Use and Accuracy of a Clamp-on Direct Current Ammeter

Unabridged Version

Introduction

This paper is about solving cathodic protection problems with a clamp-on direct current ammeter. Clamp-ons can measure interference in a gas pipe or support column, measure anode current on a subsea structure, or find lost CP current due to bad pipeline insulation, defective anode leads, or poor structural electrical contact.

The question is - how much lost current can you find? What is the resolution? Accuracy? Zero offset? The answer depends on:

- The equipment. This paper reports on results using the best DC Amp Clips.™ [Patent 3,768,011 and others pending describe the concepts we use to build our clamp-on ammeters.]

- The application. Accuracy is different with a ¾" cable or a 48" oil pipe.

- The method. A "pig" may leave spots having considerable magnetic intensity. Good use of the Floating Zero Procedure can reduce the error by ten to one.

The Equipment

The results obtained using clamp-on DC ammeters and sensors which are our best DC Amp Clips [MER™ Meter™ specification]. Production includes ¾" to 82 inch diameter aperture sensors. The 6 inch and smaller are clips for one hand use. The 8" to 82" are clamps having two "C" sections which mate at the "lips" and are secured with brass finger nuts on captive studs. This is shown in Fig. 1.

Figure 1. The sensor of a clamp-on DC ammeter is secured around a pipe carrying 1.83 Amp CP current. The sensor is said to be placed in the positive polarity sense because the bridle is nearer the source of positive return current from the earth. The zero control (Z) on the indicator was set so IM read 0.0 when all current in the pipe was cut off. The half percent high reading (IM+ = 1.84 A) is quite likely when the pipe current IC is switched back on.

When the pipe is a bit bigger than the aperture of their clamp, a few persons have asked if clamps "stretch", or if they need to fully close around the pipe. Really, no and yes. For any respectable accuracy, the clamp must close fully around the pipe as shown in Fig. 1.

However, there is no known limit on how big the clamp can be and how small the conductor carrying the direct current to be measured can be. Experiments with a #10 cable more or less centered in the aperture of a 3-foot clamp showed no important change in the precision of the meter. It is best to avoid a small cable held against the side of a big clamp, especially in the lips. Otherwise the error may approach 5%.

There are reasons for having a clamp or clip (sensor) no larger than twice the conductor's outside diameter, all covering and insulation included. Among these:

- Very large sensors cost more and are more easily damaged than smaller ones.
- Very large sensors can be difficult to get on one pipe in the midst of a group of closely spaced pipes.
- The Earth Field Effect (He) of sensors increases with size. This means that the zero offset of the meter will change more as the clamp is rotated in a vertical North - South plane. The equivalent input current change in zero offset is 0 ± 3 mA for a ¾" clip; 0 ± 100 mA for a 13" clamp, and 0 ± .75 Amp (750 mA) for a 48" diameter aperture clamp.

The sensitivity to nearby magnets may also be greater if the clamp is too big.

Resolution

Accuracy is a function of resolution. CP current in a 13" pipe or rail of an electric train can be measured up to 2 Amperes with 1 mA resolution; to 20 Amp with 10 mA resolution, or 200 Amp with 100 mA resolution. From 14 to 82 inch diameter aperture, the resolution is 10 mA on the 20 Amp range, or 100 mA on the 200 Amp range. The 2 Amp and 20 Amp current ranges having 1 and 10 mA resolution may be extended by as much as 5 times using the recorder output connector provided for logging data.

Current Reading - Precision and Linearity

The panel meter reading and the output of the recorder connector are proportional to (a linear function of) the direct current flowing through the aperture of the sensor to within 0 ± 1% of reading, ± 3 least significant decimal counts.

In other words, a meter reading of 1.8 Ampere interrupted current is good to ± 1% of 1.8 Amp (± .018 Amp or 18 mA), except that the last digit may be off as much as 3. On the 2 Amp range, this is ± 3 mA, but on the 20 Amp range this is ± 30 mA.

