Concentrated Discharges and Dry Bands on Polluted Outdoor Insulators

Krystian Leonard Chrzan and Federico Moro

***Abstract*—This paper describes concentrated discharges on polluted insulators in the laboratory and in the field. The authors have observed the concentrated discharges at the high-voltage laboratories in Stuttgart, Zittau, and Mannheim, Germany, and Wroclaw, Poland. The concentrated discharges were also documented under natural conditions. These discharges are very dangerous especially for high-voltage apparatus, bushings, and polymer insulators. It has been shown that due to uneven voltage distribution at very low surface conductivity, the concentrated discharges can ignite even under uniformly polluted and uniformly wetted insulators.**

***Index Terms*—Leakage current, pollution, surface conductivity, surface discharges.**

I. Introduction

OUTDOOR insulation is contaminated by natural or industrial pollution (sea salt, salt sands, industrial dust). Additional sources of pollution are rain (e.g., acid rains) and gases—especially sulphuric oxide and nitric oxide (SO_X, NO_X). With heavily polluted areas, the surface conductivity on outdoor insulators can exceed the value of 100 μS, which leads to arcing development and eventually to flashover at continuous operating voltage.

Due to large environmental destruction in Middle Europe during the 1950s and 1960s, the faults caused by pollution flashover became an important factor in reliable power delivery. After the introduction of better insulators, the outage rate was limited to the acceptance level. During the 1980s and 1990s, the dust and gases emission in Middle Europe decreased considerably due to the production limitation of heavy industry and the introduction of new clean technologies. As a result, pollution flashover seems to no longer occur. Despite this comfortable situation, the stress caused by pollution should not be ignored.

This paper describes the phenomenon that can decrease the flashover voltage which is very dangerous for high-voltage apparatus and for polymer insulators [1].

II. Electrical Discharges During the Pollution Test in the Laboratory

During pollution testing, the real conditions are modeled by a simplified procedure and during a limited time. The method called "flow on" is characterized by a very simple procedure and short test duration. According to this procedure, the insulator is first covered by a contamination suspension, and then the completely wet insulator is stressed by the voltage whose value is close to the 50% flashover voltage [2]. During the voltage application, the insulator is not wetted. The pollution layer dries quickly due to the large current value at the test beginning and intensive discharges. As a result, flashover occurs usually in a time interval from a few tens of seconds up to 2 min after the voltage application and the current reaches a value of order 1 A. The test duration of other procedures is longer and insulators are continuously wetted (e.g., the standardized "solid layer" or "salt fog" methods).

Since the aim of the tests is the evaluation of 50% flashover voltage, the electrical discharges are very intense. The test voltage is usually higher than the continuous operating voltage and the degree of contamination is very high. As a result, the flashover probability is close to 50%. On the other hand, under natural conditions during dangerous events, such as rain, drizzle, or fog, the flashover probability is usually very low, close to zero. On lightly polluted insulators, the leakage current can reach a value of about 1 mA and, thus, the weak micro discharges are not visible, especially in sunlight. With heavily polluted insulators, the discharges can be intense, visible during the day and leakage current can reach a value of tens of milliamperes.

Intense discharges, with currents in the range of a few tens of milliamperes, are not stable. Their length can exceed the shed distance and often result in bridging phenomena, thus decreasing the leakage path length. The electrodynamic and thermal forces result not only in arc elongation but also in them moving around the insulator axis. The typical discharges during pollution testing using the "flow on" method are shown in Fig. 1(a).

The characteristic mode of these discharges is a very uniform distribution along the leakage path and long total length of the arcs. Immediately before flashover, the total arc length reaches about 60% of the insulator height. In practice, the arcs burn on each rod between the sheds.

In tests carried out according to the "salt fog" or "solid layer" methods, the discharges often concentrate at two places or even at one place on the insulator surface. This discharge type was documented probably for the first time by Gerhard Reverey from Studiengeselschaft fuer Hochspannungsanlagen e.V. in Nellingen, Germany [Fig. 1(b)] [3]. The weak discharges are not easy to observe due to dense fog or steam inside the pollution chamber. When the test stops and the fog is quickly removed, the dry bands become visible [gray areas in Fig. 1(c)]. The remaining wet-insulator part is dark.

Manuscript received June 20, 2005; revised February 7, 2006. This work was supported by the German Foundation DAAD. Paper no. TPWRD-00355-2005.

