Application of Partial Discharge Measurement as a Diagnostic Tool for Low Voltage Cables

Ph.D. Thesis Booklet

Richárd Cselkó

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Supervisor: Dr. István Kiss

Introduction

Until recently, low-voltage secondary cabling systems of any kind, e.g. power plants or substations were considered as equipment that rarely needed attention and even then, only at their terminals. The maintenance strategy was to run them to failure or change the whole cabling during overhauls. With the expansion of secondary cabling systems, the cost of complete replacement becomes unacceptably high and is sometimes nearly unrealizable. Considering today's IT based automatics and control systems and that the operation of critical systems depends on the integrity of secondary cabling, the risk generated by the run to failure strategy has become unacceptable. During lifetime extension programs, the condition of the cabling system has to be assessed to underlie necessary steps of maintenance for safe operation.

Diagnostic measurements and online monitoring of high voltage power equipment have already proved their usefulness in increasing the resilience of energy supply and optimizing maintenance and replacement actions. There are several drivers to extend these technologies to low voltage systems, e.g. control and measurement cables in industrial systems, power plants, railway signaling centers and aircraft. One of the most important ones is the need to prove the reliability of safety equipment in case of lifetime extension of nuclear power plants, where it is impossible to realize a complete replacement.

Previous research has shown that dielectric spectroscopy and mechanical measurements are able to detect the general ageing of the LV cable material due to various stress sources, while time-domain reflectometry (TDR) and pulse arrested spark discharge (PASD) method are able to detect local defects. However, the dimensions of the insulation and the extent of the detectable damage limit the applicability of TDR and PASD. Nevertheless, detecting local defects are particularly important, as these may lead to actual failure, when performance of the cables was of utmost importance: during a loss-of-coolant accident. Therefore, the goal of this research was to prove the applicability of partial discharge (PD) testing for the detection of local defects in low voltage industrial cables.

In the thesis, I have proved that the applicability of PD measurement can be extended to low-voltage cables. I have shown that the discharges do occur in LV cables.

I have created a new measurement setup that is suitable for the detection of PD signals originating form LV cables. This measurement setup is also able to effectively reduce the conducted external noise.

I have established the testing methodology for the cable types most frequently applied in the Hungarian power plants. I have shown which features of the partial discharge signals are applicable as diagnostic parameters.

THESIS 1

I have analyzed the gaps of the available low voltage cable diagnostic tools, and defined the importance of partial discharge measurement. Partial discharge measurement would be able to detect local defects that would lead to function loss in case of critical events. I have shown with calculations, finite element field calculations and streamer inception models confirmed with measurements, that partial discharges do occur in low-voltage cables at their test voltage in intact and in damaged cables, as well. [S7] [S8] [S10] [S12]

With the increasing focus on the condition estimation of low voltage cables, various methods have been investigated worldwide. Their ability to detect aging and damages cover a wide variety, however, a sensitive and widely applicable method to detect localized damages is still required. Extensive work has been performed at the High Voltage Technology and Equipment Group of the Budapest University of Technology and Economics to show the applicability of dielectric spectroscopy performed by voltage response method and mechanical (hardness) tests to detect the ageing bulk material of low-voltage cable insulations. Direct continuation of this work is to apply partial discharge measurement as a tool to detect local defects. The first and most important question is whether partial discharges occur in low voltage cables at or below their test voltage. For a simple coaxial cable and a rectangular cavity it is possible to derive the electric field and the inception voltage by elementary calculations, while in case of multi-core cables, the electric field can be calculated by finite element method. I have identified the critical field regions of various cable types and estimated the resulting inception voltage based on a streamer inception criterion, which have been confirmed by measurements, as well. The results show that partial discharges occur at lower voltage than the test voltage in damaged cables. However, I have also found, that partial discharges occur in intact cables, as well. This fact has consequences on the applicable measurement methodology shown in the 2nd thesis and on evaluation methods presented in the 3rd thesis.

THESIS 2

I have worked out a measurement arrangement for the detection of partial discharges in low-voltage cables. Initially I have concluded that the conventional measuring device complying with the IEC 60270:2000

standard is not suitable for this application due to its slow response, as the violated impulse resolution causes the overestimation of the discharge magnitudes and the underestimation of the repetition rate. Therefore, I have created a method applying two high frequency current transformers having an upper bandwidth limit of tens of megahertz, which are suitable for the measurement. The new arrangement makes use of the distributed element behavior of the cable and is a special bridge circuit, where one of the arms is the cable under test, while the other artificial arm has the same value as the characteristic impedance of the cable in the frequency range of the high frequency current transformers. This arrangement is able to suppress the external conducted noise. [S5] [S11] [S13]