So 1.8 Amp interrupted current will read:

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1.8 A ± .018 A ± .003A; i.e.,
1.8 A ± 21 mA, or
1.8 A ± 1.2%.
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Measuring by Changing the Current with an Interrupter

When the CP direct current to be measured is interrupted, the accuracy obtainable is better, and quicker than otherwise. For example, if the 1.83 Amp CP current (IC) flowing in the pipe in Figure 1 is entirely due to a rectifier and this rectifier is disconnected, the current changes -1.83 Amp, and IC = 0. The zero control (Z) on the indicator can be set so that the indicator meter reads zero.

After a half minute the rectifier is reconnected, and IC = 1.83 Amp flows. The indicator's meter may show that IM = 1.84 Amp.

This is a current change method of measurement.

It is not necessary to set the panel meter to read zero when the rectifier is disconnected. Instead, when the CP current IC = 0, we can note the meter reading and call it ID. For example, ID may be -0.4 Amp. Then, after 2/3 minute, when the rectifier is reconnected for 1/3 minute we can again note the meter reading and call it IR. For example, IR may be +1.43 Amp. The measured CP current IMC is the algebraic difference. Restated:

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IMC = IR - ID
    = +1.43 - (-0.4) Amp
    = +1.83 Amp
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The greatest anticipated uncertainty is still ± 0.21 Amp. Hence, the real CP current is:

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IC  = IMC ± .021
    = +1.83 ± .021 Amp
    = +1.83 Amp ± 1.2%
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Put another way, the likely CP current is:

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+1.809 < IC < 1.851 Amp
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Unmeasured Current

A disadvantage of the current change or interrupted current method is that an important part of the CP current IC flowing in the pipe may be missed. For example, a serious interference current will not be noticed if it is steady. The current change method ignores constant current.

Constant Current

Suppose that the 1.83 Amp current IC flowing in the pipe in Figure 1 is practically constant for at least 20 minutes - perhaps a day, and it cannot be interrupted. This could be because it is interference current, and the source is out of our control. Or perhaps it is at least partly from sacrificial anodes hard wired to the pipe. Here the indicator's panel meter and recorder output voltage show the algebraic sum of the pipe current IC plus the input current equivalent of the zero offset called IZ. Restated:

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IM = IC + IZ
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For example, if the unknown IZ were -0.4 A; and the true IC were 1.83 A, then the meter would read:

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IM = 1.83 - 0.4 A
   = 1.43 A
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This reading is considerably off the mark. We need to do better.

The cause of zero offset IZ can be a magnet Hn near the sensor (magnetized pipe, rebar, etc.), or the Earth's magnetic field He. Also, if the indicator's zero control is well off-center, there can be a considerable zero offset.

If we knew IZ, the rest would be easy, but generally we do not. Unless, for example, a bond is opened at a known good insulating flange, and the clamp is close by. Likely we need to cancel IZ out.

Canceling IZ by Changing the Sensor

To delete IZ when the current must be constant, we change the sensor instead of changing the current. Changing the clip or clamp's position on the pipe can pretty well cancel out IZ.

Canceling Zero Offset Using a 2 Step Floating Zero Procedure

Generally the simplest way to find true CP current IC with reasonable accuracy is to cancel out IZ. This process can be thought of as "changing the sensor" instead of changing the pipe current. It is not quite as quick or quite as accurate, but it gets the job done.

The usual way to "change the sensor" is to move it. Read the current with the sensor placed on the pipe in a positive sense, as shown in Fig. 1. In this example, the meter reads IM+ = 1.84 Amp. Then turn it over to a negative sense as shown in Fig. 2. Ideally, the effect is to exactly reverse the current reading to IM- = -1.84 Amp.

However the zero offset may have changed somewhat when the clamp was moved. Magnetic effects - He and Hn - are the likely causes. Smaller clips are better. A good 4" clip has less than He = 0 ± 30 mA peak. A good 24" clamp has less than He = 0 ± 300 mA peak.

This "change the sensor" method is called the 2 Step Floating Zero (FZ) Procedure. It is usually quite accurate, and easy to do.