K. L. Chrzan is with the Wroclaw University of Technology, Wroclaw 50-370, Poland (e-mail: krystian.chrzan@pwr.wroc.pl).

F. Moro is with the Dipartimento di Ingegneria Elettrica, Università di Padova, Padova 35131, Italy (e-mail: federico.moro@di.unipd.it).

Color versions of Figs. 1–8 are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRD.2006.887093

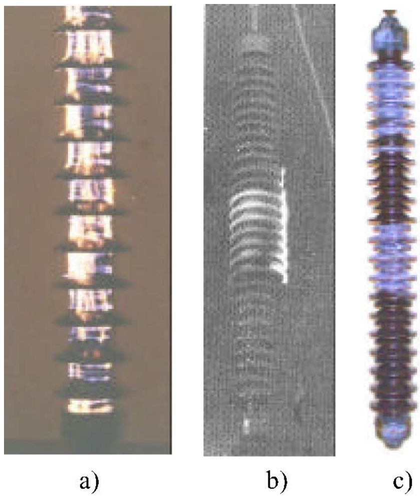


Fig. 1. Discharges and dry bands on long rod insulators. (a) Intensive discharges during “flow on” test on insulator VKL 75/14. (b) Reverey’s photography [3]. (c) Concentrated dry bands on insulator after finishing the pollution test according to the “solid layer” method.

Fig. 2. Intensive partial discharges inside a surge arrester.

A. *Pollution Test of Metal–Oxide Surge Arresters*

The aim of some pollution testing is not the evaluation of flashover voltage but the checking of thermal stability (e.g., surge arresters) or the aging resistance of the polymer material under the influence of electrical discharges. For surge arrester performance, the critical factor is a nonuniform voltage distribution after the dry band formation on their housing. The most dangerous case is the formation of a single, stable dry band in the vicinity of the upper or bottom flange. In this case, internal partial discharges can be initiated due to a high radial field between the pollution layer and the varistor column [4]. The internal discharges can develop due to very strong sparks that are able to break down the air channel inside a surge arrester (Fig. 2). In such a case, the deterioration of the varistors, or even the damage of the whole arrester, is possible [5].

The phenomenon of single dry band formation was observed first by the authors at the University of Stuttgart in 1988 during pollution testing of a two-unit surge arrester using the solid layer method for a dc voltage of 192 kV. The single dry band was formed at the top of the upper arrester unit with the width of two shed pitches. On the bottom arrester unit, the dry band was wider. The dry band on the upper unit flashed over about 70 times/s and this phenomenon caused high acoustic noise. Note that among ten performed tests, this event was noticed only during one test. The external leakage current on the top unit reached a value of 8 mA.

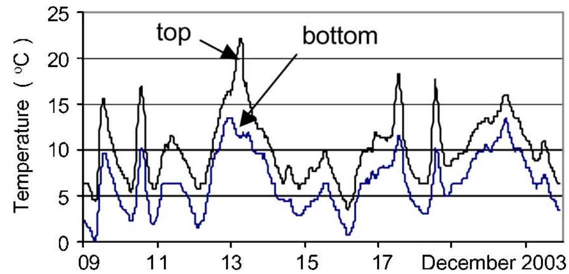


Fig. 3. Varistor temperature at the top and the bottom of a single–unit 110-kV metal–oxide surge arrester measured at the Glogow Pollution Station in December 2003.

The phenomenon of single dry band formation was observed also during the “salt fog” testing of a single unit arrester with an ac maximum continuous operating voltage of 77 kV [6]. To promote the single dry band formation, the fog density was decreased by lowering the solution output from the nozzles below the level described in IEC 60507 standard (to 0.3 l/min). Additionally, the nozzles were turned through an angle of 30° to decrease the number of droplets impacting the pollution layer directly from the nozzles. Despite these efforts, the formation of a single, stable dry band was observed during each third test only.

It is important to note that internal partial discharges can be present also when small glow discharges are burning in the region of a dry single band in the vicinity of the flange. When the external discharges develop to arcs, then the internal partial discharges extinguish due to more uniform voltage distribution along the polluted housing.

The presence of a stable dry band on a metal–oxide arrester in the field has not been documented up to now in the form of pictures. There are only indications in the form of varistor temperature changes measured inside surge arresters at the Glogow pollution station in Poland. The temperature of varistors was measured by means of two TINYTALK probes placed at the top and at the bottom of the varistor column [7]. Usually the temperature of the upper part of the varistor is only about 3 °C higher than that of the bottom part. These temperature differences are caused by the relatively low nonuniformity of voltage distribution along the varistor column under dry conditions.

