Power Cable Wave Propagation Velocity Estimation Based on Travelling-Waves

Marko Hudomalj[1,2]

[1] Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia
[2] ComSensus d.o.o., Brezje pri Dobu 8a, 1233 Dob, Slovenia
E-pošta: marko.hudomalj@ijs.si

Abstract. *This paper presents a method for estimation of power cable wave propagation velocity transfer function. The method determines signal propagation velocity based on the measurements of travelling-wave signals at each frequency. Travelling-waves are caused by different events on power cables such as partial discharges, faults and lightning strikes. The method will be used for improving localization of events on power cables. Method uses wavelet transform to analyze the signals in the frequency domain.*

The method is tested with the use of frequency-dependent transmission line model in Simulink. Propagation velocity calculated based on wavelet transform is compared to propagation velocity calculated from analytic transmission line parameters.

1 Introduction

The electrical power system (EPS) is migrating to renewable energy in order to lower pollution. With the introduction of renewable energy sources new control and protection challenges are emerging in EPS. There is also a constantly increasing demand of electrical energy especially with the transition to electric mobility and introduction of new advanced HVAC systems to the grid. With this increasing demand, EPS is being pushed to its limits during peak demand hours. The upgrades in EPS are expensive and take a lot of time, so great effort is being put into how to exploit existing EPS infrastructure. EPS must provide continuous and reliable electrical energy and must operate safely. To enable optimal control, protection and quick fault repair of the EPS, a good observability of the EPS operation must be provided. In recent times, many new Intelligent Electronic Devices (IEDs) were developed to provide a better insight into the operation of EPS. This was enabled with the development of processing units, new algorithms, measurement devices, and communication devices. However, in the field of IED there is still a lot of research opportunities. IEDs help EPS to become even more digitalized. In recent years IEDs with high sampling frequencies are being developed [1] that monitor transformers, generators, switching equipment, and power cables.

Our research focuses on devices that monitor events on the EPS at frequencies much higher than system frequency. Sampling frequency is in the range of 10 MHz and above. The main field of our research is event detection, localization on power cables and characterization of power cables. The events analyzed are faults, partial discharges (PD) and lightning strikes. Faults are meant as short circuits on the power cables between phases or between phase and ground. In the case of a fault, the rest of the EPS must be protected which is done with relays. Similarly, in the case of lightning strikes, the rest of the system must be protected against overvoltage. Faults and short circuits are one-time events on the cable, but the PD activity is constantly present on the cables with isolation. PDs happen in the cable isolation where voids occur because of cable isolation degradation. Because of the high voltages on the power cables breakthroughs happen in the voids.

The described events cause travelling-waves (TW) on the power cables. TW are short-time high-frequency transient signals. In the instance of power cables, signals propagate in both directions along the cables from the location of the event towards the cable ends. TW events and the signals are represented in Figure 1. When TW reaches an end of the cable, where medium changes, it is reflected back. Additionally, the propagating TW signal is attenuated and because the propagation velocity depends on the frequency the transient signal is elongated in time. This is the effect of dispersion. In our research, we want to exploit dispersion effects of the TW signal propagation to improve event detection and localization on power cables.

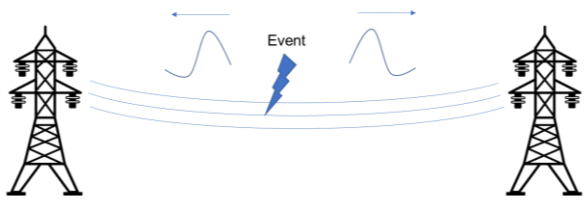

Figure 1: Representation of traveling-wave on power cables

2 State of the art

TW detection and localization methods on power cables can be either single- [2], [3] or double-ended [3], [4]. In a single-ended approach, TW is detected just on one side of power cables, using reflected waves for localization. In a double-ended approach, detection of the original signal at both sides is used for localization. Another approach is detection of TW with multiple devices on a single cable, where the methods are similar to double-ended approach.

