1. INTRODUCTION

Covered conductor (CC) lines have been widely used in medium voltage networks since early 1980’s. Recently covered conductors have been introduced to higher voltages up to 154 kV. CC lines offer an alternative for power grid companies with characteristics that can be placed between bare conductor lines and cables. One of the most important advantages of CC lines over bare conductor lines is smaller frequency of interruptions caused by, for example, trees bending or falling on the line. Recently, the economical aspect of interruptions has grown in importance in many countries due to legislative actions forcing grid companies to compensate customers for long interruptions.

Other important issues favoring CC technology are the mitigation of environmental impact of power lines and reduction of costs related to the right-of-way (e.g. expropriation and maintenance). The line structure is compact; on 110 kV lines the right-of-way is approximately 12 m wide while the most common bare conductor line structure in Finland with portal towers requires 46 m (26 m + 10 m marginal zones requiring tree topping on both sides). Compact line structure offers the possibility to upgrade medium voltage lines to higher voltage levels without the need to widen the right-of-way. Due to smaller phase clearances, the electric and magnetic fields caused by the line are significantly reduced. According to [1] the magnetic field reduction at ground level achieved with 110 kV CC lines compared to bare conductor lines is in the order of 30-50 % depending on the line types compared. Conductor clashing does not cause power supply interruptions, which allows long spans, for example, at river crossings and mountain areas. With a compact line structure such as the one in Figure 1 the impediment for farming and other human activities can be reduced, as well. The 110 kV Forest-SAX test line used in research and development of the on-line partial discharge

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monitoring system is a 9.1 km long 110 kV CC line with a narrow (12 m) right-of-way (marginal zones are not needed). The line is constructed using triangular conductor configuration with self-supporting wooden I-poles, composite line post insulators and one ground wire.

The development of automatic fault detection based on PD (partial discharge) measurements is motivated by the fact that, for example, a tree fallen on a CC line causes a very high impedance fault which cannot be detected with conventional protective relays. The high impedance fault should be detected, because eventually (usually on 110 kV after a few hours, on 20 kV after a few weeks or months) it will cause an earth fault and interruption, which would decrease the reliability benefit acquired with CC technology. Therefore, on 110 kV CC lines with a narrow right-of-way, automatic fault detection is a necessity for the reliable operation of the line. On 20 kV CC lines the earth fault risk is smaller, but automatic fault detection still improves the reliability of operation and reduces the need for visual inspection of lines.

2. **INCIPIENT FAULT CAUSED BY A TREE ON A COVERED CONDUCTOR LINE**

The term “incipient fault” is used to indicate that the tree on the conductors does not cause an immediate earth fault and that the operation of the line can be continued for a limited time in spite of the incipient fault. An incipient fault caused by a tree fallen on a covered conductor line is characterized mainly by the impedance and earthing resistance of the tree and by the impedance of conductor covering, both impedances being more or less frequency dependent. The equivalent circuit of Figure 2 describes a situation where the tree is in contact with the ground wire and a phase conductor. If more than one phase conductor are in contact with the tree, the equivalent circuit becomes more complicated.

In order to develop a method for detecting these incipient faults the resistances and partial discharge behaviour of 21 trees (12 spruces, 6 birches and 2 pines and 1 aspen) were studied in autumn 2000 / spring 2001 in different atmospheric conditions on the 110 kV Forest-SAX test line. At power frequency the impedances of trees are mainly resistive. The average values and standard deviations of tree resistances, earthing resistances of trees and resistivities of trees at foot end and top end of tree in each measurement month are plotted in Figure 3 relative to the average value in September \( (R_t \approx 37 \ \Omega, \ R_e \approx 3.4 \ \Omega, \ \rho_f \approx 190 \ \Omega m, \ \rho_t \approx 35 \ \Omega m) \). Tree resistances were measured from a point 20 cm above ground to the contact point between tree and the lowest phase conductor at a height of 10-12 m \( (R_t \text{ in the equivalent circuit above}) \). The average resistance of trees in March was approximately ten times the value in September. Two highest resistances (> 600 kΩ) were measured below zero degrees centigrade, other resistances (< 250 kΩ) were measured at or above zero degrees centigrade. Higher standard deviation in March is probably due to lower number of samples and to the temperature fluctuating below and above zero degrees centigrade. The temperature fluctuation seemed to have greater effect on the tree resistances than on the earthing resistances. The relative change in mean earthing resistances and mean tree resistances between September and March is in the same order of magnitude. The resistivities change more at foot end than at top end of tree, which should be beneficial in reducing the seasonal variation of partial discharge activity.

