Experiments with Travelling Wave Transients for Verification of Suitability of Sensor

Lauri Kütt, Jaan Järvik
Tallinn University of Technology
lauri.kutt@ttu.ee

***Abstract*- For implementing novel power line diagnostics methods, many questions are related to the sensors measuring the physical quantities on the high-voltage power lines. In this paper, a sensor suitability verification experiments are presented. Tests are carried out with high-voltage set-up and short-circuit fault transients are observed. Results show that the response of the proposed sensor is very good and this also opens up new directions of investigation and implementation.**

I. Introduction

Fast transient monitoring methods for power line condition diagnostics have previously have been available for high price making the diagnostics non-stationary. With advances and decreasing price of signal processing and communication equipment, methods that have been economically unavailable are now being more attractive for wide use in power networks. Methods like dielectric diagnostics with partial discharge detection, traveling wave methods and power line characteristics determination with time-domain reflectometry are becoming available also for distribution networks [1]. Problems making the equipment more affordable have been the fact that such measurements would need to observe very high frequency phenomena with very high speed signal processing. Non-stationary equipment does not allow performing pre-fault diagnostics, as it is very difficult to determine need to connect the equipment to particular line to observe the condition.

Target of this research is to help to build new kind of equipment designated for wide use for on-site measurements. It is needed that the measurement equipment would be affordable for stationary mounting to great number of locations in distribution networks. This would open up a totally new field for carrying out diagnostics and improving the condition of distribution networks.

Previous research for such sensors [2,3] has provided quite good perquisites but has lacked practical high-voltage testing to verify the suitability. This paper describes the practical work for testing the transients occurring on the high voltage power lines. Target of such testing is to verify the suitability of the proposed measurement methods for traveling wave measurements.

II. High-Frequency Transients in Power Networks

During normal operation, when the power network is operating with all components in full operating condition there should be no high-frequency transients observable on the power lines. Transients will occur for example with load connections or disconnections, with faults occurring that bring along sharp variations in electric quantities (such as arcing faults) or there is some other phenomenon with effects of sudden parameters variation.

If distribution networks are observed, then load disconnection and connection are mostly on the low-voltage networks and these usually do not bring along very rapid transients. Highest speed transient sources are

- faults that occur on the medium-voltage lines,
- partial discharge phenomena related to insulation breakdown of cables and overhead lines carrier insulators.

Duration of transients during such events is extremely short. Following example describes one scenario that presents voltage variation of 1000V at a distance of 10 m from the source. The test was carried out in laboratory and simulated the actual short-circuit conditions on the power line (see Fig. 1, more details below in this paper). Fault simulation presented that the voltage on the power line, measured from ground, could drop from 1000V level to 0 V level in just 10 ns time.

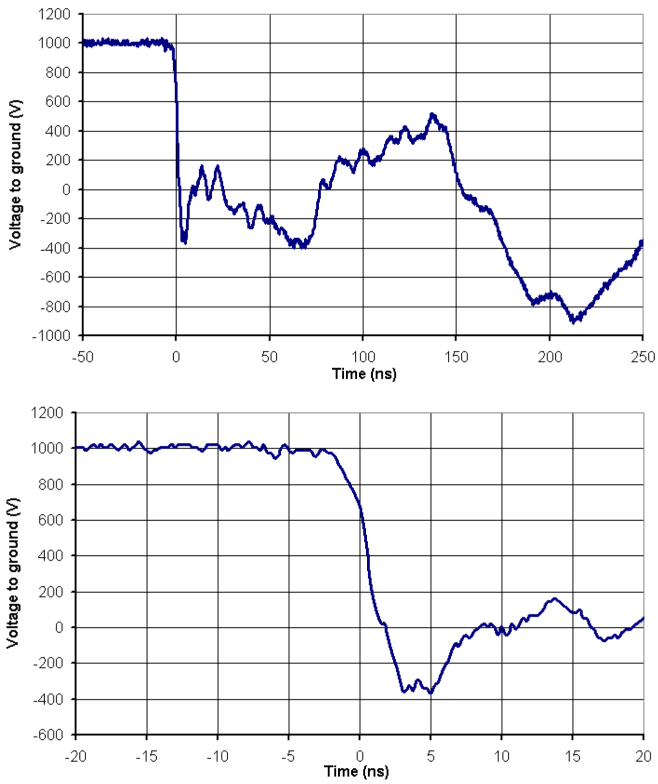

Fig. 1. Voltage variation on high voltage line upon ground fault. Upper – overview; lower – close-up view of transient.

