

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

Ph.D. Thesis



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I have never known anything more spiritual than science. We build up a world from concepts and words, and they start to work together in a manner that nobody has expected.

To my beloved ones.

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Összefoglalás

A közelmúltig kevés figyelem jutott a szekunder kábelrendszerekre, még erőművekben vagy alállomásokon is legfeljebb a végződéseiknél végeztek karbantartást. A kábeleket korrektív karbantartási stratégiával üzemeltették, illetve a teljes kábelezést cserélték átfogó felújítások esetén. A szekunder kábelezés kiterjedtségének növekedésével a teljes csere egyre inkább elfogadhatatlanná válik és bizonyos esetekben nem is megvalósítható. A mai IT alapú automatikákat és szabályozórendszereket figyelembe véve, illetve ezen kritikus rendszerek működésének függését a szekunder kábelezés épségétől, a korrektív karbantartás által okozott kockázat elfogadhatatlanná vált. Élettartam hosszabbítás esetén a kábelezés állapotát fel kell mérni, hogy megalapozottan lehessen a szükséges karbantartási lépéseket megtervezni a biztonságos üzemelés fenntartása érdekében.

Nagyfeszültségű berendezések diagnosztikai vizsgálata és felügyelete már bizonyította hasznosságát az energiaellátás megbízhatóságának növelésében és a karbantartások és cserék optimalizálásban. Számos tényező motiválja, hogy ezeket a módszereket kiterjesszük kisméretű rendszerekre, például vezérlő és mérőkábelekre ipari rendszerekben, erőművekben, vasúti jelzőberendezésekben és repülőgépekben. Ezek közül az egyik legfontosabb az atomerőművek élettartam kiterjesztése esetén a biztonsági rendszerek megbízhatóságának fenntartása, ahol a teljes csere kivitelezhetetlen.

Korábbi kutatások bizonyították, hogy a dielektromos spektrum módszerek és mechanikai mérések képesek kimutatni a kisméretű kábelek szigetelőanyagának általános öregedését különböző igénybevételek esetén, míg az időtartománybeli reflexiómérés és az impulzussal gerjesztett szikrakisülés („pulse arrested spark discharge”) képesek helyi hibák kimutatására. Ugyanakkor az utóbbiak esetén a szigetelés vastagsága és az érzékelhető hiba minimális mérete erősen korlátozzák az alkalmazhatóságot. A helyi hibák feltárása másfelől különösen fontos, mert ezek ténylegesen meghibásodáshoz vezethetnek, amikor a kábelek funkciómegtartó képessége különösen fontos lenne - hűtőközeg-vesztéses baleset esetén. Ennek megfelelően a kutatásom célja az volt, hogy bizonyítsam a részkisülés (PD, partial discharge) mérés alkalmazhatóságát kisméretű, ipari kábel típusokra.

Disszertációmban bebizonyítottam, hogy a PD mérés alkalmazhatósága kiterjeszhető kisméretű kábelekre. Bemutattam, hogy a kisülések megjelennek kisméretű kábeleekben. Megalkottam egy mérőrendszert, ami illeszkedik a kisméretű kábeleekben keletkező részkisülés jelekhez. Ez az elrendezés hatékonyan képes elnyomni a külső, vezetett zajokat. Vizsgálati módszertant hoztam létre a magyarországi erőművekben leggyakrabban alkalmazott kábel típusokra. Kimutattam a kisülések által generált jelek azon a jellemzőit, amelyek diagnosztikai paraméterként alkalmazhatók.

1. Tézis

Meghatároztam a rendelkezésre álló kisméretű kábel diagnosztikai eszköztár hiányosságait és a részkisülés mérés jelentőségét. Ennek alapján a PD mérés feladata

azon helyi hibák feltárása, amelyek funkcióvesztéssel járhatnak kritikus események folyamán. Számításokkal, végeeselemes szimulációkkal, streamer begyűjtési modellekkel, valamint mérésekkel is megerősítettem, hogy részleges kisülések megjelennek a kisfeszültségű kábelek próbafeszültségén sérült és ép kábelek esetén is. [S7] [S8] [S10] [S12]

Mivel egyre több figyelem jut a kisfeszültségű kábelek állapotfelmérésére, számos módszer alkalmazhatóságát vizsgálták meg világszerte. Ezek képesek a kábelek változatos öregedési folyamatainak és sérüléseinek feltárására. Ugyanakkor egy érzékeny és széleskörűen alkalmazható módszer a helyi sérülések feltárára még nem áll rendelkezésre. A Budapesti Műszaki és Gazdaságtudományi Egyetem Nagyfeszültségű Technika és Berendezések Csoportjánál jelentős eredmények születtek a visszatérő feszültség módszerrel mért dielektromos spektroszkópiával és mechanikai (keménység) vizsgálatokkal a kisfeszültségű kábelek szigetelőanyagának öregedésének kimutatásában. Ennek a munkának a közvetlen folytatása a részkisülés mérés alkalmazása helyi hibák kimutatására. Az első és legfontosabb kérdés, hogy a részleges kisülések megjelennek-e kisfeszültségű kábelekben a próbafeszültségükön. Egyszerű, koaxiális elrendezésre és négyszögletes üregre a villamos tér és így a kisülések gyűjtési feszültsége elemi módszerekkel számítható, míg a többberű kábelekben a kialakuló térerősség végeeselemes módszerrel számítható. Azonosítottam a kritikus térerősségű részeket számos kábeltípusra és megbecsültem az ebből következő gyűjtési feszültséget a streamer kisülés gyűjtési kritériuma alapján. A számítási eredményeket mérésekkel is igazoltam. Az eredmények alapján a részkisülések a próbafeszültség alatt megjelennek a sérült kábelekben. Egyúttal azonban azt is találtam, hogy a kisülések ép kábelekben is megjelennek. Ez következményekkel jár a 2. tézisben bemutatott mérési módszerre és a 3. tézisben bemutatott kiértékelési módszerekre is.

2. Tézis

Kidolgoztam egy mérési elrendezést kisfeszültségű kábelek részleges kisüléseinek mérésére. Első lépésként megállapítottam, hogy az IEC 60270:2000-es szabvány által definiált konvencionális részkisülés mérő berendezés nem megfelelő erre az alkalmazásra a lassú válaszdő miatt, mert a túllépett impulzus felbontó képesség a kisülés látszólagos töltésének túlbecslésével és az ismétlődés alulbecslésével jár. Ennek elkerülésére a megalkotott mérési elrendezés két nagyfrekvenciás áramváltót alkalmaz, amelyeknek a felső határfrekvenciája a néhány tíz megahertz nagyságrendbe esik és emiatt megfelelőek a mérésre. Az új elrendezés egy speciális hídkapcsolás, amelynek az egyik ága a mért kábel, míg a másik, mesterséges ága a kábel hullámimpedanciájával megegyező értékű a nagyfrekvenciás áramváltók sáv szélességében. Ez az elrendezés hatékonyan csökkenti a külső vezetett zajokat. [S5] [S13] [S11]

Az IEC 60270:2000 szabvány definiálja a leggyakrabban alkalmazott PD mérési módszereket, melyeket nagyfeszültségű berendezésektől kisfeszültségű eszközökig alkalmaznak. A szabvány által definiált konvencionális mérőberendezés integráló jellegű, mert a célja az egyedi kisülés impulzusok által szállított töltés meghatározása. Ennek

megfelelően a sáv szélessége limitált: a mérőműszerek felső törésponti frekvenciája néhány száz kilohertz, de semmiképpen sem nagyobb, mint 1 MHz, míg alsó törésponti frekvenciájuk néhány tíz kilohertzig süllyedhet. A műszer válaszüvege ennek megfelelően lassú, ami hibás kijelzést eredményez, ha gyorsan ismétlődő kisülések vannak jelen, ahogy a kisfeszültségű kábelek esetén. A műszer, kialakításának függvényében, vagy a kisülések gyakoriságát becsüli alul vagy a töltését becsüli túl. Az elvégzett kísérleteim során a gyakorlatban is megerősítést nyert, hogy a berendezés bizonyos körülmények között nem megbízható értékeket mutat.

A fenti problémát úgy lehet áthidalni, hogy nagyobb sáv szélességű mérőberendezést alkalmazunk. Mivel a kisülések által keltett jelek általában igen kis amplitúdójúak (a konvencionális mérőberendezéssel pikocoulomb nagyságrendben mérjük), a PD mérő berendezésekkel kapcsolatban alapelvárás a jó zajelnyomás. Ezt figyelembe véve alkottam meg az új elrendezést, ami két nagyfrekvenciás áramváltót (HFCT, high frequency current transformer) alkalmaz, néhány tíz megahertzes sáv szélességgel. Bebizonyítottam ezeknek az eszközöknek az alkalmasságát úgy, hogy összevetettem a mért jeleket egy ultranagy sáv szélességű (1 GHz) érzékelővel vett jelekkel.

A PD mérés során általánosságban a vezetett zavarok a legnagyobb zajforrások. A megalkotott mérési elrendezés képes elnyomni ezeket a zajokat úgy, hogy a beérkező impulzusokat kettéosztja a kábel hullámimpedanciája és egy mesterséges ág között. Ugyanakkor a kábel irányából érkező, PD által generált impulzusok a két érzékelőn különböző amplitúdóval jelennek meg. Az elrendezésben egy differenciális mérőfejet alkalmaztam, így a külső zajokat az elrendezés elnyomja, míg a hasznos PD impulzusokat kiemeli. Az elrendezés legfőbb előnye, hogy a zajt még a digitalizálás előtt, fizikai módszerrel nyomja el, így akár zajszint alatti hasznos jelek is vehetők és a digitalizálás ideális erősítés mellett történhet meg.

3. Tézis

Azonosítottam a kisfeszültségű kábelek részkisülés diagnosztikájának specialitásait, kiemelve az alapvető különbségeket a közép- és nagyfeszültségű kábelekhez képest. A legfontosabb eltérés, hogy a kisülések megjelennek az ép kábelekben is, így egy általános, látszólagos töltés alapú döntési modell nem alkalmazható, mint a közép- és nagyfeszültségű, polimer szigetelésű kábelekre általánosan elfogadott 5 pC határérték.

Bizonyítottam, hogy részleges kisülés méréssel kimutathatók RG-58, NYCY, YSLCY, SZRMKVM-J és SiHF típusú kábelek szigetelésének változásai. Ezek a változások lefednek mechanikai sértéseket, beleértve azokat, amelyek csak az árnyékolást érik el, és termikus igénybevételeket is. Megállapítottam, hogy minden típusra külön szükséges megvizsgálni, hogy milyen paraméterek alkalmasak a változások kimutatására. Az leginkább alkalmasnak mutató paraméterek a PD gyújtási feszültsége, a kisülések fázisszög szerinti eloszlásának statisztikai kiértékelése, valamint a kisülés amplitúdók hisztogramját közelítő Weibull eloszlás paraméterei. Abban az esetben, ha az érszigetelés a vezetőig sérült, a próbafeszültség átívelést okoz a sérült felületen. Azt is megállapítottam, hogy ezek

a módszerek egy eredeti állapottal való összehasonlítással alkalmasak diagnosztikára (ún. ujjlenyomat diagnosztika), mivel az ép és sérült kábeleken mért eredmények nagy szórással rendelkeznek és az eredmények gyakran átfedik egymást. [S1] [S2] [S3] [S4] [S6] [S7] [S8] [S9]

A vizsgálatok céljára kiválasztottam számos kábeltípust koaxiálistól többberűig, valamint sodrott és szalag árnyékolásúakat is. Az érszigetelés anyagai PVC, PE és EPR voltak, legnagyobb hangsúllyal a PVC-n, mivel a keleti blokk atomerőműveiben ezt használták széleskörűen.

A közép- és nagyfeszültségű kábelek tervezési villamos terének nagynak kell lennie ahhoz, hogy költséghatékony és kivitelezhető konstrukció álljon elő. Az üzemben fellépő villamos tér képes a részkisülések begyűjtására, így ezeket a kábeleket PD mentesre kell gyártani. Ennek megfelelően a gyárban illetve később üzemben elvégzett PD méréseket amplitúdó alapon ki lehet értékelni. Ezzel szemben kisfeszültségű kábelek szigetelésének tervezésekor a fő szempont a mechanikai követelmények teljesítése, így üzemi feszültségen nem várható a kisülések begyűjtása és kisülés miatti öregedés. Ugyanakkor a próbafeszültségen kialakulnak a kisülések ép kisfeszültségű kábeleken is, és a kisülések nagysága nem feltétlenül nagyobb sérült kábelek esetén.

Mivel a kisülések nagysága szerinti döntés nem alkalmazható minden esetben, a PD mérés diagnosztikai alkalmazásához a mért jelek összetettebb értékelésére van szükség. A váltakozófeszültséggel vizsgált minták esetén a kisülések megjelenése függ a vizsgálófeszültség fázisszögétől. A kisülések fázisszög szerinti eloszlásának mintázata kiértékelhető statisztikai módszerekkel úgy, hogy a félperiódusonként mért jeleket eloszlásnak tekintve kiszámoljuk azok statisztikai jellemzőit. További módszer a kisülések nagyság szerinti eloszlásának vizsgálata, amikor hosszabb idejű mérési adatokból a kisülés amplitúdók hisztogramját képezzük, és azt közelítjük Weibull eloszlással. Ekkor a közelítő eloszlás skála és alakparamétere szolgál diagnosztikai paraméterként.

A kísérleteket a következőképpen terveztem: méréseket végeztem ép és öregített kábeleken. Ezt követően a mért jeleket kiértékeltem a fenti módszerekkel, majd összehasonlítottam az ép és igénybe vett kábeleken kapott értékeket. Elsőként egyesével hasonlítottam össze az azonos kábelmintáról származó értékeket, majd összevettem az azonos típusokra és igénybevételekre kumulált eredményeket az ép kábelekről származó kumulált eredményekkel. Ezzel a módszerrel megállapítottam, hogy mely jellemzők alkalmasak kimutatni a mintákon bekövetkezett változásokat és azt is, hogy ezek közül melyek alkalmasak általános döntési szabályként való alkalmazásra. Az eredmények azt mutatják, hogy lehetséges minden esetben szignifikáns változást mutató paramétert találni egy-az-egyhez való összehasonlítás esetén, minden igénybevétel típusra. Ugyanakkor kimutattam, hogy a kumulált eredmények nagy szórással rendelkeznek és az ép illetve sérült mintákon mért eredmények eloszlása átfedésben van egymással. Ennek megfelelően azt a következtetést vontam le, hogy kisfeszültségű kábelekre a részkisülmérés ún. ujjlenyomat diagnosztikaiként alkalmazható, tehát ha korábbi mérési adattal való összehasonlítás lehetséges.

I. Introduction and motivation: the need for low-voltage cable diagnostics

Until recently, low-voltage secondary cabling systems of any kind, e.g. power plants or substations were considered as equipment that rarely need attention and only at their terminals. The maintenance strategy was to run them to failure or change the whole cabling during overhauls. With expanding of the secondary cabling systems, the cost of the complete replacement becomes unacceptable 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 the 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.

The resiliency of any system is fundamentally determined by two factors: the architecture of the system and the properties of the individual components; this work concentrates on the latter. In general, the ability of a component or more precisely, a population of components to withstand a stress factor can be handled statistically and represented by a distribution function. As the components age and get damaged, and their condition deteriorates, the distribution function shifts to lower stress values, as it is shown in Fig. 1. Accordingly, any deteriorated component of a system poses an increased risk of failure, while components in good condition may also withstand stresses well above the planned nominal value.

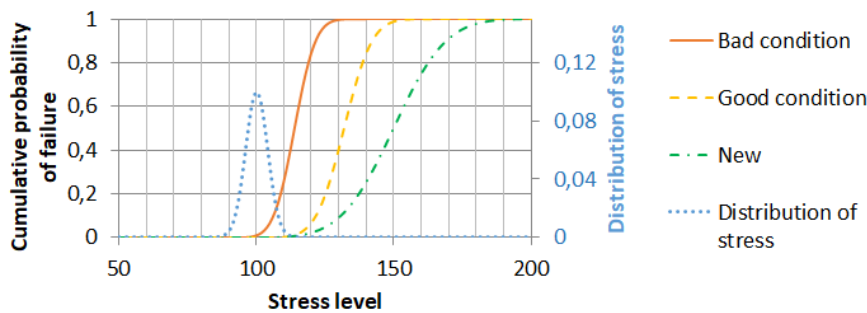


Fig. 1 Susceptibility of an element or population to failure during its lifetime (after [44])

Diagnostic measurements and online monitoring of high voltage power equipment have already proved their usefulness in increasing the resiliency 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 [40], power plants [41] [26], railway signaling centers and aircraft [27] [35]. 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. One of the possible methods is partial discharge (PD) measurement [78], detecting the local defects in insulations. This is particularly important, as these may lead

to actual failure, when performance of the cables was of utmost importance: during a loss-of-coolant accident.

The goal of this research is to improve the applicability of PD testing of low-voltage industrial cables, with emphasis on control and instrumentation cables in nuclear power plants. While PD is not expected to be an aging factor in low-voltage cables, however, it is expected to reveal defects of the insulation that may lead to failure in critical cases. To prove the applicability of PD measurement, the following questions will be answered in this thesis:

- What is its role among the other methods?
- Do partial discharges occur, when the cable is damaged?
- What is the appropriate measurement technique?
- Which features of the partial discharge activity can be applied as diagnostics parameters?

II. The role of partial discharge measurement among the available low-voltage cable diagnostic methods and the investigation of its applicability

With the increasing focus on the condition estimation of low-voltage cables, various methods have been investigated worldwide. Fig. 2. summarizes the available methods to detect global and local deterioration. Their ability to detect aging, stresses and damages are evaluated in the first part of the chapter, except for chemical tests, which are a means of understanding the underlying material degradation process but cannot be applied as a field diagnostic method. As the possible role of partial discharge measurement is defined, the most important feature is investigated – whether partial discharges occur in low-voltage cables at or below their test voltage.

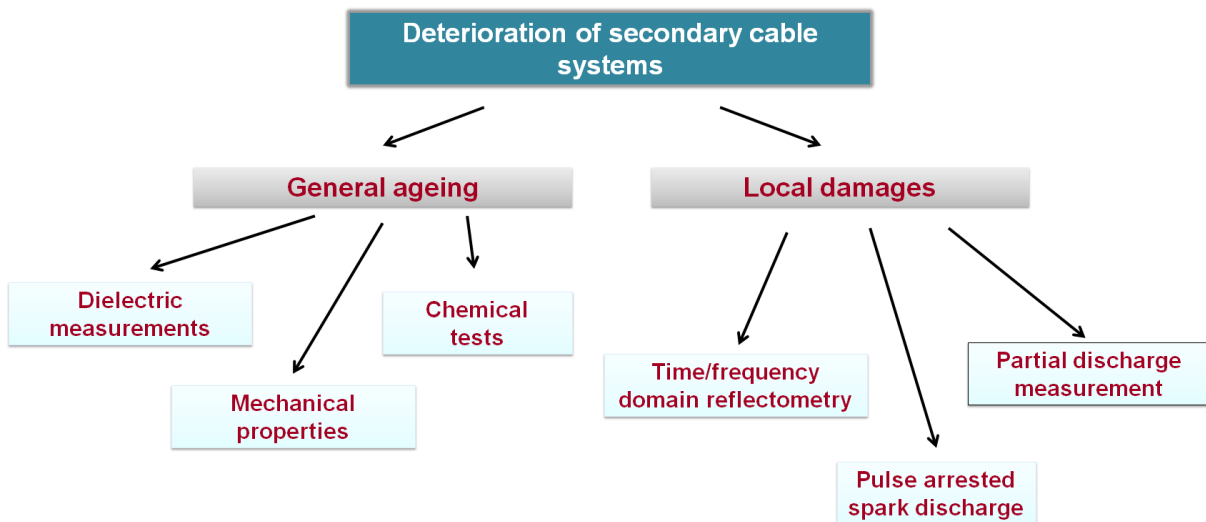


Fig. 2. Summary of the available diagnostic methods to detect global and local aging and damages.

II.1. Dielectric measurements

Dielectric characterization of insulating materials and searching for aging markers has been applied since the early ages of electrical insulation. The simplest one, insulation resistance measurement usually does not provide sufficient information. On the contrary, dielectric spectroscopy investigates much broader set of physical processes and is usually capable of revealing the changes in material properties.

The effect of voltage stress on PVC insulated cables has been investigated in [1] and [40]. After each voltage stressing cycle (25 kV AC 50 Hz, duration 1 hour), the steepness of the discharge voltage and return voltage has been measured with the voltage response method (VRM), which is one of the methods to determine the changes in the polarization phenomena appearing in the dielectric over a broad frequency range. Fig. 3 depicts the methodology of the VRM: the insulation is charged by V_{ch} charging voltage for a longer t_{ch} time (e.g. 1000 s). After the charging period, the voltage source is disconnected and the

$V_d(t)$ discharge voltage is measured for the shortest possible t_{idp} time and the initial slope S_d of the $V_d(t)$ is determined. This is followed by a short circuit period for t_{dch} , usually a few orders shorter time as the charging time (e.g. 2 s). After the short circuit is released, the $V_r(t)$ recovery voltage is measured for t_{rvp} time, and its initial slope S_r is determined. The charging and short circuit time can be adjusted to cover the important polarization phenomena.

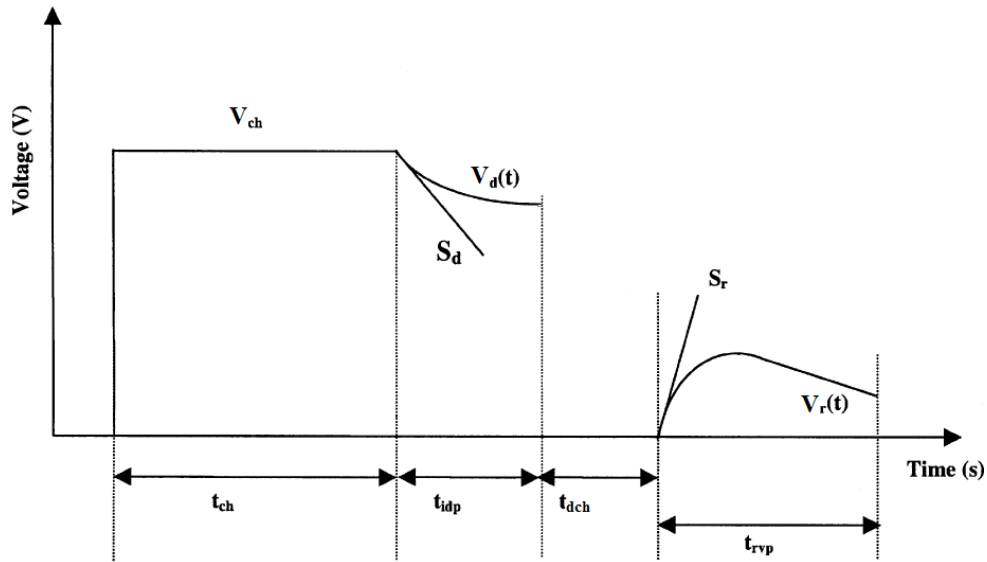


Fig. 3. Process of voltage response measurement [1].

Fig. 4 shows the changes in the steepness of the discharge voltage over a few voltage stressing periods, which are most apparent at the beginning.

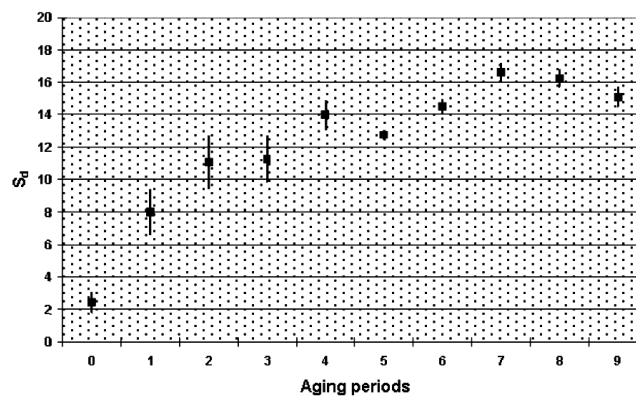


Fig. 4. Changes in the steepness of decay voltage S_d [V/s] with electrical aging [1].

The measurement of the dissipation factor over a wide frequency range proved useful in finding aging indicators for both thermal, radiation and combined aging presented in [30] and [31]. Based on Fig. 5, dissipation factor measured at 100 Hz and the frequency at the minimum of dissipation factor have been selected as aging factors, as either one or the other has shown significant changes during all aging scenarios.

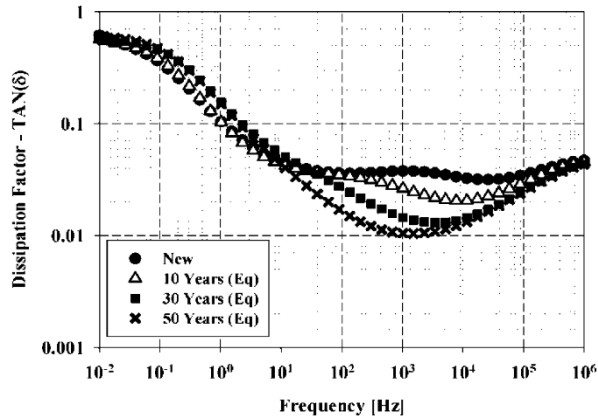


Fig. 5. The effect of thermal aging on the dissipation factor over a broad frequency range [30]

II.2. Mechanical methods

Mechanical parameters are also assumed to be in strong correlation with the chemical changes of the material. The most widely applied mechanical measurements are density, tensile (elongation at break and tensile modulus), deflection and hardness (intender modulus and shore D hardness) tests [32]. Thermal aging has a very straight effect on the density of EPR insulation, as it has been found in [33]. Other materials exhibited change as well, some of them monotone changes like in Fig. 6, whereas in case of others, almost constant periods were followed by rapid changes.

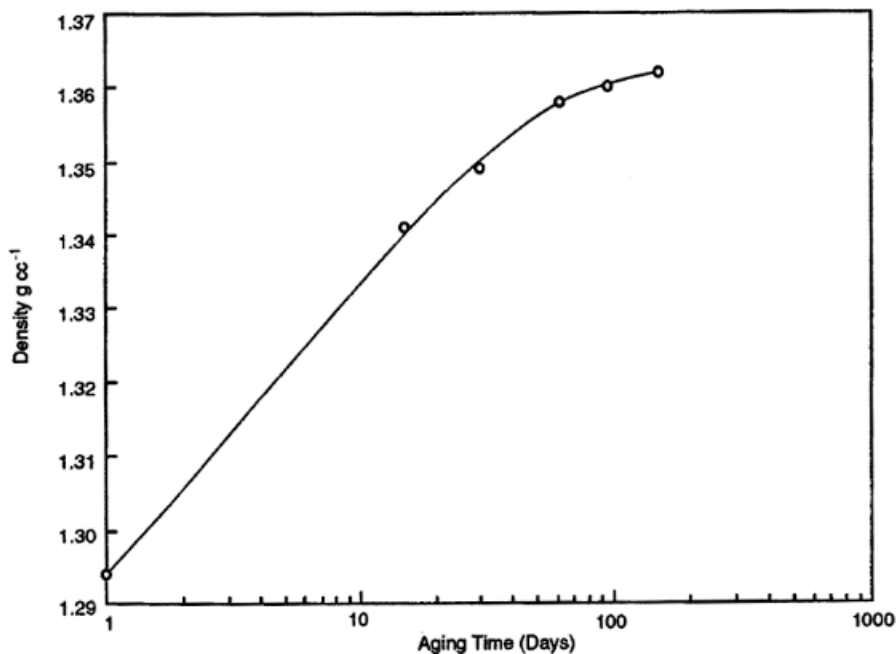


Fig. 6. Variation of density observed during thermal aging in EPR cable [33]

Elongation at break and shore D hardness of PVC cables taken from service were tested in [32]. In this case, shown in Fig. 7, shore D hardness proved to be the ideal aging factor, as one of the main deterioration process of PVC is the evaporation of the plasticizer, affecting directly the hardness of the material.

