On Partial Discharge/Corona Considerations for Low Voltage Switchgear and Controlgear

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***Abstract*—Electrical field and partial discharge (PD, corona) considerations usually are not in the foreground with low voltage switch- and control gear as per the product standards of IEC, UL and CSA. The design is mainly based on creepage and clearance dimensions, material categories described through CTI and RTI values. IEC product standards refer to the subject of insulation coordination as per the horizontal IEC 60664-family in their normative references. These standards, in principle, require PD measurements for rated voltages exceeding 500 VAC at room temperature. IEC 60664-2 gives some rules for consideration and electrical dimensioning of solid insulation. Miniaturization accompanied by increased power density and raised operational voltage as well as (non-sinusoidal) power supply generated by pulse width modulated (PWM) converters require to reconsider the relevance of electrical field stress in low voltage equipment. With variable frequency drive (VFD) fed motors reflected voltage waves were observed, causing partial discharge effects and insulation damages. Meanwhile motors and cables are available as VFD-proof versions. PD measurements on commercial manual motor controllers with sinusoidal voltages at both room temperature and a more severe elevated temperature related to the maximal operational temperature of the internal components (bimetal trip units) are presented. Conclusions are drawn and recommendations for future designs and testing are proposed.**

***Index Terms*—Partial discharge, corona, electrical field, manual motor controller, operational temperature, low voltage, variable frequency converters.**

I. Introduction

In the past, electrical field and partial discharge (PD) considerations were only taken into account when very high stress or very high reliability was required. In recent low voltage equipment high electrical field strengths can occur due to miniaturization and / or non-sinusoidal voltage application. As consequence the power density within the devices but also within switchgear assemblies rose and led to higher operational temperatures (within the limits given by standards). Additionally, insulation materials changed, e. g. from thermoset and ceramics to thermoplastics. That requires a reconsideration of this situation [1].

During development and application of low-voltage contactors and circuit-breakers over the last 20 years the topics “electrical field” and “partial discharges” appeared in different context:

- Opto-couplers e.g. in programmable logical controller (PLC) - interfaces of electronically controlled contactor coils were specified with PD < 5 pC as an option.
- For application in PV installations customers asked whether the requested switchgear does not fall below the PD extinction voltage $U_{e,peak} \geq 1.4$ kV and whether it does not exceed a PD level of 10 pC based on [2].
- Electrical field strength in electrode arrangements of manual motor starters or motor protection circuit breakers were investigated and optimized with regard to solid insulation properties [3].
- Another investigation of solid insulation of wiring accessories for switchgear was conducted in [4].
- In application of VFD fed motors insulation degradation in motors and cables was recognized due to short voltage rise times of the PWM voltage and reflected wave phenomena [5]. In this context also the term “corona” is used.
- Investigations on manual motor starters located at the output of VFDs, e.g. in multi motor applications, confirmed the occurrence of PD also in low voltage switchgear applications esp. with non-sinusoidal pulse voltage and long cable lengths to the motor [6].

In several parts of the world also the operational voltage and the tolerance resp. of the power grids has been raised during the past decades, e.g. 380 V to 400 V, 660 V to 690 V, + 10 % instead of + 5 %. The question remains whether these changes of the boundary conditions listed above require reconsideration of the standardization situation.

II. Standardization situation

Most low voltage product standards for switchgear do not directly require a consideration of partial discharge tests. However, the IEC standards at least refer to the horizontal standards of the IEC 60664 family which deals with insulation coordination in general [7], [8]. In [6] two criteria are defined according to which PD measurements shall be performed:

- the recurring peak voltage exceeds 700 V

and

- the (average) electrical field strength E across a solid insulation exceeds 1 kV/mm.

The recurring peak voltage is given through the maximum voltage rating. $U_{peak} = 700$ V corresponds to $U_{rms} = 495$ V, this means devices rated $U_{rms} = 500$ V and higher would need to be tested. In case of VFD applications, where multiple reflected voltage waves occur, the recurring peak voltage is at least doubled [5], [6].

The field strength criterion is more difficult to estimate. Due to complex geometries the simple calculation required by [6] (voltage divided by insulation thickness) is misleading since it would describe homogeneous fields only. In [4] it has been derived that at least an inhomogeneity coefficient of $\eta = 0.5$ to

0.2 or in other words a multiplication by 2 to 5 of the calculation result should be applied. Modern technology of computer simulation of course would be preferred instead. In any case PD measurements would be required at room temperature only. Exceptions are IEC62477-1 “Safety requirements for power electronic converter systems and equipment - Part1: General” [9] and IEC 61800-5-1 “Adjustable speed electrical power drive systems - Part 5-1: General requirements” [10]. These are the only standards found which describe the impact of temperature on PD measurement results and require that the type test shall be made under self-heating condition.