III. WAVE TRANSIENTS ON THE POWER NETWORKS

Every transient is propagating along power lines with finite speed, described by the medium where electromagnetic transient is moving in. Transient propagation speed is defined as

$$\upsilon = \frac{1}{\sqrt{L_0 C_0}} = \frac{1}{\sqrt{\varepsilon_a \mu_a}}. \quad (1)$$

Where L_0 is line inductance per length unit, C_0 is line capacitance per length unit, ε_a is the dielectric material absolute permittivity and μ_a is the wire absolute permeability. In case of overhead line using air as dielectric, and using aluminum as wire,

$$\varepsilon_a = 8{,}85 \cdot 10^{-12} F/m, \quad (2)$$

$$\mu_a = 4 \cdot \pi \cdot 10^{-7} H/m, \quad (3)$$

thus propagation speed

$$\upsilon = \frac{1}{\sqrt{\varepsilon_a \mu_a}} = \frac{1}{\sqrt{8{,}85 \cdot 10^{-12} \cdot 4 \cdot \pi \cdot 10^{-7}}} \cong 299{,}86 \cdot 10^6 m/s. \quad (4)$$

If substituted to smaller units, it means that the transient propagates about 0,3 m/ns. This is good to keep in mind if observing line lengths where the transient is moving.

Transient is considered to be wave transient if the line length is longer than the wavelength of a periodic process, or if it fits fully inside the line where it is moving. In case of transient described above (Fig. 1) having the voltage variation duration of 10 ns, about 3 meters of line length is enough to accommodate the whole transient.

Power line properties characterize also wave transients. One of the most important characteristics for high-frequency transients is the characteristic impedance (Z_0), which presents the ratio between the current and voltage of the wave transient. Using characteristic impedance, current *i(t)* associated with the voltage *u(t)* transient in the line can be calculated when the voltage is known as

$$Z_0 = \frac{u(t)}{i(t)}. \quad (5)$$

Different formulas are available for calculating the line characteristic impedance for a particular wire and/or ground configuration. For example, a quite simple approach of presenting impedance calculation formula for single wire line above ground is [4]

$$Z_0 = 138 \log \frac{2h}{d}, \quad (6)$$

where h – height of wire above ground, d – wire diameter .

IV. MEASUREMENT OF TRAVELLING WAVES

For measurement equipment found in substations usually at present day, the highest bandwidth of the transient that can be recorded is up to few tens of MHz. This is due to the conventional equipment like voltage and current transformers used, which have the bandwidth of few tens of kHz. Due to the relatively low highest working frequency, wave transients are often unseen by the substation equipment.

Traveling wave transients have rapid nature and they need to be observed at bandwidth reaching into tens of MHz for correct analysis. For this reason, sensor as well as signal processing path should be designed for high frequencies and high signal processing rate [3]. Previously Rogowski coil designs have been proposed [5] as well, that provide sufficiently high bandwidth for the measurements. In transmission lines and very high voltage networks (above 200 kV), capacitive voltage dividers are used that provide quite nice traveling wave response with bandwidth around 1 MHz [6]. However, distribution networks do not have such equipment available; the topology of distribution networks would also need use of multiple sensors for one outgoing feeder.