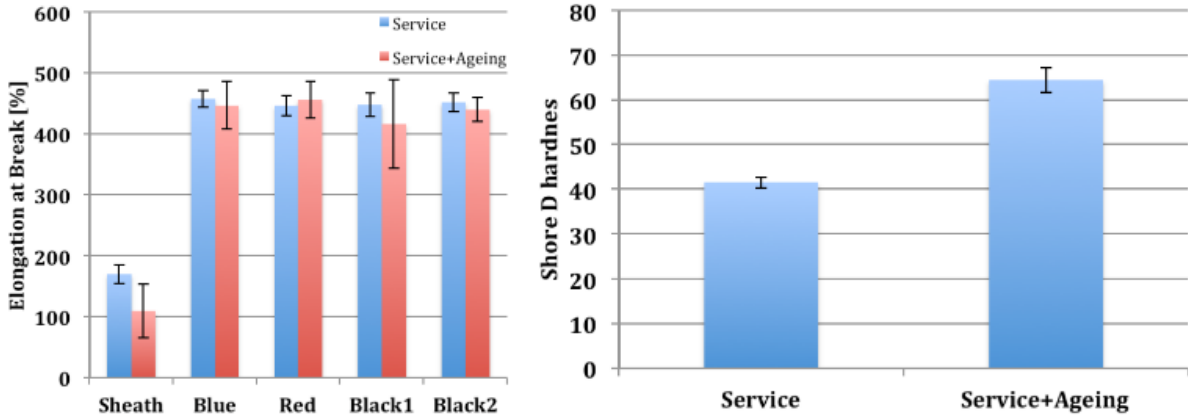


Fig. 7. Changes in elongation at break and Shore D hardness on cable cores and sheath, respectively, after service and artificial aging [32]

II.3. Time domain and frequency domain reflectometry

Local breaches in the insulation can be detected by time or frequency domain reflectometry. Time domain reflectometry consists of the injection of an impulse into the cable and then listening to the reflected signals. Fig. 8 shows a typical measurement result.

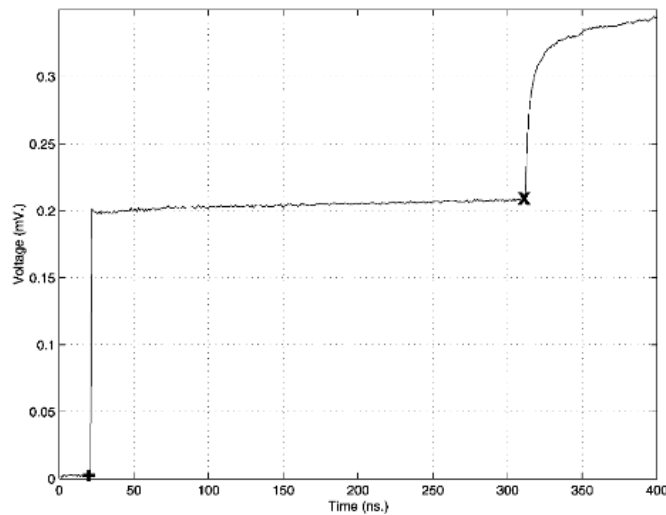


Fig. 8. Screenshot of a TDR device, identifying a fault at 30 m [34]

If reflected signals are detected other than those from the far end of the cable, a fault in the integrity of the cable can be assumed [34].

As the accuracy of time domain reflectometry is sensitive to the rise time of the injected and reflected pulses, and the latter is highly determined by the properties of the cable, further methods have been developed. One of them is the joint time and frequency domain reflectometry that applies an injected impulse specially adjusted to the cable type [34]. Reflections are detected with the time-frequency cross-correlation function, as shown in Fig. 9, where high values in the cross correlation (bottom) indicate the incident or the reflected pulses with high sensitivity. If reflection are found at locations other than the terminations, the cable can be assumed to be damaged.

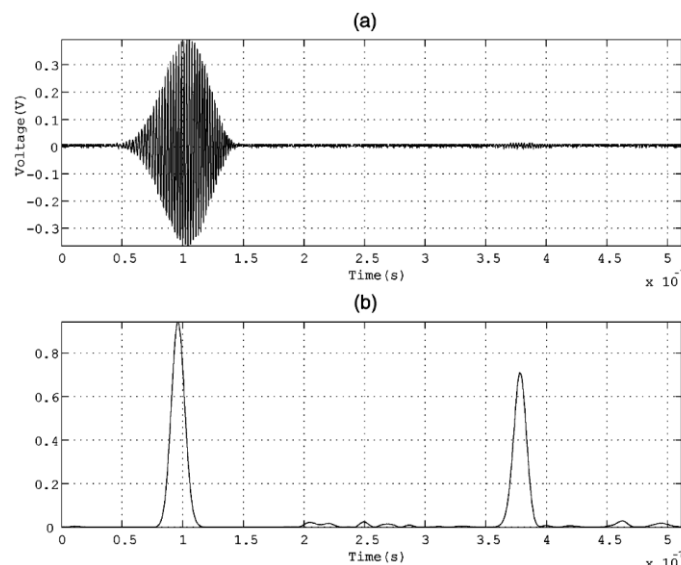


Fig. 9. Measured signal and joint time-frequency domain cross correlation function for fault location detection [34]

II.4. Pulse arrested spark discharge wiring diagnostic

Pulse arrested spark discharge (PASD) diagnostics has been developed as a non-destructive damage location method based on the injection of a low energy high voltage impulse into the cable and measuring the reflected signals [35]. The test is performed by the comparison of low-voltage characterization signals and high voltage signals. If these are in linear relation, there is no damage in the insulation; in other cases the high voltage impulse must have initiated a flashover as in the case shown in Fig. 10.

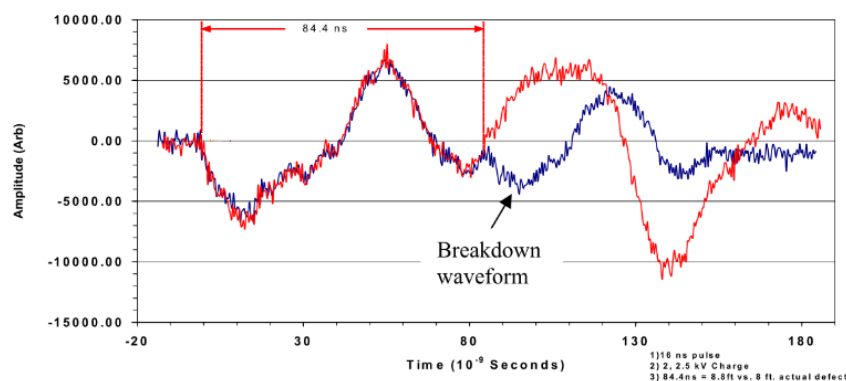


Fig. 10. Waveforms acquired from a cable with chafed insulation by PASD method [35]. Red: signal acquired at low voltage, blue: signal acquired at high voltage.

The method has been tested extensively on aircraft wiring. It has performed very well in detecting cracked insular surfaces, chaff and breach defects.

II.5. Partial discharge measurements

Partial discharge measurement is widely applied and recognized method in case of medium and high voltage cables for the detection of local, low density defects, such as air

filled cavities. The application on low-voltage cables suffers from several problems, e.g. cables are not designed to be PD free at their test voltage. In case the acceptable discharges originating from all over the length of the cable can be suppressed, the discharges can be detected and located [15], as shown in Fig. 11. To obtain these signals, the test voltage was increased significantly above the nominal voltage of the cable. The cables were damaged by

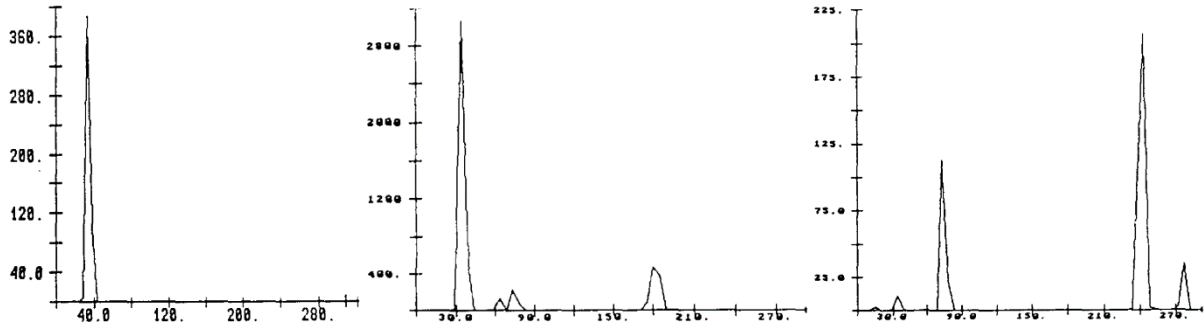


Fig. 11. Number of partial discharge events in function of cable length detected in a 600 V cable by reflectometry [15]

The detection of mechanical damages to the cable has been investigated in [S6]. The changes due to bending the cable with 30% of its allowed bending radius are shown in Fig. 12. The changes are apparent, but not significant.

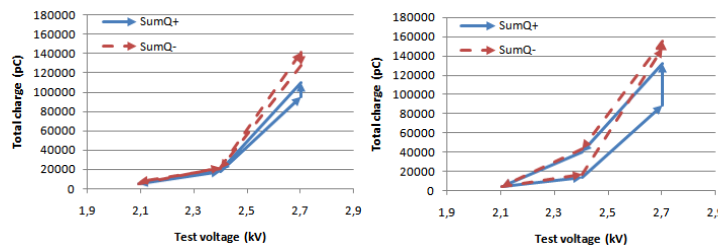


Fig. 12. Cumulated PD charge in function of voltage in new (left) and mechanically damaged (right) cable [S6]

The detection of intermittent faults in low-voltage underground cables is presented in [37]. The signals shown in Fig. 13 were obtained at the nominal voltage of the cable after drilling a hole into the insulation down to the conductor, as shown in the figure.

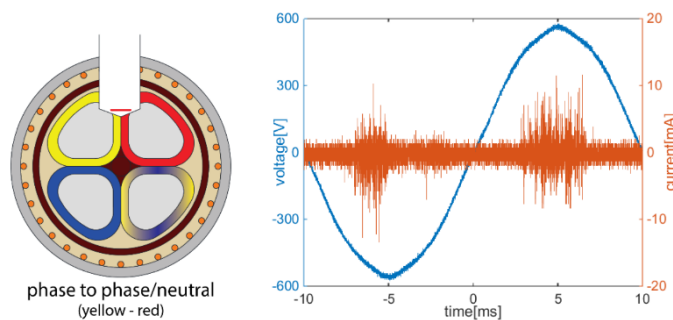


Fig. 13. Discharges detected by an HFCT in artificially damaged low-voltage PVC underground cable [37]

II.6. Further methods

Several further methods are available for cable testing [38], but their investigation is out of the scope of this thesis. Electrical methods, like impedance measurement and waveform acquisition are able to estimate signal carrying capability, but are usually not applicable as diagnostic methods. Chemical tests (Fourier transform infrared spectroscopy, oxidation induction time etc.), if adapted to the insulating material, are able to indicate the aging of the material [33]. However, these are mostly applied in the research phase and not on a regular basis as a diagnostic measurement.

II.7. Comparison of failure detection capability of different diagnostic methods and the role of PD measurement

Various methods are applicable to diagnose aging and damages in low-voltage cables. These cover a broad range of approaches and their outputs are therefore also different. Table I compares the abilities of selected methods to detect global aging, i.e. the chemical changes in the material, major local defects, that cause significant change in the local characteristic impedance and minor local defects, such as pinholes and cuts.

Dielectric spectroscopy is able to indicate processes that lead to the embrittlement of the material, which makes it prone to cracking. Although it does not detect local damages, it is an indirect indicator of a condition that makes the cable prone to fail at the (loss of coolant accident (LOCA) test, when the specimen is subjected to high temperature and high pressure steam [39].

TABLE I. COMPARISON OF FAULT DETECTION CAPABILITY OF SELECTED METHODS.

	Global aging	Major local defects	Minor local defects
Dielectric spectroscopy	Yes	Indirectly	Indirectly
Shore D hardness	Yes, but only at terminals / measured spot	Indirectly	Indirectly
TDR/FDR	No	Yes	No
PASD	No	Yes, but only in small diameter wires	Yes, but only in small diameter wires
PD	No, only if they have mechanical effects e.g. cracks	Yes	Yes

Mechanical measurements can be performed as a diagnostic test, especially the measurement of shore-D hardness as a non-destructive method is advantageous. It is a direct indicator of material embrittlement, thus indicating the increased probability of the presence of cracks in the insulation. A shortcoming of this technique is that it can rarely be performed at the actual critical locations. The terminals of the cable, where measurements are easily performed, are subjected to a different, usually less harsh environment, than the majority of the cable.

Time and frequency domain reflectometry are excellent methods to detect local faults in the cable that are definitely causing failed LOCA tests. However, these methods are based on the reflections occurring at the damage, which is caused by the local change in the characteristic impedance. To be detectable, these changes must be significant. Damages shown in Fig. 14 are rarely detectable by these methods.

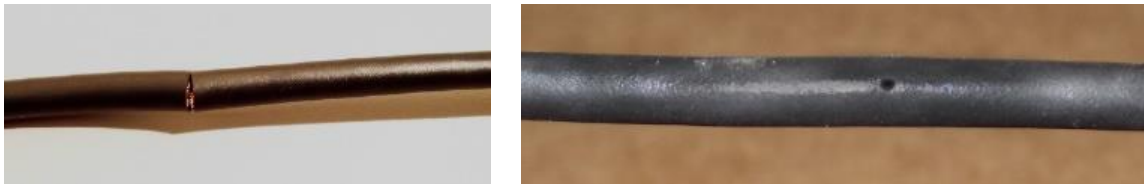


Fig. 14. Minor damages that can cause LOCA test fail [S6]

The pulse arrested spark discharge method is an excellent method to detect breaches and cracks. However, there is a limitation in its application: the energy of the injected impulse must be kept within limits and its length must be also kept short to maintain the localization ability. It was reported that PASD performs excellent up to 1 mm (distance of the conductor under test to the closest ground plane) and is usable up to 3 mm.

Partial discharge measurement is able to detect various types of local damages of the insulation, e.g. air filled voids of certain size and external damages to the insulation, including those shown in Fig. 14. The voltage during the PD measurement can be increased to the datasheet test voltage of the cable without any concern. Based on the above, the role of PD measurement is the detection of local damages, which are undetectable by TDR/FDR and where the impulse energy of PASD is insufficient to initiate discharges. To be applicable as a diagnostic method, some problems have to be solved, most importantly to be able to separate discharges that occur also in healthy cables [S8].

II.8. Summary of the methods and applicability of PD measurement

A variety of methods has been developed or is under investigation and consideration for diagnostics of aging nuclear power plant cables. Numerous cable types and aging modes have to be considered and need still research, and thus a generalized approach is not yet available.

The versatility of dielectric methods suggests that there is a high probability to find correlation between thermal or nuclear aging parameters and some measurable dielectric parameter. Destructive and non-destructive mechanical methods are available to assess the changes in material structure; however, sampling from the critical spots may not be feasible.

Pulse arrested spark discharge and time and/or frequency domain reflectometry methods are capable to detect local faults, however, both have limitations. PASD method applies a low energy impulse, which may not be able to initiate discharges in NPP cables with higher insulation thickness. The sensitivity of TDR/FDR is satisfactory for general purposes, however, in case of LOCA affected areas, minor damages of the insulation can also cause failure.

The application of partial discharge measurement is promising to avoid the deficiencies of PASD and TDR/FDR in the detection of local damages. However, the technique requires validation for every cable type, as discharges occur in healthy cables, as well. These have to be characterized in order to be able to separate the signals emerging from damages.

II.9. Inception of partial discharges in low-voltage cables

The applicability of partial discharge measurement is basically determined by the inception voltage, governed by the type of defect. If discharges are able to form considering the dimensions, construction and the electric field generated by the test voltage, their occurrence might be applied as a diagnostic method.

II.9.1. Inception voltage in coaxial constriction

The inception voltage of partial discharges for a rectangular cavity placed in coaxial cable (Fig. 15) is given by the Eq. (1) [87][88][89]:

$$V_i = E_b r_i \left[\frac{1}{\varepsilon'} \left(\ln \frac{r_i}{r} + \ln \frac{r+d_0}{r_i+d} \right) + \ln \frac{r_i+d}{r_i} \right], \quad \text{Eq. (1)}$$

where E_b is the breakdown field strength, the d is the diameter and the r_i is the distance of the cavity from the center of the cable, d_0 is the thickness of the insulation and ε' is the relative permittivity of the core insulation material.

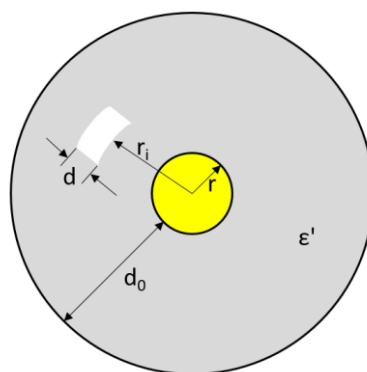


Fig. 15. Rectangular cavity in a coaxial cable for the calculation of PD inception voltage.

The inception voltages of different sized cavities with different distances from the conductor are given by substitution of the dimensions of the cable (Table II).

TABLE II. INCEPTION VOLTAGE OF PDS IN CAVITIES IN THE RG-58 CABLE INSULATION.

E_b [kV/mm]	23.23	9.0	6.22	4.5	3.89	3.35	3.11	3.07	
DIAMETER OF → CAVITY [MM]	0.001	0.01	0.03	0.1	0.2	0.5	0.9	1.024	
DISTANCE FROM CONDUCTOR [MM]	0	5.90	2.33	1.67	1.36	1.34	1.48	1.66	1.71
	0.0001	5.90	2.33	1.67	1.36	1.34	1.48	1.66	
	0.001	5.91	2.33	1.68	1.37	1.34	1.48	1.67	
	0.01	6.01	2.37	1.71	1.39	1.36	1.50	1.69	
	0.03	6.25	2.47	1.77	1.43	1.41	1.54	1.73	
	0.1	7.07	2.78	1.99	1.60	1.55	1.68		
	0.2	8.25	3.24	2.31	1.83	1.75			
	0.5	11.78	4.61	3.25	2.51				
0.9	16.49	6.43	4.51						

Above the cavity size of 0.01 mm the majority of the resulting values are below the test voltage of the cable, which is 4.5 kV. Accordingly, it can be assumed that any defect or damage in the insulation will result in the occurrence of partial discharges. This has been confirmed by measurements on new and damaged cables, where a needle with of approximately 0.8 mm diameter was indented into RG-58 type cables. Table III and Table IV show the results in function of test voltage and number of pinholes in terms of apparent charge measured by a conventional detector and magnitude measured by a high-frequency current transformer.

TABLE III. APPARENT CHARGE VALUES MEASURED ON AN RG-58 CABLE.

VOLTAGE	DISCHARGE MAGNITUDE [pC]			
	NEW CABLE	1 PINHOLE	2 PINHOLES	3 PINHOLES
1400	22	22	22	22
3200	500	600	500	400
5000	3000	4000	5000	5000

TABLE IV. DISCHARGE MAGNITUDES MEASURED ON AN RG-58 CABLE.

VOLTAGE	DISCHARGE MAGNITUDE [mA]			
	NEW CABLE	1 PINHOLE	2 PINHOLES	3 PINHOLES
1400	2.19	2.54	1.95	1.51
3200	97.03	84.32	113.24	54.05
5000	486.49	532.43	894.59	718.92

II.9.2. Electric field calculation in more complex cable constructions of SZRMKVM-J and YSLCY type cables

II.9.2.1. Electric field calculations

In order to estimate the expected partial discharge inception voltage (PDIV), the electric field in each cable type was calculated by finite element method [41] using COMSOL software. The problems were solved in two dimensions, thus considering the field within the cable and not dealing with the terminations. In all cases, the shielding was grounded as the boundary condition, one of the conductors was under test voltage and all other cores were grounded. As the applied voltage was 50 Hz, the field simulations were solved as electrostatic problems.

The basic data of the samples can be found in Table V. Two shielded cable types were selected for this study, both of them applied regularly as signaling cables in Hungarian power plants [56][61][62][63].

TABLE V. BASIC DATA OF THE CABLE SAMPLES.

Type	Core insulation	Belt insulation	Sheath	Nominal voltage	Test voltage
YSLCY	PVC	Polyester foil	PVC	300/500V	2000 V
SzRMKVM-J	PVC	EPDM	PVC	600/1000V	4000 V

Table VI details the exact types and gives further geometrical data used in the simulations.

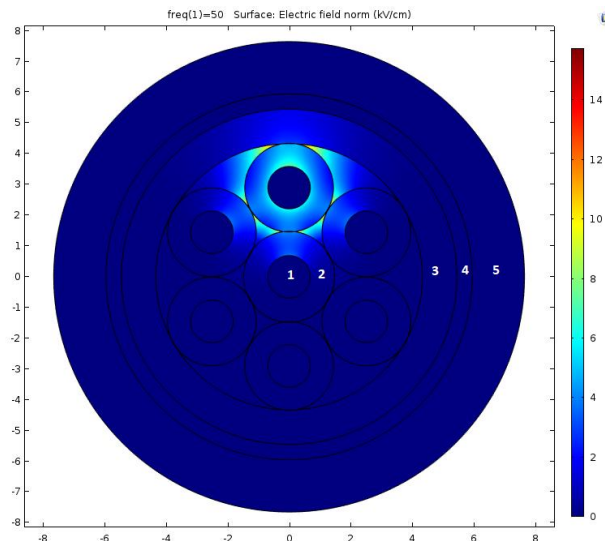
Though the geometry of low-voltage cables is generally more flexible than the high voltage class cables, it is expected that the below idealized models are still able to reveal the basic influence of conductor number, cross section and stranded or solid construction (see e.g. [64] on a similar issue).

TABLE VI. DATA OF THE SAMPLES USED IN THE SIMULATION.

Type	Conductor construction	Insulation thickness [mm]	Shielding construction	Overall diameter [mm]
YSLCY 4 x 1.5 mm ²	30 x d = 0.26 mm strands	0.8	tinned copper braided 30 x d = 0.25 mm	8.2
YSLCY 5 x 1.5 mm ²	30 x d = 0.26 mm strands	0.8	tinned copper braided 30 x d = 0.25 mm	9
YSLCY 7 x 1.5 mm ²	30 x d = 0.26 mm strands	0.8	tinned copper braided 30 x d = 0.25 mm	9.8
YSLCY 2.5 mm ²	50 x d = 0.26 mm strands	0.8	tinned copper braided 50 x d = 0.25 mm	9.9
YSLCY 4 mm ²	56 x d = 0.31 mm strands	1	tinned copper braided 50 x d = 0.3 mm	11.6
SzRMKVM-J 4 x 1.5 mm ²	solid	0.8	0.5 mm steel tape	13.5
SzRMKVM-J 5 x 1.5 mm ²	solid	0.8	0.5 mm steel tape	14.4
SzRMKVM-J 7 x 1.5 mm ²	solid	0.8	0.5 mm steel tape	15.3
SzRMKVM-J 4 x 2.5 mm ²	solid	0.8	0.5 mm steel tape	14.4
SzRMKVM-J 4 x 4 mm ²	solid	1	0.5 mm steel tape	16.6

II.9.3. Electric field calculation in the SZRMKVM-J cable

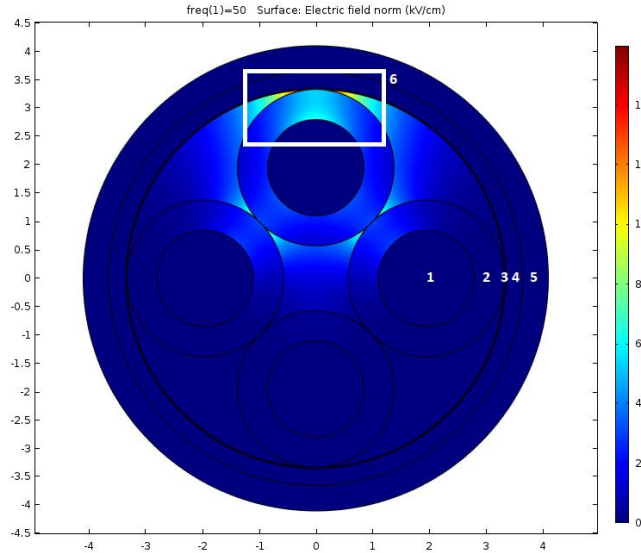
This cable type features a solid conductor and a steel tape shielding/armoring, which allows simple model building. The electric field in the cable is shown in Fig. 16 (top conductor at nominal phase-to-earth voltage, other conductors and shielding grounded).



1: conductor – 2: core insulation – 3: belt insulation – 4: shielding – 5: sheath
Fig. 16. Electric field in the SZRMKVM-J type cable, one conductor at nominal voltage

II.9.4. Electric field calculation in the YSLCY cable

A preliminary field calculation has been performed on the YSLCY cable as shown in Fig. 17.



1: conductor – 2: core insulation – 3: belt insulation – 4: shielding – 5: sheath
6: part detailed in the further calculations

Fig. 17. Simplified model of the YSLCY cable neglecting the strands of the conductors.

In this simulation, the conductor and the shield has been modelled as solid conductors instead of strands. In the second step, the strands were implemented only in the highest electric field region to save otherwise unnecessary model building time. In this model, a slight penetration of the main insulation between the strands was applied, as simplifying the model so that the main insulation only touches the strands would result in falsely large electric field values. Fig. 18 shows the electric field in the detailed part (top conductor at nominal phase-to-earth voltage, other conductors and shielding grounded).

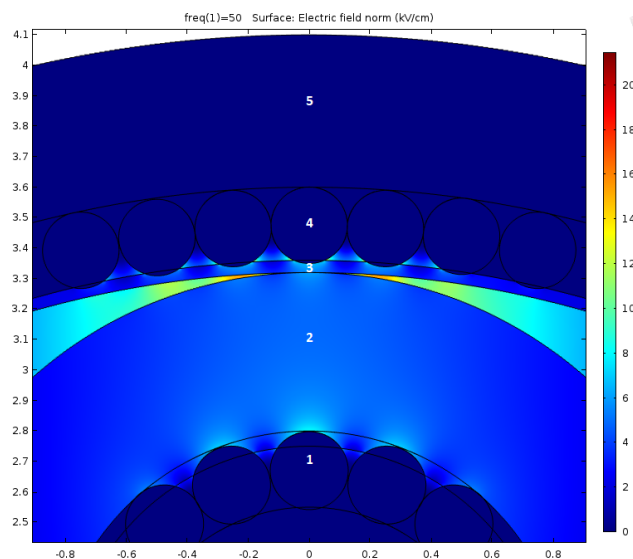


Fig. 18. Model of the YSLCY cable with the detailed strands.

