Intelligent Fault Diagnosis for On-line Condition Monitoring in Smart Distribution Networks

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***Abstract*—Partial discharge (PD) measurements can be regarded as an effective and reliable tool for on-line condition monitoring and asset management of high voltage (HV) apparatus. Recently, a novel application is observed in the monitoring of falling trees on covered-conductor (CC) overhead distribution lines. In this paper, Rogowski and Pearson coils are used as sensors to detect PDs for this specific application. These sensors are non-intrusive and superior to the conventional PD detecting methods. In the next stage of future developments, the wired sensor will be converted into a wireless one. The challenges faced while implementing future wireless technology are also described here. In future, the wireless sensors will be integrated into distribution management system (DMS) to detect and localize the falling trees. The proposed intelligent fault diagnosis system will improve the safety of CC lines and make them more attractive to utilities due to reduced maintenance costs and visual inspection work. In addition, the reliability of the distribution system will improve which is one of the significant characteristics of the future smart distribution networks.**

Keywords-Partial discharge; condition monitoring; asset management; covered-conductor; wireless sensors; fault diagnosis; distribution management system; smart distribution networks

I. INTRODUCTION

PDs are regarded as one of the major indications of the damaging of insulations in HV equipment and accessories. The early detection of initiation of PDs can be helpful to avoid the complete damages by knowing the reasons of initiation of PDs and taking corrective actions to eliminate/reduce PDs, e.g. if terminations of the cables are not well maintained in the cable boxes, PDs may take place which may damage the insulation of the cables after a certain period of time. The proper installation of terminations can be made to avoid arcing accidents [1]. Visual inspection and thermographic survey/scans can be very helping to detect such kind of faults.

The history of using CC lines in electricity networks is old. The use of CC in electricity distribution networks started in 1970s in Finland [2]. However, first time, the use of CC started around 1960s in USA. The utilities in USA had got problems at that time with CC installations, e.g. they had to cut the insulation of CC line for fixing it to the insulators, which causes heavy corrosions and then USA utilities did not opt this technology at that time. Later on, developments were made in Finland to rectify the problems associated with CC installations because it was the dire need of time to use CC lines. In Finland, the most of the land area is covered with dense forests which induce high impedance faults (HIF) in the case when bare-conductors are touching trees or its branches. HIF are very difficult to detect even by digital or numeric relays because of very low current induced. This gave a great motivation for utilities in Finland to use CC lines. Later on, CC lines were laid in many other countries, like UK, Australia and Japan.

The basic idea behind the usage of CC lines was to reduce the number of earth faults (HIFs) when trees were falling or bending on the bare-conductors resulting in high risk to human safety and curtailing the cost of associated maintenance tasks to remove those trees. But on the other hand, trees when touching the surface on CCs produce PDs that may damage the insulation as time passes by [3]. In addition, trees may damages the insulation mechanically by cutting its surface, thus producing more PDs.

Lessons have been learned from the experiences that PD detection is an efficient and reliable technique for asset management of HV apparatus. Off-line PD measurements have been successful in the history, but the system must be de-energized and special instruments should be arranged for taking measurements. The traditional PD detection methods experience certain restrictions when applied for continuous monitoring due to presence of noisy environment and lack of signal processing techniques. In addition, the frequency range of traditional instruments is not high. As PDs consist of high frequency signals and most important information (detection and location) is carried by high frequency signals, so traditional instruments have limitations and new devices have been considered for continuous monitoring of HV equipment.

The continuous measurements have already been taken by the current transformers (CTs) installed in the network. But the response of CTs at higher frequencies (comparable to the frequencies of PD signals) is not linear due to saturation effect observed in the CTs magnetic cores. There are different types of sensors already in use for various application [4], [5]. However, Rogowski and Pearson coils are used to detect bending or falling trees CC lines in this search work.