The limit of 5 pC found in literature in many places was derived for opto-couplers [1] or refers to the susceptibility of polymeric insulation materials like XLPE in cables [11]. The cable standard ICEA-T-24-380 Corona Test [12] reflects this value in conjunction with the extinction voltage as parameter. On the other hand the product standards for PV converters [2], VFDs [10] and power electronic converter systems [9] permit a limit of 10 pC, but an origin of this limit other than [1] is not retraceable.

III. Relevant Material Parameters for Electric Fields and Partial Discharges

An indirect, chemical detection of partial discharges on motor protection circuit breakers had been described in [6]. There the PD occurred in the context of VFDs and reflected voltage waves at the coils of the short circuit trip units (high surge impedance). This was accompanied by elevated temperature affecting also the coil formers until they melted.

Another encouragement to start some investigations was the consideration of insulation material properties with regard to usable electrical break down strength, depending on temperature and time, as well as the temperature dependency of the relative permittivity. In general the knowledge about insulation materials typically used in low voltage equipment is far less than of those used in high voltage applications.

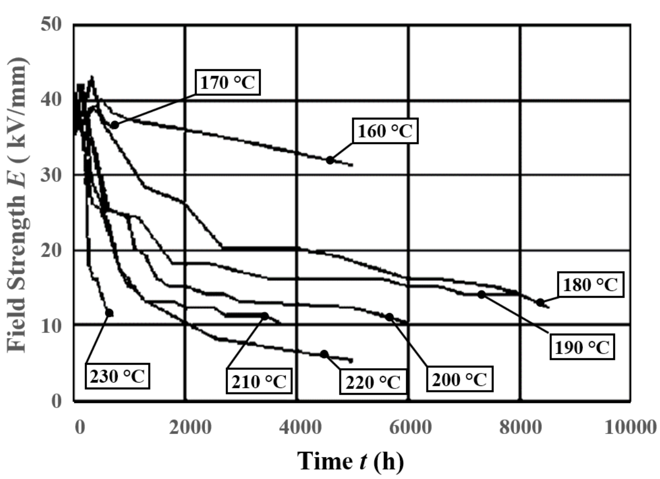


Fig. 1. Dielectric break down field strength E of a PET material Rynite 530 NC010, 0.8 mm thick, depending on temperature and time [13].

This kind of data is usually not generally available from material manufacturers or from literature. An example of the material degradation over time and temperature is given in Fig. 1 for PET [13]. As reference: 8760 h are one year, but expected useful service life of electrical power equipment is 10 to 20 times as long.

Usually designers refer to RTI (Relative Temperature Index) ratings as suitability criteria to select materials for the intended operational temperatures. These values do include some uncertainties related to their evaluation methods and they also imply that the relevant property has declined to 50 % of the initial value. In Fig. 1, e. g. for 180 °C, this condition is already reached after only 4000 h.

The electrical field distribution depends on the relative permittivity ε_r. Fig. 2 shows the temperature dependency of some examples of polyamide materials. The lower curves belong to temperature stabilized versions. Usually those curves are published for high frequency applications, i.e. measured at kHz or MHz frequency. Curves measured at different frequencies are not directly comparable. Values for 50 or 100 Hz applications are seldom available but may change considerably over temperature. Another significant influence is the condition of the material (dry or humid).

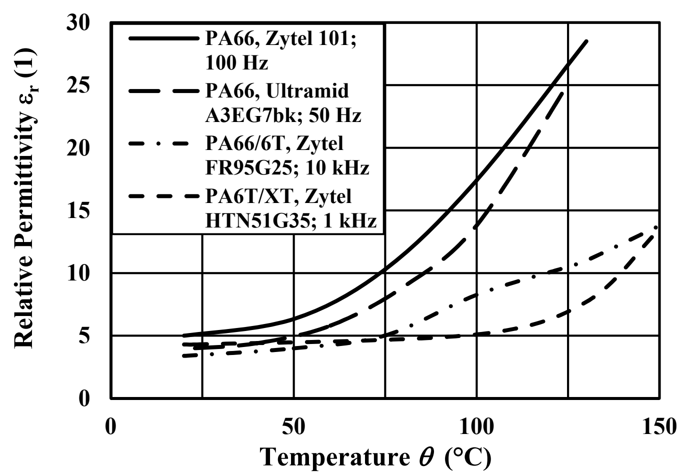


Fig. 2. Temperature dependency θ of the relative permittivity ε_r of dry Polyamides [14], [15] and [16].

In switchgears, usually a mixture of solid and gaseous (e. g. air) insulation is present. The dielectric strength of air is published as PASCHEN-curve which is valid for homogeneous fields [17]. As a reference value the breakdown field strength $\hat{E}_{d0}$ is 4 kV/mm at p·s = 1 bar·mm and room temperature T_0. The temperature dependency of the breakdown field strength is given through (1)

$$\hat{E}_d = \hat{E}_{d0} \left(\frac{p \cdot T_0}{p_0 \cdot T} \right)^{\alpha} \qquad (1)$$

with α = 0.7…0.8 [17], [18].