Interpretation is convenient. The most likely magnitude of IC is:

For example, in Figure 1, IM+ = 1.84 A. In Figure 2 IM- = 1.79A. Then the most likely magnitude of IC is:

In this example, the error, i.e., the deviation from the true IC = 1.83 Amp is -.015 Amp (-15 mA).

This 2 step FZ can work just fine. However, there is an element of chance. It can be a lot less accurate than the 8 or 16 step FZ procedure, especially if the pipe or manhole is strongly magnetized, or if the sensor is damaged.

2 Step with 4" Clip on Copper

A 4 inch diameter aperture MER™ Meter2 was used to measure the current in a #16 wire strung north-south. The zero knob on the indicator was set so that IM (Fig. 1) read zero when the clip pointed due east. There was no significant magnetism except the Earth Field. The real He of this clip was 0 ± 13 mA peak.

With the clip around the wire in the positive sense (Fig. 1), still pointing east, the meter read IM+ = +.498 A.

With the clip turned over in the negative sense (Fig. 2), but still pointing east the meter read IM- = -.491 A.

Then the most likely value of IC (average) is:

The true current was 0.500 Amp.

So the error was -.005 Amp, or error = -1% of reading. Since the He spec for the 4" clip is .03 A, the error = -0.2 He.

0.2 H_e accuracy is good with the 2 step FZ.

Figure 2. Here the "sensor has been changed". The sensor in Fig. 1 has been turned over ("changed") so that now the bridle is farther away from the source of positive pipe current IC = 1.83 Amp. This current flows through the aperture of the clamp in the opposite direction from that in Fig. 1, so the polarity of the meter reading IM- is reversed. Instead of positive, IM- reads -1.79 Amp. The ideal reading is IM- = -1.84 A, exactly the reverse of Fig. 1, but in the field it is likely that the Earth's magnetic field He and nearby magnet Hn will cause the reading IM- to deviate from the ideal. A reasonable reading is 2.2% low, i.e., IM- = -1.79 A.

8 Step

For comparison, a full 8 step FZ run gave average IC = 0.498 Amp; error = -.002 Amp; -0.4% of reading; .07 He.

2 Step with 4" Clip on Steel Pipe

Copper, aluminum, lead, etc., conductors do not have internal magnetization, but steel pipe may. The 2 step, was repeated, this time on a 3" diameter, .2" wall steel pipe with some internal magnetism. In a relatively "cool" sector (centerline + 1"), the east pointing 2 step FZ gave:

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            IM+ = .502 A
            IM- = -.492 A
     Average IC = .497 Amp
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Since the true pipe current was still 0.5 Amp, error = -.003 A; -0.6% of reading; -.1 He. Very good!

Chance

However, when a full 8 step FZ was done, the up pointing 2 step gave average IC = .471 A. This worst orientation could have been chosenin the first place and been -.029 Amp in error; i.e., 1 H_e off the mark.

8 Step

The Full 8 step FZ is more reliable. The result was:
average IC = .486 Amp; error = -.014 A; -3% of reading; -.5 He.
This is acceptable at a "cool" sector on steel pipe having mild local magnetism Hn.

General Floating Zero Procedure (FZ)

When the CP current IC in the pipe is constant and cannot readily be changed, the method of measurement is to change the position of the sensor. Meter readings IM corresponding to several sensor clamp positions are averaged. The result is likely closer to the true pipe current IC.

The next examples are taken from data measured* on a lab pipe having a calibrated continuous IC = 0.50 Amp current. This made it possible to find out what accuracy was achieved.

* AutoMER™™ SN 2517 and 4" MER™ Clip #563. The measured He is 0 ± 14 mA peak to peak. The specified maximum He is 0 ± 30 mA peak. The lab pipe is 3.3" OD; has 0.22 wall and is 45" long. It was spot magnetized at various times in connection with the design of Magnetic Error Reduction clips.

