

DLAB - A DOWNSCALED DISTRIBUTION LABORATORY FOR EDUCATION AND RESEARCH ON INTERMITTENT EARTH FAULTS

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ABSTRACT

This paper presents a general overview of DLAB, which is a distribution laboratory for education and research on resonance grounded distribution networks. Specifically, the paper shows how intermittent earth faults have been implemented in the laboratory. The experimental platform can now be used to develop and evaluate different methods for indication of intermittent earth faults.

For some years, E.ON Elnät (hereafter referred to as E.ON in the text) has sponsored LTH to build up a downscaled distribution laboratory – abbreviated DLAB. The idea is to promote education on resonance grounded distribution networks and research on current topics such as intermittent earth faults.

The increased use of cables in Swedish distribution networks, results in earth faults with different characteristic compared to overhead lines. In cabled networks, intermittent faults and also evolving faults have been recorded with a high-end fault recorder. These disturbance recordings reveal that intermittent faults have a high frequency content well above the fundamental frequency.

Traditional line models, consisting of one pi-link only, seem to be insufficient to reproduce the high frequency content found in real disturbance recordings. Therefore an effort has been made to make a new cable models with improved high frequency behavior, which expands the valid frequency range from 50 Hz up to some kHz. The first step was to make a theoretical reference model based on transmission line model with distributed parameters. In addition the skin-effect has been included in the reference model. The physical implementation has been made with several pi-links where the component values have been chosen to replicate the reference model's frequency response.

The intermittent switching is implemented by a semi-conductor relay with instantaneous on-switch on and with off-switch at the first zero crossing of the current. The relay is software controlled which makes it possible to control several switching parameters to fabricate different type of intermittent faults.

The paper compares recordings of intermittent earth faults in DLAB with real disturbance recordings from a 20 kV transformer station in southern Sweden.

INTRODUCTION

Background

E.ON is one of the major players in Swedish power distribution. In the current situation, E. ON is responsible for distribution of electricity to approximately one million end customers and sales of around EUR 630 million. In recent years, powerful storms such as Gudrun and Per hit Sweden. They caused extensive damage to the power grid and resulted in many customers were without electricity. The results of the storms in combination with increased regulatory requirements for uninterrupted power supply, led E.ON to start the project “Krafttag” which aimed to weather secure much of the overhead lines in risk areas. E.ON has in recent years improved the reliability of medium voltage networks by extensive cablification.

New problems—not previously on the daily agenda—have emerged due to increased usage of cables. One of these problems is that underground cables compared to overhead power line, causing a higher capacitive current, which in case of an earth fault results in large fault currents. Certain types of faults, such as bad cable joints or cracks in the insulators, might cause a sequence of extinguishments and re-ignitions of the earth fault. This is called intermittent ground faults and usually contains a high proportion of transients. To put focus on the new problems with increased cablification, the project DLAB was started 2008 at the Department of Industrial Electrical Engineering and Automation (IEA), Lund University, Sweden.

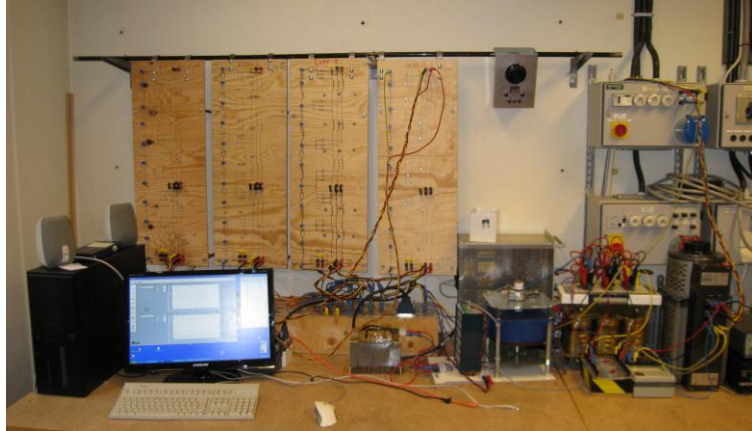
Objectives

Earth fault protection units are usually made to measure the fundamental frequency and may have trouble to function correctly at intermittent ground faults. One example is directional earth fault protection based on active zero sequence current, which in some cases fails to operate. This might lead to unselective backup tripping from neutral point voltage protection, which unnecessarily disconnects all feeders in the station.

The DLAB research project aims to increase the understanding of intermittent earth faults and the effect on earth fault protection. Work is made in DLAB to implement models for intermittent faults, which should be used to reproduce and explain erroneous protection functions.