IV. Terms and Definitions for Partial Discharges

Some terms and definitions need to be listed for better understanding of the details [19].

1) *partial discharge (PD)*
   Electric discharge that only partially bridges the insulation between conductors, may occur inside the insulation or adjacent to a conductor. Usually given in pC.

2) *internal partial discharge*
   Partial discharge inside a solid insulating material.

3) *apparent charge*
   Indirectly measured value of the discharge, usually given in pC.

4) *corona*
   Set of partial discharges in a gas, immediately adjacent to an uninsulated or lightly insulated conductor, which creates a highly divergent field remote from other conductors.

5) *partial discharge inception voltage U_i*
   Lowest peak value of the test voltage at which the apparent charge becomes greater than the specified discharge magnitude when the test voltage is increased above a low value for which no discharge occurs

6) *partial discharge extinction voltage U_e*
   Highest voltage at which partial discharges are extinguished when the voltage applied is gradually decreased from a higher value at which such discharges are observed.

7) *specified partial discharge magnitude*
   Largest magnitude of any quantity related to PD pulses permitted in a test object at a specified voltage following a specified conditioning and test procedure. For alternating voltage tests, the specified magnitude of the apparent charge q is the largest repeatedly occurring PD magnitude.

8) *surface partial discharge*
   Partial discharge along, or onto, the surface of an insulation

The electrical field strength $\vec{E}_i$ and occurrence of partial discharges in gaps or in voids of a solid insulation depend on the local external field strength $\vec{E}$ and the relative permittivity ε_r of the surrounding material and can be calculated for different configurations (Fig. 3) [17], [18].

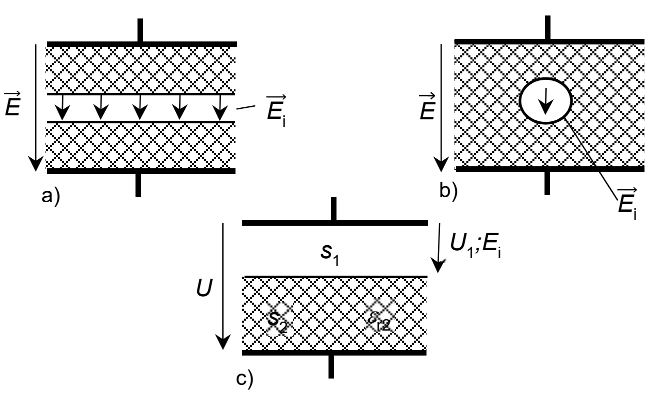


Fig. 3. Gaps and voids in a solid insulation [17].

As per (2) the plane gap within an insulation material (Fig. 3a) gives the highest internal field strength $\vec{E}_i$

$$E_i = \varepsilon_r \cdot E \tag{2}$$

The other shapes can be calculated as follows and give comparatively lower values:

perpendicular cylinder (Fig. 3b)

$$E_i = \frac{2\cdot\varepsilon_r}{1+\varepsilon_r}E \tag{3}$$

sphere (Fig. 3b)

$$E_i = \frac{3\cdot\varepsilon_r}{1+2\cdot\varepsilon_r}E \tag{4}$$

Based on $\varepsilon_r = 4$ the ranking of the internal field strength E_i in the gap is given in Table 3.

TABLE 3
RANKING OF THE INTERNAL FIELD STRENGTH OF DIFFERENT GAP AND VOID SHAPES

Shape	**Gap a)**	**Cylinder b)**	**Sphere b)**	**Gap c)**
E_i (%)	100	40	33	⩽ 100 (f(s; ε_r))

Gap (Fig. 3c)

$$E_1 = \frac{1}{s_1 + \frac{s_2}{\varepsilon_{r2}}}U \tag{5}$$

This shape in principle is representative for the current paths in switchgear and additionally depends on the distance s_3 (Fig. 4).

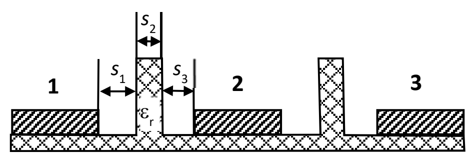


Fig. 4. Principle arrangement of electrodes and insulation walls in a 3-pole device.

