WHITE PAPER:

EFFECT OF EXTERNAL ELECTROMAGNETIC FIELDS ON THE MEASUREMENT, FAULT LOCATION & PROTECTION SCHEMES OF CURRENT TRANSFORMERS VS PERFORMANCE OF OPTICAL CURRENT TRANSFORMERS.

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Consideration of interference from an external field for any type of turn.

Introduction.

Optical current transformers have numerous advantages over conventional transformers. Two of them would be:

- No interference on electrical circuits external to the measuring turns.
- Complete indifference to where and how the magnetic field source is located within the measuring loop.

This small study will demonstrate both claims, and will open up new options for the management of differential protections.

Statement of the problem.

If optical fibre is used to measure current, closed loops are formed, which may have one or more loops, but all of them define a measurement surface S.

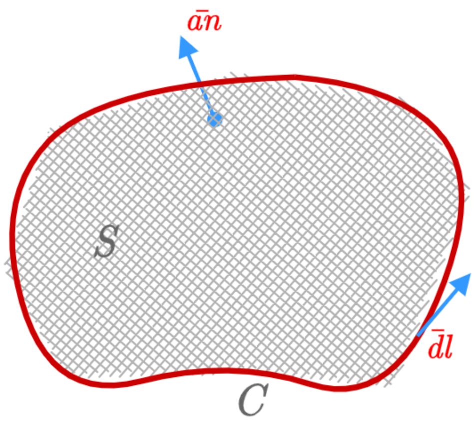

Figure 1

This coil does not have to be circular and can be of any shape, including its size, that is, it can be very small or large. When defining a surface S, associated with it, a unit vector orthogonal to that surface is defined, . A contour, C, and directly the unit vector that runs through it, are also defined, .$\overline{a_n}\bar{d}l$

Currents can pass on this surface, either internally to the surface or externally to the surface. A current transformer, therefore, must be able to measure the current that crosses that surface, and be totally refractory to the external currents defined to that surface.

Theoretical resolution

Obviously, the most correct approximation would be from Maxwell's laws, which operate both for the electric circuit and for the behavior of the change in polarization of light, due to the presence of a magnetic field.

To do this, we start from Maxwell's equations:

$$\nabla \cdot \bar{D} = \rho_v \tag{1}$$

$$\nabla \cdot \bar{B} = 0 \tag{2}$$

$$\nabla x \bar{E} = -\frac{\partial \bar{B}}{\partial t} \tag{3}$$

$$\nabla x \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t} \tag{4}$$

On this surface we can have external and internal current densities, as shown in Figure 2.

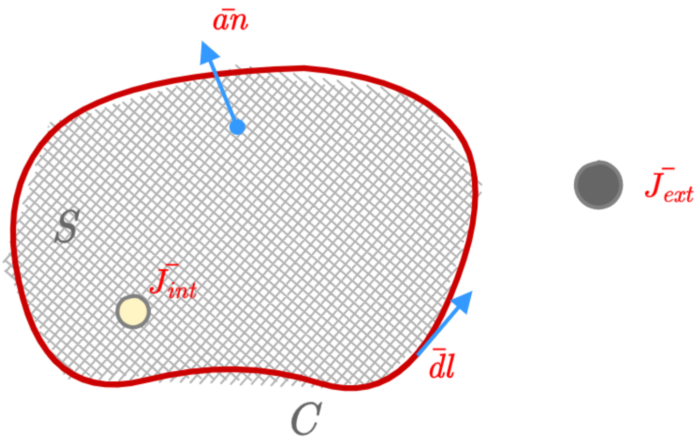

Figure 2

If we apply Stokes' theorem to equation (4) on the surface S, the result would be:

$$\int_S \nabla x \overline{H} \cdot \overline{ds} = \int_C \overline{H} \cdot \overline{dl} = \int_S \overline{J_{int}} \cdot \overline{ds} + \int_S \frac{\partial \overline{D}}{\partial t} \cdot \overline{ds} \tag{5}$$

Since the entire environment is a nonmagnetic dielectric, we can safely assume that:

$$\overline{H} = \frac{\overline{B}}{\mu_0} \tag{6}$$

Therefore, there are no ferromagnetic material conditioning factors, where magnetic permeability with hysteresis cycle is defined.

