MEASUREMENT OF MAGNETIC FLUX DENSITY IN THE VICINITY OF ELECTRICAL POWER INSTALLATION

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ABSTRACT

The measurement of the magnetic flux density (equivalent magnetic flux density) caused by electrical power systems and the identification of sources of magnetic fields are ongoing problems using modern measurement instruments with analogue or digital equipment. Especially spectral leakage, filter and damping effects of instruments are of interest. In the following paper simple method is presented to measure the spatial characteristic of magnetic fields caused by time varying currents. Furthermore a simple solution to consider the influence of parallel conductors with time varying currents on the spatial distribution of the magnetic flux density is introduced.

INTRODUCTION

The measurement of the characteristic spatial distribution of low frequency magnetic fields requires

- suitable measuring instruments
- well known and constant load flow
- one source of the magnetic field.

Usually during operation of electrical power systems few situations with constant load flow occur. In practice measurement fluctuations of the field caused by the non-continuous load flow (source of field) can be expected. In consequence the results of the measurement of the spatial distribution of the magnetic field (B-field) are affected on the one hand by the spatial characteristic of the magnetic field source and on the other hand by these time-depending load changes. The characteristic spatial distribution of the magnetic field can be acquired with the following methods:

- Two synchronous measurements of the B-field, where a reference measuring point is spatially fixed, the other measurement points supply the values of the magnetic field at the user defined positions (imission point). This value has to be corrected with the B-field-value of the reference measurement point.
- Synchronous measurement of the B-field of the imission point and the field causing current (reference measurement current). The magnetic field of the imission point has to be corrected by the fluctuations of the field causing current, acquiring in this way the distribution of the resulting magnetic field.
- Computation of the magnetic field (e.g. Finite Element Method FEM or Biot Savart).

Fields caused by more than one source can be differentiated in several sources with the same frequency (e.g. several appliances with 50 Hz) and in different sources with different frequencies (e.g. 50 Hz and 16,7 Hz). The parts of magnetic fields with sources of *different frequencies* (e.g. 50 Hz and 16,7 Hz) can be measured by use of measurement equipment including band-pass filter and analogous centre frequency. The magnetic field caused by different sources of the *same frequency* (figure 2, e.g. cable trench, substation), can be measured as a sum of the components. The allocation to each source can be very complex.

MEASUREMENT OF MAGNETIC FIELDS

Electromagnetic induction is the basis of measurement of magnetic fields by coils. The measuring sensor is a coil with an area $\vec{A}$ (absolute value and direction) and a number N of windings. The coils can be equipped with magnetic-core or air-core. The core with high permeability material concentrates the magnetic flux Φ (in Weber Wb) through the coil-area $\vec{A}$ thus increasing the sensitivity of the sensor. A time variant magnetic field, caused by a time variant current, induces a time variant voltage U_{ind} in the coil.

$$U_{ind} = N\frac{d}{dt}\int_{A}\vec{B}\cdot d\vec{A} = -N\frac{d\Phi}{dt} \qquad (1)$$

The induced voltage at the ends of an idle coil is proportional to the derivation of the time variation of the enclosed magnetic flux. The signal of the measurement, the inducted voltage U_{ind}, depends on the amplitude and on the frequency of the measured value. The size and the turns of the coil should ensure a convenient proportion factor of flux density and the induced voltage. To consider inhomogeneous magnetic fields the German standard DIN 0848 [4] claims a coil-area of 100 cm^2.

With a plain single axis coil (see figure 1) it is possible to measure only one direction of the magnetic fields. Three orthogonal arranged coils allow the acquisition of the maximal values of the magnetic flux density in these three directions. It should be mentioned that some measurement instrument generates these values without any phase information.

The frequency response of the measurement converter (coil) can be compensated with an active or a passive element. Usually the active element is an integrator. A band pass filter eliminates movement inductions caused by the natural magnetic field of the earth and user movements and reduces the measurement range to the ELF range (ELF: Extra Low Frequency) of e.g. 3 - 300 Hz.
Some instruments provide the possibility to measure with frequency selective filters to differentiate magnetic fields

with different frequencies, for example rail frequency fields with f = 16,7 Hz and fields of high voltage transmission lines with f = 50 Hz as claimed in the Austrian pre-standard ÖVE/ÖNORM E 8850 [3]. A further application of these band pass filter is the measurement of magnetic fields caused by harmonic currents in electrical power lines.