V. CURRENT RESEARCH

Investigations on seven different designs of commercial motor protection switching devices (MPSD) as per UL/IEC 60947-4-1, rated currents I_{rms} = 2.5 to 25 A, maximal rated voltage U_{rms} = 690 V, 50 Hz, have been carried out. PD measurements were made at both room temperature (20 °C) and typical, maximal operational temperature of the bimetal trip units supports [2]. Although the investigated devices are of similar design some types operate at slightly lower temperatures. For comparison all were tested at elevated temperature of 130 °C. Samples C and E were additionally tested at 100 °C. The test procedure is described in detail in the following chapter.

A. PD - Measurement setup and procedure

1) Devices under Test (DUT)

The investigated switchgears, Fig. 5, are three-phase Motor Protection Switching Devices (MPSD).

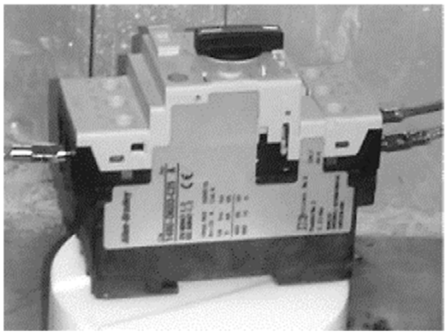


Fig. 5. Low-voltage Motor Protection Switching Device (MPSD)

2) Setup

The setup for the PD measurements is inside of an electrically shielded cabin with filters suppressing grid related disturbances and is shown in Fig. 6. It consists of a high voltage source, here a high voltage transformer (TEO 100), which provides the test voltage U, a resistor R = 50 kΩ and a coupling capacitor C_K = 1200 pF. The capacitor is in parallel to the DUT and in series with the PD measuring system (Omicron MPD 600) and the coupling device K. The PD detection device is a quadrupole with band-pass filter to detect the PD. The measured signals are digitalized and send via fiber optic cable to the recording device. The whole setup is built in accordance to the IEC 60270 standard [20]. Before testing of the DUTs, the whole setup is tested to be PD-free (q_{noise} < 1 pC) without the DUT but including the connections to it. The DUT is represented by the capacitance C_{DUT}. The DUT is mounted inside of a heating oven with an adjustable temperature, between room temperature and 150 °C, which is constantly measured using a Pt100-probe. The voltage is applied to the DUT inside of the oven through a bushing as described in [4].

Fig. 6a. Measuring setup.

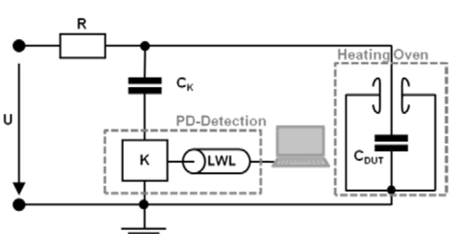


Fig. 6b. Measuring schematic.

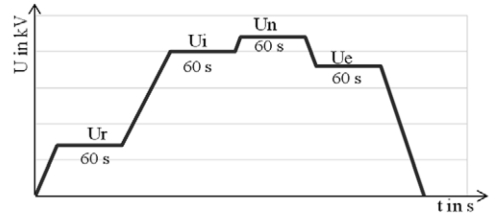


Fig. 7. Measurement procedure for PD testing [4].

3) Procedure

The middle phase of the MPSD is connected to high voltage potential and the two outer phases to ground via laboratory connectors which are fastened by the connector screws of the MPSD. The switch of the MPSD is put into the on-position in order to have the connected potential on both sides of the MPSD.

Other combinations of connections are possible, but have not been tested here as this setup covers the most common condition of the MPSD during operation and additionally stresses most of the insulation.

The MPSD is tested for PD at room temperature by increasing the voltage to 0.7 kV, which is the rated voltage U_r, with a constant rise of 7.5 kV/min. Subsequently the voltage is raised up to the inception voltage U_i at which the PD continuously initiate. If U_i occurs before reaching U_r, U_r is not recorded. Then a 200 V higher voltage than U_i is set, U_n, in order to observe changes in the PD pattern. Finally the voltage is lowered till no repetitive PD event occurs, which is the extinction voltage U_e. At each voltage step, the voltage is kept constant for 1 minute and the phase resolved PD pattern is recorded. Increasing the voltage to U_n before evaluating U_e could lead to a different result than when U_e is set directly after evaluation of U_i. Yet, the application of U_n is only for 60 s and is only 200 V higher than U_i. PD are a phenomenon associated to long-term aging and thus typically do not lead to a deterioration of the insulation during short applications. Therefore, a distinctive change is not expected and has not been observed.

This procedure of voltage application is done for all MPSD at all mentioned temperatures. At elevated temperatures the temperature is set to the required value and the oven heats up the device during one hour. When the temperature is reached it is kept constant for 30 minutes in order to ensure that the MPSD has the intended temperature as well. Then the oven is turned off to allow low noise level PD measurements.

