The impossible 3-phase measurement

Often 3-phase screened cables are used for power distribution in the medium voltage power grid. Unfortunately measuring the current flow is a challenge, as traditional clamp meters and transformers will show little or zero current flow, if attached around the cable. The reason is that the sum of the magnetic fields from the 3 phases will be zero if the currents carried in the phases are 120 degrees apart and of similar amplitude.

Almost 200 years ago, Ørsted figured out, that leading an electric current through a conductor generates a magnetic field. Later James Maxwell, Jean-Babtiste Biot and Félix Savart expanded the understanding of this finding and determined, the governing physics of the interaction between the current and magnetic field. For the case of a single infinitely long straight current carrying conductor, it ended up in a fairly simple expression describing the direction and magnitude of the magnetic field.

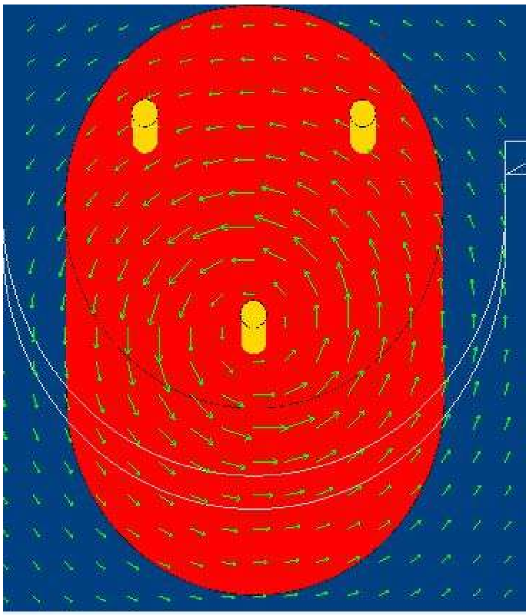

Illustration 1: One-wire current

In illustration 1, a current is running in the bottom conductor (yellow) only. The magnetic field is of similar strength in circles around the conductor. The strength of the magnetic field is inversely proportional to the distance to the conductor and proportional to the current. The relation is pretty simple. The magnetic field strengt H is:

$H = I / (2 * \pi * r)$,

where r is the distance to the conductor in meter, and H is the magnetic field strength in A/m.

As indicated by the length of the magntic field vector arrows on illustration 1 the field becomes smaller as you move away from the conductor.

From DC to AC

The picture shows a single snapshot of a situation. If the current is DC, the picture will stay static if the current is kept stable.
If you change the direction of the current like you do in an AC circuits following a sine wave, the vectors will follow. When the current crosses zero the vectors becomes zero in length. The vectors changes direction as the current changes polarity.

From 1 to 2 conductors

When current is applied to the next conductor, the vectors will sum (superposition) and a snapshot could look like shown in illustration 2.

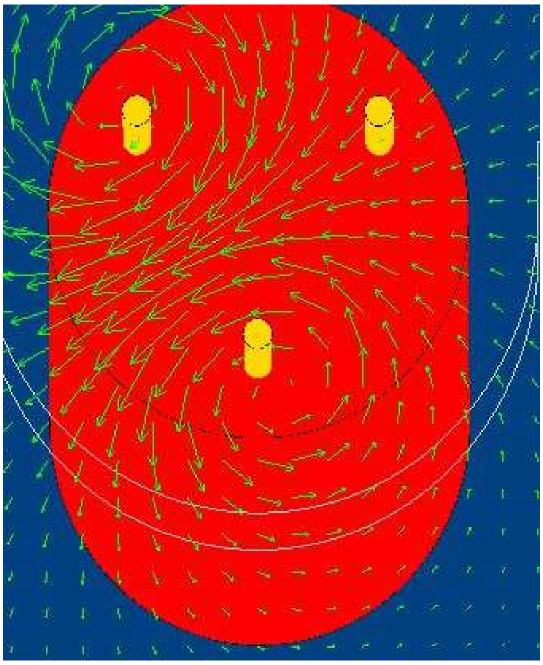

Illustration 2: 2-wire current

There is still a strict mathematical relation between the currents and the vectors. Now the individual vector is simply a sum of the vectors we would have if we made a measurement one current at a time.

3-conductor cable
Adding the third conductor adds a third component to be included in the resulting vector obtained using superposition. See illustration 3.

