Traveling-wave Event Detection and Localization on Power Cables

Marko Hudomalj[1,2][0000-0001-6893-5732]

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

Abstract. This paper compares two methods for propagation velocity transfer function estimation of power cables. Propagation velocity is determined based on traveling-waves caused by events on power cables. The method is appropriate to be used for online propagation velocity estimation on the power cables during their operation. Propagation velocity estimation is used for better event localization.

The two compared methods are based on discrete wavelet transform and short-time Fourier transform. Simulation based on of frequency dependent transmission line was used for the evaluation.

Keywords: traveling-wave, power cable, event localization, wavelet transform, short-time Fourier transform

1 Introduction

The electrical power grid system is undergoing digital transformation. The transformation is focused on better exploitation of already existing infrastructure because of the growing electrical power consumption. With better exploitation of existing infrastructure, bigger investments in electrical power grids can be postponed. Another factor for electrical power system digitalization is the ever-growing introduction of renewable electrical energy sources because of the increased environmental awareness. The introduction of renewable energy sources and battery energy storage requires a better insight into the grid operation and new control techniques.

To achieve improved grid observability, control, reliable operation and safety, many new intelligent electronic devices (IEDs) have been developed for the electrical power grids in recent years. The technological progress in the field is focused on faster IEDs operation [1]. In the past, electronic measurement devices observed the grid in the frequency range of the nominal grid frequency. Today, newly developed IEDs use higher sampling frequencies up to the range of 100MHz. With these high sampling rates, fast phenomena in the electrical power grid system can be observed, and thus appropriate control of the grid employed.

This paper focuses on IEDs for measurements of short time high frequency events on the power cables. The analyzed frequency range is above 10 kHz. These fast events on power cables are partial discharge, faults and lightning strikes.

Partial discharges occur in the power cables with isolation [2]. They are localized dielectric breakdowns that happen in the voids of the cable isolation because of high voltages. Voids are caused by the isolation material ageing, environmental variables and mechanical stress. Partial discharges are constantly present and cause short-time low power transient signals on the cables. With the analysis of partial discharges, the isolation ageing state can be determined. Aging estimation is the basis for detecting potential bigger faults and scheduling of preemptive repairs.

Faults are short circuits that can happen between different phases and or phases to ground. There can be a number of different combinations depending on which phases are shorted and also if they are shorted to the ground. The cause of the short can be an external object or cable breaking. They can be persistent or temporary and can vary in the impedance that caused the short. A fault causes a transient signal on the power cable against which the rest of the circuit must be protected. Faults are occasional events.

Lightning strikes cause fast, high power transient signals on the power cables. The rest of the electrical power grid must be protected, because high power signals can cause equipment damage.

All of the described events cause short transient signals on the power cables. These signals behave as traveling-waves (TWs). TWs are high frequency signals that travel along the medium. On the border of the medium they are reflected because of the medium change. In the case of power cables, TWs travel along the cables until the cable end where the waves are reflected.

Because of the medium characteristic, waves travel with different propagation velocities at different frequencies and are attenuated, which is also frequency dependent. This property of a medium is called dispersion.

In our research, we use the traveling-wave of an event to determine the power cable characteristics transfer function during the cable operation. We are interested especially in the propagation velocity part of the cable transfer function. With this information we want to improve event detection and localization on power cables. The initial concept was reported in [3]. In this paper, we are evaluating two different approaches for determining the propagation velocity transfer function.

2 State of the art

The methods for localization of events based on traveling-waves are grouped into two main approaches: the single- and the double-ended approach [4].

For the single-ended approach only one measuring IED is needed which is placed on one side of the power cable. Single ended approaches are further divided into passive and active methods [4]. In the passive single-ended method, the initial TW is detected by the IED which starts the timer. Then the first reflected wave stops the timer. Based on the measured time difference the event can be localized. The active single-ended method uses a reference signal generator besides the measuring IED on the same side of the cable. This method is appropriate for fault detection. With the method, the reflected wave of the reference pulse generator is captured and based on the time difference of the generated pulse and the reflected wave a fault on the cable can be located.

The double-ended approach uses two IEDs on each side of the cable. Here also two groups exist: passive and active [4]. With the passive double-ended method, the initial incident wave is captured on each side of the cable. In the passive method, IEDs must be connected with a dedicated communication link through which IEDs signal when a wave is detected. Based on the time difference of the detected waves, the event can be located. In the active double-ended method, the IEDs must be synchronized externally. This is mostly done with GPS. The incident wave is detected by both IEDs and time stamped. The timestamps are then sent to the central location where the event can be localized based on the time difference.