Under wet polluted conditions, the temperature differences can be higher. Fig. 3 shows the highest temperature differences found after more than three years of testing. It was observed that the temperature at the upper part was 11 °C higher than at the bottom. The higher temperature at the top suggests the occurrence of a stable dry band on the arrester housing in the vicinity of the high-voltage flange [4].

The dust precipitation at the Glogow pollution test station is in the range of 0.4 g/m^2 per day and is classified with pollution level I (light). Under heavier pollution applied during the laboratory tests, the occurrence of higher temperatures and greater temperature differences between the upper and bottom part was noted.

Fig. 4. Dry band changes on a porcelain insulator with silicone rubber coating during the accelerating aging test according to IEC standard 61109 [9].

B. Accelerated Aging of Polymer Insulators

Many years ago, it was observed that small discharges with currents of order 1–3 mA are more dangerous for polymer insulation than stronger discharges with current of some tens of milliamperes or even more [8]. The material erosion caused by such small and stable discharges is very high. During accelerating aging of polymer insulators ("salt fog" test with duration of 1000 h), the formation of a single, stable, dry band was also observed sometimes. The dry band can move slowly during the test. Fig. 4 shows the porcelain insulator with a room-temperature vulcanized (RTV) silicone coating tested in salt fog according to IEC standard 61109 (accelerating aging test) at the University of Applied Science, Zittau/Goerlitz, Germany [9].

During the salt fog test, the silicone coating gradually lost its hydrophobic properties. When the surface becomes hydrophilic, the discharges can concentrate in a small region. The remaining surface is wetted by salt fog and the excess salt solution is removed from it by dripping. The test was interrupted after 200, 220, and 530 h. The white region represents the places where the stable discharges were observed. In the region of stable discharges, the water evaporates and gradually salt accumulation occurs. Salt deposits give rise to the white color noticed in Fig. 4. The experience gained with the accelerating aging test confirmed that the erosion in the test with a salinity of 40 g/l (intensive discharges occur) is smaller than with a salinity of 10 g/l or even 1 g/l (small but stable discharges occur) [10].

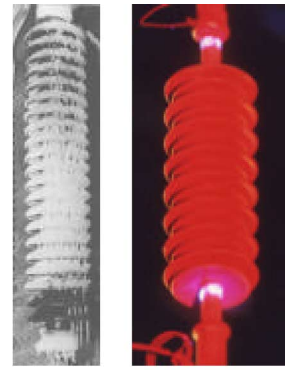
C. Icicle Test

During the testing of insulators under icicle conditions, it could be sometimes observed that the produced ice layer is very nonuniform due to ice melting in a small region Fig. 5(a) [11], [12]. The melting is caused by concentrated stable discharges during the freezing of water on the insulator surface.

III. Electrical Discharges Under Natural Conditions

Electrical discharges during pollution experiments in the laboratory are well documented, simultaneous current measurements and video records of discharges having been made. There are not so many documented observations of pollution discharges under natural conditions due to the difficulty of such experiments. The most interesting is the work of Mikio Kawai conducted in Japan and in the U.S. [13] and of Vosloo and Holzhausen in South Africa during recent years [14].

Usually, discharges under natural conditions are smaller than during laboratory tests. It means that the total discharge length is short compared with the leakage path length of the insulator. Additionally, these discharges are often not uniformly distributed along the leakage path but can concentrate in a narrow region. This results in a formation of a single dry band while the remaining insulator part is still wet. In the case of the long string of cap-and-pin insulators, so-called single unit flashover can occur [15]. This happens when the dry band extends to a whole disc insulator and the remaining discs are wet. This phenomenon occurs during drizzle, fog, or moisture condensation (during relatively low wetting) and can last for several hours. Three phases can be distinguished: light scintillation (glow corona), streamer development, and single unit flashover (arc).



a) b)

Fig. 5. Tests on long rod insulators. (a) Nonuniform ice layer during laboratory icing at the applied test voltage [11]. (b) Dry bands on a silicone rubber insulator at Koeberg pollution test station in South Africa. (Photo provided by Author W. Vosloo.)