The IEC 60270:2000 standard defines the most widely applied partial discharge measuring methods. Its application ranges from high voltage transmission equipment to low voltage components. The conventional PD detector described by the standard has integrating behavior, as it is meant to measure the charge of the individual partial discharge impulses. Therefore, its bandwidth is limited: the upper cutoff frequency of the detector is a few hundred kilohertz, but definitely not higher than 1 MHz, while its lower cutoff frequency can be as low as tens of kilohertz. The response of the detector is therefore slow, which make it prone to show false results if the repetition rate of the discharges is high, like in case of low-voltage cables: either the repetition rate is underestimated or the charge of the impulses overestimated. I have found in practical cases that the detector fails to give reliable results,

It is possible to overcome this problem with the application of detectors with higher bandwidth. As partial discharge signals are generally low, e.g. in case of conventional detectors their charge is expressed in picocoulombs, the basic requirement to a PD detection method is to effectively suppress noise. Therefore, I have created a measurement arrangement consisting of two high-frequency current transformers (HFCT) with tens of megahertz bandwidth. I have proved the suitability of these HFCTs by comparing their results to the ones obtained from an ultra-wideband (up to 1 GHz) detector. Conducted signals from the test voltage source are generally considered the highest noise source in PD measurement. The created arrangement effectively suppresses these signals by splitting them evenly between the characteristic impedance of the cable and an artificial arm. At the same time, PD signals originating in the cables are appearing on the two HFCTs with different amplitudes. The arrangement applies a differential detector, therefore the external noise impulses are suppressed, while the useful signals are highlighted. The main advantage of the method is that is suppresses noise physically before digitization, therefore useful signals below noise level can be effectively obtained and the digital conversion can be performed at ideal amplification.

THESIS 3

I have identified the specialties of the partial discharge diagnostics of low voltage cables, emphasizing the fundamental differences compared to medium and high voltage cables. The most important of all differences is that partial discharges do occur in intact cables, thus a general magnitude based decision is not possible, like the 5 pC limit in case of solid dielectric medium and high voltage cables.

I have shown that partial discharge measurement is capable of detecting changes in the insulation of RG-58, NYCY, YSLCY, SZRMKVM-J and SiHF low voltage cables. These changes cover mechanical damages, including damages reaching only the shielding, as well as thermal stresses. I have found that all types of low voltage cables have to be investigated separately and the features of the measured signal able to

diagnose damages determined. These include inception voltage, statistical evaluation of the phase-resolved partial discharge pattern and the parameters of Weibull distribution fit to the height distribution of partial discharge magnitudes are the most effective way to show these changes. In case the core insulation is also damaged down to the conductor, increasing the voltage to the test voltage of the cable causes flashover on the damaged surface. I have also found that these methods are able to detect damages based on the comparison with the original condition (so called fingerprinting diagnostics), as the test results on intact and stressed cables show high deviations and often overlap. [S1] [S2] [S3] [S4] [S6] [S7] [S8] [S9]

I have selected various cable types. The constructions covered single and multi-core, braided and tape shielded cables. The selected core insulation materials were PVC, PE and EPR, with more attention to PVC, as this was widely used in nuclear power plants across the Eastern Bloc.

The design electric field of high and medium voltage cables needs to be high in order to achieve an economical and feasible construction. The electric field occurring at the operational voltage is able to incept partial discharges, therefore these cables have to be manufactured to be PD free. Accordingly, the PD tests performed in the factory or during operation can be evaluated based on the magnitude of the discharges. In contrary, mechanical requirements prevail in the design of the insulation of low-voltage cables, thus the electric field at operational voltage is low and PD activity and subsequent ageing are not expected to occur. However, at test voltage, partial discharges do occur in LV cables, and the magnitude of the discharges is not necessarily higher in case of damaged cables compared to intact cables.

As the magnitude based evaluation is not feasible in all cases, the application of PD measurement as a diagnostic tool requires the selection of more elaborate evaluation of the measured signals. The appearance of partial discharges measured with AC test voltage is dependent on the phase angle of the test voltage. The phase resolved partial discharge pattern can be evaluated by statistical methods, i.e. the discharge pattern in each half period is considered as a distribution and its statistical features are evaluated. Another useful tool is the partial discharge height distribution, which is generated by recording the discharge magnitudes for a longer time and then a Weibull distribution is fit to their histogram. The shape and scale parameter of the Weibull fit can be used as a feature.

The experiments were designed as follows: tests were performed on intact and damaged or aged samples. Then the measured signals were evaluated with the above methods and were tested for significant deviation by comparing the results on the same sample before and after degradation and statistically, by comparing the cumulated results on intact cables and the cumulated results on degraded cables. With this method, it was possible to find features that are able to detect the changes within the samples and test these features, if they are suitable for a general decision rule. The results show that it is possible to find features that show significant changes in one-by-one comparison for all types and all degradation types. At the same time, I have shown that the cumulated results show high deviation and the distribution of the results from intact and damaged cables overlap. Accordingly, I have concluded that partial discharge measurement is applicable as a fingerprinting diagnostic method, i.e. it is able to detect damages of the insulation if previous measurement results are available.

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