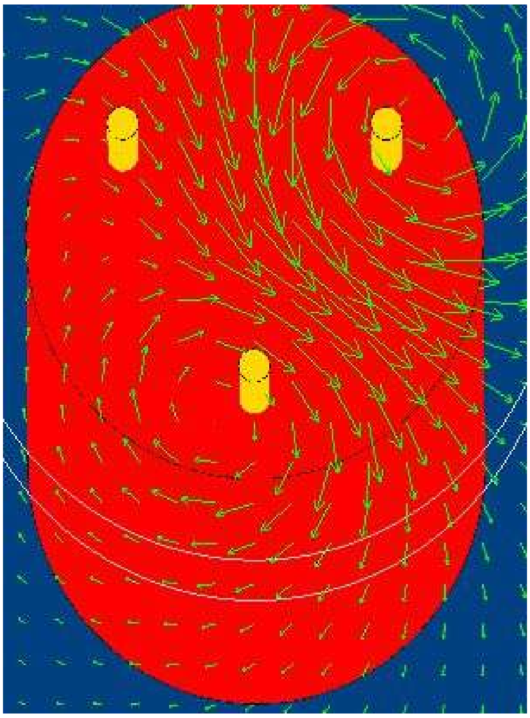

Illustration 3: 3-wire current

Vector measurement

Using the mathematical relation between the currents and the magnetic field strength and vectors, it would seem that there is a possibility of determining what current flows through each of the 3 conductors in illustration 3, given enough measurement points. Traditional measurement techniques rely on determining the sum of the magnetic field around a closed loop, which only reflects the net current flow at a given point in time. What we need is point measurements to get around the limitation of the traditional measurement techniques.

Hall Sensors
Small Hall sensors, a few mm in size, can measure the magnetic fields in what can be assumed to be discrete points. Hall sensors are magnetic field sensors which can present a voltage output proportional to the magnetic field.

If we place a number of sensors close to the cable, we can evaluate the mathematical relations both in discrete instants of time, and seen as a time series of measurements.

More snapshots
If we take several snapshots as the currents change in time (AC), it becomes possible to determine all the unknown parameters of the measurement system; The individual position of each conductor, as well as the current flow through the individual conductors at any given point in time.

Engineering challenge

Suddenly a new world of measurement possibilities is opening up. The engineering team who made the pioneering work has patented the technology involved, supporting that no one before has been able to combine these measurement concepts into a useful product before. There are many advantages to be found in the new measurement method. Among these is the frequency linearity and the installation options on screened cables.

Frequency behaviour

Hall sensors are very broadband. They can measure up into the MHz range, if needed. Therefore the new measurement principles will not have any problem in measuring frequencies far beyond the 50th harmonic (2.500 Hz for a 50Hz system) as described in many standards. Short circuit and earth fault events are now easy to detect based on phase specific information.

Screened cables

3-conductor medium voltage cables are often screened. The screen is grounded to make sure that no dangerous voltages will arise on the surface of the cable. This also makes mounting of the 3-wire sensor a safe and simple process.

One slight disadvantage to note though, is that some screened cables are armored as well where the armor is a magnetic iron alloy. The armor distorts the magnetic field pattern, so it becomes truly impossible to determine the individual currents flowing inside.

However, such cables usually have their armor stripped away, where they are interfaced into a switchgear or transformer, and as long as there is at least a 15cm stretch with no magnetic material in the immediate vicinity of the Hall sensors, the sensing functionality will not be impeded.

Another concern to cope with, is that current flowing in the screen will also influence the magnetic field measurements. Here the geometry of the cable helps out. The current flowing in the screen can be modelled as a single conductor in the centre of the cable. The solution then becomes to add such a conductor to the mathematical model of the cable.

Having 4 conductors or 5 conductors to calculate is theoretically no problem, except the number of sensors needed increases.

With these options for coping with the practical use of screened cables in the field, a sensor solution as described becomes a strong measurement tool to be used for retrofitting purposes on existing medium voltage infrastructure.

The ideal power meter

Now that we can measure currents in a 3-phase screened cable, it would be good to be able to measure the voltages as well. If we can measure voltages with similar easy options for retrofitting purposes, it becomes possible to calculate all other parameters like apparent power, active power, reactive power, direction of power flow, as well as frequency analysis on voltages and currents and on top of this alarms for short circuits and earth faults with directional indication can be made.

The next article in this series will describe a voltage measurement approach enabling a compact practical sensor and measurement processing platform.