4) Measurement Results and Interpretation

Test methods like phase-resolved measurement of partial discharges produce typical patterns which can be interpreted accordingly. As an example a typical phase-resolved test record of an MPSD with thermo-bimetal trip units is given in Fig. 8. The PD are depicted over the voltage phase angle where they occurred combined with a color/grey scale to give the number of PD initiations at a certain phase angle and charge amplitude. All patterns show a small deviation from the voltage peak and thus hint on a capacitive coupling to the initiation site of the PD. Furthermore, the pattern from 20°C to 130°C changes distinctively with considerably more PD events at 130°C. These changes may indicate the origin and type of the PDs.

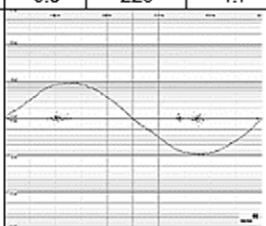
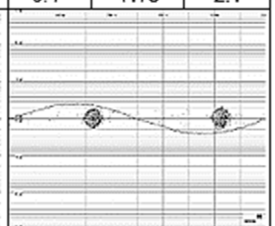
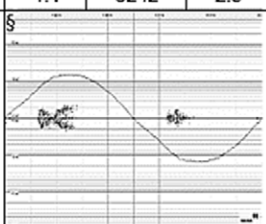
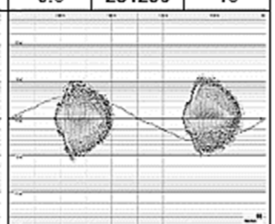
Temperature	20 °C			130 °C		
Sample C Rating 690 V	U [kV]	n discharges	q_a [pC]	U [kV]	n discharges	q_a [pC]
	0.7	none	no PD	-	-	-
U_i [kV]	0.9	226	1.7	0.4	4173	2.1
u_i, log q_a						
U_n [kV]	1.1	3242	2.5	0.6	231290	18
u_i, log q_a						
U_e [kV]	0.7	none	no PD	0.4	none	no PD

Fig. 8. Example of phase resolved partial discharge measurement on a MPSD at room temperature and at elevated operational temperature.

At room temperature the inception voltage of all samples was higher than the max. voltage rating of U = 690 V (U_i = 0.9 to 1.9 kV), the extinction voltage was higher or equal to the max. voltage rating (U_e = 0.7 to 1.7 kV). No partial discharges were recorded under this condition. So all types have passed the requirements of the existing standard [7].

The test results at elevated temperatures are summarized in Fig. 9. At 130 °C the range of inception voltage is U_i = 0.4 to 0.6 kV that of the extinction voltage is U_e = 0.3 to 0.5 kV. When tested at 100 °C ambient temperature the samples C and E achieved a 200 V higher inception voltage and 100 V higher extinction voltage.

5) Influence of the Insulation Material

At 130 °C the ratio between extinction and inception voltage is between 1 and 0.75, at 100 °C it is 0.83. Reference [18] states that for solid insulation the extinction voltage e.g. for internal PD is typically 10...35 % lower than the inception voltage. In this case the deviation observed is up to 25 %.

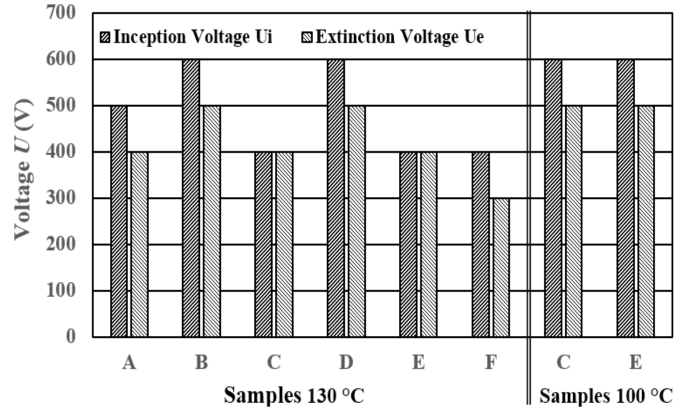


Fig. 9. Inception (U_i) and extinction (U_e) voltage during partial discharge measurements on Motor Protection Switching Devices (MPSD) at elevated temperatures.

Equation (1) [17]

$$\hat{u}_i \sim \left(\frac{1}{\varepsilon_r}\right)^{\alpha} \tag{6}$$

would predict a relation between inception voltages at elevated air temperatures compared to room temperature of 0.77 for 130 °C and of 0.81 for 100 °C. The observed ratios, however, were considerably lower, i.e. 0.2 to 0.44 at 130 °C and 0.4 to 0.45 at 100 °C. There had to be at least one additional factor involved. The inception voltage is roughly inversely proportional to the square root of the dielectric number ε_r with α = 0.45...0.5 [17].

