Fault Indicators of Partial Discharges in Medium-Voltage Systems

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Abstract. *The safety and reliability of the electricity system, these are the two basic keywords present in the energy sector. One of the ways to improve the overall security of the electricity system is to reduce the failure rate of transmission lines. In medium-voltage distribution systems, this predominantly concerns overhead lines and cable lines. This paper discusses options on how to decrease the failure rate of medium-voltage overhead lines with covered conductors.*

Keywords

Covered conductor, fault detector, indicators, medium-voltage system, partial discharge.

1. Introduction

Along with the development of covered conductors, and based on long-term experience in Nordic countries, the system with covered conductors used in medium voltage (MV) lines is now also used in the Czech Republic. The first electricity lines with covered suspended MV conductors were built in Finland in 1976, subsequently installed in Sweden and Norway, and gradually also used in other European countries. Construction of an overhead line with suspended covered conductors is not very different from lines using bare conductors; however, the most important advantage is that the covered conductors allow a shortening of the distance between phases of roughly one-third compared to the phase distance which is usual for bare conductors. The design of brackets used in Finnish production uses a distance of about 40 cm; the construction of brackets produced for Czech utility companies has a distance between phases of 50 cm. The conductors are covered with a single insulating sheath (Fig. 1) and clamped into insulators for the respective voltage range.

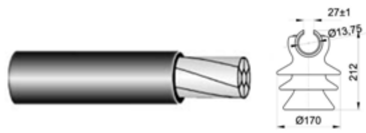

Fig. 1: This figure shows a covered conductors of the PAS system with voltage up to 35 kV, and describes attachment of the cable to a MV insulators.

Covered conductors are able to withstand mechanical and electrical stress caused by falling trees or branches. The wires are designed for environments with continuous temperatures up to +80 °C and short-term temperatures up to +200 °C.

Advantages of covered conductors:

- Reduction in failures caused by trees falling on the line, or by contact with wet branches.
- Trees fallen on the lines can be removed later when conditions are more favourable.
- There are no short circuits when the wires touch each other.
- The insulation reduces the corrosion of the conductors in extreme environmental conditions.
- The protection zone may be reduced by 2m when measured from the outer conductor, which significantly reduces the annexation of land by the lines, thus facilitating negotiations prior to construction of the PAS line type.
- Reducing the distance between phases allows the construction of multiple lines on common supports, whereas the configuration of wires on the mast head does not become wider.
- Reduction of the passage corridor is more environmentally friendly in forest land.
- Birds are not endangered when sitting on the line. The covered conductors may be additionally

equipped with isolating covers mounted on the insulators (in cases when electric arc protection is installed), as well as with covers for terminals.

The weak point of covered conductors is a higher susceptibility to damage of the insulation and the core wires due to direct or induced lightning surges.

Currently, the biggest problems that arise with the use of insulated wires are the inability to detect a tree or branch falling on the covered conductor, or conductor breakage and its subsequent fall to the ground.

Once a covered conductor falls to the ground, standard digital protection cannot detect this type of fault as there is no standard ground connection.

A methodology was developed at the VSB–Technical University of Ostrava, protected by national patent P2008-647 and a European patent, which allows these types of faults to be detected. The principle of the methodology is to find links between the original point of occurrence [1] and the partial discharges (PD).

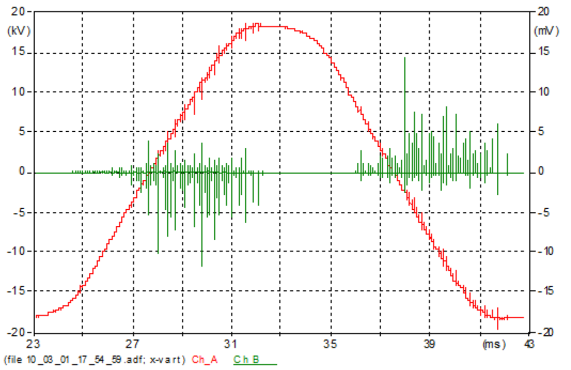

Fig. 2: Example of partial discharge activity.