DLAB

A downsized laboratory for distribution networks was initiated in 2008. The aim was, and still is, to provide a good platform for teaching and research on resonance earthed MV networks. DLAB is a research group within Lund University and is sponsored by E.ON. The name DLAB is an abbreviation of Distribution LABORatory. An additional goal is to offer an educational laboratory exercise for students as well as the power industry.



Picture 1: Laboratory setup.

Laboratory setup

Within DLAB a low voltage model of a MV distribution network has been created. The model includes underground cables, overhead lines, protection units, neutral point resistance, a Petersen coil with automatic tuning based on either network un-symmetry, or current injection. There is a possibility to apply permanent earth fault with different fault resistance, but also short duration intermittent earth faults. The model properties have been compared against both field tests and simulation results, and agrees reasonable well. The single line diagram is illustrated in Figure 1.

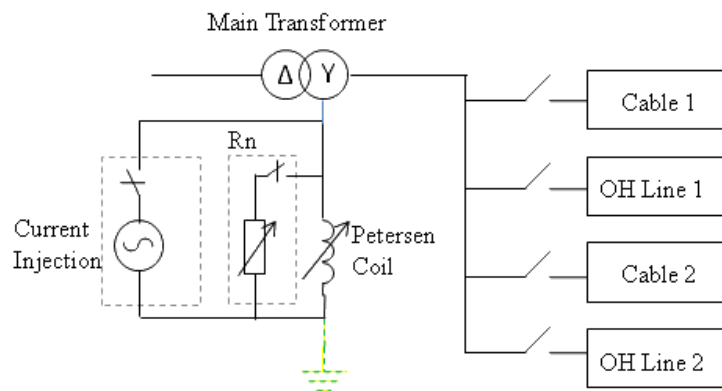


Figure 1: Single line diagram.

Conversion between MV- network and DLAB

Because experiments on MV level can be difficult and dangerous, DLAB has been scaled down to a lower voltage. With regulatory requirements and the possibility to use small components, DLAB is designed for 220 V and 5 A. To relate DLAB results to the real MV grid, conversion

factors have been calculated. The conversion factors in Table 1, are given for a 24 kV network with a base current of 50 A.

	DLAB	EON	Conversion Factor
Voltage, Phase	$\frac{240}{\sqrt{3}} \text{ V}$	$\frac{24}{\sqrt{3}} \text{ kV}$	100
Base Current	5 A	50 A	10
Base Impedance	27.7 Ω	277 Ω	10

Table 1: Conversion factor between DLAB and 24 kV network

The resulting conversion factors for capacitance and inductance are 0.1 and 10, respectively.

INTERMITTENT EARTH FAULTS

The increased use of buried cables in the MV network has led to more intermittent earth faults. As the characteristics of such faults differ from permanent faults, it adds new demands on the earth fault protection scheme.

Classification of intermittent earth faults

An intermittent earth fault is characterized by its short duration and that its repetitive behavior, which can be nearly periodic. The arc ignites when the voltage at the fault location exceed the break down voltage, and self-extinguish at some zero current crossing, only to arc again when voltage over the fault is increased.

Real field measurements

Two different field measurements have been done in the DLAB project. The procedure to fabricate the faults have been slight different:

- Test 1 was performed with a short cable (10m) connected to a not used feeder in a network station. The cabled where prepared by drilling a hole through the insulation down to the conductor, pouring water in to the hole, putting one shield wire close to the hole and at last energize the cable for about 1 second.



Picture 2a & 2b: Intermittent fault by “drilling hole and pouring water” method

- Test 2 was performed with two conductors with a small air gap in between. One conductor where connected to earth and the other to one of the phases. By slowly decreasing the gap between the conductors arcs starts to emerge.



Picture 3: Intermittent fault by “decreasing air gap” method

Recordings

The recordings presented are taken from the first field-test due to better measurement quality. The equipment used was from National Instruments and had a sampling rate of 50 kHz, with a specified effective bandwidth of about 23 kHz.

