by the Standard was determined for these conditions. Test results were obtained with the coils loaded by 1-M $\Omega$  and 1-k $\Omega$  loads. The test results are shown for coils HCT 1631, 1632, and 1633 in figures 4, 5, and 6, respectively.

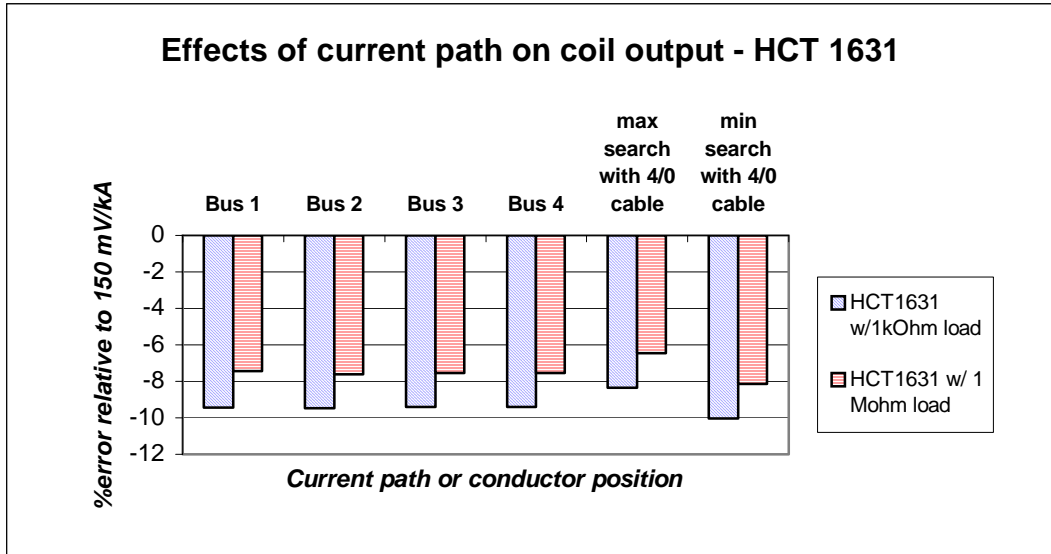


Figure 4. Change in coil output with different external current paths for HCT 1631.

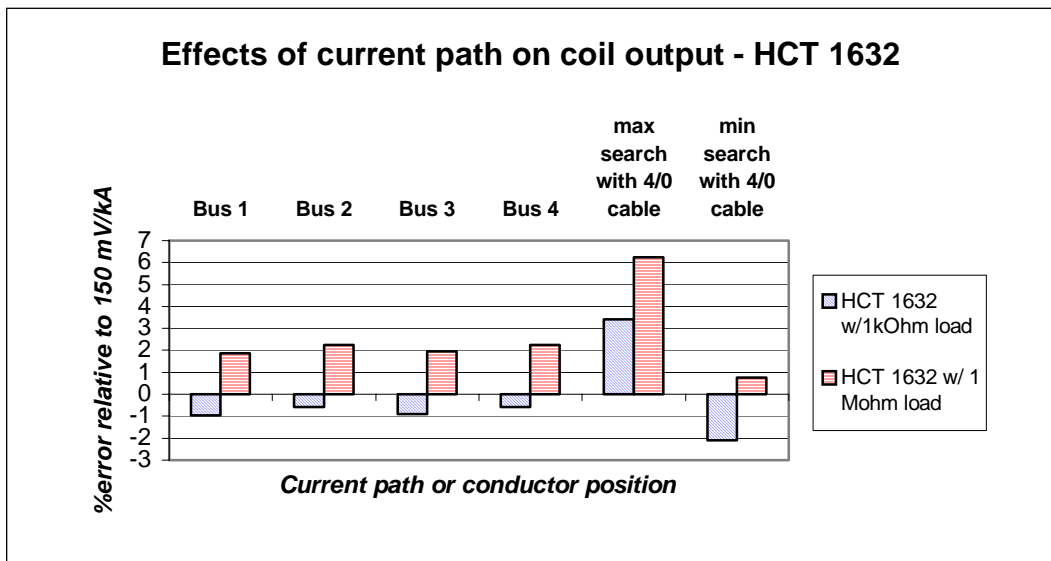


Figure 5. Change in coil output with different external current paths for HCT 1632.