ϕ VThe change in the polarization of light due to the presence of a magnetic field (Faraday effect) is given by the Verdet's constant of said material, which depends on the temperature and wavelength of measurement, but not on the magnitude of the magnetic field. The value of the change in polarization of light due to the presence of a magnetic field, along a line defined by a contour, was given by:

$$\phi = V \int_C \overline{B} \cdot \overline{dl} = V \int_C (\overline{B_{int}} + \overline{B_{ext}}) \cdot \overline{dl} = V \int_C \overline{B_{int}} \cdot \overline{dl} + V \int_C \overline{B_{ext}} \cdot \overline{dl} \tag{7}$$

Logically, the value of the magnetic field $\overline{B}$is the sum of the external and internal magnetic fields, that is, those generated by external current densities and those generated by internal current densities.

Ampere's law tells us that the second term is zero, since its sources are outside the C boundary

This change in polarization can be calculated directly, by placing the value of the magnetic field defined in (5):

$$\phi = V \int_C \overline{B_{int}} \cdot \overline{dl} = V \mu_0 \int_S \overline{J_{int}} \cdot \overline{ds} + V \mu_0 \int_S \frac{\partial \overline{D}}{\partial t} \cdot \overline{ds} \tag{8}$$

$$\phi = V \mu_0 \int_S \overline{J_{int}} \cdot \overline{ds} + V \mu_0 \int_S \frac{\partial \overline{D}}{\partial t} \cdot \overline{ds} \tag{9}$$

The **second term** can be put as follows:

$$V \mu_0 \epsilon_0 \int_S \frac{\partial \overline{E}}{\partial t} \cdot \overline{ds} = \frac{V}{c^2} \int_S \frac{\partial \overline{E}}{\partial t} \cdot \overline{ds} \tag{10}$$

Which would be the contribution of the electric field that crosses the spiral. This term can be despised for two reasons:

- The first would be the fact that it is divided by the speed of light squared. It is true that the first term, the one that applies to current densities, is affected by the value of , but the second is affected by this term and by the electrical permittivity $\mu_0 = 4\pi 10^{-7} Tm/A \epsilon_0 = 8.854\ x10^{-12} F/m$, which means that the integral value of the electric field must have a high value to be taken into consideration. This only happens for two reasons:

    - Very intense electric fields. Within the electricity sector, the most intense electric fields would be in 400kv installations between phases. Even supposing that fields of $\bar{E} = 4x10^5 V/m$, and working with frequencies of 50Hz were to exist, this term would rise to , and is therefore far from being comparable to the contribution of the term current. $1.25x10^8 V/sg\ m$

    - Electric fields with a high frequency variation. The derivative means that the more frequently there is a term that does compensate for the coefficient of electrical permittivity, and this term should be considered, but in no case can it be considered at industrial frequencies, much less if it is considered continuous.

- The second reason would be the placement of the coils themselves (Figure 3). Assuming we have a driver to a potential .V

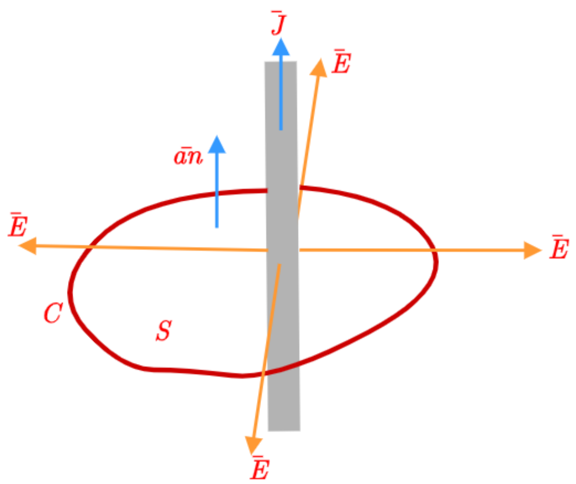

Figure 3

In general, the fiber optic coils are wound in the orthogonal plane to the cable where the current is to be measured, i.e. the unit vector of the surface goes in the same direction as the cable. But the electric field is orthogonal to the cable, i.e. the scalar product

$$\frac{\partial \bar{E}}{\partial t} \cdot \overline{ds} \approx 0 \tag{11}$$

It is practically zero, due to the position of the coils themselves, and the shape of the electric field.

The **first term**:

$$V\mu_0 \int_S \overline{J_{int}} \cdot \overline{ds} \tag{12}$$

They would be the currents inside the surface S, and this is fulfilled by the very definition of the Ampere law, on which Maxwell's equation is derived.