The impedance of conductor covering between conductor and tree is mainly a capacitive reactance. It is determined by the thickness and permittivity of conductor covering, diameter of the conductor and the number, dimensions and geometry of branches and trunk of the tree in contact with or in close
proximity of the conductor. In 110 kV covered conductor the insulation thickness is approx. 6.5 mm [2] and in 20 kV CC 2.3 mm. With numerical calculations the capacitance can be found to be in the order of tens or a few hundred picofarads. At 50 Hz this results an impedance of tens or hundreds of megaohms. Thus, the incipient tree fault cannot be detected with conventional protective relays.

With intact conductor covering and 50 Hz voltage applied to the conductor, the tree can be considered to be practically in ground potential and the voltage stress occurs mainly over conductor covering and air. The introduction of practically grounded object near the covered conductor distorts the electric field around it and causes corona on the sharp edges of the object and surface discharges along the conductor covering, especially if the object is in contact with the conductor covering. According to measurements conducted in laboratory in accordance with IEC 60270 and in the field with a reference PD source, the magnitude of the discharges is typically several nC at 20 kV and tens or hundreds of nC at 110 kV. If the phase conductors are in direct contact with each other the PD magnitude is slightly higher. Direct phase-to-phase contacts are common on 20 kV lines with horizontal pole top configuration.

3. PD SIGNAL PROPAGATION ON COVERED CONDUCTOR LINES

The propagation velocity and attenuation were studied experimentally on test lines and with numerical calculations. On 110 kV Forest-SAX test line the measured attenuation of PD pulse peak-to-peak-value was 0.7 dB/km and on a 20 kV CC double circuit line without ground or neutral wire 1.4 dB/km. The measured propagation velocities were approximately 270 m/µs (110 kV line) and 290 m/µs (20 kV double circuit line). PD pulses propagate on power line as travelling waves and at each point of surge impedance change a part of the wave energy is reflected back and part of it continues forward. Considering the amplitude distribution of PD signals caused by the 21 trees (see chapter 2) felled on the test line and the propagation attenuation and disturbance level on the line it could be estimated that on 110 kV lines tree faults can be detected with the prototype measurement system even at a distance of 15...20 km from the fault location. In 20 kV networks the distance is slightly less (5...7 km) due to smaller PD magnitude and more complicated network topology (more branches and transformers).

The influence of line structure to propagation attenuation and detection distance of PD pulses was studied using computer simulations. In simulations, the parameter of interest was the distance at which the amplitude of the transient is 1/10000 of the original pulse, that is the amplitude attenuation is 80 dB. While the attenuation may seem quite strong, the results of the simulation are of the same order of magnitude as the results obtained from the measurements.

The amplitude attenuation of transients is determined numerically by computing the unit impulse response of the transfer function of power line at various propagation distances. The transfer function is determined from surge impedances of the line. The computation of surge impedance of three-phase power line is quite complex due to asymmetry of currents and voltages, coupling between phase conductors and frequency dependent losses of ground return. In these simulations the resistive and inductive components introduced by the presence of ground were determined using Carson’s formula. The computation of surge impedance is presented in detail in reference [3]. The basis for simulations is the structure of the Forest-SAX line shown in figures 1 and 4. The suspension height of the middle
phase is assumed to be 12.95 m. Maximum line sag is assumed to be 2.5 m. Vertical difference between phase conductors is 0.95 m and ground-wire is 2.85 m above middle phase. Horizontal distance to the center of pole is 1.58 m for phase conductors and 0.32 m for ground-wire. Orientation of conductors and ground-wire is shown in figure 4. In simulations conductors were assumed to be solid (not stranded).

In simulations, the surge impedance is computed at several frequencies. Figure 5.a shows the surge impedance of Forest-SAX line, shown in figures 1 and 4, as a function of frequency. The propagation coefficient can be determined from surge impedance using equation [4]

\[ \gamma(\omega) = \alpha(\omega) + j\beta(\omega) = \sqrt{Z(\omega)Y(\omega)} \]

Further, the transfer function of power line is

\[ H(\omega, s) = e^{-\gamma(\omega)s} \]

where \( s \) is the distance the signal has travelled. Figure 5.b shows the amplitude (upper) and phase (lower) response of Forest-SAX line, when propagation distance is 1 km. The figure shows that the higher frequencies are attenuated more than the lower ones. The attenuation of a transient propagating on the line may be computed in frequency domain by multiplying the Fourier transformation of the transient with the transfer function of the line. The attenuated transient is obtained by computing the inverse Fourier transformation of the result. A general approximation of the amplitude attenuation may be obtained when the transient is assumed to be a unit impulse sequence, that is, it has value 1 at \( t=0 \), and value 0 elsewhere.

