Structure, Durability, and Accuracy of a Permanently Mounted and Buried Clamp-on Direct Current Ammeter

Introduction

A customer needed to periodically measure the current in a gas pipeline in the eastern part of The Netherlands which is under the influence of heavy stray currents of the railroad.

Three clamp-on ammeters with 32 inch diameter aperture MER™ Meter® type clamps were installed on the pipe. In September 1997 they were buried at about 2 meters depth. Useful measurements have been made. The clamps and all have been working satisfactorily.

The purpose of this paper is to:

- Outline the structure of the MER™ Meter type clamps;
- Show why we expect they will continue to work satisfactorily for a lot longer than 3 years;
- Show what accuracy and resolution can be expected.

Clamp Structure

Figure 1 outlines the structure of the clamps. Each clamp resembles an AC current transformer in that there is a core of high permeability magnetic steel ƒe surrounded by a winding Ns. To measure direct current, this winding is connected to an indicator having electronics for sensing the magnetic state of the core and driving an appropriate average current is back into the winding N_s.

Figure 1

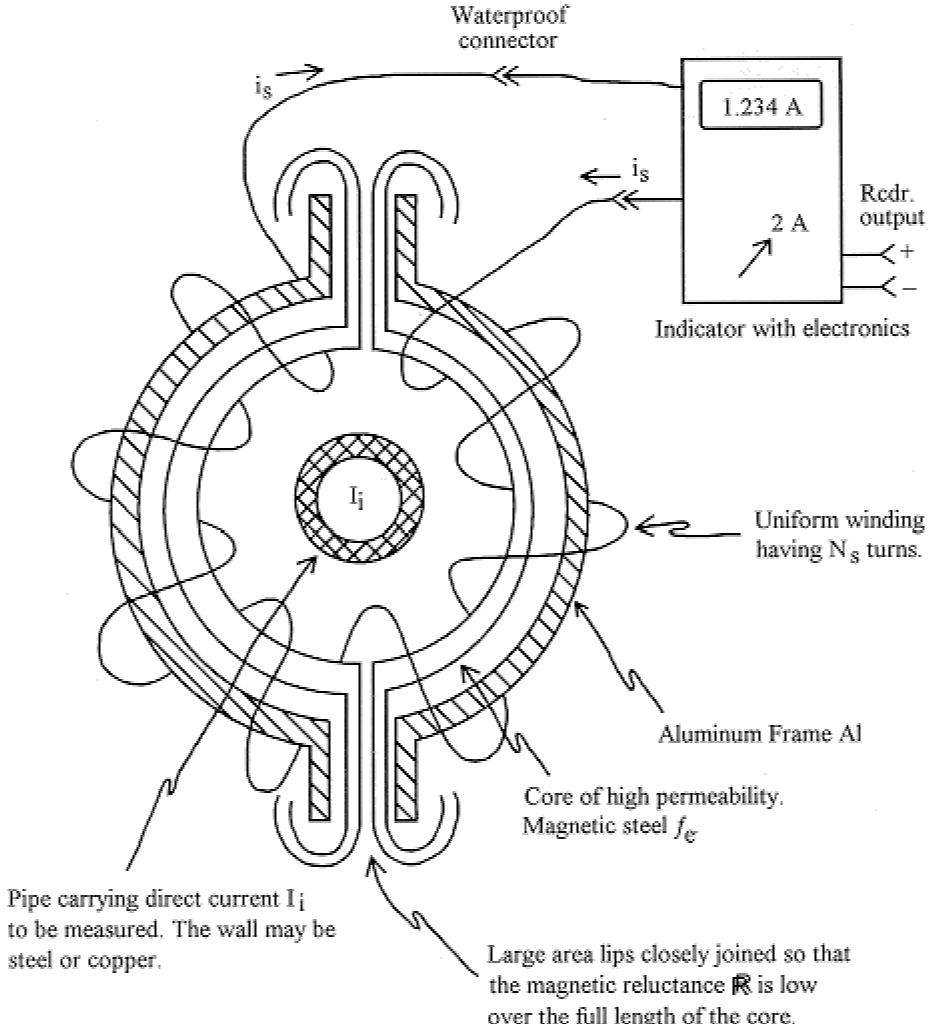

Figure 1. Structure of Clamp

This current is flowing in N_s sets up a magnetic field which, on average, balances out the field set up by the input current I_i flowing in the pipe. Thus the average magnetic state of the core is near neutral.

The indicator has electronics for converting the average value of is into a digital presentation of the magnitude and polarity of the input current I_i flowing in the pipe. It also provides an output voltage at the recording jack (Rcdr) which is proportional to the input current I_i .

