A Review of Condition Monitoring of Underground Power Cables

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***Abstract*—Power distribution system relies heavily on a vast network of medium voltage (MV) underground cables for power delivery. Condition monitoring technologies can, therefore, play a vital role in attempting to target the cables that pose the most urgent reliability concerns. Maintaining or increasing a power system's reliability at minimal cost is an important issue for most network owners. Condition monitoring gives the information needed for safe and reliable operation, replacement strategy and hence increases the system reliability. Demands for reliable power causes a growing tendency to apply different strategies in the form of condition based maintenance. Partial discharge (PD) monitoring is one of the successful diagnostic tools for accessing the insulation condition of MV cables. Data acquired by online PD measurements can help in identifying the upcoming faults in such cable networks and possibly forecast the remaining life of the insulation. This paper reviews the condition monitoring and diagnostictechniques used forunderground power cables.**

Keyword: power cables; condition monitoring; partial discharge; medium voltage.

I. INTRODUCTION

Power cableswhich representthe most important part in the power systemare vulnerable to failure due to aging or defectsthat occur with the passage of time. Cable network can be categorized as Extra High Voltage (EHV), High voltage (HV), Medium Voltage (MV) and Low Voltage (LV) networks. It has been reported that more than half of cable failuresare due to electrical reasons [1]. In particular, in MV networks, the causes of outage time are the cable (81.1%), switchgear (6.8%), transformer (3.8%) and others (8.3%).

A cable system consists of cables, joints/splices, and terminations. In modern cables, cross-linked polyethylene (XLPE) is commonly used for cable insulation in low, medium and high voltage cables. Poly Vinyl Chloride (PVC) and ethylene propylene rubber (EPR) are also suitable for lowand medium voltage cables [2]. XLPE, in particular, is popular due to its low dielectric losses. Regardless of operating voltage or frequency, the cable usually consists of aluminum or copper conductor covered with semi-conductive and insulation layers. Metallic screen over the insulation semi-conductive layer acts as the ground shield which is enclosed by external protective sheath.Cable accessories are one of the main reasons for possible faults in the network system as mentioned by [1].

Partial discharge (PD) monitoring of cables has been widely used due to its effectiveness in condition based maintenance and monitoring programs and in locating the faultycable sections. Standard procedures such as Very Low Frequency (VLF), Damped AC (DAC), Alternative Current (AC) or Direct Current (DC) testing are popular due to the fact that they can verify possible faulty areas of joint and termination after assembling, by detecting and locating PD in the cable. However, for the purpose of on-line monitoring, high attenuation of the PD signal along the long cablelength makes it difficult and challenging to pick the exact PD and its location. Nowadays on-line PD monitoring of the cable has been used by sensing the PD signal with high frequency current transformer (HFCT), and capacitive coupling sensors, etc. This paper summarizes the most important techniques for cable condition assessment and aims to provide a brief review on this subject.

II. DIFFERENT DIAGNOSIS AND MONITORING TECHNIQUES FOR CABLES

There are many ways to monitor cables on-site or off-site with on-line or off-line tests. [3].

A. Tangent delta (Loss angle, or Dissipation factor test) measurement

A perfect cable is represented by an ideal capacitor in which the phase difference between current and voltage is 90 degrees. However, due to some resistive losses, the cable insulation is represented by a series or parallel resistive-capacitive (RC) circuit with phase difference of less than 90 degrees. The greater the losses, the lesser the phase difference angle and higher will be tangent delta values. This method provides information regarding the aging of a cable and macroscopic condition of the cable [3].

B. Leakage current monitoring

This monitoring method measures leakage current over the surface or through an insulation medium. The measured valueof surface leakage current demonstrates the pollution issues of the cable accessories surfaces. For example, washing cable accessories on the cable tower can influence leakage current which can be measured with sensors and optical fiber. This method has also been commercially available in a form of on-line monitoring equipment [4, 5].

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C. Temperature monitoring

Thermal monitoring on the power cable is an efficient tool for detecting an abnormal condition which is also applicable as an on-line monitoring tool by usingappropriate temperature sensors. Semiconductor type sensor or optical fiber is popular for continuous temperature monitoring of cables. The advantage of this monitoring is to have real-time thermal behavior of the cable.