The third approach is a multi-ended approach. In this approach, multiple IEDs are placed along the line to improve localization. This approach is also employed on branched cable systems. Multi-ended approach can be viewed as a combination of multiple double-ended.

For the detection of traveling-waves many different methods were proposed. The signals analyzed are only the high frequency components, above 10 kHz. The simplest method is to use a predetermined level at which the detection is triggered. Another one is to use the rising and falling slope of the signal. However, these two methods have problems with reliability. More widely used and reliable are methods based on transformation [4]. These transform the time-series signal mostly in the frequency domain. The methods are based on Fourier transform especially on short-time Fourier transform (STFT). Other widely used transformation methods are based on wavelet transform (WT). In this paper, we compared methods for determining propagation velocity based on STFT and WT.

Researchers in the past considered that the propagation velocity of the traveling wave is constant. The velocity for the calculation of event localization was determined based on the model of the power cable system [5] or it was measured during the power cable system deployment [6] or during maintenance. Mostly only the velocity at one frequency component or a general velocity was used [6]. It was also proposed to determine the transfer function and use it to adjust the measured waves [5]. But the power cable transfer function is changing during its operation, which needs to be compensated for [7]. Approach presented in [7] is to use a reference signal generator that periodically sends reference impulses with which the transfer function can be determined and used in calculations. Another approach which uses the transfer function implicitly, is a combination of using a transformation function and the use of correlation on the detected signals [8]. This approach showed good results, because it does not use a single point on the detected wave for localization calculation. In our research we want to determine the propagation velocity transfer function during cable operation based on the traveling-waves caused by the events and with this improve the localization.

3 Methodology and results

For evaluation of our approach we prepared a simulation in Simulink. The simulation model is presented in Fig. 1. We used frequency dependent transmission line [9] to represent the power cable. The cable was of 10 km in length. At one end of the cable we generated an impulse with a signal generator and measured voltage at the other end. The sampling frequency of the simulation was 60 MHz.

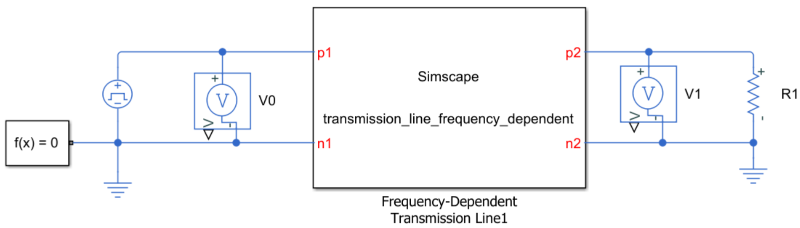

Fig. 1. Simulation of traveling-wave on power cables with the use of frequency-dependent transmission line

The time series voltage signal at the end of the cable (V1) from the simulation is shown in Fig. 2. The impulse was generated at 0.1 ms. From the Fig. 2 we can see the first incident wave and two reflected waves which are very attenuated.

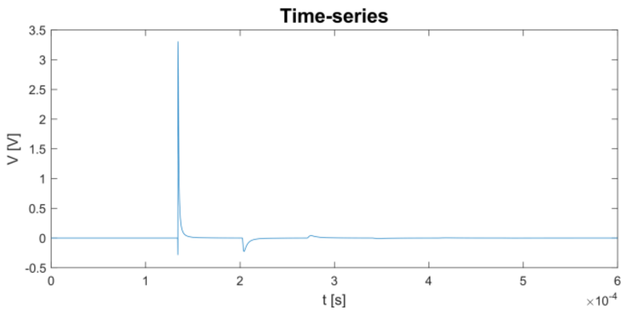

Fig. 2. Voltage measurement at V1

The simulation results where further analyzed in MATLAB. We transformed the time series signal to the frequency domain with two different transformations for comparison. First transformation was the discrete wavelet transform (DWT). For the DWT wavelets we used Daubechies wavelets with 20 vanishing moments. The second used transformation was STFT. For the windowing we used Hann windowing function of 128 samples and the FFT length was set to 512. For both of the transformed signals we then located the maximum of the transformation at each frequency component. Based on the timestamp of the transformed signal maximum, the start of the generated impulse and a known length of the cable, we then calculated the propagation velocity at each frequency component. The results are shown in Fig. 3. The figure shows the calculated propagation velocity based on DWT and STFT at each frequency component that is the output after the transformation. For reference, the simulated power cable propagation velocity is also shown.