Care has been taken to set up a mesh that is dense enough at the critical locations. Fig. 19 shows the mesh of the part shown in Fig. 18.

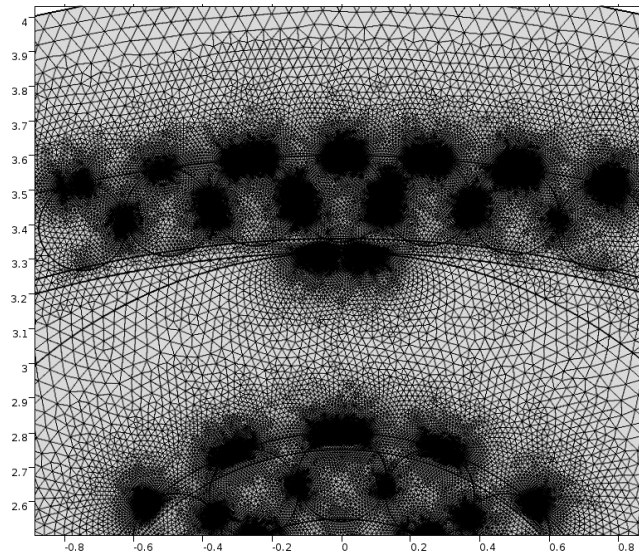


Fig. 19. Very fine mesh of the detailed part of the YSLCY cable, showing high density of points around strands.

II.9.5. Theoretical Estimation of PDIV

Various methods exist for calculating the partial discharge inception voltage or field in different void shapes and dimensions [65][66][67][16]. Eq. (2) gives the inception field for a void of radius r at atmospheric pressure [66][67]:

$$E_{inc} = 24.2 \cdot 10^5 \left(1 + \frac{8.6}{\sqrt{2r10^5}} \right) \quad \text{Eq. (2)}$$

The voids in the insulation system of the investigated cables can have different shapes and sizes in a broad range. For this study, the application of Eq. (2) was chosen for the calculation of the inception field. Based on the initial electric field calculations, the highest electric field regimes were identified to have dimensions between 100 and 500 micrometers. Fig. 20 shows the calculated corresponding inception field values.

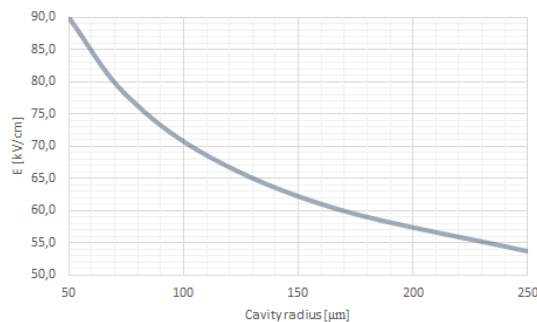


Fig. 20. Inception field for the estimated void dimensions in the samples

The electric field calculations in the previous sections connect the test voltage to the electric field in the cable, allowing to calculate the inception voltage from the inception field or to calculate the field in the cables at the measured inception voltage. The calculated values are shown below in Fig. 21 to Fig. 24 presenting the measurement results, as well.

II.9.6. Experimental Partial Discharge Inception Voltage Results

The cables have been energized by a 230/22000 V voltage transformer fed by a variable source. Partial discharge signals were detected by a high frequency current transformer (bandwidth 40 kHz to 20 MHz). Initially the arrangement has been tested to be PD free in the available voltage range. Voltage was increased from zero slowly, approximately by 100 V/s. PDIV was recorded when a signal from the HFCT surpassed twice the noise level.

The measurement results are shown in Fig. 21 to Fig. 24. The first figures show the minimum, maximum and mean values of the PDIV, furthermore the voltage necessary to generate the previously calculated electric fields (53.6 kV/cm and 90 kV/cm). The second figures show the peak electric field in the cables based on the finite element calculation and the measured value. The calculated electric fields are also included.

After the measurements on brand new cables, further tests were carried out on damaged cables. Fig. 25 and Fig. 26 show the occurrence of partial discharges in the YSLCY type cable in new condition and after the indentation of a 0.8 mm diameter needle into the insulation. Fig. 27 shows the changes in the PDIV values of SZRMKVM-J and YSLCY types before and after making a 0.5 mm wide cut in the insulation and shielding, while leaving the core insulation intact.

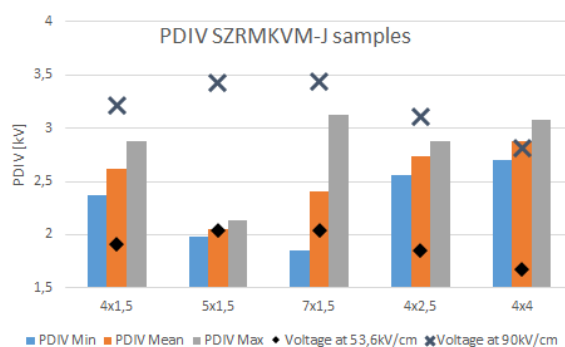


Fig. 21. Measured PDIV of SZRMKVM-J cables, minimum, mean and maximum values. The voltage corresponding to the calculated PD inception field are also indicated.

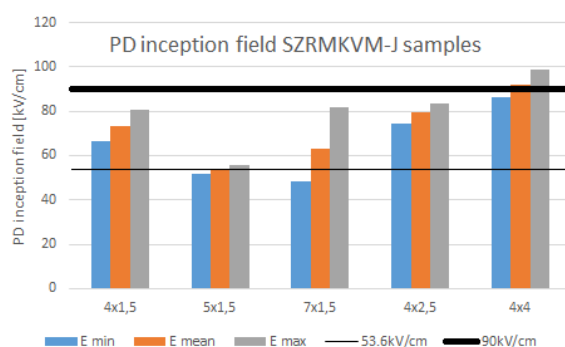


Fig. 22. Peak electric field in the SZRMKVM-J cables at PDIV.

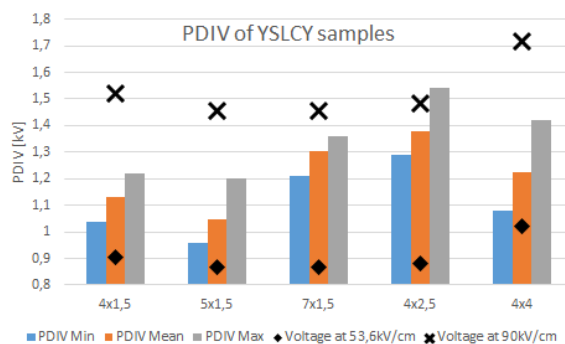


Fig. 23. Measured PDIV of YSLCY cables, minimum, mean and maximum values. The voltage corresponding to the calculated PD inception field are also indicated.

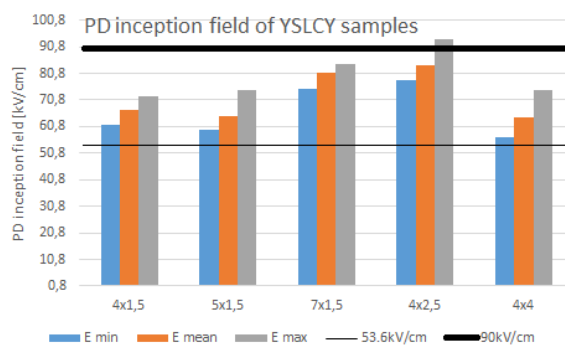


Fig. 24. Peak electric field in the SZRMKVM-J cables at PDIV.

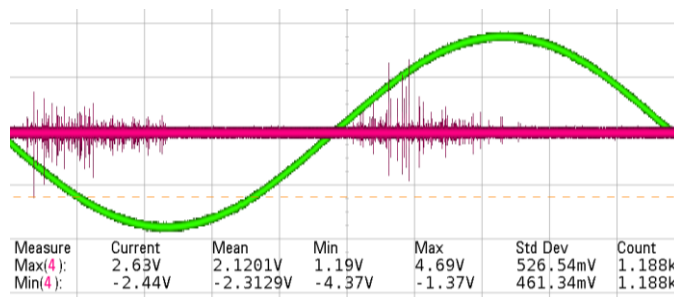


Fig. 25. PD in new YLSCY cable at its test voltage of 2 kV.

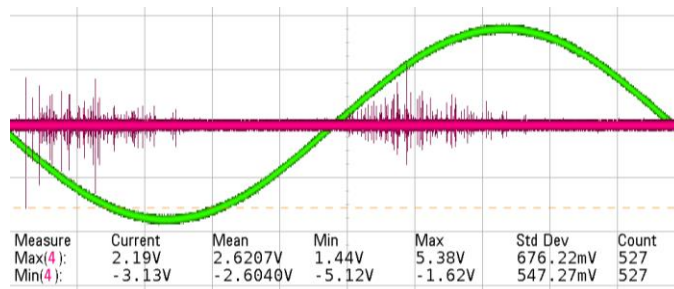


Fig. 26. PD in pinholed YLSCY cable at its test voltage.

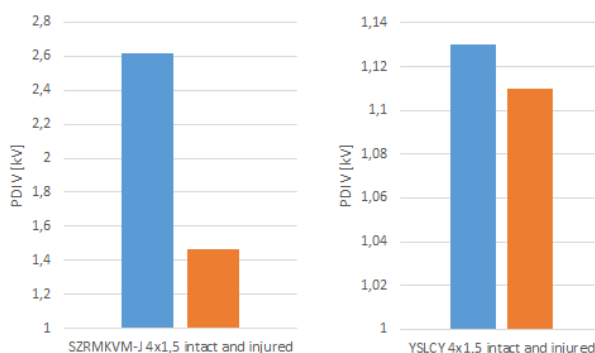


Fig. 27. The effect of a cut on the PDIV of the 4x1.5mm² samples of SZRMKVM-J and YLSCY types.

The increment in the electric field at the same voltage (Fig. 28 compared to Fig. 18) was in line with the experienced decrement of the PDIV.

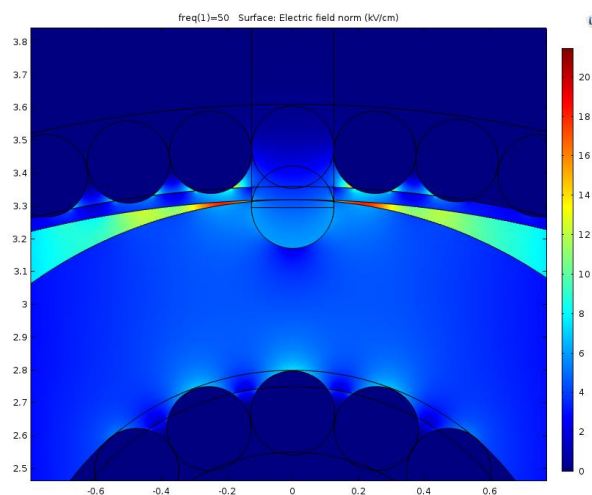


Fig. 28. Electric field in a damaged (drillhole from the top) YLSCY cable at nominal voltage.

Calculations and measurements affirmed that partial discharges occur in low-voltage cables above their nominal voltage, but well below their test voltage. The measured voltages are mostly within the range expected from the calculation. This means that PD diagnostics can be performed on these cables if signals resulting from the fault can be distinguished from the signals generated by the intact parts of the cable.

The electric field calculations revealed that both in case of the YSLCY and the SZRMKVM-J type the highest electric field occurs right below the belt insulation. This makes PD measurement suitable for detecting damages of the cable, even when the damage does not affect the core insulation. This is advantageous, as the cables may fail in critical conditions (e.g. LOCA event) even due to superficial damages.

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 by analytical calculations, finite element based simulations 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.

PUBLICATIONS SERVING AS THE BASIS OF THIS CHAPTER AND THE THESIS

R. CSELKÓ AND Á. Z. TAMUS, "OCCURRENCE OF PARTIAL DISCHARGES IN LOW-VOLTAGE CABLES AT THE FAILURE SPOT," 2012 IEEE INTERNATIONAL SYMPOSIUM ON ELECTRICAL INSULATION, SAN JUAN, PR, 2012, PP. 5-9.

R. CSELKO, I. BERTA, "CHALLENGES OF PARTIAL DISCHARGE DIAGNOSTICS OF LOW-VOLTAGE CABLES", JOURNAL OF ELECTROSTATICS, VOLUME 71, ISSUE 3, JUNE 2013, PAGES 558-563

R. CSELKÓ AND I. BERTA, "COMPARISON OF FAILURE DETECTION CAPABILITY OF AVAILABLE LOW-VOLTAGE CABLE DIAGNOSTIC METHODS," 2016 IEEE ELECTRICAL INSULATION CONFERENCE (EIC), MONTREAL, QC, 2016, PP. 346-349.

R. CSELKÓ AND I. KISS, "ESTIMATION OF THE PARTIAL DISCHARGE INCEPTION VOLTAGE OF LOW VOLTAGE CABLES", IN: 2019 IEEE ELECTRICAL INSULATION CONFERENCE (IN PRESS)

III. Specialties of the measurement of partial discharges in low-voltage cables

III.1. Available measurement methods

Partial discharge measurements on low-voltage cables during the course of this research have been performed with one or more of the methods shown in Fig. 29. A variable transformer provides the power frequency (50 Hz) test voltage. An air-core coil is inserted between the voltage source and the specimen in order to reduce the noise coming from the supply and to prevent the PD induced transients to propagate towards the source. The test voltage is connected to the oscilloscope through a voltage divider to enable precise measurement of its magnitude and to provide trigger for the phase resolved partial discharge (PRPD) measurement.

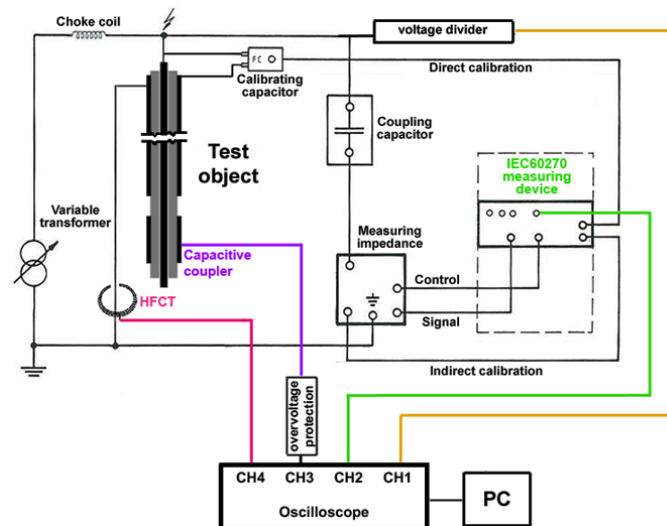


Fig. 29. Test arrangement with IEC60270 measuring device, capacitive coupler and high frequency current transformer.

In case of parallel measurements, a four channel digital oscilloscope provided opportunity to observe, acquire and transmit the signal to a PC from the voltage divider, the IEC60270 compliant PD measuring device, the capacitive coupler and the high frequency current transformer, enabling the investigation of behavior of the different methods.

III.1.1. IEC60270-compliant detector

The conventional PD measurement, complying the IEC 60270:2000 standard [41], has been performed by a commercially available Tettex 9120 [71] measuring system. It consists of a coupling capacitor, measuring impedance and the measurement device, which has 40 kHz – 200 kHz bandwidth, thus behaving as an integrating amplifier for the PD impulses. Accordingly, the output of the device is proportional to the charge carried by the impulses, thus it yields (pico-) coulombs. The low upper frequency band restricts its

impulse resolution capability to 5 μ s. As different length and construction of cable specimens have been tested, it was always necessary to calibrate the device. Before applying the test voltage, the calibrating capacitor shown in Fig. 29. has been disconnected.

Wider bandwidth detectors gained popularity recently, as they might provide better signal-to-noise ratio and the possibility of locating the impulses [14][72].

III.1.2. Capacitive coupling

The capacitive couplers have been prepared by removing the shielding of the cables and replacing it with a specific length of aluminum foil. In case of multi-core cables, the foil enclosed only one core to give higher coupling capacitance between the core voltage and the coupler. The construction of the coupler is shown in Fig. 30. The distance between the coupler and the shielding was chosen to 10 mm, the length of the coupler was 100 mm. These values resulted in moderate size and acceptable values for coupling.

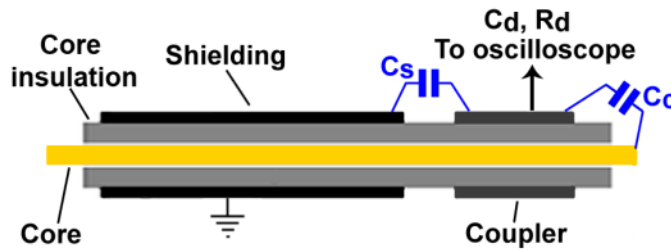


Fig. 30. Construction of the capacitive coupler.

The equivalent circuit of the capacitive coupler is shown in Fig. 31., where C_c represents the capacitance between the core and the coupler, while R_c the losses of this capacitance. C_s and R_s represent the stray capacitance and resistance between the coupler and the shielding, respectively. C_d and R_d stand for the detection impedance, i.e. the input capacitance and resistance of the measuring circuit.

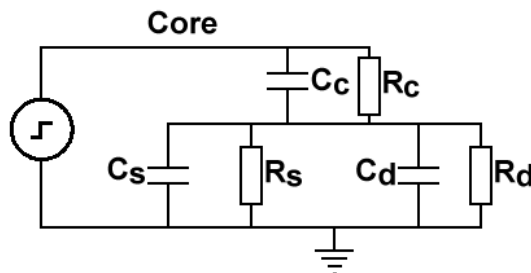


Fig. 31. Equivalent circuit of the capacitive coupler.

Before the PD measurements, the elements of the equivalent circuit, the ratio and phase shift of the complete detection circuit were measured with an impedance analyzer. The results are shown in Table VII, Fig. 32 and Fig. 33. An important issue of the capacitive coupler, besides its response to voltage transients, is its attenuation on power frequency.

This was slightly lower than expected from the previous calculations; this fact resulted in high power frequency component in the measured signal. During the post-processing, this component could be filtered out, but during the measurement a higher volts/div ratio had to be chosen on the oscilloscope, which results in lower vertical resolution.

Due to the risk of breakdown to the capacitive coupler, the input of the oscilloscope was protected by a two-stage surge arrester, which is equipped with BNC connectors, has 50 Ω characteristic impedance and bandwidth ranging from DC to several hundreds of megahertz. Therefore, the surge arrester does not disturb the measurement.

TABLE VII. COUPLING AND STRAY CAPACITANCE OF THE CAPACITIVE COUPLER.

FREQUENCY [Hz]	SINGLE-CORE CABLE				MULTI-CORE CABLE			
	C _c [pF]	R _c [MΩ]	C _s [pF]	R _s [MΩ]	C _c [pF]	R _c [MΩ]	C _s [pF]	R _s [MΩ]
50	11.7	O/R	11.65	O/R	11.7	O/R	10.28	O/R
100	11.7	O/R	11.77	O/R	11.7	O/R	10.81	O/R
1k	11.7	O/R	11.73	O/R	11.7	O/R	10.8	O/R
10k	11.7	O/R	11.72	4500	11.7	O/R	10.8	6000
100k	11.7	400	11.72	240	11.7	400	10.8	110
200k	11.7	18	11.73	18	11.7	18	10.76	18
500k	11.7	6	11.69	6	11.7	6	10.78	7

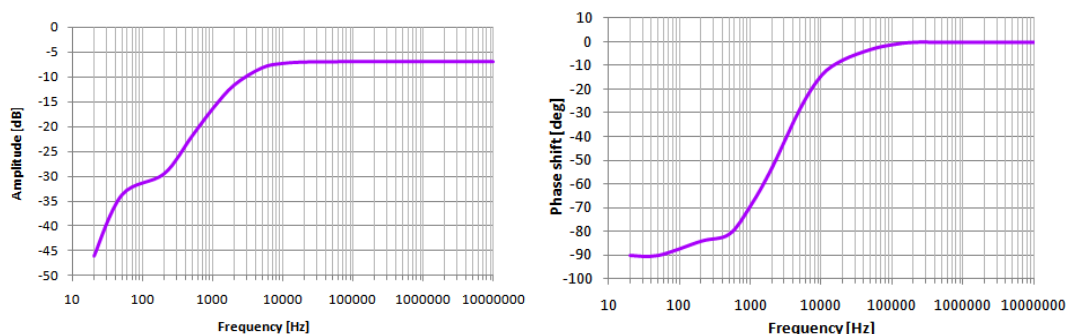


Fig. 32. Amplitude and phase vs. frequency diagram of the capacitive coupler in case of the single core cable.

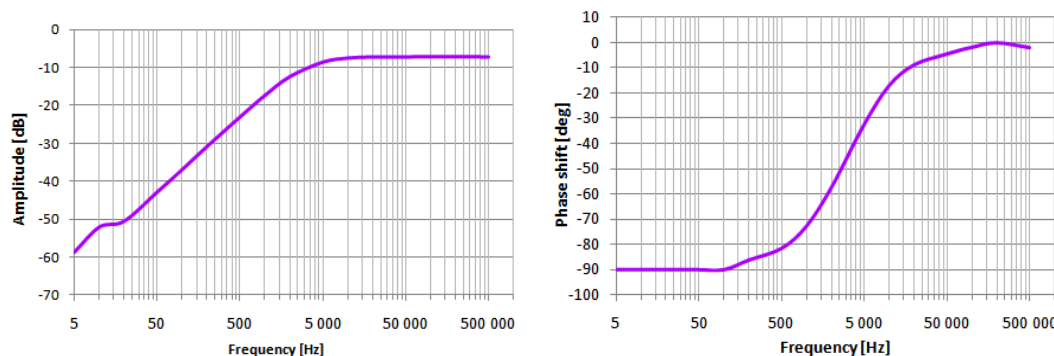


Fig. 33. Amplitude and phase vs. frequency diagram of the capacitive coupler in case of the multi-core cable.

Capacitive coupling was used for various measurements during the research, however, its field application was rejected due to the difficulty of its application.

III.1.3. High Frequency Current Transformer

The application of high frequency current transformers (HFCTs) is now an accepted and widespread method of detecting partial discharge signals. High-frequency current transformers are suitable for partial discharge measurement due to their inherent property of being able to transmit fast transients. Their application is very convenient even in case of high voltage cables, as they have to be connected on the ground lead. Clamp type HFCTs can also be installed during operation.

III.1.3.1. Closed-core HFCT

For the purpose of the first laboratory investigations a closed-core type HFCT was available. The response of the HFCT in the frequency domain is shown in Fig. 34. Due to the limitations of the measuring device only the lower cutoff frequency (30 kHz) could be determined. In the transmission band, 90mV/A sensitivity has been measured.

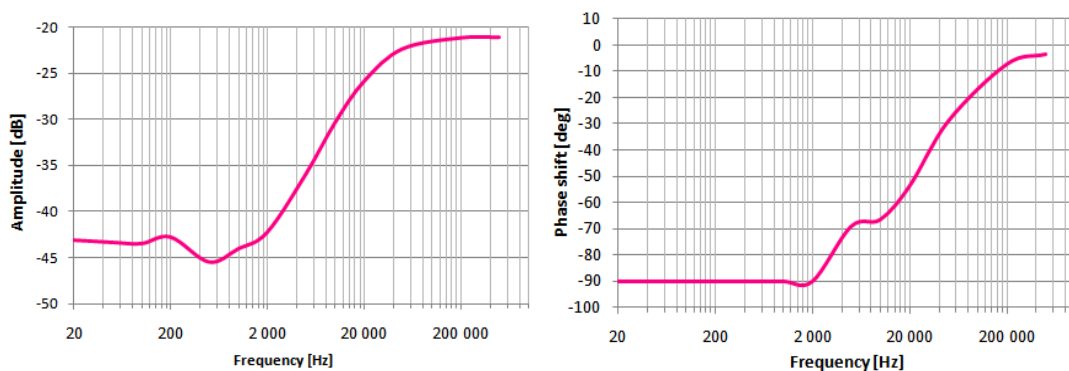


Fig. 34. Amplitude and phase vs. frequency diagram of the closed core HFCT.

III.1.3.2. Clamp-type HFCT

For more convenient application, in the later tests HVPD HFCT100/50 clamp-type high frequency current transformers [73] were connected, specially designed to measure partial discharge signals on ground leads of power cables and electrical installation. Their bandwidth is 100 kHz to 20 MHz and the rise time is 20 ns, while the transmission impedance is 3.7Ω in the transmission band. In case of higher voltage cables, this bandwidth is considered to give the most sensitive measurement [13][55][53][18].

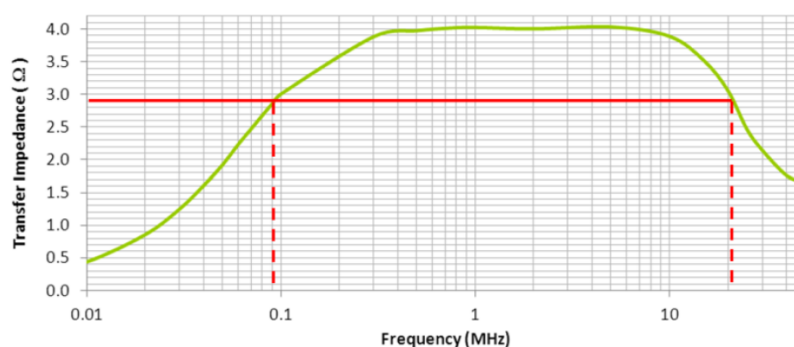


Fig. 35 Frequency response of the HVPD high frequency current transformer [72]

III.1.3.3. Ultra high bandwidth HFCT

For the purposes of the research phase, an ultra high bandwidth Tektronix CT - 1 [74] HFCT was also applied, originally designed for measuring high frequency electronics. However, the measurement was arranged in a way that it enabled the application of this device. The bandwidth of this device is 25 kHz to 1 GHz, with 350 ps rise time.

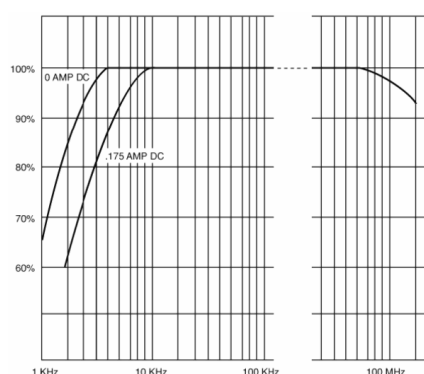


Fig. 36 Frequency response of the CT-1 high frequency current transformer [74]

III.2. Noise suppression during partial discharge measurements

The most important issue of PD testing is noise suppression, especially in case of on-site measurements on industrial systems. The measurement of PDs consists in catching tiny current impulses emerging from a defect within an insulation system. In the conventional method the charge of these current impulses are taken into account [41]. The sensitivity of the measurement goes down to the picocoulomb range in case of field tests and two orders lower in case of special factory testing; this sensitivity makes the measurement susceptible to noise. The frequency range of the conventional measuring devices is contaminated by several noise sources, like power electronics and switching phenomena. Noise can couple into the measurement system basically from the voltage source (conducted disturbances) and directly into the test specimen. Accordingly, noise mitigation is a basic need during PD measurements.