The finished clamp structure is quite rugged. Figure 1 shows an aluminum frame Al which supports the core fe during winding, etc. Fiberglass cloth insulating tape is used in several locations both to insulate and to bind the parts together so that they are firm - even before the epoxy. A thick coat of epoxy overall acts to both protect the winding and core, and also to stiffen the final assembly so that it holds its shape during normal use.

A low reluctance RR magnetic path all around the core and through the lips improves electrical stability and accuracy. This is helped by the large area lips shown in Figure 1. These also hold the bolts for securing the two half sections of the clamp to one another. For field portable use, we fix brass studs to two of the lips, and drill matching holes in the other two lips. Heavy brass thumb nuts on the studs firmly bind the lips. For permanent installation we use nylon hardware to minimize corrosion when buried for an extended time.

Clamp Stability

When a clamp is permanently mounted on a pipe and then buried underground or undersea, it is exposed to water with minerals from the soil and/or salt from the sea. The thick epoxy coating and a special seal at the lips may not prevent water penetration, especially if it is buried in deep water, or if the epoxy coating is cracked.

After considering vacuum impregnation, flexible seals, etc., there was a test ran on an unprotected standard 5 inch clamp in a 3 gallon container of Gulf of Mexico saltwater. Thankfully it has been stable over the past 5 years, even though there is abundant evidence of winding leakage and corrosion. A much longer service life can be expected with accurate performance when using a well epoxied and sealed clamp, than with one that is penetrated by sea water.

Design of Clamp is Intrinsically Tough

The clamp shown in figure 1 is intrinsically tough with regard to electrical leakage and corrosion. There are at least two reasons.

The first is low impedance. In figure 1, the inverter part of the MER™ indicator drives the winding Ns with switching current is which has a peak magnitude of about 0.4 Ampere. Since the source voltage is about 12 Volts, the impedance can be thought of as:

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12 Volt
------- = 30 Ohm
0.4 Amp
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Moreover, the circuits are balanced, so even when clamp leakage is severe, it does not much change the overall accuracy of direct current measurement

Secondly, the magnetic state of the steel in the core is the comparator. This is where the magnetic field set up by the input current I_i flowing in the pipe is equated to the magnet field operating on core fe due to the average value of inverter feedback current is flowing in winding N_s .

Steel, even the fine type we use, is tough. Since the functioning is symmetrical, some change in properties does not much alter overall accuracy. Some of this toughness, was found that after nearly 5 years, the 5" standard clamp having 1 mA resolution drifted only about ± 15 mA (He/3). Moreover, its gain (sensitivity) changed only about ± 1%. All this when tested both in and out of saltwater.

Stability of 5 inch Clamp in and out of Saltwater for 5 Years

This section includes a summary of data measured on an unprotected 5 inch standard Sea Clamp in and out of Gulf of Mexico water for the better part of 5 years.

Conditions

The clamp was constructed as outlined in Figure 1. The aluminum frame Al is made of 3/4" wide by 1/8" thick bar stock long enough so that the core, winding, tape, and epoxy coating will allow for at least a 5.0 inch diameter aperture clearance on the inside for the pipe to be measured.

The core ƒe is formed from 5 layers of high permeability nickel - steel laid on the inside of the aluminum frame. Glass cloth tape holds Al and ƒe together and insulates them from the winding. The winding N_s is about 1000 turns of #22 transformer wire. This too is taped in place with glass cloth adhesive. This is all of the protection provided for what can be called the "Tank" test.

In production use we always apply a thick conformal coat of tough epoxy. However, this was omitted for the tank test so that the saltwater could readily get at the vital parts of the clamp.