For example, in the case of covered conductor breakage and its subsequent fall to the ground, the point of contact with the ground represents a violation of the homogeneity of the electric field, resulting in a local exceeding the dielectric strength of the isolation material of the given covered conductors. This results in a discharge activity with the symptoms of all types of partial discharges. Specifically, there are discharge activities of internal, surface, and external partial discharges. Due to the partial discharges, the dielectric material gradually degrades, which can result in failure in the form of phase short circuit or ground fault. Therefore, the analysis of discharge activity can rightly be described as the main indicator useful for detecting failures of covered conductors [2], [3].

Figure 2 shows a detailed discharge activity (green line) measured as a voltage signal around the fault point; for comparison, the feed voltage curve of the covered conductor with fault (red line) is also shown.

Currently, it is possible to use the above methodology, which is protected by national and European patents, and detect different types of faults such as fall of conductors to the ground, contact of a tree branch with a conductor or fall of a tree branch; at present, it is not possible to determine the specific fault type. The aim of further research and development of the prototype of a fault detector is its optimization, allowing the fault type to be determined. For medium-voltage distribution operators, this represents very important information, since each of the above faults has a different time development, and it may be removed in different time horizons. This can be helpful for medium-voltage distribution operators for optimum planning of the schedule for defect removal, and it can thereby increase the overall safety and reliability of the system [4], [5], [6].

For such optimization, it is necessary to implement a number of experimental measurements which can help to understand the issue of partial discharge activity in the field in detail. A more detailed description will be presented in the following chapters.

2. Analysis of Partial Discharge Activity

As was mentioned in the introduction, the aim of further development of a fault detector is its optimization, which will allow not only the presence of a fault to be detected, but also to determine which type of fault it is. The methodology uses an analysis of discharge activity as an indicator for the assessment, and it is necessary to perform a series of experimental measurements for different fault types and different climatic conditions, and to clarify in detail the nature of partial discharges. For

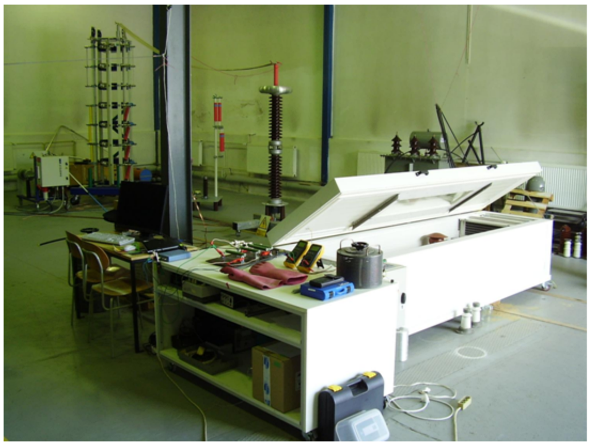

Fig. 3: Medium-voltage laboratory with climatic cabinet for testing of partial discharge activity.

the testing, VSB–Technical University of Ostrava created a special laboratory consisting of a physical model of the distribution system with covered conductors and a climatic cabinet to simulate different types of failures and weather conditions. An illustrative picture of the laboratory is shown in Fig. 3.

The following types of failures in covered conductors (CC) were simulated as part of experimental measurements on the physical model:

- Coupling rupture and fall of CC onto the mast console.
- Fall of CC to the ground – subgrade sand.
- Fall of CC onto a water level.

For each of these faults, detailed analyses were carried out as part of long-term testing, with ambient temperature range -20 °C to +60 °C to simulate the actual conditions in year-round operation of CC. The entire testing process was as follows:

- Creation of a physical model of a distribution system with CC.
- Simulation of the selected type of fault in the CC in the climatic cabinet.
- Continuous detection of the time course of the voltage signal generated by the discharge activity.
- Evaluation of the basic parameters of CC.

The basic parameters that were determined include:

- Frequency of PD (s^{-1}).
- TRMS of voltage signal with PD (mV).
- Max/Min of PD (mV).

The voltage signal with PD was measured by a sensor located near the fault in CC. Only the pulse component of PD was used for the evaluation, using band pass 1-10 MHz.

3. Coupling Rupture and Fall of CC onto the Mast Monsole

The most common faults include rupture of the CC terminal at the CC insulator and subsequent fall of the CC onto the mast console. This type of failure was tested using a physical model of a distribution system with CC for temperature range -20 °C to 60 °C. Figure 4 shows an example of PD activity (green line) for the said failure in long-term testing.