Noise suppression can be achieved by physical methods and signal post-processing. The main advantage of the physical methods is that the noise is suppressed before digitization. Some methods are applicable only in laboratory (e.g. shielding), while others may be used in field testing, as well.

Bridge or balanced circuits are applied mostly for laboratory measurements [48], as they require the test object(s) to be separated from ground, as it can be seen in Fig. 37. The principle of its operation is that in the two arms of the bridge, if balanced correctly, the same impulse current is flowing through for an external signal (i.e. coming from the H.V. generator) and generating zero differential voltage at the detector. On the contrary, the PD impulses originated in the test object flow in opposite direction in the arms, generating a measurable voltage at the detector.

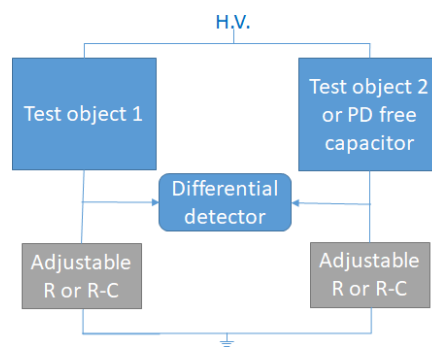


Fig. 37. Balanced circuit for partial discharge measurement.

One exception where field application has been achieved is the so-called balanced permanent coupler, which makes use of the construction of large electric machines [49][50], where the test objects are a pair of symmetrical splits of the phase winding.

Another method is based on the measurement of the signals with two sensors installed physically apart from each other, as shown in Fig. 38. The time of arrival of the signals are determined, and the signals that reach sensor 2 first are rejected as noise.

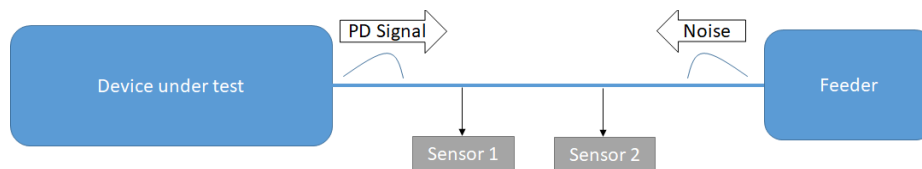


Fig. 38. Time-based discrimination of external noise (after [51]).

Increasing the frequency range of PD measurement up to the RF, VHF or UHF range on several types of equipment has some advantages, one of them being better noise rejection [23][51][83]. In a measurement arrangement developed for power transformers, where the conventional measurement is combined with a UHF sensor, external noise is rejected via gating. The transformer tank acts as a Faraday-cage, and the bushing as a low-pass filter. Accordingly, noise in the UHF range cannot penetrate the tank. Noise suppression is achieved by enabling the conventional signal only if the UHF sensor detects PD. With this

method, the noise suppression of the UHF method is exploited, while the well-known evaluation methods and standardized limits of the conventional method are preserved.

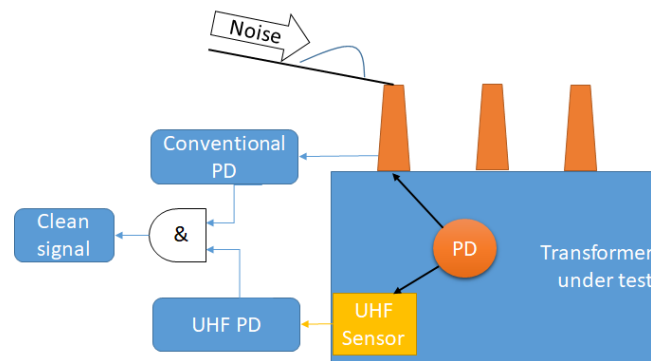


Fig. 39. Suppression of external noise by gating (after [52]).

Gating of the signal is also applied in the opposite way [51]. In this case, an external antenna detects the radiated noise, and if it exceeds a limit, it blocks the signal before the PD measuring device. The disadvantage of both methods is that noise and PD can occur at the same time or very close to each other, allowing noise to penetrate in the first, while blocking useful signals in the second case.

Besides the physical methods, several means have been developed for processing the already acquired signals that allow noise suppression. It is well beyond the scope of this thesis to give even an enumeration of the available methods; a comprehensive review with short description of the techniques can be found in [51], only some examples are given here. One method with high reputation is the phase-resolved PD pattern method (PRPD) that investigates the connection between the PD phenomena and the phase angle of the AC test voltage, mainly applied for the identification of PD sources, however, having some ability to detect noise and disturbances. Another method applied with high success is the time-frequency mapping method that plots the individual discharges in a coordinate system based on their length and frequency content. The resulting plot is then clustered by means of fuzzy logic, and then the various clusters shown in the PRPD plot [53]. Some of the available methods are able to find the useful signal even if the noise level is higher. However, if noise is by orders higher than the signal, there is a definite need for physical noise suppression to allow the acquisition of a usable signal.

III.3. Effect of the repetition rate

As shown in Section II, low-voltage cables are not designed to be partial discharge (PD) free at their test voltage. As the electric field can initiate partial discharges at any point along the cable, relatively high repetition rates are expected, as shown in previous literature for similar but not identical arrangements [69][70]. Therefore, the applicability of the various detection methods need to be verified.

The measurement arrangement used for the study of repetition rates is shown in Fig. 29, except that instead of the capacitive coupler a second, ultra high bandwidth HFCT was connected on the ground lead. Three PD detectors were used:

- a Tettex 9120 conventional measuring device, later referred to as “IEC 60270”,
- a HVPD HFCT100/50 HFCT, later referred to as “MHz HFCT” or “HFCT-M”,
- a Tektronix CT-1 HFCT, later referred to as “GHz HFCT” or “HFCT-G”.

The two HFCTs have been connected on the ground lead, measuring the same current, while the conventional devices uses a coupling capacitor in series with its detection impedance.

The tests were performed on two base types of cables, and various test specimens have been created to cover most of the features that are assumed to have an effect on the repetition rate:

- the two types have different conductor construction, the SzRMKVM-J has solid while the YSCLY has stranded cores,
- investigated number of cores were 4, 5 and 7,
- investigated cross-sections were 1.5mm², 2.5mm² and 4mm²,
- investigated lengths were 2 m, 8 m and 32 m.

III.3.1. Filtering the recorded signals

In order to measure the small signals generated by the partial discharge impulses, very sensitive detectors are applied. This makes these methods prone to noise related problems. Accordingly, one of the most important tasks related to PD measurement is to establish a methodology that filters noise and respects the response of the measurement equipment. Our goal in this case is to estimate the number and frequency of discharges. Accordingly, signals coupled into the circuit (i.e. not showing the features of the response of the detectors) are filtered out, as well as the general noise level is determined.

III.3.1.1. Filtering the IEC60270 signal

The measuring device complying the IEC 60270:2000 standard [41] was originally not designed for further digital processing. The response of the device was intended to exhibit integrating behavior and to be satisfactory for internal processing by analog electronic methods. The response of the devices to a single PD impulse is damped wave, which may be oscillating or not. The devices most commonly used, including the one for this work, exhibit an oscillating response. Accordingly, for the sake of digital processing, e.g. to calculate the number of impulses, it is necessary to separate the individual impulses and delete the tail of the response.

The original, unfiltered response of the device is shown in Fig. 40.

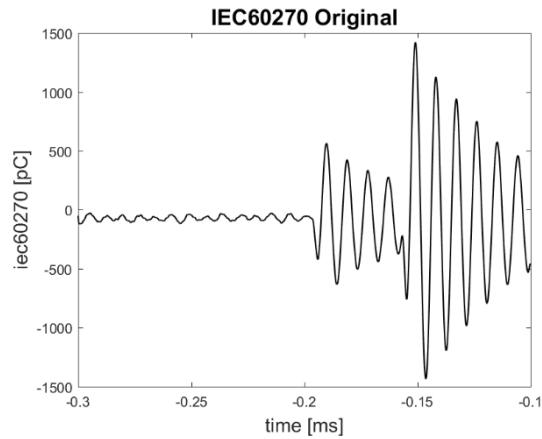


Fig. 40 Response of the conventional PD measuring device to two successive impulses as measured on the output.

The first step is the application of a digital filter matched to the bandwidth of the detector. The next step of the processing is to select the local maximums of the signal as shown in Fig. 41.

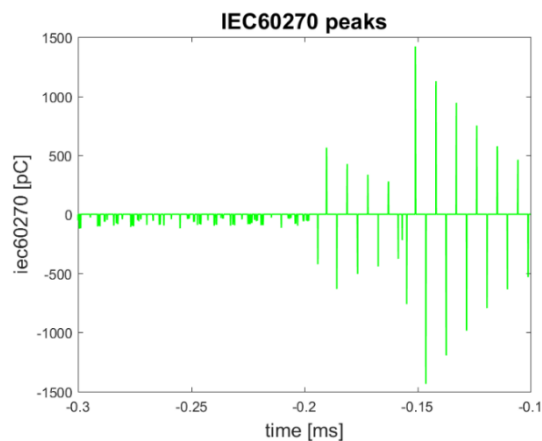


Fig. 41 Local maximums of the IEC60270 signal.

In case of the IEC60270 detector, the noise level was almost steady during the measurements; accordingly, a simple level-based filter was created. From this point, the absolute value of the signal was considered (Fig. 42).

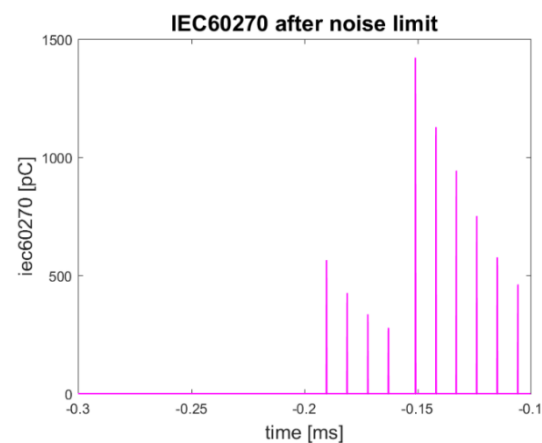


Fig. 42 The signal cleaned from the peaks below the noise level.

In the next step, the exponential damping of the response has been taken into account. As there is no method to know if a peak is just the result of the oscillation of a previous impulse or a new impulse, the exponential damping has been applied to all impulses (Fig. 43).

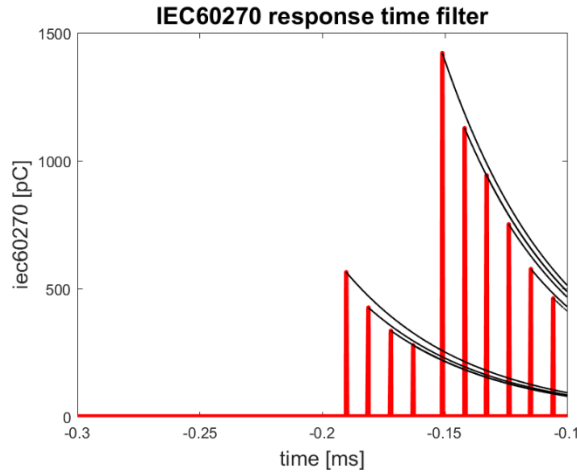


Fig. 43 Demonstration of the response time based filter.

The rule of filtering can be written as:

$$q_i < q_N * e^{-\frac{\Delta t}{\tau}} \quad \text{Eq. (3)}$$

where i and N are indices of peaks, Δt is the time difference between the two peaks, τ is the time constant of the response. Accordingly, if a peak is only resulting from the oscillating response of a previous incoming PD impulse, and as such is below the exponential damping started from the real PD impulse, it will be filtered out. This method ensures that one PD impulse appears as one single peak in the final signal (Fig. 45). In order to save calculation time, the filtering has only been calculated for a limited number of successive impulses, namely until the right side of the equation falls below noise level. It has to be noted that an unavoidable error is introduced: if an impulse is followed by another impulse in a select combination of amplitude and time delay (phase), the algorithm might filter it out. However, this error is inherent in the measurement method and applies to the original analog readings of the device, as the same filtering is implemented electronically. The second impulse will be filtered if Eq. (4) c) inequality is fulfilled.

$$U_1(t) = Q_1 \sin(\omega t) e^{-\frac{t}{\tau}} \quad \text{Eq. (4) a)}$$

$$U_2(t) = \begin{cases} Q_2 \sin(\omega(t - \Delta t)) e^{-\frac{(t-\Delta t)}{\tau}}, & \text{for } t > \Delta t \\ 0, & \text{for } t < \Delta t \end{cases} \quad \text{Eq. (4) b)}$$

$$abs(U_1(t) + U_2(t)) < Q_1 e^{-\frac{t}{\tau}} \quad \forall t \quad \text{Eq. (4) c)}$$

where $U_1(t)$ and $U_2(t)$ are the response of the detector to the first and second impulse, respectively, Δt is the time difference between the two impulses τ is the time constant of the response. Fig. 44 shows the relative amplitude - delay time combinations, where the detector rejects the second impulse.

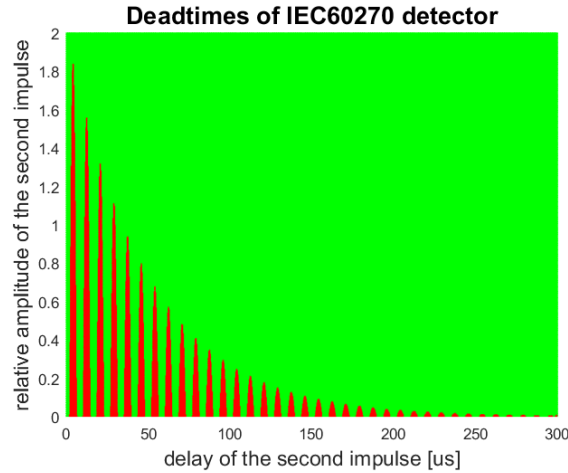


Fig. 44 Dead times of the IEC60270 detector, the delay-relative amplitude combinations in red are filtered out.

As the time constant of the detector is around $50 \mu\text{s}$, after $250 \mu\text{s}$ only very minor impulses are filtered. In contrast, if the successive impulse is close, it may even have a higher amplitude if it arrives in opposite phase. This is the main reason why the application of high frequency current transformers with higher bandwidth and accordingly shorter response times may give more accurate results.

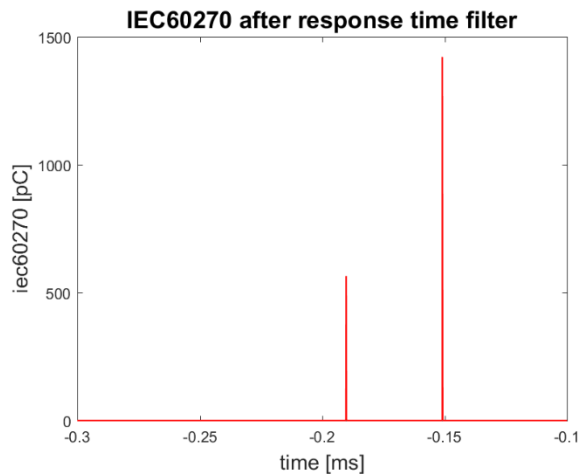


Fig. 45 Final signal after the complete processing.

III.3.1.2. Filtering the signal of the high frequency current transformers

The processing of the HFCT signals also starts with the FFT filter adjusted to the bandwidth of the sensor in question. As noise levels vary widely in the case of the HFCTs, the signals are filtered in two steps. In the first step, the impulses are augmented by calculating the

convolution of the recorded signal with a pre-recorded sample of the response of the HFCT (Fig. 46).

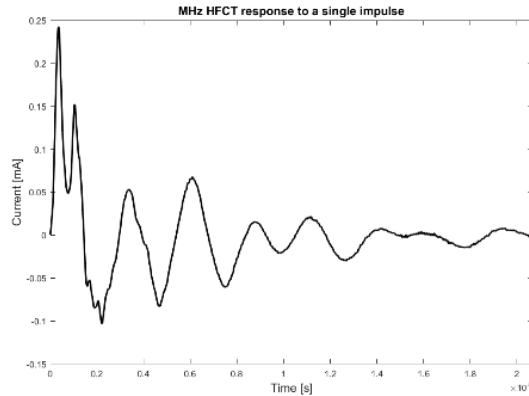


Fig. 46 Response of the MHz HFCT to a single impulse. Note the length of the response compared to the conventional detector (2 μ s vs. 250 μ s).

After this step, the noise level was determined by the statistical distribution of the signal levels, using the following formula.

$$i_{noise} = i_{max} + 2(i_{max} - i_{min}) \quad \text{Eq. (5)}$$

where i_{max} is the most frequent signal level and i_{min} is the lowest signal level. The method can be followed in Fig. 47. The points in blue in the top image are filtered out. This level is shown by the red mark in the bottom figure (histogram of signal levels).

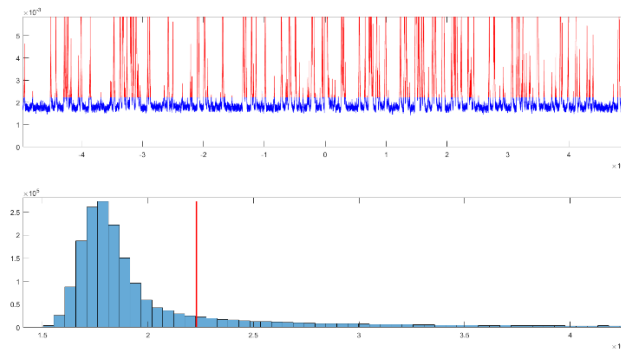


Fig. 47 The processed signal after convolution with the sample (top) and the histogram of the signal levels (bottom).

This is followed by a similar response time filtering, as shown for the case of the IEC60270 signal in Fig. 43.

III.3.2. Repetition rate measurements on low-voltage cables

In order to get insight into partial discharge repetition behavior, several measurements have been performed and evaluated.

Fig. 48 and Fig. 49 show the effect of the length of the cable.

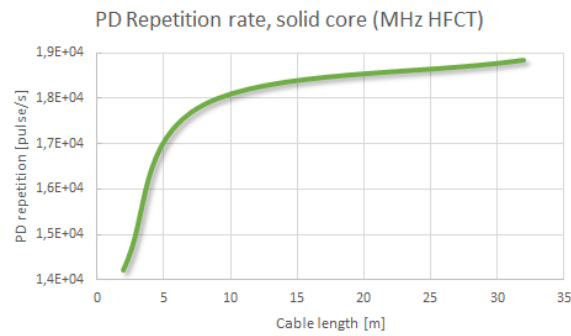


Fig. 48. Average repetition rate in function of cable length, solid core cable.

Previous calculations have shown that partial discharges occur in low-voltage cables below their test voltage [S12]. Assuming that the discharge locations are distributed evenly on a macroscopic scale, longer cables should exhibit higher number of impulses. The measurement results are in line with this expectation, showing an increasing, but saturating curve.

The saturation is caused by the fact that in case of increasing number of discharges, the probability of two impulses overlapping increases. On the other hand, impulses on the far end of the cable are damped more, accordingly the apparent repetition rate is decreased by the number of low magnitude impulses.

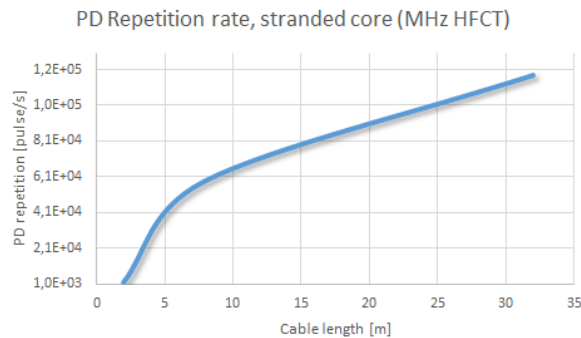


Fig. 49. Average repetition rate in function of cable length, stranded core cable.

The construction of the conductor, solid or stranded and core number do not show any trend (Fig. 50). In contrast, the repetition rate in the function of cross-section in case of 4 core cables exhibits the same behavior for solid and stranded core, a local maximum at 2.5 mm² (Fig. 51 and Fig. 52).

As the dimensions and conductor construction of the cables change, the effective area – where the electric field is above critical – changes, as well [S12].

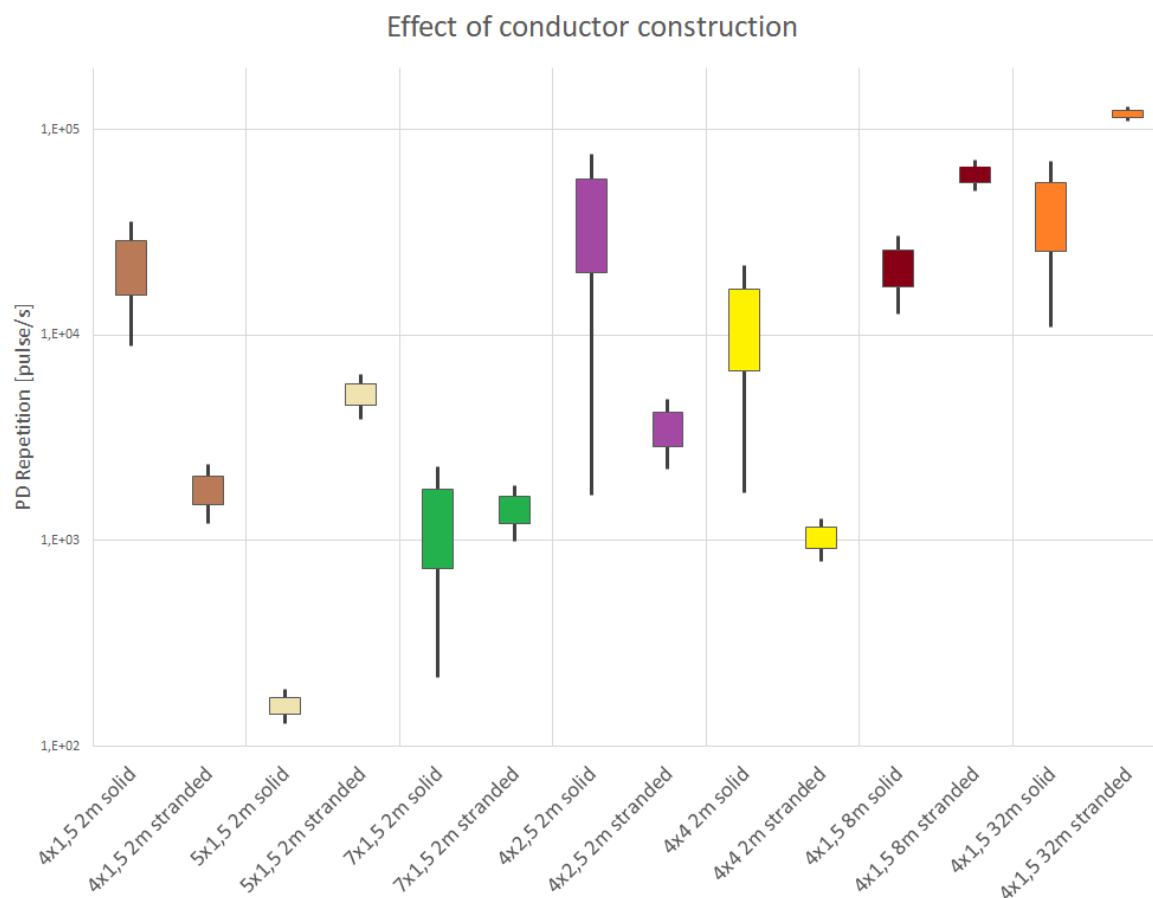


Fig. 50. Effect of conductor construction on the repetition rate.

However, this is not necessarily a change, which shows a tendency in function of the aforementioned parameters. The construction of the stranded cores change with cross-section, as well. Therefore, the expected behavior has to be estimated based on electric field calculations, which goes beyond the scope of this thesis.

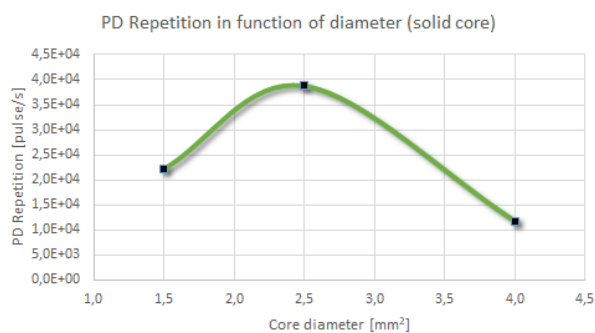


Fig. 51. Effect of conductor diameter, solid 4-core cable.

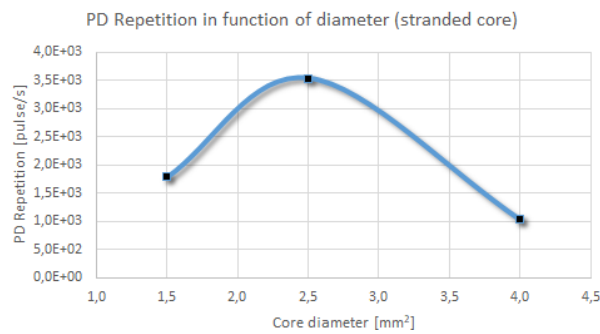


Fig. 52. Effect of conductor diameter, stranded 4-core cable.

III.3.3. Discussion

The results shown in the previous Section are average repetition rates, i.e. the number of impulses recorded over more cycles of the test voltage and divided by the length of the sample. Even these average values are relatively high, considering the conventional measurement methodology.

The conventional detectors usually have a limited impulse response capability. This is mainly due to the demand of the integrating behavior and the bandwidth limitation in order to decrease the noise level. These detectors have an impulse resolution capability in the microsecond range, 5 μ s in case of the one used in these tests. The behavior of the detectors may be different in case of violation of the resolution:

- the detectors equipped with dead-time circuit underestimate the number of impulses, as the maximum repetition rate is limited to the reciprocal value of the dead-time,
- the detectors without dead-time overestimate the magnitude of the discharges, as they allow the successive impulses to superimpose,
- any device might ignore impulses if they appear in specific moments.

Fig. 53 demonstrates these problems, where the abrupt changes in the response indicate that a new impulse superimposes on the response of a previous impulse. These occurrences are marked with arrows. The case marked with red arrow is an example when the two successive impulses are so close to each other in time that the response to the first impulse does not reach its first local maximum. Accordingly, the detector treats them as one larger impulse instead of two lower one.