Under natural conditions, the wetting process of the pollution layer develops often very slowly (e.g., during humidity increase and fog). Thanks to the hygroscopic properties of pollutants, moisture absorption from humid air is possible [16]. Therefore, the surface conductivity often increases when the relative humidity exceeds 75%. The nonuniform distribution of surface conductivity and the varying local diameter of the insulator cause variations in the local current density. In places where the current density is high, the layer temperature increases more quickly and water evaporates faster. As a result, the local resistance increases, the narrow dry band is formed, and small discharges are initiated. When the remaining pollution layer is still wetted, this state can then be stable for a longer time.

The single dry band can be formed even on silicone rubber long-rod insulators. Before the dry band can be formed on insulators with hydrophobic properties, their surfaces have to become hydrophilic. Fig. 5(b) shows the phenomenon on a silicon rubber insulator at the Koeberg pollution station in South Africa and proves that it is possible on such insulators too.

Concentrated discharges on porcelain insulators under natural conditions have been documented in various parts of the world. Usually, these are small discharges.

The location of discharges on the insulator is a matter of accident. Fig. 6 shows the discharges on the top, in the middle, and in the bottom of three line insulators. Fig. 7 shows a support insulator at the 400-kV substation of Neratovice in the Czech Republic. The picture was made by a thermovision camera during

Fig. 6. Discharges on 110-kV line insulators in Israel [17].

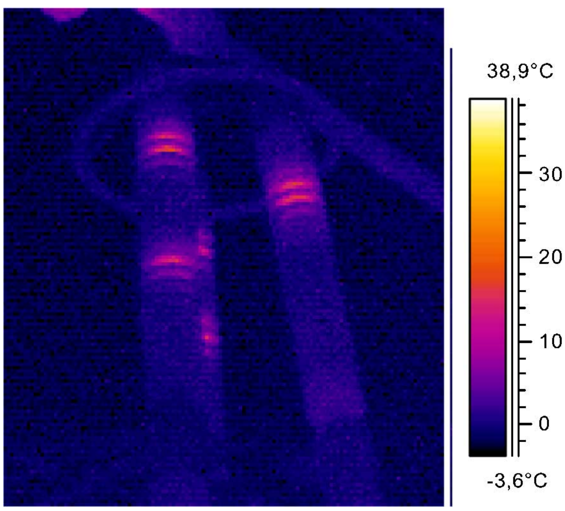


Fig. 7. Stable dry bands on 400-kV support insulators in the Czech Republic, the thermovision picture. (Photo provided by Author J. Dusbaba.)

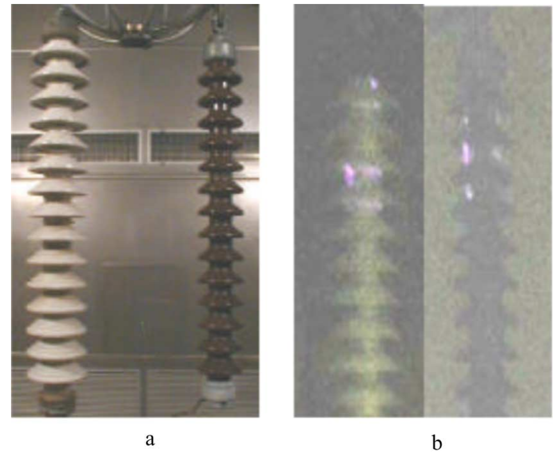


Fig. 8. Porcelain insulators in a climatic chamber. (a) Insulator view. (b) Concentrated discharges in high humidity conditions.

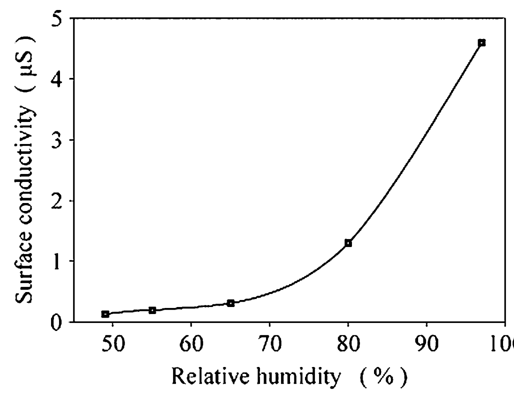


Fig. 9. Surface conductivity on uniformly polluted insulator VKL 75/14 as a function of humidity.

cloudy weather 20 min after the end of drizzle. The corona discharges were too small to be visible to the eye in daylight. Note that the temperature of the dry band region is about 8 °C higher than the ambient.