Assuming the parameter was the relative permittivity only the use of equation (7) allows to conclude a "virtual relative permittivity" ε_{rv} at elevated temperature.

$$\hat{u}_{i\theta} / \hat{u}_{i20} \sim \left(\frac{\varepsilon_{r20}}{\varepsilon_{r\theta}}\right)^{0,5} \tag{7}$$

In these cases the result is ε_{rv} = 11 for the tests at 100 °C and ε_{rv} = 20…90 in the tests at 130 °C. The first case fits very well into the range of curves shown in Fig. 2. The second case with a large scatter starts in the plausible area but values above ε_{rv} = 30 are not realistic without additional effects. It is known that the relative permittivity also depends on the humidity [4] and [18]. In [13] and [14] values up to approx. 50 can be found.

However, the inception voltage of all tested types is below the maximal rated voltage. The extinction voltage is equal or even lower than the inception voltage. Since the capacitive character of the discharges implies a basically linear dependency of the charge value q_a on the voltage u_i as per (8)

$$q_a = k_c \cdot u_i \tag{8}$$

k_c - proportionality coefficient for a specific design

the discharge values of devices with measured inception voltage $U_{i,rms}$ < 700 V were extrapolated to 700 V. Table 1 shows the maximal discharge values at U_{rms} = 700 V and 130 °C. They exceed the limit of 5 pC by far. Two groups can be defined: Samples A, D, and E with 8 to 16 pC and samples B, C, and F with 26 to 29 pC. In open position the values may be higher or lower due to changed capacitive configurations [21], actual temperature, however, will be lower then, e.g. ambient temperature of 60 °C in an assembly. In all cases the specified limit of 5 pC could be kept at operational temperatures only with reduced conventional voltage ratings (see Table 1) as per existing measured values or the dependency (8).

Statistically most of the devices have been and are used at U_{rms} = 400 V in IEC related countries or U_{rms} = 480 V in North America. Under those conditions the discharge values would remain close to 10 pC for samples B, C, and F or far below that value for samples A, D, and E. This might explain that failures related to PD have not been recognized more frequently in the past. In practice the extinction voltage is decisive and needs to be at least 20 % above the recurring peak voltage to ensure basic insulation. Temporary overvoltage would require another 10 % on top [7].

TABLE 1
RATINGS AND DESIGN PARAMETERS OF THE INVESTIGATED MOTOR PROTECTION SWITCHING DEVICES (MPSD)

	A	B	C	D	E	F
rated Current (A_{rms})	25	4	4	2.5	2.5	4
max. rated Voltage (V_{rms})	690					
Thermal trip technology	Bimetal					Current Trans-former
max. Discharges at 700 V_{rms} (pC)	12	29	26	9	16	29
reduced Voltage Rating (V_{rms}) (limit 5 pC)	500	400	400	600	480	400
max. Discharges at reduced Voltage Rating (pC)	4	2	2	2	5	2

TABLE 2
RELATIONSHIP BETWEEN ELECTRODE RADIUS R AND CORONA INCEPTION VOLTAGE $U_{I,RMS}$ [22]

r [µm]	$U_{i,rms}$ [V]
10	450
50	1000
100	1400
500	3500
1000	5500
5000	15000

6) Influence of the Electrodes

The shape and the edge radii of the electrodes have a decisive influence on the value and the local distribution and degree of inhomogeneity of the electrical field strength [3]. The homogeneity or utilization coefficient η is mainly dependent from the electrode distance d and the electrode radius r [17, 22]. A reference model in [23] shows the relation between radius r and inception voltage U_i based on real dimensions (Table 2; [23]). The graphical depiction of Table 2 up to a radius of 0.5 mm in Fig. 10 shows clearly that the inception voltage decreases more rapidly below r = 100 µm corresponding e.g. to an inception voltage of $U_{i,rms}$ only 450 V with a radius of 10 µm.

The evaluation of FEM - simulations [24] on a realistic contact arrangement in Fig. 11 also shows the progressive rise of the field strength $\hat{E}$ once the edge radius is smaller than 0.1 mm and confirms the dependencies in Table 2 and Fig. 10.

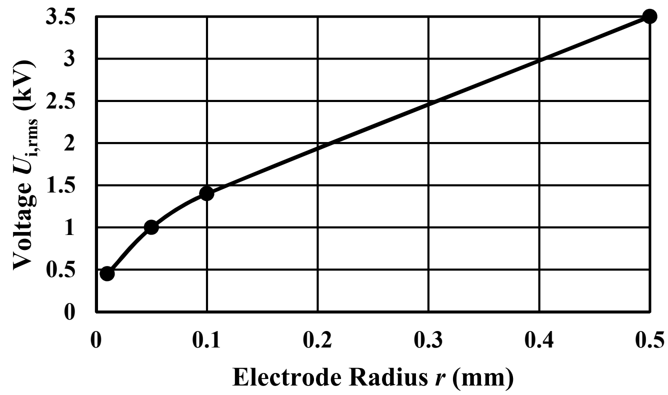


Fig. 10. Inception voltage $U_{i,rms}$ depending on the electrode radius r [23].