II. CHARACTERISTICS OF ON-LINE PD MEASUREMENTS

One of the major disadvantages of using CC lines in medium voltage (MV) networks is that leaning trees over the line can neither be detected with normal protection numeric relays nor be localized by advanced high resistance relays because the fault current is nearly zero due to the CC insulation and tree resistance itself. On the other hand, the falling trees may result in the formation of PDs in the insulation of the CC lines, which can destroy or damage after some time and various types of system faults can be initiated into the network. By keeping the records of these PDs continuously, step-by-step damages of the insulation can be monitored. Detection of faults at a good time can result in increased reliability of power. To increase the quality of power and safety of personnel, the electric utilities should be vigilant to continuously monitor the health of MV/HV equipment, which is considered one of the important priorities of distribution companies to make the business better. In Finland, many interruptions may occur every year due to heavy storms resulting in bending or falling of trees on CC lines, thus damaging the insulation or network components severely. Investigations are being carried out to cope with such dangerous situations and detecting falling trees, so that crew may be sent to remove those at good time to avoid further damages to the distribution network components [6].

It was not possible to implement on-line PD measuring system in distribution networks ever before because there were many technical and economical challenges prevailed. However, in the current situation, it is possible to do it practically because the cost of monitoring system can be very less as compared to the cost of the network components (e.g. cables, transformers etc.). The development of new smart sensors (which will be economically cheap as well) has opened many opportunities to use this technology for continuous monitoring of electricity networks. The examples of such kind of smart sensors can be Rogowski and Pearson coils and the measurements obtained from these sensors can be accessed into the digital relays. The new algorithms can be developed for digital relays to process the measurements (obtained from smart sensors) to detect and localize the leaning trees on the lines.

III. PD Measurements using Smart Sensors

Rogowski and Pearson coils are intelligent devices and can be used to detect high frequency PD signals. They are better option than traditional sensors in many aspects [7]. They can detect signals up to very high frequency range, so their bandwidth is appropriate for PD signals which are produced due to bending trees on the CC lines. The accuracy of these sensors is high and they can measure very low currents, which increases the sensitivity of the protection scheme by adjusting the relays setting at lower currents. These sensors are easy to use and they do not need long wiring. They do not pose any safety risk from MV lines as the insulation of the coil can sustain the intensity of magnetic field produced by the MV lines. A thumb rule in the design of coil is that resonance frequency should always be higher than the frequency of the signals to be detected using that coil. These sensors are mounted around the CC line (see Figs. 1 and 2) and in most cases, the position of these sensors is symmetrical around the CC line. This arrangement cancels external magnetic fields, which increases the accuracy of measurements as well as resuting in reduction of the external noise.

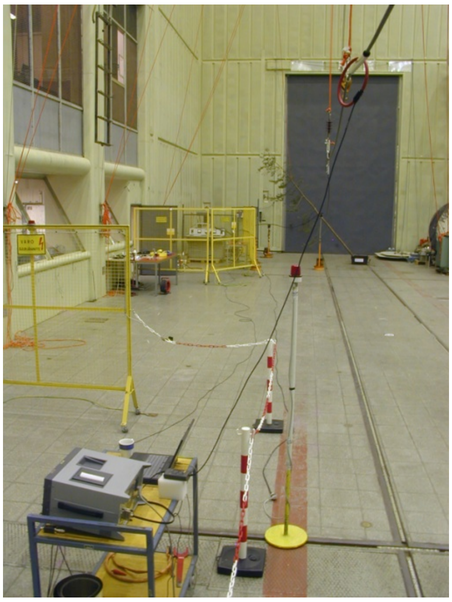

Figure 1. On-line Single-phase PD measuring set-up using Rogowski coil

Figure 2. On-line Single-phase PD measuring set-up using Pearson coil

There are two types of sensors in general; flexible and rigid coil sensors. Flexible coils are preferred because they can be mounted easily at difficult location (e.g. Rogowski coil), however, Pearson coil has rigid coil. The mutual inductance of the sensors is not fixed, it depends on design parameters. The resonance frequency of the sensors is depending on the inductance, and capacitance of the coil.

The experiments were also made when the position of these coils was not symmetrical around the CC lines, however, the variations in current or voltage waveforms obtained from these sensors were not significant. The PD signals captured by the Rogowski coil and Pearson coil due to PD activity initiated by leaning trees on the CC lines are shown in Figs. 3 and 4, respectively. The amplitude of the PD signals captured by Pearson coil is higher because the sensor is located very near to the source of PD activity (point of leaning tree on the CC line) resuting in reduced attenuation which depends upon the distance. However, propagation velocity of PD signals is independent of the ditance. It is interesting to note that attenuation and propagation velocity are frequency-dependent.