IV. Electrical Discharges in High Humidity Conditions

To study concentrated discharges under controlled conditions, two different types of porcelain insulators (VKL 75/14 and LPZs 75/15) were uniformly polluted by a suspension of bentonite. The mixture used for insulator contamination consisted of tap water (conductivity of 270 μS/cm) and bentonite with a concentration of 60 g/l and NaCl. The mixture conductivity was 10 mS/cm. After drying, the insulators were hanged in a climatic chamber with the following dimensions $305 \times 320 \times 420$ cm [see Fig. 8(a)].

First, the surface conductivity on VKL 75/14 was evaluated by a current measurement at a voltage of 5 kV. The humidity inside the chamber was increased from 49% up to 95%.

When the humidity reached the steady-state level, after 1 h of conditioning, the voltage was switched on and current was measured. A very small surface conductivity of 0.1 μS was found even at a humidity of 49% (Fig. 9). At humidity values greater than 75%, the surface conductivity increases faster because the salt starts to absorb the moisture. The conductivity at lower humidity levels is caused by the presence of other salts in the tap water and moisture absorption by bentonite. Similar low-surface conductivity at 50% relative humidity on bentonite polluted insulators was measured in [18].

Next, a voltage of 63 kV was applied, the concentrated discharges appearing shortly after voltage application, are shown on Fig. 8(b). The insulators were taken out from the climatic chamber a few times, dried, and put into high humidity again. It was observed that the discharges start to burn close to flanges (at the top or at the bottom) more often than in the middle.

V. Electric Field on Uniformly Polluted Insulators

The onset voltage of electrical discharges depends on local surface conditions, the degree of contamination, wetting conditions, and the distribution of pollution and insulator profile. To study the discharge ignition possibilities, an accurate analysis of the electric stress on the air-material interfaces at the beginning of moisture absorption is very important [19].

Integral formulations are particularly suitable in managing models with light contaminations since only the interfaces have to be discretized, thus limiting the computational effort. In this paper, a commercial code based on the boundary element technique (Electro 2D) was used.

The insulator VKL 75/14 with a 0.01-cm-thick uniform pollution layer was considered for different surface conductivity

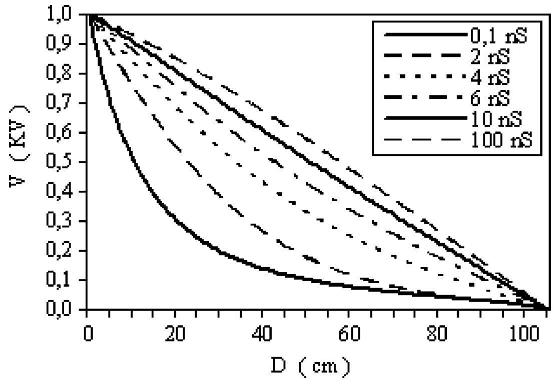


Fig. 10. Voltage distribution along the uniformly polluted insulator.

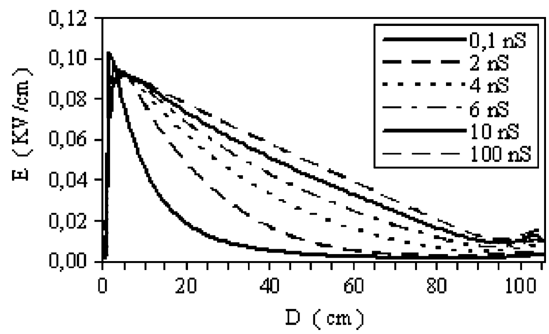


Fig. 11. Electric-field strength distribution along the uniformly polluted insulator.

values. The porcelain part of the insulator ($\varepsilon r = 6$ permittivity, $\kappa = 1.0 \times 10^{-10}$ S/m conductivity) was simplified by taking it to be a 105-cm-long cylinder 7.5 cm in diameter, thus neglecting local electric stress intensification due to the small radius of the curvature of the shed tips. Furthermore, the surface conductivity during the initial phase of moisture absorption by the pollution layer was taken to be a fixed parameter. The test chamber geometry was simplified by taking it to be a cylinder of 300 cm in diameter. The line conductors were not modeled in order to retain rotational symmetry. In this case, the field strength is higher near the top flange rather than toward the middle of the insulator.