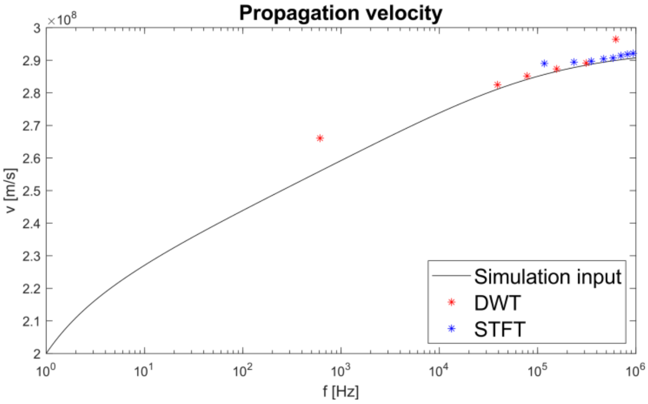

Fig. 3. Comparison of propagation velocity calculated based on DWT and STFT

From Fig. 3 we can observe the specifics of each transformation. The DWT analyses the signal in different time and frequency scales and with that it can show signal characteristic also at a lower frequency range compared to the STFT. At lower frequencies, the signal is not well defined in time. Therefore, the propagation velocity differs from the simulated power cable at the lower frequencies. On the other hand, the STFT analysis is used at the same scale for all of the time and frequency range. Therefore, lower frequency components are not present, but the resolution is better at higher frequencies.

4 Conclusion

From the result sown in this paper we can conclude that wavelet transform is better than STFT for analyzing the traveling-waves at a wider frequency range. However, STFT can still be used if only high-frequency analysis is required. The use of STFT would be especially useful in embedded IEDs because it requires fewer resources than DWT. Moreover, the processing is faster which is important for being able to detect events on the power cables.

In future work, the investigation in which events would require broader frequency analysis will be carried out and determined where STFT would suffice. Further analysis in transformation parameters will also be carried out to improve the propagation velocity calculation based on the TWs. Based on these results, we want to use the propagation velocity estimation based on the TWs during the power cable operation for improving event localization.

References

1. Schweitzer, E.O., Whitehead, D.E., Zweigle, G., Skendzic, V., Achanta, S.V.: Millisecond, microsecond, nanosecond: What can we do with more precise time? In: 2016 69th Annual Conference for Protective Relay Engineers (CPRE). pp. 1–12 (2016). https://doi.org/10.1109/CPRE.2016.7914898.
2. Shafiq, M., Kiitam, I., Kauhaniemi, K., Taklaja, P., Kütt, L., Palu, I.: Performance Comparison of PD Data Acquisition Techniques for Condition Monitoring of Medium Voltage Cables. Energies. 13, 4272 (2020). https://doi.org/10.3390/en13164272.
3. Hudomalj, M.: Power Cable Wave Propagation Velocity Estimation Based on Travelling-Waves. Proc. 30th Int. Electrotech. Comput. Sci. Conf. (2021).
4. Aftab, M.A., Hussain, S.M.S., Ali, I., Ustun, T.S.: 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. 114, 105410 (2020). https://doi.org/10.1016/j.ijepes.2019.105410.
5. Jia, H.: An Improved Traveling-Wave-Based Fault Location Method with Compensating the Dispersion Effect of Traveling Wave in Wavelet Domain. Math. Probl. Eng. 2017, e1019591 (2017). https://doi.org/10.1155/2017/1019591.
6. Shafiq, M., Kiitam, I., Taklaja, P., Kutt, L., Kauhaniemi, K., Palu, I.: Identification and Location of PD Defects in Medium voltage Underground Power Cables Using High Frequency Current Transformer. IEEE Access. 7, 103608–103618 (2019). https://doi.org/10.1109/ACCESS.2019.2930704.
7. Mahdipour, M., Akbari, A., Werle, P., Borsi, H.: Partial Discharge Localization on Power Cables Using On-Line Transfer Function. IEEE Trans. Power Deliv. 34, 1490–1498 (2019). https://doi.org/10.1109/TPWRD.2019.2908124.
8. Rao, X., Zhou, K., Li, Y., Zhu, G., Meng, P.: A New Cross-Correlation Algorithm Based on Distance for Improving Localization Accuracy of Partial Discharge in Cables Lines. Energies. 13, 4549 (2020). https://doi.org/10.3390/en13174549.
9. Frequency-Dependent Transmission Line - MATLAB & Simulink, https://www.mathworks.com/help/physmod/sps/ug/frequency-dependent-transmission-line.html, last accessed 2021/02/03.