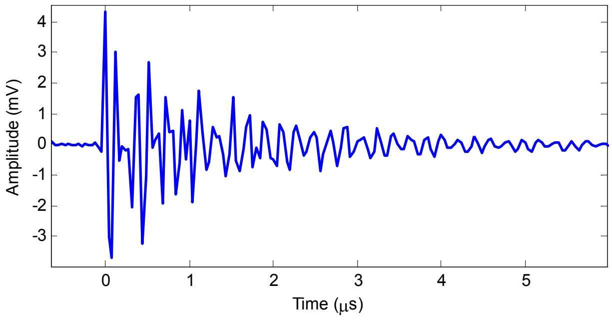

Figure 3. PD signals captured by Rogwski coil when two trees are leaning on CC line

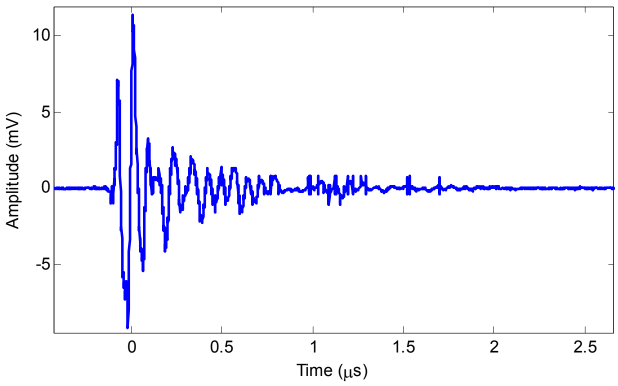

Figure 4. PD signals captured by Pearson coil when one tree is leaning on CC line

The two important parameters of these coils are sensitivity and bandwidth. The sensitivity of the sensors can be increased by increasing the number of turns (coils having more turns can detect very little amount of currents), however, by doing this the bandwith of the sensors (frequency detection range) may reduce. There could be a dominant parameter (sensitivity or bandwith) while designing sensors for specific applications and measurements in power networks

IV. FAULT DIAGNOSIS METHODOLOGY

The PD data captured by the Rogowski or Pearson coil is essentially an oscillatory voltage pulse, which needs to be processed to obtain PD characteristics such as peak value, apparent charge, phase position, repetition rate, and PD energy. The apparent charge *q(t)* entering into the system due to PDs is given as:

$$q(t) = \int i(t)dt = -\frac{1}{M}\int\int v_{out}(t)dt^2 \qquad (1)$$

where $v_{out}(t)$ is the oscillating voltage appearing at the output terminals of the sensor, M is the mutual inductance of the Rogowski coil and $i(t)$ is the current flowing in the conductor due to PDs initiation. The fast Fourier transforms (FFTs) of the acquired pulses show the spectrum of frequency contents present in the signals. Using (1), the following Simulink model can be used to quantify the PD magnitude caused by the leaning trees on CC line (see Fig. 5). An infinite impulse response (IIR) band-pass filter of order 16 having frequency band of 1-6 MHz is applied for noise elimination.

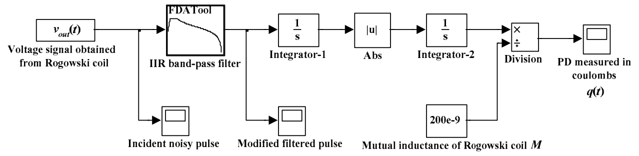

Figure 5. Simulink model to quantify PD magnitude

The magnitude of PDs increases by increasing the number of falling trees on the CC line, and this fact reveals that PD detection is easier when many trees are falling on the CC line due to heavy storms. The voltages at different points on the conductor have different amplitudes decreasing towards the downstream can be explained by the phenomenon of attenuation of PD signals when traveling down the conductor. In order to estimate the maximum length of the CC line that can be monitored with one Rogowski coil sensor for detecting PDs due to leaning trees, the wave propagation characteristics of the line should be accurately determined. The magnitude of the attenuation can give an idea about the length of the CC at which the PD signal dies, so that the sensor location can be relied on to get the required signal. Therefore, the attenuation of the PD pulses is an important consideration while deciding the number of the sensors and their positioning over the entire length of the CC line.