But now we can ask ourselves what value it has ϕ, if we have currents that are within the raised loop:

$$\phi = V \int_C \overline{B_{int}} \cdot \overline{dl} = V\mu_0 \int_S \overline{J_{int}} \cdot \overline{ds} = V\mu_0 I \tag{13}$$

Because the surface integral of the current densities on that surface would be the intensities that cross it, that is, I.

What this solution tells us is that, regardless of the shape of the coil that we make on the conductor on which we want to measure its current, its final result, whatever the shape of the coil, being closed, will always be , and if instead of having a coil, we have , the result would be:$V\mu_0 IN$

$$\phi = NV \int_C \overline{B_{int}} \cdot \overline{dl} = NV\mu_0 \int_S \overline{J_{int}} \cdot \overline{ds} = NV\mu_0 I \tag{14}$$

Conventional vs. optical comparison

A conventional transformer is derived from equation (3). If we do Stokes on both sides, we would have:

$$\int_S \nabla x \bar{E} \cdot \overline{ds} = \int_C \bar{E} \cdot \overline{dl} = \int_S \frac{\partial \bar{B}}{\partial t} \cdot \overline{ds} = \frac{d}{dt} \int_S \bar{B} \cdot \overline{ds} = \int_S \frac{d}{dt} (\mu_0 \mu_r \bar{H}) \cdot \overline{ds} \tag{15}$$

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Which is the integral version of Faraday's law for magnetic induction. The first term would be the voltage generated in the loop, and the second would be the magnetic field that passes through that surface, the magnetic flux. Several facts emerge directly from this equation:

- In this case, the magnetic field can be internal or external, and we must manage by geometry, shielding or any other term, the possible interference of external magnetic fields$\bar{B}$
- The magnetic field and the surface have a scalar product, and this makes the induced voltage depend on this scalar product, and with it the arrangement of the conductor inside the coil.
- The induced voltage depends on the time derivative of the magnetic field, that is, there is no induced voltage if the magnetic field is constant, which is why conventional transformers cannot measure direct current.
- In general, magnetic materials are needed, which help solve the previous problems. This causes , to appear, and with it problems associated with hysteresis, saturation, and remnant field.μ_r

The measure of the polarization change is given by equation (14), clearly we can conclude:

- As we have already said, by Ampere's own law, only internal current densities should be considered, so immunity to external fields is absolute.
- The current density also has a scalar product with the surface, but whatever angle it forms, that integral forms the intensity that crosses the surface, that is, the position of the conductor and the angle they form with the surface is totally indifferent.
- The change in polarization is not obtained through the time derivative of the current, and thus it is feasible to measure direct current by optical means.ϕ
- In fiber optic measurement systems, there is none, and with it all the problems derived from it do not exist μ_r

New protection schemes.

The fact that the current measurement only depends on the total current passing through the measuring loop, regardless of the size of the surface and the position of the conductors, makes it possible to establish new protection criteria, especially in defined environments, such as substations, machines, etc.

Suppose we can define a surface and on it a contour. Within this surface we will have a series of currents. What equation (14) tells us is that the change in the polarization of light along this path will be caused by the sum of all the currents, and only by them, that are within the defined surface.

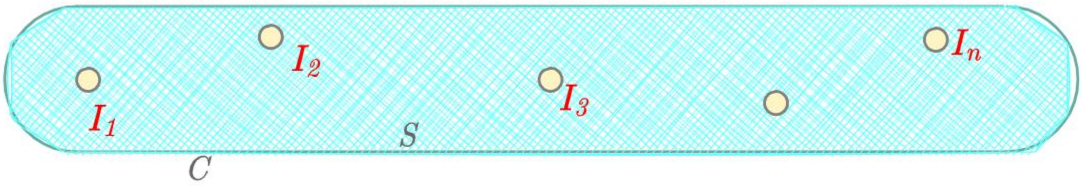

Figure 4

Let's take two practical cases.

- We define the surface as that which integrates the three phases, A, B and C. The change in polarization will be the direct measurement of the homopolar current of this line, and the sensitivity will be given, not by the size of the coil, but by the number of turns that the light makes along this contour.

- Suppose we want to perform a bar differential. To do this, we define a surface within the substation, and within it are located all the lines that enter and exit said bar. There are two interesting effects:

    - The change in the polarization of the light will depend exclusively on the differential current existing within this surface, regardless of whether a line is shorted.
    - As there are no ferrous elements, the measurement will always be linear without magnetic saturation conditions.