The lab pipe is locally magnetized - some places more than others. In the "cool" sectors a two step Floating Zero (FZ) Procedure worked fine. In the very "hot" sectors having a lot of local magnetism, it was necessary to use a 16 step FZ. This utilized 8 different orientations of the clip on the pipe - first in the positive sense and then again in the negative sense. 4 orientations, each read in both the positive and negative sense, will do for most pipes in the field. But the data in Figs. 3 and 4 and also Table 1 shows that 1" left of #4 is a "HOT" sector requiring 16 steps.

AutoMER™™ SN 2517 and 4" MER™Clip #563. The measured He is 0 ± 14 mA peak to peak. The specified maximum He is 0 ± 30 mA peak. The lab pipe is 3.3" OD; has 0.22 wall and is 45" long. It was spot magnetized at various times in connection with the design of Magnetic Error Reduction clips.

Figure 3. In this end-on view, a 4 inch diameter aperture clamp is shown mounted on a 3 inch pipe having 0.2 inch wall thickness. Four shims (s), or preferably a 9/16" foam belt position the clamp so that it is more or less centered about the pipe. The clamp is shown in the nose down orientation. The clamp is in the positive sense, i.e., the bridle is

positioned closer to the source of a known pipe current ICtrue = 0.500 Amp. The meter on the indicator reads IM+ = .479 Amp.

In Figures 3 and 4 the 4 inch diameter aperture MER™ Clip is represented as a clamp. In this end-on view the clamp is oriented nose down on the pipe. The pipe current IC is 0.5 Amp.

Figure 3 shows the clamp in the positive sense, i.e., the bridle is in front of the clamp, out above the page. The current ICtrue = 0.5 A is shown flowing into the page, so the meter reads IM+ = +0.479 A. This was the meter reading in Amperes in my experiment.

The 4 shims were really a 9/16" foam belt, loose on the pipe. Wood or plastic shims have been used, but a foam belt works better.

Figure 4 again shows the clamp on the pipe in the nose down orientation, but this time the clamp is in the negative sense; i.e., the bridle is down into the page. So when the ICtrue = 0.5 Amp pipe current flows into the page, the current IC is flowing through the clamp's aperture and out into the bridle - the reverse of the positive sense. So the meter on the indicator shows IM- = -0.461 Amp. This too is the current measured in lab setup.

Figure 4. This end-on view is similar to Figure 3 except that the 4" clamp is in the negative sense, meaning that the bridle is into the page, farther away from the source of a known 3" pipe current ICtrue = 0.500 Amp. This causes the meter on the indicator to show a negative number. Here IM- = -.461 Amp. The negative sign on the meter shows that the current is flowing from above the page, through the aperture of the clamp, and out past the bridle. This is the reverse of the positive polarity symbol marked on the clamp.

The zero control (Z) in Figs. 3 and 4 should be set when the FZ procedure is started, and then not touched. Straight up is a good guess. In my experiment the meter read zero (IM = 0) when the clip was held in a magnet free sector (except for the Earth's magnetism), in a vertical plane, pointing east. Since the lab pipe was horizontal, running north-south, this was a good start. But it is not essential. The FZ cancels out zero offset error due to indicator miss-adjustment as well as zero offset error due to magnets - both local and Earth.

What is essential is that the zero adjustment (Z) not be touched once a FZ run is started. Changing the zero control (Z) on the indicator during a FZ run invalidates the run. The data is likely bad.

Two Step FZ

Combining Figures 3 and 4 yields a two step FZ run. In Fig. 3, IM+ = .479 A.

In Fig. 4, IM- = -.461 A.

The scalar magnitude average is IC = .470 A.

The error, i.e., deviation from ICtrue = 0.5 A, is E = -.03 A, or E = -1.0 He equivalent.

This -30 mA error is equivalent to 1.0 times the He specification of the 4" clip used. It is more than we want to see, but it is better than no FZ. In the single reading IM- = -.461 , E = -.039 A, or -1.3 equivalent He.