Traveling voltage wave is accompanied by current wave, with its magnitude determined by line characteristic impedance (see above). Target of current wave measurements is to provide results so that only the current wave is measured; voltage wave should not produce response to the sensor. Current wave can be measured, for example, with the help of magnetic field present around the power line wire. Voltage wave could be measured using, for example, capacitive voltage divider due to sharp change of electric field around the conductor.

When using simple magnetic coil for current measurement and the coil has wide enough bandwidth, output of the coil should provide a function of current variation rate in time [2]

$$e \cong -Aw\mu \frac{dI}{dt}, \quad (7)$$

where A – coil area, w – number of turns in coil, μ – magentic permeability, I – current and t – time. It can also be expressed as

$$e = -M \frac{di}{dt}, \quad (8)$$

where M – mutual inductance between wire and sensor coil. For different shapes of coils, the mutual inductance values can be found in literature [7].

However, the resonant conditions of the measurement sensor could affect the measurement sensitivity as well as the output. During the tests described in this paper, the conditions of using the sensor coil to measure traveling wave transients are looked at. Main question of the experiments carried out was if the coil was sufficient to provide strong and interpretable output that could be used to trace the original waveform of transient.

V. TESTING SET-UP

A test set-up was created for verification of traveling wave measurements, consisting of a high-voltage power line replication, high-voltage source, termination, measurement probes and oscilloscope (see Fig. 2). Length of active part of line was 22 meters, with distance to fault from measurement point 10 meters. This was sufficient for establishing the wave transient, as all the transient fits to the length of 10 meters. However, transient wave edge is very sharp at this distance

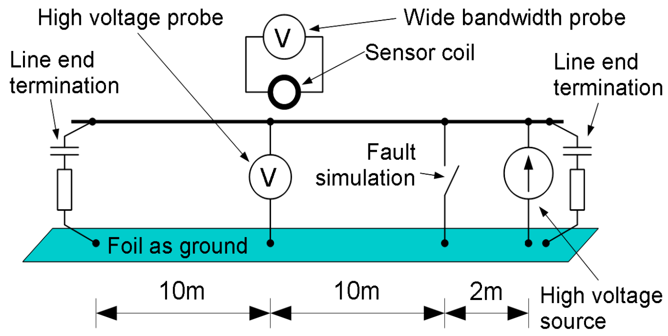

Fig. 2. Testing set-up of traveling wave measurements.

Fig. 3. Testing set-up of traveling wave measurements.

Overview of the actual testing set-up prepared for testing is shown in Fig. 3.

The power line replication was made with a stranded aluminum wire over foil, the latter representing a very good ground connection (Fig. 4).

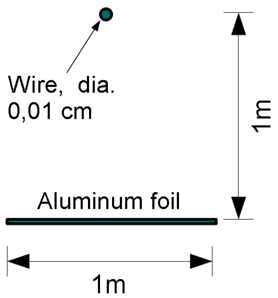

Fig. 4. Testing power line set-up.

This configuration of power line provides characteristic impedance using formula (6) of about 325 ohms. For this reason the end termination was made with 330 ohm resistors (closest value to 325 ohm). As the line was charged to high voltage values using DC voltage source, the termination resistor cannot be connected to line directly, as it would provide great power loss on the termination resistors. Rather an AC-type termination has been used with capacitor and resistor series connection (Fig. 4). This way only the transients are attenuated but the DC voltage is not loaded by resistors. 30 nF capacitance was used as the capacitor in the AC termination connection.

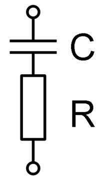

Fig. 5. AC termination with C and R series connection.

High voltage source used in testing was Megger MIT1020 high resistance insulation tester. It is able to provide up to 10 kV of DC voltage on its output, but during testing only 1 kV output level was used. Positive terminal of source instrument was connected to wire and negative terminal to ground foil.

Oscilloscope Agilent InfiniiVision MSO6104A was used for carrying out measurements. This oscilloscope provides 4 analog channels with 1 GHz of bandwidth. Agilent N2876A oscilloscope probes of 1,5 GHz bandwidth and 2,6 pF capacitance were used for coil measurements. For high-voltage measurements, a passive probe Testec HVP-15HF having measurement capability of 15 kV and 50 MHz bandwidth.