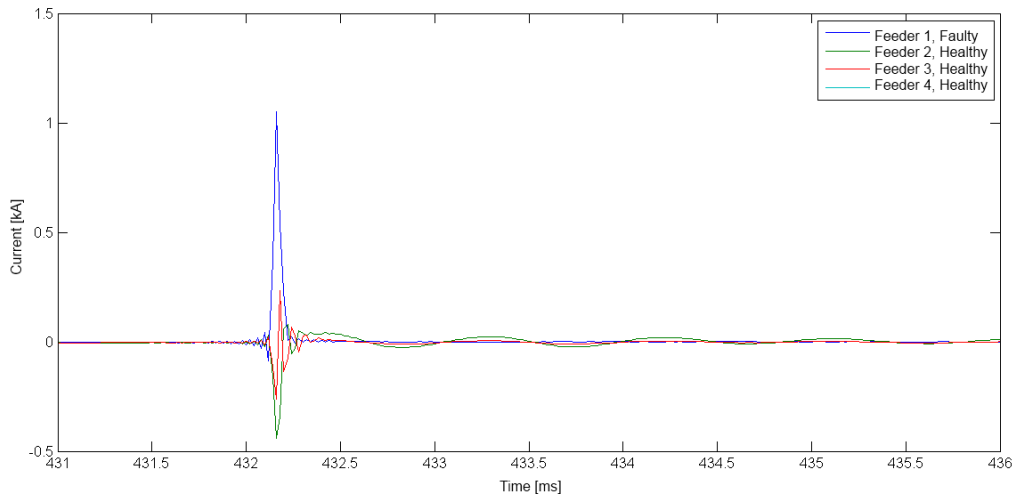


Figure 2: Zero sequence current in feeders at intermittent earth fault

Figure 2 includes an example of the current “spikes” that could occur during intermittent faults. It is shown that the whole sequence is taking a fraction of a millisecond. This indicates that high sampling rates is essential for protection unit aiming for this fault type.

Frequency content in measurements

The measurement clearly shows that intermittent faults contain high frequency components, well above the fundamental 50 Hz signal. When examining the current there are clear “spikes” in the measurement files. The rise time of these spikes imply that the fault transients also contain higher frequency components with very short time duration. Another way is to calculate the frequency content by using FFT, but the result is highly dependent on selected time window length and possible averaging, which makes it hard to draw far-reaching conclusions.

However, the fact that a fault current might contain high frequent component will have to be considered when evaluating cables model.

LINE MODELS

In many models of distribution lines resistances, capacitances and inductances are lumped together to simplify calculations. This approach is a useful approximation, as long as the distribution line can be considered to be much shorter than the wavelength of the highest interesting frequencies. When a distribution line becomes longer, the current will not be the same throughout the cable length and a model with lumped parameters is no longer valid.

A modeling approach that takes account of the resistance, capacitance and inductance are scattered along the distribution line is the so-called distributed parameter model, or transmission line model, which is a standard textbook subject. This model may be derived from a distribution line, which is divided into several series-connected parts. Each part is described as shown in

Figure 3, where all values are expressed in per length unit, where g is the leakage conductance [S/m], c is the capacitance [F/m], l is the inductance [H/m] and r is the resistance [Ω/m].

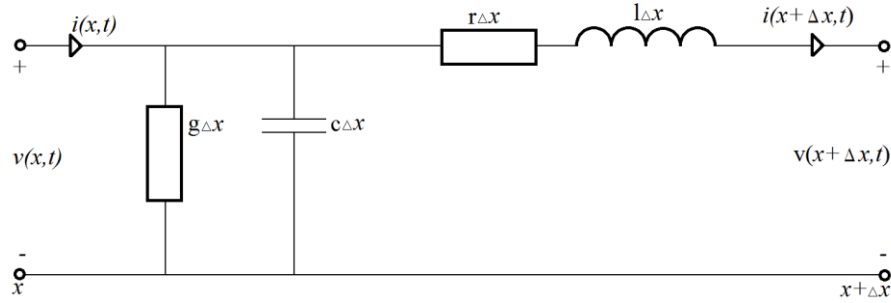


Figure 3: Line model with distributed parameters

When Δx approaches zero, we get the partial differential equation (1) (Claesson, Eriksson, Mandersson, Salomonsson 1989 s.129-130). Equation (1) can be used to represent voltages and currents by a four pole with arbitrary inputs.

$$\begin{bmatrix} V_{Sender} \\ I_{Sender} \end{bmatrix} = \begin{bmatrix} \cosh(\gamma d) & Z_0 \sinh(\gamma d) \\ Z_0^{-1} \sinh(\gamma d) & \cosh(\gamma d) \end{bmatrix} \begin{bmatrix} V_{Receiver} \\ I_{Receiver} \end{bmatrix} \quad (1)$$

γ is the wave propagation constant, d is the length of the distribution line and Z_0 is the characteristic impedance.

$$Z_0 = \sqrt{\frac{r + j\omega l}{g + j\omega c}} \quad (2)$$

$$\gamma = \sqrt{(g + j\omega c)(r + j\omega l)} \quad (3)$$

Skin effect

Since a model for intermittent faults aims at higher frequencies, it seems relevant to consider the skin effect which describes the currents behavior at higher frequencies. The net result is that with higher frequency, the current flows closer to the conductor surface. Thereby it will not take full advantage of the conductor and this will cause the effective resistance to increase with frequency.