Eight Step FZ

To help organize the data for a FZ run, we can use a chart such as Table 1. Clamp orientations can be represented by arrows for nose up, down, east, and west. The four positive clamp sense readings IM+ are presented in the column to the right of orientation, even if they are negative when read from the meter on the indicator, and they are written as negative. The currents shown are what was measured on the lab pipe with 4" MER™Clip #563.

Table 1

Summary of Eight "Square" Current Readings "Hot" Pipe Location: {1" left of #4}			
Current Reading IM- Negative Clamp Sense	Clamp Orientation	Current Reading IM+ Positive Clamp Sense	Orientation Scalar Average
-.447 A	East	+.465 A	.456 A
-.411 A	West	+.450 A	.431 A
-.466 A	Up	+.510 A	.488 A
-.461 A	Down	+.479 A	.470 A
		Average: IC =	.461 A
		Known True IC =	.500 A
		Error =	-.039 A
		Error =	-1.3 He

The four negative clamp sense readings IM- are presented in the left hand column, even if they are positive, and in such a case they are written as positive.

The result shown in Table 1 is a disappointment. This {1" left of #4} sector on our lab pipe is "Hot". The "square" 8 step FZ is no better than the 2 step. Sixteen steps are needed at this sector.

The question is - How to know that a particular pipe sector requires a 16 step FZ?

"Hot" Sector Recognition

Table 1 is for a "hot" steel pipe. Other FZ runs may be on a lead cable or copper pipe - not magnetic in themselves, but positioned in a "hot" manhole or building adjacent to magnetized material. In any case, we want to know if the readings are "hot."

Table 1A highlights the deviation of individual current readings from the scalar average of all - called the "Reference Average." The largest are -.05 A and +.049 A. These are -1.7 He and +1.6 He. In other words, the "square" orientation data is spread about a lot more than the Earth Field specification He for the 4" clip used. This is the warning to do what we can to get a more reliable result.

Table 1A

Deviation Annotated Summary of Eight "Square" Current Readings Hot Pipe Location: {1" left of #4}					
Scalar Deviation From Average IC = .461 A	Current Reading IM- Negative Clamp Sense	Clamp Orientation	Current Reading IM+ Positive Clamp Sense	Scalar Deviation From Average IC = .461 A	Orientation Scalar Average
-.014 A	-.447 A	East	+.465 A	+.004 A	.456 A
-.05 A	-.411 A	West	+.450 A	-.011 A	.431 A
+.005 A	-.466 A	Up	+.510 A	+.049 A	.488 A
0 A	-.461 A	Down	**+.479 A**	+.018 A	.470 A
Reference Average: IC =					**.461 A**

Table 2 is a summary of the 8 "square" current readings of Table 1 with 8 more "angle readings added. The "angle readings are taken with the clamp orientated more or less half way between the adjacent "square" orientation. Both are measurements made with 4" MER™clip #563 on the 3 ¼" lab pipe.

The results in Table 2 are more encouraging. The Error (difference between the calculated average IC - .490 A and the known true IC = .500 A) is -.01 Amp. This is a lot (4 times) better accuracy than the 2 step or 8 step and it may be about as well as can be done. The -.01 A error is only -.33 He, i.e., 1/3 of the 4" clip's Earth Field effect rating.

Table 2

Summary of 16 Step FZ Procedure "Hot" Pipe Location 1" Left of #4			
Current Reading IM- Negative Clamp Sense	Clamp Orientation	Current Reading IM+ Positive Clamp Sense	Scalar Average of Current Reading at Orientation
-.447 A	East	+.465 A	.456 A
-.609 A	East	+.643 A	.626 A
-.411 A	West	+.450 A	.431 A
-.612 A	West	+.650 A	.631 A
-.466 A	Up	+.510 A	.488 A
-.386 A	Up	+.421 A	.404 A
-.461 A	Down	+.479 A	.470 A
-.393 A	Down	+.433 A	.413 A
		Average: IC =	.490 A

In the field where the true current IC is known only by our measurements, how do we show that this is accurate? Suggestions:

1. Move to another location on the pipe. Be close enough so that the true current is likely the same, and measure there. If the results agree within 1 He, their average is the best bet.

