NEW OPTIMIZED ANALYSIS METHOD FOR MEASURING EXTENDED GROUNDING SYSTEMS

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ABSTRACT

The fall-of-potential method is commonly used for grounding measurements. During measurements of extended grounding systems high external influences of the measurement circuit can occur and can lead to measurement errors. Therefore different methods were investigated in the past. In this paper a new one is shown. In fact it is an upgrade of the commonly known beat-frequency method with a combination of a Fourier transform. The new method can avoid the disadvantages of known analysis methods reaching more accurate measurement results - even at environments with high external influences of the measurement circuit.

INTRODUCTION

Correct function of grounding systems is a necessary precondition for safety and reliability reasons; therefore additional to calculation of grounding systems in the planning phase a grounding measurement before putting in service and after several years of operation is necessary. IEEE Std. 80 [1] and IEEE Std. 81 [2] are dealing with the design and measurement of grounding systems. Especially IEEE Standard 81.2 [3] describes different well known methods for measuring extended grounding systems.
For improving the accuracy of measurements and a simplified measuring process a new method is presented in this paper.
Advantages and disadvantages of this new effective method are discussed and a comparison with well known methods is shown.

GROUNDING MEASUREMENTS

All grounding measurements of extended grounding systems are based on the fall-of-potential method. Also all analysis methods mentioned in this paper are based on this measurement method.
A test-current is injected into the grounding system and the earth-potential-rise-profile (EPR-profile) is measured. As counter electrode a low impedant second grounding system (e.g. from another substation, see Figure 1) is used, which is connected to the measured grounding system via an overhead line or cable.

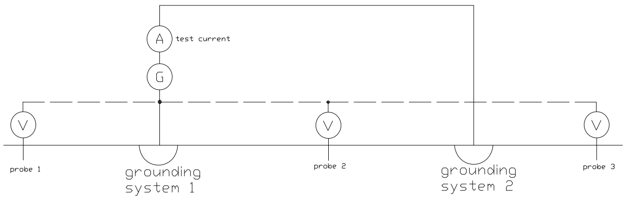

Figure 1: Fall-of-potential method

Due to inductive and ohmic coupling, influences have to be detected and eliminated by analysis methods (such as FFT, beat-frequency method, compensation method …). Most of these analysis methods are well known and even mentioned in international standards [3]. All mentioned analysis methods work more or less well, if inductive and ohmic interferences are constant in magnitude during measurement time. In some cases (e.g. in the surrounding of railways) an (inductive) interference cannot be assumed as constant during the measurements. Fourier transforms work even well with influences that are not constant but a power source with a variable frequency must be used.

BEAT-FREQUENCY METHOD

When using the beat-frequency method, a current with a small deviation from the grid frequency is fed into the grounding system by a portable emergency generator set. This source is used because it is normal easily available to grid operators and therefore a cheap solution. The result of superposing the measurement frequency and the grid frequency (interferences) is a signal with varying amplitude (single side amplitude-modulated signal). The part with grid frequency in the measured signal is induced by ohmic and inductive interferences between the grid and the measurement circuit.
The beat-frequency method was a good solution for grounding measurements with analogue volt meters. The accuracy was mainly depending on the reading accuracy and the meter's time constant (so a measurement frequency below 1 Hz difference to the grid frequency makes sense). With modern digital volt meters (with automatic max/min function) this does not matter that much any longer.
With the measured minimum (U_{min}) and maximum (U_{max}) value of the beat signal the voltage at measurement frequency (U_m) can be calculated.
Two different cases must be distinguished and evaluated when using the beat-frequency method:

If the disturbing voltage is smaller than the signal with measurement frequency, the voltage can be calculated by:

$$U_m = \frac{U_{max} + U_{min}}{2}$$

If the disturbing voltage is bigger than the signal with measurement frequency, the voltage can be calculated by:

$$U_m = \frac{U_{max} - U_{min}}{2}$$

A problem of the beat method is that the results are not always clear. One could not know if the influences are bigger or smaller than the signal with measurement frequency. Other problems of the beat method are disturbances and influences if frequencies that differ from the grid frequency and the measurement frequency occur (e.g. interference from railway currents or harmonics). These interferences cannot be detected and compensated with this method.

FREQUENCY SELECTIVE METHOD

Frequency selective measurement methods inject currents into the grounding system with a frequency unequal to the spectrum of technical frequencies occurring in the surrounding of the measurement circuit and affecting the measurements.
However, the grounding impedance and limits for touch and step voltage are defined at nominal grid frequency. If the selected measurement frequency is different from the grid frequency, an interpolation of measurements with different frequencies below and above nominal frequency has to be calculated.
A problem of frequency-selective measurement is the increased cost of the power supply for feeding the measuring current with measurement frequencies unequal to nominal frequency.