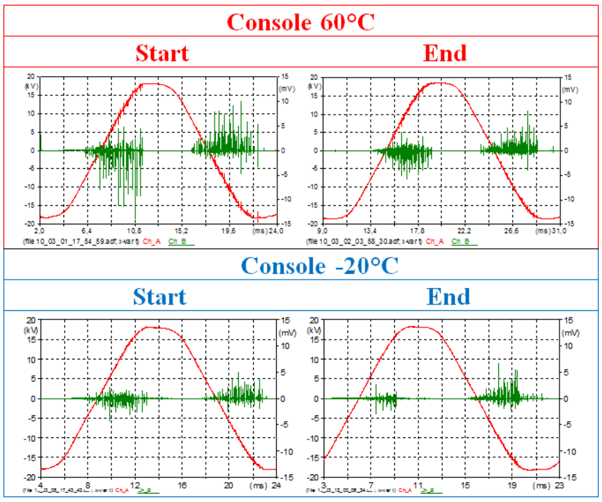

Fig. 4: Analysis of PD activity - failure: CC coupling rupture and fall of CC to the mast console.

The ambient temperature +60 °C is characterized by a high discharge frequency with high voltage pulses, which is necessary to exceed the dielectric strength of the isolation material. At the point the dielectric strength is exceeded, the number of places with local irreversible degradation will increase. The point contact of electrodes changes to a straight line contact, and the overall frequency of PD increases. Figure 5 shows a detail of degradation of the isolation systems of CC due to PD activity.

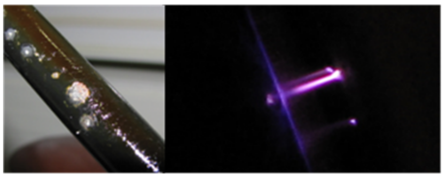

Fig. 5: Detail of degradation of insulation systems of CC by PD activity (left), PD activity (right).

In the case of failure with a fall of CC onto the mast console and temperatures around -20 °C, the situation is different. At this temperature, the isolation system is more compact than at temperature +60 °C; the isolation material does not melt so massively, nor does diffusion of the interface material occur. This corresponds to the lower discharge activity characterized by the above-mentioned parameters. Discharge activity as part of long-term measurements was almost unchanged.

Tab. 1: Measured values for the simulated fault.

	Start	End
Min. Peak [mV]	-13,9586	-5,8554
Max. Peak [mV]	10,1694	8,24488
TRMS [mV]	0,1309	0,0846923
Frequency PD [s^{-1}]	157	189

Tab. 2: Measured values for the simulated fault.

	Start	End
Min. Peak [mV]	-4,313	-3,01077
Max. Peak [mV]	5,19255	6,68968
TRMS [mV]	0,0564119	0,0507217
Frequency PD [s^{-1}]	86	56

4. CC Coupling Rupture and Fall of CC to the Ground

As another frequent failure of a line with CC, a situation with breakage of the CC coupling and fall of the CC to the ground was simulated. Sandy soil was used as the material, with the tip-plate configuration, where the tip formed by the conductor was on high potential.

Tab. 3: Measured values for the simulated fault.

	Start	End
Min. Peak [mV]	-0,3768	-0,7097
Max. Peak [mV]	0,4787	0,2434
TRMS [mV]	0,0256	0,0225
Frequency PD [s^{-1}]	385	5

Tab. 4: Measured values for the simulated fault.

	Start	End
Min. Peak [mV]	-0,1595	-0,0891
Max. Peak [mV]	0,1352	0,1587
TRMS [mV]	0,0158	0,0198
Frequency PD [s^{-1}]	25	85

The Fig. 6 shows that the highest frequency was at the beginning of the measurement and gradually fell to almost zero. This is primarily a result of changes in the type of contact between the conductor and the subgrade (sand) at 60 °C. With gradual drying of the

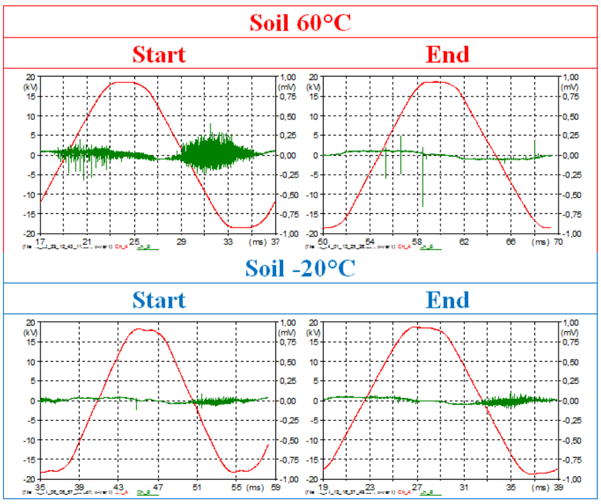

Fig. 6: Analysis of PD activity – fault: CC coupling rupture and fall of the CC to the ground.