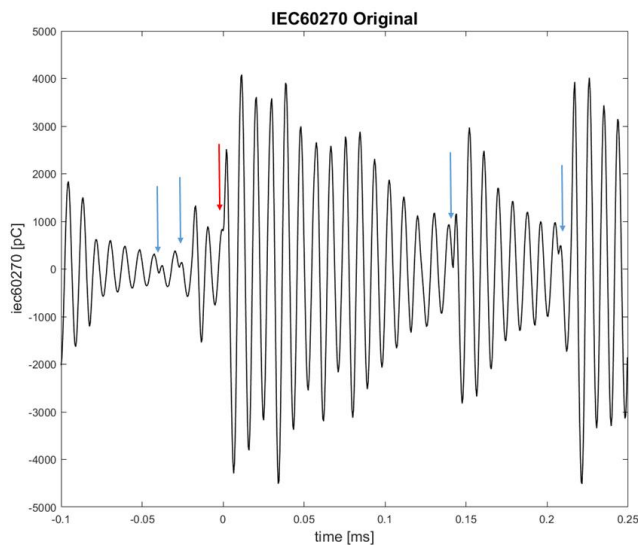
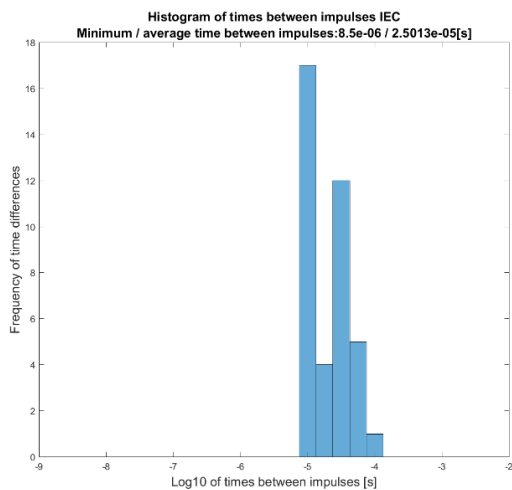
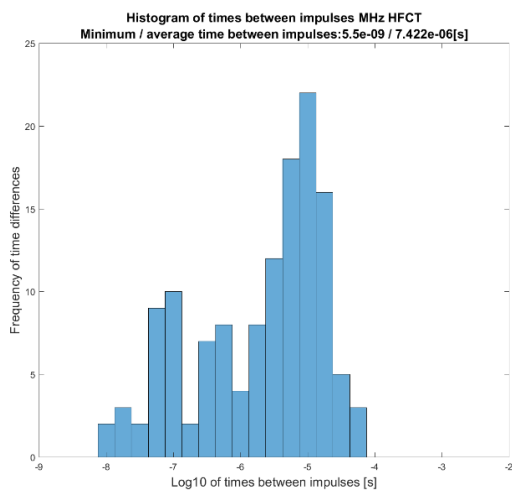


Fig. 53 Response of the IEC60270 detector in case of high repetition rate

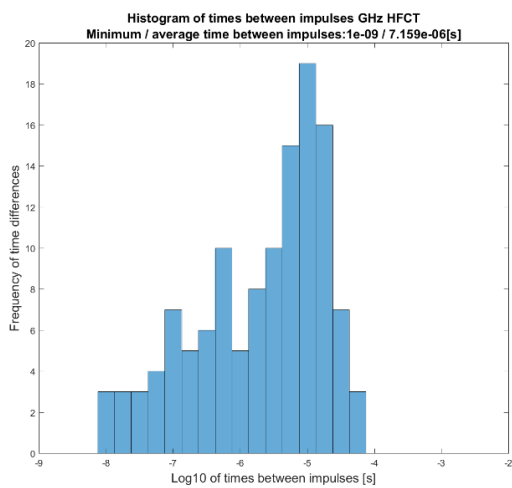
In order to decide which detector is suitable and which is not, the actual time difference between the individual impulses has to be investigated. Fig. 54 shows the histogram of the time between impulses recorded at the same measurement for the three detectors. The two HFCTs show good agreement, while the IEC60270 device obviously ignored a high number of impulses that followed each other in close proximity.



a)



b)



c)

Fig. 54. Histogram of the times between impulses.

a) IEC 60270 b) MHz HFCT c) GHz HFCT

In search of the appropriate partial discharge measurement method in low-voltage cables, the chapter discussed the detectors and signal processing methodology. The compared detectors cover a wide range of bandwidth (200 kHz, 20 MHz and 1 GHz upper limit) and rise time or resolution (5 μ s, 20 ns and 350 ps). It has been demonstrated that low-voltage cables exhibit high repetition rates of partial discharge activity. Based on the histogram of the times between impulses it is concluded that the limits of the IEC 60270 detector are violated frequently, accordingly, its application is not recommended. The results of the two HFCTs show good agreement, thus the application of the 1 GHz HFCT is not necessary, while the 20 MHz HFCT is the most suitable detector for the measurement of partial discharges in low-voltage cables.

III.4. Novel arrangement for measuring PD in low-voltage cables

Considering the requirements originating from the repetition rate and the general necessity of noise suppression, a new method has been created to measure PD in low-voltage cables. The method applies HFCTs as sensors and makes use of the architecture of the balanced circuits and the distributed element behavior of the test specimen, precisely that it can be modeled with its characteristic impedance at the input terminals. The regular arrangement is shown in Fig. 55, while the modified arrangement with two sensors is shown in Fig. 56.

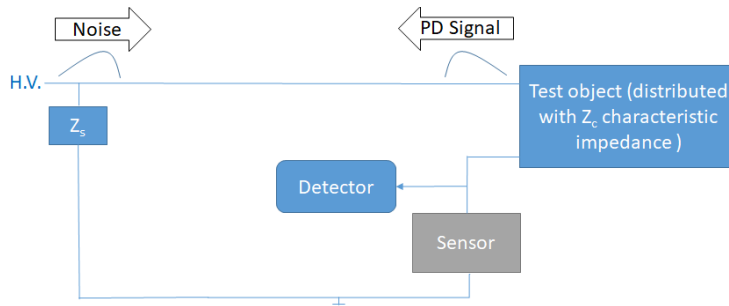


Fig. 55. Regular measurement arrangement with one sensor.

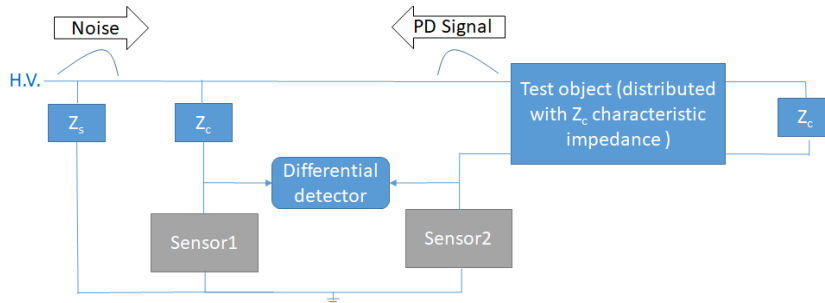


Fig. 56. Theoretical arrangement of the novel method for suppression of external noises in case the test object behaves as a distributed elements.

An extra arm of the measurement is added that has an impedance equal to the characteristic impedance of the cable. A sensor picks up the signal from this sensor, while another is attached to the ground lead of the cable that is carrying the same current as the

phase conductor but in the opposite direction. The application of HFCTs as sensors enables the test object to remain grounded, in contrary to the classic balanced bridge measurements. Additional difference compared to the original arrangement is that it is balanced for the characteristic impedance of the test object.

The theoretical arrangement in Fig. 56 has been implemented in TINA circuit analysis software. The model and the results are shown in Fig. 57 and Fig. 58. The impulse originating inside the cable causes voltage drop with different sign in the two sensors, yielding a larger differential signal, while external noise causes cancelling signals.

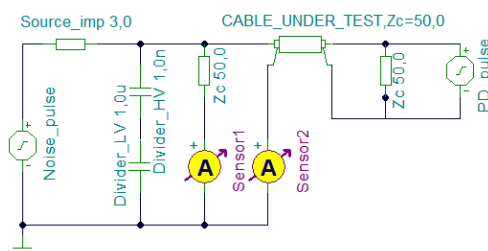


Fig. 57. Idealized simulation model.

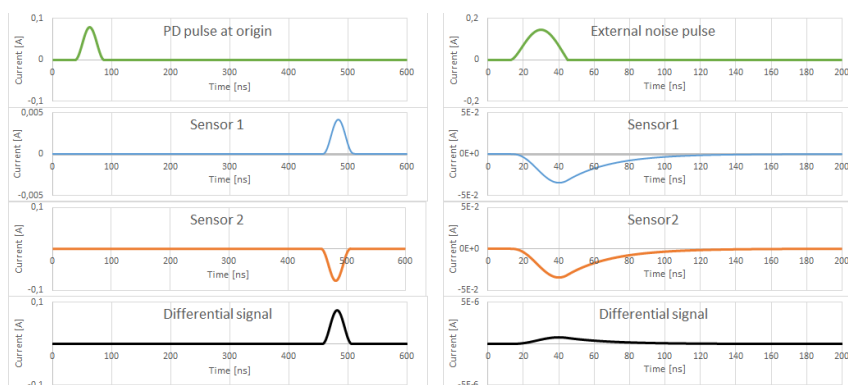


Fig. 58. Simulation of the circuit in Fig. 56 in ideal conditions.

In practice, the arrangement has been realized by the application of high frequency current transformers (HFCT), which are regularly applied for PD diagnostics, especially in case of cables [54]. Their bandwidth matches very well with the bandwidth of the PD signals reaching the terminals [55]. It is also advantageous that their lower cutoff frequency is higher than in case of the conventional PD detectors.

During the realization of the measurement, the most important difference is that the characteristic impedance cannot be directly connected to the test voltage at the near and the far end of the cable, because the test voltage must be blocked by capacitors.

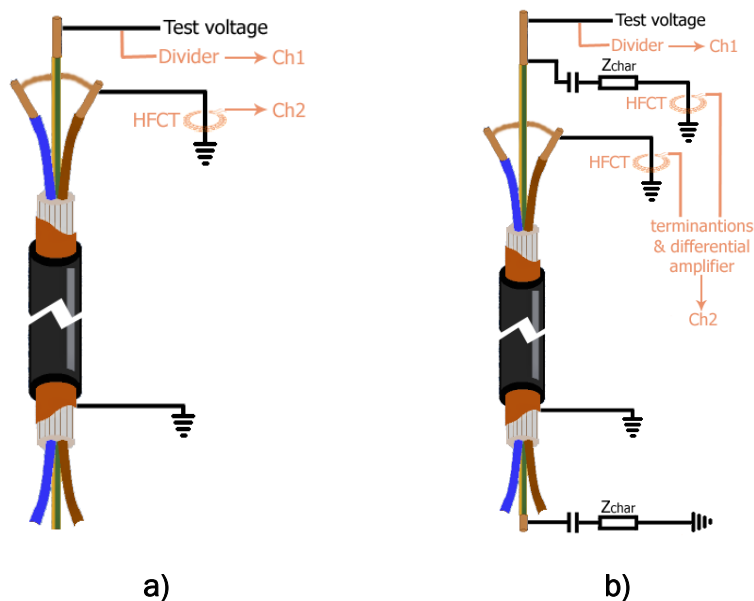


Fig. 59. (a) Regular PD measurement with HFCT and (b) Practical arrangement of the two-HFCT method for cables

The capacitor should be dimensioned so that it acts as a high impedance for the power frequency test voltage, while a small impedance for the high frequency PD impulses. Though it is possible to achieve, it complicates the case. Fig. 61 shows measurement results taken from the arrangement shown in Fig. 59b. A PD calibrating impulse has been injected externally and internally. It is obvious that the noise is attenuated, however, not perfectly. The achieved ratio is around 5, which is already useful, but lower than the expectations towards a balanced circuit.

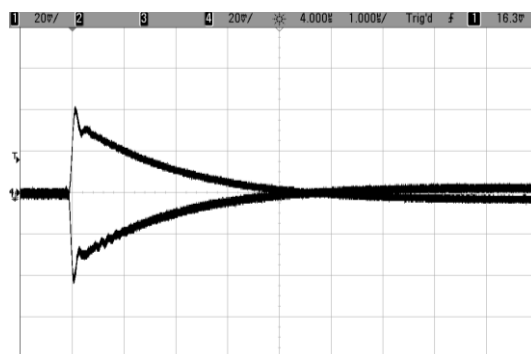


Fig. 60. Response of the two HFCTs for an external impulse without capacitors (low-voltage response).

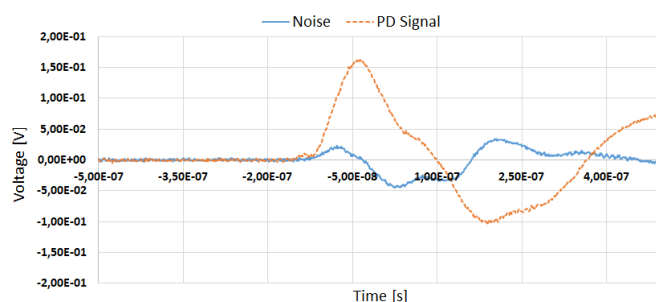


Fig. 61. Output of the realized circuit, when the same impulse is injected externally at the test voltage (Noise) and internally into the cable (PD Signal).

The main reason of the low efficiency of the noise cancellation can be followed in Fig. 62a. The output of the two sensors is similar, but some amplitude and phase error occur, which cause the differential signal to be different from zero. In Fig. 62b the amplification of the PD signal can be followed.

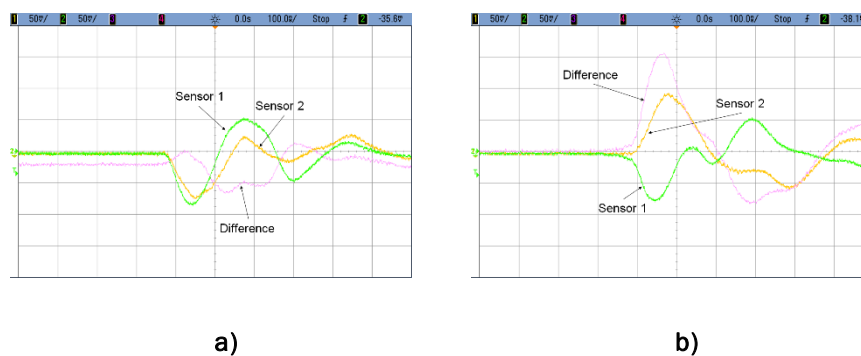


Fig. 62. Impulses measured by the HFCTs in case of external noise (a) and partial discharge originating in the cable (b).

Above, a novel technique for the suppression of external conducted noises during PD measurement has been presented and evaluated. The method can be categorized in the physical noise elimination techniques. It makes use of the distributed element behavior of the test object and the ease of the application of high frequency current transformers. Its advantages are the suppression of noise before digitization and the detection of PD signals occurring simultaneously with noise impulses. The simulations and idealized measurements have demonstrated the applicability of the method.

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 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.

PUBLICATIONS SERVING AS THE BASIS OF THIS CHAPTER AND THE THESIS

Z. Á. TAMUS, R. CSELKÓ, I. BERTA, "PRACTICAL ISSUES OF PARTIAL DISCHARGE TESTING OF LOW-VOLTAGE CABLES", JUNE 5-8, 2011, ANNAPOLIS, MD, USA

R. CSELKÓ, "REPETITION RATE OF PARTIAL DISCHARGES IN LOW VOLTAGE CABLES", PERIODICA POLYTECHNICA ELECTRICAL ENGINEERING AND COMPUTER SCIENCE 2019 (IN PRESS)

R. CSELKÓ AND I. KISS, "SUPPRESSION OF CONDUCTED DISTURBANCES DURING THE PARTIAL DISCHARGE MONITORING OF INDUSTRIAL CABLE SYSTEMS", IFIP ADVANCES IN INFORMATION AND COMMUNICATION TECHNOLOGY 521 PP. 308-316. , 9 P. (2018)

IV. Partial discharge diagnostics of low-voltage cables

Various diagnostic methods have been developed for medium and high voltage cables to determinate the condition and state of aging of insulations, whereas less attention was paid to low-voltage cables. The factors posing risk to the operation of cables can be divided into two basic groups. The first one is the aging of the insulating material itself, which is induced by all impacts affecting the cable, reflecting in change of the chemical structure. This influences the measurable diagnostic parameters of the cables. For the detection of such changes, various diagnostic systems were developed and published [12][26][30][33][38]. The second group of risks is local defects, which can be detected by partial discharge measurements.

Partial discharge measurements are the most widely and routinely used method for insulation diagnostics on medium and high voltage apparatus. Throughout the years, many measuring techniques were developed and many features of the partial discharges were established. The most promising ones are those that try to handle the statistical nature of partial discharge behavior. However, these methods cannot be directly applied to low-voltage cables, because, as it was shown, PD inception level is below the test voltage even in new and intact cables. Thus for diagnostic applications, the features of the acceptable PD activity have to be characterized, enabling to distinguish them from PD features indicating defects.

IV.1. Measurement methods

During the course of the research, several measurement methods have been applied for detecting the partial discharge activity. The results shown later in this chapter were obtained with one of the methods shown in Section III. and Fig. 29.:

- conventional detector complying the IEC 60270 standard,
- direct capacitive coupling,
- high frequency current transformer.

As during the research the limitations of the IEC 60270 method have been revealed, some of the measurements results need to be evaluated with care. Comments are made where there is a possibility of inaccurate or invalid results.

IV.2. Evaluation methods

IV.2.1. Inception and extinction voltage

The most simple evaluation method of partial discharge measurement is the recording of the inception and extinction voltage. Usually the limit is set to twice the noise level, also encouraged by the IEC 60270 standard. In case of medium and high voltage solid dielectric

cables the PD limit within the cable (not the accessories) is 5 pC, accordingly, a noise level below 2.5 pC must be achieved in a factory routine test facility. In case of on-site measurements, this is mostly impossible, thus the applicability of PDIV as a diagnostic parameter may be restricted.

IV.2.2. Characterization of the phase-resolved partial discharge pattern (PRPD)

The measurement of partial discharges with AC excitation offers a valuable tool for distinguishing between different PD phenomena. The occurrence of discharges is dependent of the phase angle of the test voltage, therefore they are often presented in the same figure, in the so-called phase-resolved partial discharge pattern (Fig. 63).

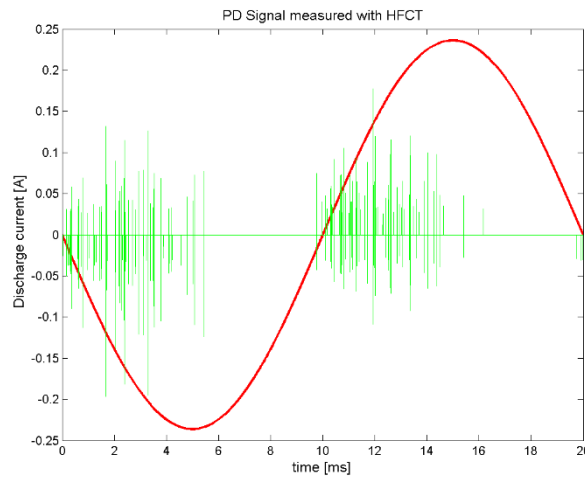


Fig. 63. PRPD in an NYCY pinholed cable at 3,8 kV

To have more insight, sometimes the so-called three-dimensional PRPD is drawn, where the discharge numbers and magnitudes can be followed in function of the phase of the test voltage (Fig. 64).

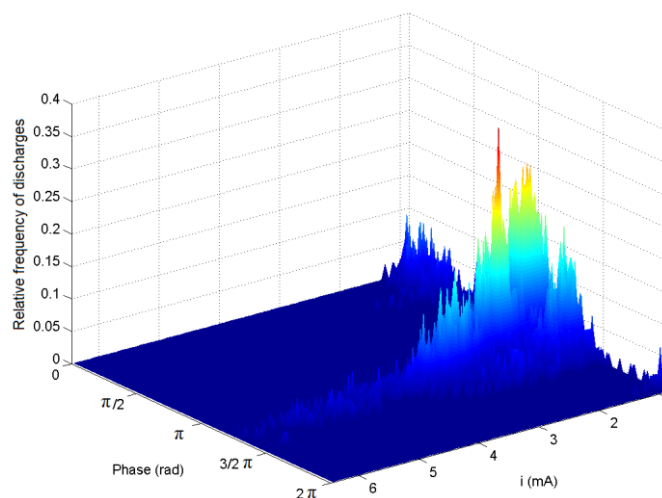


Fig. 64. Three dimensional PD diagram of a 3x2.5 mm² damaged NYCY cable at 2.1 kV.

There are numerous methods to characterize the PRPD. In this work the statistical approach has been applied [4], which extracts features of the pattern as if it was a probability density function. The properties to describe a single impulse and one phase are shown in Fig. 65.

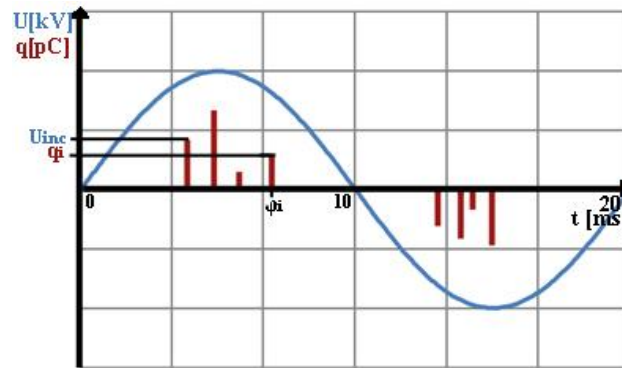


Fig. 65. Basic quantities of PD impulse characterization [4].

The quantities characterizing the PD activity can be divided into three main groups, as follows [3][4][84][85].

IV.2.2.1. Basic quantities

The basic quantities like the discharge magnitude are momentary values. Three basic quantities, the discharge magnitude (the so called apparent charge), the ignition voltage and the phase angle of the test voltage cycle are the only ones that describe the single PD pulse.

IV.2.2.2. Deduced quantities

With the measurement of basic quantities for much longer than one voltage cycle the deduced quantities can be derived. These quantities can be analyzed as the function of phase angle or as the function of time. The most important result of this kind of measurement is the distribution of the discharge amount and the mean discharge height. For these, the test voltage cycle must be divided into phase windows. Summarizing and calculating the mean pulse height of the PDs in each time window during the measurement results in the quantities mentioned above.

IV.2.2.3. Statistical operators

The introduction of these quantities was induced by the fact that PD is a statistical phenomenon. Four moments – mean value, variance, skewness and kurtosis – can be defined for a distribution. The third and fourth describe the shape of the distribution, therefore they are appropriate for the characterization of partial discharge patterns. The skewness indicates the asymmetry of a distribution and can be calculated as follows [4]:

$$Sk = \frac{\sum(x_i - \mu)^3 p_i}{\sigma^3} \quad \text{Eq. (6)}$$

where x_i is the discrete value, p_i is the probability corresponding to x_i , μ is the mean of the distribution and σ is the standard deviation. It gives the measure of asymmetry compared to the normal distribution. Positive skew means that the distribution is asymmetric to the left, negative skew means asymmetry to the right. Kurtosis gives the “peakedness” of a distribution compared to the normal distribution. It can be calculated by Eq. (7).

$$Ku = \frac{\sum(x_i - \mu)^4 p_i}{\sigma^4} - 3 \quad \text{Eq. (7)}$$

where the variables denote the same values as in case of Eq. (6). A high value of kurtosis describes a sharp, peaked distribution whereas flat distributions have low values. The kurtosis of the normal distribution equals zero.

Considering the physics of PD phenomena the comparison of the discharges occurring during the positive and negative test voltage half period further quantities can be defined. The discharge asymmetry gives the proportion of the mean pulse height in the positive and negative half as follows:

$$Q = \frac{Q_s^- / N^-}{Q_s^+ / N^+} \quad \text{Eq. (8)}$$

where Q_s^+ and Q_s^- are the sum of discharges, N^+ and N^- are the number of discharges occurring in the positive and negative half period of the test voltage, respectively. The similarity of the shapes of the discharge distributions in the positive and in the negative half is given by the cross-correlation factor:

$$cc = \frac{\sum xy - \sum x \sum y / n}{\sqrt{[\sum x^2 - (\sum x)^2 / n][\sum y^2 - (\sum y)^2 / n]}} \quad \text{Eq. (9)}$$

where x is the mean discharge magnitude in a phase window in the positive half of the voltage cycle, y is the mean discharge magnitude in the corresponding phase window in the negative half of the voltage cycle and n is the number of phase windows per half period.

IV.2.3. Characterization of the impulse height (amplitude) distribution (PDHD)

Weibull distribution [75] has several engineering applications, one of them being the statistical treatment of breakdown in electrical insulation. Its application is encouraged by the relevant international standard [81]. This led to the assumption that characterizing partial discharge activity by the parameters of the Weibull distribution fit (Fig. 66) can serve as a diagnostic method [9].

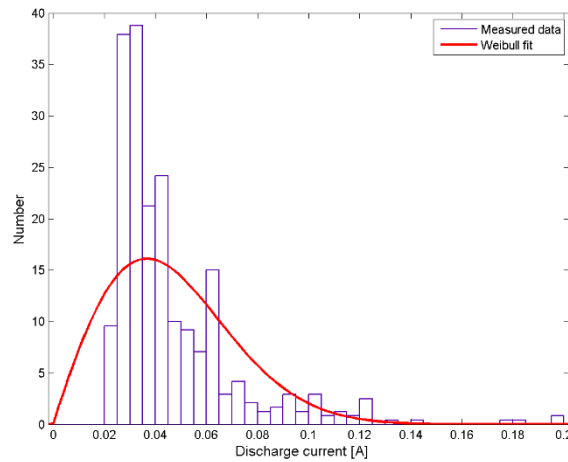


Fig. 66. PDHD diagram with the Weibull-fit

The PDHD diagram is the histogram of discharge magnitudes over some time, preferably at least several periods of the test voltage. Once this is obtained, the Weibull distribution (Eq. (10)) is fitted to the resulting curve,

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^\beta} \text{ for } x \geq 0, \quad \text{Eq. (10)}$$

where α is the scale and β is the shape parameter. During the course of the later shown applications, the parameters were obtained by the application of the maximum likelihood estimation [77], and the changes of the scale and shape parameters were applied as diagnostic criterion.

IV.2.4. Fuzzy clustering

The above quantities were found to be somehow characteristic to the different PD types. The evaluation of an actual measurement data can be performed by taking into account the different parameters one by one, but based on the experience, this approach can give inconsistent results and uses only a part of the information at a time. One solution to this problem can be fuzzy c-means clustering [86].

Clustering techniques are data processing methods that can sort information by extracting rules not known before [80]. The aim of fuzzy c-means clustering is to discover that a single measurement result falls into previously set groups and to what extent. This is performed by quantitative analysis of multiple characteristics. The process of c-means clustering with two features and two clusters can be followed up on Fig. 67. The space created by the different characteristics is called feature space. The object of the clustering process is to find the optimal cluster centers in the feature space as follows. Every cluster is considered as a fuzzy set. This means, that every data point has a membership in every cluster. The membership values are normalized, so the sum of the memberships of a single data point equals one. The membership value is proportional to the Euclidean distance

from the cluster center. Accordingly the aim of the clustering process is to minimize the total sum of the Euclidean distances from the cluster centers by positioning them with a particular iteration algorithm. The clustering has been performed by MATLAB software with its fuzzy-neural toolbox.

