Definition and Modeling of the Sensors Network for Voltage Induced by Preliminary Breakdown Pulses on Overhead Transmission and Distribution Lines

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1 Context

Project: FELINES

PRIN 2022, grant number 20224CL7HM, Italian Ministry for Education, University, and Research and the European Union-Next Generation EU. The research project Forecast of the Effects of Lightning IN Electrical Systems (FELINES) aims at designing a protection system capable of sensing phenomena that preliminary to a lightning event, and consequently disconnect part (or all) of the electric infrastructure under its protection. These phenomena are associated with the so-called Preliminary Breakdown Pulses (PBP), localized events taking place during the first phases of the lightning inception.

Work Package 2: Modeling of PBP and sensors network

Responsible Research Unit: UniGe

Task 2.2: Definition and modeling of the sensors network

Starting from results of Task 1.2 ("Indirect and direct lightning events analysis"), and basing on the characteristics of the PBP signals (frequency content, magnitude, time domain support) a set of proper sensors is identified and selected. A numerical model of the sensors' response to effects generated by PBP is developed, together with the model of the whole measurements chain, i.e. amplifiers, filters, digitizers. The parameters of the measurement system are chosen so that the input data to the early detection software will not lose any of the fundamental signatures useful for the definition of an incoming dangerous lightning, as identified in previous tasks.

Application: Overhead transmission and distribution lines

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2 Introduction

This report aims at presenting the characteristics required by the sensors from which PBP data will be measured in real-time and given as input to the early detection algorithm. The first application investigated deals with indirect lightning effects induced on overhead transmission and distribution lines. In accordance with the research activities presented in [1, 2], machine learning techniques applied for lightning location and peak current estimation from lightning-induced voltage measurements on overhead transmissions and distribution lines can produce promising results. Moreover, the lightning risk associated with such systems can be measured by comparing the induced voltage with a defined threshold (i.e., the line critical flash-over voltage increased by 50% [3]). For this reason, it has been deemed appropriate to choose as input data for the early detection algorithm the PBP-induced voltage waveform, as target the maximum voltage induced by the incoming Return Stroke (RS).

The detection of voltage waveforms induced by PBP on overhead power lines holds potential for early warning systems and lightning protection strategies. However, identifying and characterizing these waveforms through voltage sensors is challenging due to two primary reasons:

1. The signal emitted by PBP is significantly weaker compared to the RS and is more susceptible to noise.
2. The electromagnetic field characteristics associated with PBP and their coupling with power systems are not as well studied as those of the RS, leading to a lack of extensive literature on PBP-induced voltage.

3 Sensor Selection and Modeling Approach

To address these challenges, an array of Voltage Transformers (VT) installed on distribution lines is proposed as a sensing network. These sensors are capable of capturing voltage oscillations induced by PBP while maintaining robustness against environmental noise. The selected sensors must fulfill specific criteria such as:

- High sensitivity to weak voltage variations,
- Adequate bandwidth to capture high-frequency components of PBP-induced voltage,
- Stability against background noise and interference.

In what follows, the characteristics of a single data acquisition system are presented. Indeed, the first development of the early detection algorithm for transmissions and distribution lines will be performed by using data from a single source. In the future, possible strategies for the integration of signals provided form multiple sensors will be investigated.

A comprehensive numerical model is developed to analyze the sensors' response to the voltage induced by PBP. This model includes:

- The intrinsic response of the VT,

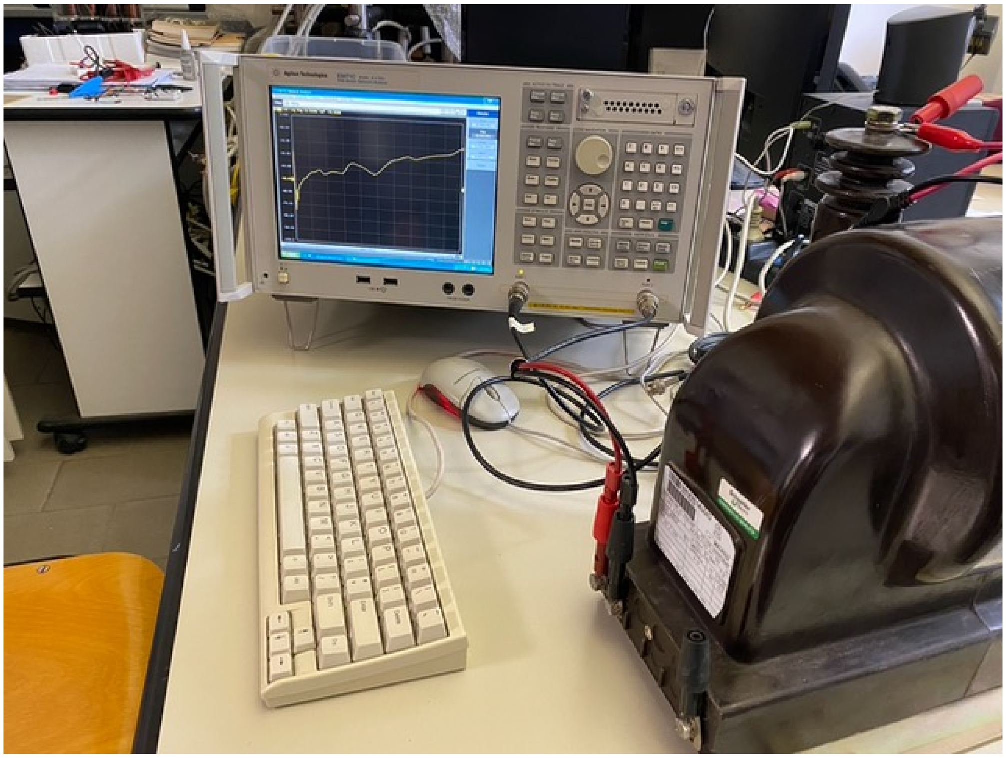

Figure 1: VT experimental setup.

- The entire measurement chain, including amplifier, filter, and digitizer.

Optimization of measurement parameters to ensure critical signal features will be achieved in next stages of the work, as well as the determination of suitable time constants of the entire measurement chain, such to be compatible with the PBP-RS time interval (in the order of some milliseconds [4]), the CPU time of the early detection algorithm and the triggering time for the eventual disconnection.

4 Determination of the Transfer Function of a Voltage Transformer

The characterization of the VT involves determining its transfer function. This process is facilitated by experimental data obtained from scattering parameters (S-parameters) measurements. S-parameters describe the electrical behavior of a device in terms of how signals are transmitted and reflected at its ports. These parameters are particularly useful in characterizing high-frequency performance. In a VT, the key S-parameters include S_{11} (input reflection coefficient), which indicates how much of the incident signal is reflected back at the input, and S_{21} (forward transmission coefficient), which represents the efficiency of power transfer from the primary to the secondary winding. Similarly, S_{22} and S_{12} describe the reflection at the output and reverse transmission, respectively. The S-matrix provides insights

Figure 2: Datasheet of the VT under test.

into impedance matching, insertion loss, and isolation, all critical factors for high-frequency applications.

Figure 1 shows the setup for the experimental measurements, including test equipment (cables, adapters) and the Vector Network Analyzer (VNA), i.e. a device designed to measure the S-parameters. The VNA sends a signal to one port and measures the reflected and transmitted signals from the device under test connected to the other ports. The datasheet of the VT under test is reported in Figure 2.

The typical spectrum of PBP in lightning is characterized by a broad frequency range, extending from a few kHz to hundreds of MHz. However, the most significant spectral intensity is usually found between 10 kHz and 10 MHz, with notable peaks in the VLF (Very Low Frequency, 3–30 kHz) and LF (Low Frequency, 30–300 kHz) bands [5]. Thus, a frequency sweep was conducted from 9 kHz to 10 MHz, capturing scattering parameters at multiple frequency points. The analyzer continuously recorded the reflection coefficient (S_{11}) and transmission coefficient (S_{21}) to evaluate the transformer's response across the frequency

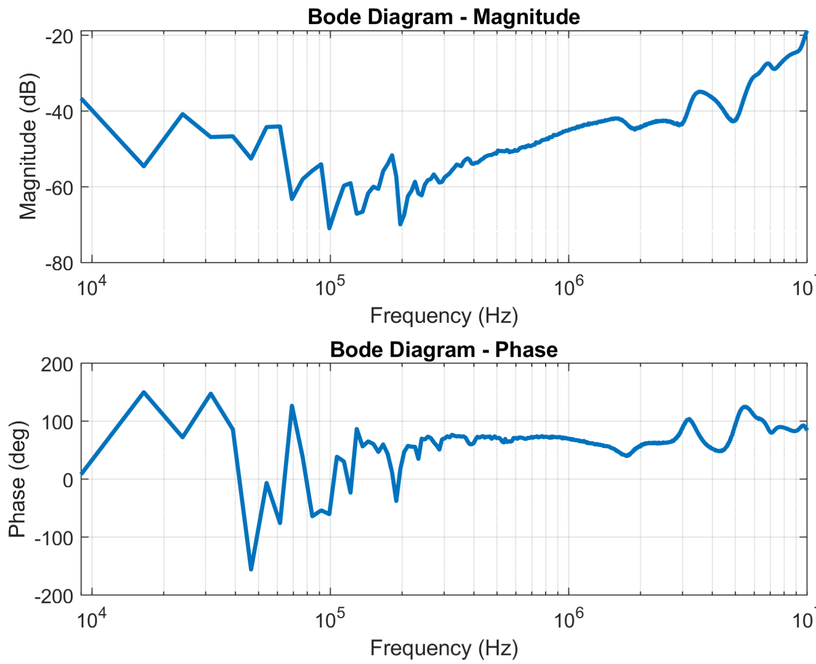

Figure 3: Bode diagram of the VT scattering parameter S_{21}.

range. Once the measurements were completed, the collected data was processed to extract the frequency-dependent scattering characteristic.