subgrade and of the conductor isolation, the original surface contact changed the linear contact. Another fact that emerged was the presence of freely moving particles around the conductor, which originated under the influence of an electrical field gradient. Due to this phenomenon, the material between the subgrade and isolated wires was gradually moving.

The fact that the foundation sand was drying out and small pieces of grain were moving from around the conductor contributed to the increase in homogeneity around the conductor.

At -20 °C, the frequency of PD and TRMS was almost unchanged. This was mainly due to the low temperature and the corresponding low relative humidity. It can be seen from this example that the presence of PD depends on the ambient conditions, particularly the temperature and humidity.

5. CC Coupling Rupture and Fall of CC onto a Water Surface

In this part of the measurements, it was very important how the contact was formed between the conductors and the water. In the event that the conductor was immersed in the liquid (water in our case); the measured values were lower than in a conductor located just above the water surface.

This is caused because when the conductor is immersed in a liquid, a semi-conducting layer occurs on the surface of a conductor. This has the effect of increasing the homogeneity of the electric field around the conductor and a reduction in discharge activity.

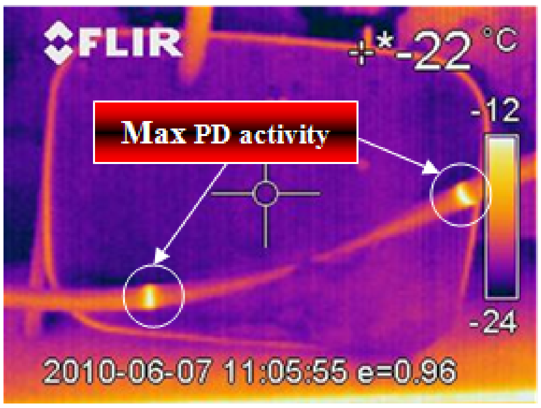

Fig. 7: Thermal analysis for temperature -22 °C.

In the case where the conductor was positioned just above the liquid surface, the occurrence frequency of PD and TRMS was much higher. This was caused mainly by changes in the type of contact between the conductor and liquid. This change occurred due to temperature effects and PD, resulting in evaporation of the water. Thus, the geometrical shape of the electrode (conductor-to-liquid) gradually changed from superficial contact to a straight line contact, and when an air gap was created between the conductor and the surface of the liquid, to point contact.

In the event that the climatic conditions and temperature changed, in this case, the temperature fell to -20 °C, the measured values fell. This was due to the fact that after freezing of the water, the area was decreased (only at the transition of the conductor into the ice), which could give rise to PD.

The above-mentioned definition of the place of PD, using thermal analysis, is shown in Fig. 7. The figure proves that the highest activity of PD is located just on the ice-air boundary line.

Tab. 5: Measured values for the simulated fault.

	Start	End
Min. Peak [mV]	-2,2076	-1,6623
Max. Peak [mV]	1,7419	1,0165
TRMS [mV]	0,0251	0,0237
Frequency PD [s^{-1}]	99	75

Tab. 6: Measured values for the simulated fault.

	Start	End
Min. Peak [mV]	-0,8049	-0,2899
Max. Peak [mV]	0,9711	0,1140
TRMS [mV]	0,0186	0,0170
Frequency PD [s^{-1}]	23	9

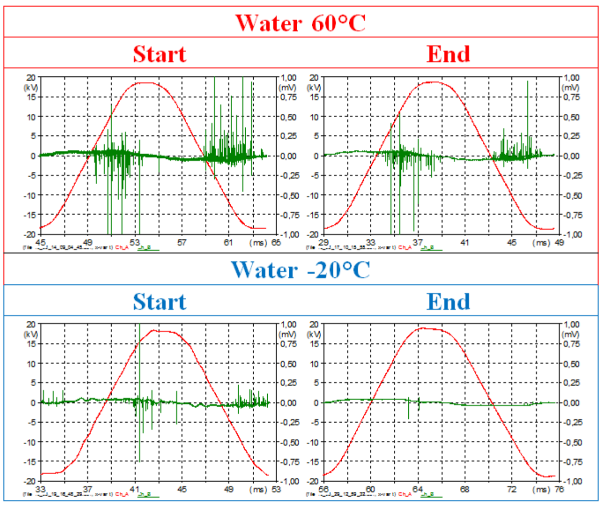

Fig. 8: Detail of degradation of insulation systems of CC by PD activity (left), PD activity (right).