For a model that is intended to work for 50 Hz only, this will have little or no impact. However when modeling lines and cables to reproduce the behavior at intermittent fault, it's of great importance that the models correctly reproduce the high frequency behavior.

Equation (4) includes the skin-effect and describes the impedance in a circular conductor.

$$R + j\omega L = R_0 \frac{kr J_0(kr)}{2 J_1(kr)} \quad (4)$$

Where J_0 and J_1 are Bessel- functions of zero and first order and R_0 is the DC-resistance,

$$R_0 = \frac{l}{\pi r^2 \sigma} \quad (5)$$

and the constant k is

$$k = \pm(1-j)\sqrt{\frac{1}{2}\omega\mu_r\mu_0\sigma} \quad (6)$$

Where r is the conductor radius (m), l is the conductor length (m), σ is the conductor conductivity (Ωm)⁻¹, μ_r is the relative permeability, $\mu_0 = 4\pi \cdot 10^{-7}$ (Vs/Am) is the permeability for vacuum, $\omega = 2\pi f$ is the angular frequency (rad/s) and f is the frequency (Hz). Appendix A lists a Matlab macro that calculates the skin effect for a 95 mm² cable. The result is shown in Figure 4.

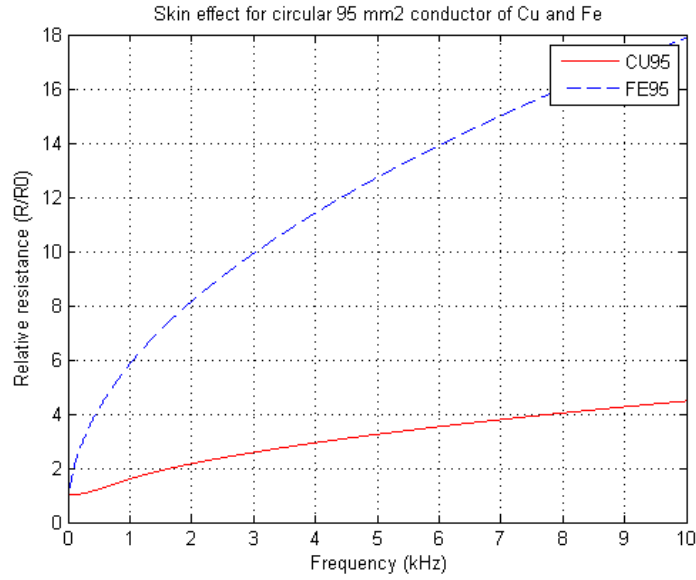


Figure 4: Relative change in resistance due to skin effects, calculated for 95 mm² cable

Implementation

The line models are made up of five series-connected π -links each, every π -link is equivalent to a 2 km long line. A jumper is placed between the second and third π -model to enable modeling of 2 km instead of 10 km and for connecting the ground fault. Ground fault can be connected at 0, 2 or 10 km.

The connections (marked by black rings in Figure 5) give the opportunity to change the neutral conductor resistance and inductance. The resistors located in series with the capacitors in the first π -model require some comments. The resistors purpose is to control the high frequency behavior, for example, it limits the current through the capacitors in case of a short circuit close to the source. The value should in theory equal the wave impedance.