D. Turned resonant test voltage method:

There are two ways of carrying out this test using different test circuits for resonant testing; Frequency Turned Resonant Circuit (FTRC) and Inductively Turned Resonant Circuit (ITRC).

The FTRC method uses power electronics converter generating harmonics and noises in the test system. Therefore appropriate signal processing techniques are required. However, there is no moving part used in this method. On the other hand, ITRC usually use auto transformer, so there are no such electronic pulse noises. Moreover, voltage can be increased smoothly which makes it easier to reach the PD inception voltage. The drawback of ITRC is its moving components which should be maintained periodically.

E. Damped AC (DAC) voltage method:

This method consists of application of damped AC voltage with the help of external inductance and cable capacitance. The frequency range of this method can differ depending on the cable length and PD inception voltage. Advantage of Damped AC method over others is relatively less power demand and it is also applicable for all types of MV and HV cables.

F. Very Low Frequency (VLF) voltage method:

Since capacitive current of the cable is proportional to the frequency, if frequency decreases, the demand of capacitive current also decreases. Therefore VLF method turns down the frequency to the range of 0.01Hz to 0.1Hz for extruded-dielectric cable. Advantage of this method is low power demand.

G. DC voltage method:

Even though the DC voltage method cannot represent AC voltage related insulation stresses, this method has been used for thermal, conductivity problems. High voltage DC can be applied for cable acceptance test for recommended duration. Advantages of this method are its simplicity and cost effectiveness with low power requirement.

H. Impulse voltage method:

Impulse voltage with a very fast rate of rise and decay rate can be applied for on-site tests. Disadvantages of this method are difficultly to determine the inception voltage of PD, high attenuation along the long cable length, distance dependent test results, and difficulty to find correlation between routine factory and on-site test results regarding partial discharge values.

I. Partial discharge monitoring

PD monitoring of the cable is the most effective method that is able to monitor electrical aging [6]. For localization of PD, Time Domain Reflectometry (TDR) which uses the reflection of pulse signals at the cable terminations [7, 8] has been used. PD monitoring of the cable systems can be categorized into the off-line and on-line methods. Regarding the off-line method, it has been widely used with an extensive voltage withstand test in order to validate the acceptance test for cables from the factory. It can also be used for on-site PD measurements.

1) On-line PD monitoring

On-line cable PD monitoring techniques have proven their efficiency and are extensively being used. On-line PD monitoring on the cable network has many advantages over the off-line method. However monitoring long cable lines while they are in operation has too much noise and attenuation compared to other application cases. Usually HFCT around cables or the earth connection, capacitive coupling sensors, and acoustic emissions have been used [9]. Due to the fact that high frequency from a PD signal is significantly attenuated in the cable, the sensors measure the HF/VHF range rather than UHF.

2) Off-line PD monitoring

The off-line method usually energizes the cable network and monitors PD occurrence by using a different voltage source. The main disadvantage of this method is the outage of electrical supply before testing the cable [10-12].

III. ON-LINE PD MONITORING ON CABLE

Broadly speaking PD types in a cable can be classified as [13, 14]:

- Internal PDs that occur in the air gaps or voids surrounded by solid insulation material. It depends on the size and the location of the void. This PD occurrence in cavity can erode the cable surface or insulation [15]. Voids are the examples of internal PD type.
- Surface PD can occur on the surface of solid-solid and solid-liquid material parallel with the surface of insulation. This can happen as a consequence of field enhancement on the area of missing outer semi-conductive screen or an incompletely removed outer semi conductive screen in the cable. Surface PDs due to improper stress cone or termination placement are examples of surface PDs.
- PDs occurring at the voids or tips of water trees generate tree-like shapes in the insulation or dielectric body where the PD occurs. The growth of electrical tree can ultimately lead to completeinsulation breakdown. Moreover, if there is a high level of moisture, a water tree can be generated resulting in an electric tree at the sometime due to some overvoltage stresses. Usually electrical tree have many branches, and produce a higher PD magnitude than in the cavities which can grow until final breakdown occurs.
- Corona occurs in open air around the cable.

IEC 60270 methods which is used for PD measurements on cable samples in labs is not appropriately applicable for on-line continuous PD monitoring on long lengths of cables. UHF detection which has high signal to noise ratio (SNR) is an attractive method for such a purpose [16-22]. Since cable

termination and joint is the most vulnerable to failure, on-line PD monitoring on cable accessories is important for cable monitoring.