6. Description of the Developed Software

Selected results were processed using software developed in the LabView Program. Looking at Fig. 9, we can see the signal measured during the fault of a line with CC. The curve displayed in black is combined with the envelope curve (red), which captures each PD formed. Figure 10 shows a detail of PD capture. This solution was implemented on the ground to eliminate the error in the identification of individual PD pulses.

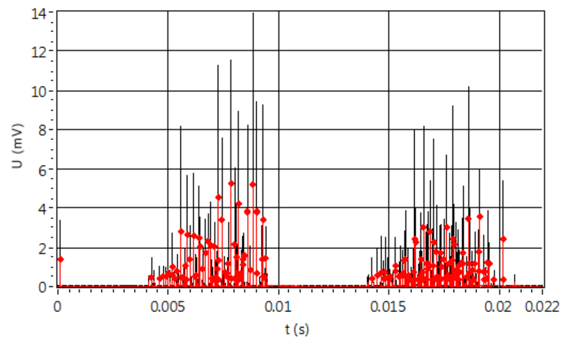

Fig. 9: Signal processing for the frequency calculation of PD (s^{-1}), TRMS of the voltage signal with PD (mV), Max/Min of PD (mV).

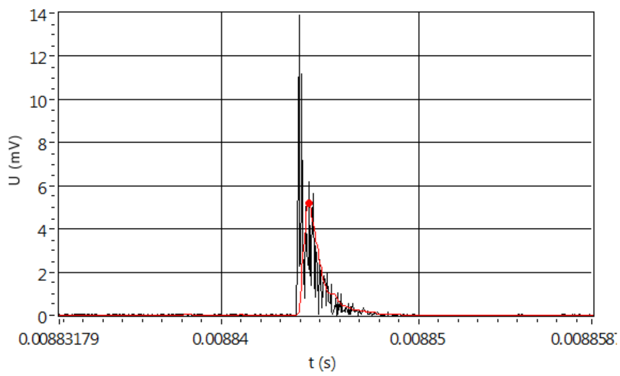

Fig. 10: Detail of PD capture using the developed software.

7. Conclusion

As nowadays lines with CC are beginning to replace cables with bare conductors, the issue of fault detection also needs to be resolved because it becomes difficult to detect faults using today's digital protection systems.

The aim of this paper was to analyse the dependence of PD on the resulting fault. A more detailed analysis discovered a close relationship between the measured value and type of fault. It can be assumed that the values measured in our laboratory can be used as indicators of faults, and that the development of other indicators, e.g. using FFT analysis of the measured signal, measurement of TRMS, or PD frequency in different periods, is also possible.

After long-term research, we expect the design of a sophisticated device that would be able to safely detect faults which cannot be detected easily nowadays.

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Stefan HAMACEK was born in Cadca. He graduated from SOUS Cadca in 2004. In 2008 he graduated from VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science. Today he is a scientific researcher in the Department of Electrical Engineering, Technical University of Ostrava and applies himself to the issue of medium-voltage lines with covered conductors and problems associated with the fault detection of covered conductors. He also deals with the problems of traction cathenary and research dissemination of stray currents in the area of traction.

Stanislav MISAK was born in Slavicin in 1978. He received his MSc. and Ph.D. degrees in Electrical power engineering in 2003 and 2007, respectively, from the Department of Electrical Power Engineering, VSB–Technical university of Ostrava, Czech Republic, where he is currently an Associate Professor. Dr. Misak has published a number of articles in peer-reviewed journals and conference proceedings. He also holds a patent for a fault detector for medium-voltage lines. In 2012 he was appointed a delegate to the European Union Commission for the strategic management of renewable energy sources. He has been successful in obtaining a number of research contracts and grants from industry and government agencies for projects related to the areas of power systems and renewable energy integration. His current work includes the implementation of smart grid technologies using prediction models and bio-inspired methods and diagnostic of insulation systems.