V. PROPOSED FUTURE WIRELESS TECHNOLOGY

The rapid development in electronics, microcontroller performance, digital signal processing, and wireless communication has opened up possibilities to implement new industrial sensor solutions on the process level. One such promising concept is the wireless sensor [8]. The wireless sensors may become a key technology, especially in on-line condition monitoring, as they are cheap and can easily be embedded in the processes (also as retrofit). They do not need wiring which is a source of noise and unreliability [9]. However, there are some practical issues associated with wireless sensors technology.

First of all, wireless sensors have limited capacity of data processing. In reality, PD signals have high frequency contents, so the sampling time of the captured measurements should be small. A data having very small sampling time might face problems while processing and transfering to control centre. Second, wireless sensors should have long-time battery capacity so that there should be no need to replace battery frequently [10]–[12]. Designing filters for wireless sensors is another area of concern that still needs more investigations. The data captured by the wireless sensor will be in the form of analogue format. This must be changed to digital format to transfer it via radio communication to the control centre. It is revealed from above discussion that wireless sensors to detect PD signals, capturing measurements, and transferring data into control centre needs new design parameters and considerations.

For on-line monitoring, especially of fast phenomena like PDs, this means that the sensor has many design challenges. For example, the design of the signal processing filters must be very energy efficient and the designer must know which frequency component are the important ones for the application (to reduce the impact of noise). Also the analogue-to-digital (A/D) conversion is difficult to implement because the A/D converters working at high frequencies have rather high energy dissipation. The samples received from the conversion must be processed by the microcontroller, which means that the requirements on processing and memory capabilities are high.

Today, one of the biggest shortcomings in distribution automation is the lack of simple and cheap instrumentation solutions that are easy to implement and are applicable in system refurbishment. The cost of instrumentation in a distribution automation system with a high degree of automation is approximately 25% [13]. The overall cost of installing and wiring a sensor exceeds the cost of the sensor by more than ten times [14]. Using wireless communication, installation costs are significantly reduced; no problems appear with damaged signaling cables that would need maintenance, and instrumentation is possible in applications where wiring is unfeasible. Typically these relate to rotating machines as well as medium and HV environments. In these environments, isolation becomes a problem and maintenance activities can be dangerous [14]. In addition, refurbishment and installation without de-energizing the power network is possible. This favors wireless over power line communications (PLC), although PLC has similar advantages to wireless technologies for sensor communication in industrial environments [15].

Practically, wired sensors take only measurements and are not capable of processing the measurements for PD detection and localization. In addition, we need data concentrators to collect the measurement data captured by the sensors store it, and transfer it to the control centre. In control centre, DMS will process the data using newly developed algorithms to detect and localize falling trees. The raw data may be corrupted with external noise and interferences, therefore, de-noising techniques based on filtering or wavelet transforms methods should be applied to get the reliable detection and localization results. The algorithms to de-noise the data should be incorporated with algorithms for fault diagnosis in the DMS. The algorithms might run after each hour to update the network status if there is any falling tree on the CC line. The data collected by sensors can also be sent to digital relay (having newly developed algorithms) to detect and localize falling trees. Another cost-effective solution can be using wireless sensors and transferring data directly to control centre or digital relay. So there will be no need to install additional equipment (data concentrator) and overall cost of the solution can be optimized.

VI. CONCLUSIONS

In this research work, Rogowski and Pearson coils (wired sensors) were used to take PD measurements. The wired sensors can be replaced with wireless sensors in the future keeping in view their advantages and simpler installation. However, the design of a wireless sensor for the measurements of PDs in CC overhead lines needs a totally new design philosophy. The proposed intelligent fault diagnosis system based on wireless sensors technology will improve the safety of CC lines and attract utilities for implementation to reduced maintenance costs and visual inspection work. In this way, the reliability and adaptability of the distribution system will improve which is one of the significant characteristics of the future self-healing smart distribution networks.

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