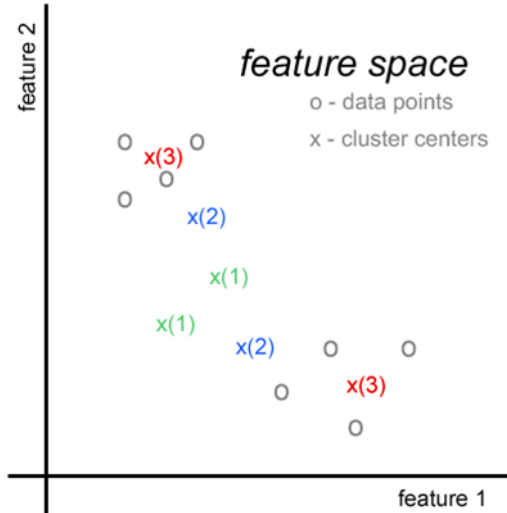


Fig. 67. Fuzzy C-mean clustering; cluster centers in the different steps, number of steps in parenthesis [80].

It is very important to bear in mind that the results are not definite sets but fuzzy sets. The data points have a level of membership in every cluster. But this quality of c-means clustering makes it possible to handle insufficient, imprecise and noisy information in a proper way or point out the inconsistency of the data.

Presumably the most important property of the statistical and fuzzy data processing techniques is that their ability of abstraction from the actual measurement circumstances and characterizing and taking into account the process and patterns of the partial discharge activity, therefore describing the physical process itself.

IV.3. Cable types

To give an overview of the tests to be discussed below, Table VIII summarizes the properties of the base cable types.

TABLE VIII. CABLE TYPES.

TYPE	SHIELDING	TYPE OF CONDUCTOR	BEDDING	CORE INSULATION	NOMINAL VOLTAGE	TEST VOLTAGE
RG-58	COPPER, BRAIDED	STRANDED	N.A. (COAXIAL)	PE	1400 V	5000 V
NYCY	TAPE AND STRANDS	SOLID	PVC	PVC	600 V	4000 V
SiHF	NONE	STRANDED	NONE	SIR	500 V	2000 V
YSLCY	COPPER, BRAIDED	STRANDED	NONE	PVC	500V	2000 V
SzRMKVM-J	STEEL ARMORE TAPE	SOLID	NONE	PVC	1000V	3000 V

The investigated cable types cover the most important features that may have an effect on partial discharge activity:

- core insulation material,
- solid or stranded conductor,
- band or braided shielding or lack of shielding,
- presence or absence of bedding in case of multi-core cables.

As an example to demonstrate the above parameters, the construction of the NYCY type cable is depicted in Fig. 68.

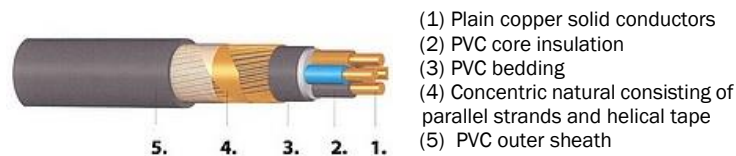


Fig. 68. Construction of the NYCY cable [56].

IV.4. Tests on RG-58 single-core coaxial cables

The first, large set of measurements were performed on RG-58 type coaxial communications and signal cables. The simple, one-conductor construction allowed to focus on the basic properties of the partial discharge phenomena. The 0.975mm thick core insulation is made of low density polyethylene and has a nominal voltage of 1900V.

IV.4.1. Initial tests

Low-voltage cables do not need special field grading terminations, as their insulation is designed based on mechanical requirements and is therefore much thicker than needed for their nominal voltage. Therefore, there was fear that at test voltage the cable terminations will exhibit such high partial discharge activity that it suppresses the useful signals. The cable ends were therefore specially developed to avoid too much of surface discharges as it can be seen on Fig. 69.

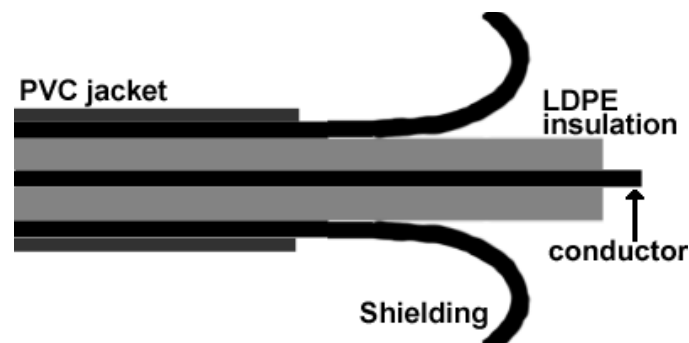


Fig. 69. Elaboration of cable ends.

Afterwards, two tests have been performed to evaluate whether discharges from the main insulation of the cable can be detected.

IV.4.1.1. Long and short cables

By comparing the results of a short (3 m) and a long (100 m) cable specimen, the main source of discharges is given. If the results are similar, then the sources are the terminations. If the sources are internal to at least some extent, then the longer cable shows higher discharge activity. According to the results shown in Fig. 70...Fig. 72, the latter situation was identified.

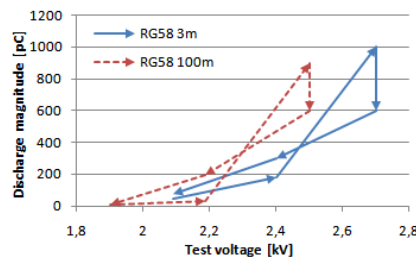


Fig. 70. IEC 60270 readings in function of the test voltage.

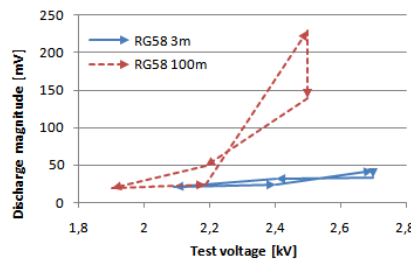


Fig. 71. Discharge magnitude measured by the capacitive coupler.

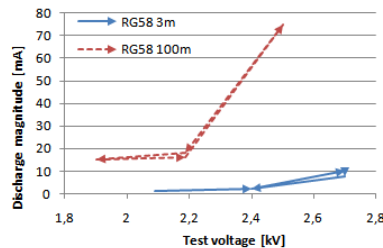


Fig. 72. Discharge magnitude measured by the HFCT.

IV.4.1.2. Measurements on dry specimen and under oil

Low-voltage cables do not possess semiconducting layers. Therefore discharges may occur on the surfaces of the insulation. With the immersion of the specimen in oil, the occurrence of discharges between the shielding and the insulation may be reduced (Fig. 73...Fig. 75). This way it is possible to determine whether the discharges occur in the insulation bulk or on its surface. For the purpose of the measurement the complete PVC jacket of the cable was removed and the cable was immersed in oil and the measurements were performed after a settling period of 1 hour. However, no further treatment (e.g.

vacuum) was applied to the specimen, thus only the reduction of the air pockets is expected and not the complete elimination of discharges between the shielding and the core insulation.

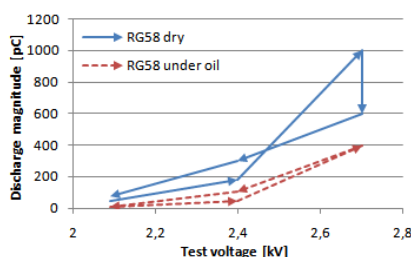


Fig. 73. IEC 60270 readings.

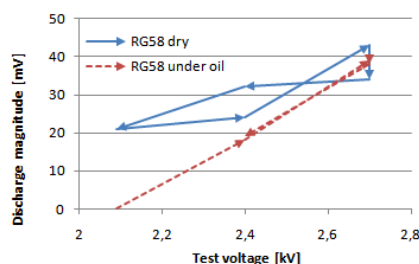


Fig. 74. Discharge manitude measured by the capacitive coupler.

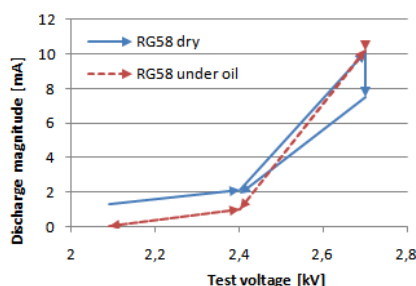


Fig. 75. Discharge magnitude detected by the HFCT.

Still, the results show only little difference; therefore, it is assumed that the origin of the discharge signals is prevalently within the core insulation, possibly at the interface of the conductor and the core insulation.

IV.4.2. The effect of thermal stress

The goal of the examination was to investigate the sensitivity of the insulation for temperature stress. The maximum normal operating temperature of the cable is 80 °C, and in NPP environments, temperatures near this value are not rare. To investigate the effect of thermal stress on the partial discharge behavior, but to consider the properties of the low-density polyethylene core insulation and the PVC jacket, the parameters in Table IX were applied.

TABLE IX. THERMAL STRESSING PARAMETERS.

	TEMPERATURE (°C)	DURATION (H)
GROUP A	90	100
GROUP B	90	400
GROUP C	95	180

IV.4.2.1. Inception voltage

Fig. 76 shows the voltage where the discharge activity reached 50pC on new and aged cables during the elevation and the decrement of the test voltage, respectively.

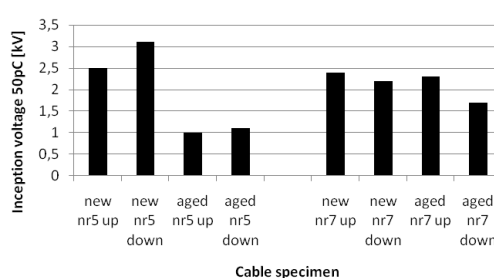


Fig. 76. Changes of the inception voltage (Group B – nr5 and Group A – nr7).

Cable nr.5 was aged in “Group B” for longer time. It seemed to have suffered heavy deterioration which results in the decrement of the inception voltage below the nominal voltage. Many cables of this group broke down during the measurement.

The inception voltage where discharge activity starts can be assessed by considering the dielectric strength and the voltage across the cavity [5]. Calculating with the data of the measured cable type results that for the majority of cavity size - distance from conductor combinations the discharges begin to occur at a lower value than the applied 4 kV test voltage.

Useful results were obtained with the measuring of the inception voltage. Considerable increment of the inception voltage of the partial discharges can be shown on all of the test objects (Fig. 77). Presumably, this can be caused by the enlargement of the cavities due to the high temperature.

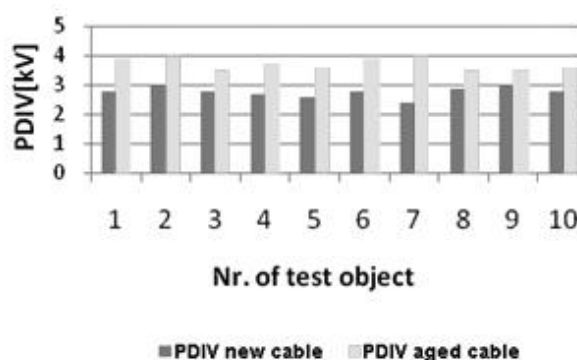


Fig. 77. Inception voltage of PDs before and after thermal aging (Group C).

IV.4.2.2. Peak values of the apparent charge and integrated charge

The peak value of the discharges is affected by the capacitance of the cavity determined by its size [4]. Fig. 78 to Fig. 80 show the peak value of discharges in new and aged cables of “Group A” and “B”, respectively.

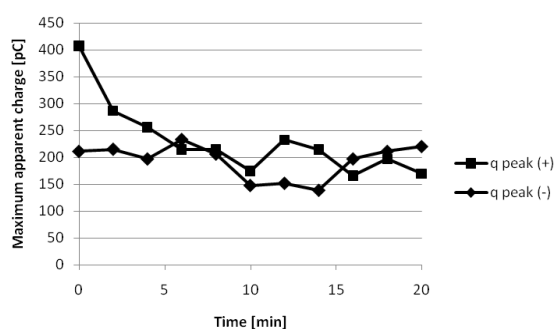


Fig. 78. Peak apparent charges of new cable.

In new cables the maximum apparent charge show a decreasing tendency during the first few minutes and then slight statistical changes.

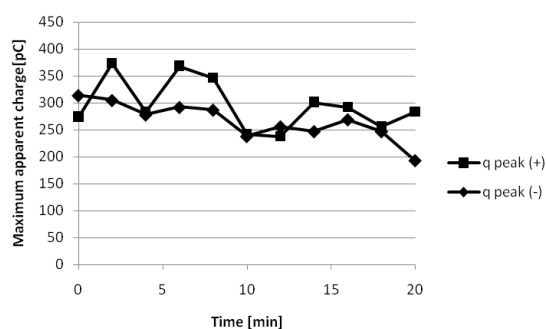


Fig. 79. Peak apparent charges in cables aged in “Group A”.

In aged cables the values did not suffer notable changes, but the decreasing period can not be observed. The maximum values show statistical changes around the peak apparent charges at the beginning. This can be caused by chemical changes of the

insulating material which prevents the formation of semiconductive layer on the walls of the cavities.

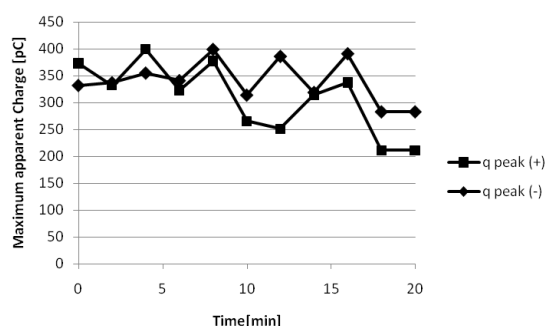


Fig. 80. Peak apparent charges in cables aged in "Group B".

The maximum amplitude of apparent charge showed considerable changes in Group C (Fig. 81). The values did not change noteworthy but the tendencies altered during the 20 minute long measurements. The original monotone decrement in time changed to a fluctuation around the initial values.

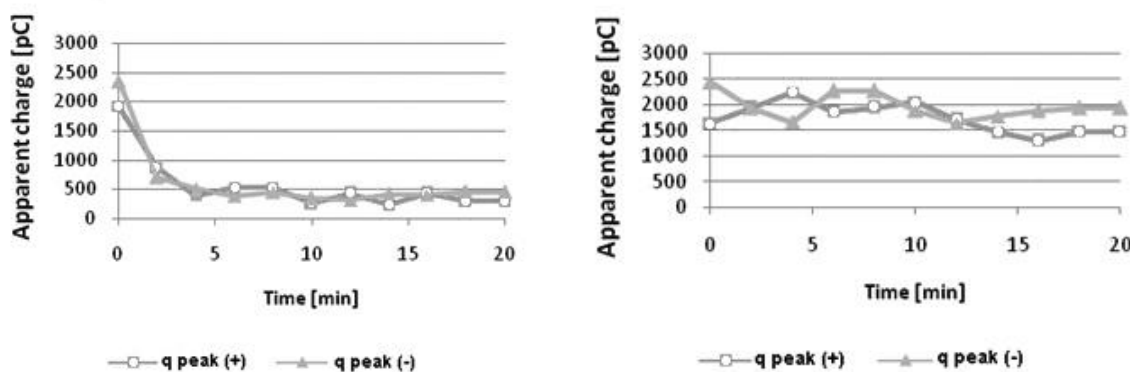


Fig. 81. Maximum apparent charge in new cable Group C, before and after aging.

The integrated apparent charge give us a general information about the discharge activity. It is determined by the number of discharges and their average height.

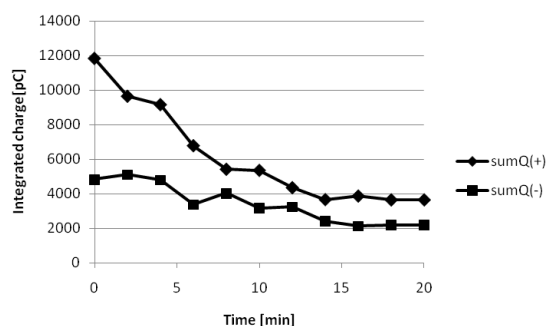


Fig. 82. Integrated apparent charge per period of new cable.

In case of new cables the same decreasing tendency can be observed as by the peak values. In "Group A" the integrated charge is in correlation with the peak values.

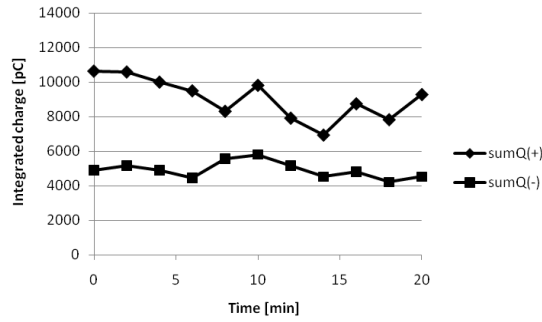


Fig. 83. Integrated apparent charge per period in cables aged in “Group A”.

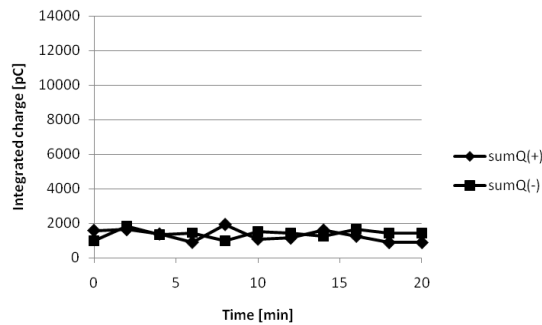


Fig. 84. Integrated apparent charge per period in cables aged in “Group B”.

In case of “Group B” the integrated charge suffered a heavy decrement although the peak values remained similar to the new cables. This is caused by the drop in the number of discharges (see Fig. 86).

The total apparent charge per period suffered a considerable increment due to the thermal stress in Group C (Fig. 85). The decreasing tendency during the measurement did not change. Considering the number of discharges, this means the average apparent charge of the discharges was increased.

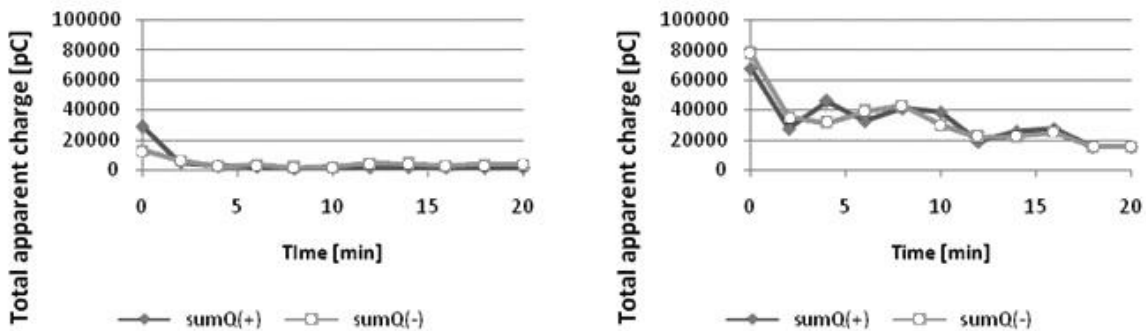


Fig. 85. Total apparent charge per period in new and aged cable (Group C)

IV.4.2.3. Number of discharges

The originally slightly decreasing number of discharges per period changed to a monotone decreasing tendency (Fig. 86). The initial values are several times higher than the ending values.

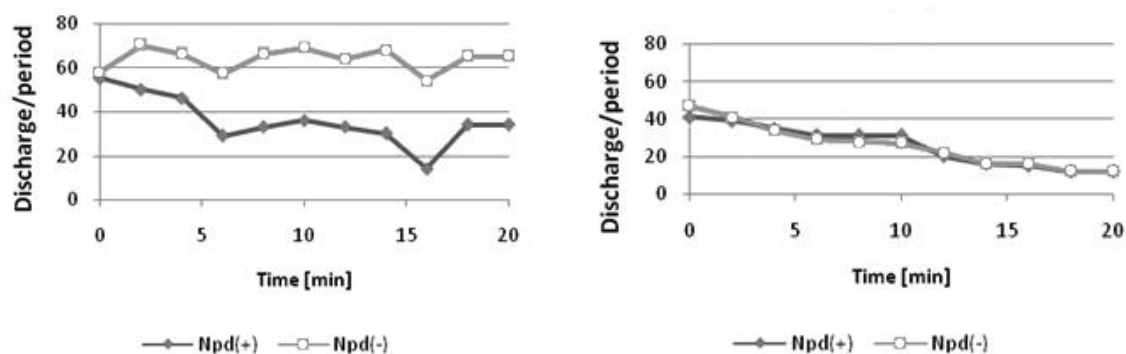


Fig. 86. Number of discharges per period in new and Group C aged cable

IV.4.2.4. Statistical operators

With the considered statistical operators the deviation from the normal distribution can be measured quantitatively.

The skew gives the level of asymmetry. The zero value means a symmetric distribution, negative values show skewness to the left while positive values to the right.

In this case positive values were measured which means that discharges occur end of the half periods i.e. before the zero point of the test voltage. This behavior is related to internal discharges.

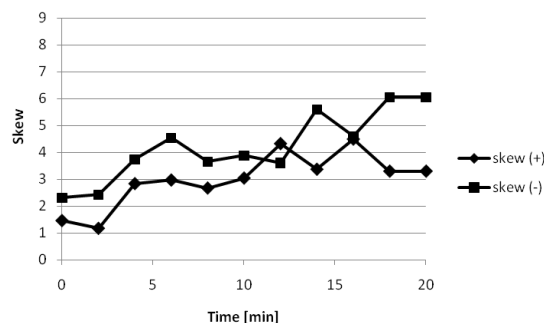


Fig. 87. Skew of the average apparent charge distribution in new cable.

The measurement results showed changes in the skew but no tendencies in correlation with the aging, so its use as diagnostic parameter had to be ignored.

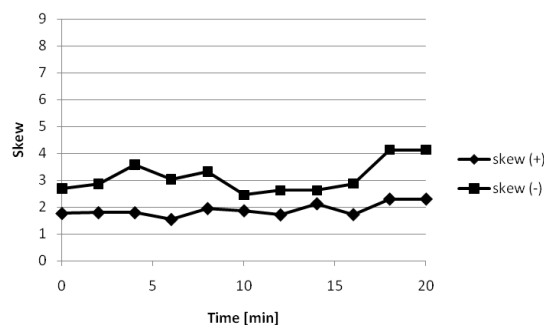


Fig. 88. Skew of the average apparent charge distribution in cables aged in (Group A).

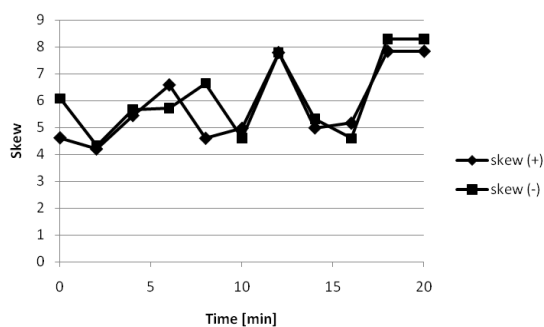


Fig. 89. Skew of the average apparent charge distribution in cables aged in (Group B).

The kurtosis is the measure of pointedness compared to the normal distribution. Normal distribution has a kurtosis of zero, flat distributions have negative while pointed distributions have a positive value.

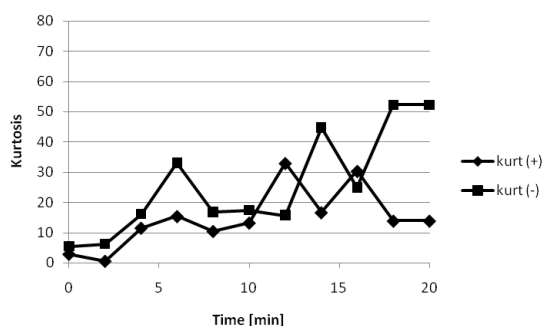


Fig. 90. Kurtosis of the average apparent charge distribution in new cable.

In new cables and “Group B” the kurtosis showed high and fast changing, while in “Group A” lower and relatively constant values. This could mean that the start of deterioration may be detected by measuring the kurtosis with the condition that the flat phase shown in Fig. 91 appears in all cases.

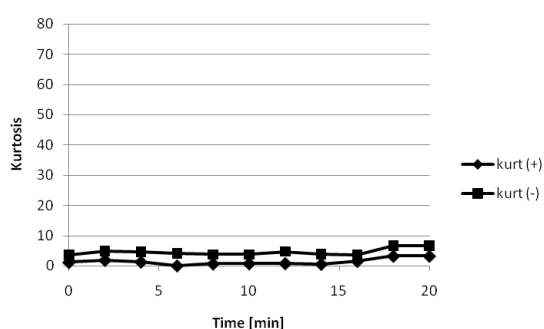


Fig. 91. Kurtosis of the average apparent charge distribution in cables aged in (Group A).

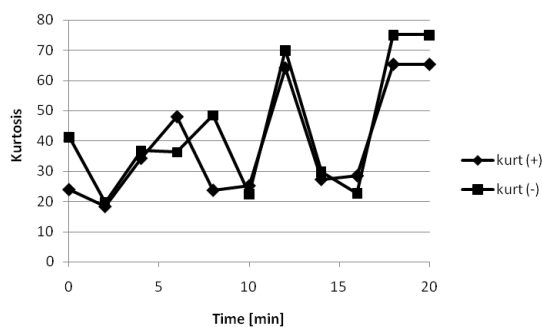


Fig. 92. Kurtosis of the average apparent charge distribution in cables aged in (“Group B).

IV.4.2.5. PD height distribution

Analysis of the height distribution is considered as a very powerful evaluation method of partial discharge measurements [9].

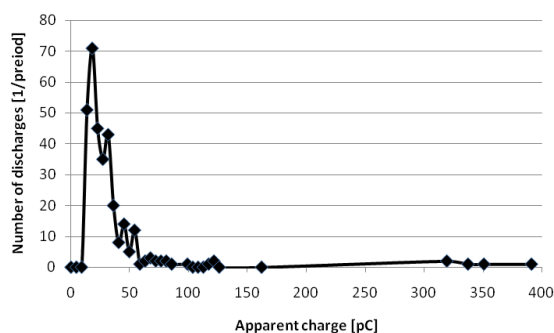


Fig. 93. PD height distribution in new cable.

The shape of the distribution started to change with the aging. The peak value of the distribution showed the largest changes. In “Group B” the distribution became lower and flatter. This significant change may be used as a diagnostic parameter, if with further stressing the tendency continues.

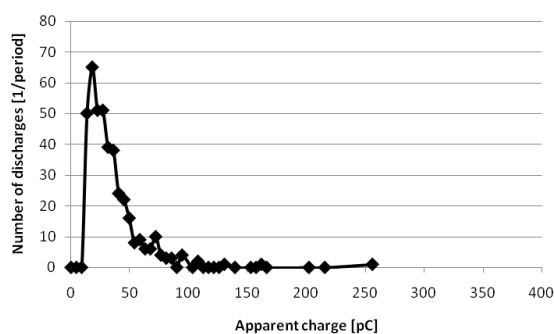


Fig. 94. PD height distribution of cables aged in “Group A”.

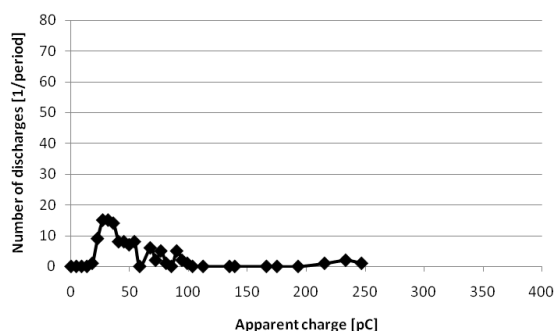


Fig. 95. PD height distribution of cables aged in “Group B”.