Circular coil (see Fig. 6) was used for testing, which characteristics were previously known to very precise level [2]. Coil had diameter of 10 cm with pitch of 0,8 mm and 4 turns of 0,5 mm wire. Its inductance was 2,71 uH and capacitance 1,34 pF. Coil centre was mounted to the distance of 15 cm from the line.

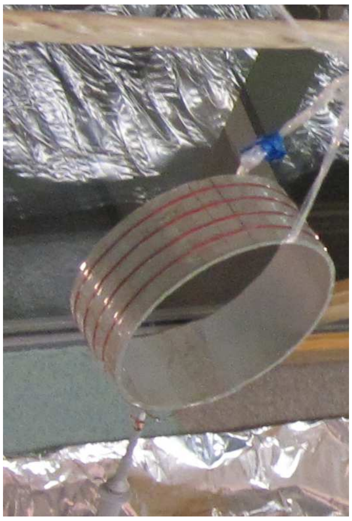

Fig. 6. Coil used for testing assembled to the line. In the bottom oscilloscope probe is visible.

Short-circuit was simulated with a simple low-inductance connection from ground foil to the wire. The shorting connection was established by mechanically forcing the conductors together.

VI. TEST RESULTS

Testing results were obtained with simultaneous measurements of sensor coil output and voltage value on the wire.

Testing was initiated by loading the line to steady voltage and then simulating the short-circuit. Time "0" refers to the oscilloscope triggering event as the line voltage decreases sharply.

Fig. 7 presents testing results with non-loaded coil. Output provides peaks reaching +120 V and having amplitude of nearly 200 V, indicating very sharp transient edges. The signal is very strong, however the oscillations make it rather difficult to interpret. As step 2, the sensor coil was fitted with load resistance.

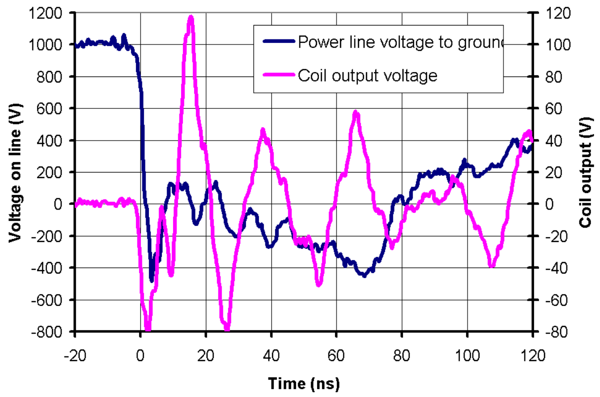

Fig. 7. Testing results with non-loaded coil.

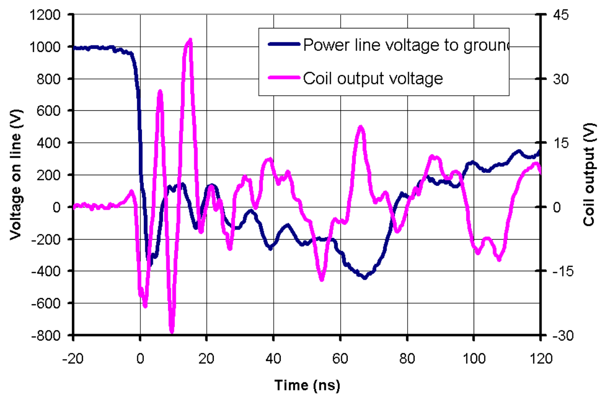

Fig. 8. Testing results with coil loaded with 330 ohm resistor.