Figure 5.c shows the unit impulse responses of the 110 kV Forest-SAX line when the propagation distance of the transient is assumed to be (from left to right) 0.5, 1.5, 3, 5 and 10 km. The figure shows that during propagation the amplitude of the transient attenuates and its shape widens. Fig. 5.d shows the amplitude attenuation on logarithmic scale. The distance at which the unit impulse response of the line has the value 0.0001 (-80 dB) is determined numerically from the impulse response calculations.

Figure 6.a shows the –80 dB detection distance as a function of ground wire suspension height measured from the height of middle phase conductor (0 m). The other two phase conductors are at heights \( \pm 0.95 \) m from the middle phase. In the 110 kV Forest-SAX test line the ground-wire is 2.85 m above the middle phase. According to simulations the propagation attenuation decreases and the detection distance increases when the suspension height of the ground wire decreases in respect to that of the phase conductors. In order to maximize the detection distance, the ground wire should be placed as close to phase conductors as possible but respecting, for example, the shielding requirements. Simulations also show that if the absolute distance to middle phase is the same, the detection distance is slightly higher when the ground wire is below the phase conductors, for example, 29 km at \( +2.85 \) m and 30 km at \( -2.85 \) m. Figure 6.b shows the –80 dB detection distance as a function of average spacing between phase conductors. Simulations show that when phase spacing decreases the detection distance increases.

Figure 7.a shows the –80 dB detection distance as a function of middle phase suspension height. The figure shows that detection distance increases when the suspension height increases. Together figures 7.a and 6.b explain why similar 20 kV and 110 kV lines have roughly the same detection distance. While the smaller phase spacing of 20 kV line increases the detection distance, smaller suspension height of the middle phase decreases it.
Figure 5. a) Surge impedance of the 110 kV Forest-SAX line as a function of frequency. b) Frequency response of the line. c) Impulse responses of the line after propagation of (left to right) 0.5, 1.5, 3, 5 and 10 km. d) Amplitude of the impulse response of the line as a function of propagation distance. Figures 5.b…5.d are computed using zero sequence parameters.

Figure 6. a) Detection distance as a function of the suspension height of the ground wire measured from the height of middle phase conductor. Horizontal line in the bottom of the figure presents the situation without a ground wire. b) Detection distance as a function of average spacing between conductors. Lines in the figure from top to bottom are; ground wire above phase conductors, ground wire below phase conductors and no ground wire.

The detection distance as a function of the upper cut-off frequency of the measurement system is shown in figure 7.b. The simulations show that the decrease in bandwidth does not have any influence on the detection distance until the cut-off frequency falls below 300-400 kHz. The filtration has no
effect because the transient has already been attenuated and filtered during the propagation. Filtration affects the transients when propagation distance is short. According to measurements, the amplitude of transients decreases 20 dB when the bandwidth decreases one decade [5]. The lower bandwidth of the measurement system decreases the dynamic range requirements of the measurement system.

Figure 7. Detection distance (-80 dB) as a function of a) middle phase suspension height and b) bandwidth of the measurement system. In both figures lines are from top to bottom: ground wire above phase conductors, ground-wire below phase conductors and no ground wire.

4. PROTOTYPE FAULT DETECTION SYSTEM

A prototype fault detection system based on PD measurements has been in use on the 110 kV Forest-SAX test line near Pori in south-western Finland since the beginning of year 2001. The line is in every-day use feeding a 110/20 kV substation (Figure 8). In case of e.g. an incipient tree fault, the substation can be temporarily fed by a 20 kV connection and the 110 kV CC line can be de-energized for the tree-removal without causing any supply interruption to customers.

![Diagram of PD monitoring systems on the 110 kV Forest-SAX test line]

Figure 8. Location of the PD monitoring systems on the 110 kV Forest-SAX test line.

There are PD monitoring systems at both ends and in the middle of the line (Figure 8). In the final implementation, only the monitoring system located at the 110/20 kV substation would be necessary with this line length, the other two have been maintained for research purposes. In each location there are three PD monitoring units (one for each phase) consisting of a PD sensor, measurement/analysis unit and a PC to collect measurement data for research purposes. A more detailed description of the PD monitoring system can be found in [6]. The same system can be used to detect partial discharges occurring in high voltage apparatus, for example, at substation.