To improve TW localization on power cables, recent developed methods consider cables transfer function

(TF). TFs are determined based on different approaches. The first approach is to determine the TF based on power cable parameters (electrical cable characteristics, geometry, isolation characteristics, etc.) [5]. Another approach is to use TF determined based on measurements when the power line was deployed [6] or measurements during maintenance. These two approaches for TF estimation do not consider the changing of the TF because of environmental changes of temperature and humidity, and ageing of cables, especially isolation degradation. To include the changing of TF for more accurate representation, some researchers have worked on determining the TF based on online measurements. One such approach is to use a reference signal generator at one end of the power cable [7]. With a known reference signal, TF can be accurately determined by measuring the signal at the other cable end, where the reference signal was induced and comparing the reference and measured signal.

Different algorithms for the detection of TW were proposed [6], [7]. Some algorithms use specific point on the TW which is then used for location. This approach requires good synchronization of the measurement equipment and stable sampling frequency. Another approach is to use the slopes of the detected TW or transform the time-based signal to the frequency domain and look at TW at different frequency components [8]. Another method is so called “propagation distance” that was proposed in the ref. [6]. The algorithm does not need to determine a specific point on TW which reduces the need for high sampling accuracy. Some proposed methods also do not need synchronization between measurement equipment, as in the case of ref. [7].

An interesting research field is also the ageing estimation of EPS equipment, which is generally based on PD measurements [9]. With an ageing estimation, preventive repair of equipment can be scheduled and potential future faults avoided.

In praxis today, TW is used for fault detection, such as the TW87 scheme (travelling-wave differential protection scheme). In recent years, analysis of different parameters of TW87 were carried out and commercial products are emerging. But there is still work being done on improving detection and localization algorithms that consider online cable TF estimation and how junctions or other network equipment affects the propagation of TW.

The presented paper focuses on developing an algorithm for online TF estimation based on TW to improve event detection and localization on power cables.

The frequency-dependent propagation of electromagnetic waves is exploited in our method to determine the fault location and simultaneously determine the dispersion function, which is dependent on the cable characteristics and the surrounding medium. In this paper, we focus on propagation velocity transfer function estimation.

3 Methods

To analyze TW on power cables, we prepared a simulation in MATLAB Simulink. For the simulation of the power cables we used the Simulink model of frequency-dependent transmission line [10]. The used transmission line model is an implementation of the Universal Line Model (ULM). It uses frequency-dependent series resistance, reactance and susceptance per unit length as the line parameters. The model is packaged to be used as a four terminal electric component. The transmission line is executed with ULM equivalent circuit in Laplace domain.

For the simulation of a power cable, we used three transient line components. For the event generation, an impulse signal generator was used. The used simulation model is presented in Figure 2.

Three transient line components were used to enable voltage measurements and impulse signal generation at different positions along the cable. In the simulations, we assigned same line parameters to all three sections to simulate a single power cable. Line parameters are shown on Figure 3.

For the impulse signal generator, we used voltage generator with a parallel resistor and a switch which