Considerable changes were initiated by the thermal stress in the cable insulation. The effect of thermal stress can be shown by the partial discharge inception voltage, the maximum of the apparent charge, the number and process of the discharges and the total apparent charge per period therefore these quantities can be useful in low-voltage cable diagnostics.

Using of alternative examination methods (e.g. optical microscope, X-ray testing or chemical analysis [6]) is needed for the confirmation of the conclusions drawn by the electrical measurements. Furthermore, all stresses in operation are needed to simulate in the examinations in order to give more information of aging of PE insulated cables.

IV.4.2.6. Detection of thermal aging with fuzzy-c clustering

In this experiment, no changes in the measurement arrangement itself were made but an attempt to use a new processing technique to low-voltage cables. The aim was to identify the source of the PD activity and get insight into the effect of thermal aging. Knowing that the PD comes from corona, surface or internal discharges we can identify the source of the problem. Corona and surface discharges designate mostly mounting errors while internal discharges failures in the insulation bulk or cable terminal.

For the use of the above mentioned separation techniques the “fingerprints” of single PD phenomena were needed. These measurements were carried out with the same measuring device as depicted above.

Fig. 96 shows the different arrangements of measurements. Corona discharges were produced by a needle – plane arrangement. Surface discharges were made on a polyethylene plate wedged between a large plane electrode and a smaller, chamfered electrode. Internal discharges were produced between embedded electrodes in ethylene-vinyl acetate, where artificial air bubbles were placed during production. The embedded electrodes assured that no surface discharges could develop. The production of multiple small air bubbles in the insulation instead of one bigger was chosen because in the cable insulation the existence of the former was more probable.

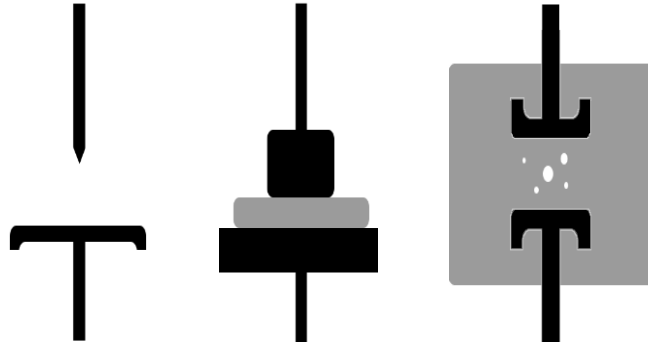


Fig. 96. Reference measurement arrangements for corona, surface and void discharges, respectively.

During the measurements as mentioned before the patterns were visually observed. Fig. 97 shows the pattern of internal discharges through one test voltage cycle. The PD activity concentrates around the zero points as it is known for void discharges.

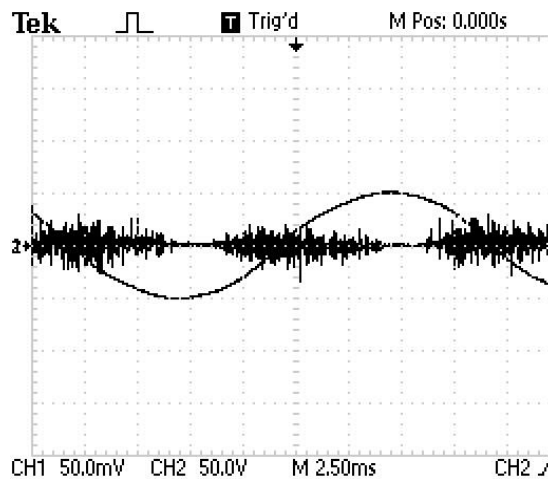


Fig. 97. Typical internal discharge pattern through one test voltage cycle.

Samples of the background noise were recorded, too. Taking them into account by the evaluation can help the noise rejection. The background noise measured stayed under the 5 pC limit usually prescribed. The most characteristic value for noise was the correlation that showed values close to zero, as expected.

The feature vector in our case consisted of the discharge asymmetry, the cross-correlation and the kurtosis and the skewness separately for the positive and negative test voltage half cycles. The cluster centers calculated from the results of the preliminary measurements (the training data) are shown by Table X.

TABLE X. CLUSTER CENTERS CALCULATED FROM THE TRAINING DATA.

	Q ASYMMETRY	CC	Sk+	Sk-	Ku+	Ku-
INTERNAL	1.01	0.13	4.59	4.31	22.91	20.37
SURFACE	0.75	0.30	4.69	5.38	30.05	40.08
CORONA	3.55	0.18	2.54	2.73	6.64	9.73
NOISE	0.97	0.01	1.71	1.72	2.08	2.01

The inception and extinction voltage values are very important in the global assessment of the insulation, but contain only a small part of information compared to the partial discharge pattern studies.

Table XI contains the membership functions of the PD measurement results calculated with the trained cluster centers.

TABLE XI. CLUSTER CENTERS CALCULATED FROM THE TRAINING DATA.

NR. OF SAMPLE	INTERNAL	SURFACE	CORONA	NOISE
1 NEW	0.653	0.109	0.165	0.073
1 AGED	0.254	0.078	0.491	0.178
2 NEW	0.584	0.048	0.267	0.101
2 AGED	0.325	0.068	0.461	0.146
3 NEW	0.540	0.173	0.194	0.092
3 AGED	0.163	0.752	0.050	0.035
4 NEW	0.851	0.070	0.050	0.029
4 AGED	0.021	0.007	0.374	0.597

The result show that most of the measured PD activity can be associated to internal discharges. Although, in some cases the surface and corona discharges were not totally eliminated.

Fuzzy clustering is a powerful method for handling large number and different type of information. Fuzzy c-means clustering seems to be able to identify the source generating partial discharge signals. This makes possible to identify the failures of cables and give guideline for repairing them.

IV.4.3. Mechanical damages

The measurements were carried out on samples with artificial defects similar to those expected on-site and on brand new cables for reference. The following samples were prepared:

- a pin was pressed into the insulation to the core and pulled out,
- the PVC jacket, the shielding and the core insulation was cut deeply,
- a specimen was clamped with a clip to 50% of its diameter at 1/3 of its length and was bent with a radii 30% of the allowed minimum at 2/3 of its length.

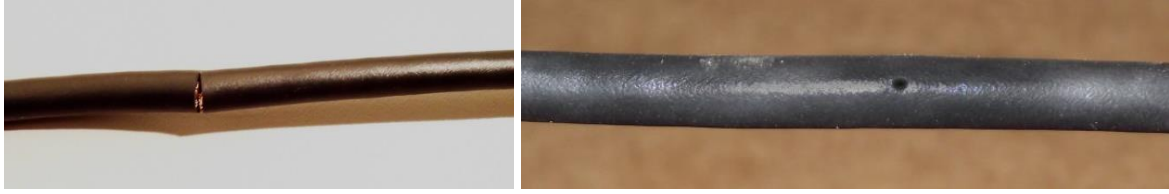


Fig. 98. Cut and pinholed RG-58 cable.

At every measurement an initial acquisition was carried out at 0 kV to gain information about noise levels. Height distribution of noise “impulses” are shown in Fig. 99 and Fig. 100. These give better insight into noise behavior than just specifying an average level. In fact, the reading from the conventional device was 4 pC at the time of acquisition of the distribution shown in Fig. 99.

The partial discharges measurements were carried out at inception voltage (U_{inc}), $1,15U_{inc}$ and $1,30U_{inc}$, with a limitation of $3U_0$ of each cable type. After 5 minutes the measurements were carried out at the same voltages in reverse order. Inception level was chosen to 10 pC, accordingly, inception voltage was determined as the voltage where discharge magnitude was constantly above this level. At the specified voltages data acquisition was carried out with a digital oscilloscope. Besides the output of the IEC 60270 device and the capacitive coupler, the test voltage was also recorded to allow phase resolved analysis.

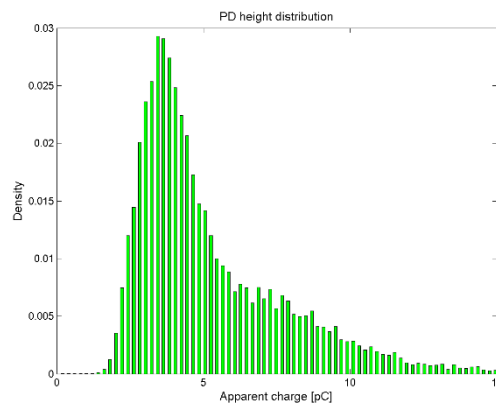


Fig. 99. PDHD diagram of noise measured by the IEC60270 device.

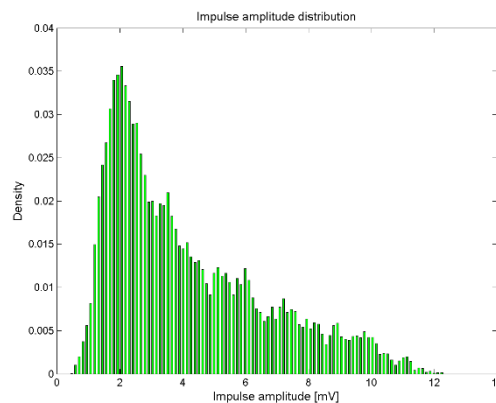


Fig. 100. PDHD diagram of noise measured with capacitive measurement.

The difficulty caused by the discharges occurring also in cables in good condition is demonstrated in Fig. 101 to Fig. 106. Maximum discharge amplitude, sum of discharges and number of discharges are depicted for the reference cable and a specimen damaged by clamping and bending. The basic properties show only slight changes, while the only visible difference is the hysteresis appearing in the number of discharges. Finding the parameters that are valuable for diagnosing mechanical injuries in low-voltage cables is not straightforward, as it will be shown below.

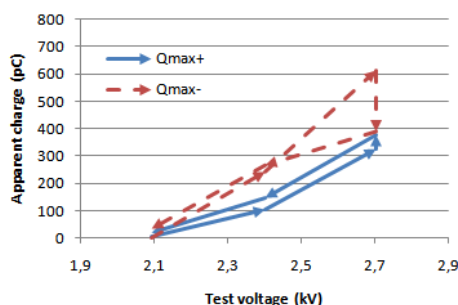


Fig. 101. Discharge magnitude measured on reference cable.

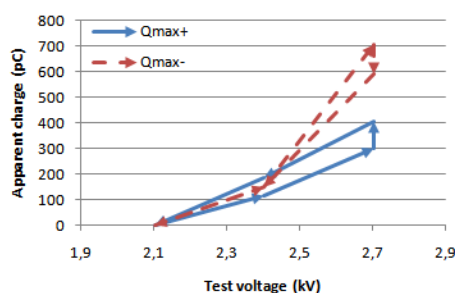


Fig. 102. Discharge magnitude in damaged cable.

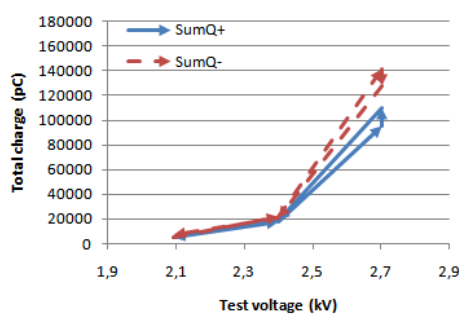


Fig. 103. Total apparent charge per period in reference cable.

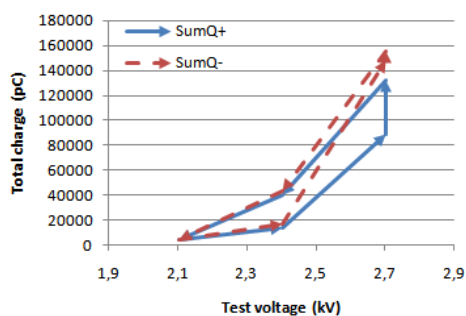


Fig. 104. Total apparent charge per period in damaged cable.

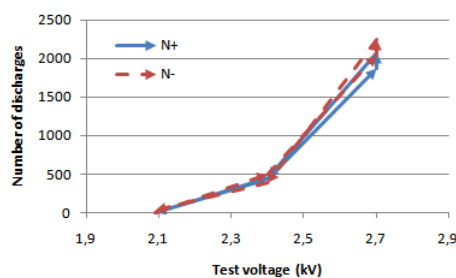


Fig. 105. Number of discharges in reference cable.

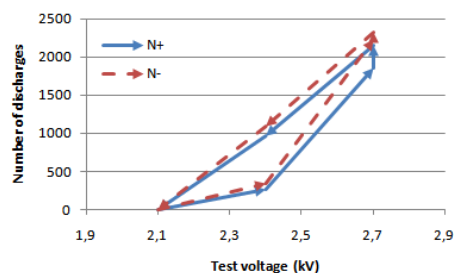
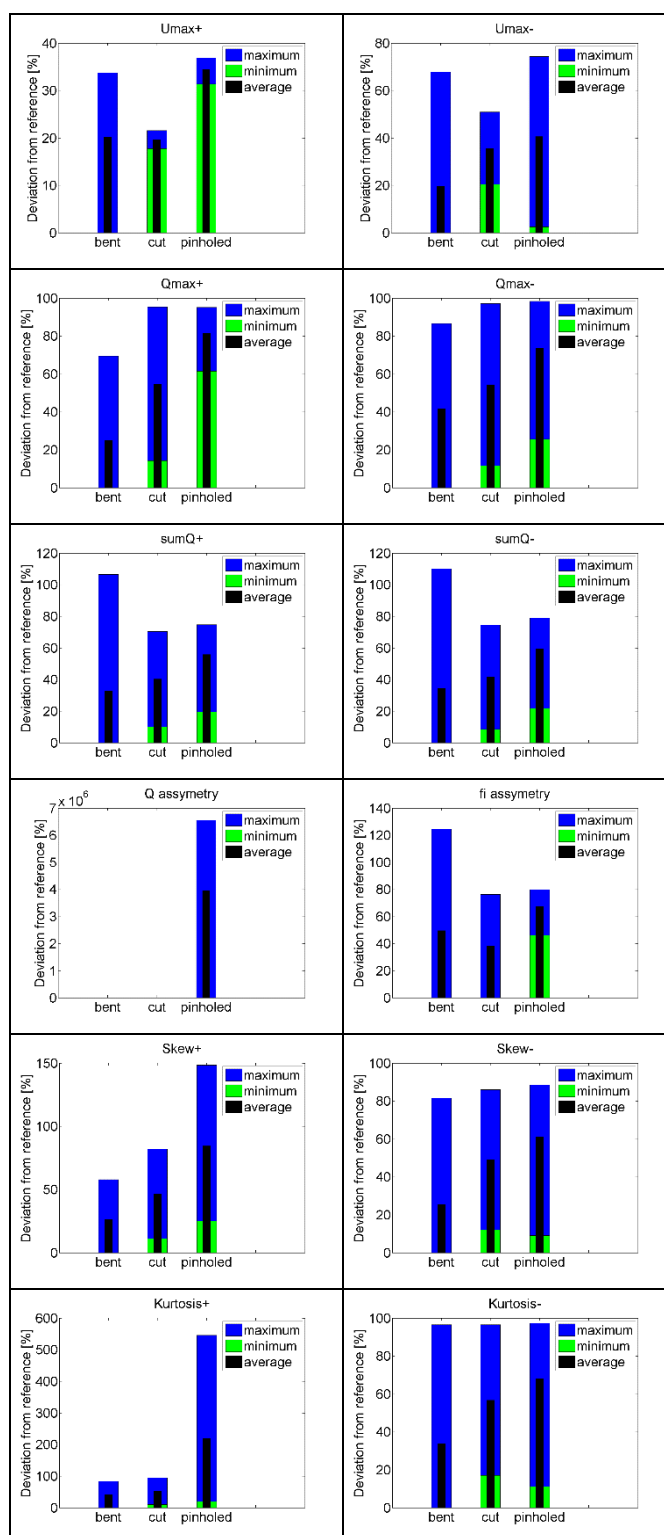


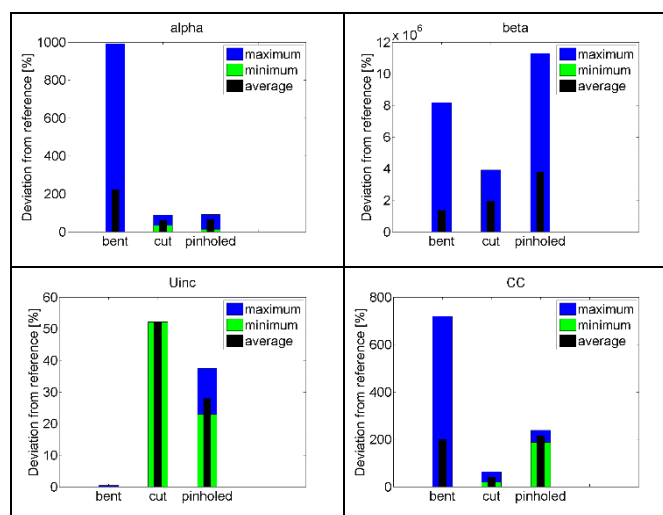
Fig. 106. Number of discharges in damaged cable.

The cut cable showed breakdown after 2 minutes at $1,15U_{inc}$, while the pinholed cable showed intermittently breakdowns during the elevation of the voltage from $1,15U_{inc}$ to $1,30U_{inc}$, consequently the test voltage was decreased back to $1,15U_{inc}$. These results suggest that in case of heavily injured cables the PD inception voltage and the breakdown voltage become very close to each other.

Table XII. shows the absolute deviation in percent in the different parameters caused by the mechanical defects. Each cell of the table evaluates a diagnostic parameter by depicting its deviation compared to the reference measurements. The values were calculated by the comparison of the parameters at the same voltage relative to the inception voltage of each sample.

TABLE XII. DEVIATION OF THE PARAMETERS FROM THE REFERENCE MEASUREMENT ON RG-58 COAXIAL CABLES.





The charts show the minimum, maximum and average deviation of the parameters from the reference data. An easy-to-handle diagnostic parameter should always show significant deviation from the reference measurement, i.e. the minimum deviation should be significant as well. Regarding this requirement discharge magnitudes, kurtosis and inception voltage can be a diagnostic parameter for the cuts and pinholes with this measurement setup. The violation of the bending radii and clamping the cable seems not to have steady effect on partial discharge occurrence, however, the maximum change in the parameters is in many cases significant.

IV.5. Tests on NYCY type cable

IV.5.1. Initial tests

The measurement of multi-core cables is closer to real field conditions, while these measurements are the most distinct from the measurement of MV and HV cables because there are gaps between the cores where discharges can occur. Also the earthing of the cores not under measurement can affect the PD behavior. According to the result shown in Table XIII, there are slight changes in the discharge magnitude when the cores not under test are earthed.

TABLE XIII. PD MAGNITUDE MEASURED IN A 3-CORE CABLE.

VOLTAGE [kV]	3-CORE CABLE ONLY SHIELDING EARTHED			3-CORE CABLE SHIELDING + 2 CORES EARTHED		
	Q [pC]	V [mV]	I [mA]	Q [pC]	V [mV]	I [mA]
1.4	7			25	2.06	0.85
1,6	50	2.05	0.9	35	2.1	1.02
1,8	275	2.23	1.15	200	2.2	1.41
1,8	100	2.02	1.05	175	2.38	2.21
1,6	40	2.01	1.03	40	2.11	1.09
1,4	10			10		

As these changes are not significant, leaving the cores not under measurement does not offer any advantage, as the electric field on the core under test is also decreased, accordingly the possibility of PD to occur at damages is also expected to be lower. Accordingly, in the further tests the other cores were earthed.

IV.5.2. Mechanical damages

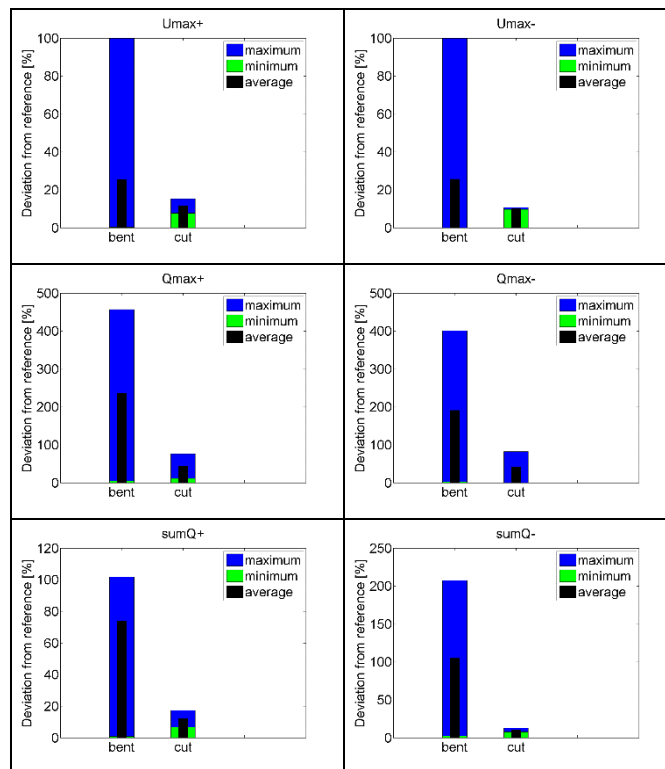
Multi-core specimens were prepared of a three-core shielded PVC cable type. Reference measurements were carried out with only the shielding earthed and with the shielding as well as the other two cores earthed. The following specimens were prepared:

- the jacket, the shielding and one core insulation of a cable was cut,
- a specimen was clamped and bent with the same parameters as the single-core cable.

The closeness of PD inception voltage and breakdown voltage is also valid for this type of cable. The cut cable suffered breakdown when the voltage was elevated from $1,15U_{inc}$ to $1,30U_{inc}$.

Table XIV. shows the results gained with the same method of calculating the deviation from the reference values.

TABLE XIV. DEVIATION OF THE PARAMETERS FROM THE REFERENCE MEASUREMENT FOR THREE CORE NYCY CABLES.



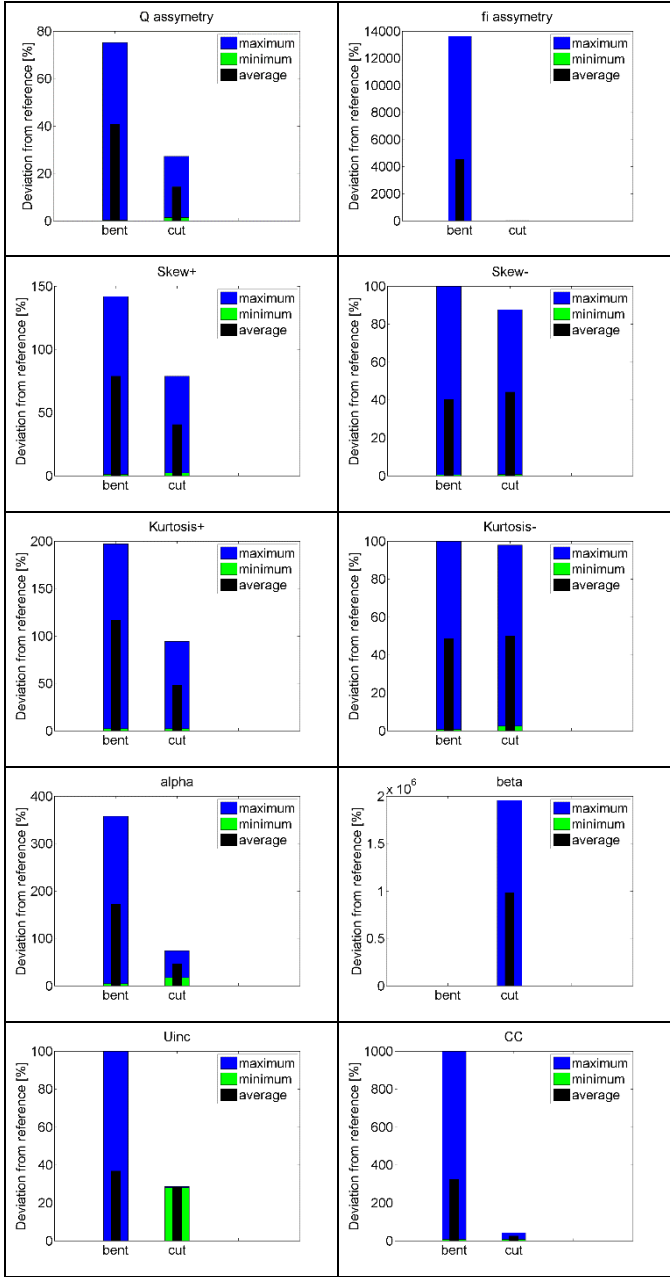


Fig. 107 shows the difference between the intact and damaged cable. The most obvious difference, causing also the changes in the statistical parameters is the appearance of discharges around the zero crossings of the test voltage.

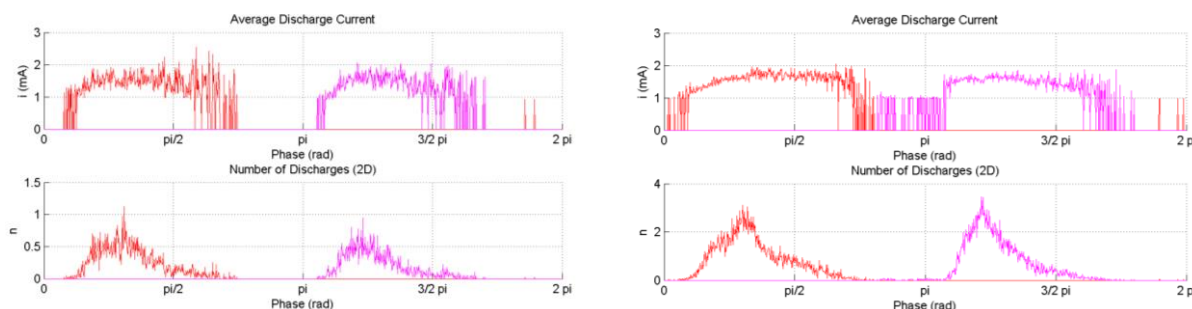


Fig. 107. Average discharge current and discharge number on new and damaged 5x1.5 mm² cable at 2.3 kV.

Almost all diagnostic parameters investigated in these experiments showed minor or major changes in mechanically damaged cables. However, in some cases the difference was obvious, because the discharges introduced into the pattern by the damage were not separated so clearly from the overall PD activity. Table XV. shows the parameters that underwent significant changes due to the defect, and appears to be good indicators of presence of damage.

TABLE XV. LIST OF PARAMETERS SHOWING SIGNIFICANT (>30%) CHANGES DUE TO THE DAMAGE.

	3x1.5 mm ²	5x1.5 mm ²	3x2.5 mm ²	3x4 mm ²
PD Height Distribution	+alpha, +area, -alpha, -area	-area	+alpha, +beta, +area, - area	-beta
Average discharge current pattern	+skew, +area, - area	+skew,	+skew, +area, - area,	-skew
Discharge number pattern	+kurtosis, -kurtosis	+kurtosis, +area, - area	+skew, +kurtosis, +area, - skew, - kurtosis, - area	none

The large number of statistical operators describing the PD patterns allows choosing those parameters that are altered significantly by defects, thus are suitable as diagnostic parameters. In case of each cable construction (core number and cross-section), such parameters were found; however, none of these parameters were significant for every cable type. Accordingly, to detect changes, all of them have to be applied and a zero condition (“fingerprint”) has to be available, as well.