NEW OPTIMIZED METHOD

General aspects

The investigated method is a combination of a beat-frequency method with a measurement frequency that differs about 1 Hz from nominal grid frequency and a discrete Fourier transform (DFT) for analysis of grounding impedance and estimation of measuring circuit's influences. A problem is the current source's frequency adjustment and stability during the measurement. As shown in the following, measurement errors due to unstable frequency and spectral leakage can be minimized.
One further advantage of this method is that for measuring of touch- and step voltages common volt meters can be used, because the interfered voltages there are normally small enough (short measurement cables) and the values can be calculated as described in the section "beat-frequency method" – so no special measurement units are needed for these measurements.

Signal processing

The first step is a digitalization of the analogue signal.
After the digitalization the cycle length of the beat-frequency must be detected. For correct calculation of the Fourier transform the window length must be the same or a multiple of the measurement signal's periodical time. In case of the beat-frequency method the minimum window length is reciprocal to the frequency's difference of the signal components.
It can be seen in Figure 2 that the signal itself has local peaks related with measurement and grid frequency and also peaks of the envelope related to the beat-frequency. Determining the correct window length is done by detection of the envelope peaks from the beat-frequency signal.
In a first step the signal is filtered by a band pass filter with high order to eliminate the harmonics and noise and keep the grid and measurement frequencies. For the beat-period detection the envelope of the signal is calculated. This is done by detecting the "local" peaks of the filtered signal which will be treated as samples of the demodulated signal (envelope).
Afterwards the peaks of this demodulated signal are detected with the time between these peaks representing the cycle length of the beat signal.
In the next step the DFT from the original measured signal is calculated with a window length matching exactly the cycling length of the beat-frequency signal.
Frequency resolution of the DFT is equal to the beat-frequency respectively to the difference between the frequencies of the measurement signal and the grid frequency. It also can be shown that leakage effects during the calculation of the DFT are reduced to zero if only the grid and the measurement frequencies and their harmonics occur in the signal.

Determination of grounding impedance

In the final step after the DFT grounding impedance can be calculated easily by taking only the spectral component at the measurement's frequency in voltage and current signal into account.

Example with test signals

For verification and error estimation the presented new analysis method was tested with the help of a known synthetic signal.
These voltage and current signals consist of:

- Component with measurement frequency of 51.69 Hz
- Component with grid frequency 50 Hz and harmonics
- Component with railway frequency 16.7 Hz and harmonics

A sample rate of 1 kS/s was used. The signal is shown in Figure 2.

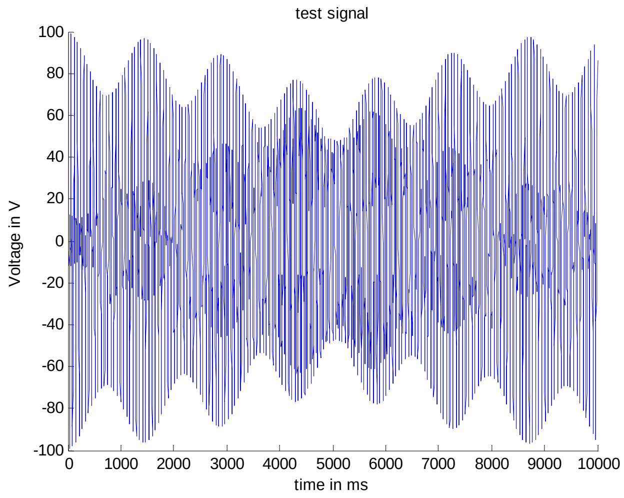

Figure 2: Unfiltered synthetic test signal

To demonstrate the positive effect of the peak detection and the consequential reduction of the leakage effect, the signal was processed according to the described method with a window length of three beat cycles (1.78 sec) and with a predefined fixed window length of 2000 samples (2 sec).

In Figure 2 the envelope of the filtered test signal is shown (demodulated signal). Due to the filter transients the first peak is not used for the window length calculation afterwards. The total length of the filtered envelope is shorter than the original test signal caused by the correction of the filter's group delay time.

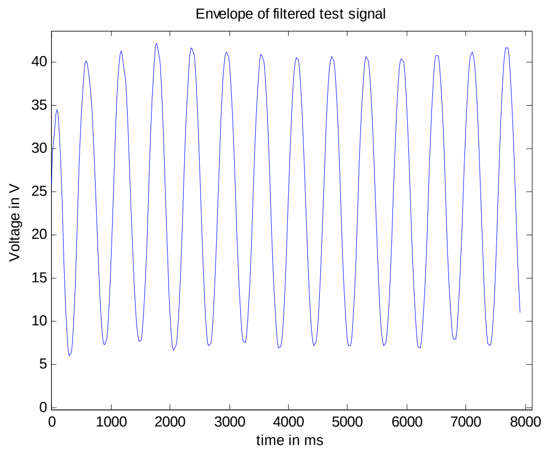

Figure 3: Envelope of filtered test signal

In Figure 4 and Figure 5 the results of the Fourier transform with and without peak detection are shown. One can see that significant differences in the results occur. This is mainly caused by leakage effect.

The DFT with peak detection over one beat-frequency period shows the same results as the DFT with peak detection over three periods. A calculation of mean value of five DFTs each over one beat-frequency period has proved to be practical.