The Bode diagram and the Nyquist diagram of the S_{21} parameter (which defines the forward transmission coefficient) are reported in Figure 3 and Figure 4, respectively.

The voltage transfer function $H_V(f)$ of the voltage transformer can be derived as follows. Since both the input and output of the transformer are terminated on a 50 Ω impedance, the measured S_{21} parameter represents the power gain in a system normalized to 50 Ω. In terms of voltage transfer function, this results in:

$$H_V(f) = \frac{|S_{21}(f)|e^{j\angle S_{21}(f)}}{2} \tag{1}$$

where $|S_{21}(f)|$ represents the magnitude response, and $\angle S_{21}(f)$ represents the phase response of the scattering parameter S_{21}. The factor 2 accounts for the relationship between the voltage and power measurements in a matched impedance system.

The derived transfer function will be implemented in a computational model to simulate the real-world behavior of voltage transformers in detecting PBP-induced voltages. For this purpose, the Vector Fitting (VF) [6] method will be applied to the experimental frequency response. The VF is a numerical technique used to approximate a transfer function using a rational series of poles and residues. This method is very effective for fitting complex frequency response functions, typical of electrical systems, and for creating stable and causal models that can be used in simulations.

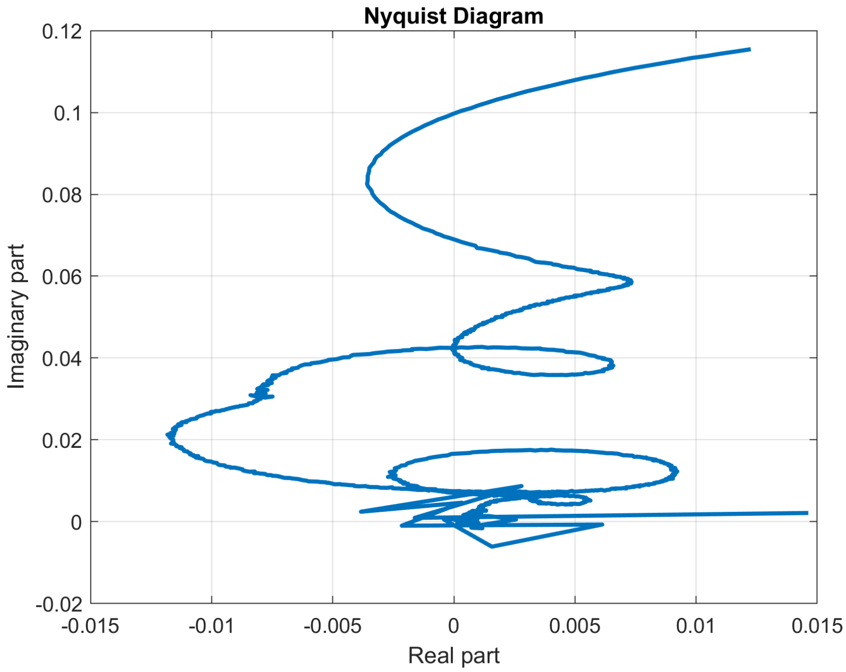

Figure 4: Nyquist diagram of the VT scattering parameter S_{21}.

5 Measurement System Design

The entire measurement system should be designed to preserve all fundamental signatures of PBP essential for lightning early detection. The components included are: amplifier, filter, digitizer. The performance of such devices in the 10 kHz – 10 MHz frequency range depends on their design parameters, including gain, bandwidth, and noise characteristics.

Amplifiers operating in the PBP frequency range are broadband amplifiers designed to provide stable gain with minimal distortion. Their frequency response can be obtained using scattering parameters measurements and transfer functions, considering parasitic effects that impact high-frequency behavior.

Filters are essential for band selection and noise reduction. The frequency response of filters is typically described by a transfer function, which defines attenuation and phase shift across the bandwidth. With some preliminary analysis (e.g., the Principal Component Analysis, PCA) on the performance of the machine learning algorithm in estimating the RS-induce voltage from the observation of the PBP-induced voltage, significant PBP frequency ranges will be selected. Thus, in real-world applications, to remove unwanted frequency components, a band-pass filter will be employed.

Digitizers convert analog signals into digital form and are characterized by their sampling rate and bit resolution. The Nyquist criterion requires that the sampling rate should be at least twice the highest signal frequency to avoid aliasing effects. For PBP electric field measurements, an 8 bits resolution and a 50 Msamples/s are typically applied (e.g., [4]). It follows that the same parameters can also be used for PBP voltage measurement.

References

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