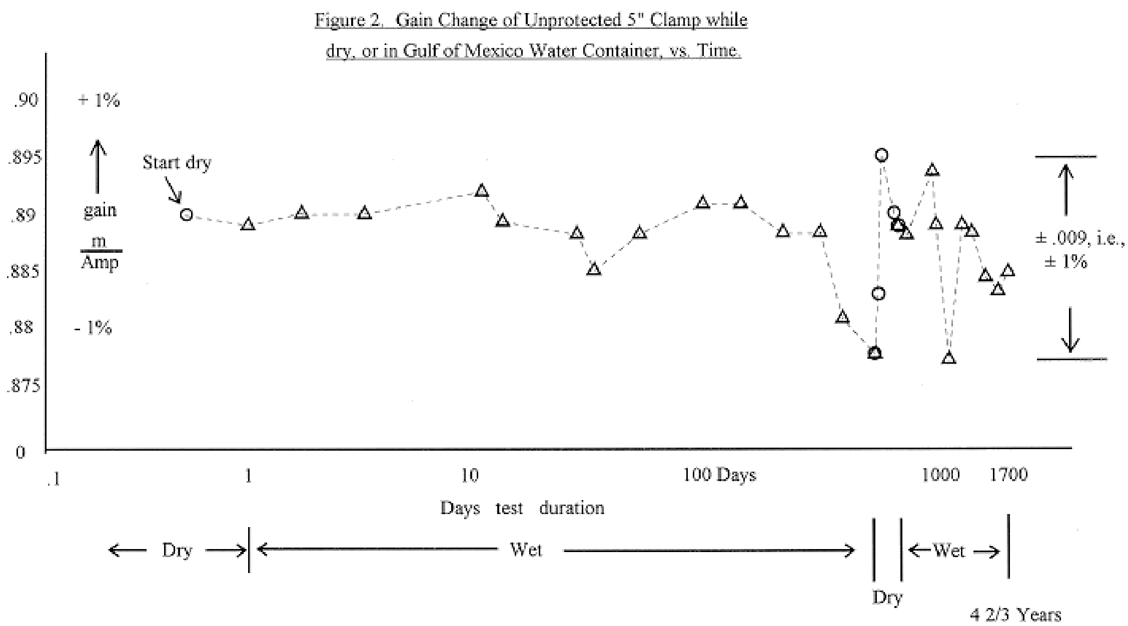
After adding 40 turns of #22 PVC insulated wire over the clamp to carry an input current to be measured, the clamp was placed in an empty 7 gallon plastic container on the lab floor between desks. The lips were bonded and firmly tied with lacing cord. While still dry, a standard type indicator, lab tester SN 0044, was used to measure gain (sensitivity), zero offset, operating frequency, and several other indicators of performance and possible damage such as leakage.

Then several gallons of Gulf of Mexico beach saltwater were put in the pail, and measurements repeated, time after time, over a 1700 day time interval.

Gain

Figure 2 summarizes the gain measurements. Since indicator SN 0044 has a digital meter, the gain or sensitivity was measured as the meter’s change m per ampere change input current Ii.

Figure 2

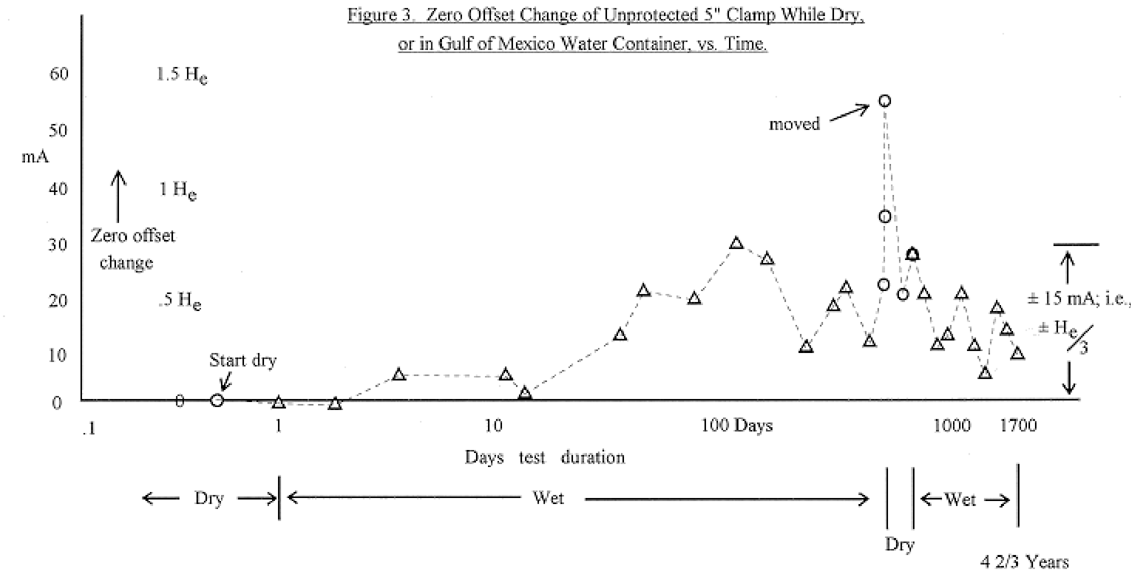


The many gain measurements are shown on Figure 2. The gain changed less than 1/3% from the dry reading when the saltwater was first added on day one. The clamp was in saltwater ("wet") for 466 days before we pulled it out of the tank ("moved"). Still, Figure 2 shows that the gain stayed within ± 1% of nominal, just a fraction of a percent less than the starting dry reading.