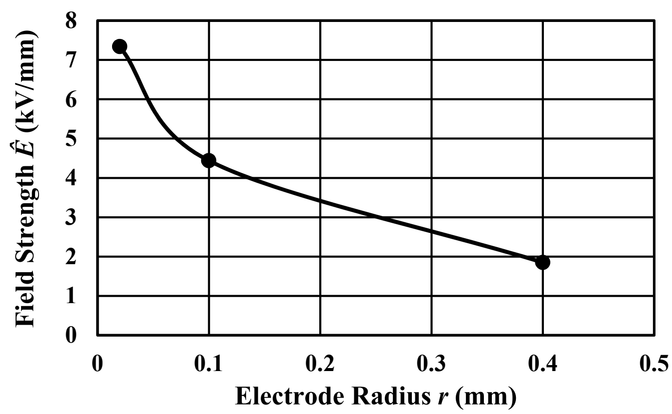


Fig. 11. Maximal electrical Field Strength $\hat{E}$ depending on the electrode edge radius r [24].

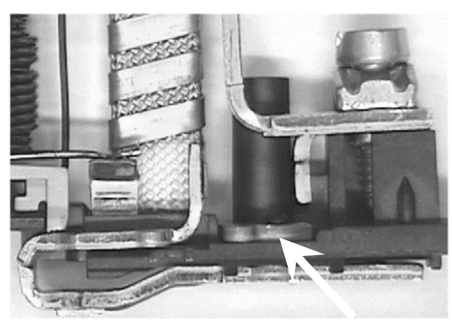


Fig. 12. Contact parts of an MPSD.

Fig. 12 shows an example of sharp edged parts e.g. a bimetal support. Reference [25] states that due to actual deburring technologies edge radii less than 25 µm can be avoided. On the indicated part in Fig. 12 radii with 20…60 µm were measured.

VI. Summarizing Discussion

Partial discharges (or corona) in electromechanical switchgear can and will appear in different ways: Through air directly (external PD), on surfaces of supporting parts (surface PD) and within voids of solid insulation components like phase separation walls (internal PD). Surface discharges in air have generally larger values than those in cavities [23]. In [21] a simulation is shown illustrating the potential locations of external PD generation in an MPSD.

For practical applications, in addition to the inception voltage, the extinction voltage is of relevance. Only if the permanent operational voltage remains below that value a discharge initiated e. g. by a disturbance can extinguish. Persisting repetitive PD would not only destroy adjacent materials thermally or by UV radiation but also chemically through ozone generation and formation of nitric acid. An experimental set-up with a motor starter combination supplied with U_{rms} = 690 V but negligible current and enclosed in a box produced easily smellable ozone after a few hours of operation. The perception limit of ozone in air is about 40 μg/m^3 [26].

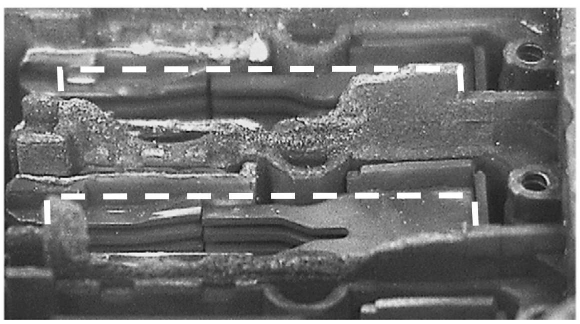


Fig. 13. Electrically eroded phase separation walls of an MPSD.

When the device A was investigated and optimized with regard to solid insulation breakdown due to elevated electrical field strength [3] there was not yet an additional consideration of a contribution through PD. In the retrospective, however, additional interpretations are possible. Partial discharges could have been present at that stage of design and could have contributed to the observed degradation of the insulation walls (Fig. 13). Dashed lines indicate eroded areas. With the optimized design no similar defects have been observed over more than one decade.

VII. Conclusions

- The occurrence of PD in low voltage switchgear has been proven esp. with motor protection switching devices at voltages above their rated voltage under the condition of operational temperature.
- Existing devices would pass the PD criterion (5 pC) of IEC 60664-1 (at room temperature only).
- The discharge values at maximal rated voltage and under operational temperature exceed the criteria of IEC 60664-1 by far. Extinction voltages were as low as U_{rms} = 300 to 400 V.
- The maximal voltage ratings should be limited to a level where at least the criteria of IEC 60664-1 are met.
- Future PD test requirements should include also measurements at operational instead of room temperature only.
- The solid insulation materials, e.g. Polyamides, need to be more carefully selected with regard to the degradation characteristic of the electrical breakdown strength over time and temperature.
- The dielectric number of Polyamides may considerably change over the temperature range. The materials should be selected by their 50 or 100 Hz characteristic.
- Edges of punched contact parts should not be smaller than 100 μm to avoid the occurrence of PD. A main task in the standardization work for switchgears is to accept the existing limits or to define a specific value. A justification for a value of a permissible discharge magnitude different from 5 pC or 10 pC at room temperature cannot be deduced from these investigations. Further research is needed.
- Ad interim the product standards for low voltage switchgear could follow the rule of 10 pC at room temperature according to standards of similar products [2], [19]. A level of 15 pC at operational temperature can be deduced from the relationships described above.