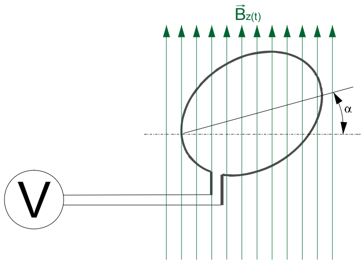

Figure 1: Principal measurement of magnetic field with a single axis coil in a homogeneous magnetic field

Equivalent magnetic flux density

In context with the evaluation of magnetic fields, following the pre-standard ÖVE/ÖNORM E 8850 [3] (similar to ICNIRP), for elliptical rotary fields the equivalent magnetic flux density B_{EFD} can be calculated in the following way:

$$B_{EFD} = \sqrt{B_x^2 + B_y^2 + B_z^2} \qquad (2)$$

This equivalent magnetic flux density can easily be measured and is a certain measure neglecting phase informations.

Effects of filter characteristics

The frequency selective measurement with filters evaluates the input signal with band pass filters e.g. as shown in **Figure 2**. These filters have a band width of 10 % respectively 20 % based on the filter middle frequency.

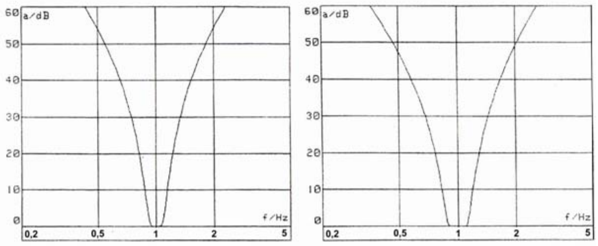

Figure 2: Normalized filter characteristics 16,7 Hz to 180 Hz and 400 Hz - 1200 Hz

Effect of finite state block damping

A Filter with selected middle frequency of 100 Hz produces the finite state block damping of 54 dB. The 50 Hz main harmonic (100 %) produces at the 100 Hz component 0,2 % of the main (50 Hz) amplitude.

Effect of filter band width

A band pass filter with a middle frequency of 600 Hz and filter characteristic shown in **Figure 2** the filter band width results in 120 Hz. Thus the result of the measurement includes the 600 Hz component and the 550 Hz and 650 Hz spectral components without any damping of those two signals.

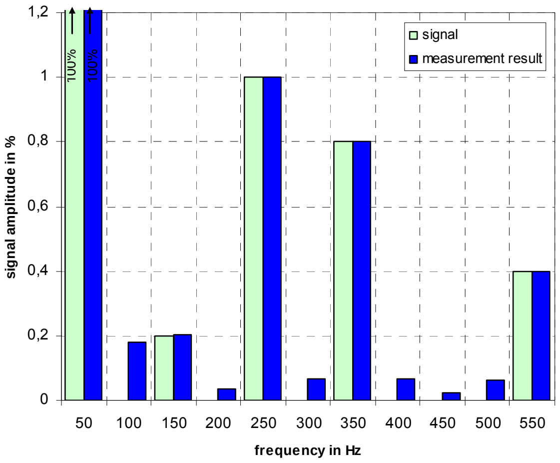

Figure 3: Comparison of real signal and measurement result using frequency selective filter

The result of this effect is demonstrated in figure 3 by comparison of a real signal (real signal - basic oscillation 50 Hz: 100 %, - spectral components: 150 Hz: 0,2 %, 250 Hz: 1 %, 350 Hz: 0,8 %, 550 Hz: 0,4 %).

None synchronous sampling of FFT (spectral leakage)

If the sampling rate of the measurement system is not exactly synchronous with the basic oscillation of the magnetic field, the calculation of the spectral components with a FFT algorithm creates an error because of spectral leakage. The harmonics in the measurement signal affect each other. The first results of the spectral-leakage effect are even-numbered harmonics although they are not included in the original signal. The second result is that the harmonics are affected by the dominant basic oscillation e.g. 50 Hz, the biggest impact is in this case onto the 2nd harmonic (100 Hz).