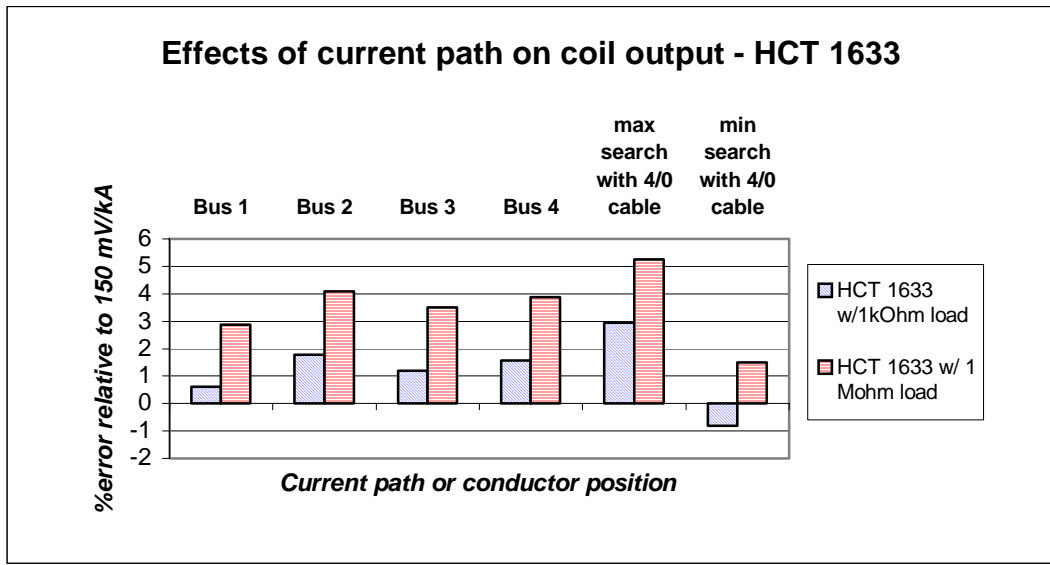


Figure 6. Change in coil output with different external current paths for HCT 1633.

As can be seen by review of the graphs, there is up to approximately 1.1% change with bus connections on HCT 1633. HCT 1632 and 1631 displayed lower effects with HCT 1631 displaying almost no sensitivity to the current paths. However, for some current paths that could be engineered, errors as great as 5% in coil readings are possible relative to 150 mV/kA as required by the Standard. HCT 1631 showed a very low position sensitivity, although its average error relative to the desired sensitivity requirement of the Standard was quite large.

## CONCLUSIONS

The goal of the subject testing was to assess the relative importance of the error sources noted above in the fabrication, procurement, and use of the coils. All testing was conducted using measurement standards directly and indirectly traceable to NIST (National Institute of Standards and Technology). Also, of general importance is whether the goals of the Standard can actually be met in practice. The widespread use of the Standard and the ever-expanding global welding market makes the need to resolve any discrepancies in the Standard as soon as possible.

Because of the differences in coils, it is not presently possible to replace a transformer having a built-in coil with another transformer without recalibration of the coil output. This is normally accomplished using an independent current measurement standard. The calibration takes time and equipment to accomplish. If care were taken and proper methods were used in the construction of the coils, testing of coils, and assessment of mutual inductance of the coils after installation in the transformers, it would be possible to have all coils provide a consistent output between transformers. This would eliminate the need for recalibration with replacement of every transformer. This would further allow weld control manufacturers to preset controls for a transformer with a built-in coil and not have to independently calibrate every coil-transformer combination.

All of the coils, whether built-in or not, had at least one significant error source which could potentially cause it to not satisfy the specifications of the Standard depending on the interpretation of the vague wording the Standard. Whether the errors are significant depends on range of temperatures of the transformer, the proximity of the secondary current path, and the systematic error in the mutual inductance of the coil. It was apparent from the data that some coil manufacturers are producing coils having errors as great as 11%. There is significant concern by the authors that the specifications outlined in the Standard are not being met by the use of built-in coils in welding transformers. Further, for precision welding applications, the use of built-in coils cannot produce consistent current measurements over wide temperature ranges. Without initial and periodic *in situ* calibration of the coil after installation of the coils in the transformers or transformers in welding equipment current measurement uncertainty much greater than  $\pm 3.0\%$  can very likely be expected. Further, the combination of errors (uncertainty) found in this testing will make it difficult for users to accurately control the welding process without additional effort of calibration of the coils to the weld controllers.

Because of the small sample of coils tested, it was not possible to assess the variability involved in multiple coils from manufacturers. In addition to the errors provided above, one cannot neglect the variability in a large population of coils from any one manufacturer. Variations in the placement of coils during the transformer assembly process and end effects of split core coils were not evaluated but are believed to be very significant error sources in meeting the Standard requirements. Further work must be conducted on larger populations of coils and coils built-into transformers to draw a final conclusion as to whether or not it is consistently possible to meet the  $\pm 3\%$  uncertainty up to 80 °C for all transformers.

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