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References

[1] W. Pfeiffer, "Dielectric Testing of Solid Insulation with Respect to Insulation Coordination of Low-Voltage Equipment", IEEE Electrical Insulation Magazine, pp.34 - 47, May/June 2001

[2] Safety of power converters for use in photovoltaic power systems –Part 1: General requirements, standard IEC 62109-1

[3] H. Weichert, P. Frei. "Simulation of Electrical Field and Breakdown Phenomena in Low Voltage Circuit Breakers," in Proc. Int. Conf. on Electrical Contacts ICEC, Sendai, Japan, 2006, pp. 577-582

[4] N. Hill, M. Hilbert, M. Kurrat, H. Weichert, P. Benz. „PD measurements on low voltage busbars at operating temperatures," in Proc. VDE-Hochspannungstechnik, Berlin, Germany, 2016 pp. 172-177

[5] M. Melfi, J. Sung, S. Bell, G. Skibinski. "Effect of Surge Voltage Risetime on the Insulation of Low-Voltage Machines Fed by PWM Converters". IEEE Trans. on Industry Applications, Vol. 34, No. 4, 1998

[6] H. Weichert, P. Benz, S. Liberto. "Application of (Motor Protection) Circuit Breakers in Combination with Variable Frequency Drives," in Proc. 57th Holm Conf. on Electrical Contacts, Portland, OR, USA, 2012, pp. 94 -100

[7] Insulation coordination for equipment within low-voltage systems, standard IEC 60664-1

[8] Insulation coordination for equipment within low-voltage systems – Part 2-1: Application guide – Explanation of the application of the IEC 60664 series, dimensioning examples and dielectric testing, standard IEC 60664-2

[9] Safety requirements for power electronic converter systems and equipment, standard IEC 62477-1.

[10] Adjustable speed electrical power drive systems – Part 5-1; standard IEC 61800-5-1.

[11] E. Gockenbach, „Grundlagen für die Diagnostik," presented at ETG-Fachtagung Diagnostik elektrischer Betriebsmittel, Köln, Germany, 1993
[12] Guide For Partial-Discharge Test Procedure, Insulated Cable Engineers Association, Inc., ICEA-T-24-380-1994.
[13] Du Pont, data sheets of Rynite PET; https://dupont.materialdatacenter.com
[14] Du Pont, data sheets of Zytel; https://dupont.materialdatacenter.com
[15] L. W. Mc. Keen, "The effect of temperature and other factors on plastics and elastomers", 2nd Ed., William Andrew Inc., 2007
[16] I. Hennig, „Prüfverfahren zur Bestimmung elektrischer Eigenschaften von Thermoplasten," presented at SKZ Seminar Prüfen von Thermoplasten, 2009, Germany
[17] D. Kind, H. Kaerner, "High-Voltage Insulation Technology." Friedr. Vieweg & Sohn Verlagsgesellschaft mbH, Braunschweig / Wiesbaden, Germany, 1985
[18] A. Kuechler, High Voltage Engineering, Springer-Verlag, Berlin, Heidelberg, 20
[19] Electropedia, the free dictionary of electrical and electronic terminology and equivalent terms in 14 languages from the IEC, http://www.electropedia.org/
[20] High-voltage test techniques.Partial discharge measurements.
[21] K. Fuchs, D. Schaffrinna, H. Schorn, F. Berger, „Teilentladungen an Niederspannungs-Schaltgeräten bei erhöhten Temperaturen," in Proc. Albert-Keil-Kontaktseminar, Karlsruhe, Germany, 2017, pp. 231-237
[22] A. Schwaiger, „Elektrische Festigkeitslehre," Springer-Verlag, Berlin. Germany, 1925
[23] F. H. Kreuger, "Partial Discharge Detection in High-Voltage Equipment," Butterworth & Co. (Publishers) Ltd, London, UK, 1989
E-T-A, internal investigations (unpublished)
[25] K. Stimper, "The physical fundamentals of low-voltage insulation co-ordination", VDE-Schriftenreihe, Vol. 57, Berlin, Offenbach VDE-verlag1991.
[26] http://www.chemie.de/lexikon/Ozon.html