Magnetic field measuring faults

The following list nummerates some characteristic faults that can occur by the measurement of magnetic fields:

- External interfering fields
- Time variation in magnetic field of measurement
- Inaccurate localisation of the immision point
- Movement induction caused by the magnetic field of the earth
- None correct measurement range
- Ferro magnetic objects in the vicinity of measurement
- Effects of filter characteristics
- Calibration faults

REFERENCE METHOD

The magnetic field in concrete measuring points along a line depends on the on hand on the time course of the field causing currents and on the other hand on the spatial field characteristic of the arrangement of the conductors. The problem is to find out the real spatial characteristic of the magnetic field seperated from the time characteristic. Two simultanous measurements of the magnetic flux density in a reference point ($B_{ref(t,x_{ref})}$) and and immission point ($B_{meas(t,x)}$) can solve this problem eq. (3). It is important that the reference point is located near the field source. This method works best with time variant magnetic fields caused by a single field source.

$$B_{corr} = \frac{B_{meas_{(t,x)}}}{B_{ref_{(t,x_{ref})}}} \cdot \max\left(B_{ref(T)}\right) \qquad (3)$$

$\max\left(B_{ref(T)}\right)$ Maximum value of the B-field measurement in µT at the reference point during the measurement period T

An example of a measurement of the magnetic flux density caused by the high-voltage cabel using the reference method is shown in Figure 4.

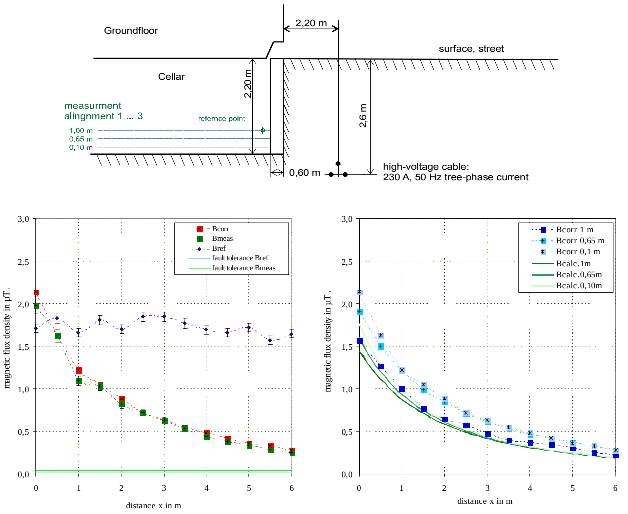

Figure 4: Magnetic field measurement using the reference method

The left diagram (measurement in 0,1 m height) in Figure 4 shows the variation in time of the magnetic flux density B_{ref} in the reference point, proportional to the load fluctuations of the field causing high-voltage cable. The B_{meas}-line is the measured magnetic field density in the imission point simultanously measured with the magnetic flux density in the reference point. The B_{cor}-line is the result of the measurement corrected with eq. (2).

The right diagram in Figure 4 shows the results of the measurements in different heights 0,1 m, 0,65 m and 1 m in comparison with the calculated magnetic flux density (I = 230 A).

The difference between measured and calculated magnetic flux density I Figure 4 (right) results from inaccurate current measurements, e.g. time shift, and the influence of other unknown conductors e.g. in the same cable trench. A proposal to solve this problem is given in this paper.

FREQUENCY-SELECTIVE MEASUREMENT

Magnetic fields with different frequencies have to be considered in electrical power systems e.g.

- when electrical power supply systems (50 Hz) approach railway facilities (16,7 Hz) and
- in case of current harmonics of electrical equipment (rectifiers, inverters, ...).

Figure 5 shows the results of a frequency selective measurement in the vicinity of a 220 kV substation. This measurement shows the characteristic of the basic harmonic (50 Hz), the 5th harmonic and the 7th harmonic of the magnetic flux density. The characteristics are measured with the reference method presented in this paper.