Zero Offset

The change of zero offset over 5 years is graphed in Figure 3. Zero offset is the difference between zero and the meter m reading when the input current I_i is zero. The initial zero offset was about 42 mA equivalent input current due to an unbalance in the indicator when its zero adjustment was disabled. This remained constant so it was subtracted from the meter reading. The remainder is the change in zero offset over time. This is what is shown in Figure 3.

Figure 3



On 15 Dec 1995, the zero offset changed only 1 mA as the water from a Gulf of Mexico beach near our home was poured into the tank over the 5 inch clamp. The zero held for 466 days to within 30 mA of the dry start.

The zero offset data was normalized in terms of the Earth Field Effect (H_e) rating of the clamp. A new 5" clip is specified to change its zero offset less than 80 milliamperes equivalent input current Ii when rotated full circle in a north-south vertical plane. This is the peak-to-peak H_e specification. The specified maximum deviation about neutral is 0 ± 40 mA or less. This is the He spec used for normalizing zero offset data.

In Figure 3, I show that over 463 days, the zero offset changed ± 15 mA about a mean shift of + 15 mA. Normalized, this zero shift is ± He/3 about a mean of + He/3 .

Inspection and Dry Out at Day 466

In February 1997 the 5" clamp was pulled ("moved) out of the tank and began to dry it out. We saw what appeared to be corroded aluminum in the form of jelly behind the lips and at several spots on the outer periphery of the clamp. The steel at the lips was dark and tarnished. Some wet black powder showed on the edge of the steel near the end of the aluminum lip.

Figure 3 shows that during the move, the zero offset shifted positive an extra 25 mA (2/3 He), and then while drying out it drifted back to normal. It stayed in this region during the ensuing 94 day "dry" time. The tank was emptied and cleaned.

Return to Wet

In July 1997 the clamp was put back in the tank and new water from our Gulf of Mexico beach was added. The double point signifies that the zero offset change was less than the 1 mA resolution as the new saltwater was poured on the dried out clamp.

For the rest of the time to 12 August 2000, the "wet" clamp’s zero offset held well within the original ± 15 mA (± He/3) range.

All in all, it seemed to me to be a good result.

Gain at Dry Out and Return to Wet

Figure 2 shows the effect of taking the clamp out of the tank ("move"). Gain quickly increased 2% at day 466. And, as with zero offset, gain returned to normal over the 94 day dry out.

Gain did not change when new Gulf water was added in July 1997. This is shown as a double entry. The gain was .889 (meter reading / Ampere input current Ii) both dried out and when new saltwater was added. And gain held within ± 1% of .885 m/Amp for the rest of the time to 4.7 years.

A pleasing result.

Corrosion

The stability of this unprotected 5" clamp for over 5 years in saltwater was noteworthy. What follows may be a partial explanation.

In Figure 1, the mass of the aluminum frame Al is much greater than the mass of the core ƒe. And they are in metal to metal contact at the lips. Therefore, the aluminum acts as a sacrificial anode to protect the core.

To verify this, I reviewed the operating frequency of the inverter working with the clamp. It stayed near the 223 to 225 Hz range over the full 4.66 years. The shift was fairly steady and upward, on average 0.6% over 5 years. And there were other changes that could have caused a ½% change in frequency. So in conclusion the core ƒe lost no more than 1% of its mass over 5 years. The aluminum did protect the steel.

In Figure 1 the mass of the aluminum frame Al is comparable to the mass of the copper magnet wire winding N_s. And the winding has a fine double layer coating of insulation. So the aluminum Al protects the copper winding N_s .

This is based on the observation that in December 1995, the DC resistance of winding N_s was 2.8±.1 ohms. In May 2000 and August 2000 it was still 2.8±.1 ohms. So there is no loss of copper within my resolution of 4%. This shows the copper was protected by the aluminum. There was leakage that indicated partial failure of the magnet wire insulation.

Leakage

In August 2000 after 4½ years of saltwater, the clamp leakage was tested between the winding and the aluminum core Al which is electrically connected to the core ƒe in Figure 1. Depending on the test method used, it was somewhere between 20,000 ohms and 360 ohms. The open circuit voltage was 0.38 Volt, aluminum negative. The source resistance was 18,000 ohms.

At the start in 1995, the dry clamp had greater than 30 Meg Ohm leakage and no measurable (<.1 mV) potential. After 4 days "wet", I found 0.25 Volt, but the source resistance was many Meg ohms. Over "wet" time, the voltage reached 0.9 Volt in March 1997, and then began decreasing. But the source resistance kept decreasing all the "wet" time.

Thus there was plenty of opportunity to lose copper. That the loss was less than 4% leads me to believe the copper was protected by the aluminum.