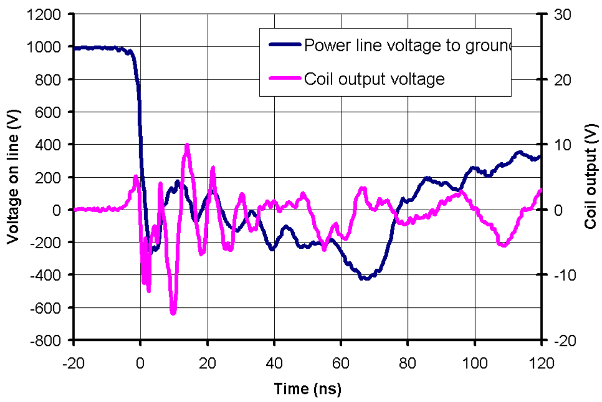

Fig. 9. Testing results coil coil loaded with 33 ohm resistor.

Fig. 8 presents the results when the coil is loaded with 330 ohm resistor. The coil output voltage magnitude is decreased almost 3 times, but it still remains very strong. Another test was carried out with 33 ohm resistor was connected to coil terminals (Fig. 9).

Even quite small resistance loading the coil still produces remarkably strong output.

VII. DISCUSSION AND CONCLUSIONS

Results present that even this type of coil having only 4 turns of wire produces very strong response in the output, which is a very good sign for the application. Important fact to point out is that the coil response initial resonance is increasing as the loading increases. With the probe connected to coil, the coil output resonant frequency should be around 50 MHz, which is also visible on the no-load coil measurement results. The strong response indicates that there could be also use for this type of measurement system on the low-voltage networks.

Furthermore it is excellent to see the reproducibility of the short-circuit event waveform, as seen when comparing different figures. This verifies that the set-up is suitable for the start of investigation on the high-speed transients.

However the damping of the small resistor is very beneficial and would help to decrease noise. It should be further investigated what is the optimum value that would be most useful for eliminating noise in this application.

ACKNOWLEDGMENT

This research was supported by European Social Fund's Doctoral Studies and Internationalisation Programme DoRa.

Authors thank Estonian Archimedes Foundation (Inter-disciplinary project "Optimal energy conversion and control in Smart and Microgrids" within the framework of Doctoral School of Energy and Geotechnology-II) for support of this study.

REFERENCES

[1] G. M. Hashmi, M. Lehtonen, A. Elhaffar, "Modeling of Rogowski Coil for On-line PD Monitoring in Covered-Conductor Overhead Distribution Networks", *19th International Conference on Electricity Distribution (CIRED07)*, Vienna, Austria, Paper No. 0207, 2007.

[2] L. Kütt, J. Järvik, "Magnetic field sensor coil in fast transient measurement application". *10th International Symposium "Topical problems in the field of electrical and power engineering. Doctoral school of energy and geotechnology". II :* Pärnu, Estonia. Estonian Society of Moritz Hermann Jacobi, 2011, 117 - 121.

[3] L. Kütt, M. Shafiq, "Magnetic Sensor Coil Shape Geometry and Bandwidth Assessment", *Proceedings of 7th International Conference-Workshop Compatibility and Power Electronics (CPE2011)*, Tallinn, IEEE, 2011.

[4] C. Dickman, A *Multiband End-fed Inverted*-V *Antenna* System; Radio ZS January 1973, copy of article available from *www.zs6ro.co.za/files/circuits/Antenna/ZS6U-Mini-Shack-Special.pdf*

[5] G. Robles, M. Argueso, J. Sanz, R. Giannetti, B. Tellini, Identification of parameters in a Rogowski coil used for the measurement of partial discharges, *Instrumentation and Measurement Technology Conference, 2007 (IMTC 2007).* Warsaw, Poland; pp 1-4.

[6] A. Elhaffar, M. Lehtonen, High Frequency Current Transformer Modeling for Traveling Waves Detection, *Proceedings of Power Engineering Society General Meeting*, 2007, IEEE.

[7] J. Hlavacek, R. Prochazka, K. Draxler, V. Kvasnicka, The Rogowski Coil Design Software, *Proceedings of 16th IMEKO TC4 Symposium Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements,* Florence, Italy 2008.