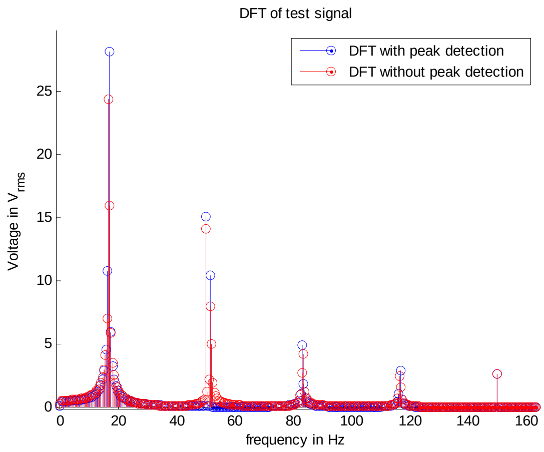

Figure 4: DFT spectrum with/without peak detection

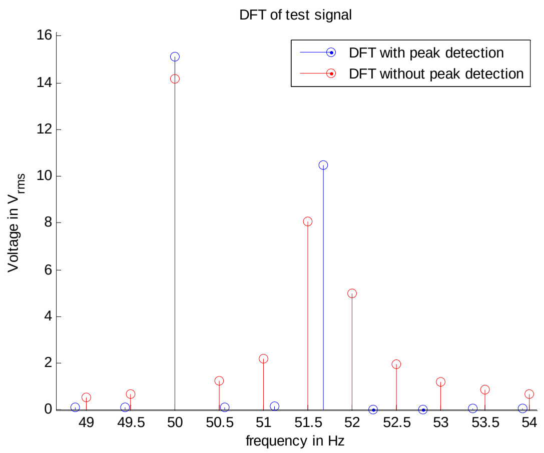

Figure 5: DFT spectrum with/without peak detection (zoomed)

If the Fourier transform is calculated with a window length equal to the beat-frequency period, the frequency resolution equals exactly the beat-frequency. Therefore both spectral components of the beat-frequency signal are calculated very accurate. In Figure 5 it can be seen that leakage effect of the DFT with peak detection is reduced significantly. All spectral components nearby grid- and measurement-frequency are zero.

If the window length equals one beat period, it is always ensured that the window length is a multiple of the period time of the grid frequency and of the measurement frequency. That is because at a peak of the beat signal, both signal components (with measurement and grid frequency) must also have their peaks. Components with other frequencies are filtered during the peak detection process.

At Table 1 the calculated RMS values of the different Fourier spectrum components are shown. Also the relative error compared to the real values from the original test signal is illustrated. One can see that even for a test signal with high interferences very low errors can be reached. On the other side the Fourier transform without peak detection can have relative errors up to 100 % (strongly depending on the test signal).

Table 1: Accuracy of the analysis method with peak detection

f [Hz]	Original values [V]	Calulated values [V]	relativ error in %
0	0.2	0.20	0
16.7	32.1	32.00	0.31
50.00	15	14.91	0.6
51.69	10.4	10.38	0.19
83.4	5.6	5.58	0.36
116.7	3.3	3.27	0.91
150	2.7	2.69	0.37
250	0.7	0.69	1.43
350	0.32	0.31	3.13

Error estimation of window length

The error is depending on the digitalization on one hand and on the Fourier transform on the other hand.

The quantization error at digitalization can be described as the ratio of one digitalization step to the window length of the Fourier transform:

$$\varepsilon = \frac{\Delta T}{T_W} = \frac{|f_{grid} - f_{measure}|}{f_{digitalization}}$$

From the equation above it can be seen that the error is depending on the beat frequency and the sample frequency from the digitalisation.

The error of the Fourier transform is depending on digitalization error and also of the selected type of window. The Fourier transform in this paper was calculated with a rectangular window (Dirichlet window).

Advantages and disadvantages

The new investigated method mentioned in this paper shows following advantages and disadvantages:

Advantages:

- Exact determination of influenced voltages and harmonics
- Measurement frequency equals nearly grid frequency
- For measuring touch- and step-voltages a normal voltmeter can be used like at the beat-frequency-method. With knowing the ratio of spectral components at measurement and grid frequency the right formula for the beat-frequency method can be chosen.
- For generating the measurement current emergency power units working near nominal frequency can be used (often available in grid operator's companies)

Disadvantages:

- A data logging unit and a computer based measurement system is needed

CONCLUSION

High influences from inductive and ohmic coupling can occur in the measurement wires during grounding measurements in high voltage environments. Especially during grounding measurements of extended substations influences into the measurement circuit caused by very long measurement cables cannot be avoided. Therefore analysis methods must be used to eliminate such interferences. The new analysis method presented in this paper presents a new idea for solving this problem. The simulation with test signals shows the good accuracy of this new method. The new method combines the advantages of the beat-frequency method (high measurement current, normal voltmeter for measuring touch voltages and often available emergency generator) with the accuracy of a Fourier transform.

Measurements at extended substations and power plants are in good comparison to other methods. The method has also shown good results even at a measurement with influences five times higher than the signal component with measurement frequency.

REFERENCES

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