Numerical simulations were carried out under quasielectrostatic (lossy) conditions to account for both capacitive and resistive effects on the field distribution. On the insulator live end (an aluminum flange, $\kappa = 34.5$ MS/m) a 50-Hz ac voltage of 1 kV (rms) was applied. Both voltage and electric field normalized strength distributions were computed for increasing surface conductivity values (from 0.1 to 100 nS) along a line at 1 mm from the insulator surface in the air region.

Figs. 10 and 11 show that voltage distribution along the uniformly polluted insulator tends to be linear if the surface conductivity is greater than 6 nS.

Fig. 12 shows that under almost dry conditions (0.1 nS), the electric-field strength is concentrated in the region next to the live end of the insulator. In particular, note that the electric field is zero at $\mathrm{D} = 0$ cm since it has to be continuous across the air-aluminum interface due to the same permittivity value of the materials.

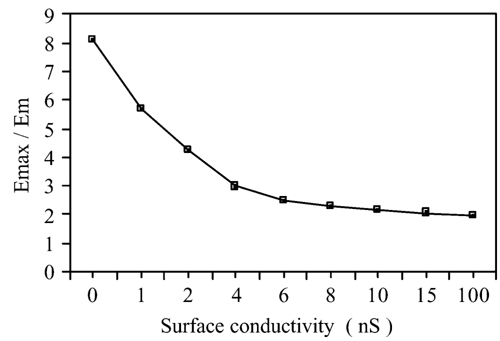


Fig. 12. Ratio between the maximum and mean strength values of the electric-field distribution as a function of surface conductivity.

Electric stresses become uniformly distributed beginning from a conductivity value of nearly 6 nS (Fig. 12). This should explain why in the presence of uniform pollution, concentrated discharges often develop in regions of the highest electrical stress, usually close to the live electrode. Under high humidity conditions, discharges can be concentrated in small areas, leading to dry band formation and material erosion.

VI. Conclusion

- Discharges and dry bands under natural pollution conditions can concentrate in relatively small regions. This phenomenon causes very nonlinear voltage distributions along the leakage path.
- Conditions of slight wetting (drizzle, fog, high humidity) are probably most favorable for building up concentrated stable zones. Their temperature is higher than the ambient, and leakage current is in the range of 1 mA.
- Concentrated stable discharges cause the degradation of polymer insulation. The related very nonuniform voltage distribution along the leakage path can initiate the ignition of internal partial discharges inside surge arresters or other high-voltage apparatus and can also decrease the flashover voltage of external insulation.
- The varistor temperature at the top of a single unit 110-kV arrester operating in lightly polluted environments, can sporadically be about 10 °C higher than the temperature at the bottom
- The electric-field strength dependence versus surface conductivity is highly nonlinear. Therefore, concentrated discharges occur even on uniformly polluted and wetted insulators in the regions of highest electrical stress.

Acknowledgment

The authors would like to thank V. Sklenicka, W. Vosloo, W. Petrusch, J. Dusbaba, and R. Munteanu for their photos. Also, thanks to Prof. R. Baersch for the delivery of two pictures and to Dr. W. Koehler for a valuable discussion.

References

[1] K. Chrzan, "Concentrated discharges and dry bands on polluted outdoor insulators," in *Proc. 12th Int. Symp. High Voltage Engineering*, Delft, The Netherlands, 2003, p. 227.