Accuracy and Resolution

The standard indicator used with the 5" clamp and used to get the data shown in Figures 2 and 3 has a resolution of 1 milliampere direct current on the 2 Amp range. For measuring a change in direct current, the typical accuracy is 0 ± 1% of the current measured ± 2 digits.

If the current to be measured cannot be interrupted, the possible zero offset error should be considered. When measuring current flowing in a non-magnetic pipe or cable in a non-magnetic environment, the Earth's magnetic field effect H_e is likely to be the primary cause of any zero offset error. Our He specification for a MER™ type 5" clamp is less than 0 ± 40 milliamperes peak equivalent input current about a mean value when the clamp is rotated full circle in a north-south vertical plane. The indicator has a "Zero" adjustment which can be used to cancel zero offset error as the clamp is held in the same spatial orientation as it will have when placed on the conductor carrying the current to be measured. Then the zero offset error may be reduced to 10 mA or less.

However, there is a difference if the environment contains magnetized metal within 3 to 10 clamp diameters (15 to 50 inches for a 5" clamp) of the clamp's position on the conductor carrying the current to be measured. This is especially true if it is a steel pipe with spots of strong local magnetism due to a magnetic quality control process. Then a form of the Floating Zero Procedure should be used when installing the clamp.

Broadly, this involves moving the clamp longitudinally up and down the pipe so as to avoid magnetic hot spots, and then reading the current with the clamp on the pipe, first positive or normally, and then reversed so that the current reads negative. The readings should be similar in scalar magnitude but opposite in polarity when the clamp is in an adequate location and the indicator's "Zero" adjustment is well set.

When a 5" clamp is installed using the full Floating Zero Procedure correctly, I expect the "Zero" adjustment can be set so that the zero offset error is less than 30 mA, i.e., less than 2/3 the peak to peak He specification for the clamp used. H_e is ± 40 mA for a 5" clamp; or ± 450 mA for a 32" clamp.

Overall Accuracy

The likely accuracy, over time, depends on the usage and installation. Two examples:

a. When a MER™ Meter is used to measure the interference direct current in a pipe due to a nearby DC electric railway, the likely overall accuracy is within ± 2% of the current measured. On clamps up to 13" diameter aperture, this is with 1 mA resolution to at least 2 Amperes, or 10 mA to 20 A, or 100 mA to at least 100 Amperes. The uncertainty of gain change over time can be avoided by providing a test wire linking the clamp and then periodically calibrating the gain. Zero offset cancels out because it is expected to be the same before, during, and after the transit of a locomotive.
b. The accuracy is not as good when a MER™ Meter is used to monitor a more or less constant direct current flowing in a pipe to assure proper long term cathodic protection. While multiple error sources seldom add directly, the uncertainties include:
    1. 0 ± 1% initial gain.
    2. 0 ± 1% gain change over time. See Figure 2.
    3. 0 ± 2/3 H_e initial zero offset.
    4. 0 ± 1/3 H_e zero offset change over time. See Figure 3.
    5. Clamp damage due to intrusion of a foreign body.

Foreign body intrusion will be hard to predict and evaluate. For example, a magnetized tool or a length of magnetized pipe dropped near the clamp could cause several amperes change in zero offset. Or an impact could bend the clamp, altering gain and zero. If the indicator's change in output is abrupt, the user will want to see if there was an accident near his pipe. If there is a need to look further, SMC has a quality control tool capable of measuring several clamp characteristics in situ.

For the most part the user can get, over a 5 year interval, data good to ± 2% of measured current, ± H_e specification for the clamp used, ± 3 least significant indicator digits, i.e., ± 3 mA on a 5" clamp. On the other hand, I expect measurement of a current change, occurring over a time less than a month, will be good to within ± 2% of the measured current, even when the change occurs years after installation. H_e will cancel out.

Conclusions

A type of clamp-on DC ammeter has been built which is suited for permanent mount on a pipe. The MER™ type clamp is fit to be buried with the pipe so as to make accurate measurements of magnitude and direction of current flowing in the pipe. The service life of a well protected clamp is expected to be a lot more than 5 years, even in saltwater.

The indicator operates in a protected environment. With a 32 inch clamp it outputs a voltage proportional to pipe current from ± 10 milliamperes to more than ± 60 Amperes when operating in the 20 Amp range.

The MER™ type clamp is intrinsically resistant to environmental stress. A 5" sample stayed accurate for 5 years in and out of saltwater, even though it had no protective covering. It could do this, partly because it is primarily made of high permeability steel and copper magnet wire. These are on an aluminum frame which supports it, and also provides cathodic protection for the copper and steel.