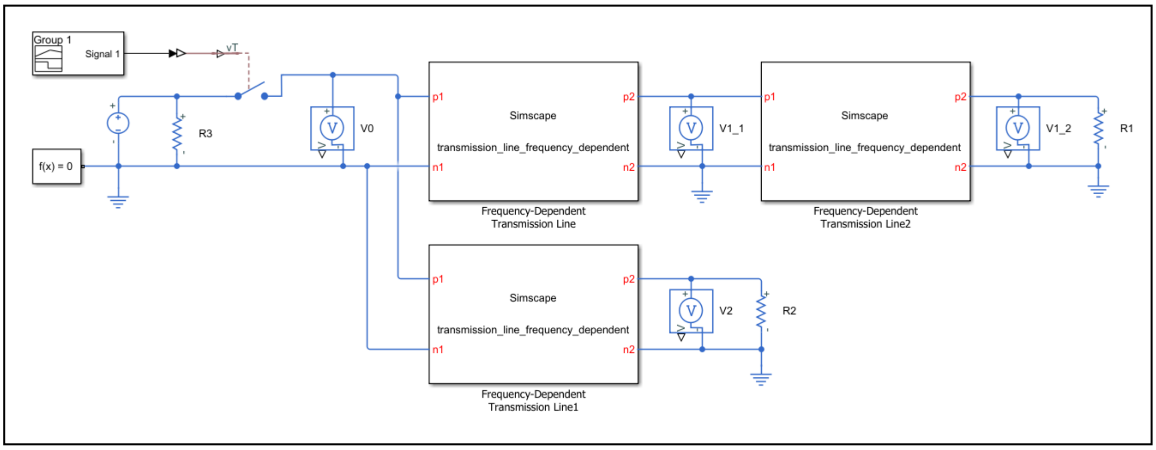

Figure 2: Simulation power cable model

applies the voltage to the frequency dependent transmission line. The circuit is represented on the left of Figure 2. Voltage measurement were done along the cable: between sections of the transmission line components and at both ends of the cable.

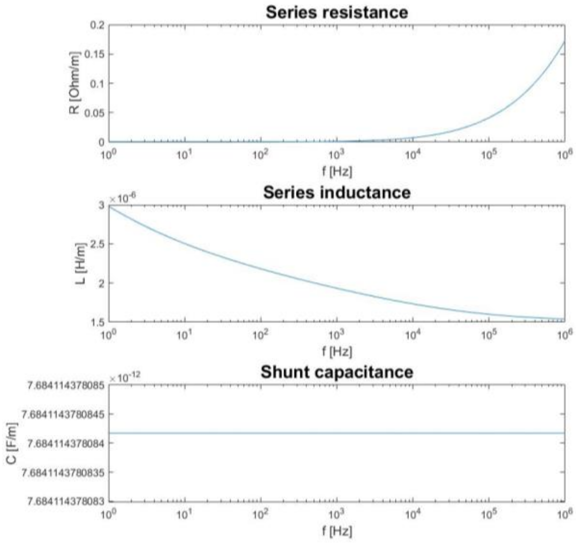

Figure 3: Transmission line parameters

The simulation results were further analyzed in MATLAB.

We determine the TF of the transmission line from the voltage measurements, in particular we were interested in propagation velocity. Generated pulse is a short time high-frequency bandwidth signal that propagates across the transmission line. We used wavelet transform to transform the time domain signal to the frequency domain and determined the peak amplitude at each frequency. The propagation velocity is then calculated based on the time of peak magnitude at different measurement locations on the transient line and the known length of the line in between.

4 Results

For the results presented in this paper we generated an impulse at the middle of a simulated 16 km long power cable. The cable was divided into three sections. Two series cable sections were 4 km in length and the third section was 8 km in length. We used a sampling frequency of 60 MHz for all of the signals. The impulse was generated at 0.1 ms from the start of the simulation and had raise time of one sampling step and one sampling step of fall time. The maximal value was 100 V which also persisted for one sampling step.

The time-series graph measured at the end of the 8 km section is shown in the lower graph in Figure 4. From the graph, the first incident wave can be observed. The reflected waves can also be observed, especially the first reflected wave.

To better observe the frequency behavior of the signal, we used continuous wavelet transform on the time-series. We used symmetrical Morse wavelet with MATLAB's continuous wavelet function *cwt()*. The upper graph of Figure 4 presents the wavelet transform magnitude in time and at different frequencies.

On the upper graph of the Figure 4, we also marked the maximal magnitude at each frequency level for the incident wave and the first reflected wave. From the graph, we can observe the dispersion effect: the magnitudes are attenuated and the lower frequency components propagate slower than the higher frequency components.