For acquiring the PD signals, capacitive coupler, inductive sensor (e.g. HFCT, Rogowski coil), and directional coupler sensor near cable joint, terminal or cable earth have been widely applied because they can be easily attached or clamped for measurement signal without interrupting the online system.

Clamp on HFCT are installed at the terminations around the cable earth. In order to locate the PD source in the cable system, dual sensor techniques (installing two sensors at each end of cable or cable joint) are required. Because of strong attenuation along the cable, PD location requires more sophisticated techniques such as the pulse injection method or TDR. The pulse injection method injects periodic pulses from one side while the sensor located at other side detects the pulse which synchronizes two sensors at each end of the cable system. Therefore the propagation time and transfer impedance can be calculated. Another technique uses TDR. Due to the symmetrical characteristic of the cable system, the pulse can propagate toward both ends of the cable with different magnitudes and times. Therefore the direct pulse and the reflected pulse can be detected by sensors which can be synchronized with GPS signals.

Online condition monitoring tools can be used as a source for condition based maintenance. With the online system, PD patterns and location of PD source can be analyzed. Currently an extensive research is going on related to the PD patterns of different defects. This can help in identifying the PD sources in long cables. However, online cable monitoring is a challenging task due to noise, external interference and attenuation problems.

IV. ONLINE PARTIAL DISCHARGE MONITOTORING EQUIPMENTS

Currently many sophisticated online PD measuring systems are commercially available in the market. Some of them are listed below:

A. Doble Lemke System

Doble Lemke employs UHF sensor that is attached to the cable termination or the GIS. The data acquired as PRPD can be analyzed and transferred over a TCP/IP network. The PD monitoring system PD GUARD/UHF is especially developed for continuous partial discharge monitoring of high voltage equipment, like GIS and Cable Systems using UHF Technology.

B. Emerson System

Emerson’s online cable PD monitoring system can locate PD source with accuracy of 1 % in up to 3 miles of cable length, andis applicable for XLPE, EPR, PILC and CLX Armored cable types.

C. HVPD System

HVPD system uses HFCT attached around the earth connections and TEV attached magnetically to the outside of metal-clad switchgear sensor which is applicable for polymeric (XLPE, PVC), paper (PILC), rubber (EPR), both 3-core and single-core cables, and 'mixed' cables with transition joints. Location of PD source using a pulse injector transponder is performed successfully for up to 5 km of MV cable length.

D. IPEC System

IPEC system employs double ended measurements for PD source location. Capacitive and airborne acoustic sensors can also be used. This system is applicable for MV, HV, and EHV cable networks.

E. KEMA System

KEMA system uses inductive sensors at two ends of cable termination. Maximum cable length of this application method is 8 km (for XLPE), 4km (for PILC, MIND), and 2km (for EPR). 3D visualization of PD in the cable helps to check PD occurrence according to the cable length, time and intensity.

F. Power PD System

Power PD system uses inductive and acoustic sensors to acquire PD patterns which can be shown as a PRPD or 3D graphs.

G. Techimp System

Techimpsystem uses HFCT and FMC (Flexible Magnetic Coupler) sensors at the two terminations of the cable. In long cables, the installations can be performed at the middle of cable. For localization of a PD source, this system analyzes amplitude/ frequency characteristics of PD, TDM method, and Arrival Time Analysis with GPS (Global Positioning System).

V. CONCLUSIONS

Online PD monitoring predicts the trend of degradation of insulation by recording PD activity with respect to time. For on-line PD monitoring on cables, IEC 60270 procedures are not appropriate because of its low frequency cover range with high level of noise and rapid signal attenuation in ling cables. Recent research shows that for on-line monitoring of cables, sensors monitoring frequency bandwidth should be up to 100 MHz because of lower noise compared to low frequency band measurements. On the other hand, the cable acts as a low-pass filter,thus the higher frequency pulses related to PD activity are only detected near the PD source.

The most appropriate sensor selection for online monitoring case is capacitive coupler and HFCT because these can be clamped or attached without interrupting the system. Since cable accessories are the biggest cause of possible faults, on-line PD monitoring near joint or terminal of cable is widely used. However, using two HFCT at each end of cable with PD localizing techniques by TDR or pulse injection method have been proven their efficiency for on-line PD monitoring of long cables.

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