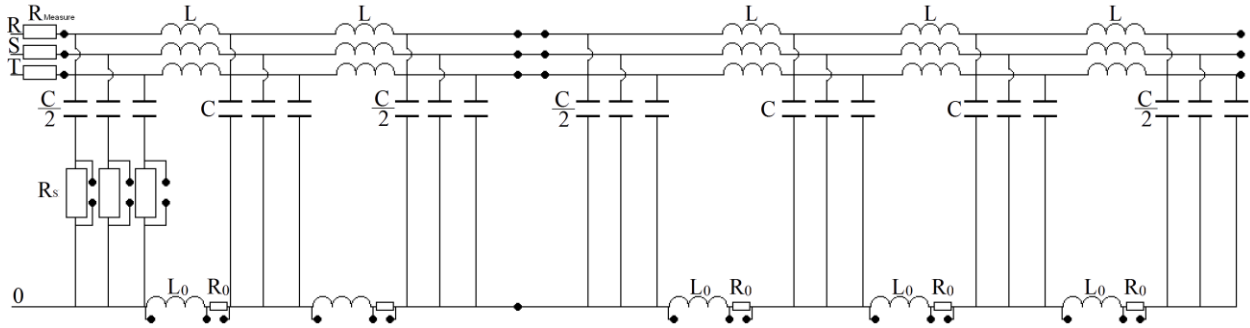


Figure 5: Implemented pi-model

To validate that these models are useful for work on intermittent faults, the frequency behavior of the impedance have been measured. Here it is of interest to see how amplitude and angle change with frequency.

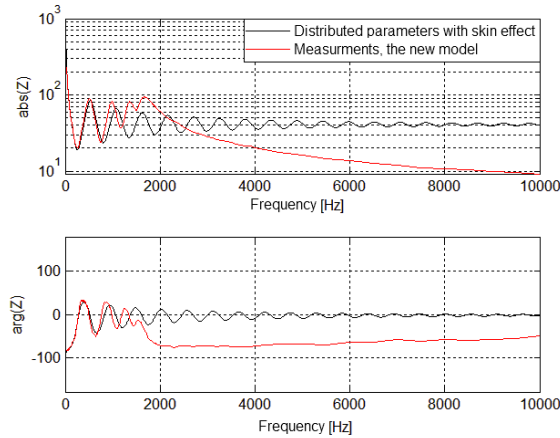


Figure 6: Frequency behavior

Figure 6 shows in black the calculated behavior for a typical ground cable. As can be seen there are distinct resonance peaks but the amplitude of them decrease with frequency. The measurement of the new models is presented in red and follows the theoretical calculation well up to around 1 kHz. This could be further increased by using even more π -link in the modeling work.

CONCLUSIONS

The goal with this work was to study intermittent earth faults and modeling methods, and to implement them in DLAB. The recorded data along with new tests, revealed need for model improvement at higher frequencies. The skin effect has been considered in the new model. The

old line model, designed for 50 Hz, seems obsolete for this application and has been retired from DLAB since 2010.

All in all the laboratory setup, DLAB, is now able to model a distribution network quite well and provides a good platform for research and education. In the near future DLAB will be used for evaluation of an earth fault protection unit available on the market today. This will also create a better understanding of how today's protection works against intermittent earth faults and cross country faults.

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APPENDIX A – MATLAB MACRO FOR SKIN EFFECT

Do_skineffect.m

```
f=[1:10e3];f_kHZ=0.001*f; area=95; %
CU95=skineffekt(area,'CU',f);
FE95=skineffekt(area,'FE',f);
plot(f_kHZ,CU95,'r',f_kHZ,FE95,'b--')
legend('CU95','FE95'); grid;
xlabel(' Frequency (kHz)'); ylabel('Relative resistance (R/R0)')
title(' Skin effect for circular 95 mm2 conductor of Cu and Fe')
print -depsc -tiff -r300 skinn_aalto
```

Skineffect.m

```
function real_corr_factor=skineffekt(area,metal,f)
% Rev. 2010-06-19, change in Eq. for kr=k*radius_m,
% corr_factor=skineffekt(area,metal,f)
% area, mm2
% metal={'AL','CU','FE'}
% f, frequency Hz
% Ref: Erik Hallén, Elektricitetslära, 1953, page 326-328
%
my=4*pi*1e-7; area_m2= area/1e6; metal=upper(metal);
switch metal
    case 'AL'
        rau=26.50e-9 ; % ohm meter
        my_r=1.00;
    case 'CU'
        rau=16.78e-9 ; % ohm meter
        my_r=1.00;
    case 'FE'
        rau=96.1e-9 ; % ohm meter
        my_r=100.00;
    otherwise
        error(['Unknown metal: ' metal])
end
sigma=1/rau; w=2*pi*f;
radius_m=sqrt(area_m2/pi);
H=sqrt(0.50*w*my*my_r*sigma); k=H*(1-j); kr=k*radius_m;
J0=besselj(0,kr); % Bessel function of first kind, zero order
J1=besselj(1,kr); % Bessel function of first kind, first order
corr_factor= 0.5 * kr .*J0 ./J1;
real_corr_factor=real(corr_factor);
imag_corr_factor=imag(corr_factor);
```