[2] B. Macciaroli and F. Turner, "A new contamination test method," *IEEE Trans. Power App. Syst.*, vol. 88, no. 9, pp. 1400–1411, Sep. 1969.
[3] G. Reverey, Hochspannungsisolatoren unter fremdschichteinfluss elektrizitaetswirtschaft band 58, 1959, H. 2 und 3.
[4] K. Feser, W. Koehler, Qiu, and K. Chrzan, "Pollution behaviour of polluted metal oxide surge arresters," *IEEE Trans. Power Del.*, vol. 6, no. 2, pp. 688–695, Apr. 1991.
[5] K. L. Chrzan, "Influence of moisture and partial discharges on the degradation of high voltage surge arresters," *Eur. Trans. Elect. Power*, pp. 175–184, 2004.
[6] K. Chrzan, Z. Pohl, S. Grzybowski, and W. Koehler, "Pollution performance of 110 kV metal oxide arresters," *IEEE Trans. Power Del.*, vol. 12, no. 2, pp. 728–733, Apr. 1997.
[7] K. L. Chrzan, "Temperature monitoring of metal oxide surge arresters," presented at the Int. Conf. Advances in Processing, Testing and Application of Dielectric Materials, Wroclaw, Poland, 2001, APTAM.
[8] M. W. Astle-Fletcher, "Proposal for preventing damage to high-voltage plastics insulators by surface electrical discharges," *Proc. Inst. Elect. Eng.*, pp. 183–184, Jan. 1970.
[9] R. Baersch, Univ. Appl. Sci, Apr. 2005. Zittau/Goerlitz, Germany, private communication.
[10] I. Gutman and R. Hartings, "Standard and reduced salinity 100 h salt fog test on silicon rubber apparatus Insulators," presented at the 10th Int. Symp. High Voltage Engineering, Montreal, QC, Canada, 1997.
[11] V. Sklenicka, "Venkovni izolace vvn v podminkach znecisteni," Ph.D. dissertation, HV Lab. EGU, Prague, Czechoslovakia, 1981.
[12] M. Farzaneh and J. F. Drapeau, "AC flashover performance of insulators covered with artificial ice," *IEEE Trans. Power Del.*, vol. 10, no. 2, pp. 1038–1051, Apr. 1995.
[13] M. Kawai, "Research at the project UHV on the performance of contaminated insulators. Part I. basic problems," *IEEE Trans. Power App. Syst.*, vol. 92, no. 3, p. 1102, May/Jun. 1973.
[14] W. L. Vosloo and J. P. Holzhausen, "Observation of discharge development and surface changes to evaluate the performance of different outdoor insulator materials at a severe coastal site," presented at the Int. Symp. High Voltage Engineering, Delft, The Netherlands, 2003.
[15] M. Fukushima, Y. Sunaga, T. Sasano, and Y. Sawada, "AN, RI, and TVI from single unit flashover of HVDC suspension insulator strings," *IEEE Trans. Power App. Syst.*, vol. 96, no. 4, pp. 1233–1241, Jul./Aug. 1977.
[16] K. Chrzan, Z. Pohl, and T. Kowalak, "Hygroscopic properties of pollutants on HV insulators," *IEEE Trans. Electr. Insul.*, vol. 24, no. 1, pp. 107–112, Feb. 1989.
[17] "Israel electric focuses on solving problems with insulators," Insul. News Market Rep., Jul./Aug. 1999, p. 24.
[18] C. S. Richards, C. L. Benner, and K. L. Buttler-Purry, "Electrical behavior of contaminated distribution insulators exposed to natural wetting," *IEEE Trans. Power Del.*, vol. 18, no. 2, pp. 551–558, Apr. 2003.
[19] W. L. Vosloo and J. P. Holzhausen, "The electric field on polluted insulators," *Proc. IEEE Africon*, pp. 599–602, 2002.

Krystian Leonard Chrzan was born in Odolanow, Poland, on October 15, 1955. He received the Dr.-Ing. degree from the Institute of Electrical Engineering Fundamentals, Wroclaw University of Technology, Wroclaw, Poland, in 1987.

Currently, he is with the Institute of Electrical Engineering Fundamentals of the Wroclaw University of Technology. From 1988 to 1989, he was a Scholar of the Alexander von Humboldt Fellowship at the High Voltage Laboratory of the University of Stuttgart, Stuttgart, Germany. From 1991 to 1993, he was with the high voltage laboratory of the Technical University of Zittau, Germany. He spent research stays at the high voltage laboratories in Stuttgart, Germany (1985, 1994, 1995, 1996, 1999, and 2003); Dresden, Germany (1995); Mannheim, Germany (FGH, 1996, 1997, and 2002); Prague, Czech Republic (EGU, 2001); Darmstadt, Germany (2002); Cardiff, U.K. (2004/2005); and at the Lightning Research Center Camp Blending in FL (2000). He is the author or coauthor of many scientific papers and the book *Surge Arresters for High Voltages*. His research interests include outdoor insulation, surge arresters, and lightning protection.

Federico Moro was born in Novara, Italy, in 1977. He is currently pursuing the Ph.D. degree in electromagnetic compatibility at the Dipartimento di Ingegneria Elettrica, University of Padova, Padova, Italy.

His research interests include numerical methods for electromagnetic modeling and related applications to electrical power devices.