Later we used discrete wavelet transform on the time-series signal. Discrete wavelet transform needs less processing power and is better suited to be implemented in an IED. We used MATLAB's maximal overlap discrete wavelet transform function *modwt()*. In our calculations we used Symlets wavelets with 20 vanishing moments. The result of the function are values in time as coefficients at different wavelet scales. Wavelet scales represent the signal in the frequency band around the scale central frequency. For our calculations, we treated the coefficients as if they would represent the signal at the wavelet scale central frequency.

Similarly to the process presented before with the continuous wavelet transform, we determined the maximal magnitudes of the transformed signal at different central frequencies in time. From the timestamps of the maximal values at both ends of the simulated power cable, we calculated the signal propagation velocity along the cable. The velocity is calculated from the time the wave travels from the source to both of the cable ends and with the known cable length.

We then compared the calculated signal propagation velocity at each central frequency with the propagation

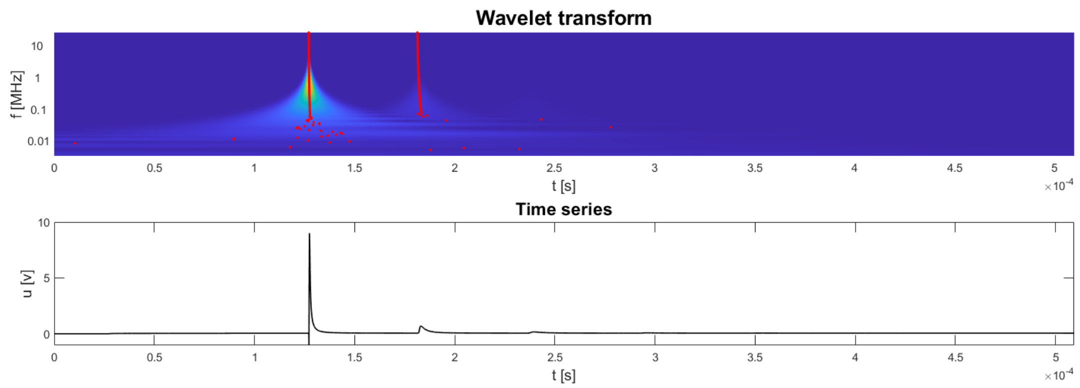

Figure 4: Time-series signal and signal wavelet transform at cable end V2.

velocity calculated from the transmission line parameters which are given as inputs to the simulation. This is shown on the graph represented in Figure 5. The graph shows the calculated transient line propagation velocity from the line parameters (represented with the solid line). For this case, the velocity is determined for each frequency point. The calculated propagation velocity after simulation and with the use of discrete wavelet transform is represented at discrete frequencies.

From Figure 5, it can be observed that the propagation velocity acquired with the use of discrete wavelet transform is well determined in the range above 10 kHz and up to 1 MHz which is the limit of our model. Velocity values at lower frequencies start to diverge more since the signal's wavelength is too high compared to the section distance, thus are not well defined in time.

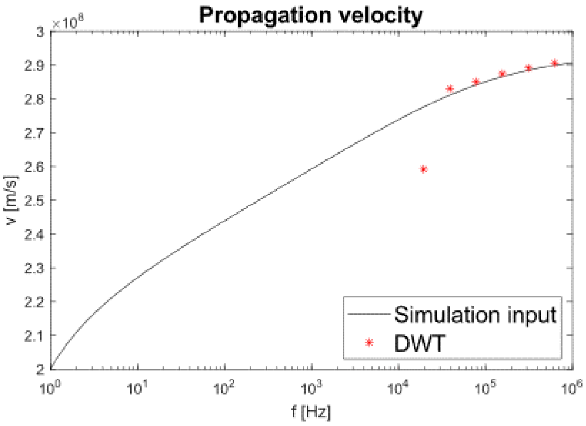

Figure 5: Comparison of propagation velocity

5 Discussion

From the results presented in this paper, we can determine that the calculation of power cable propagation velocity can be acquired by analyzing the travelling-waves caused by the events on the cable. In the paper, we used wavelet transform on the time-series signal measurements obtained by simulation to analyze the signal at different frequencies. Results show that the wavelet transform technique is an appropriate tool for determining the propagation velocity of the power cables.