2. If the diameter of the pipe exceeds 5 inches, increase the number of clamp orientations. Likely 16 orientations will work better on a 10" to 14" pipe.

3. Change the method of calculating the average IC. Throw out the "hot" data and use only the "cool" data. This method is illustrated in Table 2A. In Table 2A, called "hot", any reading having a deviation from the average IC = .490 A greater than 2 He. The 4" clip #563 has He = .030 Amp, so any deviation over .060 Amp is highlighted as "hot".

In Table 2A, shown is the orientation scalar average for only the 3 "cool" rows having deviation less than 2 He.

Table 2A

This is Table 2 plus deviations from average IC = .490 A.
Deviations greater than 2 He are highlighted.

Calculate average IC using only "cool" orientations wherein
the deviation of both IM+ and IM- is 2 He or less.

Rows having a highlighted high deviation are not used.

Scalar Deviation From Reference Average IC = .490 A	Current Reading IM- Negative Clamp Sense	Clamp Orientation	Current Reading IM+ Positive Clamp Sense	Scalar Deviation From Reference Average IC = .490 A	Orientation Scalar Average
-.043 A	-.447 A	East	+.465 A	-.025 A	.456 A
+.119 A	-.609 A	East	+.643 A	**+.153 A**	
-.079 A	-.411 A	West	+.450 A	-.040 A	
+.122 A	-.612 A	West	+.650 A	**+.160 A**	
-.024 A	-.466 A	Up	+.510 A	+.020 A	.488 A
-.104 A	-.386 A	Up	+.421 A	-.069 A	
-.029 A	-.461 A	Down	+.479 A	-.011 A	.470 A
-.097 A	-.393 A	Down	+.433 A	-.057 A	
				Average: IC =	.471 A
				Error =	-.029 A
				Error =	-1 He

The "use of this cool, delete the hot" method is a help. It gives IC = .471 A, less than true by one He. It serves as a check on other methods, and adds confidence to their result.

In Table 2A, the average of the three remaining "cool" rows is IC = .471 Amp. The error with respect to the known true IC = .500 Amp is -.029 Amp, i.e., -1 He. So this worked well enough in the lab.

Summary of Several FZ Runs

Confidence in the practical accuracy - say within ± 1 He - is gained when the result of several FZ runs pretty well agree.

"Hot" lab pipe location {1" left of #4} current IC has been measured four ways:

a. Two step FZ, Fig. 3 and 4: Result: IC = .470 Amp
b. Eight step FZ, Table 1: Result IC = .461 Amp
c. Sixteen step FZ, Table 2: Result: IC = .490 Amp
d. Deviation less than 2 He, Table 2A: Result: IC = .471 Amp

All four agree within 1 He, so we can have confidence that IC is likely between .461 and .490 Amp. Is there a basis for selecting one of the four results? Perhaps yes.

Selection Criteria

Preferred is the use of the result obtained by averaging all the current readings available. This is c) above; i.e., Table 2, where average IC = .490 A. However, some of the readings are "hot". Is it reasonably safe to rely on Table 2?Perhaps yes, on condition its result is within one H_e of the rest.

To see if this condition is satisfied, compare the average IC = .490 Amp obtained from the 16 step FZ of Table 2 with the other three.

In a), IC = .470 Amp. The deviation is -.02 A; i.e., -.7 He; This is acceptable.

In b), IC = .461 Amp. The deviation is -.029 A; i.e., -1 He. This is acceptable.

In d), IC = .471 A. The deviation is -.019 A; i.e., -0.6 He. This is acceptable.

Conclusion: We estimate we can rely on Table 2, the 16 step FZ called c), and say: "quite likely IC = .490 Amp, within ± He."

Conclusion

If in doubt, or especially when the pipe is "hot":

- Use all 4 methods (a, b, c, and d, in the Summary, above).
- Pick 3 or 4 that agree within one He from these.

Use the result of the method having the most steps.