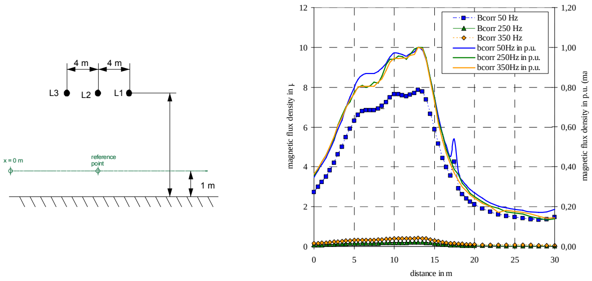

Figure 5: Magnetic flux density measurement, 50 Hz, 5th and 7th harmonic

The maximum values of 50 Hz, the 5th and 7th harmonic at a distance of 12 m (direct under phase 2) reach up to 7,87 µT, 0,41 µT and 0,21 µT. The normalized curves (bcorr in per unit of the maximum value) show that the magnetic field characteristic of 50 Hz, 5th and 7th harmonic of this conductor geometry is identical. Visible deviations in Figure 5 occur due to other field sources in this range (e.g. cable at 17 m).

ASSIGNMENT OF MAGNETIC FIELDS TO TWO SOURCES

Problem occurs if not only one source of magnetic field exists and the task is, to differentiate the measured magnetic flux density by the different sources. This is necessary if the measured magnetic flux density does not represent the maximum load situation and have to been extrapolated to the different maximum load of the sources.

If one can measure one of the field causing currents and the three vector components of the flux density in an immission point synchronously the following method can help to identify the parts of the magnetic flux density coming from the conductors even when the time course of the currents are not constant. The magnetic flux density B_I caused by the current I can be approximated by the following equation:

$$B_I \approx \frac{\Delta B}{\Delta I} \cdot I \tag{4}$$

ΔB measured change of the equivalent magnetic flux density. $\Delta B = \left| \vec{B}_{(t_2)} - \vec{B}_{(t_1)} \right|$

t_1, t_2 measuring time 1 and 2

ΔI measured change of the field causing current. $\Delta I = I_{(t2)} - I_{(t1)}$

I reference current

If the phase angles between the field causing currents are 0° and 180° the magnetic flux density parts can be assigned exactly, the change in magnetic flux density is direct proportional to the currents. If the phase angles between the field causing currents are not 0° or 180° a measuring error appears, depending on the ratio of the currents and the spatial arrangement of the conductors. In the most frequent case of two 3~ conductors in a cable trench and balanced load or the measured current is lager than the disturbing current the error can be neglected (< 20%). The following Figure 6 shows the result of the calculation of the measurement error Err for a two dimensional arrangement of two conductors ••.

$$Err = \frac{(B_{EFD\bullet\bullet} - B_{EFD\bullet})}{B_{EFD\bullet\bullet}} \cdot 100\ \% \tag{5}$$

$B_{EFD\bullet}$ equivalent magnetic flux density of caused by one conductor

$B_{EFD\bullet\bullet}$ equivalent magnetic flux density of caused by two conductors

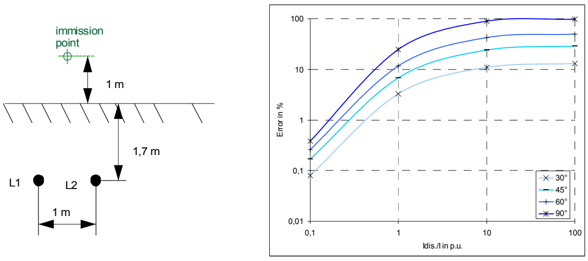

Figure 6: Measurement error for a two dimensional arrangement of two conductors

CONCLUSIONS

Basic examples show that the measurement of time and spatial varying magnetic flux densities using the reference method and the calculation of magnetic flux densities correspond in an adequate way. After the presentation of the basic principles of measurement of magnetic flux densities and the description of spectral leakage, filter and damping effects of instruments, typical measurement faults are specified. The presented reference method can be used to measure the spatial characteristic of magnetic fields caused by time varying currents. A simple and approved solution to consider the rates of currents of parallel conductors with time varying currents on the spatial distribution of the magnetic flux density is introduced, so that the maximum magnetic flux density can be extrapolated and evaluated from measured values in a correct way.

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