IV.6. Tests on SiHF type cables

The SiHF type cable was the only unshielded type in the test series. In this case, there is no other option but to earth the cores not under measurement. Otherwise, the electric field around the core under test remains uncontrolled. Despite bringing earth close to the live core, the voltage had to be elevated to 150% of the test voltage to be able to detect discharges in new and in damaged cables as well (Table XVI and Table XVII). This may be the result of the silicone rubber being soft and elastic, allowing the strands of the conductor to be “embedded” into the insulating material.

TABLE XVI. DISCHARGE MAGNITUDES MEASURED ON A SiHF CABLE.

VOLTAGE	DISCHARGE MAGNITUDE [MA]		
	NEW CABLE	1 PINHOLE	2 PINHOLES
300	2.03	1.95	2.03
2000	3.38	2.35	2.62
3000	211.08	367.57	532.43

TABLE XVII. NUMBER OF DISCHARGES IN A SiHF CABLE.

VOLTAGE	NUMBER OF DISCHARGES PER PERIOD		
	NEW CABLE	1 PINHOLE	2 PINHOLES
300	0	0	0
2000	0	0	0
3000	15	31	39

Though the results are promising, the test voltage of the cable had to be violated, which would be a definitely unacceptable from an operator’s point of view. Additionally, in case of on-site measurements, these cables would exhibit very high noise levels due to the lack of shielding. Due to these factors, the further studies were focused only on shielded cable types.

IV.7. Tests on YSLCY cables

This shielded cable with stranded conductors showed extremely high levels of apparent charge measured by the conventional method (Table XVIII). This may be the result of the lack of the bedding, the very low radius of the individual strands of the conductor, or, apparently, that the 5 μ s impulse resolution capability of the device was violated (Table XIX).

TABLE XVIII. DISCHARGE MAGNITUDES MEASURED ON AN YCLSY CABLE.

VOLTAGE	DISCHARGE MAGNITUDE [PC]		
	NEW CABLE	1 PINHOLE	2 PINHOLES
500	30	30	30
1250	5000	7000	5000
2000	20000	20000	20000

TABLE XIX. NUMBER OF DISCHARGES IN AN YCLSY CABLE.

VOLTAGE	NUMBER OF DISCHARGES PER PERIOD		
	NEW CABLE	1 PINHOLE	2 PINHOLES
500	0	0	0
1250	118	158	110
2000	5781	5359	5428

In the case of this cable type, the conventional detector did not detect any tendency after it was damaged. Considering the discharge repetition rate, it is suspected that the discharge signals from the failure spot are suppressed by the discharge signals from along the cable. Therefore, in a later experiment, the discharges were measured by a high frequency current transformer. Two groups of samples were prepared, the cables in group 1 were 8 m long, while the cables in group 2 were 32 m long. PDIV was measured and the PDHD obtained in intact condition and after damage to the shielding was applied. The damage left the core insulation intact. The results are shown in Fig. 108 to Fig. 110.

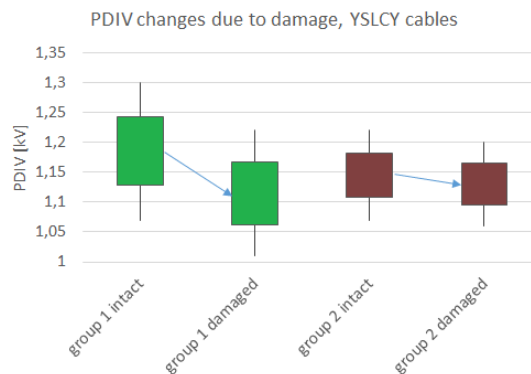


Fig. 108. PDIV change in YSLCY cables due to shielding damage

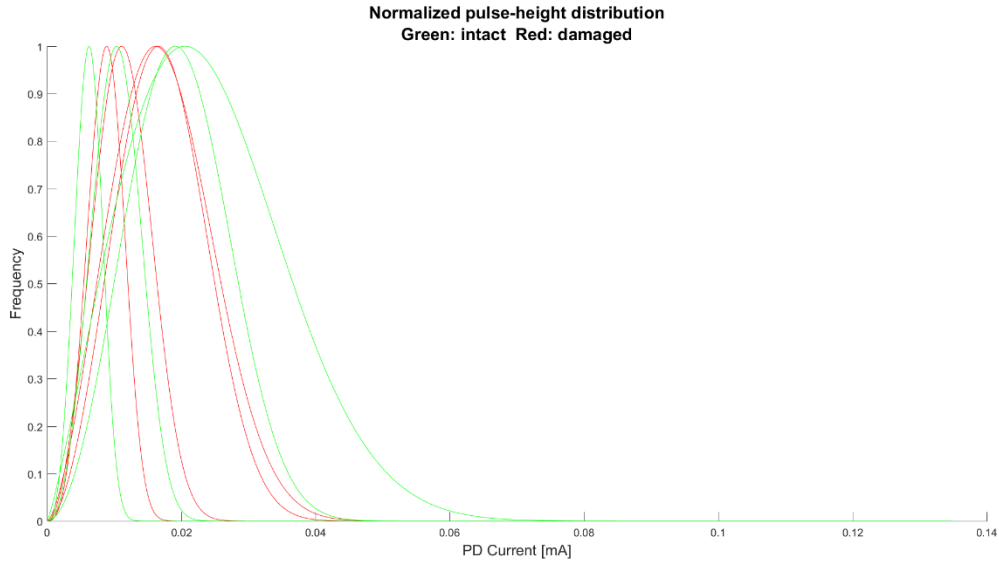


Fig. 109 Weibull fit of the PDHD of YSLCY cables group 2, before and after shielding damage

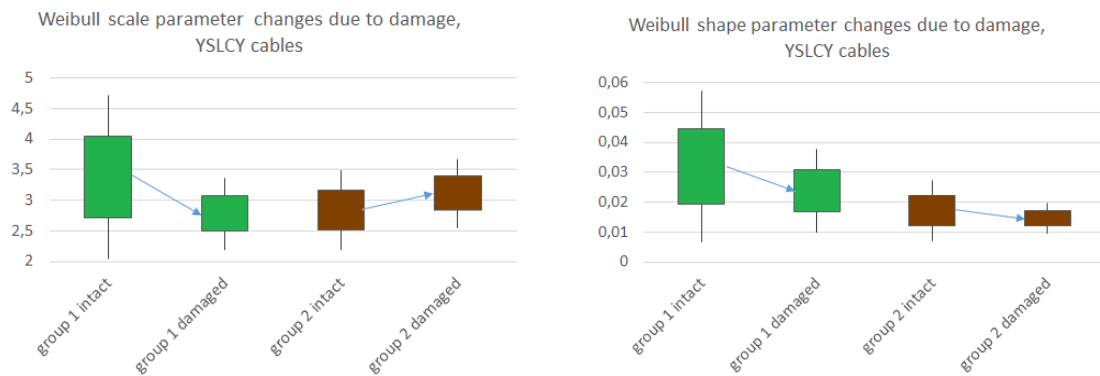


Fig. 110 Changes of the Weibull scale and shape parameters of the PDHD due to shield damage

The application of the HFCT proved to be more successful. The PDIV and the Weibull shape parameter proved to be able to detect the shield damage. However, the range of results on the damaged cables and intact cables overlapped, meaning that with these parameters, absolute diagnostics is not achievable, it is necessary to have the fingerprint of the partial discharges and degradation can be detected compared to that point.

IV.8. Tests on SZRMKVM-J type cables

The SZRMKVM-J type cables is among the most widely used in industrial applications, as it offers a good balance between cost and reliability, mainly due to its tape shield.

In the first set of experiments, half meter long samples were prepared, measured in new condition, then damaged by making a pinhole in them. This type of cable showed very low number of partial discharges (Table XX).

TABLE XX. NUMBER OF DISCHARGES IN AN SZRMKM-J CABLE.

VOLTAGE	NUMBER OF DISCHARGES DURING A PERIOD OF THE TEST VOLTAGE			
	NEW CABLE	1 PINHOLE	2 PINHOLES	3 PINHOLES
1000	0	0	0	0
2000	0	0	0	0
3000	7	24	12	8

However, the maximum discharge magnitude increased slightly, but consistently when the cable was damaged (Table XXI). In this type of cable the discharges did not incept or their magnitude remained under noise level until just below its test voltage. It may have been caused by the relatively low test voltage compared to the geometry of the cable.

TABLE XXI. DISCHARGE MAGNITUDES MEASURED ON AN SZRMKM-J CABLE.

VOLTAGE	DISCHARGE MAGNITUDE [mA]			
	NEW CABLE	1 PINHOLE	2 PINHOLES	3 PINHOLES
1000	1.95	1.78	1.89	1.95
2000	15.38	16.38	15.38	14.35
3000	155.41	162.16	177.30	180.81

In the next set of experiments, two groups of samples were prepared, group 1 with 8 m and group 2 with 32 m length. After reference measurement in new condition, the cables were damaged down to the shielding, while the core insulation was left intact. PDIV and Weibull fit and its parameters are shown in Fig. 111 to Fig. 113.

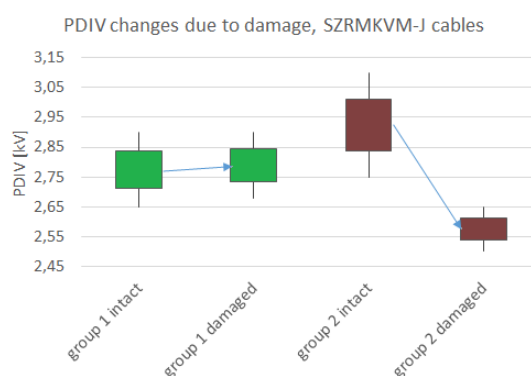


Fig. 111. Changes of the PDIV in SZRMKVM-J cables due to damage.

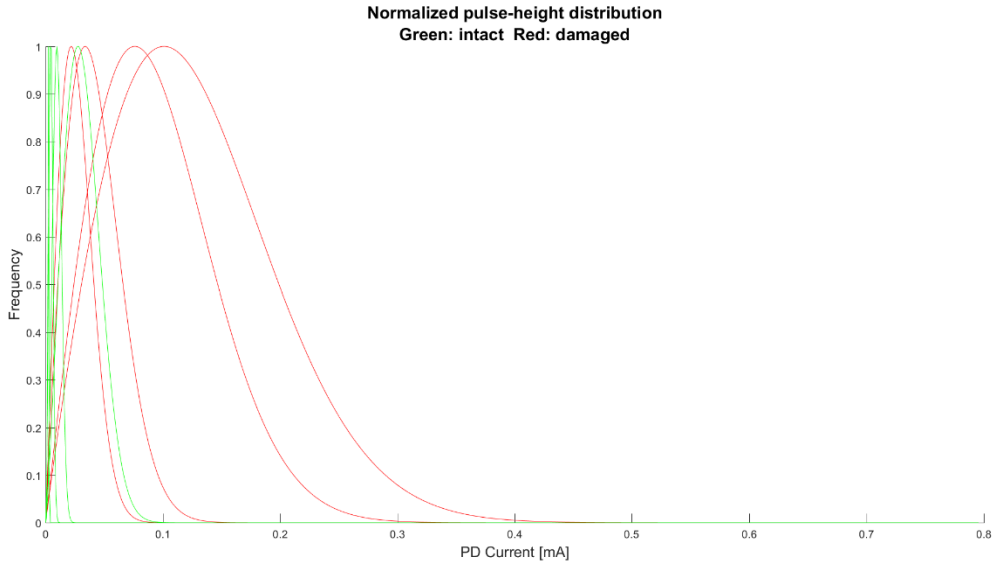


Fig. 112. PDHD Weibull fit of SZRMKVM-J group 1 cables before and after mechanical damage.

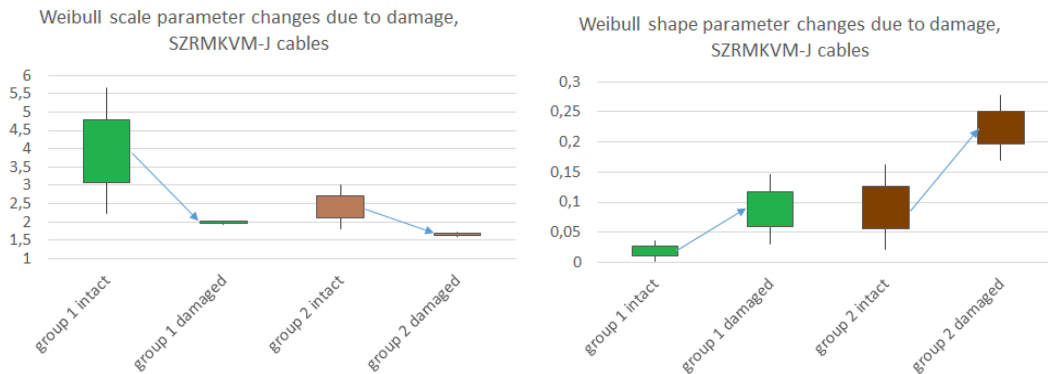


Fig. 113. Changes of the Weibull scale and shape parameters of the PDHD due to shield damage.

The PDIV in this type did not prove to be a useful parameter, but the Weibull fit of the PDHD showed significant changes. Both the scale and shape parameter are able to detect the damage, however, some overlap is present in the results, accordingly, diagnostics is possible by comparing the parameters to an earlier measurement.

IV.9. Summary of the applicable diagnostic parameters and the identified specialties

Table XXII summarizes the parameters that are applicable as diagnostic criteria. It is obvious from the results that all cable types need to be treated separately and the parameters should be selected based on the stress to be detected.

TABLE XXII. IDENTIFIED PROVABLE STRESSES AND THE RELATED DIAGNOSTIC PARAMETERS.

CABLE TYPE	STRESS	MOST EFFECTIVE PARAMETER(S)	TEST DURATION
RG-58	THERMAL	PD MAGNITUDE	TENDENCY OVER 20 MIN
		PDVI	MOMENTARY
		SKEW +/- (IN CASE OF SIGNIFICANT AGING)	TENDENCY OVER 20 MIN
		PDHD PARAMETERS (IN CASE OF SIGNIFICANT AGING)	MOMENTARY (FEW PERIODS)
		FUZZY CLUSTER CENTERS (INTERNAL)	MOMENTARY (FEW PERIODS)
	DAMAGES (CUT, PINHOLE)	DISCHARGE MAGNITUDE, KURTOSIS AND INCEPTION VOLTAGE	MOMENTARY (FEW PERIODS)
NYCY	DAMAGE (CUT)	PDIV	MOMENTARY
		INTEGRATED MAGNITUDE	MOMENTARY (FEW PERIODS)
		PDHD AREA	MOMENTARY (FEW PERIODS)
SIHF	DAMAGE (PINHOLE)	NUMBER OF DISCHARGES	MOMENTARY (FEW PERIODS)
YSLCY	DAMAGE (SHIELD)	PDIV WEIBULL SHAPE PARAMETER	MOMENTARY MOMENTARY (FEW PERIODS)
SZRMKVM-J	DAMAGE (PINHOLE)	NUMBER OF DISCHARGES DISCHARGE MAGNITUDE	MOMENTARY (FEW PERIODS)
	DAMAGE (SHIELD)	WEIBULL SCALE AND SHAPE PARAMETER	MOMENTARY (FEW PERIODS)

Low-voltage cables are not designed to be PD-free at their test voltage. They are manufactured without semiconducting layers and no attention is paid to make them absolutely void-free. Accordingly, the construction of the cables play a role in the occurrence of discharges. The type of the core (solid or stranded) determines how low the radius of curvature is on the surface of the conductor. Bedding is not always used in case of multiple core cables; accordingly there may be large voids within the cable. Nevertheless, they are PD free at their nominal voltage, which makes partial discharges only a diagnostic parameter and not a root cause of failures

In some cases extremely high values of discharge magnitude were detected, but the cables usually resisted them without breakdown, with only a few exceptions. As these discharges would lead to breakdown shortly within an insulating material, it can be concluded that these are not discharges surrounded only by insulating material. Some of them are suspected to be corona discharges occurring in the space between the conductor and core insulation. Such discharges occurring adjacent to a conductor, not affecting the insulation material, are the sole feature of low-voltage cables and is completely inexistent in higher voltage classes.

The lack of semiconducting layer has a further effect, namely these cables exhibit lower losses at high frequencies, as it was shown previously, the semiconducting layer has a significant effect on the PD impulse propagation in medium and high voltage cables [13]. This results in easier detection of discharges, but at the same time, if the cable cannot be terminated by its characteristic impedance, the reflection of the PD impulses cause false readings.

Furthermore, low-voltage cables are not equipped with stress-reducing terminations. Even though, the measurements performed on short and long cable specimens have shown that the sources of discharges are within the cable and not at its terminations. This was also confirmed by measurements under oil, where discharges at the terminations and at the interface of the shielding and the core insulation were excluded.

THESIS 3

I have shown that the most important specialty of the partial discharge diagnostics of low-voltage cables compared to medium and high voltage cables 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.

Based on my results, 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 stress. I have found that all types of low-voltage cables have to be investigated separately: the features of the measured signal able to diagnose

damages are characteristic for each type. 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.

PUBLICATIONS SERVING AS THE BASIS OF THIS CHAPTER AND THE THESIS

Z. A. TAMUS, R. CSELKÓ, I. BERTA, "PARTIAL DISCHARGE MEASUREMENT IN LOW VOLTAGE CABLE DIAGNOSTICS", CONFERENCE ON ELECTRICAL INSULATION AND DIELECTRIC PHENOMENA, 26-29 OCT. 2008, QUÉBEC CITY, CANADA

CSELKÓ, R, "RÉSZLEGES KISÜLÉSEK VIZSGÁLATA KISFESZÜLTSGŰ KÁBELEKBEN" ELEKTROTECHNIKA 101: 11 PP. 5-7. (2008)

Z. Á. TAMUS, R. CSELKÓ, I. BERTA: "APPLICATION OF PARTIAL DISCHARGE MEASUREMENT ON LABORATORY AGED LOW VOLTAGE CABLES", ELECTRICAL INSULATION CONFERENCE, MAY 31 – JUNE 3 2009, MONTREAL, CANADA

R. CSELKÓ, I. BERTA, "PARTIAL DISCHARGE MEASUREMENT EVALUATION WITH COMBINED STATISTICAL AND FUZZY TOOLS", 2ND INTERNATIONAL YOUTH CONFERENCE ON ENERGETICS, JUNE 4-6, 2009, BUDAPEST, HUNGARY

R. CSELKO, I. BERTA, "OCCURRENCE OF PARTIAL DISCHARGES IN LOW VOLTAGE CABLES DUE TO ARTIFICIAL MECHANICAL INJURIES", 2011 3RD INTERNATIONAL YOUTH CONFERENCE ON ENERGETICS, 7-9 JULY 2011, LEIRIA, PORTUGAL

R. CSELKÓ AND Á. Z. TAMUS, "OCCURRENCE OF PARTIAL DISCHARGES IN LOW-VOLTAGE CABLES AT THE FAILURE SPOT," 2012 IEEE INTERNATIONAL SYMPOSIUM ON ELECTRICAL INSULATION, SAN JUAN, PR, 2012, PP. 5-9.

R. CSELKO, I. BERTA, "CHALLENGES OF PARTIAL DISCHARGE DIAGNOSTICS OF LOW-VOLTAGE CABLES", JOURNAL OF ELECTROSTATICS, VOLUME 71, ISSUE 3, JUNE 2013, PAGES 558–563

CSELKÓ, R., GARCÍA, M. M., BERTA, I.: PARTIAL DISCHARGE CHARACTERISTICS OF NYCY LOW-VOLTAGE CABLES. IN: 2013 IEEE ELECTRICAL INSULATION CONFERENCE, OTTAWA, ON, 2013, PP. 138-141.

V. Outlook

V.1. The application of the results and further development

I have shown in my thesis the cases when partial discharge measurement offers a good solution to improve the reliability of low-voltage cables. I determined the appropriate measurement method and showed how diagnostic parameters can be extracted from the initial test results. At the current status of the research, it is safe to say that newly occurred damages to any type of low-voltage cable type can be diagnosed, if a fingerprint measurement of the initial condition is available.

The most important further development directions include the following:

- Searching for discharge parameters, presumably by the detailed characterization of individual discharge signals that may provide absolute diagnostic information.
- Improve the suppression capability of the two-HFCT method up to the level when it allow the application of switching mode electronic test voltage generators.
- Investigate the effect of inverters on the partial discharge behavior of the low-voltage utility and industrial distribution systems.

V.2. Further studies of partial discharges

Besides the research into the partial discharge behavior of low-voltage cables, I have investigated several further applications, which taught me many things about the physics of the discharges and thus helped with proceeding with the original research topic. Many parts of the below research was performed by my students under my scientific leadership.

V.2.1. Investigation of partial discharges during the tracking wheel test of composite insulators

The tracking wheel method [82] is a complex electrical, thermal and chemical aging method, that is able to detect the weaknesses of the surface material of non-ceramic (composite) insulators. The test duration according to the standard is almost three months, and is defined as a type test. However, there is an interest from utilities to apply this method as a sample test to ensure the continuously high quality of the installed insulators. To speed up the decision process, I have equipped the tracking wheel with partial discharge and leakage current measurement. The research focus, just as in case of low-voltage cables, is to find the methods to distinguish between the acceptable and non-acceptable discharges, that predict a failing insulator [S35].

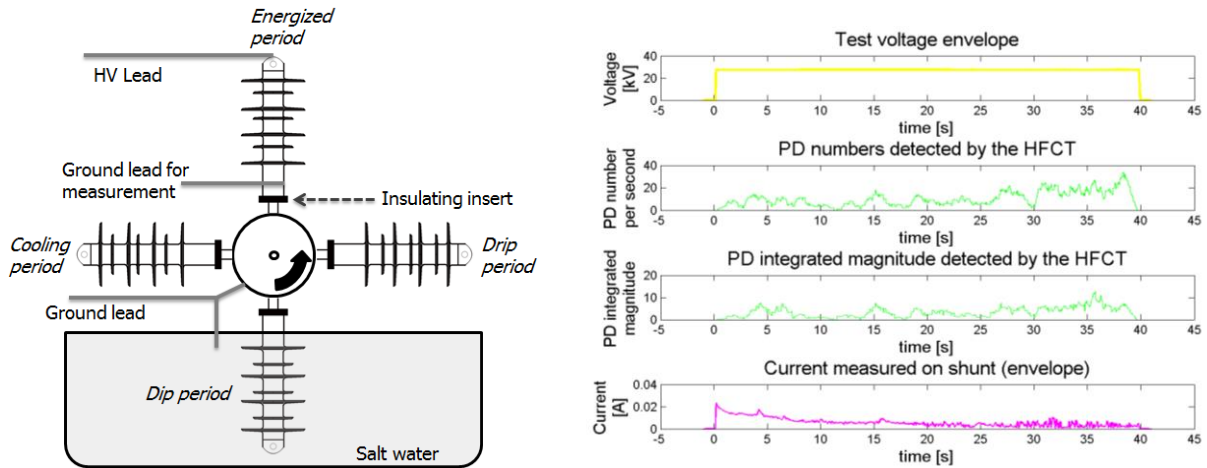


Fig. 114 Construction of the tracking wheel and partial discharges measured during an energized period in case of an insulator with almost hydrophilic surface

V.2.2.Measurement of partial discharges in transformers in the UHF range

Like in the case of cables, the increment of the bandwidth of the measuring system provides new opportunities. The most important one is that it allows the localization of the discharge sources, speeding up the repair process significantly. One of the challenges is to determine the propagation path and properties of the emitted signals in a complex insulation structure. The first step is to determine the complex permittivity of the insulating liquid in the UHF range [S29].



Fig. 115 Design and realization of 3D printed sensor for the determination of high frequency complex permittivity of dielectric liquids.

V.2.3.Early warning of the deterioration of live line tools

Various live-line maintenance tools are tested in the High Voltage Laboratory on a daily basis. The current standards prescribe go/no-go electrical tests, many of them using only the occurrence of flashover as a decision rule. If performed correctly, these measurements provide the required safety, however, do not give any indication of an ongoing deterioration. An answer to this problem might be parallel partial discharge measurements. The research

question is the same here, as surface discharges do occur normally during these tests [S25], accordingly, the features of deterioration need be identified.

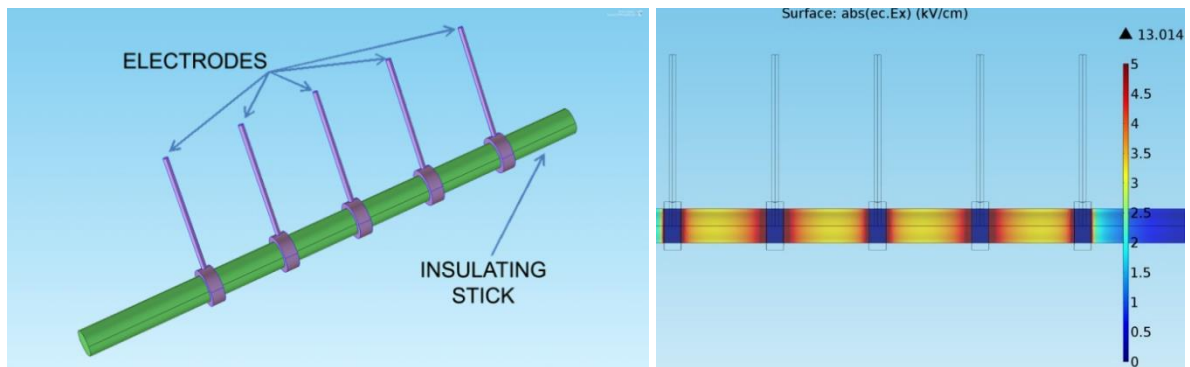


Fig. 116 Electrode arrangement for testing hot sticks and the tangential component of the electric field

V.2.4. Ozone generation with dielectric barrier discharges

Dielectric barrier discharges are intentionally generated partial discharges, where there is a need for controlled, low energy plasma. It can be achieved by covering the electrodes by dielectric barriers that prevent the formation of the (thermal) electric arc. One of its application is ozone generation. I have taken part in the design and optimization of a miniature ozone generator, manufactured with MEMS technology, in cooperation with the MEMS Laboratory of the Hungarian Academy of Sciences. The research question here is the opposite - what are the optimal parameters of the arrangement and voltage that provides the highest ozone output.

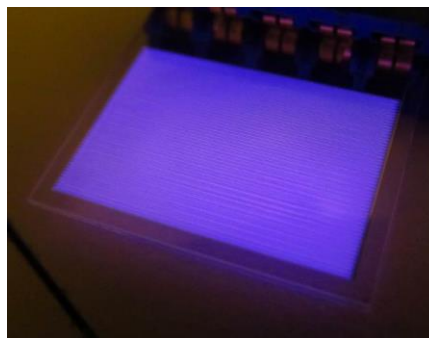


Fig. 117 Miniture MEMS DBD ozone generator during operation.

VI. Summary of the dissertation and the theses

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 from 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 it 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 and electrical 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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