At the substation the monitoring system is powered from the low voltage network of the substation and it utilizes the substation SCADA communication system. The PD sensor is integrated into a 110 kV current transformer, which could be used for normal protection and measurement purposes, as well. In new installations (at feeding substation) this minimizes the extra cost for PD sensor, because the current transformer would be needed in any case for the protection of the line. In the middle of the
line and at the branching point the prototype measurement systems are powered from the public 20 kV network and they have their own SCADA communication links. The PD sensors are similar to the ones at substation. If a measurement system is to be installed along the line, it would be beneficial to study alternative solutions for the auxiliary power, communications and PD sensor to find the most cost-effective solution. For example, due to strong high frequency coupling between phases, the measurement systems along the line could be implemented as single-phase units.

The prototype system continuously samples several 50 Hz cycles with a high sampling rate, filters the data packet and stores the pulses picked up from the data. The pulses are analyzed according to figure 9 to determine the intensity, PRPDA (phase resolved partial discharge analysis) “fingerprint” and PSA (pulse sequence analysis) “fingerprint” of the partial discharge. Different partial discharge faults are described in the fingerprint library by membership functions of fuzzy logic, one for each PRPDA and PSA parameter. With a twofold fault detection algorithm including both PD intensity and fingerprint analysis, one can achieve rapid response in case of a high PD intensity and a reliable (although a bit slower) operation in case of low PD activity. Reliability is essential considering the usability of the system, false alarms should not occur. In the prototype system the response is relatively slow (on average 10...30 minutes) due to data transfer between the measurement unit and the PC’s needed for research purposes, but it will speed up once the research period is over and the PC’s are removed. In case of a tree fault the system generates an alarm, which is transferred to the control room by the SCADA system. Additional information (such as the PD magnitude) is available with the alarm to facilitate the fault location.

5. PRACTICAL EXPERIENCE OF THE FOREST-SAX TEST LINE

The prototype fault detection system and the current version of the fault detection algorithm have been in use on the test line since the beginning of year 2001. The reliability of the system has been very good. External interference coupled to the line or partial discharges occurring, for example, in line accessories have not caused any problems. During two years of operation, the system has not caused any false alarms. During these two years two trees have naturally fallen on the line and both of them were detected by the fault detection system.

The first tree fault occurred in April 2002, when a pine fell on the line 6.8 km from the substation. The pine had grown sheltered by other trees but was exposed to winds after a large tree cutting operation (a relatively common reason for trees to fall on overhead lines). The measurement system generated an alarm (from all three locations) and after the alternative supply for the substation was arranged, the CC line was de-energized. The tree lay on live line approximately 40 minutes. The tree was found easily and after removing the tree, the line was re-energized. The customers did not suffer any supply interruption and the whole process from first alarm to back to normal operation took about 1.5 hours.

The second tree fault during normal operation occurred in April 2003. In this case a spruce decayed by a rot fungus fell on the line at 5.6 km from the substation. The PD signal measured during the incipient fault at a distance of 3.5 km from the tree (at the connection between bare and covered conductor lines) is presented in Figure 10. The process of fault management was similar to previous case, but a

![Figure 9. A block diagram of the data analysis process of the fault detection algorithm used on the 110 kV Forest-SAX line.](image-url)
little bit slower. In this case the tree lay on live line approximately 2.5 hours. The customers did not suffer any supply interruption.

Figure 10. Partial discharge signal caused by a tree on the Forest-SAX test line in April 2003.

In November 2003 the operation of the fault detection system was tested in case of a slightly modified conductor covering material. A total of 8 trees were fallen on the line (4 spruces, 2 birches, 1 pine and 1 aspen). The fault detection system detected all the trees.

6. CONCLUSION

The test results and practical experience gathered from the PD based fault detection during 2 years indicate that the method is suitable for detection of trees fallen on CC lines within a distance of 15…20 km from the measurement unit. It seems that all three phases of the line could be monitored with a single-phase measurement system located at substation or along the line. Future work should aim at testing the method in different surroundings (in terms of e.g. electromagnetic interference and environmental conditions) and developing the fault detection system further in terms of, for example, detection distance and response time. It would be worth while to study the potential application of the system to substation PD monitoring, as well.

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REFERENCES