In the future, the concepts shown in this paper will be improved to automatically determine the propagation velocity from the time-series signal measurements, thus improving the localization of the events on the power cable. Different event types have different characteristics not only related to time but also to power. Therefore the presented method would have to be adjusted accordingly. Here different timescales and measuring setups would have to be considered. Additionally, different types of wavelets could be more suitable for a different configuration. We are planning to test the methods in different electrical power grid settings.

The method is also usable for continuous online power cable observability. With the constant cable characteristic observation, also other innovative services can be developed, such as long-term aging estimation, scheduling of preemptive repairs and scheduling of maintenance.

References

[1] E. O. Schweitzer, D. E. Whitehead, G. Zweigle, V. Skendzic, and S. V. Achanta, ‘Millisecond, microsecond, nanosecond: What can we do with more precise time?’, in *2016 69th Annual Conference for Protective Relay Engineers (CPRE)*, Apr. 2016, pp. 1–12. doi: 10.1109/CPRE.2016.7914898.

[2] M. Shafiq, I. Kiitam, P. Taklaja, L. Kutt, K. Kauhaniemi, and I. Palu, ‘Identification and Location of PD Defects in Medium voltage Underground Power Cables Using High Frequency Current Transformer’, *IEEE Access*, vol. 7, pp. 103608–103618, 2019, doi: 10.1109/ACCESS.2019.2930704.

[3] M. A. Aftab, S. M. S. Hussain, I. Ali, and T. S. Ustun, ‘Dynamic protection of power systems with high penetration of renewables: A review of the traveling wave based fault location techniques’, *Int. J. Electr. Power Energy Syst.*, vol. 114, p. 105410, Jan. 2020, doi: 10.1016/j.ijepes.2019.105410.

[4] F. P. Mohamed, W. H. Siew, J. J. Soraghan, S. M. Strachan, and J. McWilliam, ‘Partial discharge location in power cables using a double ended method based on time triggering with GPS’, *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 6, pp. 2212–2221, Dec. 2013, doi: 10.1109/TDEI.2013.6678872.

[5] H. Jia, ‘An Improved Traveling-Wave-Based Fault Location Method with Compensating the Dispersion Effect of Traveling Wave in Wavelet Domain’, *Math. Probl. Eng.*, vol. 2017, p. e1019591, Feb. 2017, doi: 10.1155/2017/1019591.

[6] X. Rao, K. Zhou, Y. Li, G. Zhu, and P. Meng, ‘A New Cross-Correlation Algorithm Based on Distance for Improving Localization Accuracy of Partial Discharge in Cables Lines’, *Energies*, vol. 13, no. 17, Art. no. 17, Jan. 2020, doi: 10.3390/en13174549.

[7] M. Mahdipour, A. Akbari, P. Werle, and H. Borsi, ‘Partial Discharge Localization on Power Cables Using On-Line Transfer Function’, *IEEE Trans. Power Deliv.*, vol. 34, no. 4, pp. 1490–1498, Aug. 2019, doi: 10.1109/TPWRD.2019.2908124.

[8] A. Cavallini, G. C. Montanari, and F. Puletti, ‘A novel method to locate PD in polymeric cable systems based on amplitude-frequency (AF) map’, *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 3, pp. 726–734, Jun. 2007, doi: 10.1109/TDEI.2007.369537.

[9] N. Morette, T. Ditchi, and Y. Oussar, ‘Feature extraction and ageing state recognition using partial discharges in cables under HVDC’, *Electr. Power Syst. Res.*, vol. 178, p. 106053, Jan. 2020, doi: 10.1016/j.epsr.2019.106053.

[10] ‘Frequency-Dependent Transmission Line - MATLAB & Simulink’. https://www.mathworks.com/help/physmod/sps/ug/frequency-dependent-transmission-line.html (accessed Feb. 03, 2021).